CLIMATE CHANGE

SCIENTIFIC ASSESSMENT AND POLICY ANALYSIS

Scientific Assessment of Solar Induced Climate Change

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Wetenschappelijke Assessment en Beleidsanalyse (WAB)
Het programma Wetenschappelijke Assessment en Beleidsanalyse klimaatverandering in opdracht van het ministerie van VROM heeft tot doel:

- Het bijeenbrengen en evalueren van relevante wetenschappelijke informatie ten behoeve van beleidsontwikkeling en besluitvorming op het terrein van klimaatverandering;
- Het analyseren van voornemens en besluiten in het kader van de internationale klimaatonderhandelingen op hun consequenties.

Het betreft analyse- en assessment werk dat beoogt een gebalanceerde beoordeling te geven van de stand van de kennis ten behoeve van de onderbouwing van beleidsmatige keuzes. Deze analyse- en assessment activiteiten hebben een looptijd van enkele maanden tot ca. een jaar, afhankelijk van de complexiteit en de urgentie van de beleidsvraag. Per onderwerp wordt een assessment team samengesteld bestaande uit de beste Nederlandse experts. Het gaat om incidenteel en additioneel gefinancierde werkzaamheden, te onderscheiden van de reguliere, structureel gefinancierde activiteiten van het consortium op het gebied van klimaatonderzoek. Er dient steeds te worden uitgegaan van de actuele stand der wetenschap. Klanten zijn met name de NMP-departementen, met VROM in een coördinerende rol, maar tevens maatschappelijke groeperingen die een belangrijke rol spelen bij de besluitvorming over en uitvoering van het klimaatbeleid.
De verantwoordelijkheid voor de uitvoering berust bij een consortium bestaande uit MNP, KNMI, CCB Wageningen-UR, ECN, Vrije Universiteit/CCVUA, UM/ICIS en UU/Copernicus Instituut. Het MNP is hoofdaannemer en draagt de eindverantwoordelijkheid.

Scientific Assessment and Policy Analysis
The programme Scientific Assessment and Policy Analysis is commissioned by the ministry of the environment (VROM) and has the following objectives:

- Collection and evaluation of relevant scientific information for policy development and decision–making in the field of climate change;
- Analysis of resolutions and decisions in the framework of international climate negotiations and their implications.

The programme is concerned with analyses and assessments intended for a balanced evaluation of the state of the art knowledge for underpinning policy choices. These analyses and assessment activities are carried out within several months to about a year, depending on the complexity and the urgency of the policy issue. Assessment teams organised to handle the various topics consist of the best Dutch experts in their fields. Teams work on incidental and additionally financed activities, as opposed to the regular, structurally financed activities of the climate research consortium. The work should reflect the current state of science on the relevant topic. The main commissioning bodies are the National Environmental Policy Plan departments, with the Ministry of Housing, Spatial Planning and the Environment assuming a coordinating role. Work is also commissioned by organisations in society playing an important role in the decision-making process concerned with and the implementation of the climate policy. A consortium consisting of the Netherlands Environmental Assessment Agency (MNP), the Royal Dutch Meteorological Institute, the Climate Change and Biosphere Research Centre (CCB) of the Wageningen University and Research Centre (WUR), the Netherlands Energy Research Foundation (ECN), the Netherlands Research Programme on Climate Change Centre of the Vrije Universiteit in Amsterdam (CCVUA), the International Centre for Integrative Studies of the University of Maastricht (UM/ICIS) and the Copernicus Institute of the Utrecht University (UU) is responsible for the implementation. The Netherlands Environmental Assessment Agency – MNP as main contracting body assumes the final responsibility.

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Preface

The extent to which solar activity is a factor in climate change as compared to the human influence is a hot issue in climate research as well as in the public debate. In order to assess the understanding of the solar terrestrial relation, the Netherlands Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB) requested the Royal Netherlands meteorological Institute (KNMI) in 2003 to coordinate a project, which should include an assessment on the knowledge of the solar dynamo, the proxy records as well as on the understanding of the possible and probable mechanisms of climate change due to changes in solar variability. Since the literature on this subject is growing almost exponentially, this is a hard task. Most problematic is the fact that a vast number of hypotheses are brought up lagging the ways to validate these theories. It is not easy to resist almost perfect correlations between (derived) solar parameters and climate change even without understanding the underlying mechanisms. The immediate thought is that if you see smoke there should be a fire. However, understanding the principles of climate change is crucial to make statements on cause-effects relations. It has often been stated that the climate system is far too complex to be conclusive at all. This may be objected by the fact that also very complex systems obey the laws of physics. For the climate system a very robust constraint is the conservation of energy: what is going in must go out, at least on average. However, defining this averaging period is a problem due to the large range of time-scales related to the processes in the climate system.

Complex systems usually have non-linear and even chaotic behavior, resulting in the extreme case in no clear cause – effect relation. This is certainly the case if we try to forecast weather several days ahead, predicting the timing and location of pressure systems with their rainy frontal zones or in case of high pressure systems stable and mostly dry episodes. Uncertainties in the initial conditions result in growing errors with time, because small scale features are influencing large scale phenomena. Considering climate, the focus is on weather statistics. We actually remove the constraint on timing and location of pressure systems and try to find boundary conditions ruling average weather, i.e. the number and strength of storms or average temperatures occurring in a season. One of the boundary conditions is the change of energy flows at the top of atmosphere, referred to as radiative forcing. There is ample evidence that at least in the last few millennia radiative forcing and climate change are linked in an approximate linear way. This implies that the change in weather statistics can be described in terms of changes in solar radiation and changes in atmospheric composition due to natural causes (e.g. volcanic eruptions) and human activities (e.g. greenhouse gas emissions and aerosol production). Complicating factors are internal changes in the system, such as quasi-periodic changes in atmosphere, ocean and ice-cover. Some of these interactions are well-understood and can be taken into account as a change in boundary condition such as El Nino – Southern Oscillation. However, to which extent climate change is linked linearly with radiative forcing is a matter of debate: surprises do occur in the climate system as is demonstrated in transition periods from ice-ages to interglacials.

The Sun is a complex system as well. Solar activity is variable with five well-determined quasi-periodicities. Attempts to theoretically describe the solar dynamo, the engine of solar activity, have so far succeeded only in explaining the qualitative aspects. They fail in a numerical description and notably in one that would permit one to forecast solar activity with acceptable precision. This is so because the solar dynamo is a non-linear system that occasionally shows phase catastrophes. It is a quasi-periodic engine with the properties of deterministic chaos. The future of such a chaotic system is intrinsically unpredictable.

Writing an assessment report on the solar-terrestrial link is therefore a difficult task. It needs knowledge on the solar phenomena and recognition of features, which are potentially important for the Earth's climate. Furthermore, it needs knowledge on the mechanisms within the climate system to translate parameters of solar activity into a climate response. Since the observed climate fluctuations are the result of many influences on climate, separation of the various cause effect relations is a necessary, but almost impossible task. In this report three experts are giving their views on the solar terrestrial link. The consensus view is brought together in the executive summary and general conclusions.

Prof. dr. C. de Jager is emeritus professor on solar physics. He passed his doctor's thesis in Utrecht University (1952, cum laude) on the topic 'the Hydrogen spectrum of the Sun'. His research was since mainly directed towards determining the physical structure of the solar atmosphere and later on towards solar variability, chiefly the solar flare, its mechanisms and effects. He was director of the Utrecht Observatory, founder and first director of the Utrecht Space Research Laboratory, and founder of the Astrophysical Institute of Brussels University. He was president of COSPAR (international organization for Space Research) and of ICSU (Intl. Council for Science). He founded and was first editor of the journal 'Solar Physics'. He received honorary doctorates in Paris and Wroclaw. He was recipient of many awards and distinctions among which the Gold Medal of the Royal Astron. Soc.(UK), the Hale Medal of the Amer. Astron. Soc. (for solar research, US), the Jules Janssen Medal (for solar research, France), the Karl Schwarzschild Medal (for astrophysics, Germany), the Gagarin Medal and Ziolkowski Medal (space research, S.U.).

Dr. G.J.M. Versteegh is Guest Scientist at the Faculty of Geology, University of Bremen and Marine Biogeochemistry and Toxicology unit, Royal NIOZ. He graduated in Biology at Utrecht University in 1989 after visiting the Geological Institute of Oslo University he started a PhD at Utrecht University which was finished in 1995. Hereafter he moved to the Organic Geochemistry and Toxicology unit of Royal NIOZ. From his Ph.D. onwards his research concentrated on developing and evaluating proxies for environmental reconstruction. Through this work he became involved in evaluating evidence for solar variability and its environmental impact from the fossil record on decadal and centennial time-scales. Currently he is one of the prime investigators in two interdisciplinary and international projects directly and indirectly relate to this subject: 'Tropical environmental change and its teleconnections during the last deglaciation: a lipid biomarker study dated with ^{14}C wiggle-matching' and 'Possible solar forcing mechanisms on an alkenone-derived sea surface temperature record from the Gallipoli Platform (S. Italy)'.

The project leader dr. R. van Dorland is senior scientist at the Climate Research and Seismology Department of KNMI. He graduated in meteorology at Utrecht University in 1988 and got his PhD at the same university in 1999 on the topic 'Radiation and Climate: from Radiative Transfer Modelling to Global Temperature Response'. Onwards from 1988 his research work at KNMI was mainly related to the radiative budget of the earth- atmosphere system. Through this work he became strongly involved in the global warming problem and in the response of the climate system to variable solar radiation. Since 2004 he is a member of the Earth and Climate Council of the Royal Netherlands Academy of Arts and Sciences (KNAW). He is also involved as a lead author in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) working group I.

Rob van Dorland, 23rd of February 2006.

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Samenvatting

Het klimaatsysteem omvat de atmosfeer, de oceanen, de ijskappen, landoppervlak en de biosfeer. Naast fysische processen spelen ook chemische en biologische processen en hun onderlinge wisselwerking een belangrijke rol. Deze processen zijn actief op vele tijd- en ruimteschalen. De wisselwerking tussen de deelsystemen van het klimaat geeft aanleiding tot complex gedrag. Het klimaatsysteem wordt aangedreven door de energie afkomstig van de zon. Deze stralingsenergie wordt deels gereflecteerd naar de ruimte toe. Het resterende gedeelte wordt opgenomen (geabsorbeerd) door de atmosfeer en het aardoppervlak en wordt vervolgens omgezet in warmte. Deze warmte verlaat via infrarode straling het klimaatsysteem. De netto binnenkomende zonnestraling en uitgaande infrarood straling zijn gemiddeld over de aardbol en over een voldoende lange periode in balans.

Het klimaat is allesbehalve constant. Klimaatveranderingen worden veroorzaakt door een scala aan factoren, dat uitvoerig in de literatuur wordt beschreven. Bij klimaatveranderingen onderscheiden we interne variabiliteit en externe forcering. Interne variabiliteit – ook wel autogene forcering genoemd - wordt veroorzaakt door wisselwerkingen tussen de componenten van het klimaatsysteem met specifieke en verschillende tijdschalen van respons. In het gekoppelde systeem geven de vaak niet-lineaire wisselwerkingen aanleiding tot rode ruis, dat wil zeggen dat de amplitude van de klimaatfluctuaties in termen van temperatuur-, neerslag en circulatieveranderingen, toenemen met de tijdschaal. Spectra van klimaatvariabiliteit vertonen eveneens pieken, een manifestatie van resonanties veroorzaakt door terugkoppelings-mechanismen op specifieke tijdschalen. Externe forceringen worden veroorzaakt door veranderingen in één of meer deelsystemen van het klimaat (endogene forcering) of door veranderingen buiten het klimaatsysteem (exogene forcering), zoals veranderingen in de elektromagnetische eigenschappen of deeltjes emissies van de zon. Forceringen resulteren in veranderingen van de energie- en stralingsstromen in het klimaatsysteem. Interne variabiliteit en externe forcering zijn soms moeilijk te scheiden vanwege de altijd aanwezige terugkoppelingen of wisselwerkingen tussen de deelsystemen van het klimaat.

De belangrijkste invloed van de zon op het klimaat vindt plaats via de absorptie van zonnestraling door de atmosfeer en het aardoppervlak. De stroming in de atmosfeer wordt voor een groot deel bepaald door de verdeling van de geabsorbeerde zonnestraling en die van de uitgaande infrarood straling. Zelfs bij een constant niveau van zonneactiviteit worden klimaatprocessen dus beïnvloed door de zon. Duidelijke voorbeelden hiervan zijn de dagelijkse en jaarlijkse gang. Op de heel lange tijdschaal veroorzaakt de wisselwerking tussen de ijskappen en de periodieke veranderingen van de aardbaan, waardoor de totale hoeveelheid ontvangen zonne-energie in de poolgebieden gedurende het zomerseizoen varieert, het optreden van ijstijden en interglacialen.

Variaties in zonneactiviteit stellen het klimaatsysteem bloot aan additionele forceringen. Deze forceringen veroorzaken klimaatveranderingen op mondiale schaal en respons patronen op de regionale schaal, afhankelijk van het mechanisme van die invloed. Behalve een directe beïnvloeding via variaties in de totale hoeveelheid energie uitgestraald door de zon, wordt naarstig gezocht naar indirecte mechanismen, die de klimaatrespons versterken. Tenminste drie concurrerende mechanismen worden beschouwd:

(1) Kleine variaties in het zichtbare deel van het zonnespectrum, die de atmosfeer vanaf het aardoppervlak beïnvloeden.
(2) Variaties van ultraviolette (UV) straling, die rechtstreeks inwerken op de stratosfeer en de hoeveelheid ozon. Hierbij worden de lagere delen van de atmosfeer beïnvloed door veranderingen hogerop.
(3) Variaties van deeltjesstromen afkomstig van de zon of geïnduceerde modulaties van kosmische straling, die effect hebben op de elektrische en magnetische eigenschappen van de atmosfeer met gevolgen voor de atmosferische samenstelling hetzij door aërosolen- en wolkenformatie hetzij door effecten op de ozonconcentratie.

Verder kunnen directe en indirecte forceringen ten gevolge van variaties in zonneactiviteit in wisselwerking treden met interne klimaatvariabiliteit, zoals El Nino – Southern Oscillation (ENSO), de Northern Atlantic Oscillation (NAO) en de Quasi-Biennial Oscillation (QBO). Dit kan aanleiding geven tot het teweegbrengen, versterken of het verschuiven van deze klimaatmodi.

Overeenkomstige fluctuaties in reconstructies van zonneactiviteit en klimaatreeksen kunnen aanwijzingen geven van de invloed van variaties in zonneactiviteit op het klimaat, hoewel het in het algemeen onduidelijk is in hoeverre deze correlaties worden veroorzaakt door variaties in zonneactiviteit. De oorsprong van deze controverses is gelegen in het feit dat mogelijke zonnesignalen niet eenvoudig te onderscheiden zijn van andere bronnen van klimaatvariabiliteit, zoals de forceringen door vulkaanuitbarstingen, ENSO en lange termijn interne variabiliteit van het klimaatsysteem. Bovendien zijn de reconstructies omgeven met onzekerheden, waardoor een eenduidig bewijs van zon klimaat connecties niet eenvoudig te leveren is. Hoewel correlaties tussen zonneactiviteit en klimaatparameters niet beschouwd mogen worden als bewijs voor oorzaak gevolg relaties, kunnen ze wel een indicatie geven voor mogelijke onderliggende mechanismen van klimaatverandering door variaties in zonneactiviteit.

De respons van de diverse klimaatfactoren waaronder variaties in zonneactiviteit kan worden bestudeerd met behulp van gekoppelde atmosfeer-oceaan algemene circulatiemodellen (GCM's). Deze modellen dienen als gereedschap om het klimaat te begrijpen en om een schatting te maken van verstoringen van zowel natuurlijke als menselijke aard op het klimaat. Deze klimaatmodellen omvatten vele fysische en chemische processen en hun interacties. Evaluatie met waarnemingen is essentieel om vertrouwen te krijgen in de huidige generatie klimaatmodellen, hoewel een gelijkenis met de werkelijkheid in alle aspecten tot op heden onmogelijk is gebleken. Momenteel verschillen GCM simulaties vooral op de regionale schaal. Daarom is het niet eenvoudig om conclusies te trekken met betrekking tot oorzaak gevolg relaties, die zich op regionale schaal afspelen.

De kwantificering van de menselijke invloed op het klimaat hangt sterk samen met het begrip van het klimaatsysteem inclusief de natuurlijke variabiliteit, die aangedreven wordt door zowel interne variaties als externe forceringen. Eén van die externe forceringen wordt veroorzaakt door de veranderlijke activiteit van de zon. Vóór de industriële revolutie (die rond 1800 begon) kan de menselijke invloed worden uitgesloten en tot 1950 is deze invloed op mondiale schaal te verwaarlozen. De klimaatveranderingen die zijn opgetreden vóór 1950 zijn daarom bij uitstek geschikt om de impact van natuurlijke factoren op het klimaat te bestuderen. Helaas neemt de onzekerheid in de metingen toe naarmate we verder terug in de tijd gaan. Omdat metingen in principe lokaal zijn, kan verstoring door de mens ook plaatsvinden vóór de industriële revolutie, bijvoorbeeld door veranderend landgebruik. Een additioneel probleem bij het vinden van klimaatveranderingen door zonneactiviteit is dat verschillende natuurlijke forceringen en hun interacties met interne klimaatmodi gelijktijdig werkzaam zijn. Het is daarom van belang om ook de onderliggende mechanismen te begrijpen: met andere woorden begrijpen hoe de diverse factoren het aardse klimaat beïnvloeden. Dit vergt niet alleen begrip van relevante processen in het klimaatsysteem, maar ook begrip van de processen die de forceringen veroorzaken. In geval van de zon betekent dit het doorgronden van de zonnedynamo en de variaties daarin, die veranderingen in het elektromagnetische veld inclusief de afschermingeffecten van kosmische straling en deeltjesstromen van de zon teweegbrengen.

Het verloop van de isotopen ^{14}C en ^{10}Be in de laatste millennia is mogelijk een manifestatie van de magnetische activiteit van de zon. Veranderingen in de lichtkracht van de zon zijn pas sinds 1979 rechtstreeks door instrumenten aan boord van satellieten gemeten. De lichtkracht is gecorreleerd met het aantal zonnevlekken. Het waarnemen van zonnevlekkenaantallen is begonnen in 1610 en de reconstructie van lichtkrachtvariaties zou kunnen worden afgeleid met behulp van deze correlatie. Er zijn echter sterke aanwijzingen dat variaties in de geëmitteerde straling van de zon ook samenhangen met andere parameters van zonneactiviteit dan zonnevlekken. Het blijkt lastig om de mix van parameters, waaronder veranderingen in de magnetische activiteit van de zon te vertalen in lichtkrachtvariaties.

Om de huidige kennis van de zon klimaat connectie in kaart te brengen, heeft het Nederlands Onderzoeks Programma met thema "Global Change" (NRP-GC) zich tot het KNMI gewend met de vraag om een project te coördineren, waarin het huidige kennisniveau wordt verzameld op het gebied van de zonnedynamo, de reconstructies van zonneactiviteit en het klimaat alsook van de mogelijke en waarschijnlijke mechanismen van klimaatbeïnvloeding door de veranderingen van zonneactiviteit. Drie specialisten op het gebied van zonnedynamica, reconstructies van proxy archieven en op het gebied van de klimaatwetenschap presenteren in dit rapport hun kijk op de zon klimaat connectie. Ondanks de verschillende invalshoeken zijn we erin geslaagd gemeenschappelijke conclusies te trekken over dit thema. Dat neemt niet weg dat, hoewel de zoektocht naar de invloed van variaties in zonneactiviteit op het klimaat een lange geschiedenis heeft met een versnelling van wetenschappelijke ontwikkelingen in de laatste decennia, er nog vele hiaten zitten in het inzicht in de relatieve betekenis van de vele parameters die samenhangen met zonneactiviteit voor klimaatverandering, de interpretatie van de proxy gegevens en de kennis van mechanismen in het klimaatsysteem.

In dit rapport presenteren we de huidige inzichten in de volgende wetenschappelijke thema's:
(1) Reconstructies van zonneactiviteit, met een focus op die parameters die mogelijk relevant zijn voor klimaatverandering. Relevantie hangt sterk samen met (4).
(2) Reconstructies van proxies van zonnevariabiliteit, bijvoorbeeld de kosmogene isotopen.
(3) Reconstructies van zowel het mondiale als het regionale klimaat met betrekking tot temperatuur, neerslag en circulatie.
(4) Het fysische inzicht in de mechanismen van belang in de zon klimaat connectie.

We beperken ons in dit rapport tot het Holoceen, het tijdperk na de laatste ijstijd, met nadruk op de laatste eeuwen vanwege de beschikbaarheid van data en om verwarring te vermijden tussen de klimaatrespons door veranderingen in aardbaanparameters en die in zonneactiviteit. Bovendien is de 20^{e} eeuw interessant met betrekking tot de vergelijking van menselijke invloed en de klimaatveranderingen door variaties in zonneactiviteit.

Wat is bekend over variabiliteit van de zon?

- Zonneactiviteit manifesteert zich in vijf goed gedefinieerde quasi-periodieke veranderingen. Pogingen om de zonnedynamo theoretisch te beschrijven zijn tot op heden alleen succesvol geweest in het verklaren van kwalitatieve aspecten. De numerieke beschrijving schiet echter tekort, zodat het voorspellen van zonneactiviteit met een acceptabele precisie onmogelijk is. Dit komt doordat de zonnedynamo een niet-lineair systeem is dat soms fasecatastrofen vertoont. De zonnedynamo kan beschouwd worden als een quasi-periodieke motor met eigenschappen van deterministische chaos. De toekomst van een dergelijk chaotisch systeem is per definitie onvoorspelbaar.
- De zonnedynamo wordt gekarakteriseerd door interne toroïdale en de meer zich aan de oppervlakte manifesterende poloïdale velden met een wisselende en alternerende periode van 22 jaar. Vanuit deze twee componenten van het magnetische veld van de zon rijzen twee mogelijkheden voor de zon klimaat connectie op:

  (1) Variaties in de straling afkomstig van de zon, die samenhangen met die in het toroïdale magnetisch veld. De fractie van het zonlicht dat de onderste regionen van de troposfeer en het aardoppervlak bereikt wordt geëmitteerd door de fotosfeer van de zon. De betrekkelijk rustige fotosfeer varieert nauwelijks gedurende de cyclus. Het variabele gedeelte van de zonnestraling is voornamelijk afkomstig van het chromosferische deel van de Activiteiten Centra (CA). Deze straling met golflengten kleiner dan het zichtbare licht wordt voornamelijk geabsorbeerd in de hogere regionen van de atmosfeer (de stratosfeer en daarboven) en bereikt het aardoppervlak dus niet. Veranderingen, die een de troposfeer plaatsvinden moeten in dat geval een gevolg zijn stratosfeer-troposfeer koppeling. Het groepszonnevlekkengetal (R_G) is een maat voor de variabele component van de zonnestraling en voor de toroïdale veldfluctuaties.
  (2) De tweede component bestaat uit door de zon geëmitteerde plasma wolken, zoals de Coronale Massa Emissies (CME's) en plasma uitgestoten door de ephimerale regionen

op de zon. De CME's worden geëmitteerd vanuit de Activiteiten Centra op de zon. Deze zijn dus gerelateerd aan het toroïdale magnetische veld en dus geldt ook hiervoor dat het groepszonnevlekkengetal (R_G) maatgevend is voor de variatie van deze component. Overige coronale massa emissies houden verband met variaties in het poloïdale magnetische veld. Energetische emissies, zoals X-ray uitbarstingen, vertonen in het algemeen hun intensiteitmaximum ongeveer een jaar na het optreden van het maximum aantal zonnevlekken: dit wordt ook wel de Energetische Emissie Vertraging (Energetic Emissions Delay) genoemd. Het geëmitteerde gas vult als het ware de heliosfeer met gemagnetiseerd plasma. Door variaties van het magnetische veld in de heliosfeer wordt de aarde meer of minder afgeschermd voor de kosmische straling (CR). Modulatie is belangrijk voor deeltjes in de kosmische straling met energieën onder de 50 GeV. Deze deeltjes verhogen de ionisatie in de atmosfeer vanaf een hoogte van enkele kilometers en zijn betrekkelijk onbelangrijk nabij het aardoppervlak. De amplitude van kosmische stralingsvariaties hangt samen met de sterkte van de zonnecyclus. De atmosferische ionisatiegraad varieert met de intensiteit van kosmische straling. Volgens een hypothese beïnvloeden de wisselingen in ionisatiegraad de hoeveelheid bewolking op aarde. Hiermee kan de zon via dit plasma de aardse atmosfeer dus op een indirecte manier beïnvloeden. Kosmogene isotopen zoals ^{10}Be zijn proxies voor deze invloed en voor de poloïdale veldfluctuaties, hoewel deze proxies ook beïnvloed worden door variaties van het aardmagneetveld zelf.

- Het groep zonnevlekkengetal (R_G) en de kosmogene isotopen zijn, hoewel enigszins gecorreleerd, manifestaties van twee verschillende aspecten van de zonnedynamo met verschillende invloeden op het klimaat. Bovendien bereiken ze de maximum intensiteit niet gelijktijdig en moeten daarom als aparte parameters worden beschouwd. Er zijn gevallen bekend waarbij het ene aspect sterk varieerde, terwijl het andere aspect nagenoeg constant bleef. De verklaring hiervan is intrinsiek verbonden met de dynamotheorie.
- Nog nooit gedurende de laatste tienduizend jaar is de zon zo actief geweest in het uitstoten van gemagnetiseerd plasma als in de afgelopen halve eeuw, hoewel sinds 1950 de hoge zonneactiviteit nagenoeg constant is gebleven. Schattingen suggereren dat de zonneactiviteit momenteel over het maximum heen is en dat de komende decennia de activiteit mogelijk weer zal afnemen.

Wat vertellen proxy archieven over zonnevariabiliteit en klimaatverandering?

- Aanwijzingen voor de zonneactiviteit en klimaatveranderingen in het verleden liggen besloten in de instrumentele data (sinds 1700), historische bronnen (laatste paar duizend jaar) en proxies (laatste 10.000 jaar en verder terug) met een resolutie van één tot enkele jaren.
- Proxies geven aanwijzingen over klimaatveranderingen gedurende het relatief warme en stabiele Holoceen. Het aandeel van de zon in deze veranderingen staat ter discussie en is tegenwoordig heviger dan ooit vanwege de huidige combinatie van mondiale opwarming en de uitzonderlijk actieve zon. Publicaties voor en tegen de dominante rol van de zon in klimaatveranderingen, zowel mondiaal als regionaal, zijn in de literatuur te vinden. De aard van de klimaatrespons in combinatie met de geografische coherentie is van groot belang voor de evaluatie van mechanismen van de zonneforcering en de voor de validatie van klimaatmodellen.
- Informatie over klimaatveranderingen is door de natuur opgeslagen in bijvoorbeeld boomringen, veen, stalagmieten, landijs, meer- en marine sedimenten. Kosmogene isotopen in sedimenten, zoals ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl, vormen de belangrijkste informatiebron van zonneactiviteit in het pre-instrumentele tijdperk. Deze natuurlijke archieven zijn vaak continu over lange perioden and vormen als zodanig nuttig studiemateriaal, ook om de beperkingen van instrumentele reeksen aan te vullen.
- Kosmogene isotopen worden gevormd door hoogenergetische deeltjes, die de atmosfeer binnendringen en vervolgens botsen met atomen in de lucht, waarbij zeldzame en onstabiele isotopen ontstaan. De zonnewind beschermt de atmosfeer tegen het binnendringen van deze deeltjes in tijden van hoge zonneactiviteit. De productiesnelheid van de kosmogene isotopen neemt af als het magnetische veld sterker wordt, dus als de zonneactiviteit

toeneemt. De vorm van het magnetische veld veroorzaakt een toename van de productie van kosmogene isotopen van evenaar naar de magnetische polen.

- De productie van kosmogene isotopen wordt verder beïnvloed door fluctuaties in het aardmagnetische veld, die ontstaan door wisselwerkingen tussen de mantel en kern van de aarde. Het nauwkeurig in kaart brengen van de veranderingen van het aardmagnetische veld is dus van belang voor het begrijpen van het zonnesignaal. Kleine veranderingen in de lange termijn trend van het aardmagnetische veld kunnen de archieven van kosmogene isotopen dermate verstoren dat het moeilijk is om de amplitude en soms zelfs het teken van de zonneactiviteit af te leiden.
- Interpretatie van de proxy archieven wordt bemoeilijkt door:
  (1) vertaling van de proxies in kwantitatieve klimaatparameters
  (2) het verkrijgen van een goede datering
  (3) het ophelderen van ruimtelijke patronen en verbanden hiertussen
  (4) het scheiden van de zonneforcering van andere forceringen
  (5) het gebrek aan een compleet fysisch begrip van de mechanismen waarmee de aspecten van de zonneactiviteit het klimaat beïnvloedt.
- Om deze redenen wordt het in kaart brengen van de zonneactiviteit in het verleden vaak beperkt tot de identificatie van correlaties tussen zonneactiviteit enerzijds en klimaatverandering anderzijds. De centrale vragen zijn dus: waar, hoe en wanneer zijn klimaatveranderingen opgetreden, en hoe en in welke mate wordt het klimaat beïnvloed door de diverse parameters van zonneactiviteit?
- Hoewel de oceanen ongeveer 2/3 van de aarde beslaan, is het marine milieu ondervertegenwoordigd in de klimaatarchieven. Deze tekortkoming werkt door in het begrijpen van zowel de kwantitatieve als kwalitatieve aspecten van mechanismen werkzaam in de zon klimaat connectie.
- Alle frequentie componenten, die verondersteld worden met zonneactiviteit samen te hangen, komen tot uiting in de klimaatarchieven. Door ruis en veelal tekort schietende resolutie in de tijd kunnen de hoogfrequente signalen niet worden opgelost. Dit betreft voornamelijk de 11-jaar en 22-jaar cycli. Daar staat tegenover dat langzamere variaties, zoals de circa 90-jaar Gleissberg en de circa 200-jaar Suess cycli zowel in de ^{10}Be en ^{14}C data als proxy voor zonneactiviteit als in de archieven van klimaatverandering wel goed vertegenwoordigd zijn. Ook verschijnt de circa 1500-jaar Bond cyclus in diverse klimaatreconstructies.
- Waarschijnlijk worden de lange termijn klimaatveranderingen gedurende het preïndustriële tijdperk gedomineerd door de zonneforcering. De aanwijzingen van dergelijke zon klimaat connecties zijn echter wel ongelijk verdeeld over de aardbol. Dit suggereert dat de lange termijn respons op een verandering van zonneactiviteit een regionaal karakter heeft, waarbij het signaal in sommige regio's de amplitude door andere oorzaken van natuurlijke variabiliteit overtreft.
- De zonneforcering lijkt vooral een grote impact te hebben op de regionale neerslag en verdampingbudgetten. Dit suggereert dat het mechanisme van de door de zon gegenereerde klimaatveranderingen via variaties in de verdeling van latente warmte opereert. De oceanen spelen hier wellicht een grote rol in, hoewel nog onduidelijk is hoe.
- Verder suggereren proxy archieven dat variaties in zonneactiviteit vaak een verschuiving van klimaatregimes veroorzaken, die samenhangen met veranderingen in circulatiepatronen. Dit induceert op diverse locaties een niet-lineair signaal en is mogelijk de verklaring voor het feit dat er in archieven discontinuïteiten en fasesprongen gevonden worden. Deze complicerende factor bij het in kaart brengen van de zon klimaat connectie vraagt om een niet-lineaire analyse van proxy archieven met een hoge tijdsresolutie op de regionale schaal, aangezien alleen een regionaal netwerk de eventuele verschuivingen van klimaatregimes en daarmee zon klimaat connecties kunnen ontrafelen. Helaas is de analyse van niet-lineaire effecten van de zonneforcering nog een onontgonnen onderzoeksgebied, hoewel belangrijke klimaatmodi, zoals ENSO en de Arctische Oscillatie (AO) ook niet-lineaire dynamica volgen.
- Een bron van onzekerheid is de sterkte van de zonneforcering in vergelijking met andere forceringen. Voor diverse regio's manifesteert het zonnesignaal zich alleen gedurende perioden met grote veranderingen in zonneactiviteit. In geval van kleine variaties wordt het signaal overstemd door de respons op andere forceringen, zoals vulkanisme, of door interne

variabiliteit. De signaal ruis verhouding in de analyse van proxies kan waarschijnlijk verbeterd worden door de perioden met gelijke (veranderingen in) zonneactiviteit en de detecteerde klimaatrespons te middelen.

- Een aantal en goed gedateerde studies wijzen op een vroege en bijna instantane klimaatverandering als respons op perioden met snel afnemende zonneactiviteit. Aangezien een dergelijke instantane respons het aantal mogelijkheden voor de mechanismen van de zon klimaat connectie beperkt, zou het realiteitsgehalte en de algemene geldigheid van dit fenomeen beter onderzocht moeten worden.

Kan zonneactiviteit gereconstrueerd worden?

- Sinds 1978 worden met behulp van stralingsinstrumenten aan boord van satellieten de totale hoeveelheid zonnestraling (TSI) gemeten. Deze meetreeks is continu, maar is wel samengesteld aan de hand van verschillende instrumenten. In deze periode, die ruim twee zonnevlekkencycli beslaat, laten de waarnemingen een periodieke verandering in de totale hoeveelheid zonnestraling zien met maxima rond 1980, 1990 en 2001 en minima rond 1986 en 1996. Deze variaties corresponderen goed met zonnevlekkenaantallen. Het verschil in TSI tussen de maxima en minima bedroeg ongeveer 1 Wm^{-2}, ofwel iets minder dan 0,1% van de zonneconstante. Verder kan op basis van de metingen geconcludeerd worden dat de geëmitteerde energie door de rustige zon, dus bij afwezigheid van zonnevlekken, nagenoeg constant is: de gevonden verschillen zijn kleiner dan 0,01%, zodat er geen sprake is van een significante trend in de laatste 26 jaar. Spectrale metingen laten zien dat variaties bij alle golflengten optreden. De stralingsveranderingen correleren positief met de zonnevlekkencyclus met relatief kleine veranderingen in het infrarode deel van het spectrum en grote verschillen in het ultraviolette deel.
- Lange termijn veranderingen in de hoeveelheid straling afkomstig van de zon zijn in het algemeen gebaseerd op drie waarneembare grootheden, terwijl de calibratie meestal wordt uitgevoerd op schattingen van de verschillen tussen het Maunder Minimum (1645-1715) en de huidige rustige zon:
  (1) Veranderingen in de aa-index als een maat voor de magnetische activiteit van de zon: deze index wijst op een veel hogere activiteit van de huidige zon ten opzichte van het begin van de metingen, zo'n anderhalve eeuw geleden. Recente studies opperen de mogelijkheid dat de lange termijn trends in de aa-index gedeeltelijk te wijten zijn aan instrumentele afwijkingen.
  (2) Reconstructies van kosmogene isotopen wijzen op fluctuaties van kosmische straling, die terug te voeren zijn op de magnetische activiteit van de zon. Simulaties van het transport van de magnetische flux in de zon en de propagatie van de open flux naar de heliosfeer laten zien dat trends in de aa-index en kosmogene isotopen, beide gegenereerd door de open flux, niet noodzakelijkerwijs gelijke trends opleveren in de door de zon geëmitteerde totale hoeveelheid straling (de zogeheten gesloten flux).
  (3) De bandbreedte van variabiliteit bij zonachtige sterren. Hoewel voorheen gesuggereerd werd dat de zon in staat is een veel grotere reikwijdte aan activiteit te vertonen dan is waargenomen in de meest recente zonnevlekkencycli, laat een heranalyse van gegevens van zonachtige sterren zien dat de huidige zon veel meer een normale ster is dan bovengemiddeld actief ten opzichte van andere sterren.
- Volgens de meest recente inzichten in de bovengenoemde drie peilers, waarop de reconstructie van TSI is gebaseerd, is de lichtkracht van de zon vanaf het Maunder Minimum (1645-1715) tot de huidige rustige zon (d.w.z. bij afwezigheid van zonnevlekken) toegenomen waarschijnlijk met 0,5 Wm^{-2}, met een hoogste schatting van 1,6 Wm^{-2}. Wanneer ook de effecten van de 11-jarige zonnevlekkencyclus worden meegenomen, wordt de beste schatting van de lichtkrachttoename van het Maunder Minimum tot de huidige "gemiddelde" zon 1,1 Wm^{-2}. Omgerekend naar een wereldgemiddelde temperatuurverandering (met gebruikmaking van de hoogste schatting van lichtkrachttoename van 2,2 Wm^{-2} en een hoge klimaatgevoeligheid van 4,5 graden voor een verdubbeling van het CO_2) bedraagt deze 0,4 graden.
- Lange termijn variaties in de zonnestraling vertonen waarschijnlijk evenals variaties met betrekking tot de 11-jarige cyclus de sterkste relatieve veranderingen in het UV.

Reconstructies van TSI variaties zijn gebaseerd op diverse aannamen en keuzes, die niet of slechts gedeeltelijk kunnen worden gevalideerd. Zo worden schattingen van de mondiaal gemiddelde temperatuurverandering sinds de Kleine IJstijd gebruikt om de verandering van de toename van TSI af te schatten, terwijl onafhankelijke schattingen een betere basis zouden vormen voor het inzicht in de zon klimaat connectie.

Hoe gevoelig is het klimaatsysteem voor veranderingen in zonneactiviteit?

- De respons op verstoringen van de stralingsbalans, bijvoorbeeld in termen van de verandering van temperatuur nabij het aardoppervlak, kunnen worden versterkt of gedempt als gevolg van temperatuurafhankelijke processen in het klimaatsysteem. Deze zogeheten klimaatterugkoppelingen zijn vooral aanwezig in de hydrologische cyclus vanwege de combinatie van enerzijds de beschikbaarheid van grote hoeveelheden water op onze planeet en anderzijds de grote impact op de energiebalans van variaties in de drie aggregatietoestanden: ijs, vloeibaar water en waterdamp. De integrale werking van klimaatterugkoppelingen bepaalt de evenwichtklimaatgevoeligheid, gedefinieerd als de verhouding van verandering van evenwichttemperatuur en de mondiaal opgelegde verstoring van de stralingsbalans (de zogeheten stralingsforcering). Volgens het derde IPCC rapport [IPCC, 2001] ligt de klimaatgevoeligheid tussen de 0,5 en 1,1 K/Wm^{-2}. Dit is gebaseerd op zowel waarnemingen als modelstudies. Deze klimaatgevoeligheid geldt in feite voor de verstoring door veranderingen van goed gemengde broeikasgassen. Voor vele andere factoren laten modelstudies zien dat de forcering-respons relatie mank gaat als gevolg van de geografische en/of verticale verdeling van de forcering. Het gaat hierbij vooral om hoe deze patronen van forcering de verschillende regiogebonden terugkoppelingen aanslaan.
- Zo laten modelstudies zien dat voor zonneactiviteit met betrekking tot de 11-jarige zonnevlekkencyclus de temperatuurrespons een factor 0,75 tot 1 lager is dan voor eenzelfde forcering door veranderingen in goed gemengde broeikasgassen. Dit houdt mogelijk verband met het feit dat een aanzienlijk deel van de veranderingen in TSI in het ultraviolette gedeelte van het spectrum plaats vindt. Aangezien UV straling grotendeels wordt geabsorbeerd door zuurstof en ozon in de hogere lagen van de atmosfeer, zijn variaties in UV inefficiënt in termen van stralingsforcering voor het oppervlakte-troposfeersysteem.
- Daarentegen zijn er aanwijzingen dat de klimaatgevoeligheid voor de langzamere variaties op de schaal van decennia tot eeuwen iets hoger zou kunnen uitvallen dan voor goed gemengde broeikasgassen. Dit houdt mogelijk verband met veranderingen in oceaancirculatie en met de wisselwerkingen tussen de effecten van de zonneforcering en klimaatmodi, die versterkend kunnen werken. Dit betekent dat de eerder genoemde hoogste schatting van temperatuurverandering, namelijk 0,4 graden, tussen het huidige tijdperk (met referentie de gemiddelde zon) en het Maunder Minimum iets hoger zou kunnen uitvallen.
- Verder is de actuele temperatuurrespons (in tegenstelling tot de evenwichtrespons) van het klimaatsysteem sterk afhankelijk van de periode van de opgelegde forcering. De oorzaak hiervan is gelegen in de grote warmtecapaciteit en daarmee de bufferwerking van de oceaan. Een stralingsforcering van 1 Wm^{-2} ten gevolge van de Suess cyclus van ~200 jaar veroorzaakt een amplitude van de mondiaal gemiddelde temperatuurrespons, die een factor twee tot vier maal zo groot is als de respons op dezelfde forcering ten gevolge van de 11-jarige zonnevlekkencyclus. Deze factor is afhankelijk van de klimaatgevoeligheid, de diepte van de oceanische menglaag en de sterkte van warmtediffusie in de oceaan.
- Het klimaat kan behalve energetisch aangeslagen worden via de stralingsforcering, bijvoorbeeld door de variabele hoeveelheid zonne-energie en door mechanismen, die via de stralingsbalans verlopen of de klimaatgevoeligheid veranderen (variaties in broeikasgassen, wolken of circulatieveranderingen in de oceaan), ook beïnvloed worden via een dynamische reactie van de atmosfeer door lineaire en niet-lineaire wisselwerkingen met klimaatmodi. Zo kunnen door differentiële verwarming van de stratosfeer of door land-zee contrasten troposferische circulatie- en drukpatronen aangeslagen worden. Zulke veranderingen manifesteren zich vooral op de regionale schaal. Inzicht in deze patronen zijn cruciaal voor de interpretatie van klimaatarchieven en van modelsimulaties waarin forceringen van allerlei aard worden opgelegd.

Zijn er aanwijzingen voor de invloed van zonneactiviteit op het klimaat?

- Lineaire regressie technieken, die gebruik maken van de signatuur (in plaats van de amplitude) van de zonneforcering, laten zien dat de opwarming in de eerste helft van de 20^e eeuw gedeeltelijk veroorzaakt wordt door de toename van zonneactiviteit in die periode. Het kwantificeren van dit effect is echter geheel afhankelijk van de gebruikte tijdserie van TSI. Bovendien is het zonnesignaal in competitie met de temperatuurveranderingen door andere factoren, zoals de interne variabiliteit en de vulkaanforcering. Het is daarom onwaarschijnlijk dat een definitieve en eenduidige verklaring kan worden gegeven voor de oorzaken van het temperatuurverloop in de laatste eeuwen. Aan de andere kant is het waarschijnlijk dat een aanzienlijk deel van de waargenomen temperatuurverandering in de eerste helft van de 20e eeuw kan worden toegeschreven aan de toegenomen zonneactiviteit.
- Waarnemingen laten zien dat de ozonconcentraties in de stratosfeer positief correleren met de UV variaties met betrekking tot de 11-jarige zonnevlekkencyclus. Experimenten met algemene circulatiemodellen (GCM's), waarin de veranderende ozonconcentraties opgelegd of interactief berekend worden aan de hand van fotolyse door UV, laten een respons als functie van geografische breedte en hoogte zien die kwalitatief consistent is met de waarnemingen na correctie voor de invloed van vulkaanuitbarstingen, El Niño en ozondepletie door CFK's. Kwalitatief, omdat de modelrespons ongeveer 30% lager uitvalt dan het signaal dat uit waarnemingen is afgeleid. Met betrekking tot de zomerrespons op beide halfronden verschillen de modellen onderling aanzienlijk. Deze discrepantie wordt waarschijnlijk veroorzaakt doordat de modelklimatologie in zomersituaties slechter is. De respons op UV variaties in de troposfeer laat een bandstructuur zien met betrekking tot de wind- en temperatuuranomalieën. Dit patroon lijkt sterk op de respons met betrekking tot de zonneforcering zoals afgeleid uit de NCEP/NCAR analyse. De stralingsforcering door de ozonveranderingen geïnduceerd door UV variaties tussen een zonnevlekkenmaximum- en minimum is klein tot verwaarloosbaar. De regionale veranderingen worden daarom waarschijnlijk veroorzaakt door de dynamische respons ten gevolge van de troposfeer-stratosfeer koppeling. Dergelijke veranderingen resulteren in wijzigingen in de Arctische Oscillatie (en Noord Atlantische Oscillatie), die op haar beurt een verandering van weerregimes in Europa teweegbrengt.
- Zeer recent is een verband onderzocht tussen de zonnedeeltjes, kosmische straling en de productie van stratosferisch ozon via NO_x in de mesosfeer met behulp van een volledig interactief gekoppeld chemie Algemeen Circulatie Model. Dit resulteerde in stratosferische ozonveranderingen die vergelijkbaar zijn met die geïnduceerd door UV variaties gedurende de 11-jarige zonnevlekkencyclus. Dit vormt mogelijk de verklaring dat modelexperimenten geforceerd met alleen UV variaties een kleinere ozonrespons laten zien in vergelijking met de waarneming.
- Een andere geopperde mogelijkheid voor de versterking van de klimaatrespons op variaties in zonneactiviteit is de kosmische straling – wolken connectie: Kosmische straling wordt gemoduleerd door variaties in het magnetische veld gedurende de zonnevlekkencyclus. Volgens de hypothese zou de binnendringende galactische kosmische straling in de atmosfeer de hoeveelheid condensatiekernen en daarmee de microfysische eigenschappen van wolken en bedekkinggraad kunnen beïnvloeden. Hoewel correlaties tussen kosmische straling en (lage) bewolking in de waarnemingen gevonden zijn gedurende zonnevlekkencyclus 22, is deze periode veel te kort om definitieve uitspraken te doen over dit effect. Bovendien correleert de verandering van temperatuur uitgaande van dit effect op de bewolking slechts in de laatste vijftig jaar. In de eerste helft van de 20^e eeuw zijn de temperatuur en zonnevlekkengetallen als proxy voor de variaties in kosmische straling juist in antifase. Bovendien laat deze link over de 20^e eeuw geen temperatuurtrend toe. Verder zijn er calibratieproblemen met de ISCCP (wolken)dataset, waardoor de variatie in de bedekkinggraad en dus het verband met kosmische straling niet goed aantoonbaar is. Uit zowel theoretische als experimentele studies is het vooralsnog onduidelijk of de gestimuleerde condensatie ten gevolge van de ionisatie plaatsvindt in de hoge of juist in de lage atmosfeer. Dit is belangrijk omdat variaties in hoge en lage bewolking een tegenovergesteld effect op de verandering van temperatuur nabij het aardoppervlak bewerkstelligt. Hoewel dit mechanisme niet geheel kan worden uitgesloten, hebben ander factoren zoals vulkaanuitbarstingen en El Niño mogelijk ook bijgedragen aan

wolkenvariaties. Aangezien de pieken in de spectra van vulkaan- en zonneactiviteit in de laatste 40 jaar dicht bij elkaar liggen, is het lastig om definitieve conclusies te trekken over de oorzaak van variaties in bedekkinggraad.

- Het bestuderen van overeenkomsten tussen zonneactiviteit en klimaatveranderingen in het frequentiedomein is een ruimere benadering voor de detectie van een mogelijk zonnesignaal. Meer dan 40 cycli (waaronder hogere harmonische van de basiscycli) worden toegekend aan de invloed van de zon. Een kanttekening hierbij is dat vanwege de variabiliteit in de lengte van de cycli Fourieranalyse tot een onderschatting van de verklaarde variantie leidt en als zodanig slechts gedeeltelijk voldoet. Technieken, zoals “Wavelet analysis” waarin ook de variaties in de tijd worden meegenomen, zijn hiervoor beter toegerust. Bovendien is een dergelijke analysemethode ook geschikt om onnauw-keurigheden in de ouderdomsbepaling van proxies het hoofd te bieden.
- De in de tijd en plaats variërende correlaties tussen klimaatparameters en zonneactiviteit heeft aan het eind van de 19^{e} en het begin van de 20^{e} eeuw geleid tot de suggestie dat het klimaatsysteem in ieder geval op de regionale schaal mogelijk op een niet-lineaire manier reageert. Het probleem hierbij is dat twee niet gerelateerde tijdreeksen ook toevallig sterk lineair gecorreleerd kunnen zijn over bepaalde perioden, terwijl twee niet-lineair gerelateerde tijdreeksen een veel lagere correlatie kunnen hebben. De vraag doemt dan op hoe onderscheid te maken tussen de niet-lineaire forcing respons relatie en toevallige overeenkomsten. Slechts in een klein aantal studies is het mogelijk niet-lineair gedrag van de respons op de zonneforcering onderzocht.
- Hoewel zon klimaat connecties zijn gevonden in een groot aantal proxies in vele regio’s, zijn slechts een klein deel hiervan goed gedocumenteerd. Voor de meeste regio’s is deze connectie onduidelijk of zijn er onvoldoende data beschikbaar.
- De eenduidige bepaling van mechanismen waarmee veranderingen in zonneactiviteit het klimaat kunnen beïnvloeden is tot op heden onmogelijk gebleken, omdat de verschillende mechanismen dezelfde aspecten van het klimaatsysteem kunnen veranderen. Ook kunnen deze mechanismen gelijktijdig inwerken op een scala van fysische processen met mogelijk wederzijdse wisselwerkingen en veranderingen teweegbrengen in klimaatmodi. Elk van deze mechanismen heeft zijn eigen geografische, hoogteafhankelijke en tijdsafhankelijke patroon. Bovendien kan het mechanisme en daarmee het patroon van respons afhangen van de toestand waarin het klimaatsysteem verkeert, en dus samenhangen met andere klimaatforceringen zoals de menselijke invloed, die de basistoestand kan wijzigen.

Algemene conclusies

- Zonneactiviteit manifesteert zich in vijf goed gedefinieerde quasi-periodieke veranderingen. Pogingen om de zonnedynamo theoretisch te beschrijven zijn tot op heden alleen succesvol geweest in het verklaren van kwalitatieve aspecten. De numerieke beschrijving schiet echter tekort, zodat het voorspellen van zonneactiviteit met een acceptabele precisie onmogelijk is. Dit komt doordat de zonnedynamo een niet-lineair systeem is dat soms fasecatastrofen vertoont. De zonnedynamo kan beschouwd worden als een quasi-periodieke motor met eigenschappen van deterministische chaos. De toekomst van een dergelijk chaotisch systeem is per definitie onvoorspelbaar.
- De zonnedynamo is de motor van de variabiliteit van de zon en wordt gekarakteriseerd door interne toroïdale en de meer zich aan de oppervlakte manifesterende poloïdale velden met een wisselende en alternerende periode van 22 jaar. Vanuit deze twee componenten van het magnetische veld van de zon rijzen twee mogelijkheden voor de zon klimaat connectie op:
  (1) Variaties in de straling afkomstig van de zon, die samenhangen met die in het toroïdale magnetisch veld. Het variabele gedeelte van de zonnestraling bevindt zich in het UV deel van het spectrum en is voornamelijk afkomstig van het chromosferische deel van de Activiteiten Centra (CA). Het groep zonnevlekkengetal (R_G) is een maat voor de variabele component van de zonnestraling en voor de toroïdale veldfluctuaties.
  (2) De tweede component bestaat uit door de zon uitgestoten plasma wolken, zoals de Coronale Massa Emissies (CME's) en plasma uitgestoten door de ephimerale regionen op de zon. De CME's worden geëmitteerd vanuit de Activiteiten Centra op de zon. Deze zijn dus gerelateerd aan het toroïdale magnetische veld en dus geldt ook hiervoor dat het groepszonnevlekkengetal (R_G) maatgevend is voor deze component. Overige coronale massaemissies houden verband met variaties in het poloïdale magnetische veld. Via de uitstoot van gemagnetiseerd plasma, dat de heliosfeer vult, wordt de hoeveelheid galactische kosmische straling (CR) gemoduleerd die de atmosfeer binnendringt. Door variaties van het magnetische veld in de heliosfeer wordt de aarde meer of minder afgeschermd voor de kosmische straling (CR). De amplitude van de CR variaties hangen samen met de zonnevlekkencyclus. Kosmogene isotopen zijn proxies voor deze invloed.
- Nog nooit gedurende de laatste tienduizend jaar is de zon zo actief geweest in het uitstoten van gemagnetiseerd plasma als in de afgelopen halve eeuw, hoewel in de huidige periode de hoge zonneactiviteit nagenoeg constant is gebleven. Schattingen suggereren dat de zonneactiviteit momenteel over het maximum heen is en dat de komende decennia de activiteit mogelijk weer zal afnemen.
- Aanwijzingen voor de zonneactiviteit en klimaatveranderingen in het verleden liggen besloten in de instrumentele data (sinds 1700), historische bronnen (laatste paar duizend jaar) en proxies (laatste 10.000 jaar en verder terug) met een resolutie van één tot enkele jaren.
- Informatie over klimaatveranderingen is door de natuur opgeslagen in bijvoorbeeld boomringen, veen, stalagmieten, landijs, meer- en marine sedimenten. Kosmogene isotopen in sedimenten, zoals ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl, vormen de belangrijkste informatiebron van zonneactiviteit in het pre-instrumentele tijdperk.
- De productie van kosmogene isotopen wordt verder beïnvloed door fluctuaties in het aardmagnetische veld, die ontstaan door wisselwerkingen tussen de mantel en kern van de aarde. De veranderingen van het aardmagnetische veld zijn moeilijk in kaart te brengen. Kleine veranderingen in de lange termijn trend van het aardmagnetische veld kunnen de archieven van kosmogene isotopen dermate verstoren dat het moeilijk is om de amplitude en soms zelfs het teken van de zonneactiviteit af te leiden. Verder kunnen biochemische en meteorologische processen het beeld met betrekking tot de zonneactiviteit in de isotopenarchieven verstoren.
- Interpretatie van de proxy archieven worden bemoeilijkt door (1) de vertaling van de proxies in kwantitatieve klimaatparameters, (2) het verkrijgen van een goede datering, (3) het ophelderen van ruimtelijke patronen en verbanden hiertussen, (4) het scheiden van de

zonneforcering van andere forceringsfactoren en (5) het gebrek aan een compleet fysisch begrip van de mechanismen waarmee de aspecten van de zonneactiviteit het klimaat beïnvloedt. Om deze redenen wordt het in kaart brengen van de zonneactiviteit in het verleden vaak beperkt tot de identificatie van correlaties tussen zonneactiviteit enerzijds en klimaatverandering anderzijds.

- Alle frequentie componenten, die verondersteld worden met zonneactiviteit samen te hangen, komen tot uiting in de klimaatarchieven. Door ruis en veelal tekort schietende resolutie in de tijd kunnen de hoogfrequente signalen niet opgelost worden. Dit betreft voornamelijk de 11-jaar en 22-jaar cycli. Daar staat tegenover dat langzamere variaties, zoals de circa 90-jaar Gleissberg en de circa 200-jaar Suess cycli in de ^{10}Be en ^{14}C proxy archieven van zonneactiviteit wel goed vertegenwoordigd zijn in de archieven van klimaatverandering. Ook is de circa 1500-jaar Bond cyclus zichtbaar in diverse klimaatreconstructies.
- De klimaatrespons door variaties in zonneactiviteit is in competitie met de effecten van andere factoren, zoals de interne variabiliteit en de vulkaanforcering. Zeker als slechts één locatie beschouwd wordt, kan de klimaatinformatie in het proxy archief overstemd worden door de soms grote amplitude van natuurlijke variabiliteit. Dit kan de verklaring zijn dat voor diverse regio's het zonnesignaal alleen gedurende perioden met grote veranderingen in zonneactiviteit opduikt. Middeling van diverse Proxy archieven binnen regio's kan informatie robuuster maken, maar als sprake is van signalen met tegengesteld teken kan het eventuele zonnesignaal ook verloren gaan. De signaal ruis verhouding in de analyse van proxies kan waarschijnlijk verbeterd worden door de perioden met gelijke (veranderingen in) zonneactiviteit en de detecteerde klimaatrespons te middelen.
- Met betrekking tot individuele minima in zonneactiviteit (Spörer and Maunder-type) zijn duidelijke connecties gevonden met klimaatveranderingen in het Holoceen. In het Noord-Atlantische gebied zijn deze minima zijn geassocieerd met uitbreidingen van het zeeijs in zuidwestelijke richting en met een koel en nat klimaat in Europa. Tijdens sommige minima in zonneactiviteit blijven dit soort klimaatverandering echter uit. Er is dus geen sprake van een eenduidige link tussen zonneactiviteit en klimaat: klimaatveranderingen treden op zonder beduidende veranderingen in zonneactiviteit en omgekeerd.
- Het waargenomen verschil in TSI tussen de zonnevlekkenmaxima- en minima bedraagt ongeveer 1 Wm^{-2}, ofwel iets minder dan 0,1% van de zonneconstante. Verder kan op basis van de metingen geconcludeerd worden dat de geëmitteerde energie door de rustige zon, dus bij afwezigheid van zonnevlekken, nagenoeg constant is: de gevonden verschillen zijn kleiner dan 0,01%, zodat er geen sprake is van een significante trend in de laatste 26 jaar. De stralingsveranderingen correleren positief met de zonnevlekkencyclus met relatief kleine veranderingen in het infrarode deel van het spectrum en grote verschillen in het ultraviolette deel.
- De mondiaal gemiddelde temperatuurrespons ten gevolge van TSI veranderingen, gerelateerd aan de 11-jarige zonnevlekkencyclus, is klein. Berekeningen laten zien dat deze respons kleiner is dan 0,05 graden en daarmee dus nauwelijks zichtbaar is in de temperatuurreeks. Op de regionale schaal is de impact van de zonnevlekkencyclus op de temperatuur groter, in de orde van enkele tienden van graden. Samenhangend met de UV variaties in de zonnevlekkencyclus zijn ozonveranderingen in de stratosfeer waargenomen, die resulteren in differentiële verwarming van de stratosfeer. Via een cascade van dynamische reacties kunnen circulatiepatronen in de troposfeer worden aangeslagen. Sommige waargenomen patroonveranderingen in wind en druk worden toegeschreven aan de effecten van UV variaties. Voor de kosmische straling – wolken link bestaat echter geen duidelijk fysische basis, noch ondersteunen waarnemingen deze hypothese.
- Lange termijn veranderingen in de hoeveelheid straling afkomstig van de zon zijn in het algemeen gebaseerd op drie waarneembare grootheden, terwijl de calibratie meestal wordt uitgevoerd op schattingen van de verschillen tussen het Maunder Minimum (1645-1715) en de huidige rustige zon:
  (1) Veranderingen in de aa-index als een maat voor de magnetische activiteit van de zon: deze index wijst op een veel hogere activiteit van de huidige zon ten opzichte van het begin van de metingen, zo'n anderhalve eeuw geleden. Recente studies opperen de mogelijkheid dat de lange termijn trends in de aa-index gedeeltelijk te wijten zijn aan instrumentele afwijkingen.

(2) Reconstructies van kosmogene isotopen wijzen op fluctuaties van kosmische straling, die terug te voeren zijn op de magnetische activiteit van de zon. Simulaties van het transport van de magnetische flux in de zon en de propagatie van de open flux naar de heliosfeer laten zien dat trends in de aa-index en kosmogene isotopen, beide gegenereerd door de open flux, niet noodzakelijkerwijs gelijke trends opleveren in de door de zon geëmitteerde totale hoeveelheid straling (de zogeheten gesloten flux).

(3) De bandbreedte van variabiliteit bij zonachtige sterren. Hoewel voorheen gesuggereerd werd dat de zon in staat is een veel grotere reikwijdte aan activiteit te vertonen dan is waargenomen in de meest recente zonnevlekkencycli, laat een heranalyse van gegevens van zonachtige sterren zien dat de huidige zon veel meer een normale ster is dan bovengemiddeld actief ten opzichte van andere sterren.

- De reconstructies van TSI variaties zijn gebaseerd op diverse aannamen en keuzes, die niet of slechts gedeeltelijk kunnen worden gevalideerd. Zo worden schattingen van de mondiaal gemiddelde temperatuurverandering sinds de Kleine IJstijd gebruikt om de verandering van de toename van TSI af te schatten, terwijl onafhankelijke schattingen een betere basis zouden vormen voor het inzicht in de zon klimaatconnectie.
- Volgens de meest recente inzichten is de lichtkracht van de zon vanaf het Maunder Minimum tot de huidige rustige zon (d.w.z. bij afwezigheid van zonnevlekken) toegenomen met waarschijnlijk 0,5 Wm^{-2}, en een hoogste schatting van 1.6 Wm^{-2}. Wanneer ook de effecten van de 11-jarige zonnevlekkencyclus worden meegenomen, wordt de beste schatting van de lichtkrachttoename van het Maunder Minimum tot de huidige “gemiddelde” zon 1,1 Wm^{-2}. Omgerekend naar een wereldgemiddelde temperatuurverandering (met gebruikmaking van de hoogste schatting van lichtkrachttoename van 2,2 Wm^{-2} en een hoge klimaatgevoeligheid van 4,5 graden voor een verdubbeling van het CO_2) bedraagt deze 0,4 graden.
- Lange termijn variaties in zonneactiviteit kunnen weldegelijk leiden tot een detecteerbaar klimaatsignaal. De aanwijzingen hiervan liggen besloten in de proxy archieven en temperatuurdata van vóór 1950, toen de menselijke invloed op het klimaat zeer waarschijnlijk verwaarloosbaar klein was. Het kwantificeren van de zonneforcering is echter geheel afhankelijk van de gebruikte tijdserie van de TSI. Bovendien is het zonnesignaal in competitie met de temperatuurveranderingen door andere factoren, zoals de interne variabiliteit en de vulkaanforcering. Het is daarom onwaarschijnlijk dat een definitieve en eenduidige verklaring kan worden gegeven voor de oorzaken van het temperatuurverloop in de laatste eeuwen. Aan de andere kant is het waarschijnlijk dat een aanzienlijk deel van de waargenomen temperatuurverandering in de eerste helft van de 20e eeuw kan worden toegeschreven aan de toegenomen zonneactiviteit.

Executive summary

The Earth's climate is a complex system. It consists of the atmosphere, ocean, cryosphere (snow and ice), land surface and the biosphere. It includes many physical, chemical and biological processes acting on a huge variety of timescales as well as of spatial scales. The interactions between the compartments of the climate system give rise to very complex behaviour. The climate system is primarily driven by the energy it receives from the sun. Part of the incoming solar radiation is reflected backwards and lost to space. The remaining part is absorbed within the atmosphere and at the earth surface and is converted into heat which eventually leaves the system as infrared radiation. On the long term and globally averaged the incoming shortwave radiation and outgoing longwave radiation is approximately balanced at the top of the atmosphere

The climate is far from constant. Many factors of climate change have been reported in the literature. We may distinguish internal variability and external forcing. The former also referred to as autogenic forcing is caused by interactions between the components of the climate system, each component having typical and different time-scales of response. In a coupled mode these non-linear interactions reveal climate noise, such as temperature, precipitation and circulation variations. Spectra of temperature variations show generally red noise, indicating that fluctuations increase with time-scale. However, such spectra also show resonant peaks, indicating feedback mechanisms on typical time scales. External forcing is caused by changes in one or more climate compartments (endogenic forcing), modifying the energy flows in the climate system, or caused by changes outside the climate system (exogenic forcing), such as changes in the electromagnetic properties or particle emissions of the sun. It is sometimes difficult to separate internal variability and external forcing due to the ever existing feedback loops or mutual interactions between the compartments of the climate system.

The major sun-climate relationship is the absorption of solar radiation by the atmosphere and by the earth surface. Moreover, atmospheric flow is largely influenced by the distribution of the absorbed solar radiation as well as of the outgoing infrared radiation in the climate system. Even with a constant level of solar activity climate processes are influenced. Clear examples are the diurnal and seasonal cycle. On the very long timescale the interaction between the earth's cryosphere and the periodic changes in the earth orbital parameters, modifying the integrated seasonal solar insolation at high latitudes, results in the occurrence of ice ages.

Variations of solar activity may expose the climate system to an additional forcing which induces either climate changes on the global scale or a pattern of responses on the regional scale, depending on the physical mechanism. Besides the direct mechanism of variations in the total solar irradiance changing the radiative balance of the climate system, the search is for indirect mechanisms, which enhance variations in solar activity parameters into significant impact on climate. At least three competing mechanisms may be considered:

(1) Small variations in the visible part of the solar irradiance, affecting the atmosphere from below.
(2) Variations of UV – radiation, affecting directly the stratosphere and the ozone distribution, thus influencing the lower atmosphere from above.
(3) Variations of particle radiation of the sun and/or variations in cosmic radiation, having an effect on the electrical and magnetic properties of the earth's atmosphere, eventually causing a change in the atmospheric composition (either by aerosol or cloud formation, or an influence on the concentration of ozone).

Furthermore, direct and indirect solar forcings can interact with internal climate system variability such as El Nino – Southern Oscillation (ENSO), the Northern Atlantic Oscillation (NAO) and the Quasi-Biennial Oscillation (QBO). This may result in triggering, amplifying or shifting these modes.

Comparing reconstructions of solar activity parameters and climate records may reveal solar-terrestrial relationships, but in general there is no solid evidence to which extent these correlations are caused by changes in solar activity. The origin of these controversies lies in the fact that possible solar signals are not easily distinguished from other sources of climate variability, such as volcanic forcing, ENSO and long term internal variability. Also, uncertainties in reconstructions and climate records hamper unequivocal proof of the solar terrestrial link. Although correlations between solar activity and climate parameters do not establish cause-effect relationships, they may give indications for underlying mechanisms of climate change due to solar activity.

The impacts of climate factors, like changes in solar activity, can be further studied with coupled atmosphere-ocean general circulation models (GCMs). These are the state-of-the-art tool for understanding the present climate and estimating the effects of natural as well as anthropogenic climate perturbations. Such comprehensive models include many physical processes and their mutual interactions. The evaluation with observational data is essential for getting at least some confidence in the present generation of climate models, although it is difficult or even impossible to get correspondence with the real world in all aspects. At present, the GCM simulations differ in many aspects on the regional scale. Therefore, it is difficult to be conclusive about cause-effect relations at least on the regional scale.

The quantification of the human influence on climate depends strongly on our understanding of the climate system including climate variability driven by internal variations as well as by external forcings. One of the external forcings is due to the ever changing activity of the sun. Before the industrial revolution (set at 1750 to 1850) the human factor can be excluded and until 1950 it may be neglected at least at global scale. Studying the climate change before 1950 may therefore reveal the impact of natural climate factors alone. However, uncertainties in the measurements and hence our knowledge of climate evolution increase going backward in time. Since measurements are principally local, contamination by human influence is also possible before the industrial revolution, e.g. due to land-use. In addition, several natural forcings and their interactions with internal climate modes act at the same time. It is therefore critical to understand the underlying mechanism by which each forcing factor influences the Earth's climate. This implies knowledge on the processes in the climate system as well as on the processes causing the forcing. In case of the sun it involves understanding the solar dynamo and its variations, resulting in electromagnetic changes including shielding effects of cosmic rays and particle emissions.

Proxy records, such as the isotopes ^{14}C and ^{10}Be, may reveal the magnetic activity of the sun. Irradiance changes of the sun have been measured directly from 1979 and are correlated with the sunspot numbers. As observations of sunspot numbers go back to 1610, the evolution of solar irradiance changes may be constructed from this proportionality. However, long-term irradiance changes may be connected to processes resulting in other relevant parameters than sunspot numbers, which are difficult to retrieve. In this respect it remains unclear how to translate variations in the magnetic field in terms of irradiance changes.

In order to assess the understanding of the solar terrestrial relation, the Netherlands Research Programme on Global Change (NRP-GC) asked the Royal Netherlands meteorological Institute (KNMI) to coordinate a project, which should include an assessment on the knowledge of the solar dynamo, the proxy records as well as on the understanding of the possible and probable mechanisms of climate change due to changes in solar variability. Three specialists on the issue of solar dynamics, proxy records and climate science present their views on the subject of the solar terrestrial link. This report provides a consensus view of the experts involved in this assessment. Despite the fact that the search for solar influences on climate has a long history with strong scientific developments in the last decades, the relative importance for climate change of the various solar parameters, the containing messages in proxy data, and the mechanisms in the climate system remains to be settled.

In this report, we present an assessment on the following topics:
(1) Reconstructions of solar variability, especially with respect to those parameters which are relevant for climate change. Relevance is strongly linked with (4).
(2) Reconstructions of proxies of solar variability, e.g. cosmogenic isotopes.
(3) Reconstructions of global as well as regional climate, with respect to temperature, precipitation and circulation.
(4) Physical understanding of the mechanisms which play a role in the solar terrestrial link.

We focus on the Holocene with emphasis on the last centuries because of data availability, to avoid confusing climate responses to orbital changes with those due to solar activity and because of the relevance for human induced climate change as compared to the role of the variable sun in the 20th century.

What do we know about solar variability?

- Solar activity is variable with five well-determined quasi-periodicities. Attempts to theoretically describe the solar dynamo have so far succeeded only in explaining the qualitative aspects. They fail in a numerical description and notably in one that would permit one to forecast solar activity with acceptable precision. This is so because the solar dynamo is a non-linear system that occasionally shows phase catastrophes. It is a quasi-periodic engine with the properties of deterministic chaos. "The future of such a chaotic system is intrinsically unpredictable".
- The solar dynamo is characterised by internal toroidal and more superficial poloidal fields, interchanging and alternating in a 22-yr periodicity. From these two components in the solar magnetic fields emanate two possible scenarios for the Sun-climate interaction:
  (1) Solar irradiance variations are related to those in the solar toroidal magnetic fields. The fraction of the solar irradiance that reaches the Earth's ground level and low troposphere is emitted by the solar photosphere. That fraction varies only slightly since the quiet photosphere does hardly vary during the cycle. The variable part of the solar radiation flux is mainly emitted by the chromospheric parts of the Centers of Activity (CA). That radiation component does not reach the Earth's troposphere since it is absorbed in the higher, stratospheric terrestrial layers. Tropospheric solar-driven variations should therefore be due to stratosphere-troposphere coupling. The Group Sunspot number R_G is a proxy for the variable irradiance component and for the toroidal field variations.
  (2) The other components consist of ejected solar plasma clouds, such as the Coronal Mass Ejections (CMEs) and plasma ejected from Ephemeral Solar Regions. The CMEs are emitted from the Centers of Activity. Hence they are related to the toroidal magnetic field and a proxy for it is the group sunspot number (R_G). The other coronal emissions are related to variations in the poloidal magnetic fields. On the average the energetic emissions such as X-ray flares have their maximum intensity about a year after the maximum number of spots: we call this interval the Energetic Emissions Delay. The emitted gas clouds fill the heliosphere with magnetised plasma. Thus, by emitting magnetised plasma, the Sun influences the Earth's atmosphere indirectly, by heliospheric modulation of the component of the galactic cosmic radiation (CR) that reaches tropospheric levels. Modulation is only important for cosmic ray particles with energies below about 50 GeV. Cosmic ray ionisation plays a minor role at ground level but it is the predominant ionising agent in higher atmospheric layers, already above a few km. The amplitudes of the CR variations depend on those of the solar cycle. The atmospheric rate of ionisation varies with CR-intensity. A current hypothesis is that the variable ionisation may affect the degree of cloudiness. Cosmogenic radionuclides such as ^{10}Be are proxies for this influence and for the poloidal field variations, although they are affected by variations of the Earth magnetic field.
- The Group Sunspot number (R_G) and cosmogenic radionuclide proxies, although correlated, refer to the two different aspects of the solar dynamo with their different terrestrial effects; they do not reach maximum intensity simultaneously and should therefore not be confused

nor be interchanged. Cases have occurred in which the one varied strongly while the other did hardly or not at all. The explanation must be intrinsic in dynamo theory.

- Never during the past ten thousand years has the Sun been as active in ejecting magnetised plasma as during the last half a century, in which period it remained fairly constant. Estimates suggest that the level of solar activity may recently have passed its maximum and that it may decrease in coming decades.

What do proxy records tell us about solar variability and climate change?

- Evidence for past solar and climate variability is obtained from instrumental data (since 1700 AD), historical accounts (last few millennia) and proxy records (last 10,000 years, and more) with a resolution of one to few years.
- Proxy records provide ample evidence for climate change, during the relatively stable and warm Holocene. The issue of solar forcing of these climate changes is highly debated and reinforced by the present-day combination of global warming and an exceptionally active sun. Papers pro and contra exist for most parts of the globe. The nature of the responses and their geographical coherence is of direct relevance for evaluating solar forcing mechanisms and validating climate models.
- Information on climate change is recorded by nature in e.g. tree rings, peat, stalagmites, ice caps, lacustrine and marine sediments. Cosmogenic radionuclides in sediments, such as ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl, form the major source of information on solar activity for the pre-instrumental era. These proxy records are often continuous over much longer periods and as such, the study of these natural archives may help to overcome the limitations set by the instrumental records.
- Cosmogenic radionuclides are formed by high-energy particles entering the atmosphere where they collide with the atoms in the air and produce rare and unstable isotopes. The solar wind shields the atmosphere from these particles so that cosmogenic radionuclide production rates decrease as solar activity increases. The influence of the strength and shape of the magnetic field on the cosmic ray dose on the atmosphere, further modulates the radionuclide production such that the production increases with decreasing field strength and increases towards the magnetic poles.
- The production of cosmogenic radionuclides ^{10}Be and ^{14}C can be influenced by geomagnetic field fluctuations. These fluctuations are caused interactions between the Earth's mantle and core. Accurate assessment of changes in the geomagnetic field is thus of direct importance for understanding solar variability. Reconstructing geomagnetic activity, however, is a difficult task and, unfortunately, already relatively small changes in the long term trend substantially influence the amplitude and sign of the reconstructed solar activity changes. On smaller time scales, changes in the geomagnetic field are even less well defined.
- Interpretation of the proxy records is hampered by difficulties in:
  (1) translating the proxy records into quantitative climate parameters
  (2) obtaining an accurate age assessment
  (3) elucidating spatial patterns and relationships
  (4) separating solar forcing from other forcing mechanisms
  (5) the lack of physical understanding of the solar forcing mechanisms.
- For these reasons, assessment of past solar influence on climate often is limited to the identification correlations between environmental change and solar variability only. Central questions are thus: Where, how and when did climate change, how did solar activity change, and, how does climate relate to what extent and what kind of solar variability?
- Although marine environments cover roughly 2/3 of the Earth's surface, the marine environment is severely underrepresented with respect to high resolution records of environmental (including climatic) change. This bias hampers our understanding of the mechanisms inducing climate change both qualitatively and quantitatively.
- All frequency components attributed to solar variability re-occur in proxy records of environmental change. The noisy character and often insufficient temporal resolution of proxy records often exclude the detection of high frequency decadal and bi-decadal cycles. However, on multi-decadal and longer time scales, notably the ~90 yrs Gleissberg, and ~200

years Suess cycles in the ^{10}Be and ^{14}C proxy records of solar activity are also well presented in the environmental proxy records. Additionally, a ~1500 years Bond cycle appears to occur in several proxy records.

- Long-term climate change during the preindustrial seems to have been dominated by solar forcing. Proxy evidence for sun-climate relations is unequally distributed over the globe. Thus, long-term response to solar forcing typically has a regional character and may greatly exceed unforced variability in some regions.
- Solar forcing seems to have a particularly strong impact on regional precipitation-evaporation budgets suggesting that it operates via modulating the distribution of latent heat. The oceans may play an important but still obscure role. Proxy evidence for sun-climate relations is unequally distributed over the globe.
- Furthermore, proxy evidence for sun-climate relations often suggests a migration of climate regimes linked with changes in circulation patterns. At a given location this inherently induces a non linear response. This may be one explanation for the discontinuity in the apparent response to solar forcing at single sites. This discontinuous proxy-response as well as phase-shifts, complicate the assessment of sun - climate relations and call for nonlinear analysis of multiple long and high resolution records at regional scale since only a regional network of proxies may be capable to unravel sun-climate relations appropriately. Unfortunately non linear responses to solar forcing are still a largely barren field, despite the fact that major global climate configurations (e.g. the ENSO and AO) follow non-linear dynamics.
- Another source of uncertainty is the strength of the solar forcing relative to other forcing factors. It may explain why for several regions solar forcing appears only evident during periods of high amplitude solar variability. Solar forcing has "to compete" continuously with other climate forcings induced by e.g. volcanism or internal variability. The signal to noise ratio may be improved by stacking similar periods of solar forcing and investigating the response.
- Few but well dated studies indicate an early, almost instantaneous, climatic deterioration in response to periods with rapidly decreasing solar activity. Since such an early response puts severe limits to the solar forcing mechanisms the reality and extent of this phenomenon should be a key issue in sun-climate studies.

Can we reconstruct solar activity?

- Since 1978, radiometers on board of satellites directly measure the total solar irradiance without interruption, albeit from a variety of instruments. In this period covering two-and-a-half solar cycles, observations show a periodic variation in total solar irradiance (TSI), with maxima around 1980, 1990 and 2001 and minima around 1986 and 1996. These variations correspond reasonably well with the sunspot numbers. The difference in TSI between maxima and minima was about 1 Wm^{-2}, which corresponds to less then 0.1%. Total solar irradiance between successive solar minima has found to be constant to better than 0.01%, suggesting no significant trend of the quiet sun. Spectral measurements show that variations occur at all wavelengths, but with different relations to solar activity. Irradiance changes correlate positively with the solar cycle at most wavelengths from small changes in the IR spectrum and large changes in the UV spectrum.
- Long-term irradiance changes are generally based on three observables, while the calibration is done by estimating the solar irradiance change during the Maunder Minimum (1645-1715) and the present quiet sun:
  (1) Changes in the aa-index as a measure of the magnetic activity of the sun: it indicates a much higher activity nowadays than since the start of the measurements one and a half century ago. Recent studies raise the possibility of long-term instrumental drifts in the aa index.
  (2) Reconstructions of cosmogenic isotopes point toward cosmic ray fluctuations, which can be attributed to the sun’s magnetic activity. Simulations of the transport of magnetic flux on the Sun and propagation of open flux into the heliosphere indicate that trends in

the aa index and cosmogenic isotopes (generated by open flux) do not necessarily imply equivalent trends in solar irradiance (which track closed flux)

(3) The range of variability in Sun-like stars. Although previously suggested that the Sun is capable of a broader range of activity than witnessed during recent solar cycles, a reassessment of the stellar data shows that the current Sun is thought to have "typical" (rather than high) activity relative to other stars.

- In terms of current physical understanding, the most likely long-term total irradiance increase from the Maunder Minimum to current cycle minima is 0.5 Wm^{-2}, but it may be as much as 1.6 Wm^{-2}. When the 11-year solar cycle is taken into account, the best estimate from Maunder Minimum to the present average sun is about 1.1 Wm^{-2}. Converted into a temperature response using the upper limit of the TSI increase of 2.2 Wm^{-2} (including the effects of the 11-year solar cycle) and the high climate sensitivity of 4.5 degrees for a doubling of CO_2, the upper limit of (equilibrium) response would be 0.4 degrees.
- Like the solar cycle changes, long-term irradiance variations are expected to have significant spectral dependence with strong relative variation in the UV. Reconstructing solar irradiance changes are inevitably based on certain choices, which cannot or can only partly be validated. For instance, estimates of the global temperature during the little ice-age are used to estimate the change in TSI, while one should wish to have independent estimates.

How sensitive is the climate system to changes in solar activity?

- The response to perturbations of the radiation balance, e.g. in terms of near surface air temperature change, can either be amplified or damped as the result of temperature dependent processes in the climate system. These so-called *climate feedbacks* are dominantly present in the hydrological cycle due to the combination of large amounts of water at our planet and its strong impact on the energy balance for all its phases (ice, liquid water and water vapour). The ensemble of climate feedbacks determine the *equilibrium climate sensitivity*, defined as the ratio of the equilibrium global mean surface temperature change to the global mean imposed radiative forcing. For the generation of 3D climate models used in the IPCC Third Assessment Report [IPCC, 2001], this climate sensitivity parameter is ranging from 0.5 to 1.1 K/Wm^{-2}. However, this sensitivity is valid for radiative perturbations due to well-mixed greenhouse gases. For many other forcing agents model studies show that the forcing response relationship breaks down as the result of geographical and/or vertical distribution of the forcing due to the way it projects onto the various different (and locally confined) feedback mechanisms.
- Model studies show lower temperature response per unit of radiative forcing by a factor between 0.75 and 1 for solar variability related to the 11-year sunspot cycle than for well-mixed greenhouse gases. This is probably related to the fact that the largest variability of solar irradiance changes takes place in the UV region. UV radiation is largely absorbed in the higher atmosphere by oxygen and ozone. Changes in UV are therefore an inefficient forcing for the surface-troposphere system.
- There are some indications that the sensitivity for decadal to centennial scale variations of solar activity could be slightly higher than for well-mixed greenhouse gases. This may be related to changes in ocean circulation and to interactions with climate modes as an amplifying mechanism the solar forcing. It would result in slightly higher temperature changes from the Maunder Minimum to the present average sun than the previously mentioned estimate of 0.4 degrees.
- The actual temperature response (in contrast to the equilibrium response) of the climate system is strongly dependent on the period of the imposed radiative forcing due to the heat capacity and thus buffering of the world's oceans. For instance, for a radiative forcing of 1 Wm^{-2} due to the solar cycle of ~200 years (Suess cycle) the amplitude of the global mean temperature response is a factor two to four times larger than for the same forcing due to the 11-year sunspot cycle, depending on climate sensitivity, depth of the ocean mixing layer and the strength of the diffusion of heat within the ocean.
- Besides the global mean response of the climate system to imposed radiative forcings in an energetic way, e.g. due to changes in total solar irradiance and due to possible amplifying mechanisms affecting the radiation balance or the climate sensitivity (e.g. greenhouse gas

and cloud changes or modifications in the ocean circulation), the climate system can react dynamically through linear and non-linear interactions with climate modes. For example, the differential heating of the stratosphere or differences in land-sea temperature response can induce changes in tropospheric circulation and pressure patterns. These changes manifest predominantly at the regional scale and are crucial for the interpretation proxy records and comparison with model simulations fed with solar and other forcings.

Is there evidence for the solar influence on climate?

- Linear regression techniques making use of the signature (instead of the amplitude) of the solar forcing indicate that solar activity could be partly responsible for the early 20th century warming. Quantification, however, depends totally of the used time series of TSI. Also, the solar signal may compete with possible temperature changes due to internal variability and/or due to volcanic forcing. Therefore, it seems unlikely that a definitive and unambiguous explanation of the century time scale temperature variations can be achieved, although it is likely that a considerable fraction of the observed temperature rise in the first half of the 20th century can be attributed to the increasing activity of the sun.
- There is some observational evidence that ozone concentrations in the stratosphere correlate positively with the UV variations due to the 11-year sunspot cycle. General circulation model experiments which include the ozone changes - either imposed or calculated interactively due to photolysis by UV variations – show latitude height responses, which are qualitatively consistent with observations if corrected for volcanic activity, El Nino and ozone depletion by CFCs. However, the models responses are about 30% weaker than the signal deduced from observations and especially during the summer large discrepancies exist between the models. This discrepancy may be attributed to the poor model climatologies in that season. Tropospheric responses at the mid-latitudes in terms of wind- and temperature anomalies show a banded structure. This pattern is very similar to that deduced as the solar response in NCEP/NCAR zonal mean temperatures. The radiative forcing due to ozone changes between maximum and minimum solar activity is likely to be small or even negligible. Regional response patterns due to enhanced UV are therefore likely due to dynamical interactions between the stratosphere and the troposphere. Such interactions result in changes of the Artic Oscillation (and Northern Atlantic Oscillation) affecting weather regimes in Europe.
- Recently, the connection between solar particles, cosmic rays and the production of stratospheric ozone via NO_x in the mesosphere has been investigated using a fully interactive coupled chemistry-General Circulation Model. It was found that the stratospheric ozone changes were comparable with the ozone change chemically induced by UV variations in the 11-year solar cycle. This might explain why models using UV variations only show a lower ozone response as compared to observations.
- Another possibility of amplifying the response of changes in solar activity is the cosmic ray – cloud link: Cosmic rays are modulated by the magnetic field variations due to the sunspot cycle. These penetrating galactic cosmic rays may alter the population of cloud condensation nuclei and hence microphysical cloud properties. Although correlations between cosmic rays and (low) clouds have been found during cycle 22, this period is far too short to be conclusive on the effect. Moreover, the effect of a change in cloudiness, namely a change in global mean temperature does correlate only in the last 50 years. In the first half of the 20th century temperature and sunspot number – taken as a proxy for cosmic ray variations – show an anti-correlation. This possible link has showed by no means a temperature trend in the 20th century. Finally, due to calibration problems with the ISCCP dataset used to link cosmic rays and cloudiness, the cloud signal may be not detectable. It is also unclear from theoretical and experimental studies whether the stimulated condensation due to ionization is predominantly occurring in the higher or in the lower atmosphere. This is important because changes in high clouds would have the opposite effect on the global mean temperatures as variations in low clouds. Although this mechanism cannot be ruled out, other factors like volcanic eruptions and El Nino may have contributed to a variation in cloudiness as well. Since the peaks in the spectra of volcanic and solar activity are found to

be quite close in the last 40 years, it is difficult to be conclusive about the cause of variations in cloudiness.

- A less constrained approach for detecting possible solar forcing of climate change in proxy records is the assessment of similarities between proxies for solar activity and climate change in the frequency domain. More than 40 cycles have been attributed to solar influences. It must be noted that due to the variability in cycle length within the frequency bands of solar variability, a rigid Fourier analysis of the proxy records tends to underestimate the variance explained by such a quasiperiodic cycle and as such is not appropriate. Techniques like wavelet analyses, capable of capturing variation in the frequency domain are preferable. Moreover, such methods are also tolerant to inaccuracies in the age-model.
- The varying degrees of correlation between climatic parameters and solar activity over time and between localities already led at the end of the 19th and beginning of the 20th century to the suggestion that climate does not (and is unlikely to) respond linearly to solar forcing at least on the regional scale. The problem is that also two unrelated time series will show high linear correlation over shorter and longer intervals, just by accident whereas two non-linearly related time series may fail to do so. How to differentiate between (non-linear) forcing and accidental correspondence? Only relatively few studies investigate *a priori* non-linearity of solar forcing on climate.
- Although sun-climate links have been reported from a large variety of proxies and many regions, for only few regions sun-climate links appear to be well documented. For other regions such a relationship may be absent or insufficient data are available.
- Unequivocal determination of the mechanism(s) by which changes in solar activity influence earth's climate is complicated since the different mechanisms may alter similar aspects of the climate system in different ways. Furthermore, these mechanisms may operate simultaneously on a variety of physical processes with possible mutual interactions and with climate variability modes. In addition, each of these mechanisms has its own spatial, altitudinal and temporal response pattern. Finally, they are likely to depend on the background state of the climate system, and thus on other forcings, such as the anthropogenic forcing, that can alter this state.

General Conclusions

- The Sun is a variable star with five well-determined quasi-periodicities. Attempts to theoretically describe solar variability have so far succeeded only in explaining the qualitative aspects. They fail in a numerical description and notably in one that would permit one to forecast solar activity with acceptable precision. This is so because the solar dynamo is a non-linear system that occasionally shows phase catastrophes. It is a quasi-periodic engine with the properties of deterministic chaos. "The future of such a chaotic system is intrinsically unpredictable".
- The solar dynamo is the engine of the Sun's variability. The solar dynamo is characterised by internal toroidal and more superficial poloidal fields, interchanging and alternating in a 22-yr periodicity. From these two components in the solar magnetic fields emanate two possible scenarios for the Sun-climate interaction:
  (1) Solar irradiance variations are related to those in the solar toroidal magnetic fields. The variable part of the solar radiation flux is mainly emitted by the chromospheric parts of the Centers of Activity (CA), hence responsible for the variable UV radiance. The Group Sunspot number R_{Gs} is a proxy for the variable irradiance component and for the toroidal field variations.
  (2) The other component consists of ejected solar plasma clouds, such as the Coronal Mass Ejections (CMEs) and plasma ejected from Ephemeral Solar Regions. The CMEs are emitted from the Centers of Activity. Hence they are related to the toroidal magnetic field and a proxy for it is the sunspot group number. The other coronal emissions are related to variations in the poloidal magnetic fields. By emitting magnetised plasma, the Sun influences the Earth's atmosphere indirectly, by heliospheric modulation of the component of the galactic cosmic radiation (CR). The amplitudes of the CR variations depend on those of the solar cycle. The cosmogenic radionuclides are proxies for this influence.
- Never during the past ten thousand years has the Sun been as active in ejecting magnetised plasma as during the last half a century, in which period it remained fairly constant. Estimates suggest that the level of solar activity may recently have passed its maximum and that it may decrease in coming decades.
- Evidence for past solar and climate variability is obtained from instrumental data (since 1700 AD), historical accounts (last few millennia) and proxy records (last 10,000 years, and more) with a resolution of one to few years.
- Information on climate change is recorded by nature in e.g. tree rings, peat, stalagmites, ice caps, lacustrine and marine sediments. Cosmogenic radionuclides in sediments, such as ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl, form the major source of information on solar activity for the pre-instrumental era.
- The production of cosmogenic radionuclides can be influenced by geomagnetic field fluctuations, which are difficult to assess. These fluctuations are caused interactions between the Earth's mantle and core. Unfortunately, already relatively small changes in the long term trend substantially influence the amplitude and sign of the reconstructed solar activity changes. Furthermore, biogeochemical and meteorological processes can contaminate the isotope records.
- Interpretation of the proxy records is hampered by difficulties in (1) translating the records into quantitative climate parameters (2) obtaining an accurate age assessment (3) elucidating spatial patterns and relationships (4) separating solar forcing from other forcing mechanisms and (5) the lack of physical understanding of the solar forcing mechanisms. For these reasons, assessment of past solar influence on climate often is limited to the identification correlations between climate change and solar variability only.
- All frequency components attributed to solar variability re-occur in proxy records of climate change. The noisy character and often insufficient temporal resolution of proxy records often exclude the detection of high frequency decadal and bi-decadal cycles. However, on multi-decadal and longer time scales, notably the ~90 yrs Gleissberg, and ~200 years Suess cycles in the ^{10}Be and ^{14}C proxy records of solar activity are also well presented in the

environmental proxy records. Additionally, a ~1500 years Bond cycle appears to occur in several proxy records.

- Solar forcing has "to compete" continuously with other climate forcings, e.g. volcanism, and climate variability, e.g. changes in ocean circulation patterns. Since proxy records mostly are based on one site (e.g. a bore-hole) and thus provide a record of local climate change only, the sometimes very large amplitude of local climate variability can mask the solar signal. It may explain why for several regions solar forcing appears only evident during periods of high amplitude solar variability. Using various proxy records within a certain region the solar signal may be lost as well due to averaging signals with opposite signs. The signal to noise ratio may be improved by stacking similar periods of solar forcing and investigating the response.
- A clear link is present at the level of individual (Spörer and Maunder-type) minima in solar activity and climate throughout the Holocene. In the North Atlantic the solar minima are associated with southward advances of sea-ice whereas in Western Europe climate turns cool and wet. It must be noted that there is no unequivocal link, climatic events occur without corresponding solar forcing and vice versa, some minima in solar activity do not seem to have a corresponding climatic anomaly.
- The difference in TSI between sunspot maxima and minima as measured directly by radiometers on board of satellites was about 1 Wm^{-2}, which corresponds to less then 0.1%. Total solar irradiance between successive solar minima has found to be constant to better than 0.01%, suggesting no significant trend of the quiet sun. Spectral measurements show that variations occur at all wavelengths, but with different relations to solar activity. Irradiance changes correlate positively with the solar cycle at most wavelengths from small changes in the IR spectrum and large changes in the UV spectrum.
- The global average temperature response due to TSI changes, related to the 11-year solar cycle, is small, less than 0.05 degrees, hence hardly visible in the temperature record. On the regional scale, the impact of the 11-year solar cycle tends to be larger, in the order of a few tenth of a degree. Also, changes in the ozone concentration and subsequent differential heating of the stratosphere due to UV variations influence the lower atmosphere from above via a chain of dynamical interactions. Some of the observed changes can be attributed to the solar UV variability. For the cosmic ray – cloud link no clear physical framework exists neither do observations support the occurrence of this mechanism.
- Long-term irradiance changes are generally based on three observables, while the calibration is done by estimating the solar irradiance change during the Maunder Minimum (1645-1715) and the present quiet sun:
  (1) Changes in the aa-index as a measure of the magnetic activity of the sun: it indicates a much higher activity nowadays than since the start of the measurements one and a half century ago. Recent studies raise the possibility of long-term instrumental drifts in the aa index.
  (2) Reconstructions of cosmogenic isotopes point toward cosmic ray fluctuations, which can be attributed to the sun's magnetic activity. Simulations of the transport of magnetic flux on the Sun and propagation of open flux into the heliosphere indicate that trends in the aa index and cosmogenic isotopes (generated by open flux) do not necessarily imply equivalent trends in solar irradiance (which track closed flux).
  (3) The range of variability in Sun-like stars. Although previously suggested that the Sun is capable of a broader range of activity than witnessed during recent solar cycles, a reassessment of the stellar data shows that the current Sun is thought to have “typical” (rather than high) activity relative to other stars.
- Reconstructions of solar irradiance changes are inevitably based on certain choices, which cannot or can only partly be validated. For instance, estimates of the global temperature during the little ice-age are used to estimate the change in TSI, while one should wish to have independent estimates.
- In terms of current physical understanding, the most likely long-term total irradiance increase from the Maunder Minimum to current cycle minima is 0.5 Wm^{-2}, but it may be as much as 1.6 Wm^{-2}. When the 11-year solar cycle is taken into account, the best estimate from Maunder Minimum to the present average sun is about 1.1 Wm^{-2}. Converted into a temperature response using the upper limit of the TSI increase of 2.2 Wm^{-2} (including the

effects of the 11-year solar cycle) and the high climate sensitivity of 4.5 degrees for a doubling of CO_2, the upper limit of (equilibrium) response would be 0.4 degrees.

- Long-term variations of solar activity may thus lead to a detectable climate signal. Some evidence can be found in proxy and temperature data before 1950 when the human influence on global temperatures was very likely to be insignificant. Quantification, however, depends totally of the used time series of TSI. Also, the solar signal may compete with possible temperature changes due to internal variability and/or due to volcanic forcing. Therefore, it seems unlikely that a definitive and unambiguous explanation of the century time scale temperature variations can be achieved, although it is likely that a considerable fraction of the observed temperature rise in the first half of the 20th century can be attributed to the increasing activity of the sun.

1 Introduction

The quantification of the human influence on climate depends strongly on our understanding of climate variability driven by internal as well as external mechanisms. The attribution of observed climate change to potential causes is therefore one of the key issues in climate research. Global mean temperatures show a broad spectrum of variability, ranging from inter-annual fluctuations to a warming trend during the 20th century. On the regional scale climate variability is usually much larger, implying that attribution is even more difficult to assess. On the other hand fingerprints of some climate factors may be more visible on the regional scale. Variations in solar activity could be one of those externally driven natural climate factors. Climate change on the millennium scale is likely to be caused by a combination of changes in solar as well as volcanic activity, while human influence was negligible. Thus, reconstruction of these external forcing mechanisms combined with temperature reconstructions may point towards the sensitivity of climate for these forcings.

The extent to which solar activity is a factor in climate change is therefore still a matter of debate, but there is some consensus among climatologists that the contribution of solar activity to decadal climate variations is not negligible and even might be substantial. Opinions differ however as to the likely mechanism causing such a contribution. At least three competing mechanisms may be considered: 1. small variations of the solar constant, affecting the atmosphere from below as far as changes occur in the visible part of the spectrum, 2. variations of UV – radiation, affecting directly the stratosphere and the ozone distribution, thus influencing the lower atmosphere from above, 3. variations of particle radiation of the sun and/or variations in cosmic radiation, having an effect on the electrical and magnetic properties of the earth's atmosphere, eventually causing a change in the atmospheric composition (either by aerosol or cloud formation, or an influence on the concentration of ozone).

There are many ways in which variations of solar activity may influence the earth's climate, some of them are well-established, while others are rather controversial. This study aims to assess the present knowledge on the solar terrestrial relationship from the recent literature. Therefore, a description is made of solar parameters of electromagnetic origin or particle emissions showing variability on a wide range of time scales. Also, the effects on shielding cosmic ray intensity are discussed. On the basis of our knowledge on the solar dynamo and that of sun like stars, the uncertainties in the various parameters are analyzed. Furthermore, an assessment is made of reconstructions of these parameters for use in research on solar terrestrial relationships. Secondly, an assessment is made of the proxy records generated by solar activity, such as the isotopes ^{14}C, ^{10}Be and UV related, as well as reconstructions of climate parameters such as temperature and precipitation. Comparing those records may give clues on the solar activity – climate link, including estimates of uncertainty ranges based on measurement errors and on possible contamination due to geo-magnetic fluctuations and due to climate processes (atmospheric, ocean and biosphere interactions). In the third part of this study the sensitivity of the climate system for solar and other forcings is described using observations and present state-of-the-art models. A distinction is made between the statistical approach, finding correlations and amplitude information of the solar signal, and the modelling approach, using comprehensive climate models in order to study physical-chemical mechanisms of solar influence.

2 SOLAR VARIABILITY INFLUENCING CLIMATE

2.1 Solar Structure and Evolution

2.1.1 Generalities

The Sun is a gaseous sphere with a radius of 7×10^5 km. Since it is gaseous there is no actual surface. The *photosphere* is the part of the outer layers that emits the continuous radiation in the visual spectral range. It has an effective thickness of about 250 km and a density scale height of 110 km (varying with depth). The effective (~'surface') temperature, defined as the temperature of a black body with the same wavelength-integrated radiation flux, is 5800 K. Upward, the layer temperature passes through a minimum value of 4200 K and it rises higher up. The regions immediately above the photosphere are called the *chromosphere*. It is defined by the property that, when viewed at the solar limb, it is transparent for continuous light and opaque in wavelengths of the strongest spectral lines like the Hα line of hydrogen. This explains its colourful appearance at solar eclipses, which gave it its name. The chromospheric temperature ranges between ~ 5000 and ~ 10,000 K. It has a thickness of about 1800 km. Higher up, the temperature rises steeply. At a height of 2100 km above the Sun's limb layer it is already 500,000 K and further upward it assumes values of the order of 2 million K. This outer region, which extends to distances of many millions of kilometres from the Sun, is the *corona*. The corona, with its high temperature and low density is fully ionised: it is a perfect plasma. Its characteristic of being very irregular and changing shape is defined by the magnetic properties of the underlying chromosphere and its features, notably by the Centres of Activity (*cf.* Ch. 2), and by the location of coronal holes.

2.1.2 Evolution

The Sun originated 4.57 Ga (Giga-annum; 10^9 years) ago; its expected future life-time is some 6 Ga. At the time of its origin its total radiation flux, the irradiance was by 30% lower than the present value. Since, it increased gradually. If at that time the terrestrial albedo had been the same as at present, the Earth's average temperature would have been well below 0°C, which would have hampered or even made impossible the origin of life. There is some evidence that a thick terrestrial CO_2 atmosphere existing at that time has increased the Earth's troposphere's temperature by a strong greenhouse effect.

2.1.3 Internal temperature variation with depth

The temperature, density and pressure vary with depth inside the Sun. The central temperature is 15.7×10^6 K; the density there is 160 kg/l. Nuclear fusion reactions in the core region are responsible for the solar radiation. In these reaction chains four protons combine to one helium nucleus. The nuclear energy, thus liberated, is radiated. Hence, the core's chemical composition changes with time and this applies primarily to the number ratio of helium to hydrogen atoms in the very core, which has increased during the Sun's lifetime. But also the number densities of some other elements that are involved in the fusion reaction chains do change with time.

The radiation flux, originating in the core is transported outward, driven by the temperature gradient. The inner parts of the Sun, till 500,000 km from the centre, are in radiative equilibrium, while the uppermost 200,000 km is convective, *i.e.* characterised by up-and downward moving gas. The granulation cells, visible in the photosphere, are manifestations of these convective motions. They are short-lived and moving; upward with velocities of about 1 km/s and downward with higher velocities because of the lower temperature of the downward streaming gas.

2.1.4 Internal rotation

With the modern technique of helioseismology the variation of temperature and density with depth, as well as the variation in chemical composition with depth can be measured and compared with results of theoretical calculations. The agreement between both is reasonably good. An important additional piece of information resulting from helioseismology is that the internal rotation of the Sun can be determined as a function of depth and latitude. The differential rotation of the *surface* is known since long, from sunspot observations, but the new aspect is that its *variation with depth* has now been firmly determined. It appears (Figure 2.1) that the inner parts till ~ $0.70R_o$ (R_o is the solar radius) rotate as a rigid body, but that the outer 200,000 km show pronounced differential rotation. At that level, just beneath the basis of the convection zone, is a thin transition layer with strong depth variation of the radial differential rotation, where consequently strong shearing motions occur: the *tachocline*. Its position is at $0.692R_o \pm 0.005R_o$ (Kosovichev, 1996) or $0.693R_o \pm 0.002R_o$ (Charbonneau *et al*., 1999) and its thickness is $0.04R_o$ (Charbonneau *et al*., 1999). Its level is marginally below the base of the convection zone, which is at $0.713R_o \pm 0.003R_o$ (Christensen-Dalsgaard *et al*., 1991). The existence of the tachocline has consequences for the solar dynamo (*cf.* Ch. 9) because it is the region where poloidal magnetic fields are generated and stored.

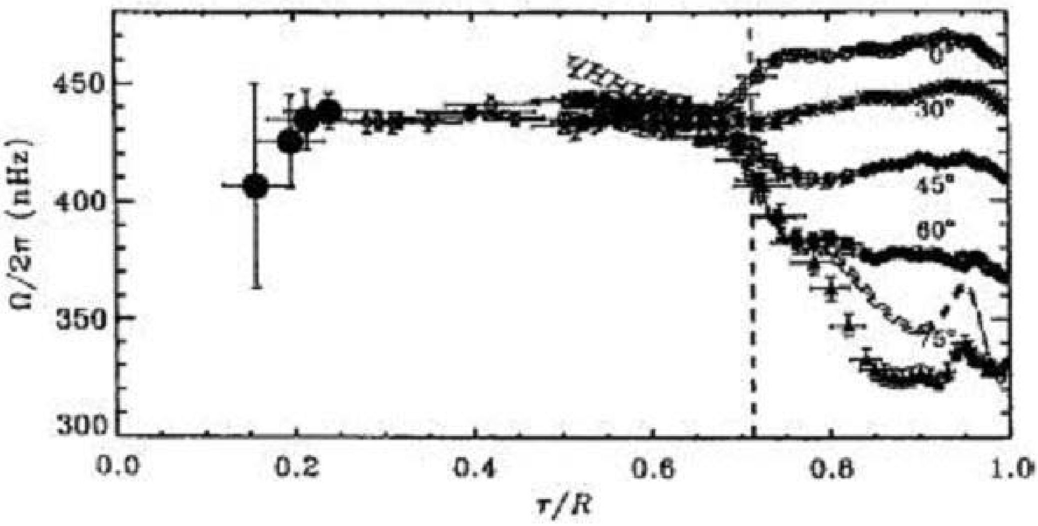

Figure 2.1: Solar interior rotational frequencies as function of solar depth and latitude (labels); R is the solar radius. Note the tachocline at $0.69R_o$. Reproduced from Thompson et al. (2003).

2.1.5 The solar wind and the heliosphere

Parts of the corona move outward: the solar wind. The most part of the wind emanates from the coronal holes. These are regions of the corona, generally situated at high latitudes, where the magnetic fields are open and do not inhibit the escape of coronal plasma from the Sun. These fields close only at a large distance from the Sun. The average velocity and particle density of the solar wind at earth distance are 470 km/s and 9 protons per cm^3. While moving along, the gas expands adiabatively. An important aspect is that the wind carries frozen-in magnetic fields along into space. Since the Sun rotates around its axis, with a syndic rotation period of 27 days at the equator, these field lines are wound up in an Archimedian spiral. The mean magnetic fields at the solar surface along the equator alternate in sign, roughly every 90° in longitude, and therefore the interplanetary magnetic field measured near the Earth changes sign roughly once a week. Clouds of particles that are emitted from the Sun, e.g. those resulting from a Coronal Mass Ejection and those related to the Ephemeral Polar Regions and the Polar Facular Regions (*cf.* Sections 2 and 5) will receive gas emitted from sources at about 50° western solar longitude.

The Sun moves through interstellar space with a velocity (with respect to the near stellar and gaseous environment) of 20 km/s towards the apex, a point in the constellation of Hercules (right ascension 18 h, declination 30°). In the collision with the interstellar gas a shock forms in front and around the moving Sun, at the distance where the dynamic pressure of the carried along solar wind equals the interstellar gas pressure. Thus the heliosphere originates; it is the drop-shaped volume inside the bow shock where the motion of the gas is dominated by the solar magnetic fields and the solar wind. Its largest diameter, measured at right angles to the direction of motion varies between about 80 and 100 AU. In the direction of motion it is much larger because of its long tail (reviewed in a book by Poletto and Suess, 2004).

2.2 Centres of Activity

2.2.1 Generalities

A *Centre of Activity* (CA), also called an *Active Region* (AR) is a region where the larger part of photospheric activity manifests itself. The average size is 40,000 km (longitude) to 20,000 km (latitude), with large variations. The main feature is a weak – bipolar and fractionised – magnetic field, which shows a small tilt – with respect to the solar equator – of the bipole axis. Consequently, the AR is slightly inclined in latitude with the leading end closer to the solar equator. Its principal structures are transient phenomena: sunspots, faculae, prominences and flares. Centres of Activity are also responsible for the *Coronal Mass Ejections*. Akasofu *et al*. (2005), after having defined a new solar coordinate system, found that during the past few cycles main solar activity was chiefly concentrated in two quadrants, one around 90° in longitude in the northern hemisphere and the other around 270° in longitude in the southern hemisphere.

The *polar faculae* and *polar prominences* are another sign of solar activity; these do not occur in the ARs, but are restricted to high latitudes, in the polar prominence zones.

2.2.2 Sunspots

The sunspots are transient features in the photosphere. They have vertically directed magnetic fields of the order of 1000 to about 4000 Gauss. At the location of the fields the convective motions are inhibited; hence less energy is carried upward than elsewhere in the photosphere. This results in the darker appearance of the spots. Yet, the spots are not dark; their effective temperature is still as high as 4200 K.

Most spots do not live longer than 2 days. The average lifetime is 6 days. Large spots may live for weeks and in rare cases even for months. Typical spot diameters range from 2000 km to more than 40,000 km. While motions are practically totally inhibited inside spots there is a complicated velocity field under and around them. Its pattern has been detected with helioseismologic techniques.

Spots seldom occur alone but often in pairs and frequently in larger groups. In a pair the magnetic fields are oppositely polarised, *i.e.* when the one spot has a positive field that of the other is negative. The *leading spot* (*i.e.* the one situated ahead with reference to the direction of solar rotation) has, as a very rough average, three times the magnetic flux of the *following spot*. Similar rules apply to spot groups and to the magnetic fields of the ARs. In such groups the distribution of the fields over the spots can be quite complicated. The *inversion line* marks the transition between positive to negative line-of-sight field components. The more complicated its shape the more favourable the situation is for the origin of solar flares. Spots, by themselves, do not emit radiation or particles that could interact in some essential way with the Earth's atmosphere, but spots are markers of the Centres of Activity. These are situated around spots. In visual spectral light they consist of many patches that are slightly brighter than the average photosphere (the *faculae* or *plages*) and this is related to the fact that the facular elements contain magnetic fields of the order of a few tens to about two hundred Gauss. They have higher temperatures than the undisturbed photosphere.

High-resolution images of Active Regions in wavelengths of selected lines, notably the Hα line of hydrogen, show typical loop-like structures, in which the loops connect oppositely polarised magnetic field regions. The spacecraft TRACE obtained excellent high-resolution EUV images of coronal loops. The loops are plasma tubes confined by helical magnetic fields. They carry electric currents, with the main component propagating along the axis of the loop. In larger loops these currents may be as large as 10^{12}–10^{13} A. These flux tubes usually consists of many thinner tubes, the *flux threads*. The number of such threads in one flux tube is of the order of ten to a few tens.

2.2.3 Solar flares

A flare is caused by a sudden release of energy in a CA. Flares seldom occur on or in a spot, but practically always in the spot's vicinity. A typical flare starts with an *impulsive phase*. This phase, generally lasting for a few seconds till one or at most a few minutes, is the period of energy release. The heated plasma can then reach temperatures of the order of 50 million K. In one case, the flare of 21-05-1984, temperatures of 400–500 million K were determined (de Jager *et al*., 1987). The period during which the heated plasma cools down is called the *gradual phase*. That phase lasts longer, a typical duration is some 10 min, but there are large variations from one flare to the other. In long-duration two-ribbon flares the energy release and plasma heating can continue till far into the gradual phase.

In the chromosphere, in light of the Balmer Hα line, flares are often quite impressive, and that was the way they were actually discovered. The chromospheric aspect of flares is a sudden increase of the density, by factors to above 100. A typical flare density in chromospheric levels is more than 10^{13} particles per cm^3.

Reconnection (Petschek, 1964) or *coalescence of flux tubes* explains the origin (the 'ignition') of flares (review by Sakai and de Jager, 1996; *cf.* also Somov *et al*., 2002). The process of reconnection transforms electromagnetic energy into heat and creates the environment for particle acceleration. After a flare the magnetic fields normally have hardly changed, which shows that not the whole of the two reconnecting flux tubes interact, but that only a few threads reconnect. This is confirmed by the finding that after a flare the helicity is significantly reduced, but not wholly annihilated (Hartkorn *et al*., 2004). Flares are complicated and diverse, and so are the models proposed for the process of reconnection.

At solar latitudes above ~ 40° the activity is manifested by *polar faculae* (Homann *et al*., 1997; Zhang and Zhang, 1999; Makarov and Sivarama, 1989; Makarov and Makarova, 1996; Makarov *et al*., in press), *ephemeral active regions* (Harvey and Martin, 1973) and by *unipolar active regions* (Callebaut and Makarov, 1992, *cf.* also Priest, 1981), the latter appearing as ~ 10^3 km spots with kilogauss magnetic fields. When the filament zones have reached the polar regions, these polar activity structures begin to show themselves.

2.2.4 Coronal Mass Ejections (CMEs)

The CMEs are magnetised clouds of plasma emitted from a Centre of Activity. A large CME can contain 10^{16} g of matter. During the CME's way outward in interplanetary space, plasma accelerated by the bow shock driven by the CME follow the Archimedean spiral magnetic field carried in the solar wind. Eventually, the shock waves associated with the many emitted CMEs can fill a significant part of the heliosphere. The heliospheric magnetised plasma only slowly neutralises or diffuses away through the heliospheric boundary. The consequence is that the heliosphere always contains a fair amount of magnetic field, even at solar minimum when only a few CMEs occur. To this, we have to add that *Co-rotating Interaction Regions*, *i.e.* interplanetary shocks formed at the collision of fast solar winds with earlier emitted slower winds (Richardson, 2004) have their highest frequency during solar minimum. Hence, at no instant the heliosphere is without interplanetary magnetised plasma. Typical values for the interplanetary magnetic field at Earth's distance are of the order of 6 nT (Svalgaard *et al*., 2003), with fluctuations of the order of a factor 10.

2.2.5 Solar energetic Particles (SEP), Solar Proton (Particle) Events (SPE) and solar Cosmic Rays (CR)

Fairly frequently the Sun emits a beam of Solar Energetic Particles. These are ejected from the bow shock of a CME and mostly from a region near its central axis. Since hydrogen is the major constituent of the solar plasma, the SEPs are often called *Solar Proton Events*. A beam of SEPs or a SPE is usually defined as a cloud of particles with an energy >1 MeV. Others advocate higher limiting values, e.g. El-Bone (2003) assumes 60 MeV, just a matter of taste. Observed energies range up to above 1000 MeV. The composition is coronal, *i.e.* hydrogen and helium. The first well-studied case was the burst of solar cosmic rays of 23-02-1956. The difference between solar CRs and SEPs is not always well defined and there is some confusion in literature about the distinction between them. All three classes of particles produce *Ground Level Enhancements* (GLEs, also called Ground Level Events). A list of the major SPEs during the period 1977–2001 was published by Lario and Simnett (2004).

CMEs, SEPs and SPEs are emitted from the Centres of Activity. The mechanism for their emission is not yet well understood, although it must be related to reconnecting flux tubes (Somov *et al*., 2002). Their occurrence is correlated with that of solar flares. CMEs associated with flares are generally more important than those that are not. Also, the CME velocity correlates with the flare strength. The more energy that is stored in the relevant part of the active centre, the better the correlation between flares and CMEs (Lin, 2004). The hypotheses that a flare would *cause* a CME, or the reverse, have not been confirmed. Rather should we assume that a flare and the associated CME are both due to a 'grand instability' in the AR (Sakai and de Jager, 1996). In that line Lin *et al*. (2003) assume a 'catastrophic loss of MHD equilibrium', which may cause (Lin, 2004) energy release in a disrupted magnetic field in the CA. Green *et al*. (2003) seek the origin in a magnetic polarity imbalance.

2.3 The Sunspot and Polar Prominence Cycles

After 17 years of sunspot observations, the apothecary Schwabe (1843, confirmed in 1851) found that the solar activity, measured by the number of sunspots, varies with time and shows an 11-year periodicity. The periods and shapes of the Schwabe cycles are not strict though, there are short and long cycles, weak and strong ones.

Hale (1924) discovered the polarity laws. These three laws apply to bipolar spot groups. The first says that the distribution of polarities between leading and following spots is the same for all spot groups on one (northern or southern) hemisphere and that this arrangement is opposite to that on the other hemisphere. This is the case during one Schwabe (~11-year) cycle. In the following and previous cycle the opposite distribution of polarities applies. This is the second polarity law. The third law says that the solar polar field reverses between two successive Schwabe cycles. In view of these polarity laws it is clear that one should rather speak of a 22-year cycle: the *Hale cycle*.

Another aspect is Carrington's law (1859), sometimes called Spörer's (1874) law, which leads to the *butterfly diagram* of spots. The first spots and Active Regions of a sunspot cycle appear at high latitudes (~30°) and spots that appear later during the Schwabe cycle are found at gradually lower (northern or southern) latitudes. In other words: during the course of a Schwabe cycle solar Active Regions are steadily found closer to the equator. During sunspot minimum it can so happen that spots and Active Regions of both cycles are visible simultaneously, those of the past cycle close to the equator, and those of the new cycle at high latitudes. Hence, a Schwabe cycle lasts longer than the time interval between two minimal spot numbers (*cf.* Figure 2.3). When counted that way, the duration of the solar cycles observed between 1860 and 1960 ranged between 11.8 and 14.4 years, and when the earlier appearance of high-latitude active regions is included too, the real duration is still longer (de Jager, 1959; *cf.* also de Meyer, 2003). This aspect is a formal point of criticism against the attempt of Friis-Christensen and Lassen (1991) to correlate the Earth's tropospheric temperatures with the length of the solar cycle: they did not use the correct lengths. The criticism is not strong, though, because what actually matters is rather something like the integrated numbers of spots in the cycle. It so appears that the time interval between two successive sunspot minima does correlate fairly well with that quantity.

A counterpart to the equator-ward shift of the spot zone is the nearly simultaneous pole-ward shift of the zone of polar prominences, as presented in Figure 2.3 by the curve labelled b_p.

The number of spots on the visible hemisphere is expressed since Wolf (1848) in the *Zürich Sunspot Numbers* R_Z. These are defined as

$$R_Z = k(10g + n),$$

where n is the number of individual spots and g the number of groups; k is a normalising factor, different for each observer. An example: if there is one spot on the visible solar hemisphere then $R_Z = 11 \times k$ (*i.e.* one spot and one group). This definition has a strong *ad hoc* character and it has been tried by several authors to replace R_Z by a quantity with a more physical character, such as the total area of the spots visible on one hemisphere or (still better) the integrated magnetic flux contained in these spots. The Zürich spot number could survive, though, because the number of spots at the visible disc is a quantity that is easy to determine and because R_Z numbers are available since 1700. A drawback, though with positive aspects, is that the Wolf numbers R_Z have remained unchanged since their original publication, in spite of later detection of errors and missed observations. Another drawback is that R_Z numbers have not been defined for the period from 1610 (first telescopic observations) to 1700.

A recent attempt to improve the definition of the sunspot number has all possibilities to become more successful. Hoyt and Schatten (1998) introduced the *Group Sunspot Number*, defined by

$$R_G = 12.08\ \Sigma_i(k_i \times G_i) / N,$$

where G_i is the number of sunspot groups recorded by the ith observer, k_i is the i-th observer's adaptation factor, N the number of observers used to form the daily values and 12.08 is a normalisation factor chosen to make the mean values of R_G and R_Z identical for the period 1894–1976. In their paper, Hoyt and Schatten also re-examined and cleaned the complete set of available observations since 1610. They corrected for apparent errors and added more than 100,000 observations that had not been included in Wolf's initial data set. It can be foreseen that the Group Sunspot Number will gradually take over from the ancient Zürich Number, also because the spot groups are more distinct markers of the bipolar magnetic fields of the CAs. Therefore the Group Sunspot Numbers relate in a clearer way than the Zürich numbers to the number of CAs on the Sun and thus to the component of the solar radiation flux that is emitted by the CAs.

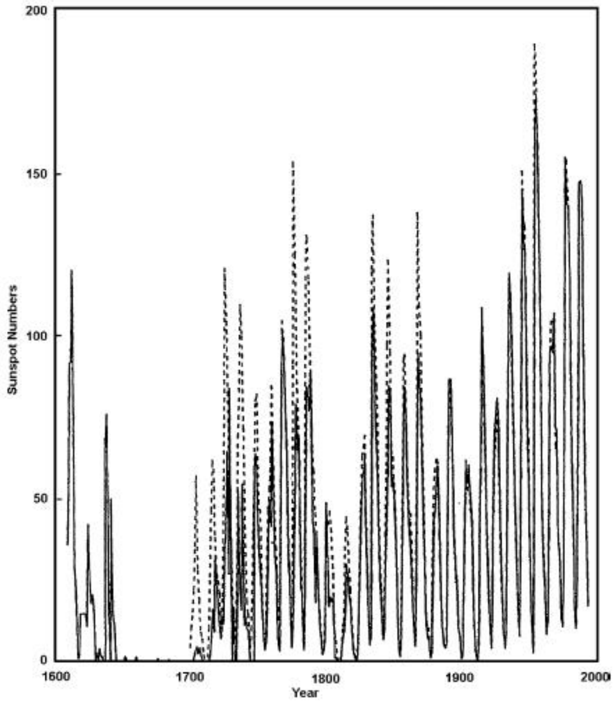

Figure 2.2: Wolf Sunspot Numbers R_Z (dashed) and Group Sunspot Numbers R_G (solid). From Hoyt and Schatten (1998).

Figure 2.2 presents the variation of R_G (solid) and R_Z (dashed) for the period 1610 – 1995 (Hoyt and Schatten, 1998). We draw attention to the (weak) tendency of successive Schwabe cycles to alternate in maximum intensity. Interesting is the nearly complete lack of spots in the second half of the seventeenth century. This is the Maunder minimum (review by Soon and Yaskel, 2004). During that period the average winter temperatures in some western European countries (main data from England, France, and The Netherlands) were below average. This observation has led to the suggestion that solar activity and climate may be correlated. Other great minima are the Oort minimum (1050), and the minima named after Wolf (1350), Spörer (1500), and Dalton (1810), *cf.* upper panel of Figure 2.12.

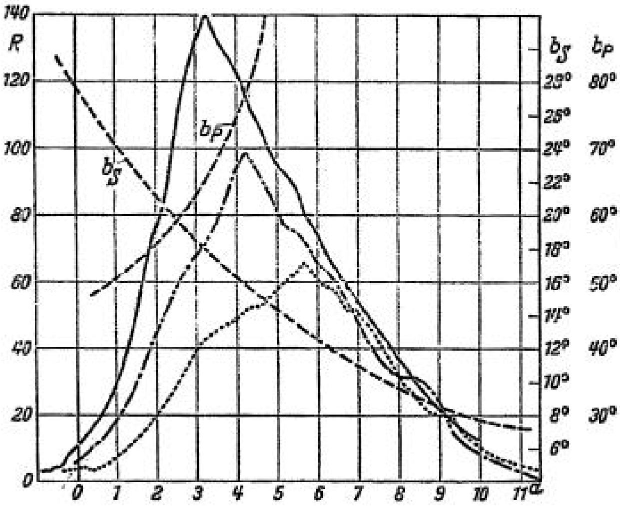

Figure 2.3: Characteristic sunspot curves, after Waldmeier (1957). Abscissa: time in years. Ordinate: Zürich sunspot number. The curves labelled b_s and b_p show the variation of the mean latitudes of the sunspot zone and of the polar prominence zone and demonstrate the two aspects of the solar dynamo: equator-ward motion of the toroidal field and pole-ward motion of the poloidal fields (b_s: latitude of spot area; b_p: latitude of polar prominence area).

Waldmeier (1957) noted the correlation between properties such as the length of a Schwabe cycle and its maximum R_Z value. Thus he defined a set of characteristic cycles (Figure 2.3). Inspection of the figure suggests that these quantities are also correlated to the *impulsivity* of the cycle, which we may define as the gradient of R_Z with time on the rising branch. An enumeration of the various empirical relations in sunspot activity is given by Tandberg-Hanssen (1967, pp. 182–184). De Meyer (2003) has presented a quantitative model for the Schwabe cycle that takes into account Waldmeier's characteristic shapes, the degree of impulsivity and the overlapping of successive Schwabe cycles. Thus he found a linear relationship between the amplitude of each Schwabe cycle and its triggering interval, the latter being defined as the time elapsed between the triggering time of the previous cycle and that of the given one.

The cycles are numbered since 1750. In that order the present cycle (1995 – 2007) is number 23. Usoskin *et al*. (2001a, b, 2002) suggested that cycle number 4, which was exceptionally long, might actually have consisted of two cycles. The discussion has not yet finished. Krivova *et al*. (2002) disagreed on the basis of statistical data including the values of the ^{14}C and ^{10}Be numbers during the suggested new cycle. Their opinion may find support in the observation that the triggering interval between cycle numbers 3 and 4, as found by de Meyer (2003) appears to be the largest of the last three centuries (*viz*. 14.46 years). These claims are debated, however, by Usoskin *et al*. (2003) on the basis of a new discussion of the statistical data. They conclude that there was really a minimum in 1792 – 1793, followed by a maximum in 1794 – 1795. If this would prove to be right, the cycle that was initially numbered number 4 should actually consist of cycles 3 and 4. The numbering of cycles 1, 2 and 3 should then be reduced by one unit. (This procedure is better than adding one unit to all cycle numbers after number 4 because that would confuse published statements about the Gnevyshev–Ohl rule, those on the role of even and odd cycles in dynamo theories and all that follows from it).

Gnevyshev and Ohl (1948) found that there exists good correlation between the properties of the even and the next following odd cycle, and not with the preceding odd one. Hence they concluded that an even and the next following odd cycle form one physical Hale cycle. This empirical Gnevyshev–Ohl rule appears to break down when $R_Z > 125$ (Komitov and Bonev, 2001); which is an example demonstrated by the present cycle number 23, whose top is lower than that of the preceding one, a feature that conflicts with the Gnevyshev–Ohl rule (but note that cycle number 23 is exceptional anyhow, Dikpati *et al*., 2004). Another significant aspect of the Hale cycle, so defined, is (Cliver *et al*., 1996) that high geomagnetic activity occurs during the second half of the even-numbered cycles and the first half of the succeeding ones.

Another feature is the often occurring duplicity of the peaks of the time-dependent values of parameters of solar activity. There are two different aspects to this and they are often confused. The first is the so-called Gnevyshev Gap (Gnevyshev, 1963, 1967, 1977; *cf.* Figure 2.4. The naming is due to Storini, 1995). Gnevyshev found that most solar activity indicators are double peaked with an average time difference of about 1 year. The two peaks are also weakly visible in the irradiance, as shown in Figure 2.5. Bazilevskaya *et al*. (2000) found that the Gnevyshev Gap is shown clearest when the two solar hemispheres are considered separately, because the hemispheric activities do not reach maximum at the same time. On closer inspection there seem to be three peaks, with irregular peak separation in a range of 6 to 18 months (Kane, 2005b)

The second aspect is the fact that the maximum frequency of energetic emissions is delayed, also by about a year, with respect to the less energetic features, such as sunspots. Since, for the first time in February–March 1942, strong radio-bursts and energetic cosmic ray bursts were detected at an unexpected time, *viz*. some years after sunspot maximum, this phenomenon has repeated itself at many subsequent solar cycles. One of the recent examples is provided by the powerful flares on 15 July 2002 and 23 July 2002. These appeared a year after spot maximum, and CMEs accompanied both. The most violent case was the series of 'Halloween Flares' of end October and early November 2003. These included the strong X-ray and white light flare of 4 November 2003 (the strongest X-ray flare ever recorded), as well as the strong CME of October 23. It swept through the heliosphere, passed the Earth after one day and encountered Voyager 1, at a distance of 14.5×10^9 km, on 13 July 2004. On 28 October 2003 the solar Region 10486 produced an X 17.2 flare, followed by a fast-moving Coronal Mass Ejection and a strong Solar Particle Event. The fast moving cloud impacted the Earth 19 h later, implying an average speed of 2200 km/s. These latter phenomena all occurred 2 years after the sunspot maximum of 2001.

In order to distinguish this latter feature clearly from the Gnevyshev Gap we suggest calling this delay between the frequency and power of energetic emissions with respect to the time of sunspot maximum the *Energetic Emissions Delay*. It is weakly visible in our Figure 2.4 where it appears that the second peak is more prominent in the geomagnetic data than in the *R*-numbers. The second peak also appears clearly in statistical data on the Solar Proton Events (Lario and Simnett, 2004). The Energetic Emissions Delay exists, in spite of the evident fact that it, as well as thr sunspots, are related to the toroidal magnetic fields. There is another observation, (Beer *et al*., 1998) that there is a time lag of 1–2 years between the maxima of sunspots and the minima of the ^{10}Be fluxes (the rate of production of ^{10}Be cosmogenic radionuclides is anticorrelated to the rate of emission of magnetised plasma from the Sun – *cf.* Ch. 5). The ^{10}Be production is related to the emission of magnetised plasma by the Sun. This is due partly to the CMEs (related to the number of spots and the toroidal magnetic fields) and partly to the plasma emission from higher latitudes, related to the poloidal magnetic fields. A fine way, actually the best way to show the Energetic Emissions Delay is by plotting the values of the amplitude modulation of the 11-year cycles in the *aa*-index (*cf.* Ch. 5 for its definition) against those in the sunspot numbers (Duhau and Chen, 2002; Duhau, 2003a), *cf.* Figure 2.14. That plot shows hysteresis: an oval-shaped, nearly closed curve instead of a single line. The additional fact that the hysteresis curve does not exactly repeat itself during subsequent cycles demonstrates the non-linear aspect of solar variability, and the sudden change of orientation reflects the occasional occurrence of a phase catastrophe (*cf.* Chs. 9 and 10).

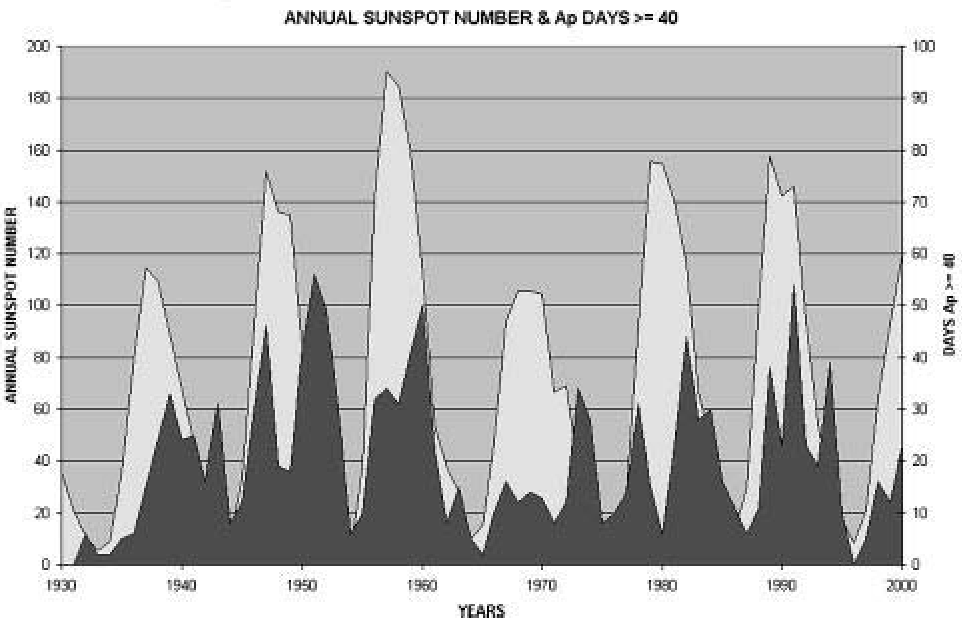

Figure 2.4: Annual number of geomagnetically disturbed days with Ap-index >40 (dashed line and hatched area) vs. annual sunspot number (solid line) for solar cycles 17–23. Courtesy J.H. Allen, NOAA National Geophysical Data Center, Boulder, Co.

The Energetic Emissions Delay seems to apply less well to flares and that is understandable since flares are associated with (complex) spot groups. In odd-numbered cycles the flare maximum lags behind the R_Z maximum by about 10–15 months, while there seems to be no such time lag in even-numbered cycles (Temmer *et al*., 2003).

It will be shown in Sections 4 and 5 that Sun–Earth related activity has two components: the variable irradiance and the energetic particle component. The first is related to the extent and number of CAs and hence to the toroidal field components. The latter is shown by various phenomena: the energetic particle emissions, the number of CMEs, the ejection of other magnetised plasma clouds, part of which are related to the toroidal field while another part is correlated with the poloidal fields. The Group Sunspot Number R_G is a proxy for the first component, while (*cf.* Ch. 5) a proxy for the emission of plasma clouds is found in the rate of deposit of cosmogenic radionuclides. The existence of these two components may be related, in a way not yet understood, to the Energetic Emissions Delay. We summarise that *the sunspot number R_G should not be used as a proxy for solar plasma ejection (apart from CMEs) or energetic phenomena. Energetic events have their maximum frequency 1–2 years after the maximum number of spots: the Energetic Emissions Delay.*

2.4 The 11-years Variation of Solar Irradiance and Radiance

The irradiance, often, though a bit superfluously also called the Total Solar Irradiance (TSI), is defined as the solar bolometric radiation flux, this being the radiation integrated over the whole Spectral range. The radiance, often also called the spectral irradiance is the flux in a limited spectral range. In the early twentieth century, Abbott (1934) and others have indefatigably tried to measure the solar irradiance, hoping to find correlation with the R_Z-number. Their attempts to detect variations in the irradiance all failed. A glimpse of the heated debates of that time can be read in Abbott (1913). The variations were apparently too small to be detected successfully from observations taken on the ground, or they were non-existent. Only after the beginning of the satellite era, from about 1978 onward, the variation of irradiance with time, including a clear dependence on the R_Z-number could be established. Observed irradiance variations are presented in Figure 2.5, taken from a review by White (2000). We refer also to the reviews by Fröhlich (2003, Figure 2.3, and 2004, Figure 2.3) and to that by Fröhlich and Lean (2004); they essentially show the same data. The variations appear to be small; the maximum relative amplitude is less than 0.1% (Unruh, in press). Preliminarily, a secular trend of 0.04% per decade was announced (Willson, 2004). In this section we will show that irradiance variations can*not* be detected from ground level.

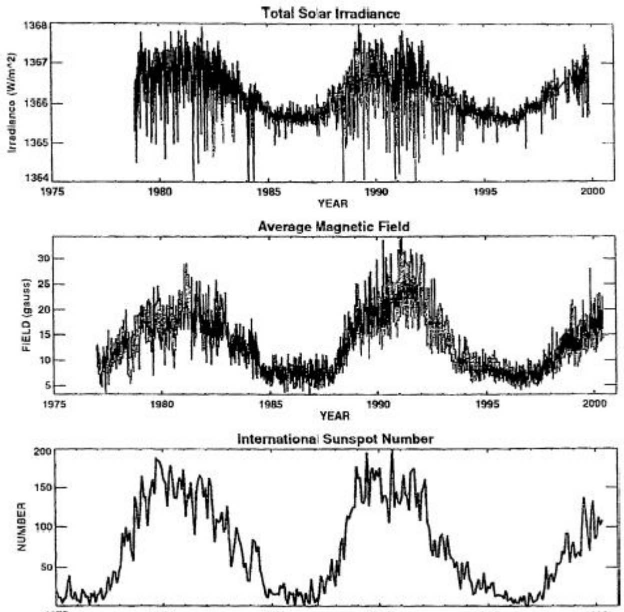

Figure 2.5: Variation in solar irradiance during two Schwabe cycles, compared with that of the average magnetic field and the sunspot numbers (White, 2000). We refer also to Lockwood (2002) and Fox (2004, Figures 2.12 and 2.13) where similar relationships are given and the correlation between the irradiance and the sunspot numbers is discussed.

The origin of the variations can easily be ascertained from a study of the solar radiation spectrum and its variability (Lean, 2000, *cf.* our Figure 2.6), and by investigating from which solar regions and height levels the radiation components from various wavelengths emerge.

The visible part of the solar spectrum is emitted by the photosphere, while the chromosphere and corona emit the infrared and – notably – the ultraviolet radiation. This is so because the absorption coefficient of the solar plasma is higher in these fairly extreme wavelengths than in the visible spectral range. Specifically, the solar radiation at 100 nm is emitted by the mid-chromosphere, that at 200 nm by the transition region between photosphere and chromosphere and that at 300 nm by the high parts of the photosphere. (The X-ray part of the spectrum is emitted from the corona because only a high-temperature plasma can emit thermal X-rays. Hard X and Gamma-rays are non-thermally emitted by flares, short-lived transient features of the solar radiation spectrum.).

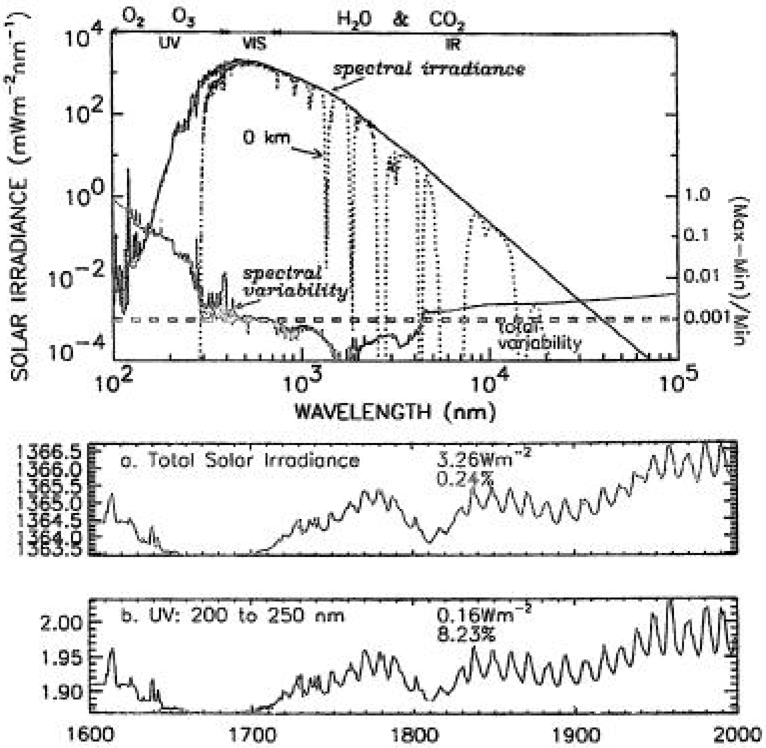

Figure 2.6: Origin of solar radiance variations. Upper diagram, solid line: the solar irradiance spectrum outside the atmosphere. Dotted is the flux received at sea level. Gray and right-hand ordinate: the relative variation of the spectral radiance as function of wavelength. Second and third diagrams: reconstructed variations of total irradiance and the UV radiance between the years 1600 and 2000. All values are in Wm^{-2} (Lean, 2000).

For understanding the origin of the variations in the irradiance it is important to note that variations in the *structure of the quiet photosphere* over the solar cycle, e.g. manifested by variations in the temperature or pressure depth-dependence, have, in my opinion, so far not been detected, despite intensive research. It is true that Gray and Livingston (1997) did find a variation of 1.5 K of the average photospheric temperature during a solar cycle. We think that this variation was caused by the fact that these authors made their observations in integrated solar light; hence their spectra included those of the Active Regions, the number and strength of which vary during the cycle. The authors, evidently suspecting that this might play a role, selected a line that is formed deep in the photosphere, where the influence of the Active Region was assumed to be weak or absent, but there is certainly no guarantee that the faculae do not have deep-seated extensions that may still have affected the profiles of the lines chosen. There is an indirect way to show that their finding cannot be reflecting the temperature variations of the undisturbed photosphere, because if that were so, then these temperature variations should result in a variation in the irradiance of $\Delta I / I = 4(\Delta T/T)$ = 0.1%, which is practically equal to the observed irradiance amplitude. But to that amount one has to add the variations of the UV part of the spectrum, caused by the variable appearances of ARs, which is of the same amount. The sum would amount to twice the observed amplitude, which is a contradiction.

The above conclusion is supported by a study of Woodard and Libbrecht (2003) who found that "the irradiance data can adequately be represented by a model in which the remaining brightness variations (*i.e.* after having corrected for the influence of sunspots, CdJ) are due entirely to facular contributions, confined to magnetically active latitudes".

In addition to the above we have to consider the occasional small reduction of the irradiance by transient sunspots (*cf.* Zahid *et al.*, in press). This is for a part compensated by the increased emission from bright structures in the surrounding CA, the so-called plages or facular fields. Anyway, the contribution of sunspots to the irradiance variations is restricted to short occasional dips and is not of importance for long-time discussions (Radick, 2004).

The facular fields are the lower parts of the chromospheric ARs. The emission of the higher photospheric and chromospheric layers is strongest in the UV part of the spectrum. Their influence on the irradiance has been studied by Unruh *et al.* (1999) and later by many others. The variable component of the irradiance, being of chromospheric origin and located in the UV and IR parts of the spectrum, is dominated by the emission from the ARs because the variable structures of the ARs are located in chromospheric and coronal levels. These structures, with their weak magnetic fields, vary strongly in number, size and intensity during the sunspot cycle. The variations of irradiance are correlated with the magnetic flux density (Kuhn and Armstrong, 2004). Krivova and Solanki (2005) found that more than 90% of the irradiance variations have a magnetic origin.

The statement that the variation of irradiance is seated in the chromospheric parts of the CAs can be amplified as follows.

Following Lean (2000) we describe the variations of the radiance. To that end we introduce the quantity $\delta = (M_{max} - M_{min})/M_{min}$, where M is the (wavelength dependent) radiance. Figure 2.6a demonstrates that only the parts of the solar spectrum with wavelengths below 300 nm and above 3000 nm have δ-values above 0.001. In addition, Lean's Figure 2.9 (reproduced here as Figure 2.6b) and the data in the review by Rottman *et al*. (2004) show that the total UV amplitude (200–250 nm) during the past two well-studied cycles was equal to the total amplitude of the whole irradiance during that period. Hence, the irradiance variations are restricted to the UV. An additional point, important for Sun-climate relations, is that there are so far only weak indications (Willson, in press) that the lowest level of the solar irradiance, *i.e.* the level at solar minimum, has significantly changed during the past few decades of continued observations.

These observations reconfirm that the part of the irradiance emitted by the photosphere does not significantly vary during the cycle and that the variable part of the irradiance originates chiefly from the chromospheric ARs, a fact that was mentioned already in the nineties by Willson and Foucal. An implication is that these radiation components do not reach the Earth's troposphere and ground level. The stratosphere absorbs it (*cf.* Haigh, 2004). The only way, therefore, for the variable solar UV flux to influence the terrestrial troposphere is by some form of stratosphere–troposphere coupling.

We conclude that the overall properties and the depth-dependent structure of the quiet photosphere do not vary during the cycle and that it is correct to accept that the observed minima of the irradiance refer to the integrated flux of the quiet photosphere, without the contribution of the ARs but including the contribution of the (magnetic) network elements, that are persistently present. The contribution to the irradiance of the network elements is, in their wavelength distribution, expected to be comparable to that of the ARs. Its amplitude is expected to be much smaller (Ortiz, in press; Chapman, in press).Unruh *et al.* (2000), Solanki (2002) and Krivova et al. (2003) summarise similar results. A successful computer model for predicting the EUV radiance due to magnetic elements has been developed by Wu *et al*. (in press).

At this point we make two additional remarks. First, that there is no time lag between the maxima of spots and of irradiance. This is evident from the physical connection between spots and faculae. This supports the statement, made earlier in this paper, that the sunspot numbers can be used as a proxy for irradiance variations. Next, that the solar radio emission at 10.7 cm wavelength, which is often used as a tracer for solar variability, is primarily emitted by those layers of the CAs that are situated between a few thousands to some 10,000 km above the surface. It should (and does) therefore vary in parallel to the UV radiance. Similar statements can be made about the Mg II and Ca K indices. These self-reversals in the resonance lines of Mg II and Ca II are emitted by magnetic structures in chromospheric height levels. Understandably, these quantities are well correlated with the irradiance variations and the sunspot numbers, as was verified by Floyd *et al*. (2005).

The conclusion from this section is that *the fraction of the solar irradiance that directly reaches the Earth's troposphere is emitted by the solar photosphere. It does not significantly vary during the solar cycle, because the photosphere does not vary during the cycle. The variable part of the solar radiation flux is emitted by chromospheric parts of the CAs, and it only directly influences the higher, stratospheric terrestrial layers. These can only influence the troposphere by some form of stratosphere–troposphere coupling.*

2.5 Ejection of Solar plasma; Cosmic Ray Modulation

In this and the next section we deal with another possible aspect of solar activity that may influence terrestrial climate. Virtually uninterruptedly the sun emits magnetised plasma into space. There are three components: the solar wind, the Coronal Mass Ejections and the emission from ephemeral active regions.

Coronal Mass Ejections (CMEs) were discovered in 1973 by R. Tousey, using observations made with OSO-7. Their existence was verified in 1974 by observations aboard Skylab. Since, thousands of them have been observed. Solar monitoring satellites such as the Solwind spacecraft (1979–1985), the Solar Maximum Mission (SMM, 1980, and 1984–1989; *cf.* Hundhausen, 1999), Yohkoh and more recently SOHO and Helios yielded a wealth of observations. CMEs are also observed from the ground at the Mauna Loa Observatory. SMM saw 31 CMEs in the minimum year 1984 and 463 in 1989, when solar activity was close to its maximum. Since, the instrumentation was improved in sensitivity. Between 1996 and 2000 the LASCO instrument aboard SOHO observed 3217 CMEs (Moon *et al*., 2002). Statistically, there is 0.5 CME per day during solar minimum against 6 per day during maximum (Gopalswamy *et al*., 2003).

CMEs appear as bright, generally loop-like outward moving structures. The shape and orientation of the loops can be complex. A typical CME contains 10^{15}–10^{16} g of plasma and it carries a mechanical energy of 10^{31}–10^{32} ergs. The electric current intensity is about 10^{9} A. CMEs leave the Sun with an initial velocity of a few tens of kilometres per second, but the velocity has increased to values between 200 and 2500 km/s at the Earth's distance. The average velocity is 400 km/s. The angle spanned by a typical CME ranges between 20 and 90 degrees. At the Earth's distance the photon density ranges between 4 and 10 cm^{-3}. The particle flux there is of the order of $1–2 \times 10^{8}\ cm^{-2}s^{-1}$.

There are two types; the one is spatially and temporarily associated with X-ray flares and the other with eruptive prominences. Those of the first type are accelerated during the impulsive phase of flares. They have larger velocities and are more energetic than the other type. About 40% of the weaker flares have no associated CME (Andrews, 2003). Those erupting filaments that are not associated with CMEs appear to be spatially confined, in contrast to the others (Choudhary and Moore, 2004). Taking all CMEs together it appears that they have a broader distribution over latitude than the spots have (Hundhausen, 1993). CMEs carry magnetised plasma from the Sun into the heliosphere. Simnett (2003) describes a well-studied succession of events including a strong shock driven by a fast CME which appeared to have been able to populate a large fraction of the inner heliosphere with accelerated ions.

The other contribution is from ephemeral active regions. These latter regions do not form spots and they have a broader distribution in latitude (Harvey, 1993) than the ARs; they occur also at high latitudes. There is uncertainty about the contribution of these regions. Lockwood *et al*. (1999) assume that they contribute to the open flux with a factor 6 smaller efficiency than the active region flux.

The third contribution, in importance comparable to the CME contribution, is the plasma streams (the solar wind) emanating from coronal holes (Shrivastava, 2003). The high-speed plasma streams are important. When these meet earlier emitted slower solar wind plasma, magnetised shocks are produced, the *Co-rotating Interaction Regions* (CRIs, Richardson, 2004; Akasofu and Fry, 1986). In that respect there is a significant difference between the periods of solar maximum and minimum. At minimum the non-thermal plasma particles occur mainly close to the heliospheric current sheet whereas at maximum the whole heliosphere is filled with Sun-generated non-thermal particles.

The *open solar flux* Φ_{open} (Lockwood *et al*., 1999) is a useful measure for the strength of the interplanetary magnetic flux at the Earth's distance. It is defined as the activity-connected magnetic flux in interplanetary space. It consists of the contributions from the three parts enumerated in the first paragraph of this section. In order to relate the interplanetary flux to solar features, Solanki *et al*. (2002) correlated the active region component with the sunspot number, used as a proxy, and the ephemeral region contribution to the shape parameters of the corresponding cycle. (We note, in passing, that the sunspot number is not the suitable proxy for the ejected plasma; the cosmogenic radionuclides are to be used). Solanki's hypothesis opens the way towards a numerical calculation of Φ_{open} starting from solar data. To that end it is also necessary to know the decay time t_{decay}, the decay being assumed to be caused by cancellation of flux of opposite polarity or by diffusion out of the heliosphere. The 'decay time' may for numerical reasons also be considered as a rough quasi for the CRI contribution. A semi-empirical value of t_{decay} = 3 yr was used by Solanki *et al*. (2002). Other values are 4 yr (Solanki and Fligge, 2000) and 5yr (Harvey, 1994).

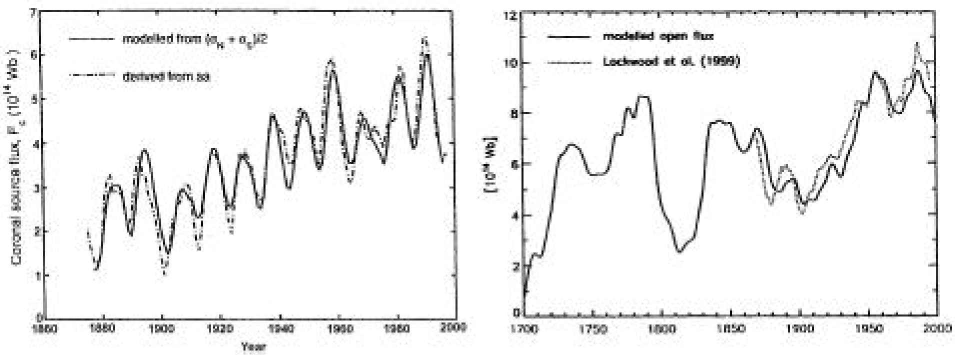

Figure 2.7: The open interplanetary magnetic flux. Left: variation of the open magnetic field derived by Lockwood et al. (1999; dash-dotted, predicted by Solanki et al. (2000) as adopted by Lockwood and Foster (2000; solid). From Lockwood and Foster (2000). Right: 11-year running means of the open magnetic flux modelled by Lockwood et al. (1999, dotted) and Solanki et al. (2002; solid line).

Figure 2.7 (left) (Lockwood and Foster, 2000) presents the variation of Φ_{open} since 1700. Figure 2.7 (right) (Solanki *et al*., 2002) gives the 11-year running mean. The diagrams are a reconstruction by Lockwood *et al*. (1999) based on geomagnetic indices available since 1860, a ^{10}Be-based reconstruction by Beer *et al*. (1990) and predictions as described above by Solanki *et al*. (2000). The dip around 1810 (the Dalton minimum) and the twentieth century maximum are conspicuous. A fascinating and unexpected observation is that the value of Φ_{open} has doubled in the course of the twentieth century (Lockwood *et al*., 1999) and it reached a maximum value in the final decades of that century (Lockwood, 2003).

Geomagnetic index. In the interaction with the terrestrial magnetosphere the heliospheric plasma contributes a Sun-related component to the magnetic field measured at ground level.

The variation with time of this so-called *aa*-index is strongly correlated with Φ_{open} and it shows the same well-known decadal cyclic variations, included the Energetic Emissions Delay. Mursula *et al*. (in press) have expressed doubt to the reliability of this index, but Clilverd *et al*. (2005) who have anew checked it, confirm its robustness.

Apart from the up and down going components there is a basic non-varying component to the *aa*-index. Its existence shows that even during sunspot minimum there remains some open solar flux in interplanetary space. This can be understood as a consequence of the relationship between interplanetary shocks and CIRs and by considering the time needed for diffusion and neutralisation of the fields. Just like the non-varying component of Φ_{open}, the basic value of the *aa*-index has more or less steadily increased during the twentieth century (Cliver *et al*., 1998; also already in Cliver *et al*., 1996). That steady increase, as depicted by the envelope of the minimum *aa*-values, is also visible, but slightly less pronounced, in the *R* numbers (compare Figures 2.2 and 2.8). The similarity to the increase of the average terrestrial ground temperature during the same period was first mentioned by Cliver *et al*. (1998). This fact, and the gradual increase in RG, suggests a solar influence on climate and invites for further investigations.

Modulation. The 11-year periodic variation of *Φopen* manifests itself in the Earth's atmosphere by variations in the received cosmic ray (CR) fluxes, because the interplanetary magnetic fields modulate the CR flux received at ground level. Cosmic rays, usually called 'galactic cosmic rays' are very energetic particles, bombarding the Earth isotropically. They cover the energy range up to 3×10^{20} eV. Apart from the most extreme energetic particles they originate in supernovae and their remnants. Understandably, the influence of galactic cosmic ray modulation is to smooth the effect of individual CMEs, but there are exceptions. Shrivastava and Jaiswal (2003) describe cases of direct correlation of CR modulation with specific high-speed solar wind streams.

The modulation of galactic cosmic rays can well be described theoretically (Wibberenz *et al*., 2002). The differential energy spectrum of the galactic cosmic rays at the Earth's orbit and its shape after heliospheric modulation is given in Figure 2.8 (*cf.* also Usoskin *et al*., 2002). Only particles with relatively low energies are deflected in the interplanetary magnetic fields. Modulation appears to be effective for particle energies below ~ 50 GeV. Hence the variable component of galactic cosmic rays received at ground level is situated in that range of energies. The Pioneer and IMP spacecraft, which moved through the heliosphere towards its border, observed an increase in the cosmic ray flux when approaching the outer heliospheric regions. The average radial gradient is ~ 2% per AU (Webber and Lockwood, 2002).

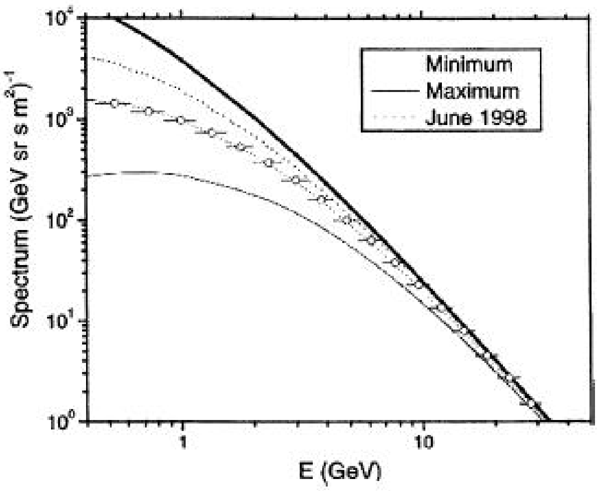

Figure 2.8: Differential energy spectrum of galactic Cosmic Rays in the local interstellar medium (thick line) and at the Earth's orbit at solar maximum (thin solid) and minimum (dotted). Also shown is the spectrum for June 1980 (with thanks to I. Ususkin).

Cosmogenic Radionuclides as tracers. For the matter of solar–terrestrial relations it is important that the galactic cosmic rays are modulated in such a way that the stronger Φ_{open} the less the flux of CRs measured at Earth. Since the amount of open solar flux is larger near sunspot maximum than near minimum, the CR flux measured at ground level is smallest at solar CME maximum. This observation offers the way to introduce useful proxies for solar CME activity (or, stated more accurately, for the variation of the open solar flux in interplanetary space) in the course of time. It allows one to get information for periods over which no observations of interplanetary solar plasma are available. The collisions of cosmic rays with molecules in the Earth's atmosphere produce showers of particles among which radioactive nuclei of various elements, the cosmogenic radionuclides, in particular ^{14}C, ^{10}Be, ^{26}Al and ^{36}Cl. The ^{14}C flux is often derived from tree rings, the ^{10}Be flux from ice cores. Ninglian *et al*.(2000) used NO_3 from ice cores. The physics of these processes is reviewed among others by Beer (2000) and Muscheler *et al*. (2003). The observation of these elements in biological sediments and in ice cores opens the possibility to obtain information on solar variability during the past, including the Holocene and earlier periods (Koudriavtsev *et al*., 2003). One has to be aware of non-solar influences, e.g. the ^{14}C record over the past 12,000 years shows a gradual slope and superimposed over it a wavy virtually sinusoidal pattern, the latter with a period of some 8000 years. These variations are assumed to be of terrestrial origin (Clilverd *et al*., 2003), such as the variation in the Earth's magnetic field. The residual curve, obtained after subtracting these variations, would then show the solar effects.

The conclusion is that *the outflow of magnetised plasma from the Sun and its confinement in the heliosphere influence the Earth's environment by modulating the flux of galactic cosmic radiation observed on Earth. Modulation is only effective for CR energies below about 50 GeV. The cosmogenic radionuclides are proxies for this influence.*

2.6 Tropospheric Ionisation by Cosmic Rays

Following earlier ideas (*cf.* Pudovkin and Veretenenko, 1995), Svensmark and Friis-Christensen (1997) and Svensmark (1998) presented a relation between the observed cosmic ray flux and data on average low-altitude cloudiness. Essentially, their claim was that an increased cosmic ray flux was correlated with more cloudiness. The effect appears to be larger at high latitudes, a finding that agrees with the expected shielding of energetic particles by the Earth's magnetic field. A weak aspect in their approach is that the statistics is restricted, because lack of data, to only two solar cycles. These ideas were followed up by others; *cf.* Bazilevskaya *et al*. (2000), Pallé and Butler, (2000, 2002), Christl *et al*. (2004) and Dergachev *et al*. (2004).

The suggested relationship between cosmic rays and cloud formation has been criticised by several authors, but was sustained anew by Ogurtsov *et al*. (2003) who linked observed high-latitude climate changes with the Hale cycle, by Usoskin *et al*. (2004) and by Dergachev *et al*. (2004). Usoskin *et al*. studied the observed global distribution of low clouds while looking for the connection with the calculated ionisation by cosmic rays. They find "strong support for the hypothesis that the CR induced ionisation modulates cloud properties" and this conclusion is confirmed by Dergachev *et al*. (2004). This is somewhat in line with Pallé *et al*. (2004) who found that the Earth's albedo, as measured by the Earth's reflectance at the moon (the 'earthshine'), decreased during the period 1984–2001. In its details this result does not fully support that of Usoskin *et al*., which may be due to the fact that Usoskin *et al*. restricted themselves to low clouds. Anyway, Pallé *et al*'s result can be used to support the hypothesis that the observed decrease of the CR flux, by 10% over the past 50 years, would be correlated with a steadily decreasing degree of cloudiness by a few percents, a result that fits with the observed increase of the open solar flux. In that connection the weak indication for a subsequent increase in the Earth's albedo after the year 2000 (observed by Pallé *et al*.) is a matter that asks for continued further observations and study. A recent review of the Sun-clouds problem is from Kristjánsson *et al*. (2004). They find support for the suggested relation between low cloud cover variations and those in the irradiance, not so with those in the cosmic ray flux; an apparent conflict that asks for further investigation.

Clearly, the assumed cosmic ray-cloud connection is not yet satisfactorily solved, but if it were confirmed, the cause of this relationship should be sought in Sun-related atmospheric ionised particles acting as condensation nuclei for water vapour drops. This observation asks for data, observational and theoretical, on atmospheric ionisation by cosmic rays.

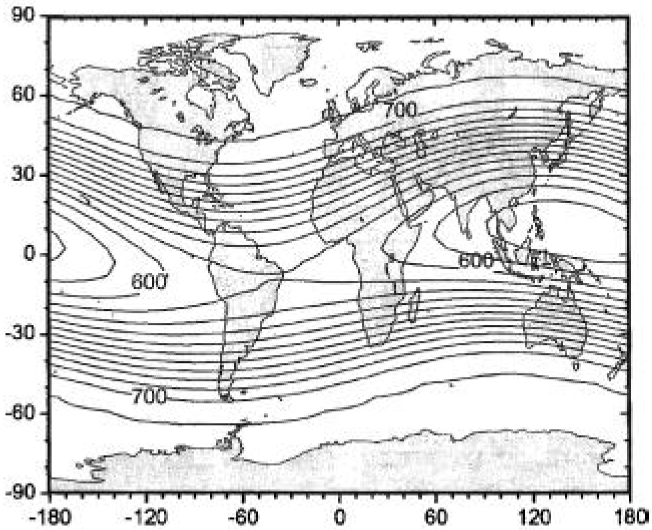

Figure 2.9: Calculated equilibrium cosmic-ray induced ionisation (in ion pairs per cm^3) at 3 km altitude. From Usoskin et al. (2004b).

Since the first cosmic rays balloon experiments by Hess and Kohlschütter in the early part of the twentieth century, the number of ion pairs at ground level is known to be about 10 – 20 per cm^3.It increases with height and already reaches twice that value at 5 km altitude, to increase further at greater heights. A recent review of cosmic ray induced ionisation is by Usoskin *et al*. (2004b). At ground level the ion-pair production due to high-energy cosmic rays (mainly decay electrons from muons) is 2 cm^{-3}s^{-1}, a value that should be compared with 9 cm^{-3}s^{-1} due to terrestrial radioactivity. This ratio changes rapidly with height; at 1–2 km cosmic rays take over and at 5 km the cosmic rays are the only source for atmospheric ionisation. Simulation experiments by Tinsley and Yu (2004) show that enhanced CRs increase the rate of ionisation at altitudes below 4 km. Such findings, and the fact that the cosmic ray ionisation varies with the observed cosmic ray flux *i.e.* by 10 – 20% during a Schwabe cycle, is a reason to assume a direct relation between the varying flux of cosmic rays and change of cloudiness. In that connection, Svensmark and Friis-Christensen (1997) remark that direct condensation in a supersaturated atmosphere, as in a Wilson chamber, must be excluded since supersaturation does not generally occur in the Earth's atmosphere. Aerosol particles, however, may initiate nucleation and the formation of liquid cloud drops in a slightly supersaturated atmosphere (Rogers and Ya, 1989; Palé Bago and Butler, 2000). The influence of aerosols is also discussed by Usoskin *et al*. (2004b) and by Dergachev *et al*. (2004). The physical aspects of cosmic-ray ionisations are treated by Bazilevskaya *et al*. (2000; *cf.* also Krainev and Bazilevskaya, in press), who discuss charge-dependent chemical reactions and the formation of droplets or ice crystals. Condensation nuclei can form in clear air directly from charged molecular clusters (Yu and Turco, 2000). An extensive review is given by Dorman (2004; pp. 565 ff). Usoskin *et al*. (2004b) calculated the equilibrium cosmic-ray induced ionisation at 3 km altitude; their result is reproduced here in our Figure 2.9.

Concluding, since *the cosmic ray flux received on Earth varies in counterphase with solar plasma emission, the same is the case for CR-ionisation in the low atmosphere at heights above 1–2 km. The rate of ionisation is expected to vary with the CR flux, with its characteristic amplitude of 10 –20% per Schwabe cycle. The variable cosmic ray flux may influence climate via variable cloudiness.*

2.7 The Solar Signal in Tropospheric Temperatures

In this section we briefly touch the question whether there is an observable solar signal in terrestrial tropospheric temperature variations, and if so, of that is due to variations in the solar irradiance or that of the emission of magnetised plasma.

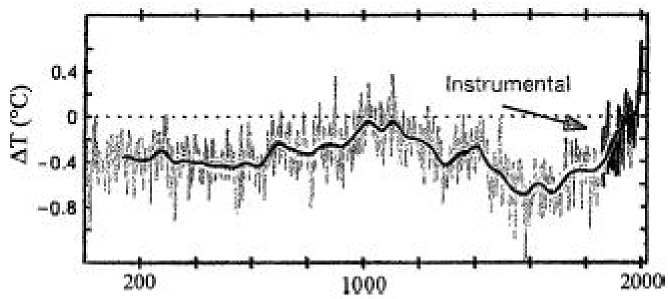

Figure 2.10: A calibrated reconstruction of Northern Hemisphere average temperature variations since the year 200 (Moberg et al., 2005).

An answer to the first question can be derived from a comparison of the time variation of global terrestrial temperatures with that of solar activity. The much debated question of the value and significance of observed variations in the mean tropospheric temperature was brought nearer to an answer in a recent investigation by Moberg *et al*. (2005, with references to earlier publications). They show the variation of mean Northern Hemisphere temperatures *ΔT(time)* since the year 200 (Figure 2.10). This curve can help to answer the question if solar variability influences climate. It appears to do so. The *ΔT(time)* curve runs reasonably well parallel to the variation of solar activity as presented in the upper frame of our Figure 2.12. A numerical comparison of these two curves (de Jager and Usoskin, in prep.) shows the fair correlation between the two. Earlier, Van Geel *et al*. (1999) found a distinct correlation between a sharp rise in the ^{14}C flux around 1600 A.D. and abrupt climate cooling.

The question then arises which is the solar origin of these variations and to that end we have to consider the two alternative mechanisms mentioned earlier: variations in the UV radiance or rather to those in the emission of magnetised plasma. There are two approaches to distinguish between the two. First, plasma emission lags behind the variation of the UV radiance by one or two years and next it is to be expected that the global distribution of temperature variation should be different according to the source: the effects of plasma emission, which works via cosmic ray modulation should be stronger at higher geomagnetic latitudes. We discuss the two alternatives.

The matter of cosmic rays influencing climate via cloud formation was discussed in the preceding section. It appears that Sun-correlated cloud formation is pronounced at high geomagnetic latitudes. Dergachev *et al*. (2004), who statistically re-investigated this assumed relationship, concluded that the "variation of the cosmic ray fluxes seem to be the most effective factor responsible for long-term climate variations". That conclusion, however, does not rule out the possible influence of UV radiance variations, because the variation of the flux of ejected solar plasma is (albeit loosely) correlated with the variation of the UV flux and also because a time lag as short as the energetic Emissions Delay can hardly be traced in the observations. We refer again to Kristjánsson *et al*. (2004), who found that cloud cover variations rather correlate with the UV flux. Hence, this question is still open.

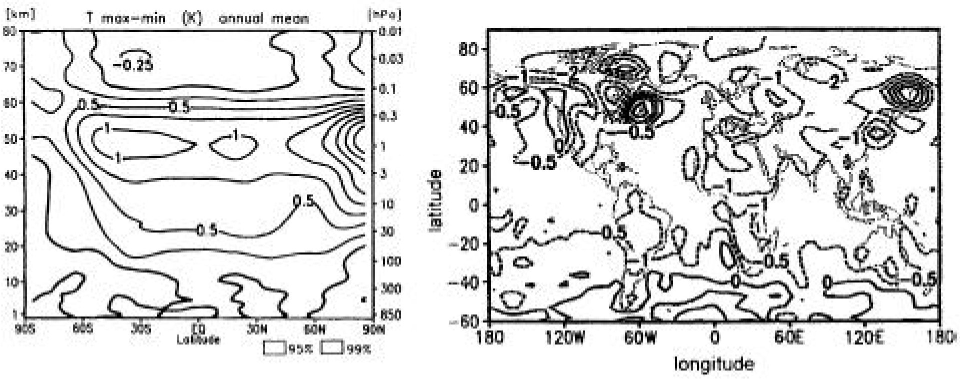

Figure 2.11: Observations of the solar signal in terrestrial atmospheric temperatures. Left: Observed differences in the Earth's temperature between solar maximum and minimum years as functions of latitude and height; steps are 0.25 K (Matthes et al., 2004). Right: global differences between tropospheric ground temperatures between the Maunder minimum and the present-day's average; steps are 0.25 K (Langematz et al., 2005).

Terrestrial observations show that the effect of heating by UV radiation is dominantly visible at stratospheric levels (Labitzke *et al*., 2002; Labitzke and Matthes, 2003; Matthes *et al*., 2004; Langematz *et al*., 2005, *cf.* Figure 2.11). The question is then relevant whether and how stratospheric heating can lead to tropospheric climate changes. In other words, if only the stratosphere reflects the variations in the solar irradiance, tropospheric heating or cooling must occur by some form of stratosphere – troposphere coupling, likely by an increased meridional circulation pattern, which might lead to changing lower atmospheric structure (with thanks to Karin Labitzke for this remark). Stratosphere–troposphere coupling is dealt with by Hood (2004), Matthes *et al*. (2004), Coughlin and Tung (2004), Ruzmaikin *et al.* (2004), Baldwin and Dunkerton (2005), Langematz *et al*. (2005), Kodera and Kuroda (2005), but there are more groups working on that theme. Individual model calculations differ in details but agree in broad outline. Coughlin and Tung (2004) found a well-observable solar signal in the troposphere, and other papers specify their conclusion in showing that the solar signal depends on the latitude (Figure 2.11, left), while also the distribution over the continents is expected to play a part (Figure 2.11, right). Some regions warm up while others cool. Therefore, studies based on a supposed unique global variation of temperature or pressure variations, to be characterized by one unique *ΔT(time)*-curve, valid for the whole Earth's surface, are likely to fail. Reliable material, observational as well as theoretical, is now available for allowing one to search for the solar signal in the observed terrestrial temperature distribution in latitude, longitude and height.
De Jager and Usoskin (in prep.) used six different sets of tropospheric temperatures and compared these with on one hand the R_G numbers, considered a proxy for the variations in the UV radiation flux, and on the other hand the solar 'source function' (Solanki et al., 2002, Usoskin et al., 2002, 2004), being the flux of ejected plasma at the Sun. They found that the former correlated considerably better with the temperature variations than the latter. The conclusion is that the variations in the solar UV flux, which are known to be due to these in the toroidal magnetic field component, are the main cause for terrestrial temperature variations.

A topical and much debated question is that of the cause of the strong terrestrial heating in the last few decades of the twentieth century. It is usually ascribed to greenhouse warming. That assumption is not supported by the findings that the warming of the past few decades is restricted to industrialised areas (de Laat and Maurellis, 2004), and the observed absence of significant global heating in satellite data. In connection with the latter aspect the ongoing lively discussions by Wentz and Schnabel (1998), Christy and Spencer (2003), Santer *et al*. (2000), Santer *et al*. (2003), Christy *et al*. (2003), Santer et al. (2003b), Vinikov and Grody (2003), Fu *et al*. (2004), Christy and Norris (2004)) are of interest.

Concluding: *There is an observable solar signal in the troposphere; it depends on latitude, longitude and height in the atmosphere. A physical investigation of the origin of the Sun-climate relationship based on a unique ΔT(time)-curve, assumed to be valid for the whole Earth's* *surface, is basically incorrect. The main cause of Sun–induced tropospheric temperature variations is the variation of solar UV radiation. It originates from the facular fields.*

2.8 Reconstruction of Past Solar Variability

Several attempts have recently been made to reconstruct aspects of solar variability over past centuries. On the basis of the correlation between the open solar flux and the ^{14}C and ^{10}Be data it is possible to obtain information on the ejection of solar magnetised plasma during the past. Ice core research offers the possibility to go far back into time.

Progress in our understanding came by the following steps: After various earlier investigations a main step forward was made by Bard *et al*. (2000) who studied the past fluxes of the cosmogenic nuclides ^{10}Be and ^{14}C and who realized that the Sun has been unusually active during the second half of the twentieth century. They found that solar activity measured through the ejected plasma "was lower than present during most of the last millennium, except during a brief period centred around 1100 AD".

This result was amplified by Usoskin *et al*. (2003, 2004c) who gave data for the period 850–2000 (Figure 2.12, upper frame). Their reconstruction was based on ^{10}Be numbers, ^{14}C data (from before 1950; atmospheric influences of nuclear bombs influencing data after 1945) and on observed sunspot numbers. Since there is no straight statistical correlation between the isotope numbers and solar activity (Mursula et al., 2003), their investigation included physical models for the heliospheric magnetic flux, a model for the transport and modulation of galactic cosmic rays in the heliosphere and one for the ^{10}Be production in the Earth's atmosphere. The Figure demonstrates that over the past 1150 years the Sun has never been as active as during the past 50 years. Not all authors did immediately adhere to this opinion, though. Raisbeck and Yiou (2004) remarked that Usoskin *et al*. did not make use of the twentieth century Antarctic ^{10}Be data, which deviate from those from the Greenland ice-core. In their answer, Usoskin *et al*. (2004b) confirmed the conflicting situation. They ascribe the difference to the fact that the uppermost parts of ice-cores may be disturbed or polluted. Therefore they used the direct observations of sunspots for the twentieth century data, which are in any case better than indirect proxy data. A corrected graph is given in their 2004b paper.

This work was extended to the whole Holocene by Weber *et al*. (2004) and Dergachev *et al*. (2004). They essentially showed that during the past 9000 years the fluxes of cosmogenic nuclei have never been as low as during the past half century.

In a subsequent paper Solanki *et al*. (2004), using independent data sources, confirmed this latter results and they demonstrated that this even applies to the past 11 millennia (lower frame of Figure 2.12).

The upper frame of Figure 2.12 shows, among other things, the 'great minima' that occurred during the past millennium, *viz*. the Oort Minimum (1050), those of Wolf (1350), Spörer (1500), Maunder (1675) and Dalton (1810). In addition, the diagram shows the broad Medieval Maximum (1100–1250), but it is clear that during that period the interplanetary magnetic activity seems to have remained below the twentieth century level of maximum intensity. The lower frame show the fascinating result that, historically speaking, the late 20th century solar maximum is unique for the larger part of the Holocene. A critical remark seems appropriate at this place: the authors converted observed fluxes of cosmogenic radionuclides into sunspot numbers, which is unnecessary and actually incorrect, because the two variables are not strongly correlated. Exclusive use of the fluxes of radionuclides, or of the open solar flux derived from them, would have been in order and more relevant.

Summarising: *never during the past ten or eleven millennia has the Sun been as active in ejecting magnetised plasma as during the second half of the twentieth century.*

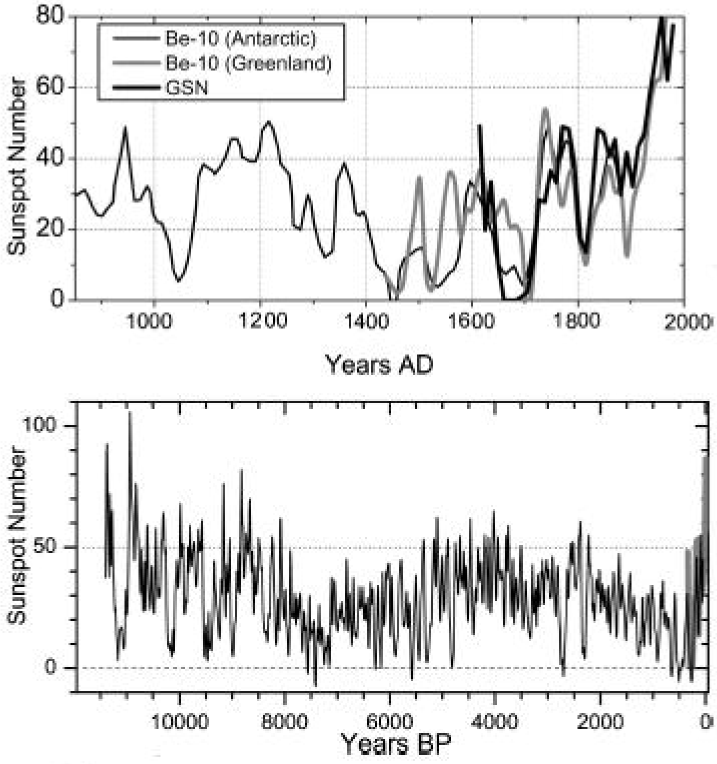

Figure 2.12 Reconstructions of past solar variability in ejecting magnetised plasma. Upper frame: solar activity since AD 850 as measured via the sunspot numbers (after 1610) and via cosmogenic radionuclides. Note the extremely high level of activity during the past century. Marked are the various 'great minima' and the Medieval Maximum (Usoskin et al., 2003). Lower frame: the same for the past 12 millennia (Solanki et al., 2004). By courtesy of I.G. Usoskin.

2.9 The Solar Dynamo

The data presented earlier in this review, lead to the question what mechanism drives solar activity. A hypothesis that is occasionally forwarded is that solar variability would be caused by planetary attractions (Jose, 1936, 1965; Fairbridge and Shirley, 1987; Landscheidt, 1999; Charvátova, 1997, 2000). And indeed, a plot of the time derivative of the Sun's angular momentum around the instantaneous centre of curvature of its path around the planetary system's barycentre shows a remarkable similarity to the sunspot curve (Jose, 1965). However, a quantitative study demonstrates that the actual accelerations inside the Sun near the tachocline level are by about three orders of magnitude larger than those due to planetary tides or the motion of the Sun around the planetary system's barycentre (de Jager and Versteegh, 2005). Therefore, the influence of planetary attractions disappears fully in the internal solar field of accelerations and therefore the planets cannot cause solar variability. The mechanism must be purely intrinsic to the Sun.

Solar activity and its variations are assumed to be driven by a magnetohydrodynamic dynamo. The theory was first proposed by Babcock (1961) and refined by Leighton (1969). A slightly different and mathematically more developed scenario is by Steenbeck and Krause (1967) and Steenbeck *et al*. (1967) and contains essential elements proposed earlier by Parker (1955).

The theory has to explain the five main elements of solar variability: the Hale cycle; Carrington's law of equator-ward drift; the origin of the poloidal field elements including the pole-ward motion of the polar prominence zone and of the ephemeral active regions; and Hale's polarity laws and the Energetic Emissions Delay.

The main aspect of the dynamo theory is that radial shear in the tachocline (*cf.* Figure 2.1), interacting with existing poloidal fields, generates toroidal fields. If these magnetic fields can be amplified, the solar dynamo works and a cyclic system can originate. Modern reviews are from Tobias *et al*. (1995), Zwaan (1996), Dikpati and Charbonneau (1999), Schrijver and Zwaan (2000), Weiss and Tobias (2000), Fisher *et al*. (2000), Hanslmeier (2002, his Ch. 6), Ossendrijver (2003), Bushby and Mason (2004), a list that is not exhaustive.

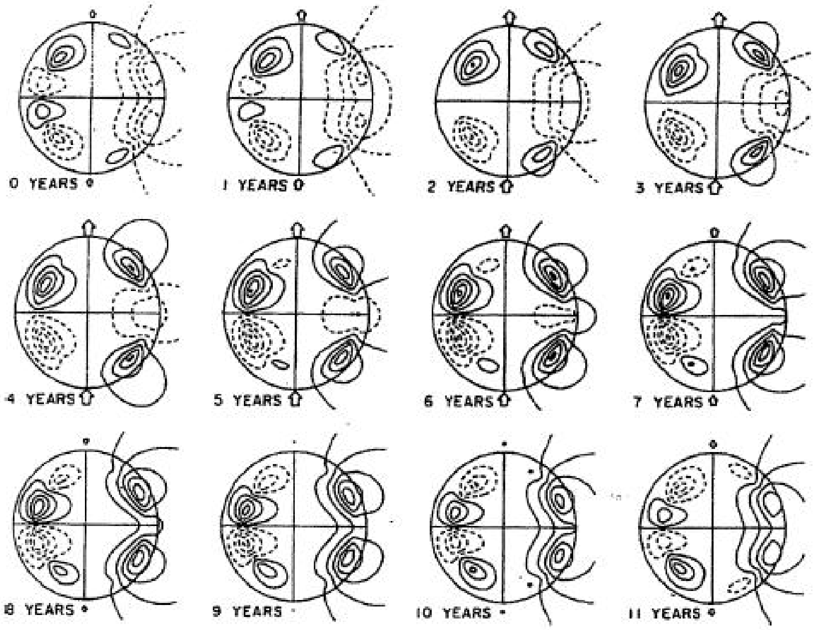

Figure 2.13: Schematic scenario of a solar α-Ω dynamo (Stix, 1977). Each annual frame is a meridional cross-section. To the left are contours of constant toroidal mean field and to the right are the field lines of the poloidal mean field. Solid lines indicate the toroidal field pointing out of the figure and clockwise poloidal field lines. Open arrows indicate the strength and direction of the polar field (copied from Schrijver and Zwaan, 2000, p. 176).

A closed theory of the dynamo, that quantitatively explains the five observed phenomena mentioned above, is still lacking but we forward below a scenario that incorporates the main elements of the various theoretical and observational aspects. We refer to the schematic picture in Figure 2.13, originally from Stix (1976) and copied by us from Schrijver and Zwaan (2000). Results from research by Dikpati and Charbonneau (1999), Dikpati and Gilman (2001), Bonanno *et al*. (2002)) and Nandy (2002) are also included in the following summarising review.

The solar dynamo is an engine driven by the interplay between poloidal and toroidal magnetic fields. In that interplay the solar differential rotation is essential. The question which of the two fields was first, the poloidal or the toroidal one, is a chicken-and-egg problem. None of the two was. As P. Hoyng wrote (private communication) "any differential rotation, *i.e.* a toroidal shear flow, can only generate toroidal fields from poloidal fields. It leaves toroidal fields unchanged. Hence one needs a starter poloidal field to amplify the toroidal one. This is either provided by the α-effect (working on the local toroidal field) or by meridional flows, which transport fields from higher up in the convection zone into the tachocline". The magnetic flux of the poloidal field is stored in the tachocline (Spiegel and Weiss, 1980, 1997, Brun, 2002; Nandy, 2004, Dikpati, 2005, in press), because of the subadiabatic stratification of these layers (Dikpati, 2005, in press). During the Schwabe cycle the dynamo transforms the poloidal field into a toroidal one, because the field lines are stretched into a direction parallel to the equator, due to the differential solar rotation in the upper levels. This process is called the Ω effect. Hence, the stretched, initially poloidal, field lines gradually change into toroidal fields. Field line stretching implies field amplification and when the fields locally exceed a certain threshold value (100 kilogauss according to D'Silva and Choudhuri (1993), Caligari *et al*. (1995) and Ruzmaikin (1998), 45 kilogauss according to Dikpati (2005, in press), buoyancy lifts the fields, causing a pair of sunspots to appear at the surface. The toroidal fields appear first at latitudes of 30° or lower. The spot groups apparently drag more scattered and weaker fields along and they eventually appear at the surface accompanied by the weaker and more scattered field elements that form the plages. Together they constitute the Active Region. Hence, the spots and the surrounding ARs are tracers of the sub-surface toroidal fields. The positions of successive Active Regions appear increasingly closer to the equator as a consequence of the – assumed single cell – meridional circulation in the convective region. There must be two oppositely directed circulatory patterns. In the low-latitude parts of the convective region the circulation moves equator-ward; at higher latitudes it is pole-ward (Dikpati and Charbonneau, 1999).

Another consequence of the above scenario is that toroidal fields appear at and above the surface as superficial poloidal fields. The removal of the toroidal field system underlying the ongoing sunspot cycle is caused by the emergence of magnetic fields (Zwaan, 1996). There are two possible scenarios for this process: in that of Parker (1955) and Steenbeck *et al.* (1966) these poloidal fields are generated in the interior of the solar convection zone by cyclonic turbulence and lifted by buoyancy: the α-effect. It occurs because a rising convective gas bubble expands and rotates due to the action of the Coriolis force, thus twisting the magnetic field (Parker, 1955, 1970). These twisted loops develop field components that are at right angles to the original field direction. Hence, when emerging at the surface and above it, they are on the average oriented poloidally.

In the Babcock–Leighton scenario the poloidal fields result from the arrival and subsequent decay of tilted bipolar active regions at the solar surface by field twisting. Nandy (2002) signals the conflict between the high tachocline fields needed to become buoyant and the need of being twisted by cyclonic motions and he therefore prefers the Babcock–Leighton scenario. In that case the poloidal fields originate by recycling of the erupted toroidal fields. In contrast to this conclusion Dikpati and Gilman (2001) argue that the α-effect originates from instabilities in the tachocline level where helical vortices are created. In their model the tachocline α-effect would create a toroidal field that is antisymmetric about the equator, as observed, in contract to the fields predicted by the Babcock–Leighton scenario. Under the influence of the single-cell meridional flow in the convective envelope, the location of these fields moves pole-ward during the solar cycle. The emerging fields are weak and diffuse and flux emergence makes them extending and expanding into the corona (Low and Zhang, 2004). They arrive at the surface about a year later than the spots. For increasingly higher latitudes they appear increasingly later at the surface and they eventually concentrate near the poles, just after the maximum of the Schwabe cycle. They are manifested by the pole-ward motion of the polar prominence zone and the region containing the ephemeral active regions. The polarity of these fields reverses every Schwabe cycle.

Inspired by Dikpati and Charbonneau (1999) we assume that the strength of the toroidal fields is determined by the radial shear at the tachocline level while that of the consequent poloidal fields depends on the interaction between rising toroidal magnetic flux ropes, the latitudinal shear component and the meridional flow pattern in the convective envelope.

Quite some research continues on this subject. For explaining the poloidal fields both scenarios, that of Babcock–Leighton and that of Parker–Steenbeck get their share. One result is that the amplitude of successive cycles as well as the cycle length alternate – as is usually observed (Hoyng, 1993, 1996; Charbonneau and Dikpati, 2000). The poloidal magnetic fields would be strongest during the decay phase of the even cycles (Cliver *et al.*, 1996). The anomalous character of the present cycle (number 23) seems to be related to a weaker photospheric magnetic flux (Dikpati *et al.*, 2004). The Babcock–Leighton theory explains the finding by Solanki *et al*. (2002) that the length of a cycle correlates with the amplitude of the next following one, which means that a new cycle maintains the ‘memory’ of the past one. The various aspects of field emergence were described by Caligari *et al*. (1995).

In spite of all this, quantitative agreement has not yet been obtained. While theory does predict a Hale cycle type periodicity, the 11 and 22-year periods do not yet emerge quantitatively from the theory. Recent attempts to fit observations into theory are therefore based on semi-quantitative attempts to make theory agree with observational data, like the following example:

Following Ruzmaikin (1998), Usoskin *et al*. (2001a, b; *cf.* also Usoskin and Mursula, 2003a) developed a model in which the solar magnetic fields consist of three components: an (alternating) 22-year dynamo field, a static relic field and a stochastic component, the latter being responsible for the sunspot instability. By introducing suitable fitting parameter values, both a 'normal' series of spot cycles, as well as the Maunder minimum can be reproduced. This is certainly a step forward, but it does not yet explain things quantitatively in a closed theory. Additional information may eventually be gained when the start and development of sunspot buoyancy during the Hale cycle will be observed by helioseismologic means. The first observations are becoming available and they appear to be promising.

In principle, stellar observations might help to acquire additional information, but present data are too scanty for crucial decisions. Cyclic activity occurs in stars with developed upper convection zones. For stars of given mass (*cf.* the brief review by Weiss and Tobias, 2000, p. 101) "both the magnetic fields and the angular rotational periods increase as they evolve, while cyclic activity is only found in slow rotators". Hanslmeier (2002) devotes a section to this topic; for further details reference is made to the book by Schrijver and Zwaan (2000) and the review by Radick (2003).

An important feature, necessary for understanding the physics behind the various kinds of solar activity and their relation with terrestrial phenomena is that solar activity reacts differently on the underlying toroidal and poloidal field variations respectively. This was already suggested by Babcock (1961) and Schatten *et al*. (1978) and expanded later by other authors, particularly Layden *et al*. (1991), Cliver *et al*. (1996) and Beer *et al*. (1998), and summarised by Duhau and Chen (2002).

We conclude:

- *The solar dynamo is the engine of the Sun's variability; it consists of two interacting and variable components: the toroidal and the poloidal magnetic fields.*
- *The toroidal component of solar magnetism is responsible for the occurrence of spots and associated Active Regions; hence for the variable UV radiance. A proxy for this component of solar variability is the sunspot number R.*
- *The poloidal field is responsible for about half of the ejected magnetised plasma. A measure for the total ejected plasma is the open solar flux in interplanetary space at the Earth's distance. A proxy for it is the rate of deposit of cosmogenic radionuclides.*
- *The equator-ward motion of the location of the Active Regions and the pole-ward motion of the region of the polar prominences are related to meridional circulation in the convective zone.*
- *The strengths of the poloidal and toroidal fields are correlated but not strongly so; neither do they reach maximum simultaneously..*
- *Theory is not yet able to yield a quantitative theory of the solar dynamo.*

The 2nd and 3rd of these conclusions conflict with an investigation of Foukal *et al*. (2004), who used, besides the sunspot numbers, also the cosmogenic radionuclides to reconstruct past tropospheric terrestrial temperatures, which is incorrect. Neither did these authors take into account that solar irradiance variations only indirectly influence the troposphere, *viz*. by stratosphere–troposphere coupling. The variable component of the solar irradiance does not reach the Earth's troposphere.

2.10 Phase Catastrophies and Deterministic Chaos

In the previous section we concluded that the poloidal and toroidal field strengths, though clearly related, are not strictly correlated. Therefore, neither the long-term variations in *aa* and *R* are. One clear example is provided by the Maunder Minimum: during that period sunspots were practically absent, but the 11-year solar-geomagnetic activity, as measured by the ^{10}Be flux, persisted (Beer *et al*., 1998; Cliver *et al*., 1998). This is confirmed by NO_3 data (Ninglian *et al*., 2000). There are other cases, *viz*. such in which climate change and variations in the flux of cosmogenic radionuclides did not occur simultaneously. One such case is the climate change that occurred ca. 2650 BP (van Geel *et al.,* 1998, 2004), another that of 8200 BP (Muscheler *et* *al.*, 2004). During the present cycle (number 23) the sunspot number did not correlate well with proxies such as Mg II, $F_{10.7}$ (Floyd *et al.*, 2005). These latter proxies reflect the variations in the chromospheric magnetic fields of Active Regions.

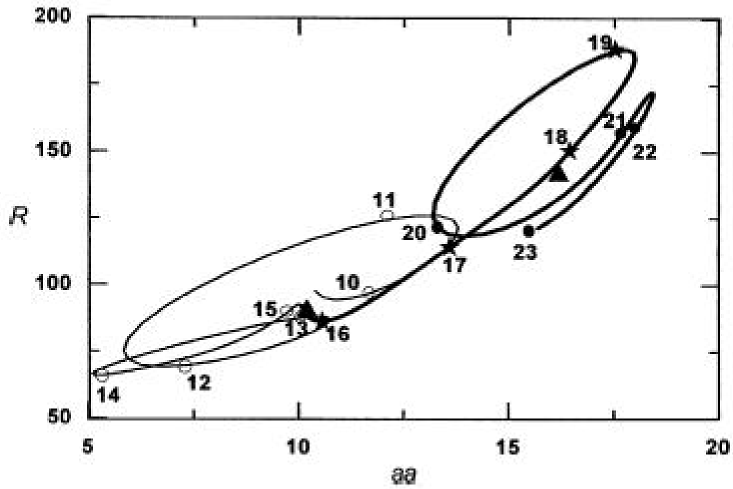

Figure 2.14: The Wolf sunspot number R vs. the long-term modulation geomagnetic aa-index prior to (light line) and after (heavy line) 1923. The open and filled circles refer to the years of sunspot maximum before 1923 and after 1949, respectively. The stars refer to the intervals between them. The triangles represent the constant level around which the long-term modulation oscillates. Numbers refer to the Schwabe cycles. The hysteresis between the aa and R proxies demonstrates their time difference of maximum strength; the changing orientation reflects a phase catastrophe (Duhau, 2003).

Assuming, as throughout in this paper, that the variations op (part of the) flux of cosmogenic nuclides and the variations in the *R*-values reflect variations in the poloidal and the toroidal fields respectively, these observations imply loss of correlation between the strength variations of these fields. Another example of the loose correlation is the element of randomness in *aa*-*R* correlation diagrams as demonstrated in Figure 2.14 (Duhau and Chen, 2002; Duhau, 2003a).

Another feature is the phase catastrophes in solar variability. Polygiannakis et al. (1996), Duhau and Chen (2002) and Duhau (2003b) mentioned the non-linearity in some of the solar variations, and the related phase catastrophes. Specifically, Duhau (2003a) described the sudden rise of the average level of solar activity in the first part of the twentieth century. This is shown by an *aa*-*R* diagram, where the character of the hysteresis curve changed drastically around 1923 (Figure 2.14). The *aa*-index and R_Z increased during the 26 years after 1923 by factors 1.9 and 1.6 respectively. At the same time (1923) the Gleissberg cycle was interrupted, to restart in 1949 (Duhau and Chen, 2002). Duhau (2003a) found some evidence that another phase catastrophe had begun near 1993, *i.e.* at the first zeroing of the last Gleissberg cycle, leading to a descending chaotic transition. She stressed the particular feature of the sudden turn to the right followed by a change in the direction of circulation of the *R* versus *aa* from counter-clockwise to clockwise. It occurred before the ascending 1923 episode. The same feature happened after 1986 but the change in the sense of circulation appears to continue till the present day. Qualitatively it seems that near 1923 and 1986 a descending tendency was established first. It aborted in 1923 but was firmly established in the second case. These features illustrate the chaotic character of the solar dynamo.

Another phase catastrophe, evidently less well documented, seems to have occurred at the end of the Maunder Minimum, in 1712–1720 (Usoskin *et al.*, 2000). Duhau (2003a) gives for that latter period the start in 1705 and she places the end, when the average *R*-level had increased nearly threefold, in 1740. Usoskin and Mursula (2003a, with references to others) describe the phase catastrophe in solar activity evolution during the Dalton Minimum.

These observations make clear that solar variability has the character of deterministic chaos (Tobias *et al*., 2004), driven by a quasi-periodic engine. In that line Hoyng (1996) found that the observed variations of amplitude and phase of the solar cycle can be described by assuming that they show correlated stochastic fluctuations, in such a way that log(amplitude) + phase variation = constant. Hoyng seeks the cause of this relationship in fast and arbitrary variations in the parameters of the solar dynamo, particularly in the parameter α. It is this feature that excludes long term predictability of solar activity. Another key to a quantitative explanation of the solar dynamo may be found in the observation that the ratio of the amplitudes of the *aa* and *R* variations appears to be oppositely correlated with the amplitude of the Hale cycle (Cliver *et al*., 1996). The rate of ^{10}Be formation is a proxy for the former. In turn, solar irradiance variations are due to the weaker and fragmented fields in the ARs and these are correlated to the spot groups, for which R_G is a proxy.

We summarise: *the solar dynamo is a case of deterministic chaos; it shows phase catastrophes. Attempts to theoretically describe the solar dynamo have so far succeeded only in explaining the qualitative aspect. They must necessarily fail in a numerical description that would permit to determine periodicities and forecast solar activity with acceptable reliability.*

2.11 Periodicies; Forecasting Solar Activity

In spite of the foregoing statement we summarise attempts to forecast solar activity. We first enumerate data on periodicities. Several 'periods', not all of them very pronounced, have so far been found.

The most important are the Schwabe and Hale periods of 11 and 22 years. These periods are not constant. The Schwabe period oscillated during the second half of the 18th century and seemed to be steady thereafter (Li *et al*., 2005). During the past four centuries the length of the Hale cycle changed. The average Hale cycle period was 22.9 years before the Maunder Minimum; during that minimum the cyclicity had periods of 24 and 15.8 years and thereafter it increased to 26 years (Raspopov *et al*., 2004). The Hale period has shortened during the past century, when it was about 21 years.

There is a claimed periodicity of 1.3 years in the solar rotation rate that reflects itself in the *R*-numbers and in the areas of sunspots (*cf.* Bazilevskaya *et al*., 2000). Benevolenskaya (2003) list it as varying between 1.0 and 1.3 yr. Starodubtsev *et al*. (in press) give 1.5–1.8 years. Kane (1997) lists six quasi-biennial and quasi-triennial periods with values between 2.0 and 3.4 years but he could not unambiguously retrieve the 1.3 years period (Kane, 2005). Krirova and Solanki (2002) suggest a relationship between the 1.3 years and the 156 days periodicity (the 'Rieger period') in the frequency of enhanced solar flaring. They mention that 156 days is a third harmonic of 1.3 years (3×156 d = 1.28 yr). In that line one may wonder if the 1.3 year period is a high harmonic of the Schwabe period, since 8 × 1.3 = 10.5 yr, etc.

The Brückner period of 30–35 years (Brückner, 1890; Ninglian *et al*., 2000) is apparently not of solar origin. Raspopov et al. (2004) ascribe it tentatively to the action of solar variability on the ocean-climate system.

On the basis of only 200 years of available observations, Gleissberg (1944, 1958) found a cycle of 88 years in the amplitude variation of R_Z. Although 200 years seems too short for a firm determination of this long period, later investigations supported its reality. Damon and Sonnett (1991) and Damon and Peristykh (1999, 2000), using ^{14}C records could trace it back over the Holocene, till 11,600 years before 1950. They found an average period of 87.8 years, but subsequent research by Ogurtsov *et al*. (2002) yielded that there is a wide frequency band with a double structure: one of 50–80 years, and another of 90–140 years. A Fourier analysis of R_Z-data over the past 400 years gave average periods of 53 and 101 years (Le and Wang, 2003). The amplitudes of the latter two components are not constant over the period investigated. The 101-year period had its largest amplitude around 1850 and the 53 years one was chiefly active between 1725 and 1850. This result is confirmed by subsequent research by Raspopov *et al*.

(2004, *cf.* their Figures 2.4 and 2.5): they confirmed that the shorter period prevailed between 1725 and 1850 but added that after 1760 the average Gleissberg period increased to 90–100 years. A similar result was reported by Li *et a*l. (2005).

The De Vries (or Suess) period of 205 years is observed in ^{14}C and ^{36}Cl data; Muscheler *et al*. (2003, 2004) gave 205, 208 and 207 years. Wagner *et al*. (2001) found the 205-year period in ^{10}Be data. Tobias *et al*. (2004), who also studied ^{10}Be data, confirmed it, also with a period of 205 years. Ogurtsov *et al*. (2002) found that the periodogram structure is single peaked in the 170–260 years band. Attempts to trace solar activity back over the Holocene period were made by Clilverd *et al*. (2003) who used ^{14}C data. After subtracting components ascribed to geomagnetic field variations, a period of 2300 years, the Hallstatt period, is weakly visible. Also Muscheler *et al*. (2003) found the Hallstatt cycle in ^{14}C records.

The solar origin is obvious for the Schwabe, Hale and Gleissberg cycles, but it seems also true for the De Vries and Hallstatt cycles. Wagner *et al*. (2001) found that part of these latter two cycles appear also in ^{36}Cl records. We conclude that there are five well-founded periods in solar variability. The question next arises if it is possible to forecast solar activity, using the above periods and their amplitudes and phases. A simple and obvious approach is based on a statement by Muscheler *et al*. (2004) who drew attention to the four great activity minima of the last millennium, which are spaced at time intervals of about 200 years. An 'easy' way of forecasting would therefore be to use the De Vries period by extrapolating over the past five large minima (Oort, Wolf, Spörer, Maunder, Dalton). Thus one would 'predict' another Maunder Minimum around 2050.

Another approach could be based on a comparison of recent cycles. Cycle numbered 21 and 22 were about equally high, while cycle 23 is lower. Does that mean that solar activity is declining? That seems too simple an approach because one has to consider the question of the persistence of the various periods. The amplitudes of the Gleissberg periods of 50–80 and 90–140 years have changed significantly over the past centuries. We already mentioned the non-linear character of the solar dynamo. That too hampers the extrapolation of solar activity. Let us for example consider the past century. During the phase catastrophe of 1923–1949 phases and amplitudes of the Schwabe and Gleissberg cycles changed, to assume new values after 1949. By the procedure of adding periodic functions, one would expect that one Gleissberg cycle (~ eight Schwabe cycles) after 1949, hence around the year 2035, solar activity should be at the 1949 level, which is (*cf.* Figures 2.8 and 2.9) still fairly high (R_G ~ 100), but slightly less than in 1985–1990. We note that this is certainly not another 'Maunder Minimum'. An obvious precondition is that no other phase catastrophe occurs in the mean time. According to Polygiannakis *et a*l. (1996) it seems unlikely that cycle suppression will occur in the forthcoming decades. That is still to be seen.

There were a few more attempts to forecast solar activity. We summarise them here:

Cliver *et al*. (1998)noted that the envelope curve of the *aa*-minima reached its maximum value in 1987. On the basis of the observed variations of the *aa*-curve, they expected that the geomagnetic minimum between cycle's numbers 23 and 24, to fall around 2006 or 2007, will not be higher than that of 1996, which was, in turn, lower than that of 1987.

De Meyer (2003) attempted to forecast the values of R_Z on the basis of his model of the solar cycle consisting of a sequence of independent overlapping events. He thus predicted that the 24th cycle would start in 2007 to reach in 2011 a peak height in the range 95–125. His model describes the observed high level of amplitude modulation in the interval 1950–2000 and forecasts a decrease afterwards. Duhau (2003a), in her study of recent phase catastrophes (Ch. 10) have estimated that the R_G = 90 average sunspot level that sustained prior to 1923 would again be reached near the year 2018. However, as the dynamo system is undergoing a chaotic transition, the forthcoming R_G level after the transition might be unpredictable. Clilverd *et al*. (2003) superimposed the average solar activity curve taken over the past three Hallstatt cycles, *i.e.* the past 6900 years, over the four past centuries of solar activity, by fitting on the R_Z values during the Maunder Minimum. The results suggest a nearly constant level of solar activity till about 2050 and a slow decrease thereafter. Their approach was criticised by Tobias *et al*. (2004). Among other things they wondered why Clilverd *et al*. ignored the Schwabe and Gleissberg cyclicities, remarking that the Hallstatt cycle is not the most dominant one of the solar cycles. Principally, however, the objection is that solar activity is non-periodic rather than multi-periodic and that the observed non-periodicity may be a case of deterministic chaos (Weiss and Tobias, 2000; Weiss 2002). “The future of such a chaotic system is intrinsically unpredictable” (Tobias *et al*., 2004).

A summary of this section: *Solar variability shows five well determined quasi-periodicities. Their lengths and amplitudes vary with time. Other periods mentioned in literature may appear to be harmonics of these main periods or they may originate in the terrestrial ocean-climate system. Predicting solar activity is intrinsically not possible but there are some weak indications that solar activity may slightly decrease in coming decades (which would not be surprising after the highest activity of the past ten millenia).*

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3 SOLAR FORCING OF CLIMATE: EVIDENCE FROM THE PAST

3.1 Introduction

Over the last century the climate at most places on our globe has changed considerably. The extent to which these changes result from human and/or natural forcings is subject to intense study (e.g. IPCC-Working Group 1, 2001; Solanki and Krivova, 2003). One reason is that both human influences on the environment (e.g. anthropogenic CO_2 in the atmosphere) and solar activity increased considerably over the last century. This covariance hampers isolation of their separate effects. Moreover, the climatic impacts of several forcing factors are still insufficiently understood. Notably, Sun-climate relations are badly defined due to lacking insight in the Sun-climate coupling. One way to improve this insight is to investigate the past: how did climate possibly respond to solar forcing and what do the spatial and temporal patterns of past climate change tell us about the solar forcing mechanism? In order to address these questions, firstly, the evidence for, and nature of past solar variability will be evaluated. Subsequently, this will be done also for climate variability. The third section will be dedicated to other sources than solar variability on climate. Finally, evidence for solar forcing of climate will be evaluated, both spatially and temporally.

3.2 Archives for Past Solar and Climate Variability

Instrumental records monitoring solar activity and climate change usually have a high temporal resolution, and quantitatively document environmental change as it occurs. However, they are relatively short, mostly covering the last decades to centuries only. As a result they usually fail to capture longer-term processes, rare events, and non-analogue situations (e.g. pre-industrial (natural) climate change). This applies to records for both solar activity and climate change and conversely, assessment of Sun-climate relations is often problematic. Historical records of solar and environmental variability may cover time spans up to several thousands of years. These records also have their drawbacks since usually they are not continuous and biased towards extreme events. Information on solar and environmental change recorded by nature in e.g. tree rings, peat, stalagmites, ice caps, lacustrine and marine sediments, are often continuous over much longer periods and as such, the study of these natural archives may help to overcome the limitations set by the instrumental records. It should, however, be kept in mind that the natural archives have their drawbacks too. First, the proxy (the variable obtained from the archives) may be of poor and changing quality with respect to amplitude, phase and frequency of the environmental change recorded, e.g. due to selective degradation of the archive. Second, a ‘transfer function’ is needed to translate the proxy record into the environmental (climatic or solar) conditions at the moment the variable-state became fixed. This function usually is calibrated by comparing the proxy record with instrumental records where they overlap, but the proxy-environment relation may have changed over time. A special case hereof is the human interference with the environment (notably over the last decades to centuries), which complicates assessment of natural climate change on the basis of proxies and its separation from human-induced changes. Finally, the age model needed to translate ‘archive-depth’ to ‘archive-age’ may be inaccurate. Nevertheless, a large body of valuable information of past climate and solar variability have been obtained from proxy records.

3.2.1 Solar Variability: Instrumental and Historical Data

With the invention of the telescope, detailed observations of sunspots, their position, size and number, became available and a continuous record is available from AD ~1700 onwards. Large sunspots can also be observed with the naked eye and these observations have been documented in oriental sources. They form the basis for a reconstruction of solar activity since 60 BC (Xu Zhentao, 1990; Wittmann, 1992) (Figure 3.1). Clearly, other events may have contaminated the record of visual observations. Aurora Borealis is a result of fluorescence of ionised atmospheric gases. This ionisation is caused by currents in the upper atmosphere, which in turn result from the interaction of solar wind with the Earth's magnetosphere. Hence, the frequency of aurorae occurrences is closely connected with the activity of the Sun (e.g. Ogurtsov *et al.*, 2002b).A historical record of Aurora Borealis is also available for the last two millennia (for more details Nagovitsyn *et al.*, 2003) (Figure 3.1). These instrumental and historical records are invaluable for calibrating the proxies for solar activity derived from the natural archive and they form together with the ^{14}C record the basis for a recent reconstruction of solar variability back to 8005 BC. By using a five box carbon exchange model that infers memory for solar activity by the Sun (Ogurtsov, 2004) it is inferred that the high maxima in sunspot numbers observed during the last decades are unprecedented during the Holocene. The more recent study of Solanki *et al.* (2004) reaches the same conclusion, but on the basis of a different carbon exchange model.

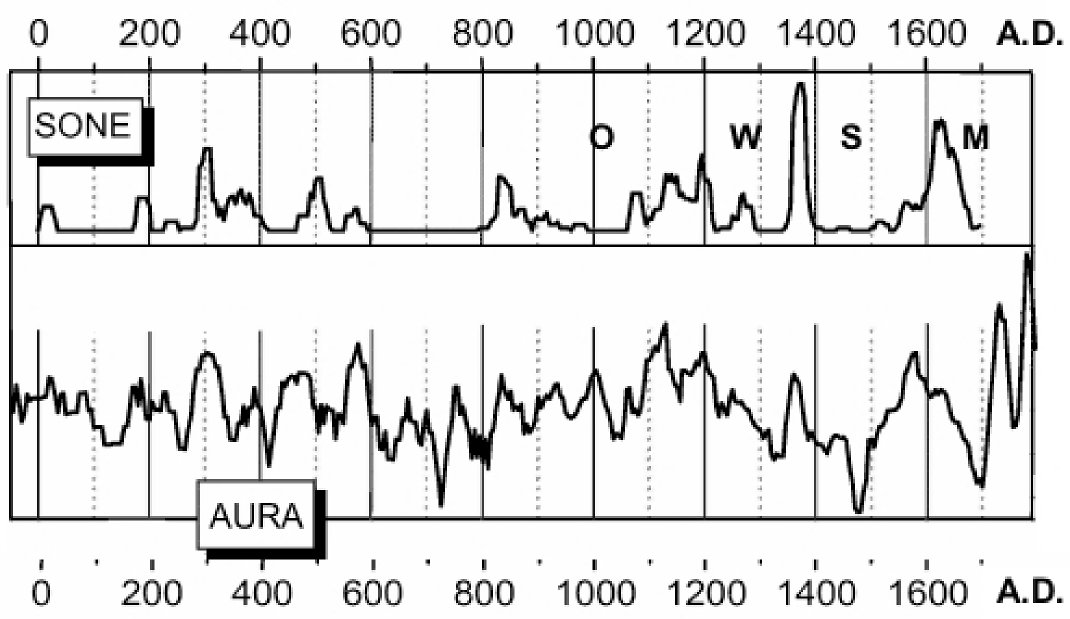

Figure 3.1: Historical records of solar activity for the last two millennia. SONE, sunspots observed by naked eye; AURA, observations of aurorae. O, W, S, M refer to the Oort, Wolf, Spörer, and Maunder minima in solar activity respectively (After Nagovitsyn et al., 2003).

3.2.2 Solar Variability: Proxy Data

Cosmogenic radionuclides in sediments form the major source of information on solar activity for the pre-instrumental era. Cosmogenic radionuclides are formed by high-energy particles entering the atmosphere where they collide with the atoms in the air and produce rare and unstable isotopes. The solar wind shields the atmosphere from these particles so that cosmogenic radionuclide production rates decrease as solar activity increases. The influence of the strength and shape of the magnetic field on the cosmic ray dose on the atmosphere further modulates the radionuclide production such that the production increases with decreasing field strength and increases towards the magnetic poles (Masarik and Beer, 1999; McCracken, 2004). The isotopes may become incorporated in natural archives (Figure 3.2). By monitoring the changes in isotopic ratios in these archives, the radionuclide production rate can be reconstructed and hence the flux of energetic particles into the atmosphere. Typically the time span that can be assessed with a given radionuclide is about 10 half-life times. Most cosmogenic radionuclides are too rare or have a too short half-life time to trace solar activity back for more than a few centuries. This is not so for ^{10}Be (1.5 My), ^{14}C (5.37 ky), ^{26}Al (0.73 My) and ^{36}Cl (30.1 kyrs). ^{10}Be becomes attached to aerosols and is removed from the atmosphere within 1–2 years mainly by wet deposition. However, due to the relatively short tropospheric residence time of 1–2 weeks it can not be considered to be globally well mixed in the atmosphere and as a result climate, atmospheric chemistry and atmospheric circulation also effect the concentrations of this isotope in precipitation.

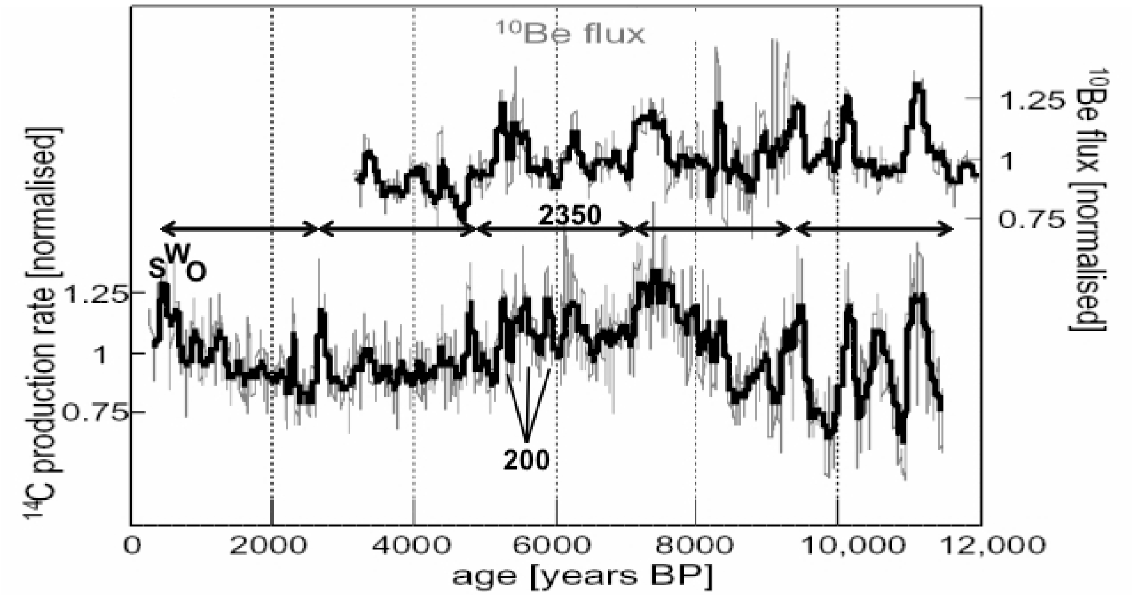

Figure 3.2: ^{10}Be flux and ^{14}C production rate (grey) with 100 years running mean (black curve) differences attributed to carbon cycle and atmospheric circulation. Numbers 200 and 2350 refer to proposed cyclicities in the data (After Muscheler et al., 2003).

Table 1. Sources of variability in observed 22 year average ^{10}Be data (McCracken, 2004)

Nature of variability	Amplitude, %
Category 1. primary variations	
Long term changes	50– 100%
Eleven year variations	20– 40%
Category 2. Corrections or elimination possible	
Unresolved 11 year variations	13 to 23%
Long term geomagnetic effects	
Polar wander	10%
Magnetic moment	15%
Category 3. Cannot be eliminated at present	
Local meteorology/instrumental	4.4% (sd)
Effects of climate change	<4%
Unresolved 11 year variations	±1.65%

The data are given either as the total range of variation of an effect or, when appropriate, as a standard deviation (sd). For comparative purposes, the standard deviation of a source of variability approximates a quarter of the total range.

Several records of ^{10}Be would therefore be needed to compensate for this local character. Comparison of Greenland DYE3 and South Pole ^{10}Be records provides a correlation coefficient of 0.85 so that the statistical noise can be considered relatively small compared to correlated secular changes in both data sets (see McCracken, 2004 for more detailed error estimates) (Table I). Despite this, the recent deviation of the Antarctic ^{10}Be record from measured solar activity has been attributed to such local effects (Usoskin *et al.*, 2004b). ^{10}Be records from ice cores have been used as proxies for solar activity e.g. by calibrating the measured ^{10}Be record through a physics-based model to the longer term (>40 years) variations in the measured sunspot number (SN). The relation obtained is used to extrapolate solar activity back to 850 A.D. (Usoskin *et al.*, 2004a). Frequency analysis reveals the Gleissberg (~100 years) and de Vries (~205 years) cycles in the data. The de Vries cycle has also been shown to persist during the last ice age for the investigated interval of 25–55 kyrs BP (Wagner *et al.*, 2001).

^{14}C is produced mainly by the interaction of thermal neutrons with nitrogen in the atmosphere. After its production it oxidises to $^{14}CO_2$ and becomes incorporated in the carbon cycle. Although changes in the atmospheric $^{14}CO_2$ concentration (often referred to as $\Delta^{14}C$) are mainly influenced by the variable production of ^{14}C they also are influenced by changes in the carbon cycle like changes in ocean ventilation or global biomass (Muscheler *et al.*, 2004). Typically, changes in ^{14}C production rates are reconstructed from high resolution archives like trees, varved sediments, ice cores, and speleothems. Due to the $^{14}CO_2$ exchange with the geosphere and biosphere the atmospheric ^{14}C variations are dampened and delayed compared to the changes in ^{14}C production rate. These phase differences vary both temporally and spatially. The phase difference between Northern Hemisphere and Southern Hemisphere tree ring-based ^{14}C calibration curves has been shown to vary between none and 70 years (average 24 years) during the last millennium whereas for the same period the phase between the calibration curves of the British Isles and western North America varies between 0 and 60 years (Knox and McFadgen, 2004). These regional differences in ^{14}C concentrations set limits to the identification of phase relations between (high precision ^{14}C dated) proxy records from different regions and solar activity variations. Only the use of multiple, regionally confined ^{14}C calibration curves, may overcome this problem and enable the identification of decadal and sub-decadal phase relationships between regions. Comparison of records of the same solar proxy but from different locations provides a good way to assess the influence of regional processes on the proxy records. Comparison of different proxies for solar activity from the same region forms another way to evaluate disturbing influences (Figure 3.2). The large differences between the global Be and C cycles are helpful in this way since they reduce the chance of covariance due to non-solar forcing (Beer *et al.*, 1994; Muscheler *et al.*, 2004). The Holocene ^{10}Be record is not complete yet, limiting detailed comparison of the ^{10}Be and ^{14}C records for the entire period. However, also for most of the intervals where both records are available, such comparison is still missing. The largest global source of odd nitrogen species (NO_y = N, NO, NO_2, NO_3, $2N_2O_5$, $BrONO_2$, $ClONO_2$, HO_2NO_2, and HNO_3) in the stratosphere is the oxidation of nitrous oxide (Vitt *et al.*, 2000). These authors further state that nitrous oxide (N_2O) is produced in the biosphere on the Earth's surface and is transported into the stratosphere where it reacts with $O(^1D)$, an electronically excited oxygen atom which is produced in the stratosphere by the photodissociation of ozone. In contrast to the production of cosmogenic radionuclides, the production of odd nitrogen compounds predominantly takes place at lower latitudes (McCracken, 2004). Odd nitrogen compounds are also formed in the polar regions by incident solar and geomagnetic energetic charged particles, which deposit their energy in the Earth's middle and upper atmosphere. These energetic particles ionise and dissociate ambient O_2 and N_2 and initiate the formation of odd nitrogen compounds. Since these particles are charged, they follow the Earth's magnetic field lines into the polar atmosphere. Changes in solar and geomagnetic activity can dramatically change the flux of incident energetic particles, e.g., solar particle events or auroral events, which lead to large variations in the formation of odd nitrogen compounds in the polar middle and upper atmosphere. The variation in abundance of galactic cosmic ray particles related to solar cycle variations also modulates the formation of odd nitrogen compounds in the middle and upper atmosphere. During the polar night the nitrogen species are long lived and may be transported down to the stratosphere where HNO_3 (the terminal species) is sequestered by stratospheric clouds. Subsequently, HNO_3 containing particulates may settle out of the stratosphere and become incorporated in the polar ice sheets. Changes in the NO_3^- with depth in the ice cores are subsequently used as a proxy for solar activity changes. Calibration of the proxy is in progress. Instrumentally recorded, single and strong solar flares appear to result in a measurable change in the polar NO_3^- ice record within the next 3–12 months. Assessment of the integrated effects of clusters of flames over longer, decadal time scales is in progress (Palmer *et al.*, 2001; Shea *et al.*, 2003). NO_3^- concentrations in the Guliya ice sheet (Tibet) have been reported to correspond well to changes in solar activity (since AD 500) and they have been used to assess solar variability during the Maunder minimum (Wang Ninglian *et al.*, 2000). In Greenland and Antarctic ice cores, NO_3^- shows quasi five-year variation, with maxima during periods of rising and falling sunspot numbers (Figure 3.3). The maxima are considered to result from maxima in the solar flare occurrence rather than to the alternation of maxima in cosmic-rays (during sunspot minima) and solar activity (during sunspot maxima) (Ogurtsov *et al.*, 2004). This would imply that *NO_3^- in ice is a direct proxy for solar activity (proton events) and does not operate via modulation of the cosmic-ray dose of the* *atmosphere as is the case for the cosmogenic radionuclides.* This, in turn, may explain why there is still no evidence for a relation between supernovae and NO_3^- spikes in ice cores (Green and Stephenson, 2004). Century-scale (60–117 years) NO_3^- variability in the Greenland ice correlates with the smoothed length of the solar cycle (Ogurtsov *et al.*, 2004) The signature of solar and cosmic-ray induced variability in the NO_3^- concentrations of ice cores is modified by a clear annual cycle, local and regional meteorology and the input of (volcanic) dust (Palmer *et al.*, 2001; Ogurtsov *et al.*, 2004). Several theories suppose that the stratosphere plays a key role in putting the solar forcing of tropospheric climates into effect (Haigh, 1999; Labitzke, 2005; Kodera and Kuroda, 2005). To test this, it would be very helpful if proxies monitoring stratospheric change would be available. One measure for changes in the stratosphere is O_3 content. The amount UV-B that penetrates the atmosphere depends on the amount of stratospheric O_3 UV-B causes harmful effects on organisms. In order to minimise these effects, UV-B screening mechanisms have been developed by biota. Higher plants respond to a change in the UV-B dose by changing the macromolecular composition of their leaf cuticles and pollen and spore walls. This information is preserved in fossil plant remains. Monitoring the past UV-B screening capacity of organisms may thus provide a way to reconstruct stratospheric O_3 variations. Current research is exploring the quality of this proxy (Rozema *et al.*, 2002). The proxy is in the testing phase with respect to its sensitivity to changes in UV-B and applicability to longer time scales.

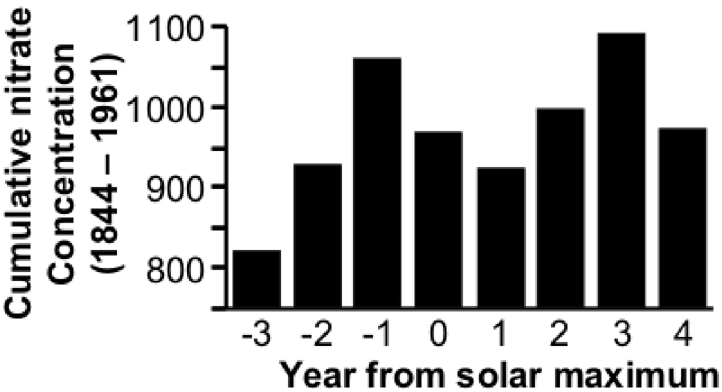

Figure 3.3: Distribution of nitrate concentrations around sunspot maxima for AD 1844–1961. (From Ogurtsov et al., 2004).

3.2.3 Note on the Origin of Solar Variability

The origin of the solar variability is not clear. It is, however, hard to explain the quasi-cyclic behaviour of the solar activity on the basis of solar internal dynamics alone. It has been suggested that the variability results from processes in the Sun itself, e.g. the 11 years cycle resulting from an endogenic cycle of the solar dynamo but this is not confirmed by solar modelling. Furthermore it does not account for the longer cycles observed. It has also been proposed that solar variability results from the motion of the Sun around the centre of mass of the solar system (e.g. Jose, 1965; Landscheidt, 1999; Charvatova, 2000; Fairbridge, 2001). The solar motion is largely caused by the varying positions of the large planets. This solar movement is considerable, the diameter of the area in which the Sun moves represents 4.4 solar radii and the Sun moves with a velocity between 9 and 16 m/s (Charvatova, 2000). A central role in these theories plays the 178.7 years cycle of solar motion (Jose, 1965; Charvatova, 2000). These cycles are put forward to explain more and less quiet phases of the Sun as well as sudden phase shifts in the solar cycles (Landscheidt, 1999). Recently, this mechanism has been shown to be unrealistic since the accelerations due to the planetary attractions are insignificant (three orders of magnitude weaker) compared to the accelerations at the solar tachocline level which are assumed to be responsible for the solar dynamo (de Jager and Versteegh, 2005). Conversely, mechanisms explaining the quasicyclic behaviour of the solar activity are currently not available.

3.3 Climate Change

3.3.1 Local versus Global Reconstructions

From our daily experience we know that climate (and weather) varies on small spatial scales as a result of local geography (e.g. climates at the windward and lee side of mountains differ), but also in a flat region like the Netherlands, the coastal climate differs significantly from the climates more inland). *This local variability is not trivial for reconstructing climate since proxy records mostly are based on one site (e.g. a bore-hole) and thus provide a record of local climate change only.* Clearly, climates from nearby locations also have a lot of climate and climate change in common. This overlap tends to decrease with increasing distance between the locations. To assess climate patterns at a larger spatial scale, information from different locations can be averaged, thus removing the local signature. However, regional changes in the *climate variability* at small spatial scales (e.g. severity rather than frequency of thunderstorms) are easily lost in this way. On a temporal scale, averaging leads also to a reduction in the amplitude of the recorded climate change (simply because a change in climate will not always have the same sign at different locations) and opposite trends between regions may be missed. To identify climate forcing mechanisms, we have to assess the spatial and temporal scales on which they work. *In case the solar forcing mainly proceeds via the atmosphere and influences the location, routes and stability of pressure systems one has to assess solar forcing via regional climate change.* In this way large regional climate changes are possible without changing the overall mean significantly. At too large scales (e.g. global) the forcing may be underestimated or even vanish, whereas at too small scales it may be lost in local peculiarities. The boundaries between climate regions are of special interest. Climate variability will be larger since upon a change in the locations and stability of pressure systems, the climate boundaries will change position. Boundaries may thus provide excellent locations to trace changes in the system. However, changes in the location of these boundaries imply also that climate records in these regions can switch from one local climate regime to the other. This may result in different amplitude and phase responses to the forcing factor and phase changes with neighbour proxy records, complicating proxy interpretation. Ways to identify regional climates and to test the obtained correlations have been recently been explored by e.g. Thejll (2001); Steinbach *et al.* (2003) and Burroughs (2003).

3.3.2 Instrumental and Historical Records

These records provide direct information on climate parameters like precipitation, temperature and pressure. They are, however, often too short to provide a good insight in climate variability and (responses to events) on longer time-scales. Most instrumental records start after about AD 1850 and only few, mostly from Europe, extend into the 18th century (e.g. Balling Jr *et al.*, 1998), whereas almost no instrumental data are available for the 17th or earlier centuries. Historical records reach much further back and may cover a few millennia but often they are biased towards unusual climate events, flooding, excessive rain, drought, glacier advance etc. (e.g. Pavese *et al.*, 1995; Camuffo and Enzi, 1996; Pfister and Brázdil, 1999; Pfister *et al.*, 1999; Buisman, 1995–2004.) Nevertheless, they may provide very detailed information on climatic and weather extremes which are not easily available from proxy records. For instance in a reconstruction of winter climate 750–1300 for W. Europe, the unusual freezing of fig trees and olives in the Po plain and Germany, (absent in these areas at present), appear to have been recorded (Pfister *et al.*, 1998). Often human-activities change the properties of the system (environment) over time and due to this interference with the natural variability the real magnitudes of the climate events are hard to assess (e.g. desertification due to overgrazing or, drainage-induced relative sea-level increase of wetlands). The study of these records has been important for acknowledging that climate did change in the near past and that periods with cooler (Little Ice Age) or warmer (Medieval Optimum, Roman Optimum) climate had a severe impact on human society (e.g. Lamb, 1965, 1979; Pustilnik and Yom Din, 2004). By analysing instrumental and historical information from different locations regional and extra-regional weather patterns and their evolution over time will emerge. From these weather patterns and their evolution, teleconnections may be identified.

3.3.3 Proxy Records from Natural Archives

For the more distant past and for less densely populated regions or regions with a poor coverage of historical and instrumental climate data we have to rely on proxies. The proxy records also provide the only means to (1) elucidate the impact of longer-term processes (for which instrumental records are too short), (2) assess the frequency, magnitude and impact of rare events (e.g. climate extremes) and (3) obtain information on non-analogue situations (including e.g. the pre-industrial climate regimes). The interpretation of proxy records is complicated by the fact that a given proxy record usually has been influenced by more than a single environmental parameter and that the relative influence of these environmental parameters on the proxy record may change temporally and spatially. Proxy records often reflect “complex” climate parameters (precipitation-evaporation budget, monsoon strength, length of the growing season) which are hard to translate into “simple” entities like temperature, precipitation, evaporation, air pressure or wind strengths. This is especially true for organism-based proxies (e.g. tree rings or coral-growth bands) since organisms usually have unimodal rather than linear response curves to environmental gradients (Figure 3.4). Moreover, they actively interact with their environment and try to optimise their living conditions on the basis of a multitude of factors. These characteristics severely complicate quantification of environmental change and conversely limit the identification of regional and interregional climate patterns and interrelationships. Further complicating factors are the difficulties to obtain an accurate age-assessment and the adequate temporal resolution to investigate (sub)decadal solar forcing of climate.

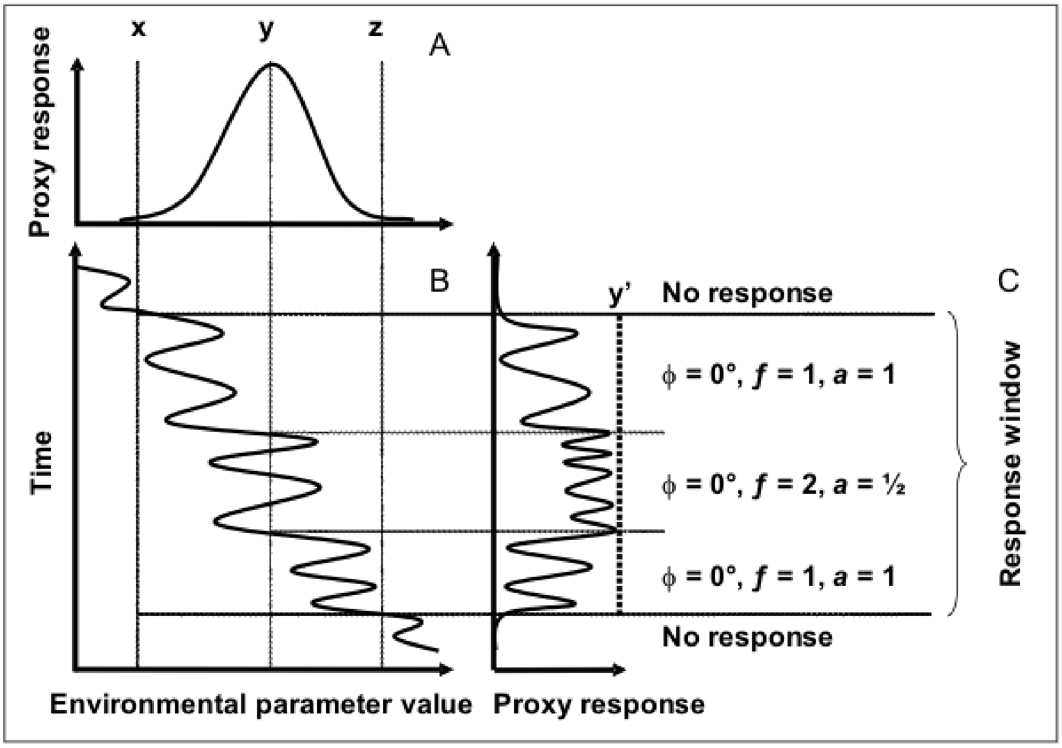

Figure 3.4: Example of the effects of a unimodal proxy response (typical for organisms) to a linear environmental change (e.g. Sun-induced). (A) The proxy-environment relation; x, the minimum value of the environmental parameter needed to obtain a proxy response (e.g., the species is absent at lower parameter values); y, the parameter value for which the proxy response maximises, z, the maximum value of the environmental parameter that still evokes a proxy response. For xy the proxy value increases with the environmental parameter value, for yz this relation is opposite. (B) A hypothetical evolution of the environmental parameter through time. (C) Proxy response resulting from the environmental change in B against time; Φ, phase; f, frequency; a, amplitude of the proxy response in C, in relation to the original environmental signal in B. Similar responses may be obtained from proxies at or near the boundaries of opposite climate regimes.

An excellent example of the different types of proxy records, the problems involved in interpreting them in terms of climate change and combining them to assess climate change over large areas forms the northern hemisphere temperature reconstructions for the last millennium (Mann *et al.*, 1999; Briffa, 2000; Cook *et al.*, 2004 see also Figure 3.7) and the associated discussion if the late 20th century temperature increase is unique ("hockey stick scenario") or not (Mann *et al.*, 2003a; Soon and Baliunas, 2003a; Soon and Baliunas, 2003b; Mann *et al.*, 2003b; Moberg *et al.*, 2005; McIntyre and McKitrick, 2005). Particularly the amplitude of the century and multi-century changes appears hard to capture, providing considerable uncertainty to the temperature decrease during the Little Ice Age (LIA, AD 1300– 1900) and increase during the Medieval Warm Period (MWP, AD 800–1300). One reason for this (and argument against the "hockey stick scenario") appears to be the present-day practice of proxy calibration against the relatively short instrumental time series. This practice underestimates the longer term variability due to the 'red noise' character of the climatic signal (Osborn and Briffa, 2004; von Storch *et al.*, 2004). It should be noted that the LIA and MWP are problematic concepts since the start, duration and end of these (and earlier) epochs are inconsistently used among authors. Furthermore, it makes a lot of difference if these epochs are evaluated on the basis of yearly, hemisphere-averaged *temperature* anomalies (increase for MWP or decrease for LIA) or seasonally (monthly) differentiated regional *climate* anomalies without prescribed direction of change (see also Jones and Mann, 2004). With respect to solar forcing of climate, these epochs show a high degree of internal variability so that assessment of solar forcing should be on higher temporal resolution (e.g. Mauquoy *et al.*, 2002), (Figure 3.5). Comparison of hemisphere-wide reconstructions with solar variability (e.g. ^{14}C) does not show an obvious correlation (Figure 3.5). This may relate to the large, hemispheric, scale of the reconstruction. If solar forcing operates via modulating pressure systems, a synoptic scale rather than hemispheric scale would be more appropriate. Furthermore, other aspects of climate, like precipitation, or wind speed and direction may show a more clear response to solar forcing. Although a large amount of information is available for such alternative climate parameters, regional proxy-based syntheses variables are presently hardly available or of insufficient detail (e.g. Soon and Baliunas, 2003b). The debate is reinforced by a study claiming that for the period since AD 1500 only for the northern hemisphere the pre-instrumental temperature reconstructions are consistent with instrument-based hemispheric temperatures (Andronova *et al.*, 2004). Clearly, in order to assess the influences of solar forcing on climate, reconstruction of climate should be unambiguous.

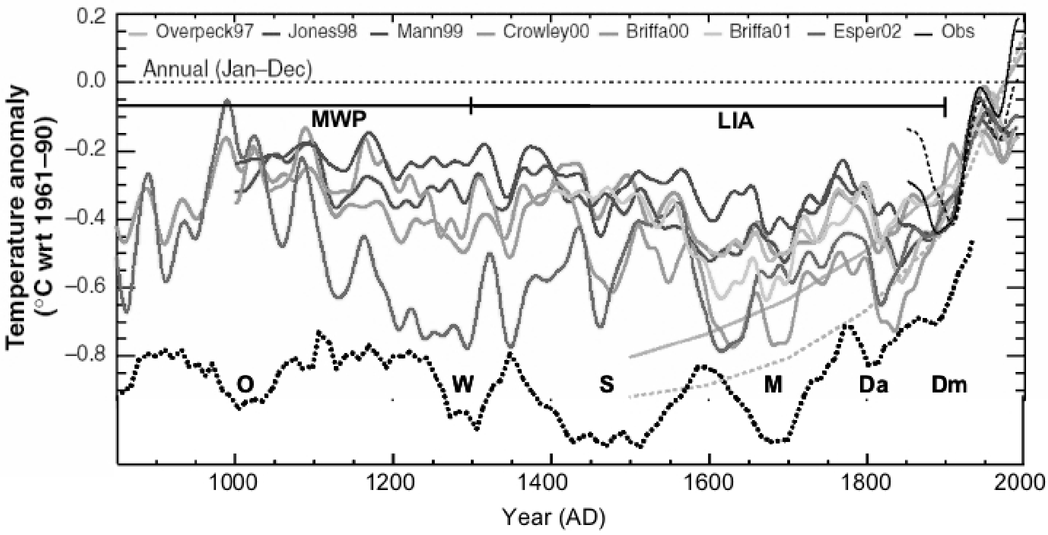

Figure 3.5: Reconstructions of Northern Hemisphere temperatures for the last millennium. Note the differences in amplitude, due to differences in choice and treatment of the proxy records, note also the larger amplitude compared to the global reconstruction (Briffa and Osborn, 2002). The names on top refer to (Overpeck et al., 1997; Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Crowley and Lowery, 2000; Briffa et al., 2001; Esper et al., 2002). Lowermost blue line $\Delta^{14}C$ (reversed scale) for comparison.

Presently, the focus of composite climate reconstructions shifts from the last millennium to the last two millennia so that the also badly defined 'Dark Age Cold Period' and 'Roman Warm Period' are examined more closely (e.g. Mann and Jones, 2003). For a recent summary on their occurrence see CO_2 science (http://www.co2science.org/subject/d/summaries/rwpdacp.htm).

3.3.4 High Resolution Archives

A large number of different archives provide information on past environment but most do not reach the high temporal resolution needed to assess decadal and century-scale effects of solar variability. Exceptions are archives with high sedimentation rates, notably in case they display annual bands (e.g. tree rings, varves, coral and glacier growth bands). The annual layering has another important advantage; it provides a highly constrained age assessment. For non-laminated sediments, wiggle-match ^{14}C dating provides an alternative and powerful tool to obtain highly constrained age assessments (van Geel and Mook, 1989; see Mauquoy *et al.*, 2004b). These archives are both land-based and marine. Paradoxically, studies on the solar-forcing of climate are biased to land-based records although the marine realm covers most of our globe. Tree ring-based records (see Briffa *et al.*, 2004 for a recent review) provide information about the conditions during the tree growing season. By selecting trees which live(d) near their natural limits of occurrence, a high degree of correlation with a particular environmental variable can be obtained (e.g. number of days with a temperature high enough for tree growth). For a long time standardisation procedures applied to build composite tree ring records of individual trees precluded the detection of changes longer than the average record length of the individual trees. The longer term relation between temperature and tree-ring density (north of 50°N) appears to break down for almost all records after AD ~1960. Proposed reasons are a shorter growth season due to a longer snow cover (Vaganov *et al.*, 1999) or the relatively recent stratospheric O_3 breakdown and associated growth-inhibiting increased UV levels (Briffa *et al.*, 2004). Solving the discrepancy is urgently needed, not in the least for assessing the likelihood of a breakdown of the correlation between temperature and tree-ring density during the past. Corals, like trees, interact with their environment to optimise their conditions for living. Many shallow water coral polyps live in symbiosis with zooxanthellae and this small ecosystem, e.g., complicates the interpretation of the changes in carbon isotopic composition of corals. Still, corals and their chemical composition provide important evidence of shallow and deep marine environmental changes in e.g. salinity, temperature and influence from land. Evidence for the NAO and ENSO is particularly clear in corals. The records of individual speleothems may be considerably longer than those from trees. Speleothems do not actively respond to environmental change which is an advantage. They are however susceptible to a range of variables changing the cave environment (e.g. cave CO_2 pressure and temperature) and groundwater composition. Ice core records are among the longest of annually banded records. The Greenland record reaches into the penultimate glaciation (e.g. Dansgaard *et al.*, 1993), whereas the Antarctic records which have much lower sedimentation rates cover over 800,000 years of glaciation and deglaciation (Augustin *et al.*, 2004). Other, lower latitude and shorter records have been obtained from high altitude ice masses in the Himalayas, American Andes and African Mountain tops (e.g. Thompson *et al.*, 2002, 2003; Bradley *et al.*, 2003). The records play an important role in the assessment of the past atmospheric composition and long term climate variability. Finally, varves in lakes and annually layered (anoxic) ocean basins form long term records of environmental change.

3.4 Climate Forcing Mechanisms

In order to be able to assess Sun-climate relations, we need to evaluate the influence of other forcing factors on climate and how they could interfere with solar forcing or provide alternatives to evaluate solar forcing mechanisms and climate sensitivity. To do this it is essential to separate climate variability induced by variability of the forcings themselves from climate variability that occurs even if the forcings are held constant. This distinguishes the climate variability that arises from solar variability from the climate variability that remains with a constant Sun. Usually we are interested in the climatic response to a change in forcing only;

ignoring the intrinsic climate variability under constant forcing conditions. From this point of view climate variability originates from three kinds of processes; exogenic, endogenic and autogenic. It must also be kept in mind, that between these main groups feedback loops may occur. Exogenic processes modulate forcing from outside the Earth influencing climate (e.g. solar variability, supernovae, changes in the Earth' orbital parameters). Endogenic processes modulate forcing from inside the Earth that influence climate (e.g. volcanism, continental drift and geomagnetism). Autogenic processes encompass climate dynamics that remain if the exogenic and endogenic forcings are *held constant*. They include the feedback mechanisms at the Earth surface (e.g. within, or between, the atmosphere, hydrosphere, cryosphere or biosphere).

3.4.1 Exogenic Forcing

On very long time scales, the exogenic forcing includes forcing of galactic spiral arms when they pass our solar system (Shaviv, 2002) and the well-established perturbations in the orbital parameters of the Earth, the so called Milankovich cycles with major periods between ca. 20,000 and 400,000 years. Exogenic forcing at shorter time scales has been attributed to the following:

a. Harmonics of the Milankovich cycles with a minimum cycle length of a few ka (Hagelberg *et al.*, 1994; McIntyre and Molfino, 1996; Kleiven *et al.*, 2003). These cycles and their climatic impact are still poorly understood. Biannual to century scale periodicities in precession and obliquity (with a.o. 11.9 and 18.6 years cycles) have been estimated to have an amplitude of ~0.1 Wm^{-2} (Loutre *et al.*, 1992). The extent to which these small variations might influence climate has not sufficiently been investigated yet.
b. The Earth–Sun–Moon gravity (tidal) cycles with major periods of ~6 h, 8.8 and 18.6 years. Despite their strong diurnal impact, relatively few studies attribute longer time environmental changes to longer cycle tidal harmonics (Berger and von Rad, 2004). Tidal energy has been proposed to influence climate via modification of upwelling intensity within the oceans (Keeling and Whorf, 2000; Wunsch, 2000; Egbert and Ray, 2000). However, the climatic significance of the longer cycle harmonics e.g., an 1800 years cycle is still heavily debated (Keeling and Whorf, 2000; Munk *et al.*, 2002). Sub-decadal and decadal tidal cycles have been suggested to influence sea surface temperatures in the Equatorial Pacific and through these, the climates of the surrounding land masses (Treloar, 2002) such as the western United States (Currie, 1996b; Cook *et al.*, 1997). Of these, the 86.8 and 20.3 years tidal cycles are so close to the quasiperiodic 22 years Hale, and 88 years Gleissberg solar cycles, that separation of tidal and solar variability climate forcings appears a challenging task. The situation is further complicated by the possible existence of a combinatory frequency of 18 years in the climate response to the solar Gleissberg and Hale cycles (Raspopov *et al.*, 2004). The good predictability of the tidal forcing may be of considerable advantage for both assessing importance of tidal forcing and separating tidal from solar forcing.
c. Variations in the solar constant/activity, operating on time scales from hours (e.g. solar flares influencing weather (Veretenenko and Thejll, 2004) to millennia. These variations will be dealt with below.
d. On short time scales, nearby supernovae could cause strong increases in the cosmic-ray dose received by the atmosphere resulting in a high production of radionuclides in the atmosphere and erosion of the stratospheric ozone layer. Such cosmic-ray events may have influenced life directly by a higher UV dose (Ellis and Schramm, 1995; Crutzen and Brühl, 1996) or indirectly via a changing climate. The impact on stratospheric ozone could result in nitrate spikes in ice cores. However, although nitrate spikes in Antarctic ice (Burgess and Zuber, 2000) have been attributed to supernovae a recent survey suggests that such relations are spurious (Green and Stephenson, 2004). Iyudin (2002) examined the terrestrial impact of supernovae for the last millennium and suggests that a relation between supernovae and climate could exist. Supernovae represent extremes with respect to the Earth's response to radiative changes. Therefore they could inform us on the boundary conditions, limitations and response properties of the Earth to radiative changes, including the response to solar variability. Unexpectedly, there does not seem to be clear evidence

supernova forcing of the Earth's life and climate. This discrepancy between theory and praxis deserves more study, despite the rarity of supernovae.

3.4.2 Endogenic Forcing

3.4.2.1. *Volcanism*

Volcanic eruptions may have a strong global (in the order of 1°C or 1 Wm^{-2}) but short-lived (few years) climatic impact (Shindell *et al.*, 2003; Hegerl *et al.*, 2003) (Figure 3.6) and as such interfere with (counteract or enhance) longer term trends. The associated injection of particles in the upper atmosphere increases the reflection of solar radiation into space, which results in global cooling and which has a decadal-scale impact on ocean heat content (Church *et al.,* 2005). The impact of eruptions depends on timing in the year and the latitude of the eruption and the amount and nature of the particles injected in the atmosphere.

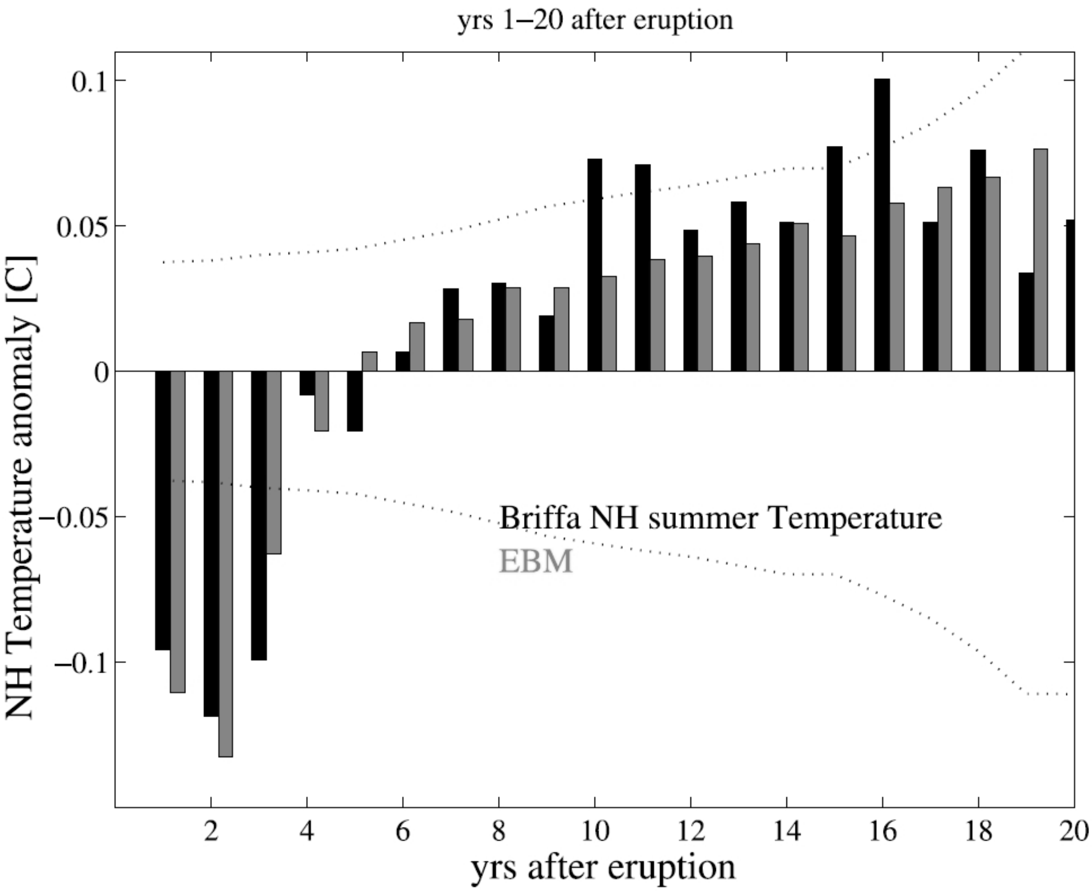

Figure 3.6: Comparison of the average response to volcanic eruptions in an energy balance model (right bar of each pair) and the Briffa et al. (2001) reconstruction from the year of the eruption (year 1) to the next major eruption (left bar of each pair). Uncertainty ranges of 5–95% for the observed response are given by the dotted lines (the sample size decreases with time) (Hegerl et al., 2003).

The effect of temporally closely spaced eruptions is additive. For a recent review see (Zielinski, 2000). On the northern hemisphere, the volcanic forcing seems to enhance the Arctic Oscillation initially, resulting in winter warming, but weakens the AO in secondary stance (Shindell *et al.*, 2003). The climatic impact of this oceanic feedback and as such .The ice cores form an important source of information on past volcanic eruptions and their magnitude (e.g. Hammer *et al.*, 1980; Zielinski, 2000). In stead of volcanism forcing climate, the opposite relationship: climate change forcing volcanism has also been proposed (Zielinski, 2000; Bay *et* *al.*, 2004). The loading/unloading of the crust with ice sheet growth/decay and the increased loading on the ocean basins by meltwater from melting ice sheets may lead to enough crustal stresses that magma chambers become much more active than during the middle of a climatic mode (Zielinski, 2000). However, the scale of this tectonically induced volcanism does not appear to have had a significant impact on the climate transitions during which it took place. Other tectonic processes, (e.g. glacioeustatic rebound at higher latitudes) and associated coast-line and altitude changes which may influence climate will not be taken in consideration, mainly since these processes are very slow. *For single eruptions, volcanic forcing of climate is too short-lived to influence climate on time scales longer than a few years. However, for series of eruptions this could be the case*.

3.4.2.1 Geomagnetism

A weaker geomagnetic field leads to a higher cosmic ray dose of the atmosphere. This influences the production of cosmogenic radionuclides ^{10}Be and ^{14}C which form the basis for reconstructing solar activity. A higher cosmic ray dose also has been suggested to result in more cloud formation, cooling the Earth ("cloud formation scenario") (Svensmark and Friis-Christensen, 1997; Kniveton and Todd, 2001; Carslaw *et al.*, 2002; Kristjánsson *et al.*, 2004) so that geomagnetic changes also could have a direct climatic effect. Accurate assessment of changes in the geomagnetic field is thus of direct importance for understanding solar variability and for testing the "cloud-formation scenario". Reconstructing geomagnetic activity, however, is a difficult task and, unfortunately, already relatively small changes in the long term trend substantially influence the amplitude and sign of the reconstructed solar activity changes (Figure 3.7). On smaller time scales, changes in the geomagnetic field are even less well defined. Usually the processes at the Earth's surface are supposed to force the geomagnetic field and not *vice versa*. It is assumed that during ice accumulation the Earth's moment of inertia decreases resulting in interactions between the Earth's mantle and core. These weaken the geomagnetic field in order to try to counter the decrease in differential rotation between the mantle and inner core that is being forced. The weakening of the Earth's magnetic field facilitates geomagnetic excursions and also causes enhanced production of cosmogenic nuclides (Westaway, 2003). In this scenario, geomagnetic weakening must follow ice accumulation, whereas in the "cloud-formation scenario" weakening of the geomagnetic field leads ice accumulation.

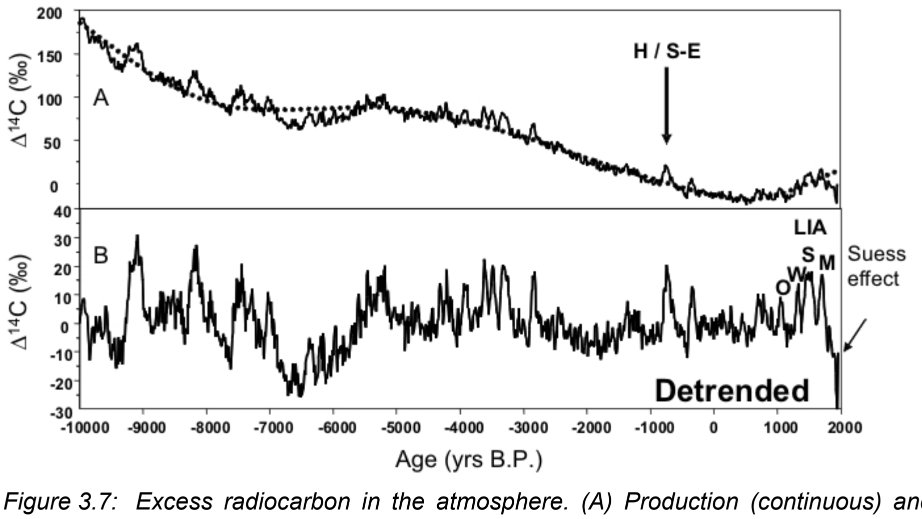

Figure 3.7: Excess radiocarbon in the atmosphere. (A) Production (continuous) and the trend (dotted) ascribed to changes in the magnetic field strength. H/SE refers to the Homeric solar minimum/Sterno- Etrussia magnetic excursion. (B) The same record as in A but after removal of the (geomagnetic) trend. Note that the shape of the curve, the amplitude and sign of the peaks, are sensitive to small changes in the trend, i.e. the accuracy of the reconstructed geomagnetic influence. LIA refers to Little Ice Age. O, W, S, M refer to Oort, Wolf, Spörer and Maunder minima, respectively.

Clearly, accurate correlation of geomagnetic reversals and ice volume are of utmost importance to unravel cause and effect relations. Some recent studies put evidence to the geomagnetic forcing of climate by showing that short term reductions in geomagnetic intensity occur during, or at the end of interglacials or interstadials (Worm, 1997; Westaway, 2003; Christl *et al.*, 2004; Thouveny *et al.*, 2004; Carcaillet *et al.*, 2004). The geomagnetic variations also have been proposed to operate more rapidly than generally thought so that the assumption that millennial and even some centennial fluctuations in cosmogenic radionuclide production are solely a function of solar variability has to be re-examined (St-Onge *et al.*, 2003; Snowball and Sandgren, 2004; Gallet *et al.,* 2005). A good example of such a short term fluctuation and its possible climatic impact is the “Sterno-Etrussia” geomagnetic excursion at about 800 BC that lasted probably only 200–300 years (Raspopov *et al.*, 2003; Dergachev *et al.*, 2004) and coincides with a sharp global cooling. Interestingly, this cooling event has also been attributed to a reduction in solar activity (e.g. van Geel *et al.*, 1998). The event coincides with a minimum in the 2400 years solar activity cycle (e.g. Vasiliev and Dergachev, 2002) (Figure 3.7). The extent to which geomagnetic and solar forcing are coupled in this case or the extent to which each factor contributes to the ^{14}C anomaly await further assessment. The Mono Lake (35 ka BP) and Lachamps (41 ka BP) geomagnetic events which left a clear signature of excess radionuclides (^{10}Be, ^{14}C and ^{36}Cl) in ice cores and sediments (Cini Castagnoli *et al.*, 1995; Baumgartner *et al.*, 1998; Hughen *et al.*, 2004) do not seem to have left unequivocal climatic signatures whereby it should be noted that the climatic effect of the geomagnetic excursions may have been lost in the (compared to Holocene) large amplitude environmental variability related to the Dansgaard-Oeschger events (see e.g. Shackleton *et al.*, 2004). Superimposed on this short “Sterno-Etrussia” event, the geomagnetic field has been weakening over the last millennia (at 1000 BC the field was 1.4 times the present value) and this must have led to a significant increase in Earth cosmic ray exposure, which, depending on the latitude, may exceed the cosmic ray modulation by solar cycles (Shea and Smart, 2004). This weakening may provide the most recent, though longer-term, test case for the “the cosmic-ray cloud-formation scenario”. Unfortunately, investigation of impacts of geomagnetic events on past climate, life and cosmic-ray induced radionuclide production is still a largely barren field. Understanding of the cause–effect relations between geomagnetism, climate and radionuclide formation are of utmost importance for reconstructing solar activity variations and thus understanding solar-climate relationships. *Accurate reconstruction of the geomagnetic field on long and short time scales is of direct importance for reconstructing solar variability and assessing possible climate forcing by cosmic rays. Notably the nature and effects of short-term fluctuations in the magnetic field require more study as do the causes and effects of geomagnetic variability which are hitherto poorly understood as well*.

3.4.3 Autogenic Processes

It is extremely hard to deduce internal climatic feedback *mechanisms* on relevant time-scales in the proxy records. There is, however, plenty evidence in proxy records for the climate perturbations that have been suggested to be driven by land–ocean– atmosphere interactions and for which no exogenic or endogenic forcing mechanism seems to be available (yet). Major autogenic climate oscillations are the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO) on the Northern Hemisphere, and the bi-hemispheric Quasi Biannual Oscillation (QBO), and the El Niño/Southern Oscillation (ENSO) on the southern hemisphere. The AO and its North Atlantic component NAO at the Earth surface seem to operate to a large degree on the basis of internal climate variability (see for extensive reviews Wanner *et al.*, 2001; Marshall *et al.*, 2004). The NAO represents the difference in sea level pressure between the Azores High and the Icelandic Low. This difference has an important influence on European and Eastern North American winter climates, influencing occurrence, direction and depth of storm tracks, and conversely temperature, precipitation (Figure 3.8) and storminess and logically, the NAO and the amount of sunshine over Europe correlate (e.g. for the Iberian Peninsula (+0.75) and Norway (−0.70) (Pozo-Vazquez *et al.*, 2004). The NAO also seems to extend its influence into the Middle East (Felis *et al.*, 2000; Cullen and DeMenocal, 2000).

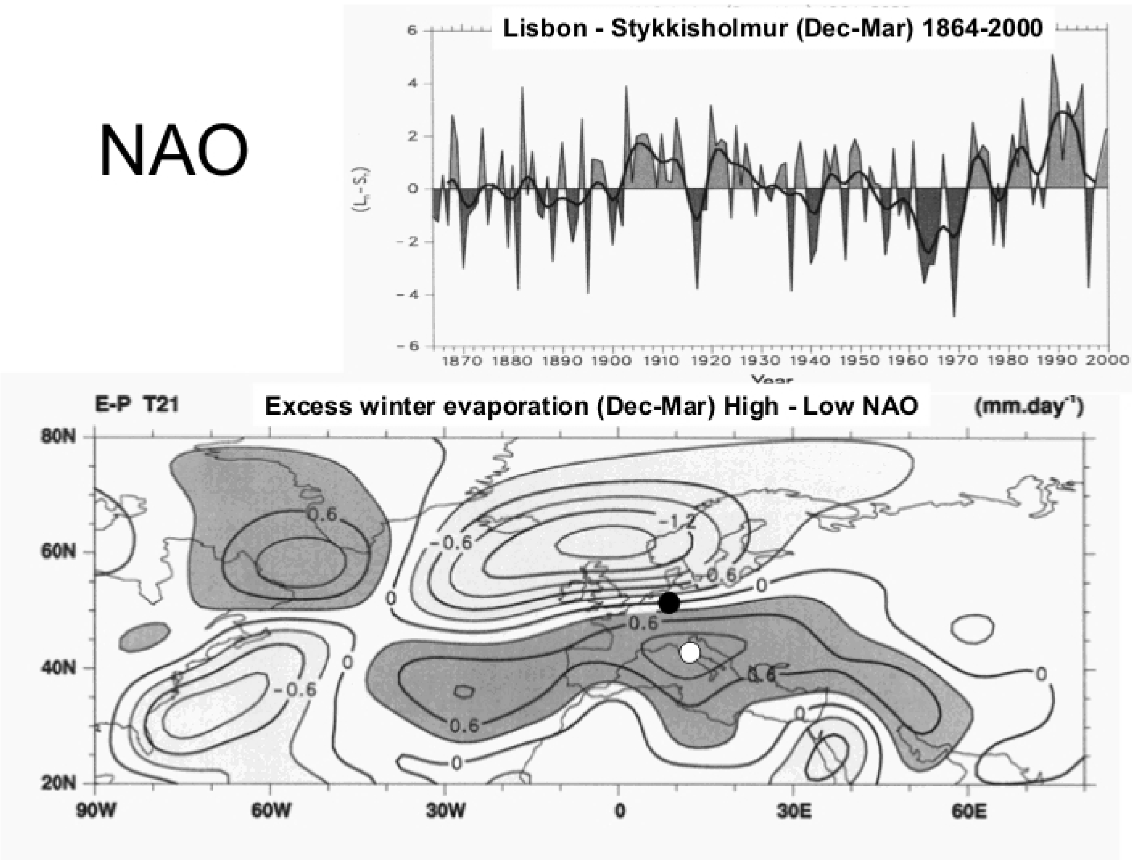

Figure 3.8: The spatial differentiation of the effects of the NAO on the water balance in the North Atlantic and surrounding land masses (Wanner et al., 2001). Note the differences in response between the black and white dots upon latitudinal shifts in the zero excess evaporation line.

Reconstructing the NAO is a difficult task. Not only the pressure difference between the Azores High and the Icelandic Low but also the exact locations of these pressure systems are climatically important. Furthermore an important East-West pressure gradient over Europe or Eurasia may interfere (EU indices) (e.g. Luterbacher *et al.*, 1999; Wanner *et al.*, 2001) and one may wonder if NAO reconstruction is not a too narrow concept for capturing European and North Atlantic climate variability. The difficulty of reconstructing the NAO is also illustrated upon comparison of recent reconstructions which go back to the 15th (Glueck and Stockton, 2001; Luterbacher *et al.*, 2002) or 14th centuries (Cook *et al.*, 2002). The large degree of difference between the reconstructions has been suggested to result from a variety of causes like overprint in recent decades by anthropogenic climate forcing in combination with a relatively short interval representing natural forcing (Schmutz *et al.*, 2000), external volcanic and solar forcing during the early eighteenth century as well as differences in the geographical distribution of the proxies used to reconstruct the NAO (Timm *et al.*, 2004). Longer and reliable reconstructed time series of the NAO/AO would be particularly useful to elucidate the existence of decadal to centennial patterns and their relation to internal feedback mechanisms and external forcing. Like the NAO/AO, the El Niño-Southern Oscillation (ENSO) with quasiperiodicities of 2–3 and 5–6 years and the Pacific Decadal Oscillation (PDO) with a 20–30 years quasiperiodicity seem to operate to a large degree on the basis of internal climate variability. The phenomena strongly influence climates along the Pacific coasts of the American continents (e.g. Mantua *et al.*, 1997; Benson *et al.*, 2003), Australasia (Jacoby *et al.*, 2004) and the Indian subcontinent (Felis *et al.*, 2000; Tiwari and Rao, 2004) and add to the climate variability almost globally. On the other hand global temperatures have been proposed to influence the ENSO (Tsonis *et al.*, 2003). Non-linear solar forcing of these systems has been proposed but further assessment is hampered by the nonlinear behaviour of the oscillations and the lack of physical understanding of the forcing mechanisms. A special case of an autogenic process forms human-induced climate change. Recently, the issue on the extent and timing of human-induced climate change got a new impulse with the statement that humans significantly influenced changed atmospheric CO_2 concentrations already 8000 years ago and CH_4 5000 years ago (Ruddiman, 2003; Crutzen and Steffen, 2003; Crowley, 2003). *Solar variability influencing nonlinear autogenic climate variability has been proposed but further assessment is hampered by the nonlinear behaviour of the oscillations and the lack of physical understanding of the autogenic processes and possible exogenic forcing mechanisms*.

3.5 Evidence for a Sun-Climate Link

To assess solar forcing of climate we need correct reconstructions of (1) solar variability, (2) climate and (3) identification of a relation between both. For most regions studies presenting evidence for solar forcing of climate coexist with studies showing no sign evidence. This lack of evidence may be due to a lacking relation to solar forcing, a lacking sensitivity of the proxy to the forcing, or a lack of interest to this topic by the authors. Instead of summing up the lack of evidence, attention will paid to those relatively few regions for which solar forcing of climate has been suggested from proxy data. Already soon after the discovery of sunspots by Harriot in 1610, a link with climate has been proposed. From about the second half of the 19th century to about 1925 a steady stream of papers on the issue appeared (see Hoyt and Schatten, 1997 for an extensive review of early papers on solar forcing). The time series are short, 50–100 years, and ‘phase shifts’ to solar forcing are often reported. All kinds of meteorological phenomena like temperature, precipitation, air pressure, wind velocity, cloud formation and storm tracks as well as proxy records like lake levels and tree rings are related to solar variability (sunspots, protuberances and magnetic activity), mostly at annual to decadal scale (see Helland-Hansen and Nansen, 1920 for a review of these early investigations). During this early period also the influence of volcanic dust in the atmosphere on climate has been recognised as well as the sub-decadal variability in the North Atlantic and Pacific which are now attributed to the NAO and ENSO. Helland-Hansen and Nansen conclude that “different groups of regions vary intact in a definite direction whereas another group varies in an opposite sense, and that again still other regions show transition phenomena. Out of this variegated picture of meteorological variations, we find also by a proper analysis the influence of the variations in solar activity which in all probability make themselves felt first in the higher layers of the atmosphere and thereby produces disturbances which again introduce changes in the lower layers” (Helland-Hansen and Nansen, 1920 p. 266). After this early period of study on solar forcing of climate, the stream of information on solar-terrestrial links almost ceases until about 1970 after which the number of papers published increases again (Benestad, 2002; pp. 185–194) to ‘explode’ during the last years. A series of publications on evidence for luni-solar 18.6-year (*M*n) and solar cycle 10–11-year (*S*c) signals in instrumental records is provided by Currie since the early 1970s (see bibliography in Currie, 1996a). In a recent summary (Currie, 1996b), including 3234 yearly sampled climate records (1179 USA air temperature, 1179 USA rainfall, 59 South African rainfall, 39 sea-level, 697 tree-ring, and 81 Chinese dryness/wetness time series) it is observed that on average both signals contribute 25% to total variance in the raw, or original, data, whereas for the 30–8 years bandwidth they contribute a mean 74% to the variance in the records. In a study on 308 Australian rainfall records both cycles account for 19% of the variance in raw data and 89% of the variance in the 30–8 years frequency interval (Currie and Vines, 1996). Most (about 62%) of the variance is contained in the 8-2 years band (Currie, 1996b) which may reflect the influence of the NAO and ENSO. The longer than 30 years band contains only a minor part of the variance, as can be expected from the analysis of relatively short records. The relative shortness of instrumental records precludes the detection of the Gleissberg (86 years) and longer cycles of solar variability. For longer periods and evidence for short term cycles in the more distant past we must rely entirely on natural climate archives. Evidence for Sun-climate links from these archives will be dealt with in the following sections.

3.5.1 Analysis of Sun-Climate Links

Several approaches are used to analyse Sun-climate relations.

- Matching individual wiggles in ^{10}Be and ^{14}C records with environmental changes.
- Matching spectral properties (phase, frequency, amplitude) of proxy records with those of solar variability.
- Matching calculated anomalies of the celestial gravity field with environmental change.

3.5.1.1 ^{14}C Wiggle Matching

A most fruitful approach is the search for a climatic response to anomalies in solar activity. By means of a high number of ^{14}C dates a local ^{14}C activity curve is generated for the proxy archive which is subsequently matched to the ^{14}C standard calibration curve. This results in a much more accurate dating than achieved on the basis of individual ^{14}C dates (Figure 3.9) while also possible links between solar activity, cosmic ray intensity and climate change can be studied (van Geel and Mook, 1989). With this method, emphasis has been on investigating the link between climate change and sudden decreases in solar activity. It should be noted that a minimum in $\Delta^{14}C$ (after correcting for the delayed response) or ^{10}Be indicates a sudden change from relatively high to low solar activity (see e.g. discussion: Schimmelmann *et al.*, 1999; van Geel *et al.*, 1999).

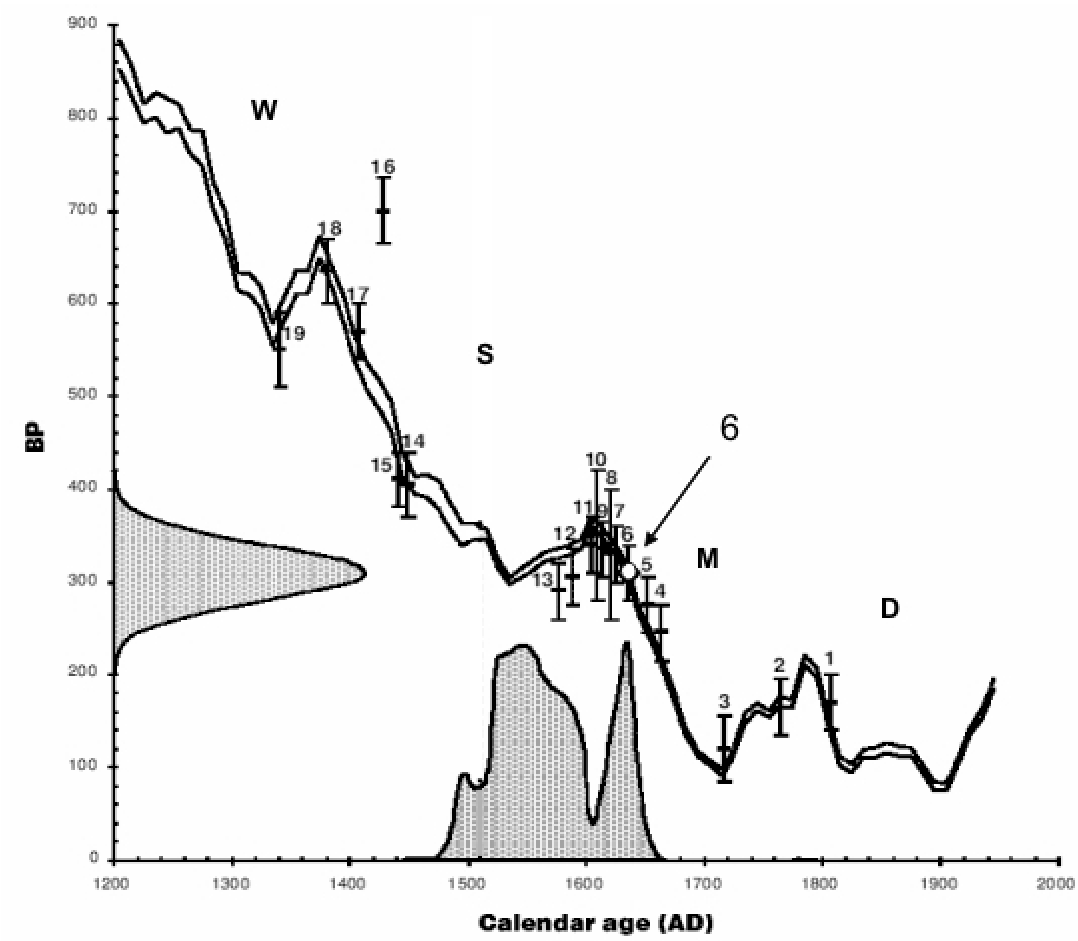

Figure 3.9: Matching the local, peat derived ^{14}C activity curve (numbered ^{14}C datings) to the standard ^{14}C calibration curve (black line). Grey areas indicate the age probability distribution for sample 6 for which the assigned age of AD 1640 only is obtained if the other dates are taken into account too. W, S, M, D refer to Wolf, Spörer, Maunder and Dalton minima of reduced ^{14}C production (Mauquoy et al., 2004b).

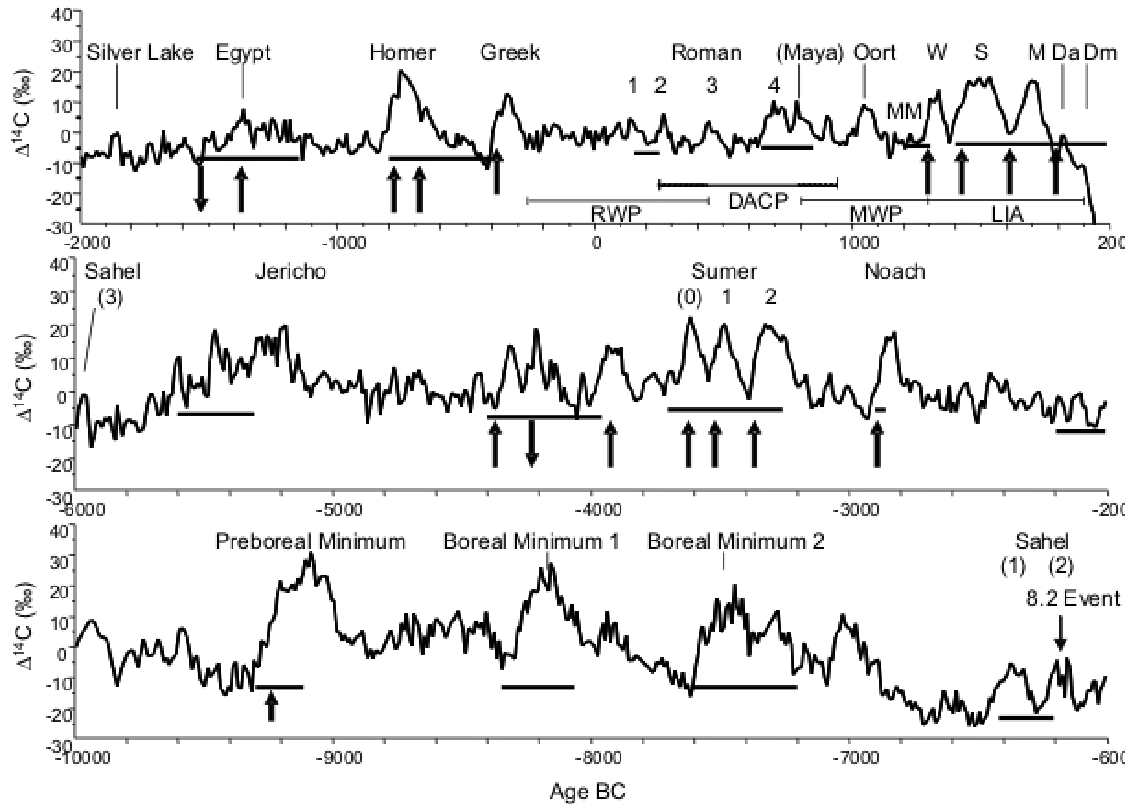

Figure 3.10: *^{14}C anomalies and climate events. Arrows correspond to investigated ^{14}C shifts. Upward arrow, moment of shift to wet/cool conditions, downward arrow, absence of evidence of a climate shift (Blaauw et al., 2004; van der Plicht et al., 2004; Mauquoy et al., 2004b). Note that the shifts occur at, or near, the beginning of the ^{14}C anomalies. Thick horizontal lined, periods with high lake levels (no such lines, lower lake levels) in the Jura mountains (Magny, 2004). ^{14}C anomaly names after Davis (1993) (and newly introduced in brackets). RWP: Roman warm period, DACP: dark age cold period, MM: mediaeval maximum.*

This implies that the large climate anomaly at the beginning of the 17th century (see evidence collected by Schimmelmann *et al.*, 1998) relates to the decrease in solar activity that also resulted in the high values of $\Delta^{14}C$ during the Maunder minimum of solar activity (Figure 3.10). The climatic shift occurs thus very early, simultaneously with the *change* in solar activity, the maximum cosmic ray intensity *lags behind* the climatic shift (van Geel *et al.*, 2001). It could be argued that the large volcanic eruption of the Huaynaputina in Peru at AD 1600 may have contributed to the early start of the climatic shift. However, a similar early response is also observed for the climatic shift associated to the Homeric ^{14}C minimum (~800 BC). Here too the shift occurs at the moment the $\Delta^{14}C$ record starts to rise and thus at the moment the solar activity (suddenly) declined. Other examples arise from comparing the ^{10}Be record with the climate anomalies at the Preboreal oscillation (9,250 BC and Boreal oscillation 1 (8,300 BC) (Muscheler *et al.*, 2003; van der Plicht *et al.*, 2004) (Figure 3.10). The climate response to a decrease in solar activity seems immediate which sets tight limits to the forcing mechanisms. Does climate respond nonlinearly to a small decrease in solar activity? Do changes in the Sun change climate prior to changing the cosmogenic isotope production? Are there unknown delays in the cosmogenic isotope proxies? Clearly, solving the timing-paradox is crucial for understanding the Sun-climate relationships.

3.5.1.2 Spectral Analyses

Spectral analysis of proxy records is a powerful tool to analyse the cyclic behaviour of time series. Since solar variability appears to be quasicyclic, spectral analysis is a most popular method for assigning environmental change to 'solar' forcing. Often spectral peaks in the environmental record that occur near spectral peaks in instrumental records of solar variability or in solar proxies are considered to originate from solar forcing. However, the quasicyclic behaviour of solar variability implies that a rigid frequency analyses is likely to underestimate an environmental response to solar forcing. This underestimation may be further enhanced by inaccuracies in the age model, as well as phase shifts in the environmental response to the forcing. Wavelet analysis is much better suited to account for these instabilities, and it may thus be no surprise that this method becomes increasingly popular. Still, more than 40 terrestrial cycles, with periods between a few days and a few millennia, have been claimed to result from solar variability (Hoyt and Schatten, 1997).

3.5.1.3 Matching Celestial Gravity Anomalies with Climate Anomalies

The hypothesis that the motion of Sun due to the movements of the planets drives solar variability has led to a body of (mostly grey) literature which relates environmental change to planetary motions (e.g. Landscheidt, 1999; Fairbridge, 2001). On this basis also future climate events have been predicted. The future will show to what extent these predictions appear to be right. The theory is largely ignored by the scientific community. Recent calculations suggest that solar variability is very unlikely to vary according to the planetary forcing mechanisms proposed (de Jager and Versteegh, 2005). This implies that if a relation between movements of the large planets and climate exists, it is unlikely to operate via changes in solar activity.

3.5.1.4 Nonlinear Responses

The varying degrees of correlation between climatic parameters and solar activity over time and between localities already led at the end of the 19th and beginning of the 20th century to the suggestion that climate does not (and is unlikely to) respond linearly to solar forcing (see Helland-Hansen and Nansen, 1920). Also today for a wide variety of localities solar forcing seems to affect climate for shorter or longer intervals (Palamara and Bryant, 2004). The problem is that also two unrelated time series will show high linear correlation over shorter and longer intervals, just by accident whereas two non-linearly related time series may fail to do so. How to differentiate between (non-linear) forcing and accidental correspondence? Only relatively few studies investigate *a priori* non-linearity of solar forcing on climate (Miranda and Andrade, 1999; van der Schrier and Versteegh, 2001). One way is to use dynamical systems theory to distinguish explicitly between internally forced and externally forced climate variability (van der Schrier and Versteegh, 2001). Applied to the instrumental central England temperature record it appears that for low values of the sunspot number, maximum summer temperatures follow internal climate dynamics whereas for high values of sunspot numbers this is not the case. The phenomenon that solar forcing seems to be present (detectable) only during periods of high solar activity and/or high amplitude changes whereas outside these periods other forcing mechanisms prevail has been proposed also for Fennoscandinavian summer temperatures (Ogurtsov *et al.*, 2002a), Brazilian climate (Rigozo *et al.*, 2004), mammal population dynamics in Boreal North America (Kvana *et al.*, 2004), the NAO/AO(Kodera, 2002; Boberg and Lundstedt, 2002; Ogi *et al.*, 2003; Gimeno *et al.*, 2003) and possibly the ENSO (Tiwari and Rao, 2004). Such a temporal behaviour of a (visible) imprint of solar forcing of climate needs to be carefully assessed. It asks for long time series of solar forcing and climate variability, longer than most instrumental records. Another kind of nonlinear behaviour has been demonstrated for varve thickness in sediments from the German Holzmaar deposited during the early Holocene. Spectral analysis shows no significant cyclicity. However, based on a supposedly non-linear transformation of the solar signal to the lake sedimentary record an adequate non-linear spectral analysis method revealed periodicities of 11, 88 and 108 years (Vos *et al.*, 1997).

3.5.2 Solar Forcing – Regional Evidence

Although Sun-climate links have been reported from a large variety of proxies and many regions, for only few regions Sun-climate links appear to be well documented. For other regions such a relationship may be absent or insufficient data are available.

3.5.2.1 Low Latitudes

Mesoamerica and South-Western North America. Solar forcing of drought with a basic cyclicity of ~200 years is held responsible for discontinuities in Maya cultural evolution (Hodell *et al.*, 2001; Rosenmeier *et al.*, 2002; Schimmelmann *et al.*, 2003). The drought events correlate to minima in both the ^{10}Be and ^{14}C records (increased solar activity) and relate to a relatively southern position of the ITCZ (Haug *et al.*, 2003; Poore *et al.*, 2004). The southern displacement of the ITCZ caused wetter conditions in the South American Altiplano (Tedesco and Thunell, 2003). Large Californian floods (recorded in the Santa Barbara Basin sediments) centre around AD 212, 440, 603, 800, 1029, 1418 and 1605 (Schimmelmann *et al.*, 1998, 2003). They all occur at or near transitions to increased ^{14}C production (Figure 3.10). Southward shifts in the ITCZ also seem to have caused southward shifts of Caribbean Loop Current (Poore *et al.*, 2004).

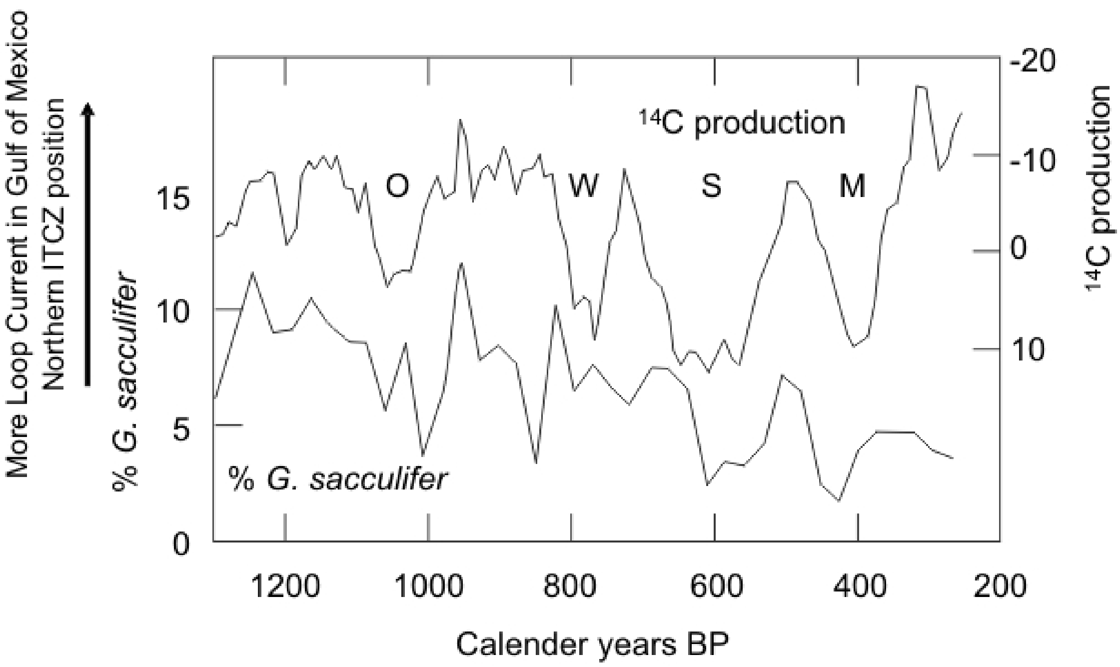

Figure 3.11: Position of the Caribbean Loop current (represented by the relative abundance of the planktic foraminifer (G. sacculifer) and the Δ^{14}C record (after Poore et al., 2004).

These southward current shifts occur during the major minima in solar activity of the last millennium (Figure 3.11). Even further east, the ~200 years cyclicity seems to modulate the Florida Current (Lund and Curry, 2004) and sedimentation at the Great Bahama Bank slope (Roth and Reijmer, 2005). A climatic response to the Oort minimum is clearly represented in the North American records (e.g. Yu and Ito, 1999; Schimmelmann *et al.*, 2003; Poore *et al.*, 2004). This response seems to be largely absent elsewhere. A persistent bidecadal drought rhythm is present in the western US, at least since AD 800. The rhythm has been suggested to result from interference of the solar 22 years Hale cycle and the 18.6 lunar nodal tidal cycle whereby dry periods relate to minima in the Hale cycle (Cook *et al.*, 1997). The lunar cycle is, however, not apparent in all frequency analyses and subject to debate (Chen and Rao, 1998). On longer time scales, the PDO and Atlantic Multidecadal Oscillation have been suggested to play an important role in the US drought frequency (Enfield *et al.*, 2001; McCabe *et al.*, 2004). A multidecadal link to solar forcing is not evident. Along the US West coast, a significant 10–11 years signal in the terrestrial temperature records (AD 1895–1960) occurs, which is in anti-phase with temperatures in the middle of the USA and the region of the Great Lakes (e.g. Thejll, 2001). In contrast to these studies, Ni *et al.* (2002) explain tree-ring based variability in winter precipitation for the last millennium with ENSO and PDO variability without mentioning any link to solar forcing. Interestingly, the reconstructed precipitation records seem to lack multidecadal and longer term variability to a large extent which may attribute to this discrepancy.

ENSO, PDO. Solar forcing of the ENSO has been suggested on decadal (Nuzhdina, 2004) and longer (multidecadal) time scales (Mehta and Lau, 1997) but evidence is not very strong. Solar forcing of the PDO has not been evidenced on the basis of proxy records. Nevertheless, it has been suggested that the positions of the major North Pacific pressure fields, the Aleutian low and North Pacific High are modulated by solar activity (Christoforou and Hameed, 1997; Patterson *et al.*, 2004). Like the NAO, solar forcing on the ENSO and PDO may be detectable during periods of high solar variability only (Tiwari and Rao, 2004).

South America. Only very limited information is available on solar forcing of South American climates. Tree ring data in Brazil indicate a relation between tree growth and solar forcing during periods of high amplitude solar activity changes (Rigozo *et al.*, 2004). In NE Brazil frequency and rescaled range analysis of historical precipitation records point to a persistent 11 years cycle (Miranda and Andrade, 1999).

The Asian Monsoons and Adjacent Regions. For the Indian Monsoon it has been postulated that periods of increased solar activity cause more evaporation in the equatorial region and/or cause a northward shift of the ITCZ, enhancing net transport of moisture flux to the Indian subcontinent via SW monsoon winds. This results in increased monsoonal precipitation in India (Agnihotri and Dutta, 2003; Hiremath and Mandi, 2004), Northern Africa and Southern Oman (Neff *et al.*, 2001; Fleitmann *et al.*, 2003, 2004; Gupta *et al.*, 2003, 2005) (Figure 3.12). The 205, 132, 105, 90, 60 and 55 years cycles have been identified for the Oman speleothem record (Fleitmann *et al.*, 2003). Closely similar cycles have also been reported for the East Asian Monsoon which also has been suggested to increase when solar activity increases (e.g. Dykoski *et al*., 2005, Ji *et al*., 2005). On shorter time scales, (decadal to interannual) the changes are linked to the intrinsic variability (ENSO) of the tropical Pacific Ocean (Burns *et al.*, 2002). Phase relations between the Afro-Asian monsoon systems are not clear yet. It has been suggested that, the ENSO signal results in inverse phase oscillations between the Indian and East Asian Monsoons (Hong *et al.*, 2005). Others report more general responses opposite to the Indian Monsoon for the East African (Verschuren *et al.*, 2000; Lamb *et al.*, 2003; Stager *et al.*, 2005) and Chinese monsoons (Hong *et al.*, 2001; Tan *et al.*, 2003, 2004); i.e. solar maxima coincide with hot and dry conditions, except for the last century when higher African lake levels coincide with sunspot maxima (Stager *et al.*, 2005).

A 725 years cycle has been reported for East central Africa humidity with warm dry periods during high sea surface salinity in the South China Sea (Russell *et al.*, 2003). The cycle may be explained by north/south displacement of the ITCZ from its equatorial mean position in relation to the 1500 years Bond quasicycle in the North Atlantic (Russell and Johnson, 2005; Broccoli *et al.* 2006).

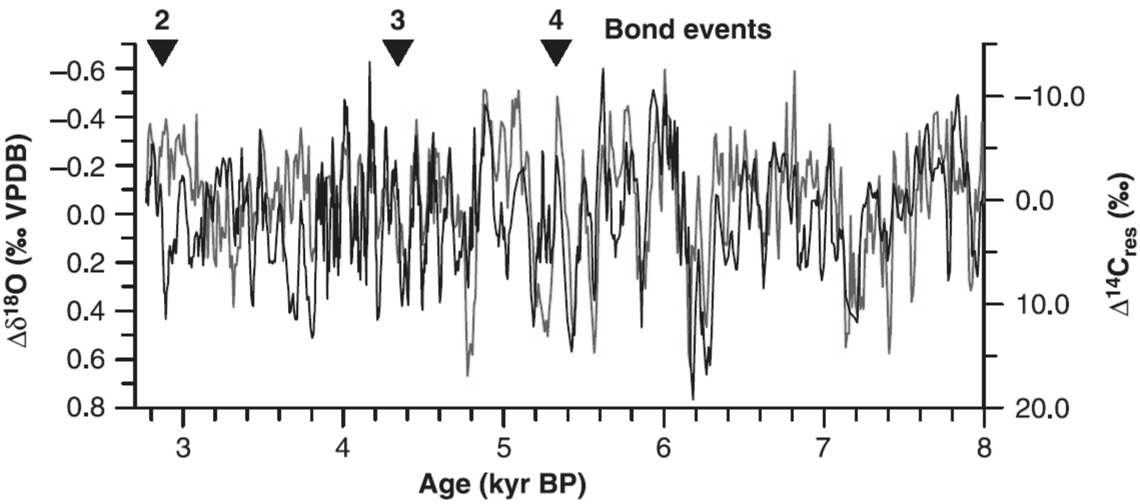

Figure 3.12: Relation between Indian monsoon strength (inferred from $\delta^{18}O$ composition of Oman speleothems) and solar activity (inferred from $\Delta^{14}C$) (Fleitmann et al., 2003).

3.5.2.2 Middle Latitudes

Australia, New Zealand and Southern South America. In the southern part of the southern hemisphere marine and atmospheric currents can travel around the globe much less hindered by topography than anywhere else. This simpler configuration could be of great help in unravelling solar forcing of climate, also for the more complex mid latitude northern hemisphere. Unfortunately, instrumental and proxy data from these southern regions are notoriously sparse. Nevertheless, important insights may be obtained. On the basis of analysis of historical climate records in Australia, Currie and Vines (1996) find evidence spectral components with cycle lengths of 18.3 years and 10.5 years and these cycles are attributed to the lunar-solar tidal forcing and solar variability respectively. Thresher (2002) observes a strong decadal pattern along the northern margins of the circum-Antarctic zonal western winds in South Africa, South America and Australia. This pattern appears in phase around the hemisphere. The variation broadly correlates with the sunspot cycle and specifically appears to reflect the sunspot-correlated, seasonally modulated shifts in the yearly latitudinal range of the subtropical ridge over eastern Australia. High sunspot numbers correlate with less winter rainfall along the east coast between 25 and 35°S and more rainfall south hereof in SW Victoria. This is explained by a more southward position of the ridge in winter during sunspot minima. Thresher (2002) stresses the local and regional character of the observed Sun-climate links. He notes that the subtropical ridge over Australia has been shifting southward since at least the 1930s so that the geographic distribution and magnitude of sunspot effects on temperate Australian climates may have changed over time. This may explain why for Melbourne winter rainfall peaks correlate to sunspot peaks prior to 1915 but with sunspot minima after 1960 and why a correlation is absent from 1915–1960 (Thresher, 2002). The example nicely illustrates how correlations between solar forcing and climate can move geographically so that at a certain (proxy) location the correlation can disappear or shift to a different phase relation temporarily (Figure 3.4), a phenomenon already discussed in the early 20th century (Helland-Hansen and Nansen, 1920). Evidence for solar forcing of New Zealand temperatures seems to arise when the tree ring based reconstruction of Palmer *et al.* (Palmer and Xiong, 2004) is compared visually with the reconstructed sunspot numbers (Usoskin *et al.*, 2004b) (Figure 3.13). Finally, in South America, cooler/wetter conditions in Tierra del Fuego, closely match with minima in solar activity (Mauquoy *et al.*, 2004a).

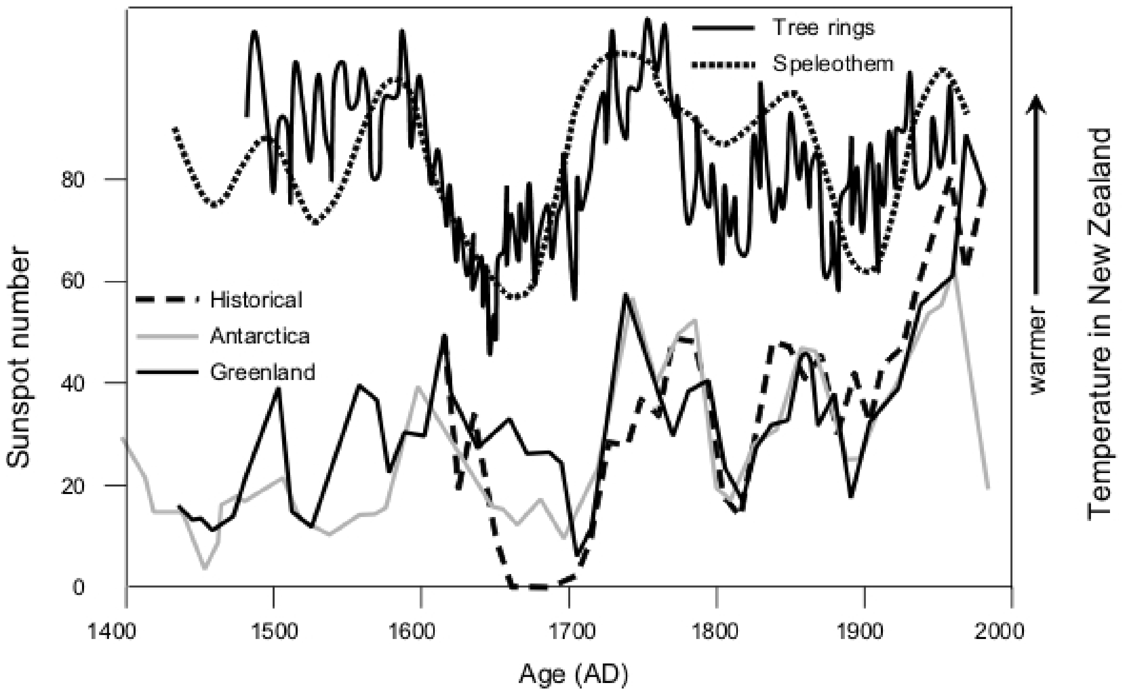

Figure 3.13: New Zealand temperatures, derived from tree rings (Libocedrus bidwillii) and speleothems (after Palmer and Xiong, 2004) compared to directly measured and reconstructed 11-year averaged sunspot numbers (after Usoskin et al., 2004b).

Central North America. Studies of instrumental temperature records show that on the North American continent, the region in the middle of the USA, including the Great Lakes shows significant decadal temperature variability which anti correlates with temperatures along the North American west coast. Times of high sunspot numbers, relative to times of low sunspot numbers, correspond to statistically significant cooling in eastern and central North America, by as much as 0.5°C. The quasi-11-years temperature cycles in this central region are in constant phase with solar activity from 1895 to 1935 but the coherence is gone by 1955. The decadal signal can be said to be in phase with the solar cycle when the former is strongest, though (Thejll, 2001). Thejll further notes that the *cooling* in North America during high sunspot numbers is striking and unique globally and reports statistically significant *warming* only off the west coast of the United States, near the Black Sea, easternmost Europe, eastern Manchuria and, particularly, in the mid- Atlantic off the West African coast. The study clearly demonstrates the importance of regional assessment of Sun-climate relationships. Cloud cover over the United States also shows a strong decadal variability but the spatial pattern is different from that of temperature. Cloud cover is increased during solar maxima for most of the region except for the Great Lakes region and the Southwest where this relation is opposite (Udelhofen and Cess, 2001). A better understanding of the Sun-climate relations in this region might be obtained by investigating why the spatial patterns of decadal variability in temperature and cloud cover are so different. On longer time scales, solar variability is considered to be responsible for the persistent decadal (10, 22, 40 and 90 years) and multicentennial periodicities in the greyness of varves in Elk Lake (NW Minnesota) (Dean *et al.*, 2002). Furthermore, on longer decadal and centennial time scales, July temperatures in Idaho (Biondi *et al.*, 1999) and humidity in Dakota (Yu and Ito, 1999) seem to increase with increasing solar activity.

Europe and Adjacent North Atlantic. A possible relation between solar activity minima and climate has been most intensely studied (and thus is most easily illustrated) for the N. Atlantic and adjacent European continent. Muscheler *et al.* (2000) attribute the largest part of the changes in the atmospheric ^{14}C concentration during the Younger Dryas event to variations in production rate. Changes in ocean circulation apparently play a subordinate role. Van der Plicht *et al.* (2004) attribute the climatic deterioration at 11250 BP (which follows the Preboreal climate reversal) to solar forcing. This relation is also observed by Magny (2004) who relates high lake levels in Eastern France and Switzerland to climatic deteriorations for the entire Holocene (Figure 3.10). The wetter phases coincide also with phases of increased ice rafted debris in the North Atlantic (Bond *et al.*, 2001) and occur at the beginning and during periods of increased ^{10}Be and ^{14}C production rates (Figure 3.14).

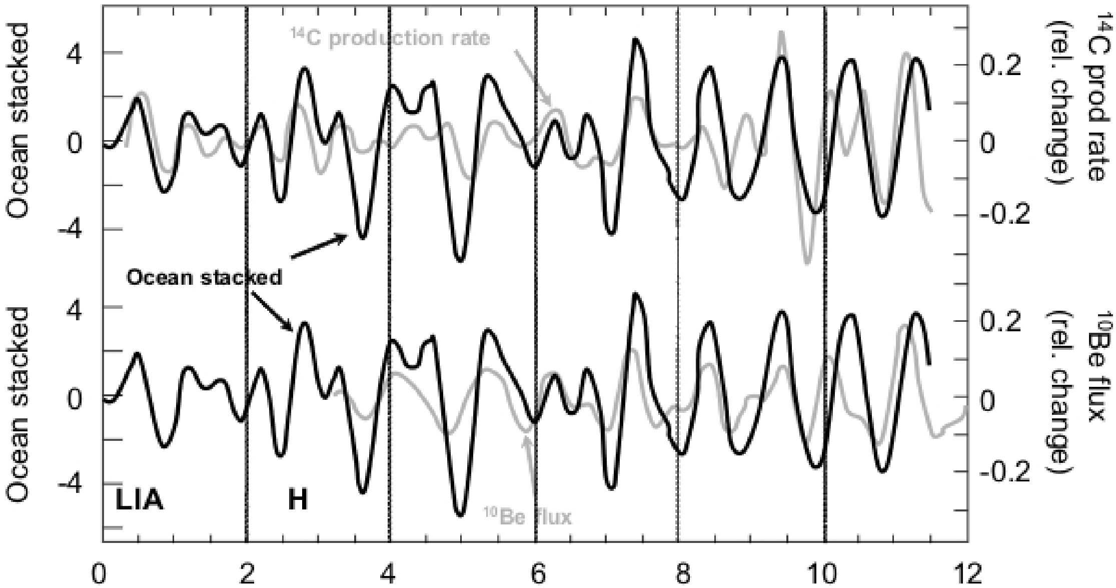

Figure 3.14: Changes in North Atlantic drift ice (derived from ice rafted debris concentrations in sediments, blue line) with ^{10}Be and ^{14}C (red). The cosmogenic isotope records are Band-pass filtered {$(1800\ yr)^{-1} = \tau = (500\ yr)^{-1}$}. The average cycle-length in drift ice ('Bond cycles') is 1340 years. LIA: Little Ice Age, H = Homeric minimum (Muscheler et al., 2003). Note that the drift ice proxies have been tuned to the $\delta^{14}C$ record by Bond et al. (2001).

Nine of these quasiperiodic cycles have been identified for the last 12,000 years (average cycle ~1500 years). The last drift ice cycle is broadly correlated with the MWP, LIA climate anomalies of the last millennium on one hand and the Maunder minimum on the other (Bond *et al.*, 2001). The cyclicity extends back into the last glaciation and has also been identified for the penultimate climate optimum (MIS 5e, ~Eemian). During the periods with cooler, ice-bearing North Atlantic surface waters, a reduction in NADW is inferred as is a reduced monsoon activity at lower latitudes. The cycles also occur in the carbonate content and thermoluminescence of the Mediterranean Gallipoli carbonate platform sediments (Cini Castagnoli *et al.*, 1998b) and North American pollen records (Viau *et al.*, 2002). Recently it has been suggested that the ~1500 years cycles derive from heterodynes of centennial-band solar cycles (Clemens, 2005; Braun *et al*., 2005). An unresolved question during the early Holocene is the extent to which meltwater pulses into the North Atlantic relate to changes in solar activity. Associated changes in ocean deep water circulation could induce changes in the atmosphere at high latitudes and through this route influence both the ^{10}Be and the ^{14}C records. These effects on the ^{10}Be record are supposed to in the order of a few percent (Table I). For the mid-Holocene nine out of eleven $\Delta^{14}C$ rises appear coeval with wet shifts in raised bogs in The Netherlands (Blaauw *et al.*, 2004). Finally, evidence from raised bogs in the UK and Denmark shows that climatic deteriorations (cooler and wetter conditions) occur in relation to the Homeric, Wolf, Spörer, Maunder and Dalton anomalies in the ^{14}C record (Mauquoy *et al.*, 2004b). In the Mediterranean a series of publications carefully documented influences of solar activity in marine proxy records ($CaCO_3$ contents and thermoluminescence of sediments, $\delta^{13}C$ and $\delta^{18}O$ of planktic foraminifera shells) in the Ionian and Tyrrhenian Seas. Strong 11, 22, 206 (Figure 3.15) and 1350 years cycles are observed in the proxy records. These cycles are, however, not or only reluctantly related to specific environmental processes (e.g. Cini Castagnoli *et al.*, 1999, 2002). In the Northern Adriatic, solar activity has been suggested to influence the possible occurrence of algal blooms through its influence on air pressure differences which in turn influence circulation in the Adriatic Sea (Ferraro and Mazzarella, 1998).

The NAO/AO. Although on short time scales the winter climates of Europe and the Middle East seem to be dominated by the NAO, these climates show clear evidence of solar forcing on longer time scales (e.g. Magny, 2004; Prasad *et al.*, 2004; Mauquoy *et al.*, 2004b). The inferred solar-induced changes in precipitation and temperature are of the same kind as the changes between different modes of the NAO/AO, and for that reason a link between the AO and solar forcing could be expected. Nevertheless, simple linear relations between NAO/AO and solar forcing (e.g. in the frequency domain) have not been evidenced. There is, however, a growing body of literature on non-linear forcing of the NAO/AO whereby forcing possibly foremost takes place during maxima in solar activity whereas during minima no relation seems to be present (Kodera, 2002; Boberg and Lundstedt, 2002; Ogi *et al.*, 2003; Gimeno *et al.*, 2003; Bochnícek and Hejda, 2005; Kodera and Kuroda, 2005).

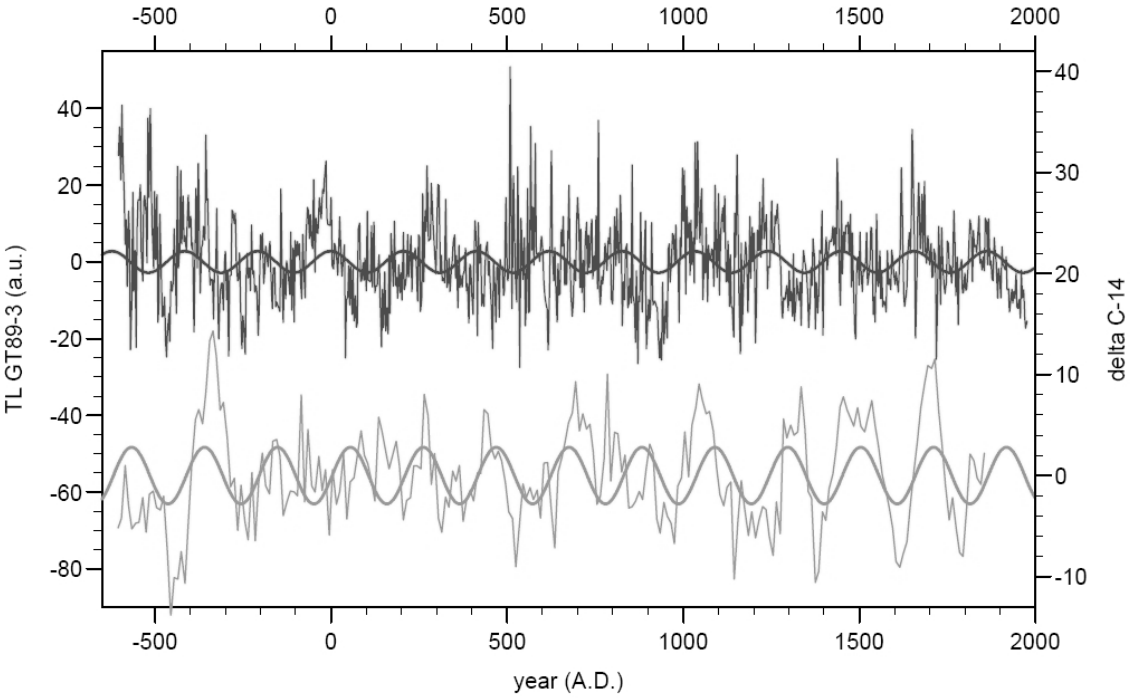

Figure 3.15: (A) Thermoluminescence of core GT89-3, detrended by singular spectrum analysis (PCs 1–2). (B) $\Delta^{14}C$ decadal tree ring record. Superposed to the data are 207 years Suess waves, estimated by the method of superposition of epochs (Cini Castagnoli et al., 1998a).

Furthermore, Maunder minimum global climate is reported to change only 0.3–0.4°C but locally, over the Northern Hemisphere continents changes are much larger, especially in winter (1–2°C). This is attributed to a shift to a low AO/NAO state as solar irradiance decreases. (Shindell *et al.*, 2001). Interestingly, among other influences, regional solar forcing during the early eighteenth century has been considered as one of the factors responsible for the differences between NAO reconstructions (Timm *et al.*, 2004). Very recently, it has been suggested that long term solar forcing affects climate predominantly through the AO and involves both the stratosphere and troposphere. This lends additional credence to the mechanism whereby solar forcing influences climate via UV irradiance changes in the stratosphere (Ruzmaikin *et al.*, 2004) although other forcing mechanisms may be at work as well (e.g. Arnold, 2002; Haigh, 2003). Irrespective of a link between solar variability and the AO/NAO a thorough assessment of the residual European climate variability after subtracting the AO/NAO effects would be useful. Such as study may also resolve alternative pathways through which solar variability may force North Atlantic and European climates.

3.5.2.3 High Latitudes

Greenland. On Greenland, the main sources of high resolution and long proxy records are the ice cores taken from the permanent ice cap. The records are of two kinds, (1) proxy records of solar variability, discussed above (2) proxy records of environmental change. These latter include, $\delta^{18}O$, dust, CO_2, CH_4 and others. For the pre-Holocene dust record from the GISP2 ice core, 11, 22, 90 and 200 years cycles have been evidenced. They are proposed to reflect aridity variations in the dust source regions induced by solar variability (Ram *et al.*, 1997; Ram and Stolz, 1999). For the period AD 1752–1988, a correlation between dust in ice and the sunspot number appears weak which is attributed to low dust concentrations in ice (compared to the pre-Holocene) and as a result a relatively high overprint of dust originating from explosive volcanism (Donarummo *et al.*, 2004). The $\delta^{18}O$ record of the GISP2 core contains among other frequencies a strong and large 11 years cycle (analysed from AD 818–1985) which is in phase with the insolation changes but leads the ^{14}C and ^{10}Be records from the same core by 4 years (Stuiver *et al.*, 1995).

The Boreal Realm. Analysis of high latitude Eurasian records shows 90, 30–35, 22–23, 18 and 11–12 years climatic variability which is attributed to reflect solar quasi-periodicity and its combinatory frequencies (Ogurtsov *et al.*, 2003; Raspopov *et al.*, 2004), longer cycles have been reported from the Arctic, e.g. Alaska (Hu *et al.*, 2003). The driving mechanism behind the 10 years cycles of snowshoe hares abundance in the North American boreal forests forms a matter of debate since the beginning of the 20th century (e.g. Elton, 1924; Krebs *et al.*, 2001) and forms an excellent example of the problems involved in assigning environmental changes to their causes. Originally, and repeatedly since, the cycles have been advocated to result from solar forcing, despite a lacking forcing mechanism. On the other hand the cycles have been suggested to be one of the few examples in nature of Lotka-Volterra predator prey equations (Blasius *et al.*, 1999). Hereby the cycles originate from the intrinsically chaotic interaction between the densities of prey (hare) and predator (lynx). It appears that the phase difference between population changes and solar activity is constant only during periods of high amplitude sunspot cycles. It has been hypothesised that the high amplitude solar cycles force the phase of the naturally occurring cyclic variability of the forest ecosystem to that of the solar cycles, probably through solar modulation of the boreal climate (Sinclair *et al.*, 1993; Sinclair and Gosline, 1997). In a recent paper, Kvana *et al.* (2004) add new and independent evidence for this hypothesis (i.e. for the 11 and 22 years cycles). They reconstruct porcupine abundance since 1868 from feeding scars on trees and propose that solar activity influences the animal populations through modulation of (possibly winter) climate. A clear link is present at the level of individual (Spörer and Maunder-type) minima in solar activity and climate throughout the Holocene. In the North Atlantic the solar minima are associated with southward advances of sea-ice whereas in W. Europe climate turns cool and wet. It must be noted that there is no one to one link; climatic events occur without corresponding solar forcing and vice versa, some minima in solar activity do not seem to have a corresponding climatic anomaly.

Antarctic. The Antarctic ice core records have much lower sedimentation rates than other ice cores. As a result, the maximum temporal resolution is lower but the record lengths are larger. Most focus has been on the glacial-interglacial variability with century and larger scale resolution. This does not mean that high resolution environmental records are absent, but, studies on the relation between solar variability and Antarctic environmental change seem almost absent. The Antarctic sea ice decline since 1950 shows an 11 years periodicity but the series is too short to relate this cyclicity to solar forcing (Curran *et al.*, 2003). Sodium winter concentrations in the Law Dome ice core from east Antarctica are strongly correlated with the mid latitude sea level pressure field. Concentrations since 1300 show 99% significant biannual and triannual cycles as well as a very strong 10.5 years cycle. The shorter periods could be attributable to ENSO variability, the 10.5 years cycle could relate to solar forcing (Goodwin *et al.*, 2004). Offshore, a magnetic susceptibility record from Palmer Deep sediment cores displays unusually strong periodicity in the 400, 200 and 50–70 years frequency bands for the last 9000 years (the interval 0–3750 has a 85 years cycle) (Domack *et al.*, 2001). It has recently been suggested that the intensity of solar UV radiation may influence the collapse of the winter circumpolar vortex. This vortex prevents that the mid-latitude ozone-rich air fills the central

Antarctic ozone hole (Troshichev and Gabis, 2005). It should be investigated to what extent these stratosphere processes (e.g. timing of the vortex collapse) may influence the troposphere and as such may be responsible for the proposed solar forcing of high southern latitude climate.

3.6 Sun-Climate Coupling

A series of mechanisms has been proposed to explain how solar variability induced climate variability (e.g. White *et al.*, 1997; Baldwin and Dunkerton, 2005). All these mechanisms are predominantly verified on the basis of instrumental records. The shortness of such records implies that in practice only the effects of the decadal solar cycle (~11 years) are taken into account, the longer solar quasicycles can not be captured and for those we primarily rely on the records of cosmogenic radionuclides. The present paper deals with proxy evidence for Sun - climate coupling. Unfortunately, there are no proxies in sediments for the atmospheric configuration, e.g. coupling between stratosphere and troposphere or cloudiness. Therefore, a thorough discussion of the mechanisms of Sun - climate coupling in the atmosphere is beyond the scope of this paper. The contributions to be expected from proxy records, as attempted here, are statements on the temporal and spatial behaviour of climate; the result of the Sun - climate coupling. The observed patterns of climate change represent what actually happened with climate over longer time-intervals, and as such provide the low frequency boundary conditions for the proposed mechanisms of Sun-climate coupling.

3.7 Future Climate Change

Reliable predictions of climate change or at least its forcing mechanisms would be very useful for planning our future societies. The character of the forcing mechanisms (cyclic, chaotic, linear) and the relation between forcing mechanisms and climate change, strongly determine to what extent prediction indeed is possible. Solar forcing is just one of these mechanisms and one could try to predict the course of climate on the basis of this variable alone. For instance, Loehle (2004) uses the 1500, 512 and the 88 years Gleissberg cycles on Sargasso and S. African 3 kyrs records to predict natural climatic forcing and estimates for the next 200 years a cooling of −0.2 to −1.4°C. Such calculations ignore that solar variability is quasicyclic and thus intrinsically unpredictable. With respect to other forcing factors, there is increasing evidence that for the last decades, humanity emerged as an important climate forcing factor (e.g. via modification of the composition of the atmosphere and vegetation cover). The human forcing is rapidly changing and we may expect climate to lag behind significantly. More importantly, human climate forcing is also unprecedented, there is no past analogue. This severely complicates extrapolation of proxy records into the future.

3.8 Conclusions

Proxy records provide ample evidence for climate change during the relatively stable and warm Holocene. The contribution of solar forcing to these changes is highly debated and reinforced by the present-day combination of global warming and an exceptionally active Sun. The problem is not so much if solar activity and climate changed but how the changes have to be interpreted. Interpretation is hampered by difficulties in (1) translating the proxy records into quantitative climate parameters (2) obtaining an accurate age assessment (3) elucidating spatial patterns and relationships (4) separating solar forcing from other forcing mechanisms (5) the lack of physical understanding of the solar forcing mechanisms. For these reasons, assessment of past solar influence on climate often is limited to the identification correlations between environmental change and solar variability only. Central questions are thus: Where, how and when did climate change, how did solar activity change, and, how does climate relate to what extent and what kind of solar variability? At present, the changing concentrations of cosmogenic radionuclides in sediments are considered to be the most reliable proxies for solar variability for the pre-instrumental record. There is still room for improvement, e.g. the timing and amplitude of rapid geomagnetic fluctuations and their influence on the cosmogenic radionuclide production (and thus reconstructed solar variability), still has been hardly investigated. All frequency components attributed to solar variability re-occur in proxy records of environmental change. The noisy character and often insufficient temporal resolution of proxy records often exclude the detection of high frequency decadal and bi-decadal cycles. However, on multi-decadal and longer time scales, notably the ~90 years Gleissberg and ~200 years Suess cycles in the ^{10}Be and ^{14}C proxy records of solar activity are also well presented in the environmental proxy records. Additionally, the ~1500 years Bond cycle which occurs in several proxy records could originate from the interference between centennial-band solar cycles. Solar forcing seems to have a particularly strong impact on regional precipitation-evaporation budgets suggesting that it operates via modulating the distribution of latent heat. The oceans may play an important but still obscure role. Proxy evidence for Sun-climate relations is unequally distributed over the globe, Africa, South America and the marine realm are clearly underrepresented, which is probably more due to a lack of information than a lack of response to solar forcing. At low latitudes, equatorward movement of the ITCZ (upward component of the Hadley cell) occurs upon a decrease in solar activity. It explains humidity changes for (1) Mesoamerica and adjacent North and South American regions and (2) East Africa and the Indian and Chinese Monsoon systems. At middle latitudes the equatorward movement of the zonal circulation during solar minima is probably involved in inducing wet and cool episodes in Western Europe, and Terra del Fuego as well humidity changes in Southern Africa, Australia, New Zealand and the Mediterranean. The Polar Regions seem to expand during solar minima which, at least for the northern hemisphere is evident in southward extension of the Atlantic ice cover. Such a forcing-induced migration of climate regimes prescribes the strategy for assessing past solar forcing. It implies that a given response to solar forcing migrates geographically. At a given location this inherently induces a non linear response which may be one explanation for the discontinuity in the apparent response to solar forcing at single sites. The discontinuous proxy response as well as phase-shifts complicate the assessment of Sun – climate relations and call for nonlinear analysis of multiple long and high resolution records at regional scale since only a regional network of proxies may be capable to unravel Sun-climate relations appropriately. Although nonlinear responses to solar forcing are still a largely barren field (despite the fact that major global climate configurations (e.g. the ENSO, AO) follow non-linear dynamics) there is increasing evidence for a link between solar forcing and the AO. The strength of the solar forcing relative to other forcing factors is another source of dynamic responses. It may explain why for several regions solar forcing appears only evident during periods of high amplitude solar variability. Solar forcing has “to compete” continuously with other climate forcings induced by e.g. volcanism, ocean circulation patterns, tides, and geomagnetism. Unfortunately the climatic effects of especially the latter two are hitherto largely enigmatic. The signal to noise ration may be improved by stacking similar periods of solar forcing and investigating the response. Few but well dated studies indicate an early, almost instantaneous, climatic deterioration in response to periods with rapidly decreasing solar activity. Since such an early response puts severe limits to the solar forcing mechanisms the reality and extent of this phenomenon should be a key issue in Sun-climate studies. Long-term climate change during the preindustrial seems to have been dominated by solar forcing. The long-term response to solar forcing typically has a regional character and greatly exceeds unforced variability (Shindell *et al.*, 2003). Although marine environments cover roughly 2/3 of the Earth’s surface, the marine environment is severely underrepresented with respect to high resolution records of environmental (including climatic) change. This bias hampers our understanding of the mechanisms inducing climate change both qualitatively and quantitatively.

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4 The solar-terrestrial link from a climate point of view

4.1 Introduction

The major sun-climate relationship is the absorption of solar radiation by the atmosphere and by the earth surface. Moreover, atmospheric flow is largely influenced by the distribution of the absorbed solar radiation as well as of the outgoing infrared radiation in the climate system. Even with a constant level of solar activity climate processes are influenced, if not caused, by solar radiation. Clear examples are the diurnal and seasonal cycle. On the very long timescale the interaction between the earth's cryosphere and the periodic changes in the earth orbital parameters, modifying the integrated seasonal solar insolation at high latitudes, results in the occurrence of ice ages.

Variations of solar activity may expose the climate system to an additional forcing which induces either climate changes on the global scale or a pattern of responses on the regional scale, depending on the physical mechanism. Besides the direct mechanism of variations in the total solar irradiance changing the radiative balance of the climate system, the search is for indirect mechanisms, which enhance effects of variations in solar activity on climate. Examples are cosmic rays – cloud correlations and UV - ozone - atmospheric circulation changes. Furthermore, direct and indirect forcings can interact with internal climate system variability (e.g., ENSO, QBO and NAO), triggering, amplifying or shifting these modes.

Comparing reconstructions of solar activity parameters and climate records may reveal solar-terrestrial relationships, but in general there is no solid evidence to which extent these correlations are caused by changes in solar activity. The origin of these controversies lies in the fact that possible solar signals are not easily distinguished from other sources of climate variability, such as volcanic forcing, ENSO and long term internal variability. Although correlations between solar activity and climate parameters do not establish cause-effect relationships, they may give indications for underlying mechanisms of climate change due to solar activity.

The impacts of climate factors, such as changes in solar activity, can be further studied with coupled atmosphere-ocean general circulation models (GCMs). These are the state-of-the-art tool for understanding the present climate and estimating the effects of natural as well as anthropogenic climate perturbations. Such comprehensive models include many physical processes and their mutual interactions. The evaluation with observational data is essential in order to gain at least some confidence in the present generation of climate models, although it is difficult or even impossible to get correspondence with the real world in all aspects. At present, the GCM simulations differ in many aspects on the regional scale. Therefore, it is difficult to be conclusive about cause-effect relations.

Section 4.2 provides an introduction on the climate system. Attention is paid to the radiative balance at the top of atmosphere and to how this balance can be perturbed and eventually restored. The link between radiative forcing and subsequent surface temperature changes using the concept of climate sensitivity and possible deviations of this concept are described. In section 4.3 the focus is on the detection of climate change with respect to temperature and atmospheric composition with emphasis on the last centuries including the Little Ice Age. Section 4.4 deals with the approaches and estimates of total solar irradiance (TSI) variations. The basis of TSI reconstructions is described in terms of observed solar parameters - by space borne instruments and extended to the past - and other indicators (proxies) of solar activity. The description of reconstructions of cosmogenic isotopes has been covered by Chapter 3. Section 4.5 is devoted to the physical mechanisms for the solar terrestrial relationship. Here, we describe the mechanism of radiative forcing due to TSI variations, the spectral dependence of these variations and hence the mechanism of influence via the middle atmosphere through changes in ultraviolet (UV) radiation. Furthermore, attention is paid to the mechanism of climate effects due to variation in cosmic ray intensity. In section 4.6, the empirical evidence of the solar terrestrial relationship is considered. This is discussed from a statistical point of view by assessing correlations of solar parameters, proxy records and climate parameters. Using a multiple regression analysis, the observed temperature in the 20th century is attributed to natural and anthropogenic causes. In the last section (4.7) the solar terrestrial link is considered from a modelling point of view. Here, we present results from experiments with General Circulation Models with respect to effects of variations in total solar irradiance and of UV changes, including the stratosphere – troposphere coupling.

4.2 The climate system

4.2.1 General Features

The Earth's climate is the state of a complex system, which consists of the atmosphere, ocean, cryosphere (snow and ice), land surface and the biosphere. It includes many physical, chemical and biological processes acting on a huge variety of timescales as well as of spatial scales. The interactions between the compartments of the climate system give rise to very complex behaviour. The climate system is primarily driven by the energy it receives from the sun. Part of the incoming solar radiation is reflected backwards and lost to space. The remaining part is absorbed within the atmosphere and at the earth surface and is converted into heat which eventually leaves the system as infrared radiation. On the long term and globally averaged the incoming shortwave radiation and outgoing longwave radiation is approximately balanced at the top of the atmosphere

Compared to our neighbour planets, Venus and Mars, the earth's system is unique with respect to hydrological, biological and carbon cycles. The temperature of the earth's surface and atmosphere allows for the coexistence of all water phases. About 70% of our planet is covered by oceans. Evaporation processes from ocean and land surfaces result in a transport of water vapour into the atmosphere. Due to transports of water vapour against a general decrease of temperature with height in our atmosphere, water vapour condensates into tiny water droplets and freezes higher up, thereby forming a large variety of clouds in our atmosphere. Cloud freezing and coagulation processes result in precipitation

Because the angle of solar insolation is dependent on latitude and season, the system is heated more in the tropics than in polar regions. In addition, more solar heating at low latitudes generates more evaporation of water here, which causes diabatic heating of the atmosphere as the water vapour condensates and eventually precipitates. This gives rise to the advection of heat from equator to poles by atmospheric flows and oceanic currents. Temperature contrasts between low and high latitudes are therefore tempered in the Earth's climate system. Hence the outgoing longwave radiation shows less latitudinal dependence than the incoming solar energy.

In the atmosphere the poleward transport of heat and momentum is the primary driver for the general circulation and therefore for weather systems. Although the general circulation shows persistent patterns, dependent on latitude and season, the weather itself is highly chaotic and is therefore unpredictable on time scales of one to three weeks. However, this does not necessarily imply that the long-term weather statistics, defined as climate, are unpredictable. These statistics are predominantly related to the general circulation, and as such driven by the gross energy flows in the climate system.

The climate is far from constant. Many factors of climate change have been reported in the literature. We may distinguish internal variability and external forcing. The former – also referred to as autogenic forcing (see Chapter 3) is caused by interactions between the components of the climate system, each component having typical and different time-scales of response. In a coupled mode these non-linear interactions reveal climate noise, such as temperature, precipitation and circulation variations. Spectra of temperature variations show generally red noise, indicating that fluctuations increase with time-scale. However, such spectra also show resonant peaks, indicating feedback mechanisms on typical time scales. External forcing is caused by changes in one or more climate compartments (endogenic forcing), modifying the energy flows in the climate system, or caused by changes outside the climate system (exogenic forcing), such as changes in the electromagnetic properties or particle emissions of the sun. It is sometimes difficult to separate internal variability and external forcing due to the ever existing feedback loops or mutual interactions between the compartments of the climate system.

The science of climate change tries to find answers on three main issues. The first issue is the detection of climate change from instrumental records as well as from proxy data, such as tree rings, sediments and ice cores. Since 1979 the climate system has been monitored using satellite information, which is in principle radiation measurements in various frequency bands from which relevant climate parameters can be retrieved.

The attribution of observed climate change to potential causes is the second key issue in climate research. Over the past century it concerns the ability to separate the climate effects due to human activities from the response due to natural climate factors and internal variability. By its various activities mankind inadvertently is changing the composition of the earth's atmosphere. The steady increase of a number of trace gases since pre industrial times is warming our planet. This is the so-called enhanced greenhouse effect. Studying the climate changes in the pre-industrial era may give more insight in the influence of the natural forcing mechanisms. However, accurate estimates are hampered due to the lack of instrumental data, the broad ranges of the character and amplitude of the natural forcing factors, that are due to the unknown amplitude of the natural variability as well as to the fact that the climate sensitivity cannot be retrieved from observations with sufficient accuracy. Moreover, climate sensitivity may also change with climate state.

The third issue is projection. Given the insights in the climate system, i.e. knowledge of physical (feedback) mechanisms, and given the observed climate parameters, climate models can be used to compute the future climate. State-of-the-art information on detection, attribution and projection can be found in the Working Group I assessment reports of the Intergovernmental Panel on Climate Change (IPCC). These reports are updated every five or six years.

4.2.2 Global Energy Balance

Atmospheric radiative transfer is one of the most important features in the climate system, because the only interaction with outer space in terms of energy exchange takes place via radiation. The sun is the primary source of energy for the earth's climate system. According to the latest measurements, made by the Solar Radiation and Climate Experiment (SORCE) since 2003, the total solar irradiance at the mean sun-earth distance has a value of 1361 Wm^{-2}, known as the solar constant.

The global energy balance is shown in Figure 4.1. On average, the globe is illuminated effectively by the solar constant times 1/4, being the ratio between the cross section of the earth, perpendicular to the solar insolation, and the earth's total surface. The shortwave radiation, originating from the sun is either absorbed, scattered or reflected in the atmosphere or at the surface of the earth. The ratio between reflected and incident irradiance at the top of the atmosphere, the so-called planetary albedo, has been measured by satellites to be around 0.3. Therefore, the true global and annual mean solar input to the earth-atmosphere system is approximately 240+/-5 Wm^{-2}. Most of the shortwave radiation, 160+/-10 Wm^{-2}, reaches the earth's surface and is absorbed by the oceans and land-masses; observations show that about 80+/-10 Wm^{-2} is absorbed in the atmosphere by ozone, water vapour, clouds and aerosols [Ellingson and Fouquart, 1990; Cess et al., 1995; Pilewskie and Valero, 1995]. There is still some debate on the amount of absorbed shortwave radiation by clouds. This explains largely the uncertainty in this value [Zhang et al., 1997].

The present global and annual mean temperature of the earth's surface is approximately 289 K. Due to the fact that the atmospheric temperature decreases with height, the thermal emission towards the surface, 330+/-10 Wm^{-2}, is larger than that escaping to space, 200+/-10 Wm^{-2}. About 90% of the counterradiation at the earth's surface is caused by greenhouse gases (70% by H2O, 15% by CO2, 5% by other gases), while clouds are responsible for the remaining 10%. Part of the total radiative energy input to the soil is returned to the atmosphere by infrared emission, 395+/-10 Wm^{-2}. This estimate is based on observations of outgoing surface radiation and of surface temperature averaged over the globe and over a long period of time.

The emission of longwave radiation does not fully compensate for the solar flux and infrared counterradiation from the sky into the surface. The deficit of about 95 Wm^{-2} is compensated by transports of latent heat due evaporation of water at the earth's surface and condensation in the atmosphere, and sensible heat. The rate at which the release of heat due to condensation of water vapour in clouds occurs is proportional to the formation rate of precipitation multiplied by the specific heat of condensation. From observations of precipitation, which amounts to a global average of about 1 m per year, it follows that averaged over the globe the latent heat transport equals 80+/-5 Wm^{-2} [Peixoto and Oort, 1992]. The transfer of sensible heat by molecular conduction and turbulent air motions is estimated to be on average 15+/-7 Wm^{-2} using observations and analysis by weather models [Randall et al., 1992].

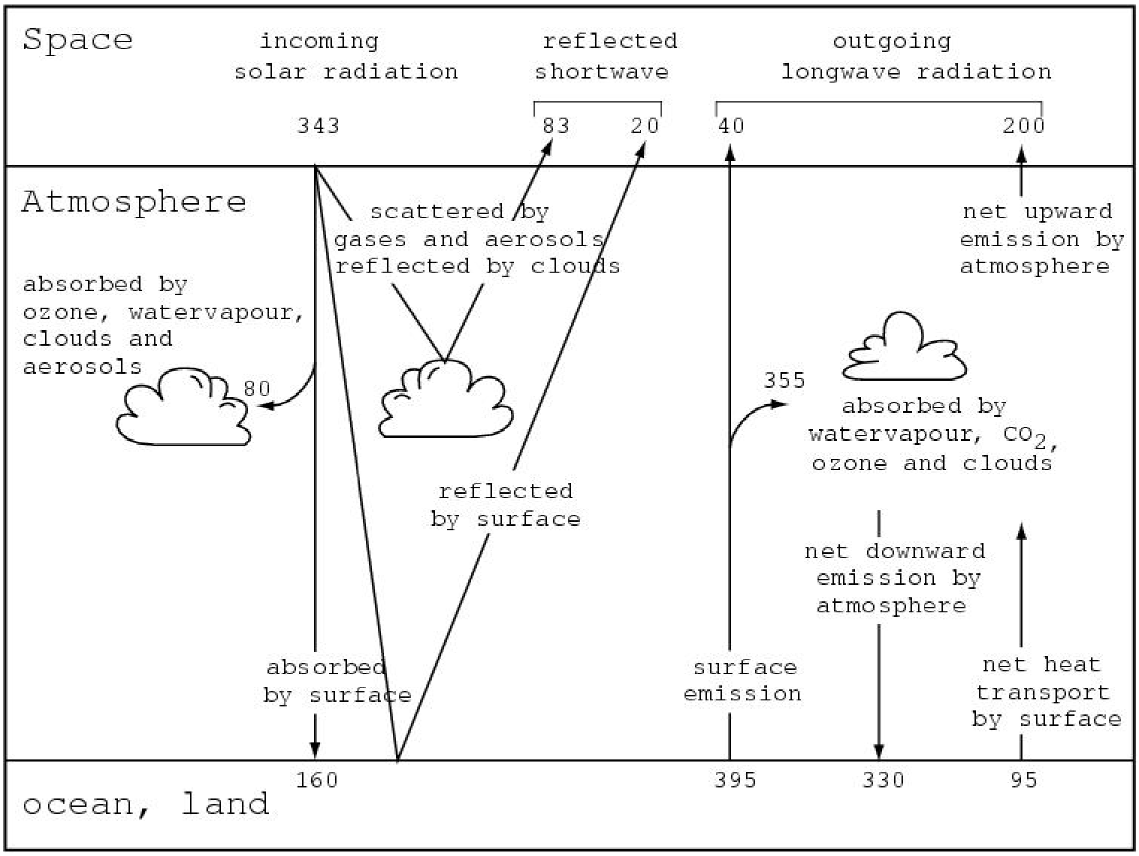

Figure 4.1: Global and annual mean energy balance of the climate system. Units in Wm^{-2}.

About 40+/-15 Wm^{-2} of the longwave radiation, originating from the earth's surface, is directly emitted to space via the most transparent part of the spectrum, the so-called atmospheric window, without being intercepted by the atmosphere, implying an average longwave absorption of 355+/-15 Wm^{-2} by greenhouse gases and clouds [MacCracken and Luther, 1985; Dickinson and Cicerone, 1986; Mitchell, 1989]. From this point of view it is clear that on average the atmosphere is effectively cooled by longwave radiation, which amounts 330+200-355=175 Wm^{2}.

The thermal structure of the atmosphere is determined by shortwave heating, infrared cooling as well as heating, vertical transports of sensible and latent heat and (horizontal) heat transports by dynamical processes. For the globally and annually averaged atmosphere simplifications can be made, because tendency terms due to horizontal heat advection cancel each other out. Since most of the shortwave radiation is absorbed by the earth's surface, while greenhouse gases cause a large inflow of infrared radiative energy into the surface, there is a general decrease of temperature with height in the troposphere, on average the lower 13 km of the atmosphere. In case of a purely radiative equilibrium, this vertical temperature gradient would be much larger than the dry adiabatic lapse rate, while surface temperatures would be substantially higher than observed. Latent and sensible heat flows from the surface and strong vertical mixing in the troposphere compensate for this unstable configuration of radiative equilibrium, causing an average decrease of temperature with height of 6.5 K per km. Therefore, the aforementioned convective heat flows cause a cooling of the surface and a heating of the troposphere. Also, absorption of shortwave radiation by water vapour and ozone warms the troposphere.

The radiative tendencies due to the most important atmospheric gases, active in the shortwave as well as in the longwave region, are shown in Figure 4.2. This figure is constructed by calculating the difference between the tendencies in the present atmosphere and those without the greenhouse gas under consideration, using a radiative transfer scheme. Water vapour generally cools the troposphere, implying that the infrared emission is larger than the absorption. CO_2 warms the lower troposphere up to about 7 km altitude. Also other greenhouse gases show complex longwave behaviour in the troposphere, but are less pronounced than CO_2. It should be noted that there are strong radiative interactions between the various greenhouse gases [Kiehl and Ramanathan, 1983], implying that the background atmosphere influences the specific behaviour of radiative transfer by the gas under consideration.

The thermal structure of the stratosphere is largely determined by the absorption of solar radiation by the ozone layer, causing an increase of temperature with height. This gain of energy is balanced primarily by the strong infrared emission due to CO_2, mainly through its 15 μm band. Globally averaged, the stratosphere is in approximate radiative balance, because convection stops by definition at the tropopause, the interface between the critically unstable troposphere and the stable stratosphere. The thermal structure of the atmosphere is in turn important for the cascade of absorption and emission of infrared radiation by greenhouse gases. Emission is proportional to the Planck function and therefore coupled to the local temperature. Absorption is proportional to the incident radiative flux, which is dependent on the emitted as well as the absorbed radiation upstream of the considered atmospheric level. Moreover, absorption coefficients are temperature and pressure dependent.

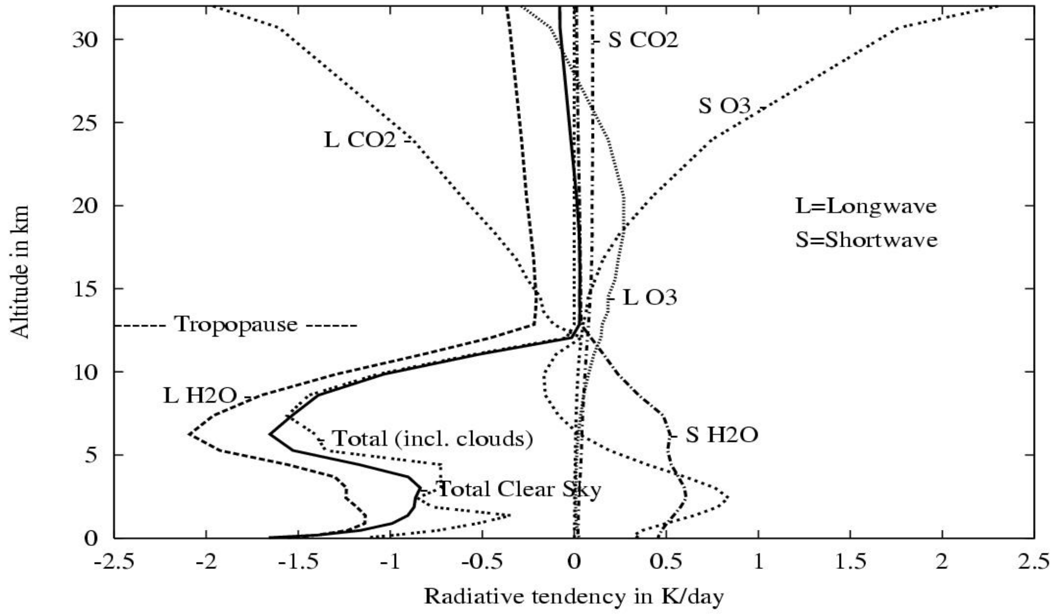

Figure 4.2: Contribution of radiatively active gases to the global mean radiative balance in terms of radiative tendencies in K/day. Also shown is the sum of these contributions in the clear sky part of the global mean atmosphere as well as including average cloudiness [source: Van Dorland, 1999].

4.2.3 Radiative Forcing

On a global scale, perturbations of the radiation balance, either in the longwave or in the shortwave part of the spectrum, result in a climate change, since the energy balance at the top of the atmosphere has to be restored by changing the temperature of the earth's surface and the atmosphere. In reality, perturbations of the radiation balance, e.g. due to steady increases of greenhouse gases or changes in solar radiation, and the subsequent climate response in terms of temperature adjustments, elapse gradually. However, the new climate equilibrium, i.e. the restored balance at the top of atmosphere, is independent of the time evolution of a radiative perturbation under the condition that the climate feedbacks behave linearly. This is at least valid for relatively small perturbations, as compared to the background radiative fluxes. For example, doubling the CO_2 content of the atmosphere results in an imbalance of about 4 Wm^{-2}, which is about 2% of the total outgoing longwave radiation at the top of atmosphere. Therefore, we may couple equilibrium climate change to instantaneous perturbations of the radiation balance. The best link between surface temperature change and radiative perturbations on a global scale is given by the net radiative flux change at the tropopause (on average at 13 km altitude) after allowing the stratospheric temperatures to adjust to a new radiative equilibrium. This net flux change at the tropopause is also known as radiative forcing.

The rationalization behind the concept of radiative forcing is that on global scale the stratosphere is in approximate radiative equilibrium. Radiative adjustment is reached within a few months after applying the perturbation, whereas this adjustment takes of the order of a decade in the troposphere due to the large heat capacity of the oceans. In addition, the surface and troposphere are tightly coupled due to efficient vertical mixing processes with very short timescales and may therefore be considered as one thermodynamic (sub) system. This implies that global mean changes of the radiation at the tropopause roughly determine the final response to climate forcing mechanisms. Note that if the stratosphere reaches a new radiative equilibrium, the imbalance at the tropopause equals that at the top of atmosphere with respect to the sum of the infrared and solar radiation changes.

In general, the radiative forcing is not equally distributed over the globe. Even for the well-mixed greenhouse gases, such as CO_2, the forcing shows a distinct forcing pattern due to dependencies on the temperature lapse rate as well as cloud and water vapour amounts. Although there is a robust link between radiative forcing and subsequent climate response, i.e. in terms of surface air temperature change, on a global scale, the regional forcing response relationship is ambiguous. On one hand, strong regional negative radiative forcing due to tropospheric aerosol increases reduces the solar insolation at the surface and may influence the sensible and latent heat flows such as the attenuation of convective activity. This exhibits in fact a direct climate response. On the other hand, gradients in the radiative forcing may influence the circulation patterns resulting in a climate response which cannot be derived from the amplitude of the forcing in the same way as for the global forcing response relationship [Van Dorland et al., 2001].

4.2.4 Climate Sensitivity and Temperature Response

The response to perturbations of the radiation balance, e.g. in terms of near surface air temperature change, can either be amplified or damped as the result of temperature dependent processes in the climate system. These so-called *climate feedbacks* are dominantly present in the hydrological cycle due to the combination of large amounts of water at our planet and its strong impact on the energy balance for all its phases (ice, liquid water and water vapour). The ensemble of climate feedback's determine the *equilibrium climate sensitivity*, defined as the ratio of the equilibrium global mean surface temperature change to the global mean imposed radiative forcing.

With respect to changes in well-mixed greenhouse gas concentrations the climate sensitivity parameter behaves in near-invariant manner, such that the radiative forcing acts as a good metric for global mean temperature response. However, for many other forcing agents model studies show that the forcing response relationship breaks down as the result of geographical and/or vertical distribution of the forcing due to the way it projects onto the various different (and locally confined) feedback mechanisms [Boer and Yu, 2003]. This drawback has lead to the introduction of the concept of efficacies of different forcing agents [Joshi et al., 2003; Hansen and Nazarenko, 2004]. Efficacy, E, is defined as the ratio of the climate sensitivity parameter for a given forcing agent to the climate sensitivity for a doubling of CO_2 as computed by General Circulation Models (GCM). The efficacy is then used to define an effective forcing $\Delta F_e = E \cdot \Delta F$. However, for the indirect effects of absorbing aerosols, like soot, even the correction with an efficacy does not work due to the strong impact on climate feedbacks, such as cloud lifetime, precipitation and tropospheric lapse rate, while the forcing is nearly zero. For solar forcing due to irradiance changes the efficacy lies between 0.75 and 1, although there are some indications that the efficacy for decadal to centennial scale variations could be higher than 1, implying a larger response per unit of radiative forcing than for greenhouse gases.

For the generation of 3D climate models used in the IPCC Third Assessment Report [IPCC, 2001], this climate sensitivity parameter is ranging from 0.5 to 1.1 K/Wm^{-2} (Figure 4.3, Wigley and Raper curve). This range is mainly the result of uncertainties in the climate feedbacks induced by temperature dependent processes in the climate system. The response to perturbations of the radiation balance can either be amplified or damped as the result of these feedback mechanisms. Most pronounced is the positive water vapour feedback: if the temperature increases, e.g. due to increases of the atmospheric CO_2 level, the air will contain more water vapour. This is based on the observation that in our present climate the relative humidity especially over the oceans is quite constant. Since water vapour is an important greenhouse gas, increases herein result in an amplification of the global warming. The feedbacks related to changes in cloud properties are highly uncertain and are therefore largely responsible for the uncertainties in climate sensitivity [IPCC, 2001].

The equilibrium response due to changes in forcing agents would only be reached after several decades in case the forcing remains constant, hence a strictly academic situation. The determination of the transient response under the condition of ever changing forcing agents includes the role of the oceans. The partition between the heat storage in the oceans and the directly rendered energy into the atmosphere through either longwave radiation or latent and sensible heat flows, is largely dependent on the thermal and salinity structure of the oceans, thereby regulating the heat diffusion as well as the upwelling processes. Since the climate system acts as a low pass filter due to the large heat capacity of these oceans, the partition is also dependent on the period of the climate perturbation. Moreover, it is very difficult to evaluate this partition of heat with observational data. Although the mechanisms of the human influence on the radiation balance are physically well understood, accumulation of uncertainties due to the total anthropogenic radiative forcing, the climate sensitivity and due to the partition of energy, results in broad range of estimates of subsequent global mean temperature changes.

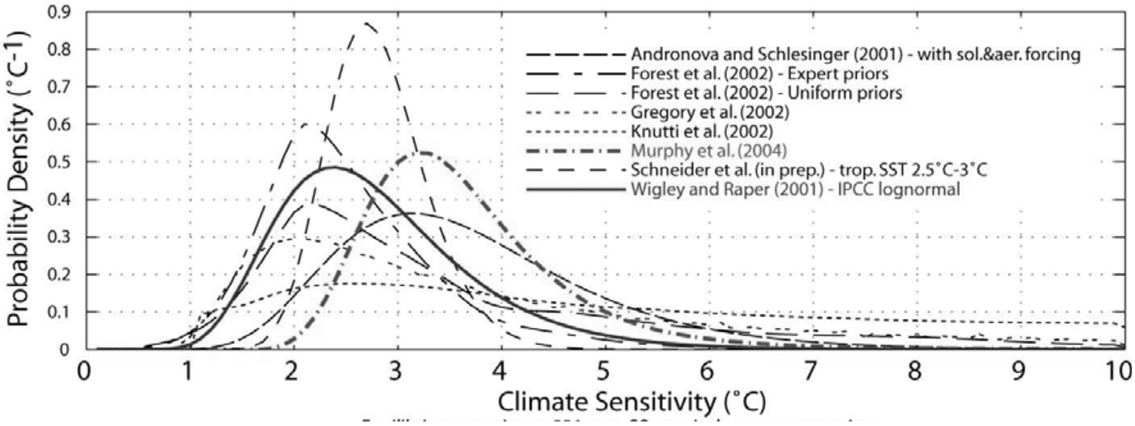

Figure 4.3: Probability density functions of the climate sensitivity as derived from observations and climate models [source: Hare and Meinshausen, 2004].

4.3 Changes in Temperature and Composition of the Atmosphere

4.3.1 Glacials and Interglacials

All through the geological past and human history climate and atmospheric composition have been changing. Changes occur at practically all time scales from years to millions of years. At geological time-scales continental drift is an important (external) factor, as it changes the configuration of oceans, and therefore the heat transports from equator to poles. There are strong indications that the alternation of ice-ages and interglacials is triggered by periodic changes of earth's orbital parameters, namely the precession of the equinoxes, the axial precession and the precession of the ellipse, on timescales of 20,000 to 100,000 years. These are the so-called Milankovitch orbital effects. It is important to note that these result in changes of the total received solar energy during the summer season at high latitude and are not related to changes in solar activity. During the last ice-age, which had its maximum some 18,000 years ago, global average temperature most probably was in the order of 5 K lower than at present (Fig 4.4), while the CO2 concentration of the air amounted to only 60% of the present value [IPCC, 2001].

The strong correlation between temperature and greenhouse gas concentrations (CO_2 and CH_4) is probably the result of climate feedbacks. Increasing (decreasing) temperatures cause less (more) uptake of CO_2 by the oceans leading to higher (lower) concentrations in the atmosphere. Also, increasing temperatures result in the disappearance permafrost leading to the release of large amounts of CH_4. Furthermore, the change in biological activity may induce changes of the concentration of greenhouse gases. The increase of these greenhouse gases result in turn to an enhancement of the greenhouse effect, causing higher temperatures.

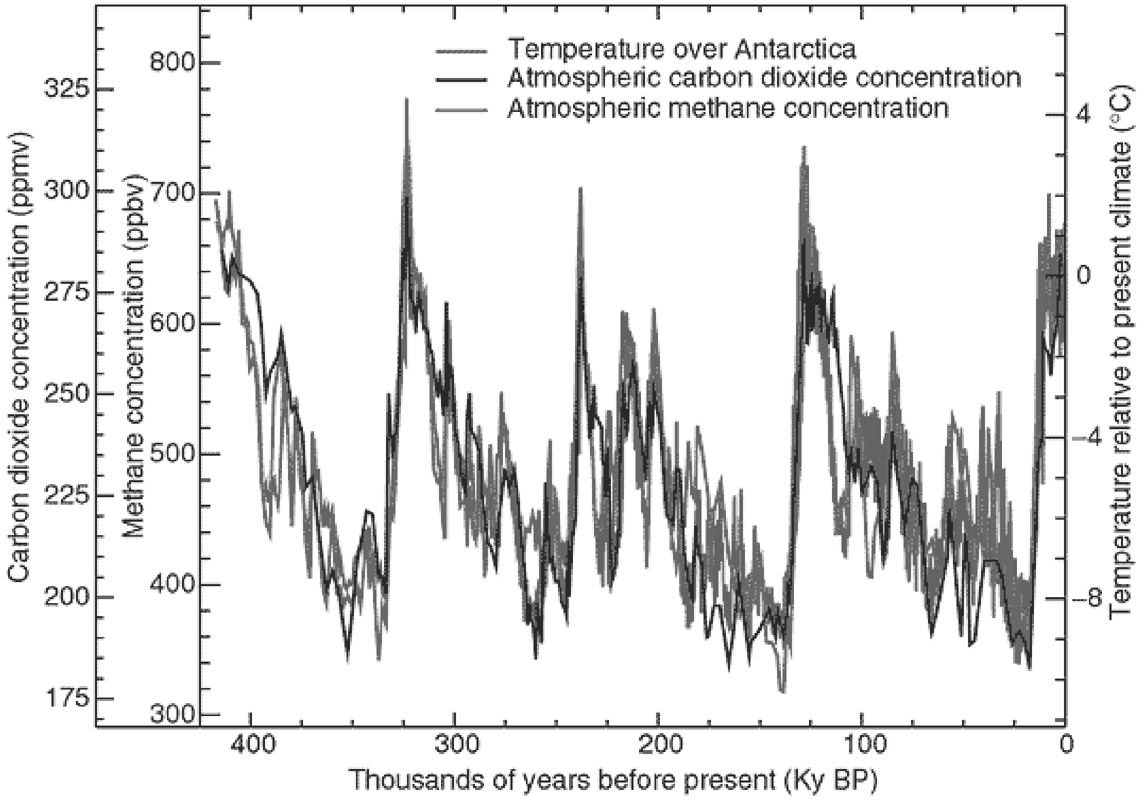

Figure 4.4: Local temperature, CO_2 and CH_4 fluctuations over the past 420,000 years as measured in the ice-core (Vostok) at Antarctica. The appearance of ice-ages (low temperatures) and interglacials (high temperatures) are clearly visible. Greenhouse gas concentrations show similar fluctuations as the result of biogeochemical feedbacks in the climate system [source: IPCC, 2001].

4.3.2 Holocene

After the last ice age global temperatures reached present levels at about 12,000 years before present. Since then variations were numerous but their amplitude has generally been smaller than 2 K on a world average basis, with the exception of some events of fast climate change during and just after the end of the glacial period related to the melt of large ice-volumes and subsequent changes in the ocean circulation.

For the last millennia a variety of proxy data are available to reconstruct northern hemisphere temperatures (section 3.2.3 and Fig.3.5). Although the general features such as the warm medieval period and the little ice age are more or less visible in the reconstructions, there is still debate on the amplitude of the temperature fluctuations on century time scales [Mann et al., 1999; Von Storch, 2004; McIntyre and McKitrick, 2005; Ammann and Wahl, 2005].

The temperature changes at least up to the first half of the 20th century can be attributed to natural climate forcings alone, such as changes in solar activity or in volcanic activity, and to internal climate variability. Apart from changes in solar irradiance, UV radiation changes may alter the ozone content of the stratosphere and concurrent changes in cosmic rays may influence cloudiness. The mechanisms by which changes in solar activity may influence the earth climate will be described in detail in section 4.5.

Major volcanic eruptions create stratospheric dust clouds, mainly sulfate aerosols, which enhance the reflection of solar radiation, and therefore produce negative radiative forcings [Sato et al, 1993; Lacis et al., 1992]. There is fairly solid evidence of volcanic signals in surface temperature records [Mass and Portman, 1989; Robock and Mao, 1995; Crowley and Kim, 1999; Crowley, 2000; Robock, 2000]. The lifetime of volcanic dust clouds is relatively short, approximately 2 years. However series of major volcanic eruptions can produce variability on decadal and centennial time scales due to the thermal inertia of the oceans. Although reconstructions of optical depth can be retrieved from ice core measurements [Sato et al., 1993], there is still a considerable uncertainty due to the conversion from optical depth to radiative forcing, since this is dependent on the size distribution of the aerosol particles.

Internal variability causes temperature fluctuations on numerous time scales as the result of interactions between the ocean, atmosphere, cryosphere and biosphere. Changes in ocean circulation may cause changes in sea ice extent altering the earth planetary albedo. These changes may also trigger anomalous circulation patterns in the atmosphere leading to (long-lasting) changes in regional precipitation, cloud amount and snow cover. In addition the growing season may be affected. On the annual time scale fluctuations of the Dimethylsulfide (DMS) production by phytoplankton can cause changes in the natural aerosol content of the atmosphere. Another manifestation of internal variability is the occurrence of El Niño, a result of the complex interaction between ocean and atmosphere. At an average of once every three to four years the seawater temperature of a large area west of Peru becomes higher. Interaction with the atmosphere causes a global deviation of clouds and precipitation and therefore influences the global temperature (Van Ulden and Van Dorland, 2000).

4.3.3 20th Century

The changes we observe at present in earth's climate show a general tendency for warming, i.e. an increase of the global average near surface air temperature of about 0.4-0.8 K from the beginning of the 20th century up to now (Fig. 4.5) and a retreat of mountain glaciers all over the world [IPCC, 2001; Oerlemans et al., 2005]. Related to this, a sea level rise of 10 to 20 cm over the past century is observed.

Over ages, human communities have had little or no effect on the composition of the global atmosphere. In the last one-and-a-half century the rapid growth of the world's population and the development of technology caused an immense increase of energy use. Most of this energy was and still is produced by burning fossil fuels. The direct consequence has been an increase of the atmospheric CO2 level by about 35% since 1750, the beginning of the industrial era, while the CO2 concentration remained fairly constant at 280 ppmv (parts per million by volume) in the period 1000-1750 (Fig. 4.6). Routine measurements of the concentration of atmospheric CO2, which started in 1958, clearly show an average increase of about 0.4% per year [IPCC, 2001]. The CO2 concentration has reached a level of 379 ppmv in 2004. Isotopic analysis proves that this increase is largely due to human activity. Anthropogenic emissions of CO2 are partly absorbed by the oceans (35-40%) and the biosphere (5-10%). The remanent fraction of CO2 in the atmosphere, at present 50-60%, is dependent on temperature and biotic content of the oceans as well as on the amount and type of vegetation.

The concentrations of other naturally occurring greenhouse gases, such as CH_4 and N_2O, are increasing rapidly by human activities such as the combustion of fossil fuels, urbanization, agriculture and deforestation. Also the level of purely anthropogenic trace gases, like chlorofluorocarbons (CFCs), has increased. Besides the fact that CFCs are strong greenhouse gases, they chemically destroy the ozone layer in the upper atmosphere. It is due to the latter effect that international agreements have been made on a production stop. Since 1992, increases of CFC-concentrations are slowing down. The radiative forcing due to changes of the aforementioned well-mixed greenhouse gases is known within the relatively small uncertainty limit of about 15%. CO_2 contributes most to this forcing with about 60%.

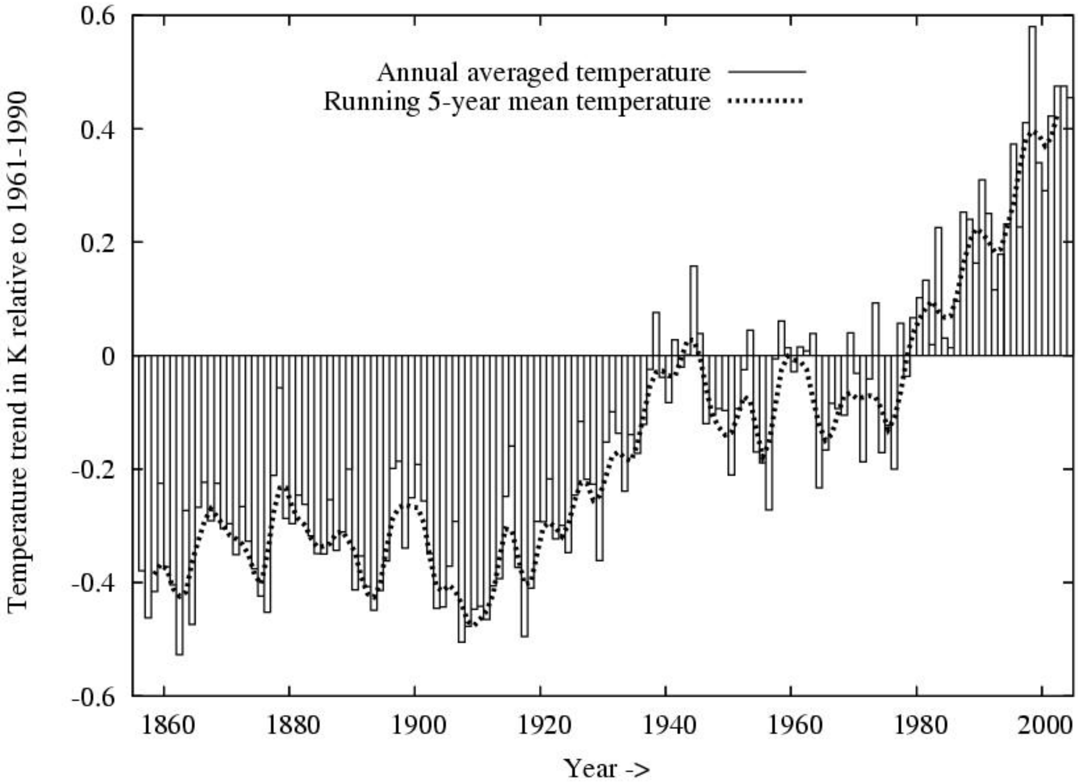

Figure 4.5: Observed global average temperature trend during the instrumental period since 1856 relative to the climatological epoch 1961-1990. Red bars show anomalies of individual years. Blue line is the 5-year running mean.

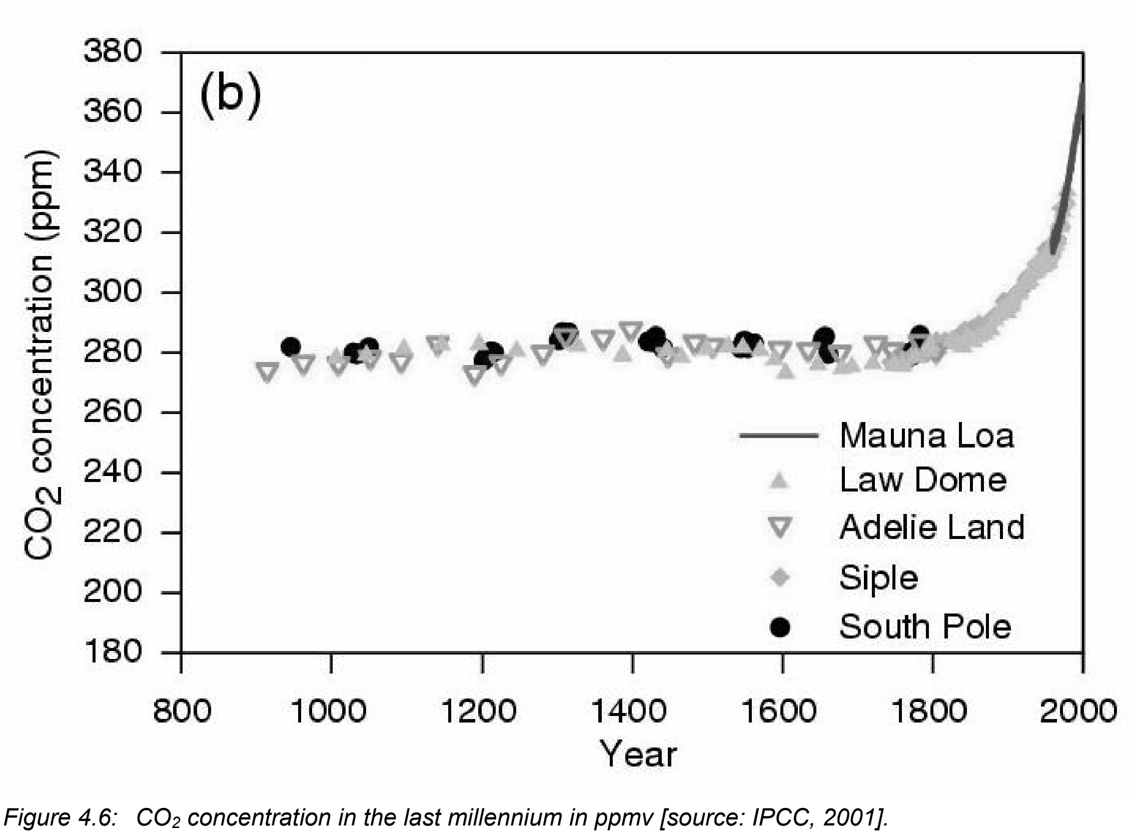

Figure 4.6: CO_2 concentration in the last millennium in ppmv [source: IPCC, 2001].

In addition to these uniformly mixed greenhouse gases, various short-lived radiatively active atmospheric constituents have changed due to industrial activities. Emissions of NO_x and CO, together with the already mentioned greenhouse gas CH_4, lead via a number of complex chemical reactions to the production of tropospheric ozone [Crutzen and Zimmermann, 1991; Lelieveld and Van Dorland, 1995; Roelofs et al., 1997; Van Dorland et al., 1997; Stordal et al., 2003]. In the stratosphere, increases of CFCs cause a depletion of ozone. In the vicinity of the tropopause, aircraft emissions result in ozone increases [Fortuin et al., 1995a]. The radiative effects of tropospheric increases and stratospheric decreases of ozone are quite uncertain due to the fact that patterns of change are highly variable in space and time [Fortuin et al., 1995b; Shine et al., 1995]. Moreover, the radiative forcing is strongly dependent on the altitude at which ozone changes occur (fig. 4.7) [Lacis et al., 1990; Van Dorland and Fortuin, 1994].

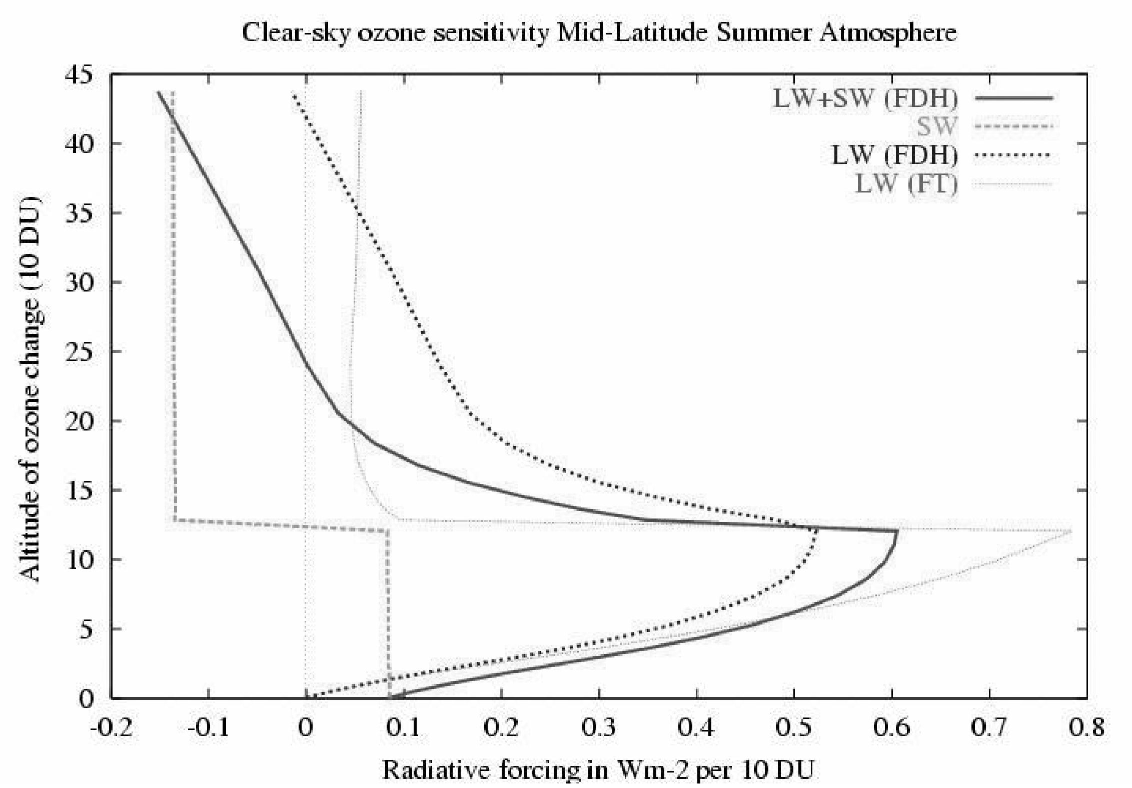

Figure 4.7: Ozone sensitivity curve in a clear-sky mid-latitude summer atmosphere in terms of radiative forcing per 10 DU (Dobson Units)ozone increase at a given altitude. Shown are the total forcing (solid line), the longwave (dotted line) and the shortwave (dashed line) radiative forcing using the fixed dynamical heating (FDH) concept. The thin line represents the longwave forcing using the fixed temperature (FT) concept. The difference between FDH and FT represents the effect of taking into account the stratospheric temperature changes [source: Bregman et al., 2003].

Changes in the tropospheric sulfate aerosol content exhibit even larger uncertainties in the radiative forcing. Anthropogenic sulfur emissions lead to the formation of sulfate aerosols, which act to cool the climate by virtue of their ability to scatter shortwave radiation back to space, known as the direct effect. The estimated radiative forcing due to the indirect effects of sulphate aerosols, i.e. the changes the optical properties and lifetimes of clouds, has a very low confidence level [IPCC, 2001]. Since the eighties emissions of sulphate aerosols have decreased and are projected to decrease further or remain constant in the 21st century. There are many other aerosol components which are increasing due to human activities. Some of them, such as soot, have strong absorption properties causing a positive radiative forcing. In addition, local warming due to absorption of sunlight may cause evaporation of clouds and changes in atmospheric stability, hence changing convection. The net effect of the total change in atmospheric aerosol loading since pre-industrial times is estimated to be a negative forcing. Due to the large uncertainties predominantly in the direct as well as indirect cooling effects of sulfate aerosols, the total global mean radiative forcing of greenhouse gases and aerosols from human activities is poorly known, ranging from practically 0 Wm^{-2} to as much as +3. Wm^{-2} (Fig.4.8). However, a net positive forcing due to the dominancy of greenhouse gas forcing is very likely.

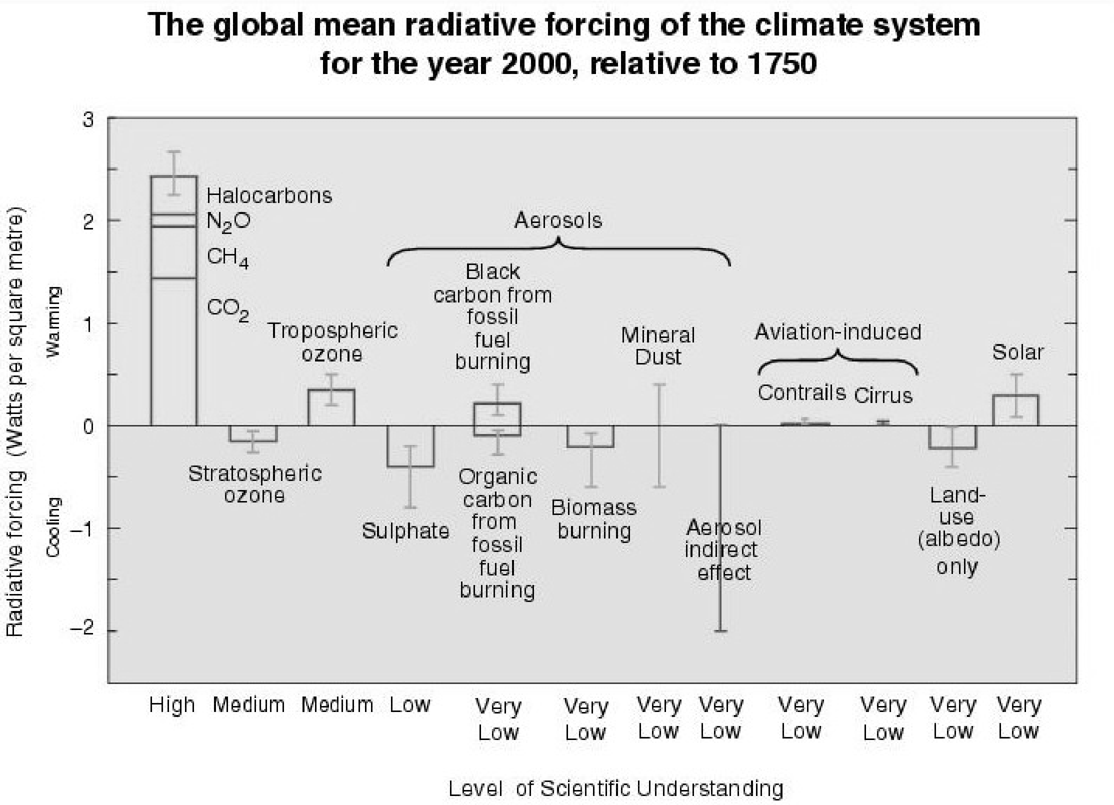

Figure 4.8: Radiative forcing 2000 due to human activities since pre-industrial times (~1750) and due to solar activity [IPCC, 2001].

In the 20th century, climate change is caused by the combination of human influence, natural climate forcing and internal variability. Since large uncertainties exist with respect to the amplitude of the various forcing mechanisms and of internal variability, as well as to the climate sensitivity, it remains very difficult to estimate the individual contributions to the global average temperature changes. However, the different signatures of the evolution of radiative forcing of the various forcing mechanisms may reveal some insight in the cause effect relationships, using linear regression techniques. Such techniques indicate a considerable human influence since 1950 (see section 4.6.2). Main point of debate is whether solar activity has increased in the last 50 years, since this forcing may compete with the human influence. Therefore, estimates of long-term trends of solar activity are of utmost importance.

4.3.4 Regional Climate Change

In contrast with global temperature changes, which are largely associated with changes in the global energy flows, regional temperature changes are affected by atmospheric circulation patterns as well. The changes in these patterns may be caused by changes in ocean temperatures, circulation and sea ice-extent. Therefore, to attribute regional temperature changes to climate factors is much more difficult. In addition, regional temperatures show larger variations than the global average. This means that signals associated with climate factors often disappear in the noise, i.e. results lack statistical significance. On the other hand the fingerprints of climate factors may be much larger on the regional scale than on global scale. In fact, it may happen that climate is changing almost everywhere without a net global average change of e.g. temperature and precipitation. Alternatively, temperature changes may be very unequally distributed over the globe. This implies that regional changes of climate are far less predictable than global average changes.

There are a number of regional climate variations, each having characteristic patterns. These patterns and temporal variations are often referred to as modes and are affected by the rest of the climate system as well as by spatial and temporal radiative forcing patterns. Hence, it is not easy to isolate these patterns in terms of cause. The modes of natural variability include the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), considered as one manifestation of the Arctic Oscillation (AO) and the Northern Annular Mode (NAM), the Southern Annular Mode (SAM), the Quasi-Biennial Oscillation (QBO) in the tropical stratosphere and Pacific Decadal Oscillation (PDO). These modes may interact (in a non-linear way) with each other as for example ENSO and AO and may influence the general circulation, like the Hadley Cell, the Ferrell Cell and the South East Asia Monsoon. New understanding is emerging of the multiple climate and weather fluctuations attributable to these climate variability modes. However, models show a wide range of teleconnections, which are dependent to a large extent on the basic state of the models. Thus different models give different results in amplitude and temporal variations. In section 4.6 and 4.7 we will focus on the influence of changes in solar activity on the internal variability modes as seen in observations and in GCMs, respectively.

4.4 Solar Reconstruction Approaches and Estimates

4.4.1 Direct Measurements of Solar Irradiance

Since 1978, radiometers on board of satellites directly measure the total solar irradiance without interruption, albeit from a variety of different instruments. There have been attempts to provide reference values for the solar constant. Crommelynck et al. [1995] have derived a Space Absolute Radiometer Reference by using simultaneous observations of the TSI from 8 different instruments in April 1993, including shuttle-borne radiometers, with a maximum difference among the sensors of only 0.16%, and found a solar minimum reference value of 1367 Wm^{-2}. Frohlich and Lean [1998] have attempted to merge the available data into a single coherent series by accounting for the inter-satellite differences and the degradation of individual instruments and computed a reference value of 1365.5 Wm^{-2}. Recently, the SORCE (SOlar Radiation and Climate Experiment) instrument, which employs a new approach of phase sensitive detection, measures absolute solar irradiances that are 4 Wm^{-2} lower than the other radiometers. This significant difference exceeds considerably the claimed accuracies of the TSI measurements (±0.01% for SORCE). The SORCE measurement of average total solar irradiance is 1361 Wm^{-2}, rather than the currently adopted 1365.5 Wm^{-2}.

There is ample evidence that solar irradiance is not constant. For the last two-and-a-half solar cycles observations show a periodic variation in TSI, with maxima around 1980, 1990 and 2001 and minima around 1986 and 1996. The difference in TSI between maxima and minima was about 1 Wm^{-2}, which is less then 0.1%. Fröhlich and Lean [1998, 2004] made a composite from various space-born instruments by accounting for inter-satellite differences and the degradation of the individual instruments, in which total irradiance between successive solar minima is constant to better than 0.01%. However, Wilson [1997] suggests that the TSI had increased by about 0.036% per decade based on the comparison of the TSI at solar minima measured by ACRIM I and ACRIM II. Although this upward trend is in agreement with the independently derived values by Crommelynck, the accuracy of current TSI measurements cannot be used to reliably determine trends that may be of climatic significance [Harrison and Shine, 1999]. Furthermore, the irradiance “trend” is not the result of a slow secular increase but of a single episodic increase between 1989 and 1992 that was measured by instruments on board of the Nimbus 7 satellite. Independent, overlapping ERBS observations do not show this increase, nor do they have a significant secular trend [Lee III et al., 1995].

The SIM (Spectral Irradiance Monitor) and SORCE instruments also measure the solar spectral irradiance in the visible and near IR spectrum. Initial results confirm that variations occur at all wavelengths, but with different relations to solar activity. Irradiance changes correlate positively with the solar cycle at most wavelengths from small changes in the IR spectrum and large changes in the UV spectrum (Fig.4.9). The fact that most of the change is in the UV may result in a smaller radiative forcing than on the basis of the TSI change, since most of the UV is absorbed in the stratosphere and does not reach the surface troposphere system. This suggests an efficacy factor (see section 4.2.4) which is less than one.

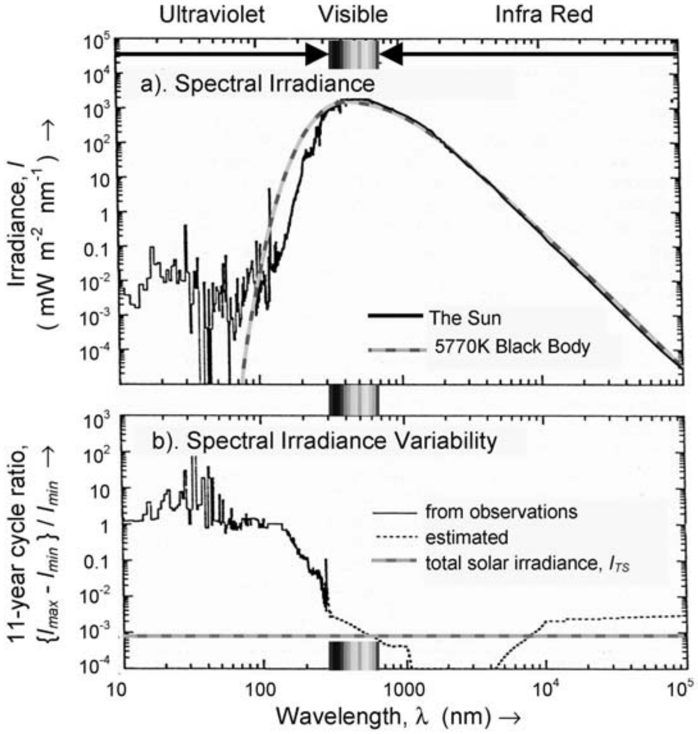

Figure 4.9: Spectral solar irradiance changes in the 11-year solar cycle from observations and estimated from modelling [source: Lean, 1991].

4.4.2 Measurements of Other Indicators of Solar Activity

Other indicators than total solar irradiance have been observed at ground level that go further back than 1978. These include the sunspot number since 1610, solar radio flux at a wavelength of 10.7 cm, dating back to 1947, the aa geomagnetic index, which is an approximate measure of the magnetic field of the sun at the location of the earth, measured since 1869, and the solar diameter since 1683 with some interruptions. Another indicator of the magnetic activity of the sun is the amount of galactic cosmic rays (GCR) bombarding the earth. This flux is greater during solar (sunspot) minima than during maxima due to the shielding effect of the sun's magnetic field. However, GCRs show some differences from the sunspot record, e.g. GCR decreases tend to occur 1 to 2 years after the corresponding sunspot peaks and the magnitude of GCRs does not correspond uniquely to the magnitude of the sunspot maxima. Direct measurements using ground based ionisation chambers go back until 1934.

Apart from these directly measured indicators, some indicators have been derived from the sunspot numbers, such as the solar cycle length and the solar cycle decay rate. Solar cycle length and sunspot number show a large dependency: in general, short cycles have a large amplitude in the sunspot number, while long cycles are characterized by low sunspot numbers. Hence, the smoothed sunspot number and the inverse cycle length can be used as a proxy for long term changes of solar activity (Fig. 4.10). However, it remains unclear how these derived indicators represent changes in total solar irradiance. The period of direct satellite measurements is far too short to draw conclusions with respect to TSI changes in the long-term.

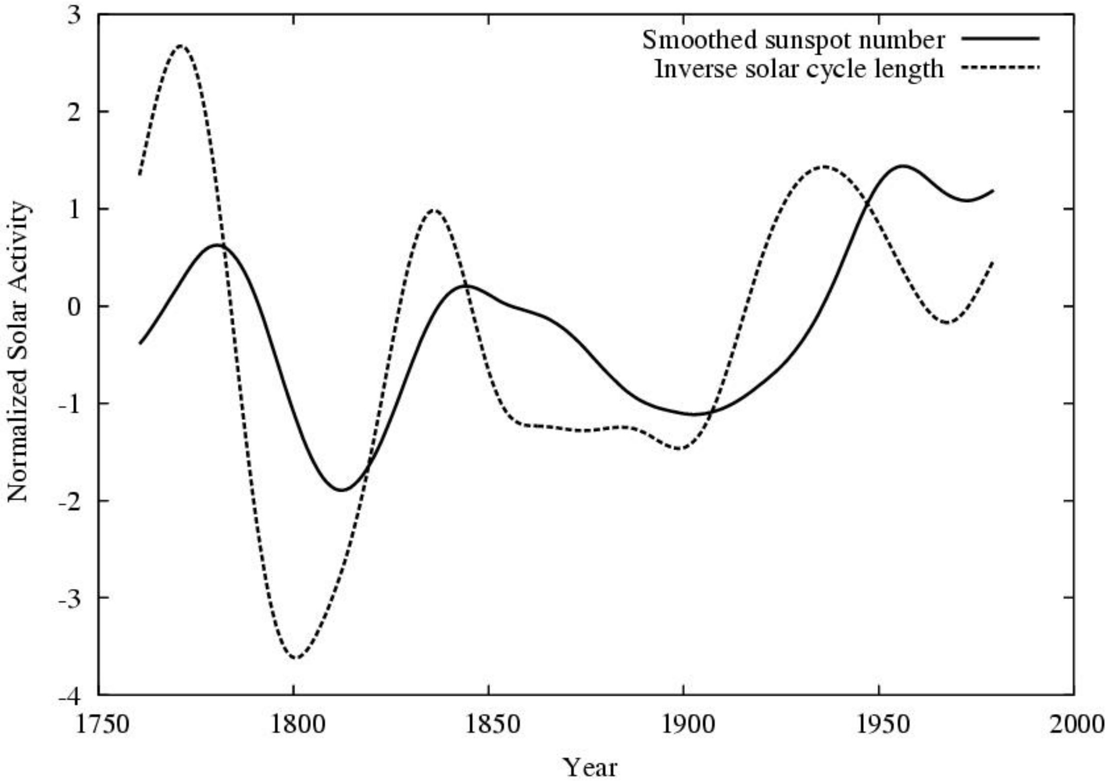

Figure 4.10: Normalized solar activity since 1960. Solid line: smoothed sunspot number; broken line: inverse solar cycle length. Both records have been smoothed with a 30-year lowpass filter and normalized with their standard deviations. The records show both similarities and differences [Source: Van Ulden and Van Dorland, 1999].

The long-term evolution of galactic cosmic rays can be derived from isotope records, such as ^{14}C and ^{10}Be (see Chapter 3). But also for these indicators there are problems with the interpretation in terms of TSI variation. In addition, these isotopes are influenced by more than solar activity alone. For instance, these cosmogenic radionuclides can be influenced by geomagnetic field fluctuations (see Chapter 3). Also, ^{14}C is modified by the (marine) biosphere and thus dependent on variation in ocean circulation. The deposition of ^{10}Be is strongly influenced by atmospheric circulation, hence dependent on the measurement site. Moreover, ^{10}Be show much more similarity with the sunspot number than ^{14}C, which is more or less smoothed, in other words an integrated indicator, and can only be compared with lowpass filtered sunspot reconstructions, albeit with a considerable time-lag (see Fig3.2). Clearly, each proxy is indicating a different aspect of complex changes in the sun. Which proxy or combination of proxies is best for use in the solar terrestrial link, depends strongly on the physical mechanisms involved.

4.4.3 Long-term Reconstructions

As direct measurements of TSI are only available over the past twenty-five years long-term solar irradiance reconstructions are being assessed by using some proxy of changes in solar output, such as sunspot number, in conjunction with recent observations in TSI. The existence of long-term irradiance changes is, in fact, based on three observables: firstly, changes in the aa-index as a measure of the magnetic activity of the sun indicate a much higher activity nowadays than during the Maunder Minimum. Secondly, reconstructions of cosmogenic isotopes (see Chapter 3) point toward cosmic ray fluctuations, which can be attributed to the sun's magnetic activity as well. Thirdly, the range of variability in Sun-like stars [Baliunas and Jastrow, 1990] suggested that the Sun is capable of a broader range of activity than witnessed during recent solar cycles.

In order to derive long term TSI series usually three steps are taken. The first step is to be able to characterize the variability of the solar irradiance in terms of observable proxies, such as sunspots or the length of the solar cycles. The next step is to determine the size of the irradiance variations. Much of the calibration is done by estimating the solar irradiance change during the Maunder Minimum and the present quiet sun. Such an estimate is often achieved by observations of emissions of specific spectral lines of sun-like stars. The final step is to reference the absolute level of solar brightness to recent observations. All these steps lead inevitably to certain choices, which cannot or can only partly be validated. For instance, estimates of the global temperature during the little ice-age are used to estimate the change in TSI, while one should wish to have independent estimates. The biggest hope for validation of these series of TSI is the continued monitoring of the TSI in future, which will indicate which set of proxies most closely predict the actual variation in solar output [Harrison and Shine, 1999].

In the simplest type of reconstruction a single indicator, such as sunspot number [Stevens and North, 1996] or solar diameter [Nesme-Ribes et al., 1993] is calibrated against recent TSI measurements and extrapolated backwards using a linear relationship. It is generally assumed that the periodic changes in TSI can be ascribed to two opposing mechanisms: polar faculae account for most of the periodic increase in TSI, while dark sunspots reduce the TSI. The sunspot darkening depends on the area of the solar disk covered by sunspots, whereas the facular brightening is related to a variety of indices. These include sunspot number [Lean et al., 1995], ultraviolet emission (Ca line at 393.4 nm) [Lean et al., 1992; 1995; 2000], solar cycle length, solar cycle decay rate, solar rotation rate and various empirical combinations of these indicators [Hoyt and Schatten, 1993; Solanki and Fligge, 1998; Fligge and Solanki, 2000].

A very different approach is followed by Lockwood and Stamper [1999], who based their reconstruction on the aa geomagnetic index. These irradiance reconstructions assumed the existence of a long-term variability component such that during the seventeenth century Maunder Minimum total irradiance was reduced from 0.15% to 0.4% (2 to 5 Wm^{-2} or in terms of radiative forcing 0.4 Wm^{-2} to 0.9 Wm^{-2}) below present quiet sun (Fig.4.11). Exception is the curve produced by Reid [1997], showing a radiative forcing of 1.4 Wm^{-2}. However, there is some discussion about the method to obtain this reconstruction: Reid is essentially using the earth's surface temperature as a radiometer, but it is a radiometer with uncertain calibration, it is inadequately sampled over the period of interest, and it has almost certainly been degraded by changes in atmospheric composition that are themselves the subject of significant uncertainties [Harrison and Shine, 1999].

New studies [Lean et al., 2002; Foster, 2004; Foukal et al., 2004; Wang et al., 2005] suggest that long-term irradiance changes are notably less over the past four hundred years than in the previously mentioned reconstructions (Fig 4.11). These studies question each of the three assumptions of changes in aa-index, cosmogenic isotopes and comparison with sun-like stars and points to long-term total solar irradiance variations a factor of about 3 less than those in the previous reconstructions.

A reassessment of the stellar data shows that the current Sun is thought to have "typical" (rather than high) activity relative to other stars. This is based on the comparison of Ca emission in non-cycling stars (assumed to be in Maunder Minimum type states) compared with (higher) emission in cycling stars [Hall and Lockwood, 2004]. Other studies raise the possibility of long-term instrumental drifts in the aa index [Svalgaard, 2004], which would reduce somewhat the long-term trend in the current aa index on which the Lockwood and Stamper [1999] irradiance reconstruction is based. Furthermore, simulations of the transport of magnetic flux on the Sun and propagation of open flux into the heliosphere indicate that long-term trends in the aa index and cosmogenic isotopes (generated by open flux) do not necessarily imply equivalent long-term trends in solar irradiance (which track closed flux) [Lean et al., 2002; Wang et al., 2005].

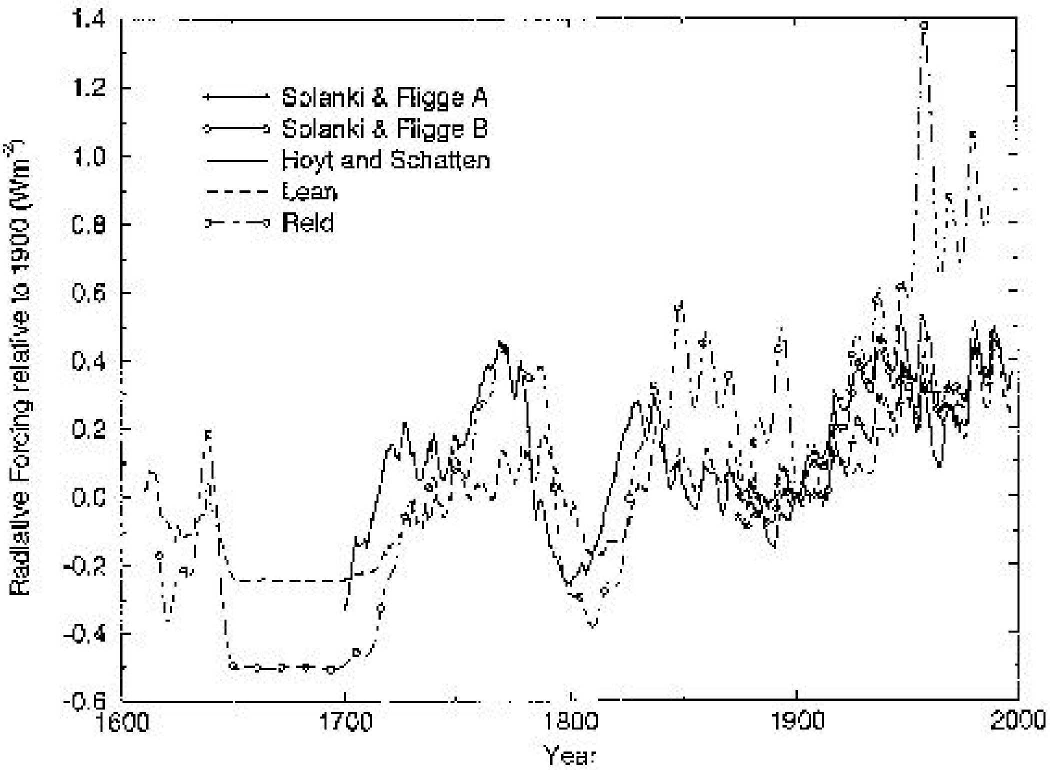

Figure 4.11: Reconstruction of long-term solar activity in terms of radiative forcing (equivalent to changes in TSI, devided by 4 and corrected for the planetary albedo of 0.3) relative to 1900 [Source: Harrison and Shine, 1999].

Usoskin [2004] claimed an unprecedented high but almost constant solar activity in the last 50 years since 11,000 years, based on aa-index (shown in the radionuclide record). However, the sunspot number shows this to a less extent. Bard et al. [2000] investigated the ^{10}Be record from the South Pole and concluded that the period of high solar activity in the last 50 years is not unique during the last 1000 years: during the Medevial Warm Period similar levels of solar activity were found.

The two most recent reconstructions of solar irradiance [Foster, 2004; Wang et al., 2005] have been derived from solar considerations alone, without invoking geomagnetic, cosmogenic or stellar proxies. From the identification of bright faculae in MDI images Foster [2004] estimates that removing this component would reduce solar irradiance by 1.6 Wm^{-2}. This estimate of the irradiance of the "non-magnetic" Sun is consistent with an earlier estimate of Lean et al. [1992], who inferred a reduction of 1.5 Wm^{-2} from a similar analysis of solar Ca K images and fluxes (removal of all network but no alteration of basal cell centre brightness). Both the Foster [2004] and Lean et al. [1992] approaches suggest that if the Maunder Minimum irradiance is equivalent to the "non-magnetic" Sun, then the irradiance reduction from the present is about half that of earlier estimates, which were adopted for the long-term irradiance reconstructions in IPCC [2001].

A quite different approach also suggests that the amplitude of the background component is significantly less than has been assumed, specifically 0.28 times that of Lean [2000]. This estimate is the result of simulations of the eruption, transport and accumulation of magnetic flux during the past 300 years using a flux transport model with variable meridional flow [Wang et al., 2005]. Both open and total flux variations are estimated, arising from the deposition of bipolar magnetic regions (active regions) and smaller-scale ephemeral regions on the Sun's surface, in strengths and numbers proportional to the sunspot number. The open flux compares reasonably well with the geomagnetic and cosmogenic isotopes which gives confidence that the approach is plausible. A small accumulation of total flux (and possibly of ephemeral regions) produces a net increase in facular brightness which, in combination with sunspot blocking, permits the reconstruction of total solar irradiance. The increase from the Maunder Minimum to the present quiet Sun is ~0.5 Wm^{-2}, i.e., about one third of the reduction estimated for the 'non-magnetic" Sun. When the 11-year solar cycle is taken into account as well, the best estimate from Maunder Minimum to the present average Sun is ~1.1 Wm^{-2}.

In terms of current physical understanding, the most likely long-term total irradiance increase from the Maunder Minimum to current cycle minima is 0.5 Wm^{-2}, but it may be as much as 1.6 Wm^{-2}. Including the effects of the 11-year solar cycle (~0.6 Wm^{-2}), the probable radiative forcing between Maunder Minimum and present average sun is therefore 0.19 Wm^{-2}, and in the upper limit 0.39 Wm^{-2}. Converted into a temperature response using the high climate sensitivity of 4.5 degrees for a doubling of CO2 and an efficacy factor of 1, the upper limit of (equilibrium) response would be 0.4 degrees. Like the solar cycle changes, long-term irradiance variations are expected to have significant spectral dependence with most of the relative change occurring in the UV.

4.5 Mechanisms for Solar Climate Forcing

4.5.1 Radiative Forcing due to Total Solar Irradiance Variations

The mechanism of climate effects due to TSI variations has been studied quite substantially in various types of climate model experiments (see section 4.7.1). From these experiments the characteristics of the atmospheric and climatic response of changes in the total solar irradiance (TSI) are relatively well known [Sadourny, 1994; Van Ulden and van Dorland, 2000]. It has been measured that variations in TSI on time scales of the 11-year solar cycle are small (order of magnitude 0.1 %). On the longer time scale TSI variations are estimated to be of the same magnitude or slightly larger, namely between 1.1 Wm^{-2} and 2.2 Wm^{-2}, (see section 4.4.3) in contrast to earlier estimates in the range between 1 and 15 Wm^{-2}, i.e. 0.07% and 1.1%, respectively [Lean et al., 1992; Baliunas and Soon, 1995; Zhang, 1994; Mendoza, 1998]. As a consequence, the radiative forcing since pre-industrial times (1750) due to changes in solar activity is likely to be between 0.1 Wm^{-2} and 0.3 Wm^{-2}. Hence, the "mean" estimate is lower than stated in the IPCC report [2001].

Although the radiative forcing associated with the 11-year solar cycle and the long term changes in TSI are of the same order, the latter will have a larger effect on the global mean temperature change than the changes related to the sunspot cycle due to buffering of the world's oceans. For a cycle with a period of 200 year global mean temperature change is a factor two to four times larger than for an 11-year cycle, depending on climate sensitivity, depth of the ocean mixed layer and the strength of diffusion of heat within the ocean. Besides these attenuation differences, a considerable time lag of response is expected, which is relatively small for the 11-year solar cycle (in the order of two years) and large for the Gleissberg cycle (in the order of six years).

4.5.2 Climate Effects due to Ultra-Violet Variations

The physics behind the influence of UV- radiation on the atmospheric composition and state is well established. It can be directly studied in GCM- experiments, as has been demonstrated by several authors. A convincing approach was followed by Haigh [1996]. Tourpali et al. [2001; 2003; 2005] used a fully interactive 3-D coupled chemistry-general circulation model with a complete seasonal cycle and found that the stratosphere-troposphere system shows a response to a realistic solar cycle enhancement of UV radiation, which compares reasonably well with the features derived from observations. Since the climate effects are relatively small as compared to climate variability, model results are only statistically significant in some regions.

As shown from observations in section 4.4.1 the changes in TSI are concentrated in the UV spectral region, implying an influence mainly in the stratosphere and mesosphere as only a small amount of UV radiation is entering the troposphere. Changes in the UV have the potential to alter the chemical composition of the higher atmosphere due to photolysis. Especially, ozone concentrations are affected by changes in UV.

The changes of stratospheric ozone due to UV variations, being of the order of a few percent, are dependent on latitude, longitude and season. They create a differential heating pattern in the stratosphere due to absorption properties of ozone for solar radiation. Moreover, changes in stratospheric ozone interact with the longwave radiation from the surface, greenhouse gases and clouds by absorbing and emitting radiation. Therefore, a complex pattern of temperature changes occurs modifying in turn geopotential height and wind patterns within the stratosphere.

These changes are likely to induce a chain of dynamical interactions with the troposphere. This includes the stretching of the Hadley circulation mainly affecting the general circulation in the tropics and influencing the monsoon and the position of the Inter Tropical Convergence Zone (ITCZ). Apart from this, momentum and heat transports may be modulated, thereby changing the propagation of planetary waves in the mid-latitudes and hence influencing the tracks of low pressure systems. A second way of interaction with the troposphere is by modulating the reflection and deflection of planetary waves due to changes in the zonal winds in the stratosphere [Holton, 1979]. Also, as the polar vortex is affected by ozone changes in this region, vorticity changes in the troposphere can be expected [Ambaum and Hoskins, 2001]. All these modulations may also interact with climate modes, such as the NAO, AO, NAM, SAM, and PDO. Although progress has been made in this field, the dependency on the model's state hamper unequivocal conclusions of the relative importance of the various dynamical mechanisms.

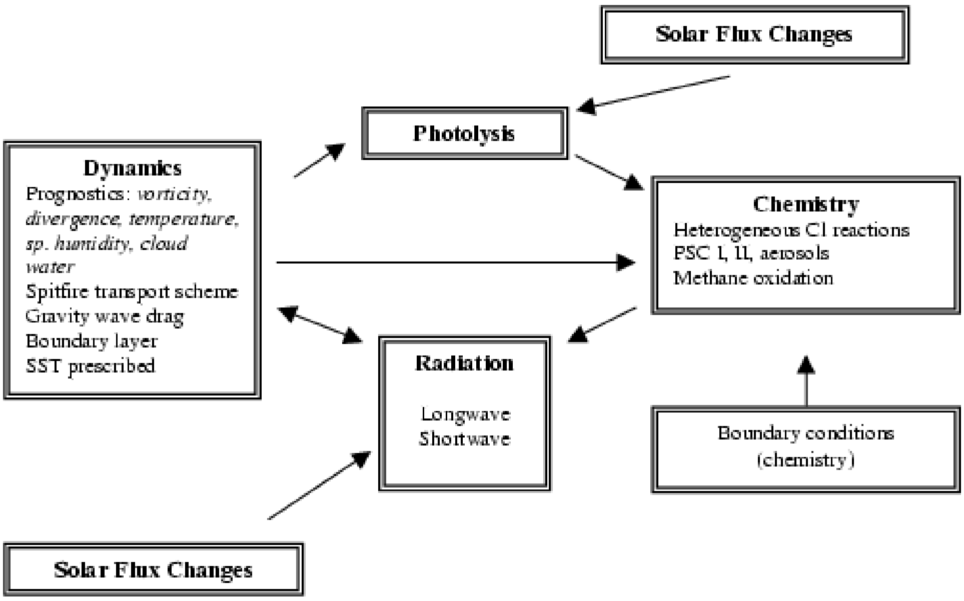

Figure 4.12: Schematic overview of the processes involved in the UV – climate link [source: Tourpali et al., 2001].

4.5.3 Climate Effects due to Cosmic Ray Variations

From an energetic point of view, the approximate 15% modulation of cosmic ray flux by solar activity produces an energy change less than one millionth of the energy change in the 0.1% total solar irradiance cycle. Nevertheless, various scenarios have been proposed whereby galactic cosmic rays might influence climate by altering, for example, the tropospheric electric field and cloud cover. The galactic cosmic rays that reach the troposphere and are supposed to provide nuclei for cloud condensation may amplify the climate response as cloud changes may be translated into an additional radiative forcing. When solar activity is high, the more complex magnetic configuration of the heliosphere reduces the cosmic ray flux.

By altering the population of cloud condensation nuclei and hence microphysical cloud properties (droplet number and concentration) cosmic rays may induce processes analogous to the indirect effect of tropospheric aerosols [Carslaw et al., 2002]. Since the plasma produced by cosmic ray ionization in the troposphere is part of an electric circuit that extends from the Earth's surface to the ionosphere, cosmic rays may also affect thunderstorm electrification [Carslaw et al., 2002]. Noting the altitude dependence of cosmic ray ionization and precursor gas concentrations, Yu [2002] suggests, furthermore, that solar activity also affects high clouds. The response on high cloud changes acts in an opposite way to low cloud changes. Langematz et al. [2005b] investigated the connection between solar particles, cosmic rays and the production of stratospheric ozone via NO_x in the mesosphere. They found a comparable effect on stratospheric ozone chemically induced by UV variations in the 11-year solar cycle.

There are many ambiguities still to be resolved regarding cloud cover variations and solar activity. These concern the reality of the decadal signal itself, the phasing or anti-phasing with solar activity (Fig. 4.16), and its separate dependence for low, mid and high clouds as well as alternative explanations such as ENSO. However, the presence of ions, such as produced by cosmic rays, is recognized as influencing several microphysical mechanisms [Harrison and Carslaw, 2003]. Aerosols nucleate preferentially on atmospheric cluster ions. In case of low gas-phase sulphuric acid concentrations, ion-induced nucleation may dominate over binary sulphuric acid-water nucleation. Also, increased ion nucleation and increased scavenging rates of aerosols in turbulent regions around clouds seem likely. However, because of the difficulty in tracking the influence of one particular modification brought about by ions through the long chain of complex interacting processes, quantitative estimates of the magnitude of galactic cosmic ray-induced changes in aerosol and cloud formation have not been produced.

Other mechanisms of climate effects due to variations in solar activity, such as the recently suggested Coronal Mass Emissions, which is thought to influence the aa-index to a large extent and therefore the degree of ionization and temperature in the upper atmosphere [Cliver et al., 1998; Pallé and Butler, 2002], are not well established and should be subjected to further scientific research. On the longer time scales radioactive isotopes, such as ^{10}Be and ^{14}C, may tell the story line of solar activity, although the translation toward surface temperature changes needs knowledge on the mechanisms involved. Moreover, these isotopes can be influenced by the geomagnetic field, atmospheric flow and interactions with the ocean and biosphere.

Unequivocal determination of the mechanism(s) by which changes in solar activity influence earth's climate is complicated since the different mechanisms may alter similar aspects of the climate system in different ways. For example, stratospheric heating at solar maximum suppresses and expands the Hadley cells in the troposphere towards the subtropics, whereas direct surface heating enhances the Hadley cell vertically. Furthermore, these mechanisms may operate simultaneously on a variety of physical processes with possible mutual interactions and with climate variability modes. In addition, each of these mechanisms has its own spatial, altitudinal and temporal response pattern. Furthermore, they are likely to depend on the background state of the climate system, and thus on other forcings, such as the anthropogenic forcing, that can alter this state.

4.6 Empirical Evidence of Solar Variability on Climate

4.6.1 Introduction

Many studies try to derive the importance of solar forcings by looking at correlations between solar forcing records and climate records, because firstly little direct information is available on the magnitude of solar forcings, secondly the climate sensitivity is not accurately known and thirdly the mechanisms by which solar activity influences the climate is not fully known. Also, poor knowledge of the actual surface temperature changes before the instrumental period [Mann et al., 1999; Esper et al., 2002; Oerlemans, 2005] hamper unequivocal proof of the solar influence. Two groups of empirical studies can be distinguished: studies which focus on the 11-year activity cycle and studies which consider long-term changes. The literature on this topic is both abundant and controversial. In general there is no solid evidence that to which extent these correlations are caused by changes in solar activity, even if they are statistically significant. The origin of these controversies lies in the fact that possible solar signals are not easily distinguished from other sources of climate variability, such as volcanic forcing, ENSO and long term internal variability. It should be emphasized that although correlations between solar activity and climate parameters do not establish cause-effect relationships, they may give indications for underlying mechanisms of climate change due to solar activity, which can be further studied with GCMs (see section 4.7).

The relative importance of solar and volcanic forcing of pre-industrial climate change is under debate. Whereas some studies report a significant response to volcanic forcing [Hegerl et al., 2003; van Ulden and van Dorland, 2000], others question whether it has any influence at all on long time scales [Blender and Fraedrich, 2004]. As well statistical fingerprint detection techniques may be biased against small signals such as forcing by solar irradiance. Furthermore, it is becoming increasingly clear that the detection of natural signals in the climate record requires proper specification of unforced climate variability arising from ENSO, the NAO and QBO. This is especially true when detecting volcanic signals which have a similar time scale as ENSO and are in phase in recent decades. There is also evidence of a causal relationship in the past century, in which volcanic forcing doubles the likelihood of an El Niño event in the following winter [Adams et al., 2003].

Paleo evidence for the influence of natural forcings also continues to expand, from correlations of high quality solar and climate proxy records throughout the Holocene [Bond et al., 2001; Neff et al., 2001; Verschuren et al., 2000; Magny, 2004]. Multiple high-resolution paleo records at quite different geographical locations often vary in-phase with each other and are additionally in phase with solar activity. This suggests a global response to solar forcing. Drought and rainfall seem particularly sensitive to solar variability, especially in vulnerable geographical regions such as those in the vicinity of the ITCZ (see section 3.5.2).

4.6.2 Multiple Regression Analysis

Multiparametric analyses have been performed to reveal the sources and nature of the variance in ever-lengthening, high-quality, global datasets. Space-based monitoring of solar irradiance and volcanic aerosols now exist for more than 25 years, as do records of parameters related to climate feedbacks (cloud cover and cloud properties, water vapour), climate variability modes (ENSO, NAO, QBO) and climate itself (surface temperatures, circulation patterns), including the overlying atmosphere (temperatures, ozone, geopotential height). Reanalysis continues to improve the reliability of original datasets that cover an even longer time period. Examples include the NCEP and ECMWF (ERA40) reanalysis of atmospheric variables, ISCCP cloud data, and ground-based Dobson ozone network. Furthermore, the period of the past 25 years is sufficiently long that a range of natural radiative forcing strengths and internal variability modes are sampled concurrently with known anthropogenic forcings. The period includes notable volcanic episodes (El Chichon, Mt. Pinatubo), almost three solar activity cycles (including the most recent cycle free of volcanic interference), a few major ENSO events, and significant increases in greenhouse gases, CFCs and changes in tropospheric (industrial) aerosols.

Multiple regression analyses have decomposed observed temperature changes at the Earth's surface and in the lower atmosphere in terms of the simultaneous effects of volcanic aerosols (parameterized by stratospheric optical depth), solar variability (expressed by total irradiance or the 10.7 cm flux), ENSO (defined by tropical Pacific sea surface temperatures) and a linear trend attributable to some combination of greenhouse gas warming and aerosols cooling. These influences together account for approximately 50% of the observed variance in global surface (GISS), and similarly lower tropospheric (MSU) temperatures. Using this approach with total solar irradiance, Douglass and Clader [2002] inferred a global mean cooling in MSU temperatures of 0.5°C and 0.1°C for, respectively, the Mt Pinatubo eruption (estimated forcing of 3 Wm^{-2} [Hansen et al., 2002]) and the solar cycle decrease (forcing of 0.2 Wm^{-2}). The effects of these forcings were statistically found to peak at lags of no more than a few months.

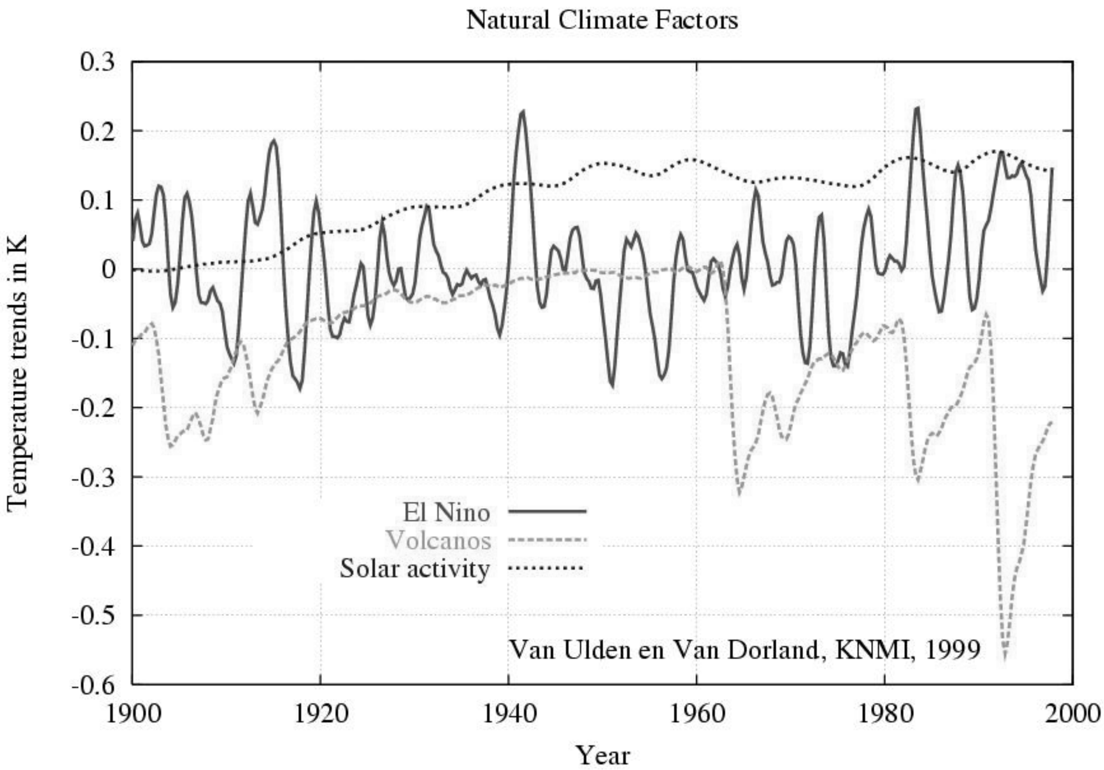

Figure 4.13: Regressed temperature changes in K during the 20th century due to solar activity, volcanic forcing and ENSO [source: Van Ulden and Van Dorland, 2000].

Van Ulden and Van Dorland [2000] analysed the contributions of solar irradiance changes, volcanic eruptions and ENSO to global mean temperature variations from 1882 to 1999 using an energy balance upwelling diffusion climate model. It appeared that fast temperature variations (2-20y) are primary due to ENSO and volcanic forcings. The 11-year solar activity cycle is poorly correlated with temperature and plays a minor role. However, decadal variations in solar irradiance and in volcanic forcing provide a plausible explanation for the observed global warming in the first half of the 20th century (Fig.4.13). By subtracting the best estimate of temperature response due to natural climate factors from the observed temperatures (Fig.4.5), a residual positive temperature trend since 1950 remains, which resembles the computed trend using a plausible estimate of the anthropogenic radiative forcing (Fig.4.14).

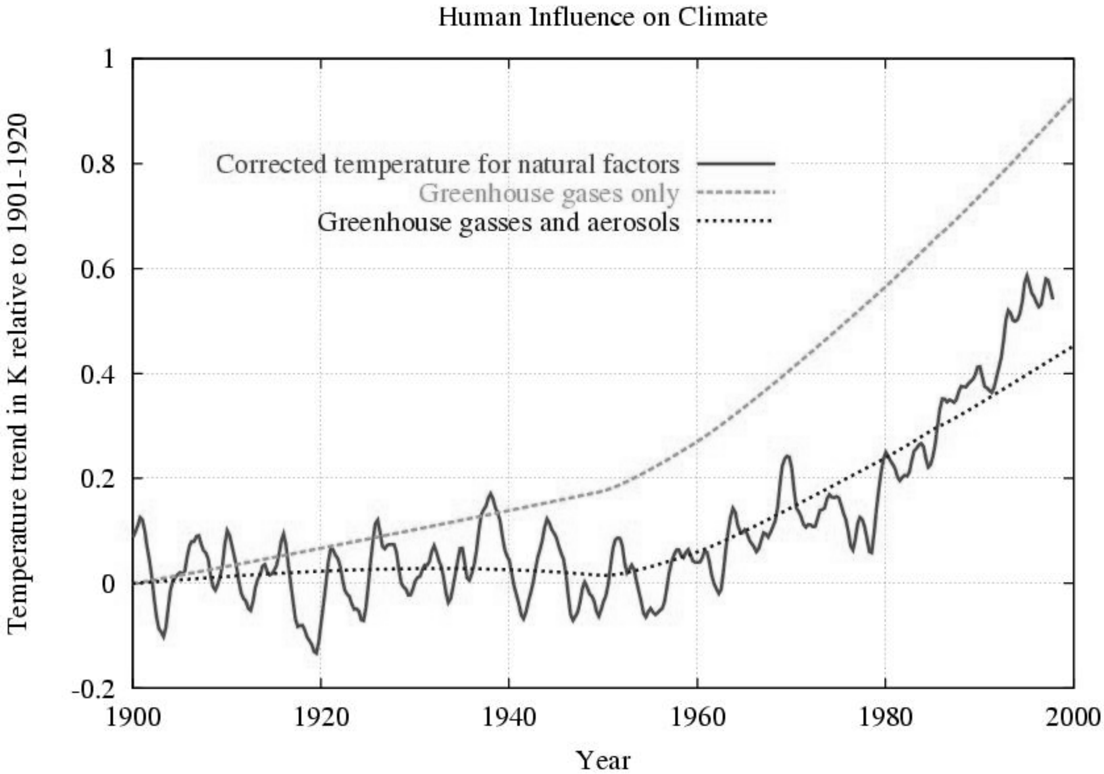

Figure 4.14: Residual temperature trend if contributions of natural climate factors are subtracted from the observed temperature. Also shown are the plausible estimates of the anthropogenic contributions and the anthropogenic contribution of greenhouse gases only [source: Van Ulden and Van Dorland, 2000].

The separation of surface temperatures into natural and anthropogenic components supports prior detections of solar effects in the atmosphere [Labitzke and Van Loon, 1997], and are broadly substantiated by several independent analyses that further explore the latitudinal and height dependences of the natural forcings (with additional variance related to the NAO and QBO, e.g. see Fig. 4.15). Overall, the troposphere is warmer and moister during solar maximum, and thickens in response to solar variability (indicated by the 10.7 cm flux) with a distinct zonal signature. The strongest response occurs near the equator and at mid latitudes (40°–50°) with sub tropical minima [Gleisner and Thejll, 2003]. The primary surface temperature expression of these changes is warming in two mid-latitude bands (increases of 0.5 K at 20ºN–60ºN and S) that extend vertically to the lower stratosphere where they expand equatorward [Haigh, 2003]. Surface and atmospheric temperature responses to volcanic activity have a somewhat similar structure but are opposite in sign near the surface where there is midlatitude cooling (of 0.5º), with warming in the lower stratosphere throughout the equatorial, sub tropical and mid-latitudes. A number of authors deduce from these patterns that natural forcings invoke clear dynamical responses in the troposphere, involving the Hadley, Walker and Ferrel circulation cells. The sub tropical polar jets are weaker and further poleward at solar maximum, the Hadley cells weaken and expand, and the Ferrel circulation strengthens.

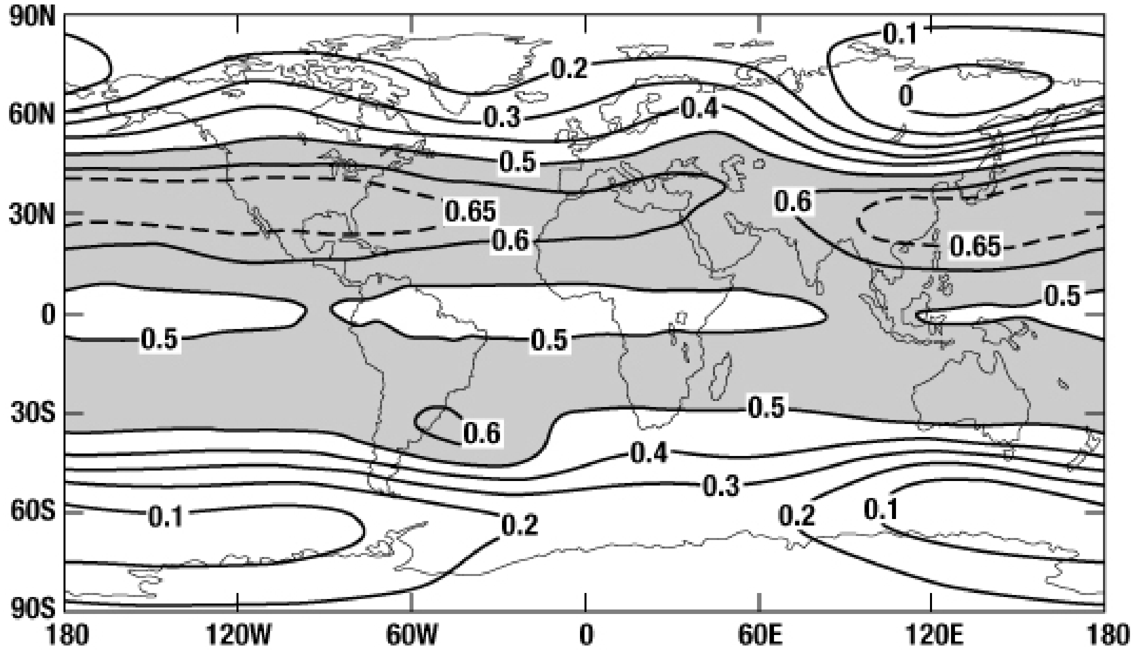

Figure 4.15: Correlation of changes in the geopotential height of the 30 hPa level in the tropical atmosphere and the 11-year solar cycle in the period 1958-1996 [source: Labitzke and Van Loon, 1997].

4.6.3 Solar Cycle Length

The long-term variation of the Northern Hemisphere land air temperature has been found to be negatively correlated with the long-term variation of solar activity in terms of solar cycle length (SCL) during the period of instrumental temperature measurements from 1861 to 1989 [Friis-Christensen and Lassen, 1991]. An impressive agreement was found. However, they merged heavily filtered data (44 year filter) with unfiltered ones in the last 22 years, showing a steep rise which corresponds to the observed warming since 1976. Laut [2003] investigated the correlation between SCL and Northern hemispheric temperatures, and in particular whether the analysis of Friis-Christensen and Lassen [1991] argues for or against an existing warming trend. Laut [2003] concluded that adding the unfiltered points should have been avoided. Replacing these unfiltered points by filtered ones (in 2003) results in rather constant temperatures as opposed to what has been observed during the eighties. By adding artificial warming and cooling trends on the observed temperature record Laut [2003] finds correlations with the SCL which are as strong as those that are found with the unmodified temperature series, indicating that using the SCL model leads to statistically insignificant results. Thejll and Lassen [2000] found that since around 1990 the type of solar forcing that is described by the SCL model no longer dominates the long-term variation of the northern hemispheric land air temperature. Although there are some similarities between inverse SCL and smoothed sunspot number, giving the impression of 78-year (Gleissberg-cycle) and 181 year cycles, the relation between SCL and solar irradiance changes is lacking. Also other mechanisms than via TSI variations using the SCL model remain unclear.

4.6.4 Cosmic Rays and Clouds

Statistical approaches continue to be used to link solar activity and cloud cover but with ambiguous findings [Udelhofen and Cess, 2003; Kristjanson et al., 2002; Usoskin et al., 2004; Sun and Bradley, 2002]. In the ISCCP dataset low clouds are apparently increased at low solar activity, mainly at sub tropical and mid latitudes. But it is under debate whether the cause is enhanced cloud condensation nuclei from increased cosmic ray fluxes [Usoskin et al., 2004], solar irradiance heating of sea surface temperatures [Kristjansen et al., 2002] or ENSO, rather than solar variability [Kerhthaler et al.]. However, the relation between solar heating and cloud cover over the (sub)tropical oceans as studied by Kristjansen et al. [2002] is questionable since most of the change in irradiance from minimum to maximum solar activity is located at the shorter wavelengths, which do not reach the earth surface. Furthermore, in contrast to the inverse association of low ISCCP cloud cover with solar activity in recent decades, total US cloud cover and solar activity are positively correlated during the past century [Udelhofen and Cess, 2001]. Sun and Bradley [2002] pointed out that the evidence in the ISCCP datasets is only confined to the Atlantic Ocean, and no meaningful relationship is found between cosmic ray intensity and cloud cover over tropical and extratropical land areas in longer datasets that extend back to the 1950s.

For the particle mechanism a clear physical framework is lacking and no convincing studies been published in recent years. For example, the frequently mentioned study by Svensmark and Friis- Christensen [1997] is certainly not convincing on a number of points. They claim a relation between cloud cover and cosmic radiation on the basis of a correlation of the two over (part of) a solar cycle using ISCCP C-2 data. Physical evidence is lacking in the paper, while in addition the consequences of the claimed relation, i.e. a strong 11- year cycle in temperature and a long term decrease of cloudiness, are contrary to observations (Fig. 4.16) [Van Dorland and Van Ulden, 1998; Van Ulden and Van Dorland, 1999; 2000].

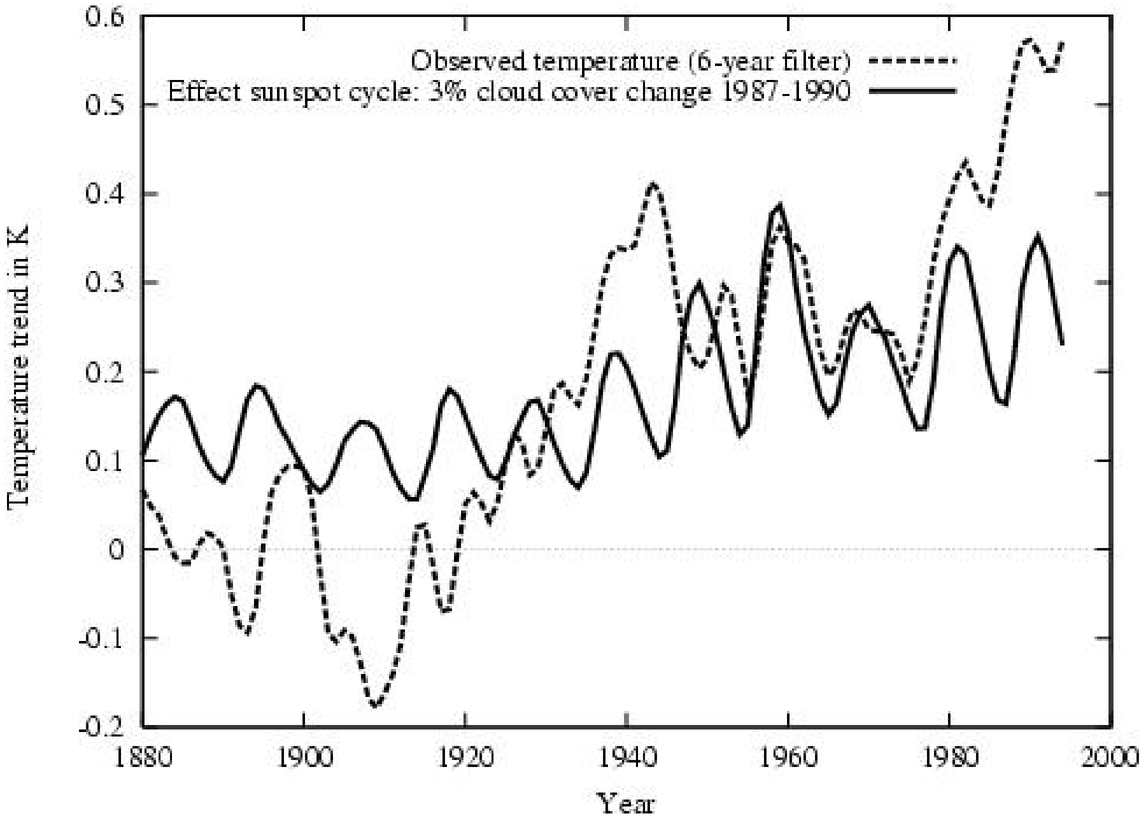

Figure 4.16: Test of the cosmic ray – cloud hypothesis of Svensmark and Friis-Christensen [1997]. A decrease of average cloud cover is adopted between the minimum (1987) and the maximum (1990) solar activity of cycle 22, resulting in a radiative forcing of 1.25 Wm^{-2}. This concept is proportionally applied to the number of sunspots since 1880. Although some of the observed 11-year fluctuations match the computed effects of the sunspot cycle, this solar signal is out of phase before 1950. Moreover, the observed long-term temperature trends are considerably larger and cannot be explained by the cosmic ray signal [source: Van Dorland, 1999].

Svensmark [1998] presents evidence using other cloud climatologies (from Nimbus-7 data, from DMSP data and from D-2 data from ISCCP) that extends the analysis from 1980 to 1995. In this analysis only the smoothed data support the signal found in the ISCCP C-2 data. Moreover, the way the individual datasets have been connected together, namely without rescaling, is questionable. For instance, the ISCCP data and DMSP data do not show the same trend in the period of overlap (1987 to 1990). In addition, the phasing of cloud cover changes with cosmic rays differs in the Nimbus 7 and ISCCP C-2 datasets. Hence, the evidence indicating a strong cosmic ray – cloud link is not reinforced by the use of these extra data.

4.6.5 Evidence for UV Induced Climate Change

Changes in solar UV radiation and volcanic aerosols affect ozone and middle atmosphere dynamics. Stratospheric responses to natural forcings are potentially significant for climate change, since they may couple with the troposphere and impact the surface. Ongoing studies reinforce the role of the stratosphere in climate change [Haigh et al., 2004; Baldwin, 2003]. As with tropospheric climate, stratospheric changes occur simultaneously with anthropogenic effects and internal variability (e.g., QBO) [Geller and Smyshlyaev, 2002]. Regression analyses that include the annual cycle, solar activity, the QBO, and a linear trend account empirically for significant variance in the total ozone records [McCormack et al., 2003; Fioletov et al., 2002].

On the time scale of the 27-day solar rotation period, UV variations result in an observed stratospheric ozone production, which agrees approximately with current photochemical model predictions. In addition, statistical studies suggest an uptil now unmodeled dynamical component of the 27-day response that extends to the low and middle stratosphere. On the time scale of the 11-year solar cycle, the ozone response derived from the available data is characterized by a strong maximum in the upper stratosphere, a negligible response in the middle stratosphere, and a second strong maximum in the tropical lower stratosphere. This results in an approximately 2% change for the global annual average (Fig. 4.17) [Zerefos et al. 1997; McCormack and Hood, 1996; Wang et al., 1996], accompanied by temperature responses that increase with altitude, to 0.3 K at 10 km, and 1 K around 50 km. The 11-year temperature response derived from NCEP/CPC data is characterized by similar altitude dependence. However, in the middle and upper stratosphere, there is disagreements between analyses of the various temperature data sets and further studies are needed to establish more accurately the 11-year temperature response. In the lower stratosphere relatively large amplitude variations of geopotential height (Fig. 4.15), ozone, and temperature at the tropical and subtropical latitudes are observed, which can be attributed to the 11-year solar cycle. Additional large responses can be detected in the polar winter lower stratosphere if the data are separated according to the equatorial QBO phase.

It is now relatively well established that changes in solar UV radiation and in volcanic aerosol concentrations induce middle atmospheric effects that vary with geographical location and altitude, in ways that are not clearly related linearly to the distribution of the forcing. For example, solar forcing appears to induce a significant and unexpected (from a modelling perspective) tropopause response [Hood, 2003].

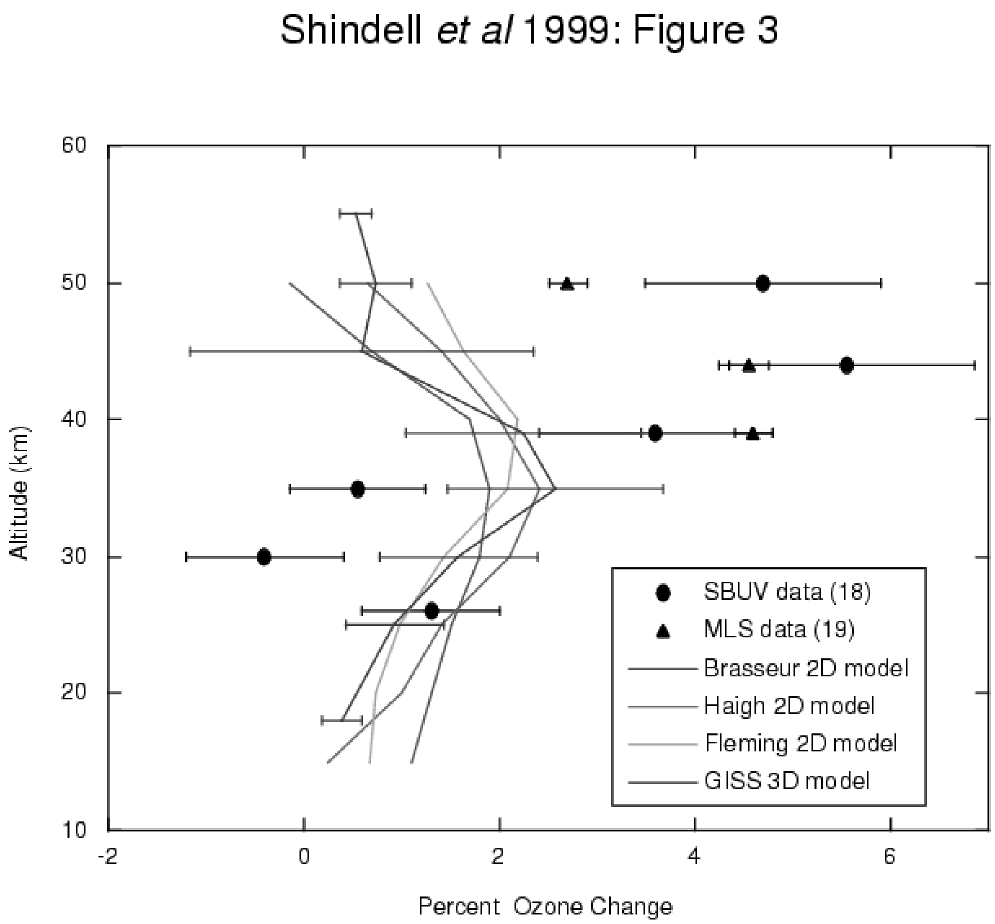

Figure 4.17: Observed and modelled ozone changes due to the solar cycle [source: Shindell et al., 1999].

4.7 Modelling the Solar-Terrestrial Relationship

4.7.1 Total Solar Irradiance Variations

The first reported coupled ocean-atmosphere GCM study to include the impact of centennial scale variations of TSI has been performed by Cubasch et al. [1997]. They use the ECHAM-3 climate model forced with the TSI series of Hoyt and Schatten [1993]. From two model runs using different initial conditions, Cubasch et al. [1997] find a warming of 0.15 to 0.25 K during the 20th century, quite similar to that obtained by a linear regression technique using a simple climate model to translate radiative forcing into temperature response [Van Ulden and Van Dorland, 2000] in which the average is used of the reconstructions by Hoyt and Schatten [1993], Lean et al. [1995] and Solanki and Fligge [1998] before 1980 and direct observations of TSI after 1980 [Frohlich and Lean, 1998] (see section 4.6.2). However, due to the use of different data, Cubasch et al. find a solar warming of 0.16 +/- 0.09 K in the last 30 year, whereas Van Ulden and Van Dorland [2000] find a trend of less than 0.05 K. This is substantial as compared to the warming due to the increase of greenhouse gases in the same model of 0.54 +/- 0.13 K.

Recent simulations by general circulation models of climate responses to natural and anthropogenic forcings in the past 150 years support the general conclusions of the earlier models studies and show additional aspects, such as the amplification of the solar response by the greenhouse gas forcing through an alteration of the cloud patterns affecting the heterogeneity of solar surface heating and regional climate feedbacks. However, the strength and the character of these interactions depend to a large extent on the basic state and sensitivities of the model. By including the Hoyt and Schatten [1992] or Lean et al. [1995] solar forcing the simulations are better able to account for surface warming in the first half of the 20th century by contributing a few tenths Kelvin warming [Stott et al., 2000].

Recent studies generally concur that both solar and volcanic influences are also detectable in pre-industrial surface temperatures in the recent past – from 50 to 1,000 years ago [Crowley, 2000]. These studies are semi-empirical since they typically use statistical techniques to compare reconstructed surface temperatures (and other climate variables such as precipitation) with the changes estimated from forced climate models. Surface temperature fluctuations of order 0.2 K are evident in association with natural forcings on time scales of centuries. In a 200-year preindustrial period, Waple et al. [2002] determined an apparent strong tropical western Pacific sensitivity to solar forcing from climate records, relative to that suggested by models. Responses were found for both longer term and decadal solar variability, but with different geographical fingerprints, the latter dominated by resonance with known modes of decadal climate variability.

Centennial timescale variability during the Holocene has been studied by Weber et al. [2004] using an intermediate-complexity climate model, i.e. a low resolution atmosphere-ocean model and a thermodynamic sea-ice model. Two experiments have been performed using orbital forcing and solar irradiance forcing – based on the Stuiver et al. [1998] residual ^{14}C record scaled to the Lean et al. [1995] reconstruction – and orbital forcing alone. A timescale analysis shows that the response in atmospheric parameters to the irradiance forcing can be characterised as the linear response of a system with a large thermal inertia. This is evident in parameters like surface air temperature and monsoon precipitation, which show a stronger response for longer timescales. The oceanic response, on the other hand, is strongly modified by internal feedback processes. The solar irradiance forcing excites a (damped) mode of the thermohaline circulation (THC) in the North Atlantic ocean with a significant peak at time scales of 200 – 250 years in the THC spectrum. The THC response diminishes the sea surface temperature response at high latitudes, while it gives rise to a signal in the sea surface salinity. These model results do provide a possible explanation for a centennial signal in oceanic fields, namely through a resonant THC response that amplifies the rather weak solar irradiance forcing.

4.7.2 Effects of UV Variations on the Middle Atmosphere

Since changes in solar irradiance are not evenly distributed across the solar spectrum, but are concentrated in the UV part of the spectrum, the influence of changes in solar activity is well manifested in the middle atmosphere as can be derived from observations (see 4.6.5) with possible consequences in the troposphere via dynamic coupling. Many model experiments, with and without interactive (stratospheric) chemistry, have been designed in order to assess the impact of solar variability effects on stratospheric ozone via the change in UV radiation during the 11-year solar cycle. Haigh [1994; 1996] has demonstrated the importance of the solar induced ozone changes in the assessment of the solar cycle effects on the atmosphere and climate with the use of climate models.

The predicted changes from two dimensional chemistry-transport models are in the order of 1-2% for total ozone, with seasonal and latitudinal variation [Zerefos et al., 1997]. GCM simulations generally show much more variation in ozone especially at high latitudes (Fig.4.18). Moreover, using GCMs the effects on the circulation patterns in the stratosphere and troposphere can be studied. Shindell et al. [1999] found that the model could simulate qualitatively aspects of the observed response, including 30 hPa height variations in the northern winter hemisphere. However, for those runs that adopted realistic solar (spectral) irradiance and stratospheric ozone changes, the amplitudes of the calculated solar induced changes in the lower stratosphere were generally less than those derived from observations.

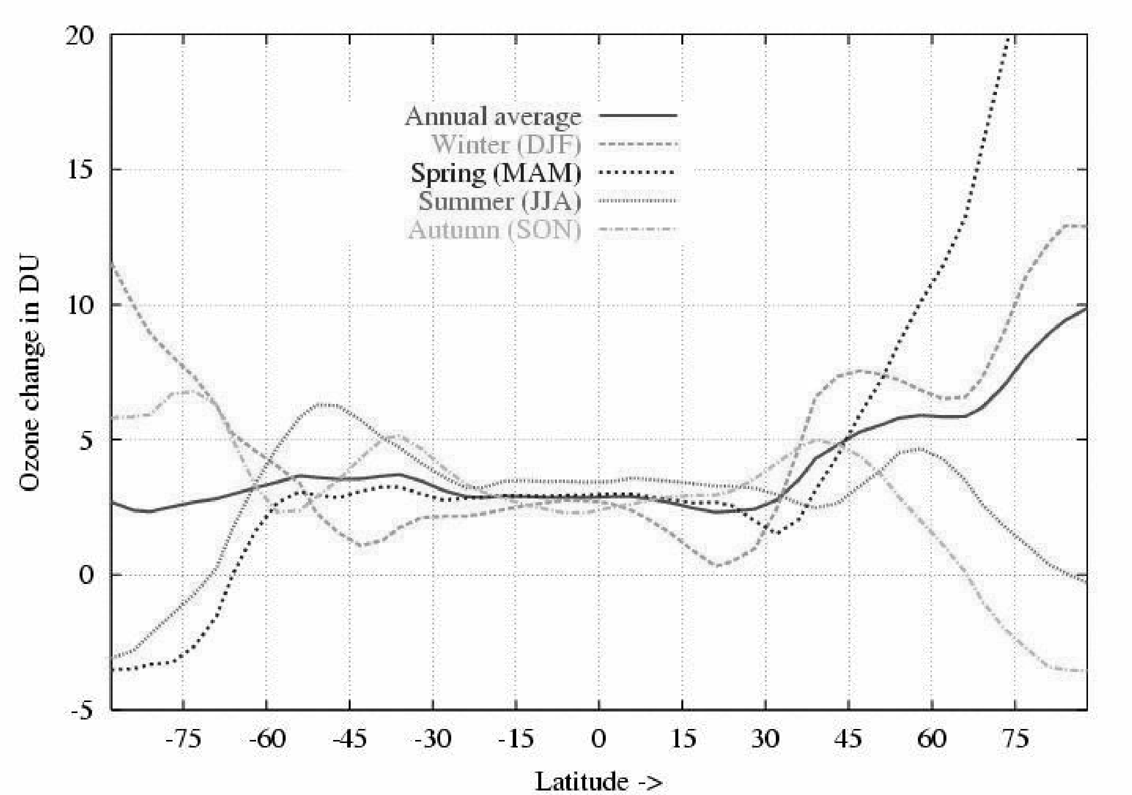

Figure 4.18: Mean difference of modelled ozone in DU for solar maximum relative to solar minimum for the seasonal averages and annual average using the Middle-Atmosphere ECHAM4 Chemistry model.

Tourpali et al. [2001; 2003] using an interactive chemistry-climate model found that the response of the troposphere is strongest in the Northern Hemisphere winter, but is by no means restricted to the winter season. In fact model results show a remarkable continuity from month-to- month in the latitudinal shifts of the zonal wind, parallel to the seasonal shift in the latitudinal position of the sun. In the stratosphere, enhanced UV is associated with higher temperatures, caused by direct heating in the equatorial regions and by changed advection at the higher latitudes. In the winter hemisphere the zonal wind in the stratosphere decreases, most pronounced in the northern winter. However, individual (northern) winter months differ in response: in December the polar vortex is stronger, while it is weakened in January and especially in February. Exactly the same differences in response between December and February were found by Shindell et al. [2001], using a completely different atmospheric model. Therefore, these differences are most probably real.

Variable solar UV most probably does not contribute significantly to variations in global mean temperature. The radiative forcing associated with the TSI changes is small, in the order of 0.2 Wm^{-2}, while the contribution of the ozone increases to the radiative forcing is negligible [Tourpali et al., 2003] as shown in Figure 4.19. This is mainly due to the fact that a considerable part of the ozone increases are confined to the upper stratosphere, tending to negative radiative forcings. Radiative forcing due to stratospheric ozone changes is very much dependent on the profile of change [Van Dorland and Fortuin, 1994; Bregman et al., 2003]. In the lower stratosphere ozone increases lead to a positive forcing. Haigh [1999] calculated a forcing of 0.1 Wm^{-2} using observed ozone changes, which were put in only two stratospheric layers of their model. Myhre et al. [1998] used the modelled variations in ozone due to the solar cycle presented by Zerefos et al [1997] and found a negative radiative forcing of -0.02 Wm^{-2}.

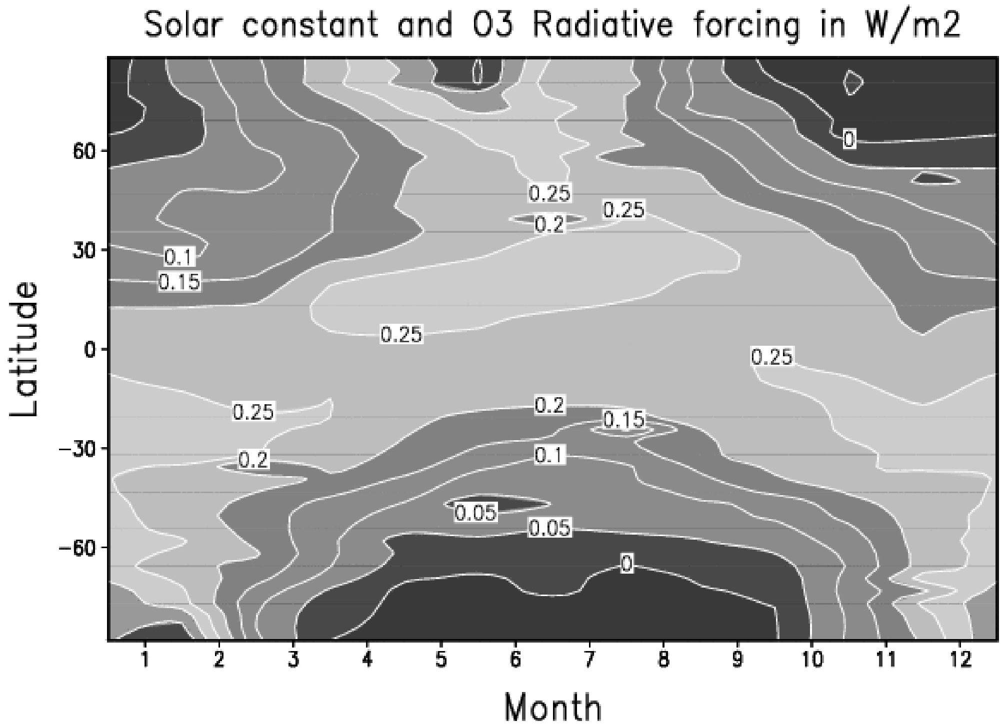

Figure 4.19: Latitude-month plot of the annual zonal mean radiative forcing in Wm^{-2} due to total solar irradiance increase and due to ozone changes from solar minimum to solar maximum.

Wuebbles et al. [1998] have looked at the impact of long term changes of solar UV by simulating the ozone change during the Maunder Minimum. For this purpose they performed a run with a 2-D chemistry-transport model using the estimate of UV changes at that era of Lean et al. [1995]. Wuebbles et al. found that the global ozone column would have been 3% lower relative to the present day solar output of the quiet sun, while ignoring human-induced changes in ozone. The increase in ozone since the Maunder Minimum is calculated to have caused a negative radiative forcing of -0.13 Wm^{-2}, again due to the fact that the computed change peaks in the upper stratosphere. This is a potentially non-negligible offset to their estimated forcing of 0.5 Wm^{-2} due to direct changes in TSI over the same period. Langematz et al. [2005a] performed a run with a fully coupled GCM with chemistry and found a global mean temperature change between the Maunder Minimum and present day of 0.86 K. In the present day climate they included the human effect on the atmospheric composition, which resulted in a temperature change of about 0.6 K, leaving approximately 0.3 K for the solar induced temperature change.

4.7.3 Effects of UV Variations on the Troposphere

Because ozone controls solar energy absorption in the stratosphere, changes in ozone concentration alter both the altitudinal temperature gradient from the troposphere to the stratosphere, and the latitudinal gradient in the stratosphere, from the equator to the poles. Therefore, these differential temperature responses in the stratosphere, which are dependent on season as well, have the potential to alter winds (Fig 4.20) and the large scales planetary waves (which extend into the stratosphere). Through a cascade of feedbacks involving thermal and dynamical processes, such effects are thought to propagate surface-wards and influence tropospheric circulation patterns. Equatorial winds in the stratosphere appear to play an important role in this process because of their impact on wind climatology [Matthes et al., 2004], such as stretching of the Hadley cell and changing the reflection and absorption properties of planetary waves in the stratosphere (see 4.5.2). Model simulations suggest that solar-driven radiative coupling effects of this type can alter the strength of the Hadley cell circulation, with attendant effects on, for example, Atlantic hurricane flows [Haigh, 2001; 2005].

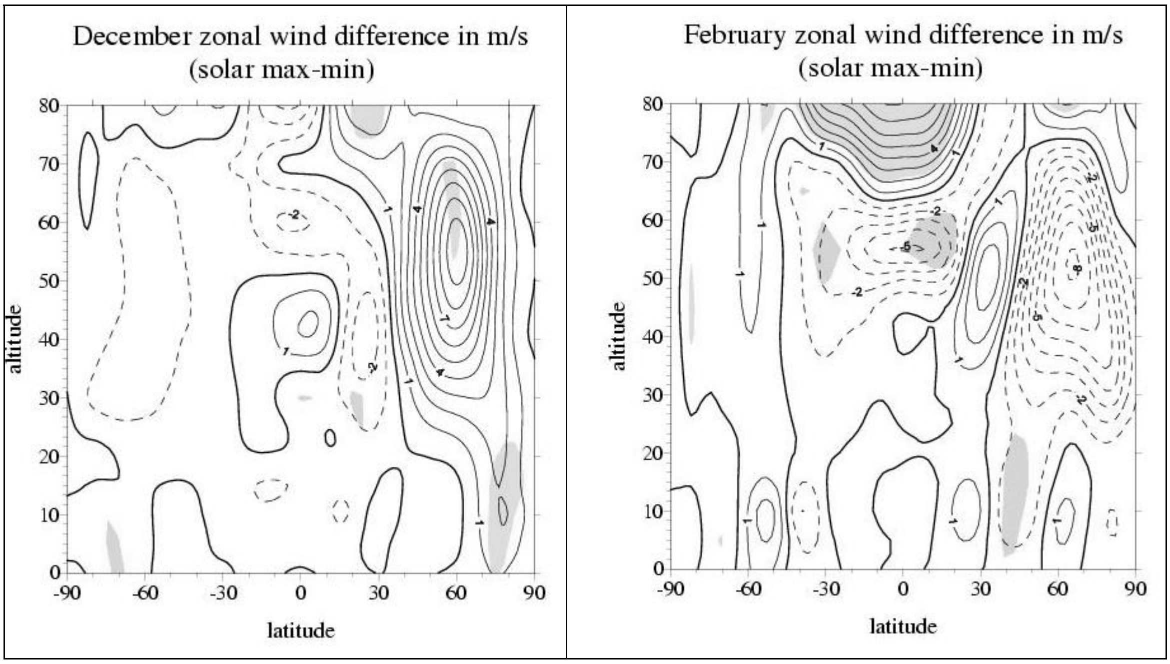

Figure 4.20: Zonal wind differences (m/s) for solar maximum relative to solar minimum for December (a) and February (b) using the Middle-Atmosphere ECHAM4 Chemistry model [source: Tourpali et al., 2003].

Modelling studies and data comparisons suggest that solar – but also other climate factors like volcanic activity and increased greenhouse gas concentrations - can alter the NAO via their effects on the high latitude stratospheric and the polar vortex [Shindell et al., 2001, 2003]. Contemporary observations suggest that the Northern Annular Mode (NAM) manifests itself primarily in the North Atlantic sector, as the NAO, during solar cycle minimum, and extends more uniformly over all longitudes, as the AO, during solar maximum [Kodera, 2002; Tourpali et al., 2005]. Model simulations and analysis of patterns of variability suggest that the Artic Oscillation, or NAM, and its subset the North Atlantic Oscillation (NAO) propagates from the stratosphere to the troposphere, altering the location of storm tracks and the likelihood of storms (Fig. 4.21). The effect of solar activity on the NAM and SAM may further depend on the phase of the quasi-biennial oscillation in stratospheric equatorial winds [Ruzmaikin et al., 2004; Kuroda and Kodera, 2005].

Reduced solar activity in the Maunder Minimum may have produced a negative NAO phase (compared with the current positive phase), based on empirical analysis of historical surface temperature fields and model simulations [Shindell et al., 2001]. Empirical evidence similarly suggests that historical surface temperature changes in the Little Ice Age can be explained by solar-related changes in NAO patterns [Ruzmaikin et al., 2004).

The effects of variable UV forcing, related to solar activity, play a significant role in atmospheric variability, especially in the stratosphere. In the troposphere the effects are less, and likely of climatological significance at a regional scale and perhaps in some regions only. The model responses of the zonal wind in the troposphere especially in winter season follow a characteristic pattern, but the exact locations of these wind changes are model dependent. Qualitative agreement on this aspect among models of quite different nature and with observations might be an indication that the simulated effect of changes in UV radiation is real.

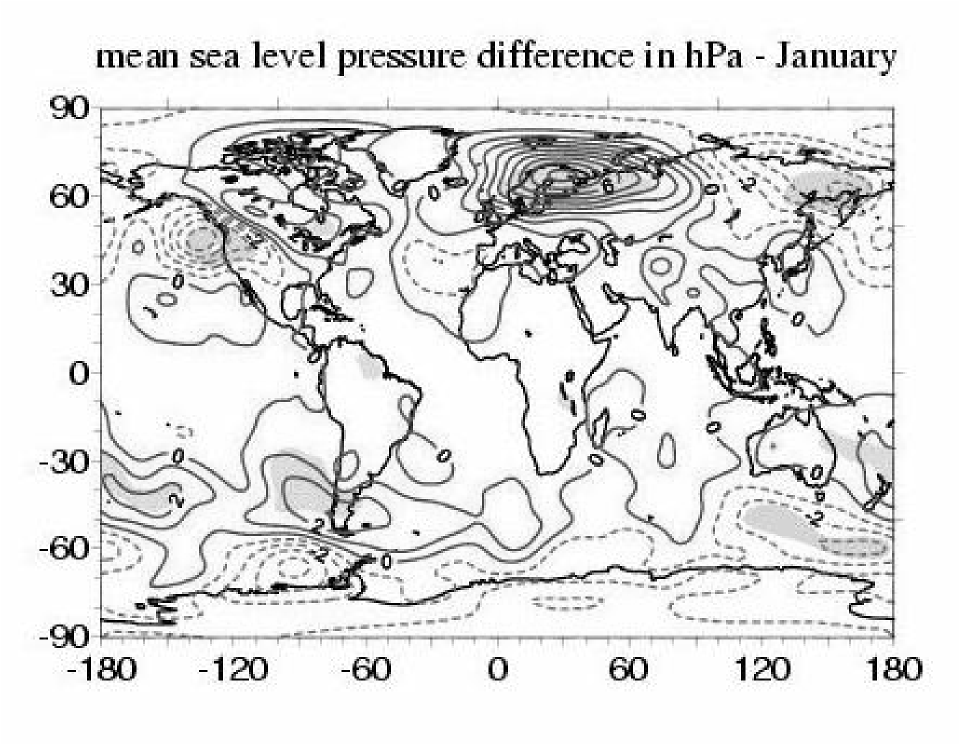

Figure 4.21: Mean sea level pressure change (hPa) from solar minimum to solar maximum in January as computed using the Middle-Atmosphere ECHAM4 Chemistry model [source: Tourpali et al., 2003].

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Klairie Tourpali, Cor Schuurmans, Bas van Geel, Kees de Jager and Gerard Versteegh are thanked for reviewing this chapter and making helpful comments to improve the manuscript. I acknowledge Judith Lean for her research concerning the present status of research on the solar terrestrial link. I greatly appreciated the discussions with the authors of chapter 2 and 3, Kees de Jager and Gerard Versteegh, and thank them for their patience during the process of writing this chapter.

5 CONCLUSIONS

5.1 Solar Variability

- Solar activity is variable with five well-determined quasi-periodicities. Attempts to theoretically describe the solar dynamo have so far succeeded only in explaining the qualitative aspects. They fail in a numerical description and notably in one that would permit one to forecast solar activity with acceptable precision. This is so because the solar dynamo is a non-linear system that occasionally shows phase catastrophes. It is a quasi-periodic engine with the properties of deterministic chaos. “The future of such a chaotic system is intrinsically unpredictable”.
- In recent years clarity has arisen as to the origin of solar variability. The hypothesis that it would result from the motion of the sun around the centre of mass of the solar system appears to be incorrect. Solar variability is rather due to endogenic factors: The solar dynamo is an electromagnetic engine seated in the solar tachocline, which is the thin layer where strong shearing motions occur, located at the bottom of the region of convective motions, which is at a depth of about 200.000 km below the surface. At that level toroidal magnetic fields are generated. When these are sufficiently amplified and are strong enough they rise upward and eventually appear as sunspots at the surface. The area around the spots, the Active Region is the seats of variable Ultra Violet emission. From the active regions and their surroundings magnetised gas clouds are emitted into space: the Coronal Mass Ejections. Higher up in the convective region poloidal fields are produced that are at the basis of high latitude magnetic fields. Also from these areas magnetised gas clouds are ejected into space. Theory is not yet capable to explain the 22 years quasicyclic periodicity nor the other observed periods in solar activity, nor the 'grand minima' such as the Spörer, Maunder and Dalton minima.
- The solar dynamo is the engine of the Sun’s variability. The solar dynamo is characterised by internal toroidal and more superficial poloidal fields, interchanging and alternating in a 22-yr periodicity. From these two components in the solar magnetic fields emanate two possible scenarios for the Sun-climate interaction:
  (1) Solar irradiance variations are related to those in the solar toroidal magnetic fields. The variable part of the solar radiation flux is mainly emitted by the chromospheric parts of the Centers of Activity (CA), hence responsible for the variable UV radiance. The Group Sunspot number R_{Gs} is a proxy for the variable irradiance component and for the toroidal field variations.
  (2) The other component consists of ejected solar plasma clouds, such as the Coronal Mass Ejections (CMEs) and plasma ejected from Ephemeral Solar Regions. The CMEs are emitted from the Centers of Activity. Hence they are related to the toroidal magnetic field and a proxy for it is the sunspot group number. The other coronal emissions are related to variations in the poloidal magnetic fields. By emitting magnetised plasma, the Sun influences the Earth’s atmosphere indirectly, by heliospheric modulation of the component of the galactic cosmic radiation (CR). The amplitudes of the CR variations depend on those of the solar cycle. The cosmogenic radionuclides are proxies for this influence.
- The strengths of the poloidal and toroidal fields are correlated but not strongly so; neither do they reach maximum simultaneously: On the average the ejected solar plasma clouds, not related to CMEs, have their maximum intensity about a year after the maximum number of spots. Also, energetic emissions such as X-ray flares and strong cosmic ray emissions occur one or two years after spot maxima: we call this the Energetic Emissions Delay.
- The Group Sunspot number (R_G) and cosmogenic radionuclide proxies, although loosely correlated, refer to the two different aspects of the solar dynamo with their different terrestrial effects; they do not reach maximum intensity simultaneously and should therefore not be confused nor be interchanged. Cases have occurred in which the one varied strongly while the other did hardly or not at all. The explanation must be intrinsic in dynamo theory.

- Never during the past ten thousand years has the Sun been as active in ejecting magnetised plasma as during the last half a century, in which period it remained fairly constant. Estimates suggest that the level of solar activity may recently have passed its maximum and that it may decrease in coming decades.

5.2 Records of Climate Change and Solar Variability

- Evidence for past solar and climate variability is obtained from instrumental data (since 1700 AD), historical accounts (last few millennia) and proxy records (last 10,000 years, and more) with a resolution of one to few years.
- Instrumental records monitoring solar activity and climate change usually have a high temporal resolution, and quantitatively document environmental change as it occurs. However, they are relatively short, mostly covering the last decades to centuries only. As a result they usually fail to capture longer-term processes, rare events, and non-analogue situations (e.g. pre-industrial (natural) climate change). This applies to records for both solar activity and climate change and conversely, assessment of Sun-climate relations is often problematic.
- Historical records of solar and climate variability may cover time spans up to several thousands of years. These records also have their drawbacks since usually they are not continuous and biased towards extreme events.
- Information on climate change is recorded by nature in e.g. tree rings, peat, stalagmites, ice caps, lacustrine and marine sediments. Cosmogenic radionuclides in sediments, such as ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl, form the major source of information on solar activity for the pre-instrumental era. These proxy records are often continuous over much longer periods and as such, the study of these natural archives may help to overcome the limitations set by the instrumental records.
- Cosmogenic radionuclides are formed by high-energy particles entering the atmosphere where they collide with the atoms in the air and produce rare and unstable isotopes. The solar wind shields the atmosphere from these particles so that cosmogenic radionuclide production rates decrease as solar activity increases. The influence of the strength and shape of the magnetic field on the cosmic ray dose on the atmosphere, further modulates the radionuclide production such that the production increases with decreasing field strength and increases towards the magnetic poles.
- The production of cosmogenic radionuclides ^{10}Be and ^{14}C can be influenced by geomagnetic field fluctuations. These fluctuations are caused by interactions between the Earth's mantle and core. Accurate assessment of changes in the geomagnetic field is thus of direct importance for understanding solar variability. Reconstructing geomagnetic activity, however, is a difficult task and, unfortunately, already relatively small changes in the long term trend substantially influence the amplitude and sign of the reconstructed solar activity changes. On smaller time scales, changes in the geomagnetic field are even less well defined.
- Interpretation of the proxy records is hampered by difficulties in (1) translating the records into quantitative climate parameters (2) obtaining an accurate age assessment (3) elucidating spatial patterns and relationships (4) separating solar forcing from other forcing mechanisms and (5) the lack of physical understanding of the solar forcing mechanisms. For these reasons, assessment of past solar influence on climate often is limited to the identification correlations between climate change and solar variability only.

5.3 Reconstructions of Solar Variability

- Since 1978, radiometers on board of satellites directly measure the total solar irradiance without interruption, albeit from a variety of instruments. In this period covering two-and-a-half solar cycles, observations show a periodic variation in total solar irradiance (TSI), with maxima around 1980, 1990 and 2001 and minima around 1986 and 1996. These variations correspond reasonably well with the sunspot numbers.
- The difference in TSI between maxima and minima was about 1 Wm^{-2}, which corresponds to less then 0.1%. Total solar irradiance between successive solar minima has found to be

constant to better than 0.01%, suggesting no significant trend of the quiet sun. Spectral measurements show that variations occur at all wavelengths, but with different relations to solar activity. Irradiance changes correlate positively with the solar cycle at most wavelengths from small changes in the IR spectrum and large changes in the UV spectrum.

- Long-term irradiance changes are generally based on three observables, while the calibration is done by estimating the solar irradiance change during the Maunder Minimum (1645-1715) and the present quiet sun:
  (1) Changes in the aa-index as a measure of the magnetic activity of the sun: it indicates a much higher activity nowadays than since the start of the measurements one and a half century ago. Recent studies raise the possibility of long-term instrumental drifts in the aa index.
  (2) Reconstructions of cosmogenic isotopes point toward cosmic ray fluctuations, which can be attributed to the sun's magnetic activity. Simulations of the transport of magnetic flux on the Sun and propagation of open flux into the heliosphere indicate that trends in the aa index and cosmogenic isotopes (generated by open flux) do not necessarily imply equivalent trends in solar irradiance (which track closed flux)
  (3) The range of variability in Sun-like stars. Although previously suggested that the Sun is capable of a broader range of activity than witnessed during recent solar cycles, a reassessment of the stellar data shows that the current Sun is thought to have "typical" (rather than high) activity relative to other stars.
- In terms of current physical understanding, the most likely long-term total irradiance increase from the Maunder Minimum to current cycle minima is 0.5 Wm^{-2}, but it may be as much as 1.6 Wm^{-2}. When the 11-year solar cycle is taken into account, the best estimate from Maunder Minimum to the present average sun is about 1.1 Wm^{-2}. Converted into a temperature response using the upper limit of the TSI increase of 2.2 Wm^{-2} (including the effects of the 11-year solar cycle) and the high climate sensitivity of 4.5 degrees for a doubling of CO_2, the upper limit of (equilibrium) response would be 0.4 degrees.
- Like the solar cycle changes, long-term irradiance variations are expected to have significant spectral dependence with strong relative variation in the UV. Reconstructing solar irradiance changes are inevitably based on certain choices, which cannot or can only partly be validated. For instance, estimates of the global temperature during the little ice-age are used to estimate the change in TSI, while one should wish to have independent estimates.

5.4 Evidence for the Solar Signal in Proxy Records

- All frequency components attributed to solar variability re-occur in proxy records of climate change. The noisy character and often insufficient temporal resolution of proxy records often exclude the detection of high frequency decadal and bi-decadal cycles. However, on multi-decadal and longer time scales, notably the ~90 yrs Gleissberg, and ~200 years Suess cycles in the ^{10}Be and ^{14}C proxy records of solar activity are also well presented in the environmental proxy records. Additionally, a ~1500 years Bond cycle appears to occur in several proxy records.
- Solar forcing has "to compete" continuously with other climate forcings, e.g. volcanism, and climate variability, such as changes in ocean circulation patterns. Since proxy records mostly are based on one site (e.g. a bore-hole) and thus provide a record of local climate change only, the sometimes very large amplitude of local climate variability can mask the solar signal. It may explain why for several regions solar forcing appears only evident during periods of high amplitude solar variability. The signal to noise ratio may be improved by stacking similar periods of solar forcing and investigating the response. However, using various proxy records within a certain region the solar signal may be lost as well due to averaging signals with opposite signs.
- Solar forcing seems to have a particularly strong impact on regional precipitation-evaporation budgets suggesting that it operates via modulating the distribution of latent heat. The oceans may play an important role. Proxy evidence for sun-climate relations is unequally distributed over the globe, Africa, South America and the marine realm are clearly underrepresented, which is probably more due to a lack of information than a lack of response to solar forcing.

- Proxy records suggest, by comparing climate parameters and cosmogenic isotopes, a forcing-induced migration of climate regimes in many cases. At a given location this inherently induces a non-linear response. This may be one explanation for the discontinuity in the apparent response to solar forcing at single sites. This discontinuous proxy-response as well as phase-shifts complicate the assessment of sun - climate relations and call for non-linear analysis of multiple long and high resolution records at regional scale since only a regional network of proxies may be capable to unravel sun-climate relations appropriately. Unfortunately nonlinear responses to solar forcing are still a largely barren field, despite the fact that major global climate configurations (e.g. the ENSO and AO) follow non-linear dynamics.
- Few but well dated studies indicate an early, almost instantaneous, climatic deterioration in response to periods with rapidly decreasing solar activity. Since such an early response puts severe limits to the solar forcing mechanisms the reality and extent of this phenomenon should be a key issue in sun-climate studies.
- Several theories suppose that the stratosphere plays a key role in putting the solar forcing of tropospheric climates into effect. To test this, it would be very helpful if proxies monitoring stratospheric change would be available. One measure for changes in the stratosphere is O_3 content. The amount UV-B that penetrates the atmosphere depends on the amount of stratospheric O_3. UV-B causes harmful effects on organisms. In order to minimise these effects, UV-B screening mechanisms have been developed by biota. Higher plants respond to a change in the UV-B dose by changing the macromolecular composition of their leaf cuticles and pollen and spore walls. This information is preserved in fossil plant remains. Monitoring the past UV-B screening capacity of organisms may thus provide a way to reconstruct stratospheric O_3 variations.
- A clear link is present at the level of individual (Spörer and Maunder-type) minima in solar activity and climate throughout the Holocene. In the North Atlantic the solar minima are associated with southward advances of sea-ice whereas in Western Europe climate turns cool and wet. It must be noted that there is no unequivocal link; climatic events occur without corresponding solar forcing and vice versa, some minima in solar activity do not seem to have a corresponding climatic anomaly.

5.5 Evidence for the Solar Signal in Instrumental Data

- Linear regression techniques making use of the signature (instead of the amplitude) of the solar forcing indicate that solar activity could be partly responsible for the early 20th century warming. Quantification, however, depends totally of the used time series of TSI. Also, the solar signal may compete with possible temperature changes due to internal variability and/or due to volcanic forcing. Therefore, it seems unlikely that a definitive and unambiguous explanation of the century time scale temperature variations can be achieved, although it is likely that a considerable fraction of the observed temperature rise in the first half of the 20th century can be attributed to the increasing activity of the sun.
- There is some observational evidence that ozone concentrations in the stratosphere correlate positively with the UV variations due to the 11-year sunspot cycle. Statistical studies also suggest a dynamical 27-day response due to the rotation of the sun in the low and middle stratosphere. In addition, from multiparametric analyses using consistent datasets (e.g. NCEP and ECMWF (ERA40) reanalysis) solar fingerprints are found in temperature, humidity and pressure (wind) patterns, including interactions with climate modes such as QBO and AO. However, uncertainties exist due simultaneous effects of volcanic aerosols, human effects through greenhouse gases and aerosols, effects of climate modes such as ENSO as well as due to disagreement between the datasets especially in the middle and upper stratosphere.
- Although an impressive agreement was found between the long-term variation of the Northern hemisphere land air temperature and the long-term variation of solar activity in terms of inverse solar cycle length (SCL) during the period of instrumental temperature measurements from 1861 to 1989, new studies indicate that methodological errors were made in the analysis and that results were highly insignificant. Also, it has been found that since around 1990 the type of solar forcing that is described by the SCL model no longer

dominates the long-term variation of the northern hemispheric land air temperature. Moreover, it remains unclear by what mechanism the solar cycle length influences climate.
- Statistical approaches continue to be used to link solar activity and cloud cover but with ambiguous findings. In the ISCCP dataset low clouds are apparently increased at low solar activity, mainly at sub tropical and mid latitudes. But under debate is whether the cause is enhanced cloud condensation nuclei from increased cosmic ray fluxes, solar irradiance heating of sea surface temperatures or ENSO, rather than solar variability. However, the relation between solar heating and cloud cover over the (sub)tropical oceans is questionable since most of the change in irradiance from minimum to maximum solar activity is located at the shorter wavelengths, which do not reach the earth surface. Furthermore, the consequences of the claimed relation, i.e. a strong 11- year cycle in temperature and a long term decrease of cloudiness, are contrary to observations.

5.6 Mechanisms of Solar Influence on Climate

- Variations in the visible part of the solar irradiance affect the atmosphere from below and can be dealt with as a radiative forcing. This mechanism has been studied quite substantially in various types of climate model experiments and the climate response of changes in the total solar irradiance (TSI) is relatively well known. It is concluded that most probably variations in TSI on time scales of the 11-year solar cycle are small (order of magnitude 0.1 %). Model studies show lower temperature response per unit of radiative forcing (expressed as a fraction of the change TSI) by a factor between 0.75 and 1 for solar variability related to the 11-year sunspot cycle than for well-mixed greenhouse gases. This is probably related to the fact that the largest variability of solar irradiance changes takes place in the UV region. UV radiation is largely absorbed in the higher atmosphere by oxygen and ozone. Changes in UV are therefore an inefficient forcing for the surface-troposphere system.
- There are some indications that the sensitivity for decadal to centennial scale variations of solar activity could be slightly higher than for well-mixed greenhouse gases. This may be related to changes in ocean circulation and to interactions with climate modes as an amplifying mechanism the solar forcing. It would result in slightly higher temperature changes from the Maunder Minimum to the present average sun than the previously mentioned upper limit of 0.4 degrees.
- The actual temperature response (in contrast to the equilibrium response) of the climate system is strongly dependent on the period of the imposed radiative forcing due to the heat capacity and thus buffering of the world’s oceans. For instance, for a radiative forcing of 1 Wm^{-2} due to the solar cycle of ~200 years (Suess cycle) the amplitude of the global mean temperature response is a factor two to four times larger than for the same forcing due to the 11-year sunspot cycle, depending on climate sensitivity, depth of the ocean mixing layer and the strength of the diffusion of heat within the ocean.
- The physics behind the influence of UV- radiation on the atmospheric composition and state are well established. Changes in UV-radiation affect directly the stratosphere and the ozone distribution, thus influencing the lower atmosphere from above. The computed changes of stratospheric ozone, temperature, zonal wind and geopotential heights are in general agreement with observed changes between solar minimum and maximum, especially during early and late winter. Radiative forcing results show that the 11-year solar cycle effect on global mean temperature is negligible, but simulated responses of sea-level pressure do suggest that regional effects are probably significant, e.g. by affecting the North Atlantic Oscillation. This tropospheric response is likely to be generated by a chain of dynamical interactions, such as stretching of the Hadley cell and changing the reflection and absorption properties of planetary waves in the stratosphere. Up till now, from the available model studies no definite conclusions can be drawn.
- Variations of particle radiation of the sun, such as the Coronal Mass Ejections and/or variations in cosmic radiation, hence features related to the outflow of magnetised plasma from the Sun and its confinement into the heliosphere, may influence the aa-index and may also have an effect on the electrical and magnetic properties of the earth’s atmosphere, eventually causing a change in the atmospheric composition (either by aerosol or cloud formation, or an influence on the concentration of ozone). However, for the cosmic ray –

cloud link no clear physical framework exists neither have any convincing studies been published in recent years.

- Unequivocal determination of the mechanism(s) by which changes in solar activity influence earth's climate is complicated since the different mechanisms may alter similar aspects of the climate system in different ways. Furthermore, these mechanisms may operate simultaneously on a variety of physical processes with possible mutual interactions and with climate variability modes. In addition, each of these mechanisms has its own spatial, altitudinal and temporal response pattern. Finally, they are likely to depend on the background state of the climate system, and thus on other forcings, such as the anthropogenic forcing, that can alter this state.

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Chapter 2. SOLAR VARIABILITY INFLUENCING CLIMATE

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Chapter 3. SOLAR FORCING OF CLIMATE: EVIDENCE FROM THE PAST

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Chapter 4. The solar-terrestrial link from a climate point of view

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