Influence of Solar Activity Cycles on Earth's Climate

Task 6 – Modelling Potentials

WP 601 – External Forcing
WP 602 – Interaction Mechanisms

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1 Introduction

Under Task 5 various physical mechanisms whereby solar variability may influence climate were identified. Here the tools required to test these hypotheses are assessed. In Section 2 the nature of the solar forcing for each mechanism is outlined and the necessary solar data identified. Section 3 suggests experiments with general circulation models (GCMs) designed to test the various mechanisms, the necessary configurations and feasibility of implementation.

2 External Forcing

In WP201 sources of data related to different aspects of solar variability were identified. In Table 1 the specifications for those required as input for assessment of the various hypothetical mechanisms are given.

Table 1 Solar forcing parameter requirements for each mechanism.

Mechanism	Solar input	Time-scale	Requirements	Availability
TSI	Total solar irradiance	11-year cycle	Many cycles $\Delta t \sim 1$ month	Yes, for nearly 3 cycles, although absolute value and underlying trends not well established.
		Multi-decade to century	$\Delta t \sim 1$ year (annual cycle imposed)	Yes – based on proxy solar activity measures - but absolute value not known and large uncertainties in secular trend.
Radiative heating of the middle and lower atmosphere	UV/visible spectral irradiance	27-day cycle	$\nu \sim 4{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 4{,}000\text{cm}^{-1}$ Many cycles (at solar max) $\Delta t \sim 1$ day	Yes, for 3 solar maxima.
		11-year cycle	$\nu \sim 4{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 4{,}000\text{cm}^{-1}$ Many cycles $\Delta t \sim 1$ month	Yes, for nearly 3 cycles, but data not contiguous and uncertainties in spectrum.
		Multi-decade to century	$\nu \sim 4{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 4{,}000\text{cm}^{-1}$ $\Delta t \sim 1$ month	No

UV production / destruction of ozone	UV spectral irradiance	Solar flares	$\nu \sim 14{,}000 - 23{,}000\text{cm}^{-1}$ $\Delta\nu \sim 200\text{cm}^{-1}$ and $\nu \sim 28{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 500\text{cm}^{-1}$ Many flares $\Delta t \sim 1$ hour	Records of flare events but not of spectra.
		27-day cycle	$\nu \sim 14{,}000 - 23{,}000\text{cm}^{-1}$ $\Delta\nu \sim 200\text{cm}^{-1}$ and $\nu \sim 28{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 500\text{cm}^{-1}$ Many cycles (at solar max) $\Delta t \sim 1$ day	Yes, for 3 solar maxima.
		11-year cycle	$\nu \sim 14{,}000 - 23{,}000\text{cm}^{-1}$ $\Delta\nu \sim 200\text{cm}^{-1}$ and $\nu \sim 28{,}000 - 86{,}000\text{cm}^{-1}$ $\Delta\nu \sim 500\text{cm}^{-1}$ $\Delta\nu \sim 400\text{cm}^{-1}$ Many cycles $\Delta t \sim 1$ month	Yes, for nearly 3 cycles, but data not contiguous and uncertainties in spectrum.
SPEs destruction of ozone	Solar proton flux spectra	Several days (for each event)	$E \sim 0.5$ - 500MeV $\Delta E/E \sim 1$ Many events $\Delta t \sim 1$ day Geographical distribution of insertion locations.	Yes
Solar wind	V and Bz	Months	Daily	Yes, since 1962
Ionisation	Solar-modulated cosmic rays	Forbush decreases	Many events $\Delta t \sim 1$ hour	Yes, 50 years data, but only indirectly in the form of neutron counts
		11-year cycle	Many cycles $\Delta t \sim 1$ month	Yes, but only indirectly in the form of neutron counts

Table 2 identifies the data inputs and anticipated outputs of a scheme designed to test the various hypothetical mechanisms.

Table 2 Fundamental physical/chemical processes associated with each mechanism.

Mechanism	Process	Inputs	Outputs
TSI	Variations of heating of land and sea surface; influence on cycle atmospheric and oceanic circulation and on hydrological cycle.	Temporal variations in TSI.	Response in temperature, wind, precipitation, ocean currents.
UV	Direct heating by UV.	UV spectral irradiance. Distributions of radiatively active gases (esp. ozone). Cloud distribution and radiative properties.	Heating rates as a function of latitude, longitude, altitude and time.
	Dynamical coupling (within the middle atmosphere).	Solar heating rate anomalies as a function of position and time (with and without ozone response).	Response of the middle atmosphere to solar UV variation: temperatures, wind and wave activity. Any additional effects due to ozone changes.
	Stratosphere-troposphere dynamical coupling.	Solar heating rate anomalies plus the response to these of stratospheric temperatures and winds.	Response of tropospheric circulations to perturbations in the stratosphere.
	Production of ozone by UV.	UV spectral irradiance as a function of time. Distributions of source gases and temperature.	Photochemical production rate of ozone as a function of latitude, longitude, altitude and time.
	Ozone transport.	Dynamical response of atmosphere to enhanced UV (i.e. changes in wind distribution).	Response of ozone concentration distribution to solar UV as a function of latitude, longitude, altitude and time.

SPEs	Destruction of ozone by SPEs.	SPE flux spectra. Distributions (climatology) of temperature, wind and chemically active constituents.	Response of NO_x and O_3 to solar proton events.
Solar wind	Reconnection	V and Bz	Magnetospheric/ionospheric disturbances: downward propagation and influence on polar dynamics.
Ionisation	Cosmic ray induced ionization plus ion induced nucleation	Ionization (cosmic rays) Aerosol and source gas concentrations Water vapour concentration	Cloud distribution and properties

3 Interaction Mechanisms

The influence of different values of TSI on tropospheric climate have been studied since the inception of climate models. In an early study, using a model with "swamp" ocean and fixed cloud cover, Wetherald and Manabe (1975) found greatest response at high latitudes due to ice-albedo feedback and an enhanced sensitivity of the tropical hydrological cycle. These signals were essentially similar to those derived in response to an enhanced concentration of carbon dioxide (Manabe and Wetherald, 1975) with both showing enhanced downward fluxes of thermal radiation at the surface, due to higher water vapour concentrations, and reduced static stability in mid to low latitudes where moist convection dominates. Despite the advances in GCMs since that date, subsequent studies have shown overall similar responses to variations in TSI and greenhouse gas concentrations: more water vapor in the atmosphere, reduced vertical overturning in the tropics and resultant increases in equatorial precipitation and decreases in the subtropics, as explained by Held and Soden (2006). Shindell et al (2006) show these features but also demonstrate that the solar signal is greater when ozone changes are taken into account. Meehl et al (2003), however, suggest that there are cloud-radiation feedbacks which act preferentially for solar, rather than greenhouse gas forcing. These occur because solar forcing is more spatially heterogeneous - acting more strongly in areas where sunlight reaches the surface - while greenhouse gas forcing is more spatially uniform.

Modelling studies of the solar modulation of climate via UV have traditionally been carried out by first estimating the predicted ozone changes between solar minimum and solar maximum (or 20th century versus Maunder Minimum values) using 2-D models that include relatively sophisticated chemical schemes (Haigh, 1996; Shindell, 1999). These monthly-averaged, zonally-averaged ozone changes are then used as input to the radiation schemes of full GCM simulations. In this way, the temperature and circulation response to the ozone changes can be assessed, although there is no possibility for those temperature and circulation changes to interactively feed back onto the ozone distributions. The prime methodology employed to assess the impact of including these

additional ozone changes is to carry out model simulations with only TSI changes and compare them with simulations with both TSI and ozone changes. Results suggest that inclusion of solar-induced ozone changes do indeed enhance the solar signal in the troposphere.

Most 'process' modelling studies, that seek to simulate the solar signal and thence explore the process mechanisms, employ models that extend from the ground to around 80 km in order to fully resolve the ozone distribution in the stratosphere. Most of these, however, are unable to reproduce the secondary temperature (and ozone) maximum in the lower stratosphere (see section 7 of WP403). This is important because it not only represents a deficiency in the simulation of the middle atmosphere itself but also means that the stratospheric anomaly required as forcing for any stratosphere-troposphere coupling mechanisms is not adequately provided. It suggests an underestimation of the modelled dynamical feedback through a modification of the meridional circulation and this requires further investigation. There are also many deficiencies in the model simulations of the interaction between the solar and QBO influences (Labitzke et al. 2002) and these may be related to the same dynamical problems. Very few of the models employed include an adequate gravity wave parametrization scheme and this may be one factor that requires improvement (Arnold and Robinson, 2003).

Because of computing resource constraints, GCM simulations of solar influence have often consisted of two 20-30 year runs, under perpetual solar minimum conditions and perpetual solar maximum conditions respectively, and the difference between the two runs used as an estimate of the peak-to-peak solar signal. By running for many years in 'perpetual' mode like this, the statistical significance of the results is substantially improved. In order to gain the equivalent statistical significance from a single simulation in which the time-varying 11-year solar signal is imposed, the simulation would need to be many hundreds of years long. Employing a coupled ocean-atmosphere model in which the ocean temperatures can adjust to the imposed solar changes is inappropriate for integrations of this type employed for 11-year solar cycle studies, because the atmosphere is never actually in solar minimum or maximum for long enough for the ocean to adjust to any great extent. In this case, the models have been used with observed or climatological-mean sea surface temperatures imposed at their lower boundaries. On the other hand, estimates of longer term solar changes, such as those between 20th century and Maunder Minimum values, are more appropriately carried out using a coupled model in which the ocean temperatures are able to respond and feedback onto the atmosphere component of the model.

Recently, improved computing capabilities have allowed the development of GCMs that include fully-coupled chemistry schemes so that improved feedback is possible not only from the ozone changes on to the temperature and circulation patterns but vice versa. However, the use of these fully-interactive chemistry GCMs for studies of the solar cycle influence is still at a relatively immature stage (e.g. Labitzke et al. 2002, Tourpali et al. 2003, Egorova et al. 2004, Haigh et al. 2004, Langematz et al. 2005, Schmidt et al. 2006). Runs with both coupled oceans and chemistry are at the limit of what is possible with current computing capacity: the two fully-coupled 100-year integrations carried out by Shindell et al (2006) took 9 months CPU time.

To study effects of changes in the solar wind, through coupling downwards from the magnetosphere/ ionosphere, models which extend to the upper atmosphere and include ion chemistry are needed. Models of the upper atmosphere including the necessary physical and chemical processes have existed for some time but it is only recently that "whole atmosphere" models have been developed such as the NCAR WACCM model (e.g. Richter and Garcia, 2006) and the Hamburg HAMMONIA model (Schmidt et al, 2006). With their full vertical extent these have only been run in atmosphere-only mode.

To test the effect of ion-induced nucleation on cloud cover it would be necessary to represent the entire chain of processes from the initial ionization to the growth of a particle to the size required for a cloud condensation nucleus. All these processes are not yet fully understood and, in any event, would be too complex and small-scale to simulate in a GCM. However, the influence of the presence of atmospheric aerosol on cloud droplet size and concentration (the so-called "first indirect effect" of aerosol on cloud radiative forcing) is already represented in many GCMs and so, to simulate a hypothesized effect of ion-induced nucleation would only require a parameterization of aerosol growth as a function of cosmic ray ionization (presumably dependent on altitude and latitude). The main problem would be the assumptions necessary to determine to what extent this process took place in competition with all other aerosol-producing factors.

Table 3 attempts to present a picture of the model developments, and experiments, required to test the solar-climate mechanisms identified in this project. The basic models required exist, and relevant experiments have already been conducted, but many questions remain.

Table 3 Proposed GCM experiments to test mechanisms.

Mechanism	**Process**	**GCM experiment**	**GCM type/specification**	**Notes**
TSI	Effects of different TSI on atmosphere-ocean system.	Time slice runs at low and high TSI values.	"Standard" climate model extending from surface to mid-stratosphere, with coupled ocean. [We refer to this model as M0]	> 20 year runs.
	Effects of time-varying TSI on atmosphere-ocean system.	Decadal-centennial scale response.	M0	Need ensemble of runs plus statistics from very long (~1000 year) control run of model.

UV	Effects of enhanced UV on the dynamical structure of the middle and lower atmosphere.	Time slice runs at low and high (spectrally-resolved) UV.	M0 without coupled ocean but extending from surface to mesopause. Good vertical resolution (need intrinsic QBO). Radiation scheme with adequate spectral resolution. [M1]	> 40 year runs.
		Mechanistic studies of wave effects in middle atmosphere.	Stripped-down M1. E.g. raise lower boundary to tropopause, remove tropospheric physics (clouds etc)	Multiple runs to investigate statistics of wave propagation, sudden stratospheric warmings, link to radiative forcing distribution.
		11-year cycle modulations	M1	> 20 cycles (~200 years).
		Role of ocean in 11-year cycle.	M1 with coupled ocean. [M2]	ditto
		Decadal-centennial scale response to solar UV.	M2	Need ensemble of runs plus statistics from very long (~1000 year) control run of model.
	Coupling between dynamics and chemistry (ozone)	Time slice solar max and solar min runs, response of oceans.	M1 with coupled chemistry scheme [M3]	> 20 year runs.
		27-day cycle modulations	M3	~ 20 year run
		11-year cycle modulations	M3	Many cycles.

	Fully-coupled atmosphere-ocean-chemistry	Decadal-centennial scale.	M2 with coupled chemistry. [M4]	Long runs with coupled oceans and chemistry not currently feasible. Could (i) repeat centennial run of M2 with prescribed (varying) ozone or (ii) time slice runs of M4 with high and low solar activity.
	Stratosphere-troposphere dynamical coupling.	Mechanistic studies of tropospheric response to perturbations in stratosphere.	Adapted M1. E.g. lower top to mid-stratosphere, increase vertical resolution near tropopause, simplify radiation scheme.	Multiple runs to investigate dynamical processes, especially wave propagation, response to stratospheric heating.
SPEs	Destruction of ozone by SPEs.	Effect of enhanced NO_x, including subsequent transport of low O_3 air.	M3 extended upwards into ionosphere [M5] or M3 with specified downward flux of NO_x.	Each run few months. Need ensembles to confirm statistics.
		Combined effects of UV and SPEs.	ditto	Ensemble of >20 year time slice solar max and solar min runs with SPEs added in solar max runs.
Solar wind	Reconnection, planetary waves	CME frequency/ proton events	M5	>40 years

Ionisation	Cosmic ray modulation of cloud cover.	Impact of ionisation on local cloud (timescale of Forbush decreases)	M0 plus specified ion-induced aerosol. [Parameterisations of aerosol "indirect" effect on cloud already exist.]	Ensemble of many events
		Impact of ionisation on cloud plus cloud-radiation feedbacks	ditto	Ensemble of >20 year time slice solar max and solar min runs with GCRs increased in solar min runs.

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