Description and First Results of the EC Project SOLICE (Solar Influences on Climate and the Environment)

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Abstract

Recent statistical studies of observational records suggest that solar effects do play a significant part in natural climate variability. However, a physical mechanism to account for the apparent solar effects has not been fully developed. Variations in solar ultraviolet radiation (UV) are much greater than that in total irradiance and, because this UV is absorbed in the middle atmosphere causing additional ozone formation, it is possible that stratospheric processes may excite a response in the climate of the lower atmosphere. In the SOLICE project we adopt a co-ordinated plan of modelling and observational studies designed to produce new assessments of the impact of solar variability on climate and to address some of the key questions concerning the mechanisms whereby these take place.

Introduction: Mechanisms for solar-climate links

The most simple way in which a change in solar output can impact the Earth's climate system is through the change in the wavelength-integrated irradiance reaching the Earth, generally referred to as the Total Solar Irradiance (TSI). Many studies have explored the direct relationship between solar irradiance and climate by correlating time series of TSI or various proxies of solar activity (e.g. solar cycle length) with surface temperature. Alternatively, model studies have examined the impact of including solar forcing in addition to other forcing such as greenhouse gases and tropospheric aerosol amounts. These studies suggest that the direct effect of solar variation is not negligible but do not explain the amplitude of the apparent response in, for example, the 30hPa geopotential height. Considering that the amplitude of solar variability is the largest in the UV part of the spectrum and the fact that UV irradiance change affects both the radiative forcing and the mean meridional circulation, we intend to examine in detail in this project whether this could induce indirectly a change in the atmosphere and in the climate compatible with the observations. Let us summarise below the two main ways whereby it could enhance or modify the impacts of changing TSI.

a) Radiative Forcing

Variations in stratospheric composition and thermal structure resulting from UV changes may have an impact on tropospheric climate through changes in radiative forcing (Haigh, 1994). Thus, in addition to a direct increase in downward short-wave irradiance at the tropopause, higher solar activity can cause an increase in downward infrared flux by heating the stratosphere and also a radiative forcing due to ozone changes. However, the sign of the ozone effect is not well established. The direct solar radiative forcing between minimum and maximum periods of solar activity over the 11-year activity cycle is about 0.3 Wm^{-2}. The additional forcing due to ozone increases and lower stratospheric warming has been calculated by different authors (including Haigh, 1994) with quite different results ranging from – 0.13 to + 0.05 Wm^{-2}. This disparity in both sign and amplitude may reflect the different approaches used in specifying and/or calculating ozone changes and the stratospheric temperature response

b) Mean meridional circulation and wave-mean flow interaction

Changes in the ozone in response to the solar cycle also have the potential to change circulation patterns via the changes in temperature. For example, changes in the latitudinal temperature gradients will lead to changes in zonal and meridional wind distributions at all levels of the atmosphere. Haigh, (1999) found a sensitivity of the strength and width of the Hadley circulation to typical changes in ozone: during a solar maximum the subtropical jets moved polewards and the associated Hadley circulation was found to weaken and broaden. Shindell et al., (1999) on the other hand, although reporting a similar poleward movement of the subtropical jets, found the strength of the Hadley circulation to increase. The difference may be due to the way in which the ozone changes are

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imposed and the extent to which they alter the static stability of the tropical lower stratosphere. In the stratosphere temperature changes will lead both to meridional circulation changes and also to changes in zonal wind strength, which will then alter the pattern of planetary wave propagation

Observations of the middle atmosphere response to solar forcing.

The enhancement of shorter wavelength radiation during periods of greater solar activity means that the largest direct radiative heating of the atmosphere is felt at higher altitudes. More specifically increased levels of ultraviolet radiation in the wavelength range 175-320 nm heat the stratosphere and mesosphere due to absorption by ozone and oxygen. The temperature response to the 11-year solar cycle has been observed in the last decades in the whole middle atmosphere and above using a number of different techniques. From the thermosphere to the troposphere, one can mention : incoherent radar, sodium trails, rockets, Rayleigh lidar, SSU satellites, and, for the lower part of the stratosphere and the troposphere, radiosondes (e.g.: Labitzke and van Loon 1997). Most of those results have been reviewed in Chanin et al., (1989) and more recently by Chanin and Ramaswamy in the recent WMO-UNEP Scientific Assessment of Ozone Depletion, 1998 (WMO, 1999). The horizontal structure of the response is obtained by the global maps obtained from radiosondes and SSU, whereas the other sets of data provided a description of the vertical structure of the response at different latitudes. The analysis of all the available data indicates that the solar signature on atmospheric temperature is highly variable in amplitude (from 50K to a fraction of 1K) and in sign, both with latitude and altitude. The facts that the response changes its sign with altitude with a vertical wavelength of the order of 20-30 km and that its amplitude depends on the sign of the quasi-biennial oscillation (QBO) have been interpreted as indicating a role of planetary waves in amplifying the direct solar signal. (Chanin et al., 1989), but no clear mechanism was put forward to explain this result. The change of ultraviolet spectral irradiance should also affect the ozone concentration. However the ozone changes are less well documented, even though there are some results from ozone measurements obtained by ground-based and satellite which suggest a variation of about 2% in global total ozone between periods of minimum and maximum activity over the Sun's 11 year cycle.

However until recently the models could not reproduce the latitude and altitude structure of the observations of both the temperature and ozone changes, very likely because they were only two-dimensional (2D) (Brasseur 1993, Haigh 1994). If the agreement between temperature data and 2D models at the tropics is quite satisfactory, this is not at all the case at mid and high latitudes, as the models do not predict the change of sign of the correlation. Similarly the 2D photochemical-transport models predict a variation of around 2% change in global total ozone in response to changes in ultraviolet spectral irradiance, as measured by satellite instruments. However, the models do not reproduce the latitude and altitude structure observed in the satellite data and tend to overestimate the response in the middle stratosphere and underestimate it in the lower stratosphere. It is well known that 2D models cannot satisfactorily represent changes in three-dimensional planetary-scale wave transport of ozone and this may be the cause of the discrepancies. It should also be recognised that the satellite data cover less than two solar cycles and it is possible that other effects have been aliased onto the solar signal.

Results of recent modelling studies

More recently, the impact of the heating of the middle atmosphere on the dynamics has been recognised in several 3D modelling studies. Kodera et al. (1991), Kodera (1995), Balachandran and Rind (1995) and Shindell et al.,(1999) used climate models and data analysis to study the response of the winter polar stratosphere to solar ultraviolet changes. They showed that anomalies in mean zonal wind, introduced into the mid-latitude upper stratosphere in early winter by changes in the latitudinal distribution of solar heating, could modify the interaction with the mean flow of vertically propagating planetary waves such that the zonal wind anomaly propagated downwards and polewards through the winter. They also modelled the extra-tropical response to the QBO of tropical lower stratospheric winds and proposed that the QBO could modulate the solar effect such that the downward and poleward propagation of a westerly wind solar anomaly would be more likely to take place during the east phase of the QBO. This is consistent with the observations of Labitzke and van Loon (e.g. 1997) which showed much stronger correlation between 30hPa geopotential height and 10.7cm solar index in winter when the data were sorted by the phase of the QBO. It may also explain the planetary wave structure observed in the other dataset (Chanin et al, 1989). In Kodera's studies, the westerly wind anomaly penetrates down to the troposphere so that his work may explain some of the observations of apparent climatic response to solar variability in the lower atmosphere in winter.

Variations in solar UV also affect stratospheric ozone concentrations. Haigh (1996, 1999) and Shindell et al (1999) have shown that the inclusion of solar-induced ozone variations significantly enhances the ability of GCMs to reproduce the observed solar effects.

These recent results have built the ground on which the SOLICE project is based.

Objectives of SOLICE

The main objectives of the study are to:

- Assess the effects of solar variability on climate, including regional and seasonal effects, using a range of general circulation models (GCMs).
- Assess the impact of solar variability on stratospheric ozone, radiative forcing of climate and surface UV using coupled chemistry-climate models.
- Investigate the internal variability of the stratosphere and the impact of the quasi-biennial oscillation on solar effects using GCMs and mechanistic models.
- Provide 3D measures of the solar signal in temperature, geopotential height and ozone using a unified methodology and data extending over the next solar maximum.
- Carry out a detailed intercomparison and analysis of model and observational results to advance understanding of the mechanisms behind solar-climate links.
- Contribute to international model intercomparisons and trend assessments such as those under the remit of the SPARC project.

Participants in SOLICE

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- Aristotle University of Thessaloniki, Greece (AUTH): Prof. C. Zerefos
- Council for the Central Laboratory of the Research Councils, UK (CCLRC), Rutherford Appleton Laboratory (RAL): Dr. L. J. Gray
- University of Arizona, Tucson, USA (LAPL): Prof. L. L. Hood
- Goddard Institute for Space Sciences, USA (GISS): Dr. D. T. Shindell

Description of the Project

A co-ordinated programme of numerical modelling and data analysis is planned.

a) Numerical Modelling

In order to achieve these objectives we propose a study involving several co-ordinated modelling and data activities. Long (twenty year) simulations of the effects of enhanced solar spectral irradiance, and of solar-induced stratospheric ozone increases, on the climates of two different general circulation models (GCMs), extending throughout the troposphere and middle atmosphere, will be produced and the results analysed to assess the role of troposphere-stratosphere interactions in amplifying the solar effects. By imposing appropriate accelerations in the tropical lower stratosphere the same models will be used to assess the impact of the quasi-biennial oscillation (QBO) on these results. The natural internal variability of the stratosphere and its sensitivity to changes in solar irradiance and the QBO will be assessed using a stratosphere-mesosphere model, which will allow multiple long runs for sensitivity studies.

The modelling studies will incorporate series of experiments with models of various types designed to investigate different aspects of the interaction of solar radiation with the chemical and dynamical structure of the lower and middle atmosphere. These will include the first ever simulations of the effect of variations in solar spectral irradiance, on both 27-day and 11-year timescales, on stratospheric ozone using general circulation models (GCMs) with coupled stratospheric chemistry. GCMs will also be used to study links between the stratosphere and tropospheric climate including the effects of solar-induced changes in stratospheric climate on wave propagation and how this is modulated by the quasi-biennial oscillation (QBO). The modulation of sea surface temperatures by solar variations and the effect on climate will be studied using a GCM with a coupled ocean in the context of other GCM climate simulations. Chemical transport models will allow detailed investigations of solar impact on stratospheric chemistry and a 3D dynamical model of the middle atmosphere will be used to investigate the internal variability of the stratosphere, its response to solar variability and how this is impacted by the QBO.

b) Updating of data sets

The data studies will involve the development of a unified method for the analysis of global three-dimensional fields of temperature and ozone in the context of the response of these fields to other factors including the QBO and volcanic eruptions. We propose to update the analysis of the solar signature in the longest available data sets of atmospheric parameters from the ground to the mesosphere. This large altitude region is considered to include both direct responses on ozone and molecular oxygen but also signatures associated with possible downward propagating effects and feedback. The parameters considered are temperature, geopotential heights, ozone and winds. This choice is made for the following reasons: temperature results partly from radiative equilibrium and plays a central role in chemistry and dynamics; geopotential heights reflect the temperature of the underlying column; ozone is a key parameter in the atmospheric radiative balance and its density is directly related to UV solar changes. Those three parameters have already been analysed in term of solar influence in the past, but these studies suffer from inhomogeneities in the calculation of the solar relationship (temporal and spatial average, QBO phases, different analysis method etc.). And finally, wind measurements are also of great interest as they can answer some of the questions related to the dynamical contribution and have not yet been investigated by many authors in a systematic manner. Almost all the existing data sets will continue to acquire new data during the coming years (except SSU). This period will be of major interest as a new solar maximum is due which we hope will be free of any disturbance by major volcanic eruptions, as was the case during the last two solar maxima.

The unified analysis method will include the use of a linear regression model and EOF analysis. The linear regression model used will include seasonal components (annual and semi-annual), a trend, a function related to solar activity (10.7 cm solar flux), a function of the QBO, a function of ENSO, and a function related to stratospheric aerosol optical depth (AOD) The addition of the EOF analysis represents a valuable complementary analysis technique as EOFs are derived from the data itself without need of any a priori assumptions or external functions. These methods are being implemented, but the reanalysis is delayed to include the solar maximum into the data set. Only the set of data used by Labitzke and van Loon (1997) has been updated. It confirms the high correlation between 30hPa geopotential height and the 10.7cm solar index over nearly four solar cycles between 1958 and 1999.

c) Intercomparison between data and models

Comparison of the results of the modelling and data studies will be made to validate the models and the model results will then be analysed to elucidate details of the mechanisms whereby solar variability affects climate. The results will also be used to calculate solar radiative forcing parameters, taking proper account of the response of stratospheric ozone, and to estimate the regional impacts of solar variability.

Selected First Results

The first SOLICE results to date have been obtained by Larkin et al., (2000) from GCM runs using different assumptions concerning changes in solar irradiance and solar-induced ozone. The results presented in figures 1 and 2 show the sensitivity to the assumptions made. This is a key issue at the early stage of the project, as these conclusions need to be taken account by the other groups before doing the 20 years runs.

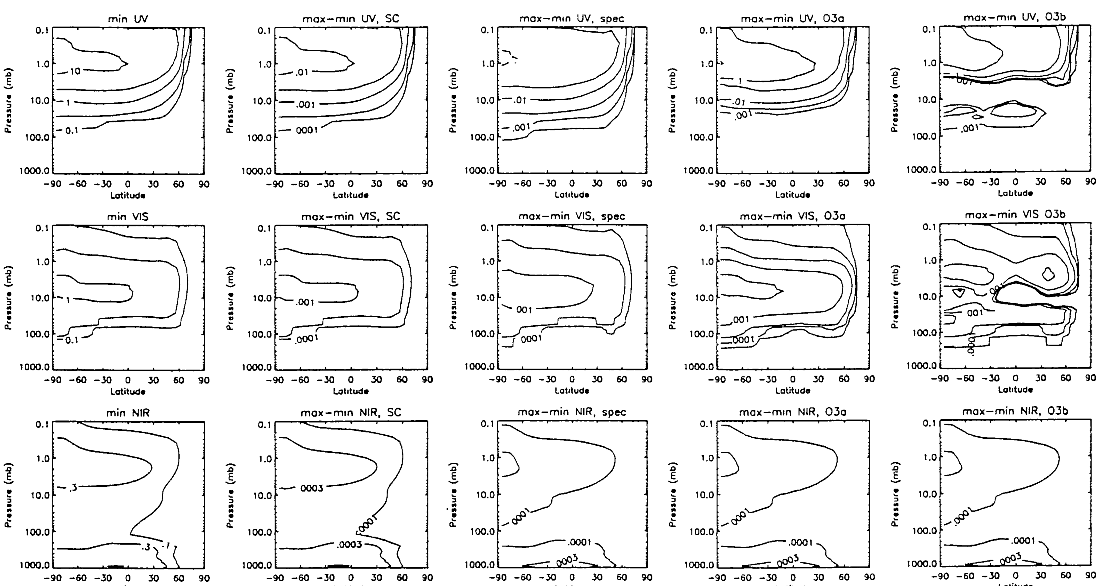

Figure 1 : zonal mean solar heating rates (K d^{-1})
First column solar minimum values.
Columns 2-5 show difference between solar max. and solar min. assuming:
Column 2: 0.08% in TSI uniform across spectrum.
Column 3: 0.08% in TSI with spectral distribution.
Column 4: As col.3 plus ozone increase from 2D model.
Column 5: As col.3 plus ozone increase from SBUV/TOMS.
Contours are shown at 1x10n and 3x10n with the range of n varying between frames.

The figure 1 shows the zonal mean solar heating rates (K d^{-1})) for solar minimum and for the difference Max-Min, and this for different spectral ranges: (220-320nm, 320-690nm, 690-10000nm), different spectral distribution of the TSI (0.08% in TSI uniform across spectrum and 0.08% in TSI with spectral distribution, and different distributions of the ozone increase: ozone increase from 2D model and ozone increase from SBUV/TOMS. The conclusions from these runs show that one should include in the models the spectral distribution of irradiance change (which gives almost an order of magnitude increase in stratospheric heating rates) and also include ozone changes (which gives another factor of about 3 in the stratosphere and shows that the structure of heating rate change depends on the structure of the ozone change). The issue is that the vertical and latitudinal structure of the ozone change are not well known and therefore should be better extracted from the data if possible before the runs are performed.

The figure 2 shows the mean meridional circulation for 2 seasons (DJF and JJA) for solar minimum and for the difference solar maximum-solar minimum with 2 different imposed ozone changes: 2D model ozone changes and TOMS/SBUV ozone changes. The solar minimum case shows large winter Hadley cell with positive (clockwise) values in DJF and opposite in JJA. One can also see weaker summer hemisphere Hadley cell and mid-latitude Ferrel cells. The conclusions from these second sets of runs are that in both experiments the winter cells weaken, and there is some indication that summer cells do likewise and that Ferrel cells get push polewards. This has implications for local changes in climate, especially in mid-latitudes where vertical air motion changes significantly.

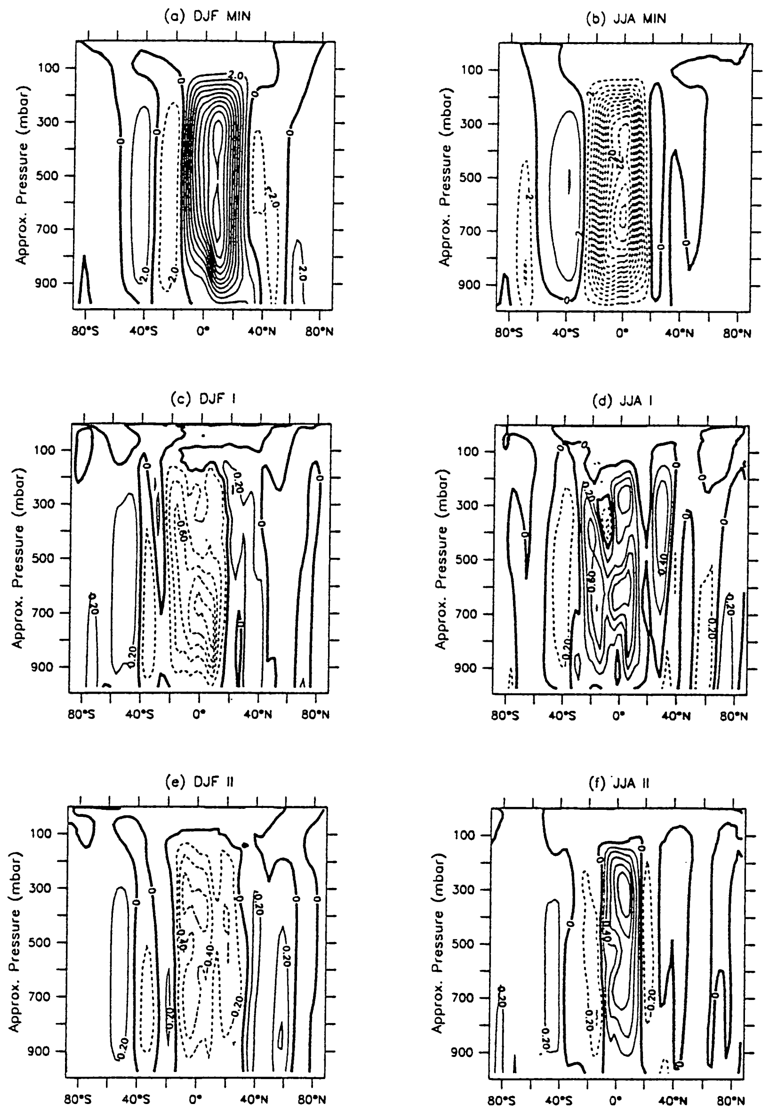

Figure 2 : mean meridional circulation for 2 seasons (left DJF, right JJA).
Top row: solar minimum run.
Second row: difference between solar min. and solar max. in experiment with 2D model ozone changes.
Third row: as above but with TOMS/SBUV ozone changes.

Contribution of SOLICE to the international Project SPARC/WCRP

The SPARC Project (Stratospheric Processes and their Role in the Climate) has been asked by the World Climate Research Programme (WCRP) to study further the issue of the solar influence in climate. This is being done within the modelling component of SPARC: GRIPS. SOLICE has already contributed to the international intercomparison of the response of different models to solar forcing. The first set of models includes the Imperial College, GISS and MRI models. The results of the intercomparison indicates very clearly the influence of the structure of ozone distribution between solar maximum and solar minimum on the short wave heating rate difference and therefore on the mean temperature difference between solar max and solar min. However the zonal-mean wind difference between solar maximum and solar minimum has similar features for the 3 models.

Conclusion

After this project is over, more definitive statements will be possible concerning (a) whether and how variations in solar irradiance affect the circulation of the middle atmosphere and the lower atmosphere (including the Hadley circulation) and how these are inter-related, (b) how and to what extent solar variations affect planetary wave propagation in the middle atmosphere and (c) the sensitivity of climate studies to the inclusion of various factors such as interactive ozone and the QBO. As a result of these model intercomparisons it will be possible to make well based statements on which factors need to be included in GCMs for realistic simulations of climate and climate change.

New model results of the impact of solar variability on atmospheric chemistry and climate and new analysis, including data from the next solar maximum, of the solar signal in observations of temperature and ozone are expected in the next 3 years from SOLICE

It should contribute to advance our understanding of the mechanisms whereby solar variability affects climate and lead to a new assessment of the solar radiative forcing of climate.

An assessment of the impacts of solar variability on seasonal and regional variations in climate and on surface UV should also be obtained. This research effort carried out in cooperation with SPARC should contribute to international detection/attribution studies.

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