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An influence of solar spectral variations on radiative forcing of climate

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The thermal structure and composition of the atmosphere is determined fundamentally by the incoming solar irradiance. Radiation at ultraviolet wavelengths dissociates atmospheric molecules, initiating chains of chemical reactions—specifically those producing stratospheric ozone—and providing the major source of heating for the middle atmosphere, while radiation at visible and near-infrared wavelengths mainly reaches and warms the lower atmosphere and the Earth's surface[1]. Thus the spectral composition of solar radiation is crucial in determining atmospheric structure, as well as surface temperature, and it follows that the response of the atmosphere to variations in solar irradiance depends on the spectrum[2]. Daily measurements of the solar spectrum between 0.2 µm and 2.4 µm, made by the Spectral Irradiance Monitor (SIM) instrument on the Solar Radiation and Climate Experiment (SORCE) satellite[3] since April 2004, have revealed[4] that over this declining phase of the solar cycle there was a four to six times larger decline in ultraviolet than would have been predicted on the basis of our previous understanding. This reduction was partially compensated in the total solar output by an increase in radiation at visible wavelengths. Here we show that these spectral changes appear to have led to a significant decline from 2004 to 2007 in stratospheric ozone below an altitude of 45 km, with an increase above this altitude. Our results, simulated with a radiative-photochemical model, are consistent with contemporaneous measurements of ozone from the Aura-MLS satellite, although the short time period makes precise attribution to solar effects difficult. We also show, using the SIM data, that solar radiative forcing of surface climate is out of phase with solar activity. Currently there is insufficient observational evidence to validate the spectral variations observed by SIM, or to fully characterize other solar cycles, but our findings raise the possibility that the effects of solar variability on temperature throughout the atmosphere may be contrary to current expectations.

The peak of the most recent '11-year' solar cycle (identified as number 23) occurred 2000–2002, and from then until about December 2009 the Sun's activity declined. Figure 1 shows the difference between 2004 and 2007 in solar spectral irradiance measured by SIM. This is quite unlike that predicted by multi-component empirical models, based on activity indicators such as sunspot number and area, as exemplified by that of Lean[5] (also shown in Fig. 1). The SIM data indicate a decline in ultraviolet from 2004 to 2007 that is a factor of 4 to 6 larger than in the Lean data and an increase in visible radiation, compared with a small decline in the Lean data. Other empirical models[6,7] show larger-amplitude variations in the near-ultraviolet than does the Lean model but none reflect the behaviour apparent in the SIM data. Also shown in Fig. 1, for wavelengths 116–290 nm, are independent measurements made by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instrument on SORCE. The data from SIM and SOLSTICE both indicate substantially more ultraviolet variability than does the Lean model. SIM calibration, and instrument comparisons, are discussed in detail in ref. 8.

To investigate how these very different spectral changes might affect the stratosphere, experiments have been carried out using a two-dimensional (latitude-height) radiative-chemical-transport model of the atmosphere[9]. This model includes detailed representations of photochemistry and radiative transfer and has been used in many studies involving radiation-chemistry interactions[10,11]. (See Supplementary Information for further details.) This type of model produces realistic simulations of the upper stratosphere (above about 25 km) but is less reliable at lower altitudes where photochemical time constants are longer and a more accurate representation of transport processes is required. The results below come from four model runs using solar spectra derived from the SIM measurements (with SOLSTICE data for wavelengths less than 200 nm) and those produced by the Lean model, each for both 2004 and 2007.

In Fig. 2 we present latitude–height maps of the difference between 2004 and 2007 in December ozone concentrations. The Lean spectral data produce a broad structure of ozone concentrations greater in 2004 than in 2007, with maximum values of around 0.8% near 40 km, whereas the SIM data produce a peak enhancement of over 2% in low latitudes around 35 km, along with significant reductions above 45 km. The predicted temperature differences (Supplementary Fig. 1) are also very different, with the Lean data set showing temperatures 0.3–0.4 K greater in 2004 than in 2007 at the top of the model domain, whereas the SIM data set produces a peak warming of 1.8 K at the summer polar stratopause. These temperature differences are qualitatively similar to, but about 50% larger than, those estimated by ref. 12 with an idealized forcing in a full climate model, possibly owing to the broader spectral

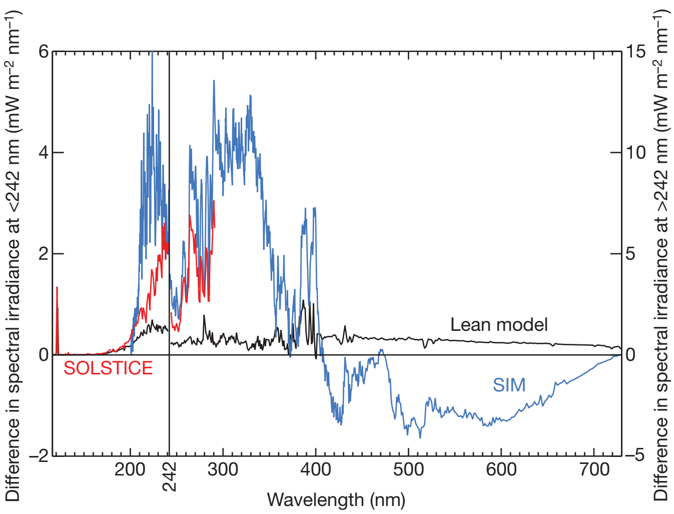

Figure 1 | Difference in solar spectrum between April 2004 and November 2007. The difference (2004–2007) in solar spectral irradiance (W m^{-2} nm^{-1}) derived from SIM data[4] (in blue), SOLSTICE data[8] (in red) and from the Lean model[5] (in black). Different scales are used for values at wavelengths less and more than 242 nm (see left and right axes respectively).

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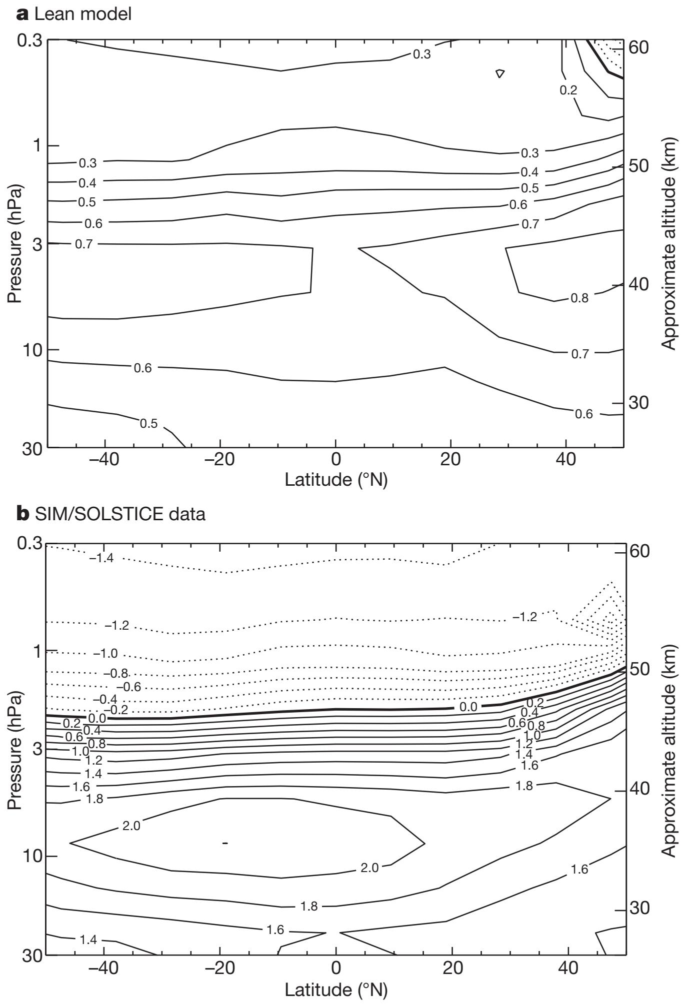

Figure 2 | Modelled difference in ozone between December 2004 and December 2007. Estimates of the percentage difference (2004–2007) in zonal mean ozone concentration (labels on contour lines in per cent) produced by the model using solar spectra from the Lean model (**a**) and SIM/SOLSTICE data (**b**).

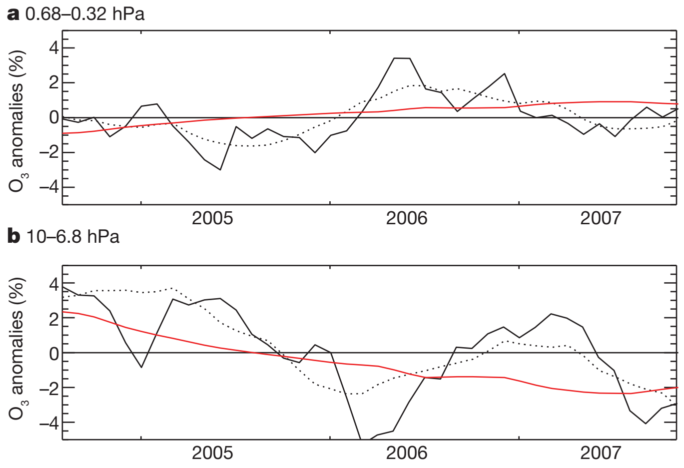

Figure 3 | Time series of AURA-MLS v2.2 ozone concentrations. The data (solid black lines) are percentage anomalies of tropical (22.5 °S–22.5 °N) deseasonalized monthly means from August 2004 to November 2007. The values reconstructed from the 4-component regression model are shown as dashed lines. The solar component of the regression is shown in red. Other components are shown, along with the solar component, in Supplementary Fig. 2. Data were averaged between 0.68 hPa and 0.32 hPa (**a**) and 10 hPa and 6.8 hPa (**b**).

resolution imposed and the lack of ozone–temperature feedback in that model version.

The very different scenarios produced by the two spectral data sets suggest they might be distinguishable in observational records. A multiple regression analysis has been carried out of deseasonalized monthly mean ozone data from the Microwave Limb Sounder (MLS) instrument on the Earth Observing System (EOS) Aura satellite. Four regression indices were used: a constant, two orthogonal indices representing the quasi-biennial oscillation (which dominates ozone variability in the tropical stratosphere)[13] and a solar index constructed from SIM data integrated over 200–400 nm. Motivated by the model results (Fig. 2), we chose two spatial regions, both spanning the tropics, one at altitude 10–6.8 hPa, where the model predicts the largest difference 2004–2007, and one at 0.68–0.32 hPa, where the model shows largest negative values. Figure 3 shows the raw data and the fits reconstructed from the four regression components; it also shows (in red) the derived solar component, which is statistically significant at >95% at the upper levels and >99% at the lower levels (see Supplementary Information).

Over the period from the late 1970s to the late 1990s tropical ozone at altitudes 35–50 km decreased by about 9% (ref. 13) in response to increasing concentrations of active chlorine species. Since about 2000, however, the trend in chlorine has reversed and ozone has stopped declining. Stratospheric cooling by greenhouse gases has probably also contributed to the ozone trend reversal by slowing the chemical reactions that destroy it[14]. Over the short period of the present study it is not possible statistically to differentiate these factors from each other, or from any solar influence. Nevertheless, it seems likely that the Sun is important in the apparent decrease in ozone below 45 km from 2004 to 2007. The change in sign near 45 km is also more consistent with the modelled response to the SIM spectral variations than to the Lean spectra. Previous analyses[13,15] of the solar signal in ozone, averaged over approximately 2.5 solar cycles (1979 to 2005 or 2003), have not shown this structure. This suggests that the declining phase of solar cycle 23 is behaving differently to previous solar cycles or possibly that the solar cycle exhibits different behaviours during its ascending and descending phases.

To understand the different spatial structures, and magnitudes, of the modelled ozone responses we consider photochemical processes. The sharp decrease in ozone above 45 km with the SIM spectra (Fig. 2b) is consistent with it being in photochemical steady state with the dominant sinks, that is, increased levels of HO_x and O. These losses are compensated by the greater production of O_x through photodissociation of O_2 in the Huggins band and this dominates the loss lower down. Furthermore, the ozone decreases produce a self-healing effect whereby more ultraviolet radiation is transmitted to lower levels, resulting in greater O_2 photolysis and thus more O_3. (See Supplementary Information.)

To assess the sensitivity of our results to uncertainty in the measured irradiance values at 200–240 nm (see Fig. 1) we carried out another set of experiments (not shown) in which the switchover from SOLSTICE to SIM was imposed at 240 nm (rather than 200 nm). There are differences in detail in the resulting temperature and ozone fields but the general picture is the same: reduced ozone in the upper stratosphere and mesosphere and a positive peak in the middle stratosphere. Therefore there is uncertainty in the magnitude of the response but this does not affect our conclusions with respect to the impact on the middle atmosphere. It also has little bearing on the radiative forcing estimates now presented.

The response of tropospheric and surface climate to variations in solar activity is an important consideration in the attribution of surface temperature trends to human or natural factors. Radiative forcing of climate is defined by the Intergovernmental Panel on Climate Change as the change in net flux at the tropopause, taking into account the effects of any stratospheric adjustment[16]. It is known that solar radiative forcing is modulated by the ozone response to changes in solar

Table 1 | Difference in global average downward radiative flux

Wavelength	200–310 nm		310–500 nm		500–700 nm		700–1,600 nm		Total solar 200–1,600 nm		Thermal		Net	
Level	TOA	TPS	TOA	TPS	TOA	TPS	TOA	TPS*	TOA	TPS	TOA	TPS	TOA	TPS
Lean data ($W m^{-2}$)	0.02	0.00	0.04	0.03	0.03	0.01	0.02	0.02	0.11	0.06	0	0.02	0.11	0.08
SIM data ($W m^{-2}$)	0.16	0.00	0.11	0.06	−0.13	−0.17	−0.05	−0.05	0.09	−0.16	0	0.06	0.09	−0.10

The flux difference between 2004 and 2007 at the top of the atmosphere (TOA) and at 105 hPa (representing the tropopause, TPS) was calculated for December in the model using the two spectral data sets.
* The radiation scheme in the 2D model does not calculate flux propagation in this spectral region. The radiation at these wavelengths is absorbed very little by stratospheric gases so the tropopause values here are assumed to be the same as the TOA values.

ultraviolet[2]. The effect of an increase in ozone is twofold: first to reduce the flux of solar radiation reaching the tropopause and second to increase the flux of infrared radiation, mainly through its impact on stratospheric temperatures. The net effect has been assessed to be a small increase in the net downward flux[17].

Simulations of the effect of solar variability on tropospheric climate, such as those reviewed in the IPCC assessments[16], tend to incorporate broad spectral bands that resolve neither details of the spectrum nor the effect of stratospheric ozone. The SIM measurements provide an additional perspective for this. Although the change in total irradiance from 2004 to 2007 is similar in the Lean and SIM data sets their very different spectral compositions, and the resulting impacts on the stratosphere, produce quite different pictures of the transmission of radiation to the tropopause, and thus different modulations of radiative forcing. Table 1 presents the change from 2004 to 2007 in global average downward solar flux at the top of the atmosphere (TOA), and at the tropopause, in four spectral bands, along with the resulting change in downward thermal radiation at the tropopause.

Little of the radiation in the 200–310 nm wavelength band reaches the tropopause, so that the large increase in the SIM irradiance at the TOA is not found here. In the 310–500 nm region, the radiation reaching the tropopause is modulated by the ozone column above, so that the larger increase in ozone produced by the SIM spectra significantly diminishes radiation reaching 105 hPa. In the 500–700 nm region, ozone absorption again plays a part so that the decrease in the TOA value in the SIM experiment becomes an even larger decrease at the tropopause. The change in spectrally integrated solar irradiance at the TOA in the two experiments is very similar: 0.11 $W m^{-2}$ with Lean and 0.09 $W m^{-2}$ with SIM. However, at the tropopause, whereas the Lean experiment shows an increase of 0.06 $W m^{-2}$, the SIM shows a decrease of 0.16 $W m^{-2}$. The thermal radiation increases the Lean radiative forcing slightly, and moderates the decrease in SIM, so that the net solar radiative forcing 2004–2007 estimated using the two data sets is +0.08 $W m^{-2}$ with Lean (consistent with previous studies of radiative forcing over a solar cycle[17]) but −0.10 $W m^{-2}$ when the SIM data are used. The latter suggests that radiative forcing of surface climate by the Sun is out of phase with solar activity, at least over this declining phase of solar cycle 23. In their study Cahalan *et al.*[12] did not find this out-of-phase relationship in near-surface air temperature, perhaps because their radiative–convective model did not incorporate the ozone response.

The SIM data provide an entirely different picture from the one currently accepted for the variation of solar irradiance. It is pertinent to ask whether this spectral variability is typical of solar activity cycles and, if so, why it has not been observed previously. It is possible that the Sun has been behaving in an anomalous fashion recently; certainly the current solar minimum is lower and longer than any of those observed over recent decades[18] and perhaps the solar spectrum has different characteristics when the Sun is in a state of very low activity. Gaps in understanding will only be resolved by the acquisition of long-term, well-calibrated, high-vertical-resolution measurements of stratospheric composition and temperature acquired coincidently with essential solar spectral data that have also been properly degradation-corrected and calibrated.

The SORCE observations are, however, consistent with a solar-activity-dependent change in the temperature gradient of the solar photosphere[4], suggesting that the offsetting irradiance trends with wavelength seen in SIM should appear in each solar cycle. If this is the case, then it is necessary to reconsider the current understanding[19] of the mechanisms whereby solar cycle variability influences climate: the impact on the stratosphere is much larger than previously thought and the radiative forcing of surface climate is out of phase with solar activity. At present there is no evidence to ascertain whether this behaviour has occurred before, but if this were the case during previous multi-decadal periods of low solar activity it would be necessary to revisit assessments of the solar influence on climate and to revise the methods whereby these are represented in global models.

METHODS SUMMARY

Solar spectra. The spectra used were ten-day averages of the Lean model and SORCE data centred on 21 April 2004 and 7 November 2007, chosen as the furthest spaced dates of calibrated SORCE data. The data were interpolated onto the 171 wavebands of the two-dimensional (2D) model in the range 116–730 nm.

2D model. The 2D (latitude–log pressure) zonal mean model incorporates interactions between radiative, chemical and dynamical processes. The same solar spectra are used for the calculation of chemical photodissocation and heating rates. The model was run to (seasonally varying) equilibrium with each of the four spectral data sets. All results are presented for December.

Multiple regression analysis. The code (Myles Allen, Oxford University, personal communication) estimates the coefficients of regression indices simultaneously with the parameters of a red noise model, here taken to be of order unity. The fit is iterated until the noise model fits within a pre-defined threshold. This method minimizes the possibility of noise being interpreted as a signal and can produce, using a Student's *t*-test, measures of the confidence intervals of the resultant regression coefficients, taking into account any covariance between the indices.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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