# Solar Forcing for CMIP6

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The importance of radiative solar forcing in particular for regional climate variability is becoming increasingly evident (Gray et al., 2010; Seppälä et al., 2014). These regional effects are a combination of stratospheric induced UV-variations ("top-down") as well as surface effects induced by visible and IR-variations and atmosphere-ocean coupling ("bottom-up"). However there are still uncertainties in the atmospheric solar signal and its transfer mechanism(s). In order to best represent regional solar effects, it is important for climate models to use spectrally resolved solar irradiance data. This can be done only in models with a well resolved radiation scheme. There has been some discussion on the magnitude of spectral solar irradiance (SSI) changes in particular in the UV part of the spectrum, which is important not only for middle atmosphere heating but also ozone chemistry (Ermolli et al., 2013). Recent progress has been made to better constrain the SSI forcing and an improved version of earlier SSI recommendations will be provided this time.

Precipitating energetic particles from the sun (predominantly protons) and the magnetosphere (predominantly electrons) provide an additional pathway of solar forcing . They affect the ionization levels in the polar middle and upper atmosphere, leading to significant changes of the chemical composition. In particular, the production of NOx and HOx imposes changes of ozone via catalytic cycles, potentially affecting temperature and winds. Recent model studies and the analysis of meteorological data have provided evidence for a dynamical coupling of this signal to the lower atmosphere, leading to EPP-induced surface climate variations on the regional scale (e.g., Seppälä et al, 2009; Rozanov et al., 2012). In addition, cosmic rays (CR, predominantly protons and alpha particles) - also modulated by the Sun - are the main source of ionization in the troposphere and lower stratosphere. While the connection between CR ionization and cloud production and therefore convection is still under debate, its chemical impact via ozone-depleting catalytic cycles and subsequent dynamical forcing are rather well understood (Callisto et al., 2011). Due to the increasing evidence for particle-induced surface climate impacts in addition to SSI-related variations, recommendations for consideration of proton-, electron- and CR-induced chemical modulations have been added to the CMIP6 solar forcing dataset.

In particular the importance of solar induced ozone changes is becoming increasingly evident for a correct representation of solar climate signals. We therefore recommend for climate models without interactive chemistry to use the CMIP6 ozone database (provided by CCMI, M. Hegglin and J.-F. Lamarque) which is consistent with the here proposed solar forcing recommendations.

## 1. Historical solar forcing data (1850-2014)

SSI and TSI

We propose a record of Solar Spectral Irradiance (SSI) that is a product of the collaboration between the European SOLID[1] data analysis project and the US NRLSSI2 model team (NRL and LASP, USA). The NRLSSI2 model provides the framework for specifying daily SSI values from 1882 to 2014 and annual values from 1850 to 1882 in 3785 wavelength bands of variable width from 115.5 ± 0.5 nm to 99,975 ± 25 nm, in units of W $m^{-2}$ per band. EUV spectra at wavelengths below 115nm are also available on a 1nm grid. The model is an updated version of the original NRLSSI model [Lean 2000, Lean et al. 2005, Lean and Woods, 2010] that has been widely used in past climate change studies [see e.g., Haigh et al. 2010, Schmidt et al. 2011], particularly for past model intercomparison projects, i.e. CMIP5, CCMVal, CCMI (http://solarisheppa.geomar.de/input-data). It uses indices of sunspot blocking (calculated from solar imagery) and facular brightening (the Mg-II index) to calculate solar total and spectral irradiance variations using coefficients derived from the regression of the indices again solar irradiance observations. The SORCE/SOLSTICE and SORCE/SIM observations provide relative spectral shape from rotational variability, with the solar cycle SSI variations constrained such that the spectral integral of the changes due to sunspots and faculae, and their net influences, all match those derived for the independently measured SORCE/TIM total solar irradiance [Coddington et al., 2015].

The key determinant of the NRLSSI2 model performance is the quality and stability of the solar irradiance time series and indices from which the model is formulated. To produce a record of SSI for CMIP6, the NRLSSI2 model will use newly improved composite records of TSI and the Mg-II index, both of which are now being produced consistently using advanced statistical methods as part of the SOLID project [Dudok de Wit et al., 2015]. Confidence intervals for the SSI record will be also provided taking into account uncertainties in both the input irradiance and indices and the statistical uncertainties of the model coefficients. Moreover, the SSI variations of the NRLSSI2 model will be further constrained and iterated against the UV SSI composite derived by the SOLID project, which relies on the, to date, most comprehensive set of observations, also taking into account their uncertainties. In this way the output of the NRLSSI2 model is guaranteed to be consistent with what is currently the most objective time series of SSI variation in the UV - one of the most crucial ingredients for providing solar irradiance forcing for climate model studies. Furthermore, since constraining the SSI variability in the UV spectrum further constrains SSI variability at other wavelengths (such that the integral of SSI equals TSI) the product will include realistic and defensible SSI variability at visible and infrared wavelengths. The SSI timeseries of the US-European collaboration provides the best estimate of our understanding of solar variability and agrees with respect to the relative spectral changes well with other SSI reconstructions such as the SATIRE-S model (Krivova et al., 2006; Krivova et al., 2011; Ball et al., 2012;

[1] SOLID: First European Comprehensive SOLar Irradiance Data exploitation

Yeo et al., 2015 under review). However, the largest difference between the NRLSSI2 and the SATIRE estimate is the long-term TSI trend, which is much larger in the latter estimate and exceeds the uncertainty of the TIM trend. We therefore recommend the NRLSSI2 data set for climate model studies in order to avoid potential impacts of long-term trends in the solar irradiance.

Proton forcing

We recommend the inclusion of HOx and NOx productions by solar protons in models with interactive stratospheric chemistry by using the daily ionization data compiled by Charles Jackman and available from the SOLARIS-HEPPA website (http://solarisheppa.geomar.de/solarisheppa/solarprotonfluxes). This longest available record is calculated from solar proton flux satellite measurements . Details about the source of the proton fluxes for the various time periods are given by Jackman et al. (2008). The daily averaged SPE-produced ionization rates from 1963 through 2014 are provided as functions of pressure between 888 hPa (~1 km) and 8x10-5 hPa (~115 km). A reliable reconstruction of ionization rates due to solar protons back in time (pre-satellite era, 1850-1962) is not feasible due to the lack of adequate proxy data. In order to avoid unphysical jumps in the forcing data when setting the proton forcing for the pre-satellite era to zero, an artificial proton forcing will be created for the 1850-1962 period by projecting sequences of individual solar cycles covered by the satellite-derived dataset to the past. Statistical analyses of observed proton fluences over the last 4 solar cycles (Nymmik, 2007; Barnard and Lockwood, 2011) have shown that both solar proton event occurrence frequency and proton fluence depend strongly on solar activity. This will be taken into account by (i) temporal alignment of the solar maxima in the projected and historical cycles, and (ii) adequate selection of the cycle to be projected in order to best fit the average strength of the historical cycle (in terms of SSN). HOx production should be calculated by using the lookup table from Jackman et al. (2005a, Table 1), which is based on the work of Solomon et al. (1981). For SPE-induced NOx production, we recommend to use the commonly accepted efficiency of 1.25 N per ion pair (0.55 N(4S) and 0.70 N(2D)) as reported by Porter et al. (1976). A more detailed description of the conversion of ionization rates to HOx and NOx production rates can be found at http://solarisheppa.geomar.de/solarisheppa/sites/default/files/data/SOLARIS_Jackman_SPEs.pdf.

Electron forcing

Due to the lack of continuous observations of precipitating energetic electrons from auroral and radiation belt sources, datasets such as those used for solar protons are currently not available. As a best estimate for the impact of electron precipitation we recommend the use of parameterisations based on geomagnetic activity indices such as the Kp- or Ap-index to describe ionisation from electron precipitation in the lower thermosphere and upper mesosphere (for those models that explicitly include those height levels in their code). Since the Kp-Ap record covers only the period from 1932 to present, historical geomagnetic indices such as the aa index (1868 to present) and the Ak index of the Helsinki observatory (Nevanlinna, 2014, available from 1844 to 1912) will be combined with Ap data to provide a homogenized daily record for the 1850-

2014 period. The resulting Ap (and Kp) reconstruction for 1850-2014 will be made available on the SOLARIS-HEPPA webpage.

For lower top models (models with upper limit in the mesosphere) auroral production of NOx and the subsequent descent from higher altitudes to the model domain is commonly described by a semi-empirical upper boundary condition in function of Ap. An updated Ap-based parametrization, based on recent satellite observations (Funke et al., 2014a,b), will be made available.

Cosmic Ray forcing

We recommend the use of the CRAC:CRII (Cosmic Ray induced Cascade: Application for Cosmic Ray Induced Ionization) model extended toward the upper atmosphere (Usoskin et al. 2010). The model is based on a Monte Carlo simulation of the atmospheric cascade and reproduces the observed data within 10 % accuracy in the troposphere and lower stratosphere. The results of the CRAC:CRII model are parameterized (see Usoskin and Kovaltsov 2006) to give ion pair production rate as a function of the altitude (quantified via the barometric pressure), geomagnetic latitude (quantified via geomagnetic cut-off rigidity), and solar activity (quantified via the modulation potential θ). The reconstruction of θ for the last 4 centuries (Usoskin, 2002), based on the solar magnetic flux model of Solanski et al. (2000, 2002), allows to constrain the CR forcing during the whole simulation period 1850-2014. The corresponding lookup tables will be made available on the SOLARIS-HEPPA webpage. HOx and NOx productions as a function of the CR ion pair production rate should be considered in models with interactive chemistry in the same manner as for proton forcing, using the efficiencies provided by Solomon et al. (1981) and Porter et al. (1976).

## 2. Future Solar forcing data (2015-2100, extended to 2300)

Predictions about how solar activity will develop in the next 100-300 years are at present not possible. Thus only statistical estimates of future activity can be made based on the analysis of solar activity reconstructions. The CMIP6 future solar forcing scenario will be constructed by projecting past sequences of both solar and geomagnetic data into the future in order to guarantee consistency of different solar forcing types. The choice/ combination of adequate historic sequences will be motivated by statistical estimates of future solar activity (e.g., Steinhilber et al., 2013).

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