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Book of Abstracts

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Large Ensembles for Attribution of Dynamically-driven Extremes (LEADER): revisiting the climate response to solar variability

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The long-predicted climate change signal is emerging outside the noise in many regions. These changes in climate are accompanied by changes in extreme events that impact society. While early warnings of such changes are now potentially possible through, e.g., operational decadal predictions, there are several challenges: there is a lack of understanding of the dynamical mechanisms that enable such projections, there is evidence that global models underestimate some predictable signals (including the solar signal), and these models suffer from biases. A better understanding of the causes of regional changes in climate is needed both to attribute recent events and to gain further confidence in forecasts. One of the phenomena that can lead to seasonal to decadal predictability of near-surface extremes is solar variability.

We will first introduce the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP), the dataset that forms the bedrock of attribution and prediction activities of the WCRP's EPESC lighthouse activity and the APARC LEADER activity. Next, we will present preliminary results from the hist-solar runs archived for the LESFMIP, so as to motivate future community efforts using this dataset. This community effort is motivated by the need to (1) ensure visibility of APARC science in WMO State of Climate and Global Annual to Decadal Climate Updates and IPCC reports; and also (2) to communicate with operational centres as to which diagnostics are required for future analysis.

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Reconstructing solar irradiance variations with SATIRE

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Direct measurements of solar irradiance variations began in the late 1970s.
Recovery of irradiance over earlier periods is only possible with appropriate models.
Such reconstructions require solid understanding of the physical processes driving the irradiance

fluctuations as well as information on the past changes of the magnetic activity of the Sun.
The magnetic field emerging at the solar surface forms bright faculae and dark sunspots, which eventually modulate irradiance changes.
Since about 1974 direct measurements of the solar surface magnetic field, magnetograms, are available, which provide the best suitable input.
A good alternative to the measured magnetograms is offered by Ca II K full-disc observations, which carry information on faculae, can be used to recover the magnetic field maps, and extend back to 1892.
At earlier times, only sunspot observations are available, so that facular distribution has to be inferred from those. This, in turn, requires understanding of how facular emergence and evolution are linked to those of sunspots, which can be gained from an analysis of various available modern and historical solar data.
Here we will provide an overview of the recent progress and current status of modelling and reconstruction solar irradiance with SATIRE.

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 5

Assessment of thermospheric nitric oxide NO formation and loss in high-top chemistry-climate models

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Geomagnetic forcing is considered part of the natural forcing of the climate system, and recommended to be included in chemistry-climate model experiments since CMIP6. The starting point is the formation of NO mainly in the lower thermosphere by energetic electron precipitation from the aurora and radiation belts and EUV radiation. We compare results of NO from five high-top chemistry-climate models in the mesosphere and thermosphere with satellite observations for low geomagnetic forcing throughout the year 2010. While qualitatively, the latitudinal and temporal variability is well captured by all models compared with the observations, we find disagreements between models reaching several orders of magnitude in the winter-time high-latitude lower thermosphere. Possible reasons are explored using snapshots of one day, and two main drivers of the large differences are tentatively identified: the treatment of neutral chemistry on the one hand, and an impact of the thermospheric circulation in the winter hemisphere driven by sub-scale gravity waves

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CMIP-7 forcing and implementation in Earth system models / 6

New medium-energy electron precitpiation solar forcing dataset for CMIP7

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A new dataset has been provided for CMIP7, to model the ion pair production due to mid-energy electron precipitation.

The data set has been calculated using an updated version of the CMIP6 electron flux model and an atmospheric ionization parameterization (Fang et al., Geophys. Res. Lett., 37, L22106, doi:10.1029/2010GL045406, 2010). The electron flux model is fit to equivalent isotropic precipitating electron fluxes estimated from observations of the MEPED detectors onboard POES NOAA-6, 8, 10, 12 and 15 satellites during 1979 to 2023. The isotropic fluxes were estimated by fitting the measurements of the two MEPED telescopes to a theoretical form of pitch angle distribution describing pitch angle diffusion under wave-particle-interactions (Nesse-Tyssoy, J. Geophys. Res. Space Physics, 121, https://doi.org/10.1002/2016JA022752; Asikainen, 2024 pers. comm.). These data have been instrumentally calibrated and corrected for proton contamination (Asikainen and Mursula, (2013), J. Geophys. Res, 118, https://doi.org/10.1002/jgra.50584) as well as temporally and spatially corrected for background noise, changing satellite orbits and differences in satellite instrumentation (Asikainen and Ruopsa (2019), J. Geophys. Res. Space Phys., 124, https://doi.org/10.1029/2018JA026214 and Asikainen (2019), J. Geophys. Res. Space Phys., 124, https://doi.org/10.1029/2019JA026699).

The flux model depends on the geomagnetic Ap index. The CMIP7 reconstruction of Ap has been used to cover the whole period between 1850 and 2023. The valid range of MEE IPR data is 44.5-71.5 deg geomagnetic latitude (both hemispheres) and 7.26e-5 –10 hPa. Outside this range MEE IPR data are set to zero. Standard data represent the median values of the 1850-1873 period.

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CMIP-7 forcing and implementation in Earth system models / 9

Variable solar forcing of the Icosahedral Non-hydrostatic -ICON) model: implementations and tests in the upper atmosphere extension to apply varying CMIP7 forcing

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The Icosahedral Non-hydrostatic model framework is the open-source numerical weather prediction model and climate model developed by the German Weather Service DWD and the Max-Planck Institute of Meteorology. A consolidated climate setup with interactive ocean, land surface and atmosphere is currently being developed and tested. However, while ICON in its base setup includes varying solar TSI and SSI forcing, this implementation is rudimentary at the moment, and the ability of UV irradiances and energetic particle precipitation (EPP) to change atmospheric composition has not been considered so far.
The upper atmosphere extension of ICON (UA-ICON) currently is a modelling framework allowing the analysis of dynamic phenomena from the ground to the lower thermosphere (150 km). Implementing varying solar forcing and interactive chemistry is expected to hugely influence the thermal structure and composition in the mesosphere/lower thermosphere (MLT).
Updated solar forcing datasets for the 7th phase of the Coupled Model Intercomparison Project (CMIP7) are now prepared. These include daily varying SSI, TSI and ion pair production rates for solar protons, cosmic rays, and medium-energy electrons to model EPP. Implementing these solar forcing data and the interactive chemistry is still ongoing work, and we present the first results of this effort where we focus on the MLT and UA-ICON.

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Solar Irradiance and Particle Variability / 10

Intercomparision of SSUSI and AISstorm

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This study compares the electron ionization peak altitudes observed by the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) and the Atmospheric Ionization during Substorm Model (AISstorm) over 70.2°N during 2010. SSUSI data predominantly shows ionization peaks at 100 km altitude, while AISstorm data indicates peaks primarily at 110 km. The discrepancy may partly be impacted by the energy coverage limitations of AISstorm, which relies on particle measurements from POES and

Metop, creating an energy gap between 10 and 30 keV that imposes uncertainty to exactly these altitude levels. On the other hand SSUSI employs the energy deposition model by Fang et al. (2010), which differs from the Geant4-based algorithm used in AISstorm, resulting in lower altitude peaks. Statistical studies, such as those by Bösinger et al. (2004), support the occurrence of ionization peaks at 110 km but also indicate variability with local time and ionospheric conditions. The observed discrepancies suggest that energy deposition models and atmospheric conditions significantly influence the altitude of ionization peaks. Temporal and local time variations generally match well at 115km altitude but also highlight differences in the dynamic range and spatial processing between the two datasets, with SSUSI showing higher ionization rates, especially in polar regions.

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 12

Polar mesospheric ozone loss initiates downward coupling of solar signal

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In recent years, increasing evidence has pointed that winter-time middle atmospheric ozone changes initiated by energetic particle precipitation (EPP) are linked to regional climate variability at ground-level. The mechanism for this link is, however, still unclear. Proposed explanations focusing on EPP-indirect effect does not explain the timing of the observed ground-level changes, which take place during winter, rather than in spring.

In this study we present results from Whole Atmosphere Community Climate Model (WACCM) simulations where polar winter upper mesospheric ozone is reduced to levels corresponding to observed in situ ozone changes driven by EPP. The results show a rapid coupling of atmospheric heating to dynamics, with signal propagating downwards resulting in poleward shift of the tropospheric jet. Large scale background atmospheric conditions determined by the Quasi Biennial Oscillation (QBO) influence the stratospheric response to EPP, but significant responses in the tropospheric eddy-driven jet take place broadly consistently for both QBO phases.

Based on our results, the signals from the initial EPP driven in situ ozone changes at high mesospheric altitudes propagate downwards in timescales that correspond to observed tropospheric level climatic changes linked to EPP.

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CMIP-7 forcing and implementation in Earth system models / 13

EPP-climate link by reactive nitrogen polar winter descent: MIPAS v8 reprocessing and NOy UBC for climate models

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Polar winter descent of reactive nitrogen (NOy) produced by energetic particle precipitation (EPP) in the mesosphere and lower thermosphere affects polar stratospheric ozone by catalytic reactions. This, in turn, may have implications for regional climate via radiative and dynamical feedbacks. NOy observations taken by the MIPAS/Envisat instrument during 2002–2012 have provided observational constraints on the solar-activity modulated variability of stratospheric EPP-NOy amounts. These constraints have allowed to formulate a chemical upper boundary condition (UBC) for whole-atmosphere chemistry–climate models in the context of solar forcing recommendations for CMIP6.

Recently, a reprocessed MIPAS version 8 dataset has been released. Here we present the derived NOy and EPP-induced NOy amounts, and compare them to the previous version. In particular, we assess what impact the changes in this new data version have on the EPP-NOy quantification, and we assess its impact on the formulation of chemical upper boundary conditions for climate models. We also present an updated version of the UBC from the updated data set which is about to be included in the upcoming solar forcing recommendations for CMIP7.

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CMIP-7 forcing and implementation in Earth system models / 14

Evaluation of the chemistry and climate impact of the new solar forcing dataset for CMIP7 using the Whole Atmosphere Community Climate Model

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The solar forcing dataset prepared for the 6th round of the Coupled Model Intercomparison Project (CMIP6) has been used extensively in climate model experiments. Recently, an International Space Science Institute (ISSI) Working Group was established to revisit the solar forcing recommendations in order to define a roadmap for building a revised solar forcing dataset for the upcoming 7th round of CMIP (Funke et al., 2023). This new dataset will introduce changes in the radiative forcing of climate either directly, or indirectly via changes in atmospheric composition. In CMIP6, the solar forcing consisted of both a total solar irradiance (TSI), along with a spectrally resolved solar irradiance (SSI). The TSI for solar minimum was set to 1360.8±0.5Wm-2 and the SSI covered the 10nm to 100mm spectral region. A similar approach is proposed for CMIP7 except for two major aspects of the reconstruction: 1) the definition of the reference spectrum for the quite Sun; 2) the temporal variability. The major difference between the proposed CMIP7 SSI quiet sun reference spectrum and that used for CMIP6 is the spectral shape. The new SSI spectrum has an irradiance that is 1-5% higher in the visible band and lower by 1-2% in the Near-IR wavelength range (1000-2000nm).

In this work we used the Whole Atmosphere Community Climate Model (WACCM) to examine the chemical and climate implications of the proposed CMIP7 solar forcing updates compared to the CMIP6 approach. WACCM is a chemistry-climate model that extends from the surface to 140km and has a detailed representation of chemical and dynamical processes from the troposphere through the lower thermosphere. We present two sets of results derived from two numerical experiments: 1) "chemical only"impacts of the solar forcing choice in WACCM run in the specified dynamics mode using NASA Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2) and 2) "climate"impacts in simulations with the model free-running with interactive dynamics coupled to a deep ocean. We find stratospheric ozone and temperature differences caused by changes in the SSI forcing to be similar in magnitude to changes simulated over the solar cycle. The stratospheric surface climate is cooler everywhere and largest near the poles where statistically significant increases are sea ice fraction are simulated. This highlights the need for modelling centres to use the new SSI dataset as early as possible in their model development cycle for CMIP7.

Funke, B., Dudok de Wit, T., Ermolli, I., Haberreiter, M., Kinnison, D., Marsh, D., Nesse, H., Seppälä, A., Sinnhuber, M., and Usoskin, I.: Towards the definition of a solar forcing dataset for CMIP7, Geosci. Model Dev. Discuss. https://doi.org/10.5194/gmd-2023-100.

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 16

Satellite observations of the polar vortex variations related to energetic electron precipitation

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Energetic electron precipitation (EEP) directly impacts the high-latitude thermosphere and mesosphere by forming ozone-depleting NOx and HOx. During winter the EEP-NOy (NOx and its reservoir species such as HNO3 formed by EEP) molecules descend to the stratosphere and establish the indirect effect of EEP. Earlier studies based on models and reanalysis datasets have shown that increased EEP is related to a strengthening of the northern winter polar vortex, a westerly wind system around the pole in the stratosphere.
Here we examine the EEP effect on chemical and dynamical properties of wintertime mesosphere and stratosphere with satellite observations of both EEP (POES/MEPED) and atmospheric variables (Aura/MLS). We confirm earlier findings that EEP decreases ozone, affects the temperatures in the polar stratosphere and strengthens the stratospheric polar vortex. We find that increased EEP is associated with a weakening of the mesospheric polar vortex. We also confirm our recent results based on reanalysis data that the EEP effect on polar vortex depends on planetary waves and their latitudinal distribution.

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CMIP-7 forcing and implementation in Earth system models / 18

New reconstruction of energetic electron precipitation and atmospheric ionization for 1844-2023 using deep learning networks

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Reconstructions of energetic electron precipitation (EEP) and the atmospheric ionization it produces are important for state-of-the-art chemistry-climate models, which aim to model the climate impacts of EEP. The current version of the Coupled Model Inter-comparison Project, CMIP6, includes a reconstruction of EEP-induced ionization based on a parameterization dependent on geomagnetic Ap index. This reconstruction has been used in several climate studies over the past years. However, recent investigations have shown that the CMIP6 reconstruction underestimates the level of precipitation. Therefore, the atmospheric/climate impacts of EEP might be underestimated as well.

To address this issue we introduce here a new reconstruction of EEP and the ionization it produces. This reconstruction is based on a new composite of energetic electron measurements from POES satellites which have been corrected for various instrumental and sampling effects. A theoretically motivated form of a pitch angle distribution consistent with pitch angle diffusion is fitted to these data to obtain a more realistic estimate of electron precipitation into the atmosphere.

For the reconstruction we developed a deep learning network, which ingests homogenized geomagnetic aa index, sunspot number as well as seasonal variations and solar cycle phase. The network gives as output the daily latitude distributions of precipitating electron fluxes in three energy channels. This is then used to calculate the precipitating electron energy spectrum and associated atmospheric ionization from year 1844 to present.

Here we present the main aspects of this new reconstruction and also compare it with the earlier CMIP6 reconstruction.

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Solar Irradiance and Particle Variability / **20**

Ionospheric Absorption Modelling: A Sensitivity Study on Input Variables

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Energetic particle precipitation (EPP) increases ionization in the D-region ionosphere, elevating cosmic radio signal absorption. This impact is monitored by a Canadian network of wide-beam passive radio receivers, or riometers. Ionospheric absorption expected during a specific EPP event, as recorded by a Polar Orbiting Environmental Satellite (POES), is modelled and compared with measurements from a riometer in Gillam (56° N, 95° W). This study explores the impact of D-region chemical models and precipitation spectra on the accuracy of modelled ionospheric absorption. Different ionospheric chemistry models are applied to determine which best matches the observed absorption with the variations in precipitation spectra.

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Solar Irradiance and Particle Variability / **22**

The High-Energy Tail of Energetic Electron Precipitation

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Precipitating plasma sheet, ring current, and radiation belt electrons will affect the ionization level and composition of the neutral atmosphere. Knowledge gaps remain regarding the frequency, intensity, and energy spectrum of the Medium Energy Electron (MEE) precipitation ($gtrsim$30 keV). In particular, the understanding and predictive capabilities of the high-energy tail ($gtrsim$300 keV) are, in general, poor. This study builds on a recently published statistical analysis based on loss cone electron flux estimates on MEPED observations on board the POES/Metop satellites over a full solar cycle from 2004-2014. Data from the Northern and Southern Hemispheres (55-70°N/S) were combined in daily flux estimates. Flux peaks above the 90th percentile of the >43 kev flux were identified. The 33% highest and lowest associated responses in the >292 keV fluxes were labeled "E3 events" and "E1 events", respectively, resulting in 55 events of each type. It was evident that high geomagnetic activity increases the probability of E3 events. While no single solar wind parameter nor geomagnetic index was able to identify the type of event, Kp and Dst possessed the best predictive capabilities. By detailed examination of the 55 E1 and 55 E3 events, this follow-up study shows that the Kp-index partly classifies a different subset of E1 and E3 events compared to the Dst-index. This makes a combined determination of the limits Dst $\geq$ -26 and $\leq$ -48 nT and Kp $\leq$ 33 and $\geq$ 40, highly effective. Knowing the solar wind driver modifies the combined Kp and Dst limits slightly and correctly labels 85% of events. Despite their differences, common features become apparent for the ambiguous events: a persistent southward Bz alongside sustained substorm onset activity will generate high-energy tail electron precipitation. The concurrent criteria provide insight into when and why high-energy tail electron precipitation occurs.

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New missions and tools / **23**

The Canadian RADiation Impacts on Climate and Atmospheric Loss Satellite (RADICALS) Mission

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The RADiation Impacts on Climate and Atmospheric Loss Satellite (RADICALS) is a low-Earth orbiting Canadian small satellite mission investigating the transport of space radiation into the atmosphere, and its impact on Earth's climate. Scheduled for launch in late 2026, the mission will launch into a polar orbit with an integrated payload comprising two back-to-back look direction High Energy Particle (HEP)telescopes, two back-to-back X-Ray Imagers (XRI) to remote sense energetic particle precipitation using back-scattered Bremsstrahlung X-rays, and boom mounted Flux-Gate Magnetometer (FGM) and Search Coil Magnetometers (SCM). Using an innovative Thomson spin-stabilized configuration, the satellite will sample the pitch angle distributions in the spin-plane twice per spin. The back-to-back HEP look directions allow for a contemporaneous view of the down-going and back-scattered up-going electrons, at the same time as XRI remote-senses the related Bremsstrahlung, and the magnetometers provide in-situ magnetic signatures of a range of plasma waves. The key measurement of the pitch angle resolved energetic electron precipitation (EEP) and related back-scatter, including a resolved loss cone, will allow a detailed assessment of the energetic particle energy input to the atmosphere. Measurements of EEP, in addition to measurements of solar energetic particle (SEP) precipitation, will represent a critical data set for assessing the role of space radiation in the climate system, for example through the catalytic destruction of ozone in the middle atmosphere by NOx and HOx. Accurately quantifying the impacts of this space radiation on climate requires accurate and loss cone-resolved characterization of the flux of these precipitating energetic particles for inclusion into whole atmosphere models. The RADICALS explorer will also enable research into potentially catastrophic space-weather radiation effects on satellite infrastructure, and assess impacts on space weather-related interruptions to high frequency radio communications including in relation to aircraft operations in polar regions.

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Solar Irradiance and Particle Variability / 24

Links of eigen vectors of solar magnetic field with the indices of solar activity in sunspots and flares

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The eigen vectors of magnetic oscillations obtained with Principal Component Analysis from full disk synoptic maps of solar background magnetic field (SBMF) from the Wilcox Solar Observatory are shown to come in pairs assigned to magnetic waves produced by dipole, quadruple, sextuple and octuple magnetic sources. The first pair is linked to dipole magnetic waves with their summary curve revealing a reasonable fit to the averaged sunspot numbers in cycles 21-24. This verifies the previous results and confirms the summary curve as additional proxy of solar activity decreasing towards grand solar minimum in cycles 25-27, or grand solar minimum. There is also a noticeable asymmetry in latitudinal distributions of these PCs showing an increased activity in northern hemisphere in odd cycles and in south- ern hemisphere in even ones similar to the N-S asymmetries observed in sunspots. The second pair of PCs linked to quadruple magnetic sources, has 50% smaller amplitudes than the first, while their summary curve correlate closely with SXR fluxes in solar flares. Flare occurrences are also linked to variations of the next two pairs of eigen vectors, quadruple and sextuple components, revealing additional periodicity of about 2.75-3.1 years similar to observed oscillations in flares. Strong latitudinal asymmetries in quadruple and sextuple components are correlating with the N-S asymmetries of flare occurrences skewed to southern hemisphere in even cycles and to northern hemisphere in odd ones. PCA of solar magnetic field raises perspectives for simultaneous prediction of general and flaring solar activity.

Solicited or Contributed:

Contributed

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Solar Irradiance and Particle Variability / 26

Radiation Belt Loss Derived from Measurements of the Total Radiation Belt Electron Content

Author: Christopher Cully[1]

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The Total Radiation Belt Electron Content (TRBEC) is a measure of the global number of electrons that occupy the radiation belts. It can be calculated based on electron flux measurements and provides a simple, global assessment of the radiation belts. When expressed in adiabatic coordinates, the TRBEC increases abruptly during storms and then decreases with a repeatable and consistent exponential decay during quiet periods as the particles are scattered into the atmosphere. Based on TRBEC measurements from the entire Van Allen probes mission, we quantify the global loss rate of electrons during non-storm periods and compare our results with atmospheric precipitation models.

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 27

Wavenumber-4 longitudinal structure in ICON-MIGHTI thermospheric meridional wind

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The wavenumber-4 (wave-4) structure in the longitude variation of zonal and meridional winds observed by the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard the Ionospheric Connection Explorer (ICON) satellite is investigated. The amplitude of the wave-4 pattern in meridional wind displays semi-annual variation with equinoctial maxima. In contrast, its seasonal variation in zonal wind shows maxima during August-October over the equatorial and low latitudes. The wave-4 longitude variation maximises at lower thermospheric heights (below 130 km) in zonal and meridional winds. It is considered primarily driven by the non-migrating eastward propagating diurnal tide with zonal wavenumber-3 (DE3) in the zonal wind. However, the amplitude of DE3 tide in the meridional wind does not show any enhancement during September-October. The seasonal variations of the wave-4 amplitude and the DE3 tide are not similar in the zonal and meridional winds. The migrating ter-diurnal tide (TW3) exhibits significant amplitudes during March-April and September-November in the meridional wind. In addition, the latitude variation of non-migrating TE1 tide shows maximum amplitude during September-October. These results suggest that the non-linear interaction between the TW3 and TE1 tides can serve as a potential source for the wave-4 longitude variation in the meridional wind at lower thermospheric altitudes.

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CMIP-7 forcing and implementation in Earth system models / 29

Energetic Electron Precipitation from the Radiation Belts: Geomagnetic and Solar Wind Proxies for Precipitation Flux Magnitudes

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In order to determine the effect of energetic particle forcing on the Earth's atmosphere over decadal timespans it has been necessary to develop models of energetic electron precipitation (EEP) based on long time-series geomagnetic indices. This has been done using the geomagnetic index, Ap, and recommended for use as one of the solar forcing factors in the Coupled Model Intercomparison Project Phase 6 of the World Climate Research Programme. However, in that process Ap was not selected as a proxy for EEP based on its merit, but for convenience. Here we use the EEP measurements from three different satellite datasets, 2 individual spacecraft and 1 constellation. We look over different observation periods, and use a range of particle detector configurations to test for the 'best'proxy; investigating both geomagnetic and solar wind parameters. In all we tested seven different indices to see how good they were as proxies for EEP and found that for medium energy electrons the best proxies were Ap, and Dst –both geomagnetic indices. That is good news for the use of Ap in previous solar forcing modelling. For higher energies, relativistic electron precipitation is best proxied by Kp or AE. This should be considered if and when any solar forcing factors are expanded into these relativistic energies for EEP.

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Solicited or Contributed:

Contributed

Solar Irradiance and Particle Variability / 30

Reconstruction of Past Solar Irradiance Variations from Sunspot Observations: A new approach

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Solar irradiance is one of the forcing agents of the Earth's climate system. Space-based monitoring of solar irradiance since the late 1970s has revealed variations across all observed time scales, providing crucial insights into the physical mechanisms behind solar irradiance changes. However, the relatively short duration of these records limits our ability to fully assess the Sun's impact on Earth's climate, necessitating reconstructions of past irradiance variations.
Solar variability on time scales relevant to climate is driven by the solar surface magnetism, and thus reconstructing past irradiance changes requires knowledge of the historical evolution of the Sun's magnetic field. The longest direct proxy for solar magnetic activity is the sunspot number record, which extends back 400 years.
However, existing reconstructions of solar irradiance from sunspot numbers have a serious limitation in that sunspot observations alone do not account for the evolution of bright features such as faculae and the network.
Unluckily, exactly these features are the main driver of irradiance changes on longer time scales. This leads to high uncertainty in estimates of the secular variability. Particularly problematic are

extended periods without sunspots, such as the Maunder Minimum or other grand minima of solar activity.
This limitation has been addressed more realistically by a recent model of the evolution of the solar surface magnetic flux, which linked the emergence rate of faculae to that of sunspots using relationships based on modern observations of the Sun. This approach, in turn, allows a more realistic reconstruction of solar irradiance from sunspot observations, direct or reconstructed using cosmogenic isotope data.

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Solar Irradiance and Particle Variability / 34

Modeling Electron Precipitation in a Non-dipole Field

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The Earth's magnetic field is a complex entity with a heterogeneous structure, exhibiting varying strengths across different coordinates. Of particular interest is the South Atlantic Anomaly (SAA), a region characterized by a strong magnetic field and intense precipitation processes. Accurate modeling of this area demands a comprehensive approach, involving the calculation of magnetic fields and bounce times. Incorporating realistic field models, such as T89 for external and IGRF for internal fields, is essential for correct modeling. Furthermore, dividing the loss cone into drift and bounce components, correlated with geomagnetic latitudes, accounts for the disparate numbers of precipitated particles. By simulating a geomagnetic storm occurring in 2016 and validating our findings against observations from the ELFIN-L instrument on board the Lomonosov satellite in low-Earth orbit, we studied and compared precipitation activity during this event. Our investigation underscores the significance of incorporating the non-dipole loss cone model, leading to improved estimations of precipitated flux into the atmosphere. Moreover, our study unveils a noteworthy connection between the magnetospheric waves activity and precipitation at low latitudes.

Solicited or Contributed:

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 35

Extension of a linearized Ozone scheme to include solar forcing impact

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We have extended the Linearized ozone scheme LINOZ in the ICON (ICOsahedral Nonhydrostatic)-ART (the extension for Aerosols and Reactive Trace gases) model system to include ozone loss caused by energetic particle precipitation (EPP) and changes in the rate of ozone formation due to the variability of the solar radiation in the ultraviolet wavelength range. This extension allows us to represent variable solar forcing in the middle atmosphere using a very simple ozone scheme. The LINOZ scheme is computationally very cheap compared to a full middle atmosphere chemistry scheme, yet provides realistic ozone fields consistent with the stratospheric circulation and temperatures, and can thus be used in climate models instead of prescribed ozone climatologies. To include the energetic particle precipitation indirect effect on ozone via NOy, we use LINOZ version 3 with a NOy-based tendency term only. The additional NOy is brought to the model as an upper boundary condition of NOy, parameterized using the geomagnetic Ap index, as recommended for chemistry-climate models for the CMIP6 experiments. With this extension, the model simulates realistic „tongues"of NOy propagating downward from the model top in the upper mesosphere to the mid-stratosphere in every polar winter and a corresponding ozone loss. In addition, the tabulated coefficients forming the basis of the LINOZ scheme are provided separately for solar maximum and solar minimum conditions. These coefficients are then interpolated to ICON-ART using the F10.7 index as a proxy for daily solar spectra (UV) variability to account for solar UV forcing. This solar UV forcing in the model leads to changes in ozone in the tropical and mid-latitude stratosphere consistent with observed solar signals in stratospheric ozone.

Solicited or Contributed:

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Solar Irradiance and Particle Variability / 37

How can high-resolution magnetohydrodynamic models help in understanding solar variability on various timescales?

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Cross-disciplinary research efforts have led to the emergence of numerical tools capable of taking advantage of the present-day heterogeneous supercomputers, enabling computing at Exa-scale. The first results of running these tools in full production are emerging. In contrast to the CPU paradigm, these runs can be completed within days - a week in contrast to several months. Hence, when submitting this abstract I cannot be totally sure what results I will have at hand in September - fantastic!

These results shed new light into the relevance of small-scale dynamo instability in global solar magnetism and its variability, but also the role of this instability for angular momentum transport, crucial in generating differential rotation, one key ingredient in large-scale dynamo action. It is evident that all the scales (from very short and small spatial scale, in the order of days and size of the magnetic network, to very long and global scale in size) are coupled. In my talk I will review the latest results (available then) and their implications for the global solar variability.

Solicited or Contributed:

Solicited

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Climate response / Earth Radiation Budget / S2S prediction / 39

Seasonal forecast sudden stratospheric warmings and associated winter temperature anomalies based on solar forcing and QBO

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The ground temperature variability in the Northern Hemisphere winter is greatly influenced by the state of the polar vortex. When the vortex collapses during sudden stratospheric warmings (SSWs), rapid changes in stratospheric circulations propagate downward to the troposphere in the subsequent weeks. The ground effect following SSWs is typically manifested as the negative phase of the North Atlantic Oscillation. Our findings reveal a higher frequency of cold temperature anomalies in the Northern part of Eurasia during winters with SSWs, and conversely, in winters with a strong and stable vortex. This behavior is particularly evident when temperature anomalies are categorized into three equal subgroups, or terciles. Recently, we developed a statistical model that successfully predicts SSW occurrences with an 86% accuracy rate. The model utilizes the stratospheric Quasi-Biennial Oscillation (QBO) phase and two parameters associated with solar activity: the geomagnetic aa-index as a proxy for energetic particle precipitations and solar irradiance. In this study, we explore the model's potential to provide a seasonal forecast for ground temperatures. We assessed the probabilities of regional temperature anomalies falling into the lowest or highest terciles based on the predicted weak or strong vortex state. Additionally, we demonstrate that the QBO phase further enhances the forecast's quality. As the model provides SSW predictions as early as preceding August, our results carry significant societal relevance as well, e.g., for the energy sector, which is highly dependent on prevailing weather conditions.

Solicited or Contributed:

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Climate response / Earth Radiation Budget / S2S prediction / 41

Modelling solar cycle responses on climate: from CMIP5 to CMIP6

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There is growing evidence that variability associated with the 11-year solar cycle has an impact at the Earth's surface and influences its weather and climate. Although the direct global response to the Sun's variability is extremely small, a number of different mechanisms have been suggested that could amplify the signal, resulting in regional signals that are much larger than expected. The climate models participated to the 5th phase of the coupled model intercomparison project (CMIP5) showed a clear warming in the stratosphere in association to the 11-yr spectral irradiance forcing but the 11-year solar cycle component of climate variability was found weaker and key mechanisms where not well simulated. We demonstrate that updated models participated in the CMIP6 activity suffer from similar discrepancies compared to solar cycle signatures in reanalyses. In some models, the solar cycle component is unreasonably weak, which might be related to improper consideration of the solar cycle forcing. Solar cycle signatures in the CMIP6 models from the stratosphere to the surface are discussed and uncertainties are highlighted.

Solicited or Contributed:

Solicited

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 42

Approaches to capturing coupled solar-ozone variability in climate models

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Solicited talk

Solar variability contributes to climate variability at global and regional scales. It is therefore important to include this forcing alongside other natural and anthropogenic factors to simulate past climate and to account for the potential solar influence on future climate projections. However, many challenges exist particularly around how to capture the full effect of spectral solar irradiance variations and associated impacts of composition, particularly stratospheric ozone. This talk will review the approaches for capturing solar-ozone forcing in past CMIP exercises, reflect on what we have learned, and consider what could be done for the upcoming CMIP7 simulations.

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Solicited

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New missions and tools / **43**

The ESA EE12 Candidate Mission: Keystone

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Keystone is a proposed upper atmospheric limb sounding mission with the aim of providing a comprehensive measurement of the Mesosphere and Lower Thermosphere (MLT) composition, temperature and winds, and its variability (from a diurnal to a seasonal scale). It's currently in Phase-0 study as ESA's 12th Earth Explorer.

The MLT is the upper atmosphere region which goes from 70km to 120km, subject to high energy inputs from space as solar electromagnetic radiation and energetic particles. The resulting photodissociation, photo-ionisation and high-energy collisions generate radicals and ions, often with internal excitation.

The key science objective (SO) of the Keystone mission is to gain knowledge of geophysical parameters in the MLT that will allow a better understanding of its behaviour. Keystone SO has the aim of improving the understanding of space weather and climate change processes, in particular their impact on the MLT region. This translates in understanding the composition, gradients and variability of the atmospheric neutral density, temperature, winds and trace gases.

To deliver its science, Keystone will pursue the following five mission objectives (MOs):

1. "Thermal balance"(MO1): to quantify reaction rates in chemical and photochemical models of the upper atmosphere by providing global vertical distribution profiles of the key MLT species atomic oxygen (O), in combination with co-located measurements of infrared heat fluxes and visible ultraviolet (UV-Vis) airglow. MO1 will be fulfilled from measurements of: O, temperature, infrared (IR) heat loss, and
airglow.
2. "Diurnal variations of the whole atmosphere"(MO2): to investigate the 4-D spacetime structure of the diurnal variations (atmospheric tides) in view of dynamics, chemistry, and electromagnetic processes. MO2 will be achieved from measurements of winds, temperature, O, ozone (O3), and ozone related species (e.g., HOx, H2O).

3. "Upward coupling"(MO3): to unveil the vertical propagation of synoptic-to-planetary scale disturbances from the middle atmosphere (non-migrating tides and Sudden Stratospheric Warming (SSW) events) to the upper atmosphere. MO3 will be achieved from measurements of temperature, winds, ion density and gravity waves.
4. "Downward coupling"(MO4): to understand atmospheric variations due to energy inputs from the magnetosphere (particle precipitation and magnetic storms). MO4 will be achieved from measurements of NOx, HOx.
5. "Models & applications"(MO5): to provide benchmarks for the whole atmosphere models and climate models with detailed description of the background thermal structure and distribution of minor species. MO5 will be achieved from measurements of H2O, O3, CO (tracer).

The Keystone concept includes a comprehensive remote sensing payload, covering spectral windows in the Terahertz (THz), IR and UV-Vis regions of the electromagnetic spectrum in order to fulfil its science objectives.

The primary instrument foreseen for this mission is a supra-THz radiometer with high spectral resolution for the retrieval of vertical distribution profiles of trace gases, temperature, and mesospheric winds (passive limb-emission spectroscopy). It would be flown in combination with heritage IR and UV-Vis instruments (passive limb-emission sounding).

Keystone would operate from a Low-Earth Orbit (LEO) satellite platform and scan the limb of the atmosphere at tangent height from 50 km to 150 km with high vertical resolution. The exact orbit parameters and viewing geometry are under investigation in the ongoing Phase-0 science requirements study.

Solicited or Contributed:

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 44

Space Weather Impacts on the Mesospheric Metal Layers

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Cosmic dust particles are produced from the sublimation of comets and by collisions between asteroids. The input rate to the atmosphere is estimated to be 27 +/- 14 tonnes per day globally. Because the particles enter the atmosphere at hypersonic velocities, collisional heating with air molecules causes about 30% of them to melt, leading to vaporization of their metallic constituents. The injection of these elements causes a wide variety of atmospheric phenomena, including: the formation of global layers of metal atoms between 80 and 105 km; airglow emissions; layers of metallic ions which affect radio communications; and the production of meteoric smoke particles which enable

the nucleation of mesospheric ice clouds. Certain metal atoms can be observed very precisely by ground-based lidar and from satellites, providing an excellent tracer of dynamics and chemistry at the edge of geospace.
Atmospheric models of 10 meteoric elements (Na, Mg, Al, Si, P, S, K, Ca, Fe and Ni) have been constructed from laboratory measurements of the rate coefficients of over 180 individual reactions involving neutral and ionized species, together with theoretical estimates of rate coefficients which have not been measured. This chemistry, together with the relevant metal injection rates as a function of height, location and time, has been inserted into the Whole Atmosphere Community Climate Model (WACCM). Model simulations compare well against observations of metal atoms/ions from ground-based lidar, rocket-borne mass spectrometry and satellite remote sensing.
This presentation will describe a modelling study of the impacts of energetic particle precipitation (EPP) on the Fe, Na, K layers. Increased ionization above 90 km reduces the neutral metal densities through charge transfer with NO+ and O2+ ions. However, increased atomic O and H below 90 km increases the neutral metal densities, since O and H reduce molecular compounds (oxides, hydroxides and carbonates) back to metal atoms. During and immediately after the very strong solar proton event (SPE) in January 2005, the column abundances of Fe, Na and K below 90 km all show significant increases. A superposed epoch analysis of the metal densities during 19 SPEs of varying strengths between 2003 and 2005 is used to explore the relationship between these metal layers and SPEs in greater detail.

Solicited or Contributed:

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Climate response / Earth Radiation Budget / S2S prediction / 45

Long range forecasting

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We discuss long range forecasting from months to a few years ahead with a focus on current predictions systems, levels of prediction skill and the physical mechanisms that provide predictability, including the role of solar variability and its representation in prediction systems. On these timescales, initial conditions play a significant role in predictability and initialised climate predictions are needed to provide skilful and reliable information. We outline the state of the science, the state of our current predictive capability and take a view on the likely areas for future improvement.

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 46

Atmospheric odd nitrogen response to electron forcing from a 6D magnetospheric hybrid-kinetic simulation

Authors: Tuomas Häkkilä[1]; Maxim Grandin[2]; Markus Battarbee[2]; Monika Szelag[None]; Markku Alho[2]; Leo Kotipalo[2]; Niilo Kalakoski[1]; Pekka Verronen[None]; Minna Palmroth[2]

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Modelling the distribution of odd nitrogen (NOx) in the polar middle and upper atmosphere has proven to be a complex task.
Firstly, its production by energetic electron precipitation is highly variable on hourly time scales. Secondly, there are uncertainties in the measurement-based but simplified electron flux data sets that are currently used in atmosphere and climate models. The altitude distribution of NOx is strongly affected by atmospheric dynamics also on monthly time scales, particularly in the polar winter periods when the isolated air inside the polar vortex descends from lower thermosphere to mesosphere and stratosphere. Recent comparisons between measurements and simulations have revealed strong differences in the NOx distribution, with questions remaining about the representation of both production and transport in models.
Here we present for the first time a novel approach, where the electron atmospheric forcing in the auroral energy range (50 eV - 50keV) is derived from a magnetospheric hybrid-kinetic simulation with a detailed description of energy range and resolution, and spatial and diurnal distribution. These electron data are used as input in a global whole atmosphere model to study the impact on polar NOx and ozone. We will show that the magnetospheric electron data provides a realistic representation of the forcing which leads to considerable impact in the lower thermosphere, mesosphere and stratosphere. We find that during the polar winter the simulated auroral electron precipitation increases the polar NOx concentrations up to 200 %, 50 %, and 7 % in the lower thermosphere, mesosphere, and upper stratosphere, respectively, when compared to no auroral electron forcing in the atmospheric model. These results demonstrate the potential of combining magnetospheric and atmospheric simulations for detailed studies of solar wind - atmosphere coupling.

Solicited or Contributed:

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 47

Enhanced downward transport of thermospheric nitric oxide in a regionally-refined version of WACCM

Authors: Marcin Kupilas[1]; Daniel Marsh[1]; Nicholas Davis[2]; Peter Lauritzen[2]; Wuhu Feng[3]; Chester Gardner[4]; Maria Vittoria Guarino[5]; John Plane[1]

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Earth system models with tops in the thermosphere have historically struggled to recreate the large nitric oxide (NO) mixing ratios in the high-latitude winter and spring mesosphere and stratosphere. Possible causes include missing sources of energetic particle precipitation, missing chemistry, and errors in the general circulation of the upper atmosphere. Additionally, transport by atmospheric waves that are ubiquitous near the mesopause could play a role in transporting the abundant thermospheric NO downward into the mesosphere and stratosphere. Typically, transport by waves that are not resolved by coarse resolution models is parameterized, and a potential source of the NO model-data bias. In this study, we resolve what would normally be subgrid-scale waves natively using a version of the Whole Atmosphere Community Climate Model with regional refinement (WACCM-RR). WACCM-RR resolves limited regions down to as far as 1/32° horizontally at a lower computational cost compared to global high-resolution models. Here we examine the distribution of NO in the upper atmosphere in a WACCM-RR simulation for the full year of 2010 employing 3 levels of refinement down to a 1/8° grid over the Continental US (1° outside of the regionally refined area). At the end of spring at mesopause heights, an increase of a factor of 2.5 is seen over the regionally refined area, which decreases to about a doubling during the summer months. This difference then increases again to around a factor of 2.5 at the end of summer and persists until the start of autumn. Since the additional wave-induced transport is not restricted to NO, other species are impacted (i.e., O, O_3, CO_2). The results point to the applicability of WACCM-RR for detailed investigations of wave-transport processes, and their impact on the dynamics and composition of the stratosphere-mesosphere-lower thermosphere system .

Solicited or Contributed:

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Solar Irradiance and Particle Variability / 48

The NOAA/NCEI Solar Irradiance Climate Data Record, Version 3

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Incoming solar irradiance establishes Earth's surface and atmospheric temperature, driving coupled radiative, dynamical, and chemical processes that produce myriad land, ocean, and atmospheric interactions. The Sun's irradiance is spectrally dependent, as is its variability, on time scales from days to centuries and longer. A fundamental quantity for Earth's energy and climate studies, solar spectral irradiance must be reliably specified on multiple time scales. As well, solar irradiance "reference"spectra with high-accuracy and high spectral resolution for certain levels of solar activity, are important inputs for multiple Earth science applications, including retrievals of aerosols and trace gases, converting satellite observed reflectance to radiance and vice versa, and for solar irradiance modeling.

Improvements in knowledge of total and spectral solar irradiance variability, acquired at higher accuracy and precision by the Total and Spectral Solar Irradiance Sensor (TSIS-1) and Compact Total Irradiance Monitor (CTIM) missions relative to predecessor missions, have been translated into Version 3 of the operational NOAA/NCEI Solar Irradiance Climate Data Record (CDR). The CDR V3 is prescribed by Version 1 of the NASA NOAA LASP (NNL) solar variability models for total solar irradiance (TSI) and solar spectral irradiance (SSI). The NNLTSI1 and NNLSSI1 models hold heritage from the Naval Research Laboratory (NRL) models. The CDR V3 daily- and monthly-averaged data records span from 1874 to present, and the yearly-averaged data record spans from 1610 to present. The CDR V3 prescribes the solar forcing dataset of the 7th Coupled Model Intercomparison Project.

The CDR V3 replaces the CDR V2, which became operational in 2015 and was based on Version 2 of the NRL models. Relative to the CDR V2, the CDR V3 incorporates many advances and new capabilities such as: the absolute irradiance scale of the full spectrum TSIS-1 Hybrid Solar Reference Spectrum (HSRS), a broader spectral range from the extreme ultraviolet through the far-infared (~0 to 200,000 nm) to support both the space weather and climate modeling communities, a separate higher spectral resolution SSI product to support the study of atmospheric chemistry and dynamics processes, and an irradiance prediction product forecasts TSI and SSI in several bands through 2100.

We will focus our discussions on the CDR V3 formulation and compare irradiance variability results on rotational and solar cycle time scale to irradiance observations and other models.

Solicited or Contributed:

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Climate response / Earth Radiation Budget / S2S prediction / 68

Assessment of the 11-year solar cycle signals in the middle atmosphere in multiple-model ensemble simulations

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To better understand possible reasons for the diverse modeling results and large discrepancies of the detected solar fingerprints, we took one step back and assessed the "initial" solar signals in the middle atmosphere based on large ensemble simulations with multiple climate models —FOCI, EMAC, and MPI-ESM-HR. Consistent with previous work, we find that the 11-year solar cycle signals in the short wave heating rate (SWHR) and ozone anomalies are robust and statistically significant in all three models. These "initial" solar cycle signals in SWHR, ozone, and temperature anomalies are sensitive to the strength of the solar forcing. Correlation coefficients of the solar cycle with the SWHR, ozone, and temperature anomalies linearly increase along with the enhancement of the solar

cycle amplitude, and this reliance becomes more complex when the solar cycle amplitude exceeds a certain threshold. In addition, the cold bias in the tropical stratopause of EMAC dampens the subsequent results of the "initial" solar signal. The warm pole bias in MPI-ESM-HR leads to a weak polar night jet (PNJ), which may limit the top-down propagation of the initial solar signal. Although FOCI simulated a so-called top-down response as revealed in previous studies in a period with large solar cycle amplitudes, its warm bias in the tropical upper stratosphere results in a positive bias in PNJ and can lead to a "reversed" response in some extreme cases. We suggest a careful interpretation of the single model result and further re-examination of the solar signal based on more climate models.

Solicited or Contributed:

Contributed

Presenting author:

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Climate response / Earth Radiation Budget / S2S prediction / 69

Lagged Response of MJO-Related Subseasonal Climate to Short-Term Solar Ultraviolet Variations

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The tropical Madden-Julian oscillation (MJO), also known as the 40-50 day oscillation, is an eastward-propagating,convectively-coupled wave which functions as a key driver of sub-seasonal to seasonal convection and precipitation variability in the tropics (e.g., Madden and Julian 1994). The MJO generates a Rossby wave train that strongly influences weather in the extratropics on subseasonal time scales and evolves continuously through eight phases. Each phase is associated with either suppressed or enhanced convection within sub-regions of the tropics that progress eastward with time. Previous research has shown that the stratospheric quasi-biennial oscillation (QBO) modulates the strength of the MJO during boreal winter (e.g., Yoo and Son, GRL, 2016). The modulation is such that the MJO is about 40% stronger and persists about 10 days longer during the easterly QBO phase (QBOE) than during the westerly phase (QBOW).

Recent composite analyses over 6 solar maximum periods supports the existence of a response of MJO-related tropical convection and precipitation to short-term (~27-day) solar ultraviolet variations (Hoopes, Hood, & Galarneau, GRL, 2024, https://doi.org/10.1029/2023GL107701). Following solar UV peaks, the response consists of an increase in average convection and precipitation in the equatorial Indian Ocean and a decrease in the western and central tropical Pacific, with maximum amplitude at a lag of 4 to 8 days. The opposite occurs following short-term solar UV minima. The observed responses are most detectable when the Madden-Julian oscillation (MJO) is active and appear to be related to a reduced ability of the MJO to propagate across the Maritime Continent barrier following solar UV peaks relative to UV minima. A similar behavior has previously been found when the QBO is in its westerly phase relative to its easterly phase.

Following solar UV peaks, the hypothesized mechanism involves direct solar UV increases of ozone production and radiative heating in the upper stratosphere, a slowing of the residual meridional (Brewer-Dobson) circulation, relative downwelling in the tropics, and an increase in static stability in the tropical lower stratosphere. The current results apply specifically to the ~27-day solar rotational time scale. However, observational evidence on this time scale supports the view that similar effects should also occur on the 11-year time scale. Thus, MJO eastward propagation across the MC barrier may also be inhibited near 11-yr solar maxima relative to solar minima. In this sense, the MJO may represent a key link between solar spectral irradiance variability, which directly affects only the tropical upper stratosphere, and tropospheric climate.

Current work in progress is aimed toward an initial investigation of the extratropical consequences of the ~ 27-day modulation of MJO convection and precipitation. In particular, we are investigating effects on the Northern Hemisphere storm track, which is strongly influenced by the MJO. Results will be presented at the conference.

Solicited or Contributed:

Contributed

Presenting author:

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Author list and affiliations:

Climate response / Earth Radiation Budget / S2S prediction / 71

Solar Flux Effects on the Variations of Equatorial Electrojet (EEJ) and Counter-Electrojet (CEJ) Current across the Different Longitudinal Sectors during Low and High Solar Activity

Author: Alemayehu Cherkos[1]

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This study examined the effect of solar flux (F10.7) and sunspots number (R) on the daily variation of equatorial electrojet (EEJ) and morning/afternoon counter electrojet (MCEJ/ACEJ) in the ionospheric E region across the eight longitudinal sectors during quiet days from January 2008 to December 2013. In particular, we focus on both minimum and maximum solar cycle of 24. For this purpose, we have collected a 6-year ground-based magnetic data from multiple stations to investigate EEJ/CEJ climatology in the Peruvian, Brazilian, West & East African, Indian, Southeast Asian, Philippine, and Pacific sectors with the corresponding F10.7 and R data from satellites simultaneously. Our results reveal that the variations of monthly mean EEJ intensities were consistent with the variations of solar flux and sunspot number patterns of a cycle, further indicating that there is a significant seasonal and longitudinal dependence. During the high solar cycle period, F10.7 and R have shown a strong peak around equinoctial months, consequently, the strong daytime EEJs occurred in the Peruvian and Southeast Asian sectors followed by the Philippine regions throughout the years investigated. In those sectors, the correlation between the day Maxima EEJ and F10.7 strengths have a positive value during periods of high solar activity, and they have relatively higher values than the other sectors. A predominance of MCEJ occurrences is observed in the Brazilian (TTB), East African (AAE), and Peruvian (HUA) sectors. We have also observed the CEJ dependence on solar flux with an anti-correlation between ACEJ events and F10.7 are observed especially during a high solar cycle period.

Solicited or Contributed:

Presenting author:

Author list and affiliations:

Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 72

Empirical model of SSUSI-derived auroral ionization rates

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Solar, auroral, and radiation belt electrons enter the atmosphere at polar regions leading to ionization and affecting its chemistry. Whole-atmosphere chemistry–climate models such as WACCM(-X) or EDITh usually parametrize this ionization based on in-situ satellite particle measurements. Widely used particle data are derived from the POES and GOES satellite measurements which provide in-situ electron and proton spectra at the satellite location.

Here we present an empirical model derived from the electron energy and flux data products from the Special Sensor Ultraviolet Spectrographic Imagers (SSUSI) on board the Defense Meteorological Satellite Program (DMSP) satellites. This formation of currently three operating satellites observes the auroral zone in the UV from which electron energies and fluxes are inferred in the range from 2 keV to 20 keV. We use these observed electron energies and fluxes to calculate auroral ionization rates in the lower thermosphere (≈ 90–150 km). We derived our empirical parametrization from these previously validated ionization rates on a magnetic local time/geomagnetic latitude grid. The regression model is driven by geomagnetic indexes Kp, PC, and Ap, and the solar radio flux F10.7. The resulting parametrization is simple in application and particularly targeted for use in whole-atmosphere chemistry–climate models that include the upper atmosphere, such as WACCM-X or EDITh. An initial comparison to the AIMOS/AISstorm ionization rates shows that the order of magnitudes are comparable, but we observe differences in the peak ionization altitude.

Solicited or Contributed:

Contributed

Presenting author:

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Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 73

Observations of particle precipitation with EISCAT radars

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The EISCAT incoherent scatter radars in Tromsø, northern Norway, and in Longyearbyen, Svalbard measure key parameters of the ionospheric plasma (electron density, electron and ion temperatures, and plasma bulk velocity) at multiple altitudes along the radar beam. The radars are thus ideal instruments for observing electron density enhancements produced by particle impact ionization.

Electron density profiles measured along a geomagnetic field-line at D and E region altitudes can be inverted into electron precipitation energy spectra. We have inverted energy spectra of 1-100 keV electron precipitation with about 1 minute time resolution from all available EISCAT data measured

with field-aligned radar beam at 80-150 km altitudes since 1998. The dataset enables statistical studies of electron precipitation characteristics at two magnetic latitudes, one in the auroral oval (66.73° MLAT) and one in polar cap (75.43° MLAT). Ionization produced by > 100 keV electrons below 80 km altitude is observed with some radar operation modes, but the complex D region chemistry makes the energy spectra inversion more demanding than below 100 keV. Also ionization by proton precipitation is observed, but it is less common than electron precipitation and its energy spectra have not been inverted.

The radars in Tromsø will be soon replaced with the next-generation EISCAT3D radar with a core site in Skibotn, Norway, and remote receivers in Finland and Sweden at about 130 km distance from the core site. EISCAT3D will use aperture array antennas and digital beamforming, enabling multiple simultaneous beams and virtually instantaneous beam steering. The radar can thus paint the sky with a rapidly moving transmission beam and produce 3D maps of the ionosphere. Novel analysis techniques are expected to enable electron energy spectra fits along multiple field-lines from EISCAT3D data.

Solicited or Contributed:

Solicited

Presenting author:

Ilkka Virtanen

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Solar Irradiance and Particle Variability / 74

AISstorm 2.1 - Modeling Particle induced atmospheric Ionization

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AISstorm (Atmospheric Ionization during Substorms Model) derives the global atmospheric ionization due to particle precipitation based on in-situ particle measurements. The model covers auroral precipitation as well as solar particle events on an altitude range of about 250km down to 16km for protons and down to 70km for electrons.
The ionization of alpha particles is also included, but in a smaller height range.
The overall structure is divided into an empirical model, which determines the 2D flux of the precipitating particles, and a numerical model, which determines the ionization profile of the individual particles. The combination of these two models results in a high-resolution 3D particle ionization rate pattern.
AISstorm is the successor to the Atmospheric Ionization Module Osnabrück (AIMOS).

The main advantage of the updated ionization rates is a wider dynamic range during substorms and during the onset of geomagnetic storms, especially in the mesosphere - in agreement with observations.

The internal structure of the model has been completely revised in AISstorm. The main aspects are: a) an internal magnetic coordinate system, b) the inclusion of substorm properties, c) a higher temporal resolution, d) a higher spatial resolution, e) an energy-specific, separate treatment of auroral precipitation, polar cap precipitation and crosstalk-affected areas, f) a better MLT resolution.

We compare the new ionization rates to AIMOS 1.6, AISstorm 2.0 and the HEPPA III multi-model study.

Solicited or Contributed:

Contributed

Presenting author:

Jan Maik Wissing

Author list and affiliations:

Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 75

About EPP-Driven Variability of Upper Atmospheric Nitric Oxide Over the Syowa Station in Antarctica

Author: Pekka Verronen[None]

Co-authors: Akira Mizuno ; Antti Kero ; Esa Turunen ; Monika Szelag ; Satonori Nozawa ; Shin-Ichiro Oyama ; Tac Nakajima ; Tomoo Nagahama ; Yoshi Miyoshi

In the polar middle and upper atmosphere, Nitric Oxide (NO) is produced in large amounts by both solar EUV and X-ray radiation and energetic particle precipitation (EPP), and its chemical loss is driven by photodissociation. As a results, polar atmospheric NO has a clear seasonal variability and a solar cycle dependency which have been measured by satellite-based instruments. On shorter timescales, NO response to magnetospheric electron precipitation has been shown to take place on a day-to-day basis. Despite recent studies using observations and simulations, it remains challenging to understand NO daily distribution in the mesosphere-lower thermosphere during geomagnetic storms, and to separate contributions of EPP forcing and atmospheric chemistry and dynamics. This is due to the uncertainties existing in the available EPP flux observations, differences in representation of NO chemistry in models, and differences between NO observations from satellite instruments. Nagoya University has operated a millimeter-wave spectroscopic radiometer at the Syowa station in Antarctica since 2012. In this paper, we use NO data from the Syowa radiometer measured in the period 2012 - 2017 to study both its long-term and short-term variability. Comparisons are made with results from the Whole Atmosphere Community Climate Model (WACCM) to understand the shortcomings of current EPP forcing in models and how the representation of the NO variability can be improved in simulations.

Solicited or Contributed:

Contributed

Presenting author:

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Author list and affiliations:

Climate response / Earth Radiation Budget / S2S prediction / 76

Influence of energetic electron precipitation on wintertime electricity consumption in Finland and wind power generation in Europe

Authors: Antti Salminen[None]; Timo Asikainen[1]; Veera Juntunen[1]

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Recent studies have shown that geomagnetic activity, used as a proxy for energetic electron precipitation (EEP), influences weather conditions, e.g. temperature and wind speed, during winter in certain regions of the Northern hemisphere. EEP forms ozone-depleting hydrogen and nitrogen oxides (HOx & NOx), which alter the radiative balance in wintertime atmosphere and enhance the northern polar vortex, the westerly wind system circulating the northern polar area during winter. In Northern (Southern) Europe a stronger polar vortex leads to mild, wet and windier (dry and less windy) winter weather, while a weaker vortex leads to cold and less windy (wet and windier) winters in Northern (Southern) Europe. The influence of EEP on the polar vortex has been found to be stronger when so called quasi-biennial oscillation (QBO), the equatorial stratospheric zonal wind varying between easterly and westerly phases every ca. 14 month, is in easterly phase.

It is known that in countries with cold winter temperatures a great amount of electricity consumption is used for heating houses. E.g. in North Europe, notably in Finland, electricity consumption is increased during cold winters and decreased during milder winters. Previously it has also been shown that polar vortex related changes in ground level wind speed have an influence on the electricity production by wind power in different European countries.

Here we show that the EEP effect on the polar vortex has a significant impact on wintertime electricity consumption in Finland and on wind power generation in Northern and Southern Europe through temperature and wind speed variations. We also find that this effect is valid only during easterly QBO winds.

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Contributed

Presenting author:

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CMIP-7 forcing and implementation in Earth system models / 77

Solar forcing recommendations for CMIP7

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Back in 2017, solar forcing recommendations for the 6th round of the Coupled Model Intercomparison Project (CMIP) were provided which covered, for the first time, all relevant solar irradiance and energetic particle contributions. Since then, this dataset has been extensively used in climate model experiments and has been tested in various intercomparison studies. Further, new datasets have been come available. An International Space Sciene Institute (ISSI) Working Group has been established to review these recent achievements in order to define the strategy for building a revised solar forcing dataset for the upcoming 7th round of CMIP. After receiving community feedback on this strategy, a preliminary histrorical solar forcing dataset for CMIP7 has been recently constructed. Major changes with respect to CMIP6 include the adoption of the new Total and Spectral Solar Irradiance Sensor (TSIS-1) solar reference spectrum for solar spectral irradiance and an improved description of top-of-the-atmosphere energetic electron fluxes, as well as their reconstruction back to 1850 by means of geomagnetic proxy data. Solar irradiance varaibility in the reference forcing dataset is based on historical reconstructions generated with a preliminary version of the new empirical NASA NOAA LASP (NNL) Solar Spectral Irradiance Version 1 model, NNLSSI1. In adition, an alternative solar irradiance dataset, based on SATIRE, is provided for sensitivity experiments. In this talk we will discuss the applied modifications with respect to CMIP6 and their implication for climate modeling. Ongoing activities on solar forcing uncertainty quantification and the contruction of future solar forcing scenarios will also be summarized.

Solicited or Contributed:

Contributed

Presenting author:

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CMIP-7 forcing and implementation in Earth system models / 78

Creation of the next generation CMIP7 ozone forcing database

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This presentation will provide an overview of the next generation ozone forcing database in support of the Coupled Model Intercomparison Project phase 7 (CMIP7). Tropospheric and stratospheric ozone changes are key drivers of climate change and need to be accounted for in climate model simulations that aim at understanding past and future climate responses to anthropogenic emissions of long-lived greenhouse gases and precursors. A new three-dimensional ozone dataset covering the time period 1850-2021, plus a set of comprehensive future scenarios out to 2100 will be prepared, consistent with other climate forcings (including solar) and the timeline envisaged by the CMIP Forcings Task Team. The dataset, an update to the CMIP6 ozone forcing by Hegglin et al. (ESGF, 2016), will be purely model based using a couple state-of-the-art chemistry-climate models that include stratosphere-troposphere resolving chemistry. Validation against observations ensures reliability.

The process behind this effort will be discussed in detail. The resulting database supports CMIP's goals of improving climate projections and understanding ozone's role in climate change.

Solicited or Contributed:

Solicited

Presenting author:

Michaela Imelda Hegglin

Author list and affiliations:

Climate response / Earth Radiation Budget / S2S prediction / 79

Terrestrial temperature, sea level and ENSO index variations linked with solar and volcanic activity

Author: Valentina Zharkova[1]

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In this paper we investigated the Oceanic Niño Index (ONI), for simplicity called in this paper an El Nino Southern Oscillation (ENSO) index in 1950-2023 by applying the wavelet spectral transform and the IBM SPSS correlations analysis. ONI follows the three months current measurements of an average temperature of the sea surface in the East-Central tropical part of the Pacific ocean nearby the international line of the date change over the average sea surface temperature over the past 30 years. The ENSO index is found to have a strong ($> 87\%$) correlation with the Global Land-Ocean Temperature (GLOT). The scatter plots of the ENSO-GLOT correlation with the linear and cubic fits have shown that the ENSO index is better fit by the cubic polynomial increasing proportionally to a cubic power of the GLOT variations. The wavelet analysis allowed us to detect the two key periods in the ENSO (ONI) index: 4-5 year and 12 years. The smaller period of 4.5 years can be linked to the motion of tectonic plates while the larger period of 12 years is shown to have a noticeable correlation of 25% with frequencies of the under-water (submarine) volcanic eruptions in the areas with ENSO occurrences. Not withholding any local terrestrial factors considered to contribute to the ENSO occurrences, we investigated the possibility of the volcanic eruptions causing ENSO to be also induced by the tidal forces of Jupiter and Sun showing the correlation of the under-water volcanic eruption frequency with the Jupiter-Earth distances to be 12% and with the Sun-Earth distances, induced by the solar inertial motion, in January, when the Earth is turned to the Sun with the southern hemisphere where the ENSO occurs, to become 15% . Hence, the underwater volcanic eruptions induced by tidal forces of Jupiter and Sun can be the essential additional factors imposing this 12 year period of the ENSO (ONI) index variations.

Solicited or Contributed:

Contributed

Presenting author:

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Author list and affiliations:

New missions and tools / 80

A new scheme to improve the spectral representation of solar forcing for photolysis and heating in Earth System Models.

Author: James Manners[1]

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A flexible new scheme has been implemented in the Socrates radiative transfer code in order to parametrise a unified treatment of radiative heating, photolysis and photoionisation covering the whole spectrum of solar emission.

Socrates is currently used only for radiative heating within the UK Earth System Model. For CMIP7 this will represent solar spectral variability in 12 bands including 7 in the ultra-violet. The new scheme introduced here will allow much finer spectral resolution along with an integrated treatment of photolysis that is currently handled by the separate Fast-JX scheme.

Photolysis calculations generally require a higher wavelength resolution than is used for calculations of radiative heating in Earth System Models. In order to maintain accuracy for photolysis calculations whilst reducing computational cost a novel wavelength mapping technique is implemented as part of the correlated-k method. This allows the mapping of radiative fluxes onto thousands of sub-bands that are individually scaled with the time-varying solar spectrum. Photolysis is then calculated at high-wavelength resolution and absorption leading to photodissociation is not double-counted for radiative heating.

A further novel technique is introduced to replace the plane-parallel approximation with the pseudo-spherical approximation for both radiative heating and photolysis. This allows the calculation of solar radiation absorbed in the twilight regions of the atmosphere where the solar zenith angle is greater than 90°. While this is often done in photolysis calculations, the effect on radiative heating has been generally ignored.

Prototype configurations covering far and extreme-UV wavelengths will be discussed along with plans for future climate model configurations.

Solicited or Contributed:

Contributed

Presenting author:

James Manners

Author list and affiliations:

Stratosphere / mesosphere / thermosphere response and coupling of atmospheric layers / 81

Atmospheric impact of the extreme geomagnetic storm of May 10/11, 2024

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On May 10-11, two CMEs arriving within few hours initiated a geomagnetic storm with a DST of around -400 nT in the main phase. With a Kp of 9 for several hours, the threshold for an "extreme" geomagnetic storm was reached for the first time since the Halloween storm in October/November

2003, and polar lights were clearly visible well into magnetic midlatitudes. Proton fluxes were enhanced for several days, reinforced by a third CME arriving on May 13; however, they were distinctly lower than for the Halloween SPE of October 2003, making this a fairly moderate solar proton event. Analyses of the still ongoing satellite data-sets MLS/AURA and ACE-FTS/SCISAT will be discussed, showing a small ozone loss in the high-latitude upper mesosphere, as well as moderate increases of NO and N_2O in the upper mesosphere. The spatial structure of the response is consistent with a small, soft-spectra solar proton event, but it appears to be weaker, and restricted to higher altitudes, than, e.g., the response to the much more moderate geomagnetic storm of April 2010. However, a direct comparison is difficult as the instruments used to assess the April 2010 storm (MIPAS/ENVISAT, SCIAMACHY/ENVISAT, SOFIE/AIM) are inoperable now. This emphasizes on the one hand the large spread of possible impacts of geomagnetic storms, on the other hand the need for continuing global observations.

Solicited or Contributed:

Contributed

Presenting author:

Miriam Sinnhuber

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Solar Irradiance and Particle Variability / 82

Recent Progress on Modelling Energetic Electron Precipitation to the Atmosphere

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Co-authors: Alexander Drozdov [2]; Alina Grishina ; Bernhard Haas ; Yuri Shprits

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The energetic electrons in the Earth's radiation belts and ring current can precipitate to the atmosphere. Such precipitation of energetic particles from space can generate nitric oxide in the atmosphere, and nitric oxide can destroy ozone very efficiently. Geomagnetic activity that controls the precipitation of magnetospheric particles is now recommended as part of the solar forcing of the climate system for model experiments. The complication of estimating the effect of the precipitating particles usually arises from the fact that measurements are sparse and the global models of the precipitating particle environment are not available. In this presentation, we show our recent progress on modelling energetic electron precipitation to the atmosphere.

Solicited or Contributed:

Solicited

Presenting author:

Dedong Wang

Author list and affiliations:

New missions and tools / 83

The Changing-Atmosphere Infra-Red Tomography Explorer CAIRT –a candidate for ESA's Earth Explorer 11

Author: Björn-Martin Sinnhuber[1]

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The Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) is currently in Phase A as one of two candidates for ESA's Earth Explorer 11. As a Fourier transform infrared limb imager, CAIRT will observe simultaneously from the middle troposphere to the lower thermosphere at high spectral resolution and with unprecedented horizontal and vertical resolution. With this, CAIRT will provide critical information on (a) atmospheric gravity waves, circulation and mixing, (b) coupling with the upper atmosphere, solar variability and space weather and, (c) aerosols and pollutants in the upper troposphere and lower stratosphere. In this presentation we will give an overview of CAIRT' s science goals with a focus on the mesosphere and lower thermosphere region and the expected mission performance, based on latest results from Phase A studies.

Solicited or Contributed:

Solicited

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Observations of TSI and OLR with CLARA onboard NorSat-1

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Solar variability varies on many timescales from minutes to decades and beyond. To determine the effect of solar irradiance on the Earth's system the knowledge of the incoming solar radiation needs to be known with high precision. We report on latest advances in measuring TSI with the CLARA radiometer onboard NorSat-1 and compare it to the latest TSI measurements. Besides TSI, CLARA also measures the terrestrial longwave outgoing radiation. The OLR measurements are a first step towards the measurement of the Earth Radiation Budget (ERB) from the top of the atmosphere with an SI-traceable radiometer. As such these measurements are an important step towards measuring the Earth Energy Imbalance from space.

Solicited or Contributed:

Contributed

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Solar activity parameters do not follow each other: What happens in the solar atmosphere?

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The Sun experienced a period of unprecedented activity during solar cycle 19 in 1950s and 1960s, now called the Modern Maximum (MM). The decay of the MM has changed the Sun, the heliosphere and the planetary environments in many ways. However, this decay may not have proceeded synchronously in all solar parameters. One of the related key issues is if the relation between the two long parameters of solar activity, sunspot number and the solar 10.7cm radio flux, has remained the same during this decay.

Here we use the 10.7cm radio flux, sunspot numbers and several other, independent measures of solar activity in order to study their mutual relations during the decay of MM. We find that, during this overall decay, the 10.7cm radio flux increases relative to sunspot numbers. This is supported by found other radio fluxes measured independently in Japan. All five radio fluxes depict an increasing trend with respect to the sunspot number from 1970s to 2010s. This excludes the possibility for an inhomogeneity in the 10.7cm flux.

Interestingly, the fluxes of longer radio waves increased with respect to the shorter waves, which implies a long-term change in the solar spectrum at radio frequencies. We also find that solar UV irradiance, and the number of active regions also increased with respect to the sunspot number, indicating a difference in the long-term evolution in chromospheric and photospheric parameters.

These results give evidence for important structural changes in solar magnetic fields and solar atmosphere during the decay of the MM when solar activity weakened considerably. We show that these changes are related to the centennial Gleissberg cycle and opposite changes are already ongoing with the increasing solar activity from cycle 25 onwards.

Solicited or Contributed:

Contributed

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New missions and tools / 86

Ozone-temperature response to 11-year solar variability as depicted in CCMI and CMIP6 models

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The evolution of changes in the zonal mean vertical distribution of ozone from the set of models participating in the CCMI-2022 project, using data from the REF-D1 and REF-D2 series of simulations is examined. This work presents the effects of natural variability forcings, focusing on solar cycle effects, as well as ENSO and volcanic eruptions on ozone and temperature profiles using the regression analysis and tools presented in the LOTUS SPARC Project.
Results are compared to satellite-derived for their common periods, as well as to CMIP5 and CMIP6 ESMs with resolved stratosphere and interactive chemistry. An initial comparison between linear and DLM results in the lower stratosphere is also shown.

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Controversies in sun-climate studies, role of natural factors and areas of disagreement between observation and CMIP models

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Causes of a Lack of QBO/Solar-MJO Connection in Certain CMIP6 Models

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Causes of a Lack of QBO/Solar-MJO Connection in Certain CMIP6 Models

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