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Workshop Abstracts
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Transport of polar winter lower-thermospheric Nitric Oxide to the Stratosphere

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In this talk, we discuss observations of atmospheric Nitric Oxide from the Solar Occultation for Ice Experiment (SOFIE) instrument on-board the Aeronomy of Ice in the Mesosphere (AIM) satellite. Over a decade of polar NO observations from 40 to 140 km are now available. SOFIE shows dramatic transport of NO in the NH winters of both 2008-2009 and 2012-2013. Both of these episodes occur after major SSWs. A weaker but very large enhancement of NO was observed in 2011-2012 after a minor SSW. In each case, SOFIE observations of water also show evidence of transport and SOFIE observations of temperature show an elevated stratopause. These results are consistent with previous observations and the inferred role of SSWs. We will show the SOFIE observations and explore how the strength and timing of SSWs control the magnitude of the NO transport.

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The Energetic Particle Precipitation Impacts and Coupling (EPPIC) Mission

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The Energetic Particle Precipitation Impacts and Coupling (EPPIC) mission is a satellite constellation concept in development to be proposed in 2019. The goal of EPPIC is to determine how precipitating solar and magnetospheric energetic particles drive the ionization patterns in the lower thermosphere and middle atmosphere of Earth, and how they ultimately impact the electrical, chemical, and dynamical properties in the upper and lower regions of the atmosphere. EPPIC will measure in unprecedented detail the magnetospheric and solar particle inputs that determine the chemical and electrodynamic processes of Earth’s atmospheric system. It will also measure altitude profiles of polar region NOx, the chemical agent by which energetic particles couple the upper and lower regions of the atmosphere and impact the chemical and thermal structure throughout. Finally, EPPIC will obtain the meteorological information – temperature, winds, and tracer profiles, to understand how the atmosphere transports NOx in and out of the polar region and from upper altitudes where particle energy is deposited to the stratosphere. In this talk we will describe the mission plan and proposed observations. We will also discuss key trade studies and the maturity of some of the key technology.
New Simulations of the 2003 Halloween Solar Storms Using WACCM-X

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The “Halloween” storms from October to November of 2003 are a period of extreme solar activity including X28, X17, and X7 class flares. We revisit these storms with the latest release of the Whole Atmosphere Community Climate Model with thermosphere and ionosphere (WACCM-X), which is a comprehensive chemistry climate model covering the Earth’s surface to the upper thermosphere. These results are the first simulations of these storms using WACCMX and highlight the ability of the model to capture the extreme events during this time period. We show comparisons of the total electron content (TEC) from the model with MAPGPS observations, conduct sensitivity tests identifying the contributions from the flares and increased auroral activity to the TEC, and explore the sensitivity of the results to the amount of ionization and to changes in the reaction rate for N(2D) + O2. Comparisons between the free running simulations and those with the lower atmosphere nudged to observations suggest a coupling of the lower atmosphere with the upper atmosphere that has a significant effect on TEC.

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Empirical model of nitric oxide in the mesosphere from SCIAMACHY/Envisat satellite observations

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Solar, auroral, and radiation belt electrons as well as soft solar X-rays produce nitric oxide (NO) in the mesosphere and lower thermosphere (MLT, 50-150 km). NO downward transport, in particular during polar winters, influences the lower atmosphere by, for example, catalytically reducing ozone. These changes in the NO and ozone chemistry also change the dynamics of the mesosphere and can impact the stratosphere. We present ten years of daily global NO number density measurements obtained by the satellite instrument SCIAMACHY on board Envisat. The densities are derived from UV limb scans of the mesosphere for altitudes from 60km to 90 km. From this data set, from 08/2002 to 04/2012, we construct an empirical model of NO in the mesosphere. In particular, we link NO production and its lifetime to geomagnetic disturbances (given by the AE index) and to the solar UV radiation (using the Lyman-alpha index). The derived parameters constrain how solar and geomagnetic activity influence the NO content in the mesosphere. Our model will help to fill gaps in measurements and to validate and improve chemistry climate models. In the longer term, additionally including dynamical effects in the model can help to distinguish between direct production and transport processes.

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SuperDARN radar measurements of HF radio attenuation during the September 2017 solar proton events

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Solar proton events are known to cause widespread disruption to high frequency (HF) radio communications in the high latitude and polar regions. This disruption arises due to strong radio wave attenuation in the D-region ionosphere, and is typically monitored using networks of riometers. In this talk we demonstrate a novel application of the Super Dual Auroral Radar Network (SuperDARN) for monitoring HF radio attenuation from middle to polar latitudes. Our method uses routine measurements of the background HF radio noise, a measurement which is required for data processing but is not normally used for science applications. Focusing on the two solar proton events which occurred in September 2017, we show that the temporal evolution of the SuperDARN-derived radio attenuation closely follows riometer measurements of cosmic noise absorption. We also observe brief periods of enhanced attenuation at mid-latitudes following the arrival of M- and X-class solar flares. In addition to solar proton events, we anticipate that SuperDARN radars may also be used to measure HF attenuation during other events such as substorms, which may be particularly useful when riometer data are not available.

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Northern Hemisphere Stratospheric Ozone and the Polar Vortex.

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Ozonesonde data from four sites are analyzed in relation to 191 solar proton events from 1989 to 2016. Analysis shows ozone depletion (\textasciitilde 10–35 km altitude) commencing following the SPEs. Seasonally corrected ozone data demonstrate that depletions occur only in winter/early spring above sites where the northern hemisphere polar vortex (PV) can be present. A rapid reduction in stratospheric ozone is observed with the maximum decrease occurring \textasciitilde 10–20 days after solar proton events. Ozone levels remain depleted in excess of 30 days. No depletion is observed above sites completely outside the PV. No depletion is observed in relation to 191 random epochs at any site at any time of year. The association of the winter-time PV in our results suggests that the rapid transport of long-lived NOx species plays a role in causing indirect ozone destruction.

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Estimates of impacts on atmospheric chemistry from radiation belt electrons using observations from FIREBIRD and the Van Allen Probes

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This study considers the impact of atmospheric electron precipitation from the Van Allen radiation belts on atmospheric composition using observations from the NSF Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) CubeSats and Van Allen Probes RBSP-ECT. Total radiation belt electron content (TRBEC) calculated from Van Allen Probes RBSP-ECT/MagEIS data provide an estimate of precipitation during electron loss events. We use ratios of electron flux between FIREBIRD (low polar orbit) and RBSP-ECT/MagEIS (near-equatorial orbit in the radiation belts) during conjunctions to estimate the precipitation flux. Atmospheric ionization profiles are calculated by integrating monoenergetic ionization rates across the differential flux spectrum and are used along with the NCAR Whole Atmosphere Community Climate Model (WACCM) to quantify enhancements of atmospheric HOx and NOx and subsequent destruction of O3. We assess the relative importance of these events with respect to solar protons in an effort to explain a missing source of upper atmospheric NOx in models that include only solar protons and auroral electrons.

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The stratospheric reactive nitrogen budget: what is the role of energetic particle precipitation?

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Reactive nitrogen (NOy) makes the largest contribution to ozone depletion in the middle stratosphere. Thus, changes of its amount will have an impact on the ozone budget and hence on the thermal structure and dynamics of the stratosphere. Here we use MIPAS observations of NOy, ozone, and nitrous oxide during 2002-2012 to constrain the global stratospheric NOy amount as well as its dominant sources (i.e., N2O oxidation and energetic particle precipitation) and sinks (i.e., photochemical losses of NO and the NOy flux into the troposphere). Results are compared to chemistry climate model simulations conducted with EMAC, SOCOL, and WACCM. Also, the sensitivity of past, present, and future stratospheric NOy to external and internal forcings is discussed. A particular emphasis will be given to the contribution of NOy produced by energetic particle precipitation.

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Production and transport mechanisms of polar MLT region NO in AIM/SOFIE observations and SD-WACCM simulations

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A reservoir of Nitric Oxide (NO) in the lower thermosphere efficiently cools the atmosphere after periods of enhanced geomagnetic activity. Transport from this reservoir to the stratosphere within the winter polar vortex allows NO to deplete ozone levels and thereby affect the middle atmospheric heat budget. As more climate models resolve the mesosphere and lower thermosphere (MLT) region, the need for an improved representation of NO related processes increases. This work presents a detailed comparison of NO in the Antarctic MLT region between observations made by the Solar Occultation for Ice Experiment (SOFIE) instrument onboard the Aeronomy of Ice in the Mesosphere (AIM) satellite and simulations performed by the Whole Atmosphere Community Climate Model with Specified Dynamics (SD-WACCM). We investigate 7 years of SOFIE observations and focus on the Southern hemisphere, rather than on dynamical variability in the Northern hemisphere or a specific geomagnetic perturbed event. The morphology of the simulated NO is in agreement with observations though the long-term mean is too high and the short term variability is too low. Number densities are more similar during winter, though the altitude of peak densities, which reaches between 102 - 106 km in WACCM and between 98-104 km in SOFIE, is most separated during winter. Using multiple linear regressions and superposed epoch analyses we investigate how well the NO production and transport are represented in the model. The impact of geomagnetic activity is shown to drive NO variations in the lower thermosphere similarly across both datasets. The dynamical transport from the lower thermosphere into the mesosphere during polar winter is found to agree very well, with a descent rate of about 2.2 km/day in the 80 - 110 km region in both datasets. The downward transported NO fluxes are however too low in WACCM, which is likely due to medium energy electrons and D-region chemistry that are not represented in the model.

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Incoherent Scatter Radar Observations of Energetic Particle Precipitation in Conjunction with Satellite Observations.

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Since 2015, the Poker Flat Incoherent Scatter Radar (PFISR) has been routinely run in a mode conducive to quantifying energetic particle precipitation in conjunction with the Van Allen Probes and the Arase satellites. Incoherent scatter radar is a powerful remote sensing technique that is sensitive to electron density enhancements. The objective of this investigation is to quantify the magnitude of energetic particle precipitation that generates enhanced D-region electron density and to infer which wave particle interactions are consistent with the enhanced D-region electron density using in situ satellite observations of particles and fields. Rigorous experimental validation of these mechanisms is difficult to achieve because nearly simultaneous, spatially conjugate observations of in-situ particle scattering and precipitation into the atmosphere are required. The near conjunctions of the Van Allen Probes and Arase satellites provide a unique opportunity to address questions surrounding energetic particle precipitation. Here, we present an overview of the radar observation technique. We also present preliminary results that show our estimates of the energetic particle precipitation from the ISR observations of enhanced D-region electron density, using a simplified D-region chemistry model and electron transport models. PFISR observations show frequent occurrence of D-region ionization events during both quiet-time and storm-time conditions. We present a preliminary statistical study of energetic particle precipitation observed by PFISR using all available data. We also present preliminary results from case-study events when the foot-points of the satellite were within 500 km of PFISR. PFISR observations of the D-region ionization signatures are presented, along with simultaneous conjugate observations of the magnetic field, electric field, and electron flux. Plasma waves are identified using the electric and magnetic field data, and evaluated as possible pitch angle scattering mechanisms. Additional ground- and space-based data are used to provide the context for these events. In-situ satellite data and ground-based PFISR observations are combined to obtain new insights into wave-particle mechanisms that can cause loss of energetic particles into the atmosphere.

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Players in the Long-term Thermospheric Energy Budget: Nitric Oxide and Gravity Waves

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Over the past decades, temperature and density of the upper atmosphere show negative trends and decrease of the upper atmospheric temperature is attributed to the declining neutral density. Attention has been paid to the carbon dioxide (CO2) contribution as its abundance has consistently raised owing to the mankind activity in the lower atmosphere over the period. Long-term variability of nitric oxide (NO), serving as another cooling agent alongside with CO2, however, has not yet a focus of recent research. This is mainly owing to the complexity of the active role that NO plays in the thermospheric photochemical chains of reactions and the difficulty to isolate the role of NO in the long-term trend. On the other hand, the long-term variation of gravity wave (GW) activity at lower (below 100 km) and higher (above 300 km) altitudes has been observed in a consistent manner over the recent decades. In this study, we separately investigate the roles of NO and GWs in the long-term thermospheric energy budget using the Global Ionosphere Thermosphere Model.

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Effects of Energetic Particles in Thermospheric Nitric Oxide Cooling during Shock-led Storms

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Satellite measurements have revealed significant enhancement of nitric oxide (NO) emission at 5.3-μm during shock-led geomagnetic storms. In this study, energetic electrons at four energy bands associated with and without shocks measured by Defense Meteorological Satellite Program (DMSP) spacecraft are incorporated into the Global Ionosphere-Thermosphere Model (GITM). Our results show that NO responses during storms are dominated by electrons at 1.4–30.2 keV, out of which 1.4–4.4 keV electrons contribute to ~60%. Across the energy bands investigated, NO cooling responds approximately linearly to combinations of bands. Shock-led storms tend to result in 35–45% more of NO cooling during stormtime compared to storms without shocks.

Superposed epoch analysis performed on nearly 200 events shows that NO emission measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) has distinct (nearly doubled) response to geomagnetic storms associated with interplanetary shocks [Knipp et al., 2017]. Recently, the photochemical scheme in GITM was updated. In this study, we drive the model with particle precipitation data measured by the DMSP spacecraft to explore the sequential response of NO cooling to typical storms with and without shock-leading. This study also allows us to investigate the contribution of energetic particles at various energy bands to NO cooling under the stated scenarios. Contribution brought by proton precipitation to the observed emission may explain the additional enhancement and is within our scope of investigation as well.

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Solar cycle modulation of the North Atlantic Oscillation: The role of Rossby wave breaking, internal wave reflection and critical layer instability

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Rossby wave breaking (RWB), a process that is known to be very sensitive to the meridional gradient of potential vorticity (PV), plays an important role in the dynamics and meridional transfer of the Earth’s atmosphere. In the winter stratosphere, the meridional PV gradient is largely defined by the vertical structure and meridional extent of the polar vortex. Solar ultra-violet (UV) radiation that varies a few percent over an 11-year is readily absorbed by stratospheric ozone, gives rise to a decadal variation of stratospheric temperature. Studies have suggested that the solar forcing may affect the planetary-scale Rossby wave propagation and breaking, as well as wave mean-flow interaction. Further feedbacks in the lower atmosphere are expected via the stratosphere-troposphere coupling, whereby the solar cycle may in turn lead to a preferred phase of large-scale atmospheric oscillation mode such as the North Atlantic Oscillation (NAO).

This study investigates these feedback processes using the reanalysis data set in both pressure and isentropic coordinates from the National Centers for Environmental Prediction Climate Forecast System (NCEP/CFSR). Our focus is on the seasonal development and a downward transfer of the upper stratospheric solar UV signals. We demonstrate that the feedback processes involved a sharpening of the PV gradient in the subtropical upper stratosphere in association with enhanced breaking of quasi-stationary waves in early winter. Eastward propagating transient waves with zonal wavenumber one and 5-7 day periodicity were generated in the upper stratospheric surf zone as the part of absorption, reflection and overreflection cycle of nonlinear critical layers. These internally generated waves then propagated polewards with filaments of low PV air extruding from the sub-tropics and stirring into the polar latitudes. As these waves meet their critical layers, their subsequent growth of breaking lead to the formation of turning surfaces in the high-latitude upper stratosphere. In middle winter, a feedback process between the eddy momentum fluxes of the reflected waves from the polar upper stratosphere and the polar vortex in the middle stratosphere gave rise to enhanced downward wave propagation along the polar vortex edge. As high PV air being continuously transferred into the extratropical lower stratosphere via enhanced downward wave propagation, the westerlies in the polar lower stratosphere were strengthened via critical layer instability. Such changes in background meanflow then lead to a latitudinal shift of synoptic wave breaking in the troposphere that was manifested by significantly reduced anti-cyclonic and moderate increased cyclonic RWB events. These effects are dynamically consistent with a positive NAO at solar maxima. Nevertheless, we suggest that the observed correlations among the 11-year solar cycle, the RWBs and the NAO may be specific to the recent period owing to the relatively small amplitudes of transient planetary scale Rossby waves. The relevance of these dynamical processes to stratosphere-troposphere response to energetic particle precipitation will be briefly mentioned as well.

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Quantifying the Energetic Particle Precipitation Influences on the Budgets of Stratospheric NOy and Ozone using a new ‘tagging’ scheme in the Whole Atmosphere Community Climate Model

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Energetic particle precipitation (EPP) is thought to be one of the ways the geospace environment can affect the middle and lower atmosphere. EPP leads to ionization of the major molecular species, and through a series of neutral and ion reactions leads to the production of odd-hydrogen (HOx = \{H, OH, HO2\}) and odd-nitrogen (NOx = \{N, NO, NO2\}). NOx is of particular interest because it can catalytically destroy ozone, affecting the energy budget of the stratosphere. Energetic particles that precipitate in the stratosphere, mesosphere include medium energy electrons (MEE, 30 keV - 300 keV), energetic solar protons (1-300 MeV), and galactic cosmic rays (GCRs). These EPP NOx sources are now part of the recommended forcings used to drive upcoming simulations for Coupled Model Intercomparison Project Phase 6 (CMIP6). To date, it has been difficult to quantify the influence of EPP on the budgets of stratospheric total inorganic nitrogen (NOy) and ozone. In this work, we employ the approach developed for tropospheric chemistry studies [Emmons et al., Geosci. Model Dev., 2012] to ‘tag’ NOy from specific sources and the associated ozone production and loss. This ‘tagging’ approach allows us to quantify the relative impacts on NOy and ozone loss rates from each of the GCR, MEE, and proton EPP sources. Furthermore, we are able to calculate the residence time of EPP NOy in the stratosphere following a large EPP event; a necessary step in understanding solar cycle induced variability on stratospheric ozone. The Chemistry Climate Model Initiative (CCMI) version of the NCAR Community Earth System Model Whole Atmosphere Community Climate Model is used in this study. The CCMI REF-C1SD scenario is followed with the inclusion of the updated CMIP6 EPP forcings. The model is ‘nudged’ to the NASA Global Modeling and Assimilation Office Modern-Era Retrospective analysis for Research and Applications, Version 2 meteorological fields. Using assimilated meteorology allows us to remove the any perturbation based dynamical variability and just focus on the chemical signature from the above mentioned EEP process.

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Estimating Energetic Electron Precipitation Fluxes from Subionospheric Very-Low-Frequency Transmitter Signals

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Energetic Electron Precipitation (EEP) is both a primary loss mechanism for radiation belt electrons and a key input into the upper atmosphere, driving chemistry and circulation. However, measuring EEP fluxes with spatial resolution has proven to be exceedingly difficult: spacecraft with particle detectors make single-point, in-situ measurements that typically cannot resolve the loss cone, and space-based measurements naturally have a spacetime ambiguity due to the velocity of the spacecraft. Other measurements of EEP include balloon-based X-ray measurements and ground-based radar or riometer measurements; each of these methods has its own advantages and drawbacks.

In this paper, we explore the use of subionospheric very-low-frequency (VLF) signals, broadcast by high-power ground-based transmitters, as a probe of EEP. Narrowband VLF signals, typically broadcast between 15–40 kHz, propagate efficiently in the Earth-ionosphere waveguide over thousands of km; a distant receiver can measure the amplitude and phase of the carrier signal. Variations in the amplitude and phase are entirely caused by changes in the D-region ionosphere between 70–90 km altitude. At moderate latitudes below the auroral oval, those D-region changes are largely driven by EEP. We use a three-step modeling procedure to explore the relationship between EEP fluxes and the resulting VLF signatures. First, we use a Monte Carlo model of precipitation to generate ionization rate profiles for different EEP fluxes and spectra. Next, these ionization profiles are input into a D-region chemistry model to determine the resulting electron density profile. Finally, electron density profiles are used as inputs to a VLF propagation model to estimate the amplitude and phase of the signal at the receiver location. We explore the variation in the received amplitude and phase with EEP flux and spectra, background D-region electron density, and precipitation region spatial scale sizes. Overall, we find that the relationship between these inputs and the measured VLF signal is not straightforward, making the inversion from VLF measurements to estimated EEP fluxes exceedingly difficult.

As an alternative approach, we next explore the more complex problem: with an overlapping grid of VLF transmitter-receiver “links”, can we solve an inverse problem to determine the precipitation fluxes over a large 2D region? To this end, we use an Ensemble Kalman Filter (EnKF) approach to investigate this inversion problem. VLF signal phase at notional receiver locations is simulated using the VLF propagation model, and then these phases are used to estimate the ionosphere parameters over a large region. Preliminary work on the EnKF inversion model has shown promising results, with the potential to continuously measure and monitor EPP over large regions of geospace.

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A SOLARIS-HEPPA analysis of solar signatures in the CCMI simulations

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The importance of solar forcing on climate is now firmly established. Nevertheless, considerable uncertainty remains in the characterization of solar signals in the climate system in both models and observations. The SPARC SOLARIS-HEPPA initiative aims at narrowing the uncertainties related to solar cycle forcing and its effects on climate. To this end, model experiments performed under the Chemistry-Climate Model Initiative (CCMI) are analysed to examine solar signals in the atmosphere and the ocean. The adopted methodology collectively considers a range of possible pathways whereby solar variability can affect climate, including UV irradiance, energetic particles and their effects on the physics, chemistry and dynamics of the stratosphere. Special emphasis is given on the downward propagation of solar signals from the middle and upper atmosphere to the surface and solar-induced ozone changes and feedbacks arising from atmosphere-ocean coupling. The analysis of free-running (REFC1) and specified dynamics (REFC1-SD) simulations are used to provide evidence for the solar origin of the observed signals in the stratosphere, and infer the role of the dynamics. The analysis of REF-C2 simulations, on the other hand, are used to characterise the coupled atmosphere-ocean response to solar variability. The impact of energetic particles on the composition of the middle atmosphere is analyzed and compared with recent satellite observations with a special focus on NOx and HOx, and their impact on stratospheric ozone and dynamics is assessed. Finally, the sensitivity of the solar signals to statistical methodology will be carefully addressed. Here we provide an overview of these current activities from the five new SOLARIS-HEPPA working groups and highlight selected preliminary results.

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Comparing solar irradiance and auroral effects on climate

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This study aims at comparing climate signals associated with solar cycle variabilities of solar irradiance and auroral electron precipitation. Dedicated simulations with two state-of-the-art chemistry climate models – CESM1(WACCM) and EMAC – which incorporate spectral solar irradiances as well as either direct auroral electron impact or a NOy upper boundary forcing, will be quantitatively analyzed.

We conducted a number of timeslice experiments. External forcings and lower boundary conditions are fixed and identical for all experiments, except for the solar and geomagnetic forcing. A reference simulation represents low solar irradiance and low auroral activity conditions. This is done by prescribing constant spectral solar irradiance (SSI) according to the observation-based reference spectrum RSSV1-ATLAS3 and constant low geomagnetic activity (Ap/Kp). This reference simulation is compared to five different solar irradiance maximum simulations and one aurora maximum simulation. The former are produced by constantly prescribing SSI-forcings that result from adding the 11-year solar cycle amplitude according to the five reconstructions (NRLSSI1, NRLSSI2, SATIRE-T, SATIRE-S, CMIP6-SSI) to RSSV1-ATLAS3. The latter is produced by prescribing daily-varying Ap/Kp-time series representing strong aurora activity.

Detailed analysis of the simulations reveals substantial differences between Northern and Southern Hemisphere responses to irradiance and auroral forcing, respectively, especially when considering dynamical signals such as the impact on NH and SH polar vortices. However, the overall structure of these impacts on climate dynamics is robust across the different models and forcings applied. We will present climate effects of enhanced auroral and irradiance forcing and discuss their spatial variability and magnitude also in terms of the large internal model variability.

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Decadal variability in the Northern Hemisphere winter circulation: Role of internal and external drivers

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Northern Hemisphere winter circulation is affected by both internal and external (solar-related) forcings. ENSO (El Nino Southern Oscillation) and volcanic activity have shown to produce negative and positive North Atlantic Oscillation (NAO) signatures, respectively. Recent studies show a positive NAO signature related to both geomagnetic activity (proxy for solar wind driven particle precipitation) and sunspot activity (proxy for solar irradiance). Here the relative role of these drivers on Northern Hemisphere wintertime circulation is studied. The phase of the quasi-biennial oscillation (QBO) is used to study driver signals in different stratospheric conditions. Moreover, the effects are separated for early/mid- and late winter. ENSO produces a negative pressure signal in the North Pacific, regardless of the QBO phase or time of the winter. However, the negative NAO signal in the Atlantic due to ENSO reported in previous studies, is observed only in late winter and in the easterly QBO phase during early/mid-winter. The positive NAO related to volcanic activity is found to be stronger for westerly QBO in late winter. The positive NAO signal related to geomagnetic activity is observed during easterly QBO phase in both early/mid- and late winter. Sunspots produce a positive pressure anomaly in the North Pacific in early/mid-winter regardless of the QBO, whereas the late winter signal resembles a positive NAO in the easterly QBO. These results imply that the signatures for all drivers in the Atlantic are significantly modulated by the QBO, thus suggesting stratospheric pathway. However, signals in the North Pacific remain rather similar in different QBO phases and suggest direct forcing from the troposphere by ENSO and bottom-up sunspot mechanism.

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Potential Influence of Elevated Stratopause Events on the Lower Atmospheric Circulation in MRI-ESM

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The reformation of a separated elevated stratopause after strong stratospheric warmings is an important phenomenon in the coupling between the stratosphere and mesosphere-lower thermosphere. Since such events, called as the Elevated Stratopause Events (ESEs), are closely linked to the downward transport of NOx produced in the mesosphere and thermosphere via the Energetic Particle Precipitation (EPP), they could contribute to catalytic ozone destruction in the stratosphere. This is a notable case of the so called EPP indirect effect. Here, we analyze the polar stratospheric ozone loss due to ESEs and its impact on the lower atmospheric circulation in the Earth System Model of Meteorological Research Institute (MRI-ESM). By introducing the energetic particle forcing in the MRI-ESM, the EPP indirect effect is examined for multiple ESEs. In simulations which are nudged toward reanalysis data in the troposphere and stratosphere while being unconstrained above, ozone reduces by up to 40% in the upper stratosphere for several weeks after ESEs due to the NOx enhancements. The reduction of stratospheric ozone causes cooling anomalies of the polar-cap temperature and westerly anomalies of the zonal-mean zonal wind during the period of sunlit. Further, it is revealed that such anomalies can modulate the behavior of the stratospheric final warming by conducting a series of ensemble simulations, without the nudging, for a case of the largest ESE accompanied by large EPP. Thus, this study presents the possible coupling between the upper-to-middle atmosphere and lower atmosphere via the ESE.

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Coordinated observations with the ground-based instruments and satellites to study energetic electron precipitation and auroral morphology at the substorm recovery phase

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It is well known that auroral patterns at the substorm recovery phase are characterized by diffuse or patch structures with intensity pulsation. According to satellite measurements and simulation studies, the precipitating electrons associated with these aurorae can reach or exceed energies of a few hundreds of keV through resonant wave-particle interactions in the magnetosphere. However, because of difficulty of simultaneous measurements, the dependency of energetic electron precipitation (EEP) on auroral morphological changes in the mesoscale has not been investigated to date. Elucidation of the dependency may give more insights to study of EEP impacts on the atmospheric minor components. We expect to identify EEP events from optical data alone in future utilizing its characteristics of the spatiotemporally wide coverage from the ground and easy access to the data. In order to study the dependency, we have analyzed data from the European Incoherent Scatter (EISCAT) radar, the Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA) riometer, collocated cameras, ground-based magnetometers, the Van Allen Probe satellites, Polar Operational Environmental Satellites (POES), and the Antarctic Arctic Radiationbelt (Dynamic) Deposition-VLF Atmospheric Research Konsortium (AARDDVARK). Here we undertake a detailed examination of two case studies. The selected two events suggest that the highest energy of EEP on those days occurred with auroral patch formation from postmidnight to dawn, coinciding with the substorm onset at local midnight. Measurements of the EISCAT radar showed ionization as low as 65 km altitude, corresponding to EEP with energies of about 500 keV. Methods applicable to ground-based measurements for energy-flux estimation have been developed for more than three decades. One is the application of optical measurements for a set of prompt emitters predominantly originating in the E and F regions. We may be able to capture evolution of the auroral morphological change as a sign of the EEP along with the precipitating electron energy flux by applying this method on allsky images measured at multiple wavelengths. To achieve this goal, as the first step, we made several coordinated experiments with the EISCAT radar and a photometer directing at the local magnetic field line at Tromsø, Norway, and compared with energy changes estimated from the both instruments. The presentation will report the initial result and discuss its application on the EEP event found from optical data based on knowledge of the dependency of the EEP on auroral morphological changes.

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Solar Flares and Energetic Electron Precipitation in WACCM

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Two bodies of work will be presented here. The first study investigates middle atmosphere effects of the September 2005 solar flares and solar proton events (SPEs). X-17 and X-6.2 flares occurred on 7 and 9 September, respectively, while two moderate SPEs occurred on 10 September and 15 September. Flare ionization and dissociation were calculated in the Whole Atmosphere Community Climate Model (WACCM) using the Flare Irradiance Spectral Model. Proton measurements from the Geostationary Operational Environmental Satellite system were used to compute solar proton ionization. SPEs are shown to have a larger impact than solar flares on the polar stratosphere and mesosphere; however, flares have a larger influence in the sunlit and equatorial lower thermosphere. The two flares differed significantly with respect to photon spectrum. The larger, X-17 flare was stronger during the impulsive phase, while the X-6.2 flare was stronger during the gradual phase. This resulted in the X-17 flare causing more initial ionization, but for a shorter duration. The simulated flare impacts also differed because specific wavelengths of the flares influenced the atmosphere above the model top. Model-measurement comparisons show that WACCM captures the overall timing and spatial distribution of the observed electron enhancements, indicating a reasonable simulation of flare and SPE-induced ionization. Nitric Oxide (NO) increases in the polar regions can be seen in the SPE simulations, and NO increases on the dayside of the earth can be seen in the flare simulations. Additionally, small temperature increases from the flares occur in the lower thermosphere.

The second study examines the effects of energetic particle precipitation (EPP) during 2003 and 2004. Observations showed record levels of EPP-produced odd nitrogen (EPP-NO\textsubscript{x}) reaching the Arctic stratosphere in April of 2004, but high-top global climate models have been unable to reproduce these results. Speculation is that the models are deficient in their simulation of the transport and/or production of EPP-NO\textsubscript{x}. This presentation describes simulations from WACCM that incorporated ionization from solar protons, auroral electrons, and medium energy electrons. The latter were based on two different estimates of the differential spectrum of precipitating electron flux derived from POES MEPED measurements [Peck et al., 2015; van der Kamp et al., 2016]. All simulations are run from 1 Jan 2003 to 1 June 2004, a time period during which significant energetic electron precipitation occurred. By including the 2003 southern hemisphere winter, where dynamical perturbations are small relative to those in the northern hemisphere, the goal is to better isolate errors in simulations of EPP-NO\textsubscript{x} production. Comparisons between the WACCM results and satellite observations of odd nitrogen and ozone are presented.

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A statistical study on the effects of Forbush Decreases on the climate at different latitudes

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Considering the ground temperature like an essential parameter to characterize the Earth’s climate, we present a statistical study about possible changes on the air surface temperature in different latitudes, during periods with decrease of atmospheric ionization induced by Galactic Cosmic Rays (GCR) on the Earth’s troposphere. These GCR flux reductions are called Forbush Decreases (FD). They are mainly caused by Interplanetary Coronal Mass Ejections (ICMEs) deflection of GCR around Earth’s orbit. This work was performed considering the possible influence of the cosmogenic atmospheric ionization on the water vapor condensation patterns (link GCR – cloud condensation nuclei) as the main hypothesis to be tested. For that, we have conducted a study to analyze the possible effects on the daily air surface temperature, using superposed epoch analysis around the ten strongest FD events occurred between 1987 and 2015. GCR data were collected from Oulu neutron monitor (cosmicrays.oulu.fi), and daily air surface temperature data were obtained from NOAA - National Oceanic Atmospheric Administration / GSOD - Global Surface Summary of the Day (https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod) of ten meteorological stations of three latitudinal ranges of Northern and Southern hemispheres (200 - 300, 400 - 500 and 600 - 700). We investigate here the variation of the daily air surface temperature mean during FD for each one of the three latitudinal ranges (low, medium and high). The possible climatic effects of GCR decrease were investigated using linear and cross correlation methods. The comparison between the daily air surface temperature averages during FD events periods and equivalent periods without FDs (during solar minima years of 1987, 1996 and 2008) was also performed. Some results for the Northern hemisphere have showed a latitudinal dependence of the induced ionization by GCR on the atmospheric parameters. It was possible to note the anti-correlation between the air surface temperature mean and the GCR flux, increasing from low to high latitudes. However, for the Southern hemisphere, the anti-correlation between these data was only found for the high and medium latitudes, also with a poleward increase. From these results it seems that the possible FD effect on climate/weather is more prominent in the Northern hemisphere and that there are increases with latitude.

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Response of the Atmosphere to Impulsive Solar Events (RAISE)

Cora Randall¹ and the RAISE Science Team

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The Response of the Atmosphere to Impulsive Solar Events (RAISE) project is a 5-year Targeted Science Team effort funded by the NASA Living With a Star program. The primary goal of RAISE is to investigate how the Earth's atmosphere responds to impulsive solar events (ISEs). The work addresses four primary questions:

- How well do coupled chemistry climate models (CCMs) simulate effects of recent ISEs?
- What are the primary factors that control the atmospheric response to ISEs?
- What is the range and sensitivity of the atmospheric response to ISEs?
- Are there long-term, cumulative effects of ISEs on the atmosphere and climate, and with what certainty can these effects be modeled?

To answer these questions, RAISE uses the Community Earth System Model (CESM), with the Whole Atmosphere Community Climate Model (WACCM or WACCM-X) atmospheric component. This talk will briefly summarize some recent RAISE progress and plans for the next year. Topics include recently published WACCM-X simulations of anthropogenic global change, new developments in providing solar spectral irradiance input to models, climatological calculations of the mesospheric polar vortex as related to the energetic particle precipitation indirect effect, and solar-induced changes in ionospheric total electron content.

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Modelling the chemical impact of particle precipitation in the middle atmosphere and comparison with observations

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Energetic particles from the Sun or originating in the magnetosphere of the Earth cause partial ionization in the atmosphere leading to considerable amounts of NOx and HOx in the lower thermosphere and mesosphere. Depending on the energy of the particles, these radicals affect the ozone chemistry on short and longer time-scales directly or via vertical transport in the stratosphere and impact dynamics by radiative coupling. Here we present simulations of the direct and indirect effects of energetic particle precipitation with the Karlsruhe Simulation Model of the Middle Atmosphere KASIMA. The primary production of the radicals HOx and NOx is calculated using ionization rates from the AIMOS model and an Ap-index based parameterization for comparison. The model is run with specified dynamics in the stratosphere using ERA-Interim analyses. The gravity wave drag scheme has been modified in this version of the model to yield a more realistic representation of downward transport from the lower thermosphere during elevated stratosphere events in the northern polar winter middle atmosphere. The model simulations are compared with observations of the MIPAS-Instrument on the ENVISAT satellite.

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Observed Responses of Mesospheric Water Vapor to Solar Cycle and Dynamical Forcings

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This presentation is a summary of the findings in Remsberg et al. (2018). It focuses on responses of mesospheric water vapor (H2O) to the solar cycle flux at Lyman-α wavelength and to dynamical forcings according to the multivariate ENSO index (MEI). The zonal-averaged responses are for latitudes from 60°S to 60°N and pressure-altitudes from 0.01 to 1.0 hPa, as obtained from multiple linear regression (MLR) analyses of time series of H2O from the Halogen Occultation Experiment (HALOE) for July 1992 to November 2005. The results compare very well with those from a separate, simultaneous temporal and spatial (STS) method that also confirms that there are no significant sampling biases affecting both sets of results. Distributions of the seasonal amplitudes for temperature and H2O are in accord with the seasonal net circulation. In general, the responses of H2O to ENSO are anti-correlated with those of temperature. H2O responses to MEI are negative in the upper mesosphere and largest in the northern hemisphere; responses in the lower mesosphere are more symmetric with latitude. H2O responses to the Lyman-α flux (Lya) vary from strong negative values in the uppermost mesosphere to very weak, positive values in the tropical lowermost mesosphere. However, the effects of those H2O responses to the solar activity extend to the rest of the mesosphere via dynamical processes. Profiles of the responses to ENSO and Lya also agree reasonably with published results for H2O at the low latitudes from the Microwave Limb Sounder (MLS).


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Dynamical response of the middle atmosphere to geomagnetic forcing in three coupled chemistry-climate models

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We analyze results from 40-year long time-slice experiments with high and low geomagnetic forcing in three chemistry-climate models: a medium-top model using a parameterization of upper boundary NOy as geomagnetic forcing signal, and two high-top models forced by different ionization rates. The medium-top model represents EPP NOy in the middle atmosphere polar winter very well for both high and low auroral forcing, both in the timing of the NOy signal, and in the amount of NOy transported down into the stratosphere. The two high-top models both perform less well, but are quite different: one, incorporating auroral electrons only, underestimates EPP NOy for the high forcing, while the other, incorporating auroral and middle-energy electrons, overestimates EPP NOy for low forcing. All three models show a qualitatively similar stratospheric ozone loss which differs in strength and timing from model to model similar to the EPP NOy signal. All three models show a response of upper and middle stratosphere temperatures which however varies from model to model, even reverting sign in late winter, and which is mostly not statistically significant. The multi-model mean in high Southern latitudes, however, show a statistically significant warming in the mid-winter upper stratosphere and lower mesosphere as expected from observations and from theoretical considerations of the change in radiative forcing.

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Nitric oxide response to the April 2010 electron precipitation event

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Energetic electrons from the magnetosphere deposit their energy in the atmosphere and lead to production of nitric oxide (NO) in the mesosphere and lower thermosphere. We study the atmospheric NO response to a moderate geomagnetic storm in April 2010 using satellite observations of precipitating electrons (TED and MEPED / POES), satellite observations of the NO response (SOFIE / AIM), and a state of the art climate model (WACCM). Starting with a pure observational approach, we find that medium energy electrons (>10kev) are important for the direct production of NO well into the lower mesosphere. Medium energy electrons are also responsible for the transported indirect effect on NO, and we estimate the source region for 60 km increase to be at 75-90 km altitude. This observational based knowledge of the direct and indirect effects, is then used when we investigate the same event with the model. WACCM is normally used with a parametrization of auroral electrons, and with five ions present in the thermosphere. The modelled NO production fits well in timing though strongly underestimated compared to SOFIE observations around 100 km, while no mesospheric NO is produced at all. We attempt to improve this, by replacing the auroral electrons with a full energy range from POES and by using WACCM-D with ions also in the thermosphere. When applying a better electron source which includes both low and high energy electrons, and ions present in both the thermosphere and mesosphere, the modelled mesospheric NO levels are well represented. The biggest underestimate of the NO productions is now in the lower thermosphere, and can not be accounted for with an improved source or chemistry. An additional source of NO production is likely still missing here, and the resulting deficit gets transported down in the mesosphere.

![Time evolution of nitric oxide [ppb] as observed by SOFIE (black line), modeled by standard WACCM (orange line), WACCM with a full range energy spectrum from POES (red line) and WACCM-D also with POES data (blue line), for three different altitude regions.](image)

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Gravity wave variability in terms of polar vortex position and its effect on ozone

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The polar vortex, a large circumpolar cyclone characterized by high westerly winds, is a dominant feature in the Arctic and Antarctic winter stratospheres. The characteristics of the polar vortex play a major role in the distribution of the stratospheric ozone. Moreover, a disruption of the polar vortex as seen during major stratospheric sudden warming events can couple the stratosphere to the mesosphere and thermosphere to bring down the EPP produced NO and subsequently destroy ozone. Atmospheric gravity waves play a major role in influencing the thermal and dynamical structure of the middle atmosphere. Previous studies have shown that the gravity wave activity in the stratosphere is stronger in the jet/edge of the polar vortex and weaker at the core. In this study we investigate the wave activity in terms of the polar vortex and anticyclone position in the stratosphere and mesosphere i.e. 30-70 km. The gravity wave activity is characterized in terms of SOFIE/AIM temperature amplitude and the vortex-anticyclone airmass is identified using meteorological parameters from the MERRA2 re-analysis data. We also investigate the effect that the gravity wave associated temperature changes have on the ozone in the stratosphere and mesosphere.

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New Emerging Data of Atmospheric Forcing by Relativistic Electron Precipitation from the EISCAT_3D Incoherent Scatter Facility and its Complementary Research Infrastructure

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Particle precipitation as source of atmospheric variability challenges us to implement better and continuously monitoring observational infrastructure at high latitudes. A currently experimentally poorly covered research target is the atmospheric effect of relativistic electron precipitation. It is known that for example during high-energy electron precipitation in pulsating aurora, the concentration of mesospheric ozone may be reduced by several tens of percent. The reduction is similar as during some solar proton events, which are known to occur more rarely than pulsating aurora. However, the spatial and temporal occurrence of electron precipitation events with highest energies, in the MeV range, is poorly known due to lacking atmospheric observations.

We show the research potential of new ground-based radio measurement techniques, the spectral riometry and incoherent scatter by new phased-array radar facility, the EISCAT_3D, which will be a volumetric, 3-dimensionally imaging radar, distributed in Norway, Sweden, and Finland. It is expected to be operational from year 2022 onwards, surpassing all the current IS radars of the world in technology. It will be able to produce continuous information of ionospheric plasma parameters in a volume, including 3D-vector plasma velocities. For the first time we will be able to continuously map the 3D electric currents in ionosphere, as well as we will have continuous vector wind measurements in mesosphere. The geographical area covered by the EISCAT_3D measurements is expanded by suitably selected other continuous observations, such as optical and satellite tomography networks.

A new 100 Hz all-sky camera network was recently installed in Northern Scandinavia in order to support the Japanese Arase satellite mission. In near future the ground-based measurement network will also include new mesospheric ozone observations and a north south chain of spectral riometers in Finland. New space missions will gain from this emerging enhancement of ground-based observations. Possibly essential new data will be provided by polar orbiting cubesats for which scientific level instrumentation is currently being developed. We will also describe a balloon-borne observation technique, which is currently being proposed as a new in-situ measurement of highest energy relativistic electron fluxes.

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Inter-comparison of the POES/MEPED Loss Cone Electron fluxes with the CMIP6 Parametrization

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Quantitative measurements of medium energy electron (MEE) precipitation (> 40 keV) are a key to understand the total effect of particle precipitation on the atmosphere. The Medium Energy Proton and Electron Detector (MEPED) instrument on board the NOAA/Polar Orbiting Environmental Satellites (POES) has two sets of electron telescopes pointing ~0° and ~90° to the local vertical. Pitch angle anisotropy, which varies with particle energy, location, and geomagnetic activity, makes the 0° detector measurements a lower estimate of the flux of precipitating electrons. In the solar forcing recommended for CMIP6 (v3.2) MEE precipitation is parameterized by Ap based on 0° detector measurements hence providing a general underestimate of the flux level. In order to assess the accuracy of the Ap-model, we compare the modeled electron fluxes with estimates of the loss cone fluxes using both detectors in combination with electron pitch angle distributions from theory of wave-particle interactions. The Ap-model fails to reproduce the flux level and variability associated with strong CME storms (Ap >40) as well as the duration of CIR storms causing a systematic bias within a solar cycle. As the Ap-parameterized fluxes reach a plateau for Ap > 40, the model’s ability to reflect the flux level of previous solar cycles associated with generally higher Ap values is questioned. The objective of this comparison is to understand the potential uncertainty in the EPP impact applying the CMIP6 particle energy input in order to assess its subsequent impact on the atmosphere.

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A model providing long-term datasets of energetic electron precipitation including zonal dependence

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In this study 30–1000 keV energetic electron precipitation (EEP) data from low Earth orbiting POES satellites were processed in two improved ways, compared to previous studies. Firstly, all noise-affected data were more carefully removed, in order to provide more realistic representations of low fluxes during geomagnetically quiet times. Secondly, the data were analyzed dependent on magnetic local time (MLT), which is an important factor affecting precipitation flux characteristics. We developed a zonally averaged EEP model, and a new model dependent on MLT, which both provide better modeling of low fluxes during quiet times. The models provide the spectrum of EEP assuming a power-law gradient. Using the geomagnetic index Ap with a time resolution of 1 day, the spectral parameters are provided as functions of the L-shell value relative to the plasmapause. Results from the models compare well with EEP observations over the period of 1998–2012. Analysis of the MLT-dependent data finds that during magnetically quiet times, any significant fluxes are only observed around local midnight. As disturbance levels increase, the flux increases at all MLT. During disturbed times, the flux is strongest in the dawn sector, and weakest in the late afternoon sector. The MLT-dependent model emulates this behaviour. The results of the models can be used to produce ionization rate datasets over any period of time for which the geomagnetic Ap index is available (recorded or predicted). This ionization rate dataset will enable simulations of EEP impacts on the atmosphere and climate with realistic EEP variability.

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Chemically produced infrared emissions from Nitric Oxide: Energy loss rate and Efficiencies

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Nascent vibrational excitation of nitric oxide is known to occur in the thermosphere as it is produced from the exothermic reactions of N(2D) and N(4S) with O2. Using updated values for the rate coefficients and vibrational yields for the processes involved, a model that solves for the populations of NO(v≤10) is presented. It is shown that the energy loss rate due to the nascent vibrational excitation forms 15-40% of the total emissions from nitric oxide on the dayside thermosphere under quiescent conditions, but only causes a 2-3% reduction in the exospheric temperature. We explore the efficiency of this energy loss mechanism from the thermosphere by incorporating it into 1D and 3D thermospheric models.

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Connection between descending odd nitrogen, stratospheric ozone, short-wave heating, and temperature from 147 years of WACCM simulations

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One of the key challenges in polar middle atmosphere research is to quantify the total forcing by energetic particle precipitation (EPP) and assess the related response and dynamically-driven climate connections over solar cycle time scales. The most recent solar forcing recommendation for the Coupled Model Intercomparison Project (CMIP) includes EPP for the first time (Matthes et al., 2017), with the so-called medium-energy electrons (MEE) represented as daily zonal mean using a proxy model driven by the geomagnetic Ap index (van de Kamp et al., 2016).

Here we use the Whole Atmosphere Community Climate Model (WACCM) with a set of EPP forcing that includes solar proton events, auroral electron precipitation, and MEE precipitation. We have contrasted our results from an ensemble of simulations (147 years in total) with those from the fifth phase of CMIP in order to show the importance of the recommended MEE forcing to the middle atmospheric ozone over decadal time scales (Andersson et al., 2018). We also study the connection between odd nitrogen (NOx) descent and the expected decrease in stratospheric ozone, short-wave heating, and temperature.

Our results indicate EPP-induced polar ozone variability of 12–24% in the mesosphere, and 5–7% in the middle and upper stratosphere. In addition to the major impact on the mesosphere, MEE enhances the stratospheric ozone response by a factor of two. In the Southern Hemisphere springtime, we find a connection between descending NOx, upper stratospheric ozone decrease, and decrease in short-wave heating. However, similar to the result by Lu et al. (2008), there is no clear temperature decrease as would be expected. Instead, air descent drives temperature increases through adiabatic heating and dominates over the ozone effect.

References

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Towards Better Understanding of Bremsstrahlung X-rays during Energetic Electron Precipitation

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Determination of energetic particle precipitation (EPP) into the Earth's atmosphere is of critical importance for radiation belt dynamics [Lyons and Thorne, JGR, 78, 2142, 1973], magnetosphere-ionosphere coupling [Baker et al., GRL, 14, 1027, 1987], as well as atmospheric chemistry [Sinnhuber et al., Surv. Geophys., 33, 1281, 2012]. Various techniques and instrumentations have been designed for the measurements of precipitating particles, including space-based flux measurements, ground-based radio measurements, and balloon-based X-ray measurements. Despite these efforts, it is still challenging to accurately estimate the fluxes of energetic particles dumping into the upper atmosphere. Space-based measurements at both equatorial and low-earth-orbit trajectories cannot precisely map the precipitating fluxes as the loss cone is difficult to resolve [e.g., Whittaker et al., JGR, 119, 6386, 2014; Peck et al., JGR, 120, 4596, 2015]. Ground-based VLF measurements are limited by the uncertainties in determining the impacted propagation path and in modeling VLF subionospheric signals [e.g., Clilverd et al., JGR, 122, 534, 2017]. Balloon-based X-ray measurements are not hindered by the complexity of loss cone in that they collect in the stratosphere secondary photons resulting directly from precipitating particles [Millan et al., Space Sci. Rev., 179, 503, 2013]. However, measurements are restricted in spatial extent to the precipitation region, and the inversion of X-ray measurements to source precipitating fluxes is complicated [e.g., Woodger et al., JGR, 120, 4922, 2015].

In this study, using first-principles Monte Carlo models, we explore electron precipitation events from the perspective of bremsstrahlung X-rays: the spatial distribution of X-rays is quantified from the ground level up to satellite altitudes, X-ray images that would be captured by an ideal pinhole-type camera are simulated, and energy spectra of X-rays originating from monoenergetic beams of energetic electrons are calculated. We demonstrate how these impulse responses to monoenergetic beams can be used to invert X-ray measurements and reconstruct the precipitation source. Moreover, modeling results suggest that space-borne imaging of X-ray backscatters are also promising means to monitor precipitation events.

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A Revised Model for NO Equilibrium in the Thermosphere

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In this talk the standard model for thermospheric equilibrium of nitric oxide (NO) is revised to include the contribution of excited atomic nitrogen. This revision leads to a simple modification of the standard expression. Differences between the models are demonstrated by comparing model results with NO data from the Student Nitric Oxide Explorer (SNOE). Uncertainties in the temperature dependence and branching ratios of the relevant reaction and quenching rates are discussed but it is shown that use of the consensus room temperature rates in the revised model still results in substantially improved model/data agreement.

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