ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

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2016:4

6TH INTERNATIONAL HEPPA-SOLARIS WORKSHOP

BOOK OF ABSTRACTS

P. T. VERRONEN (editor)

RAPORTTEJA
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6th International HEPPA-SOLARIS Workshop
Book of Abstracts

P. T. Verronen (editor)

Ilmatieteen laitos
Meteorologiska institutet
Finnish Meteorological Institute

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Title

6th International HEPPA-SOLARIS Workshop, Book of Abstracts

Abstract

Welcome to the 6th International HEPPA-SOLARIS Workshop which will be held on 13-17 June, 2016, at the Finnish Meteorological Institute, Helsinki, Finland. The workshop continues the series of meetings organized since 2008 and will focus on observational and modeling studies of the influences of solar radiation (SR) and energetic particle precipitation (EPP) on the atmosphere and climate. This report is the official abstract book of the workshop.

Broad topics to be covered in the workshop include a) the causes and phenomenology of SR and EPP variability, b) mechanisms by which SR and EPP forcing affect atmospheric chemistry and dynamics, c) contributions of SR and EPP forcing to variations in space, atmosphere, and climate, and d) the current state of the art and outlook for relevant observations and models.

The workshop is scientifically and financially sponsored by IAMAS/IUGG, VarSITI/SCOSTEP, and SPARC.

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Classification (UDK)	Keywords
551.510 551.510.413 551.510.535 551.510.537 551.521 551.521.31	energetic particle precipitation, solar radiation, magnetosphere, ionosphere, thermosphere, mesosphere, stratosphere, troposphere, polar regions, odd nitrogen, odd hydrogen, ozone, polar vortex, top-down coupling

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Toimeksiantaja

Nimeke

6. kansainvälinen HEPPA-SOLARIS-kokous, esitysten tiivistelmät

Tiivistelmä

Tervetuloa kuudenteen kansainväliseen HEPPA-SOLARIS-kokoukseen, jonka Ilmatieteen laitos järjestää 13.-17. kesäkuuta 2016 Helsingissä. Kokous jatkaa vuodesta 2008 järjestettyjen kokousten sarjaa, jonka aiheena on auringon säteilyn ja korkeaenergisen hiukkaspresipitaation vaikutukset ilmakehään ja ilmastoon. Kokoukseen osallistuu kansainvälinen joukko tutkijoita, jotka esittelevät sekä havaintoihin että tietokonemallinnukseen perustuvia tuloksiaan. Tämä raportti sisältää em. esitysten tiivistelmät.

Kokouksen aihepiiri kattaa a) auringon säteilyn ja hiukkaspresipitaation vaihtelut ja näihin liittyvät ilmiöt, b) kemiallisten ja dynaamisten ilmakehävaikutusten mekanismit c) vaikutukset avaruudessa ja ilmakehässä sekä kytkennät ilmastoon, d) tutkimusta tukevat havainnot, tietokonemallit ja menetelmät nyt ja tulevaisuudessa.

IAMAS/IUGG, VarSITI/SCOSTEP ja SPARC tukevat kokousta tieteellisesti ja taloudellisesti.

Julkaisijayksikkö
Uudet havaintomenetelmät

Luokitus (UDK)	Asiasanat
551.510 551.510.413 551.510.535 551.510.537 551.521 551.521.31	energeettinen hiukkaspresipitaation, auringon säteily, magnetosfääri, ionosfääri, termosfääri, mesosfääri, stratosfääri, troposfääri, napa-alueet, pariton vety, pariton typpi, otsoni, polaaripyörre, top-down-kytkentä

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Contents

Welcome to Finnish Meteorological Institute

Dear workshop participant,

the first High-Energy Particle Precipitation in the Atmosphere (HEPPA) workshop was organised at Finnish Meteorological Institute in May 2008. The weather was great and there was excitement in the air. Observations, such as those from the Envisat instruments GOMOS and MIPAS and the Aura instrument MLS, had allowed us for the first time to study the effects of energetic particle precipitation in the polar regions in wintertime. A lot of new results were published and the study of particle precipitation benefited from the new generation of scientists entering the field. As C. H. Jackman put it back in 2008: the time is certainly ripe for the first HEPPA workshop.

Later, workshops in the series have been organised by National Center for Atmospheric Research (2009, 2012), Instituto de Astrofísica de Andalucía (2011), and Karlsruhe Institute of Technology (2014). From 2012 onwards, the workshops have been held together with the SOLARIS community, and we now together form the SPARC SOLARIS-HEPPA international group working on atmospheric and climate effects of solar radiation and energetic particles. The latest, substantial effort of this group was the definition of the recommended solar forcing for the Coupled Model Intercomparison Project Phase 6 (CMIP6) which for the first time includes particle precipitation.

As we start the 2016 workshop, those of us who have been around from 2008 will have noticed the advancement from short-term to longer-term, solar-cycle studies, as well as advancement in modelling of the climate response to solar forcing. Although the journey is still on-going, the science in the field has advanced considerably since the first workshop. I have no doubt that we will see more advancement in the future, and one important part of this will be the assessment of combined effects of solar radiation and particles for the regional climate variability.

I wish you a successful workshop and an enjoyable time in Finland!

P. T. Verronen
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SPARC	http://www.sparc-climate.org

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6th International HEPPA-SOLARIS Workshop
13-17 June, 2016, Helsinki, Finland

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Daily schedule,	**oral and poster program**
6th International	HEPPA-SOLARIS Workshop
13-17 June, 2016	Helsinki, Finland

Invited talks 30+5 min.	Talks 15+5 min.	3+1 poster sessions, 6 h total

	MONDAY 13	**TUESDAY 14**	**WEDNESDAY 15**	**THURSDAY 16**	**FRIDAY 17**
9:00		Partamies (S4)	Espy (S2)	Orsolini (S2)	Nieder (S2)
9:20	Registration	Turunen (S2)	Verronen (S2)	Meraner (S2)	Andersson (S3)
9:40	Welcome	Matthes/Funke (S3)	Pérot (S2)	Chiodo (S3)	Turner (S4)
10:15	Tea and coffee	Tea and coffee	Tea and coffee	Tea and coffee	Tea and coffee
10:45	Nesse Tyssøy (S1)	Yeo (S1)	Thiéblemont (S3)	Coddington (S4)	Sinnhuber (S4)
11:20	Kilpua (S1)	Marsh (S2)	Bender (S2)	Lu (S2)	Arsenovic (S2)
11:40	Asikainen (S1)	Kunze (S2)	Kuchar (S2)	von Clarmann (S3)	Maliniemi (S3)
12:00	Pettit (S4)	Misios (S2)	Shieferdecker (S2)	Duderstadt (S3)	Final Discussion
12:20	Lunch	Lunch	Lunch	Lunch	Conclusion
13:20	Posters 1	Posters 2	Posters all	Posters 3	
14:50	Tea and coffee	Tea and coffee	Excursion	Tea and coffee	
15:20	van de Kamp (S4)	Ball (S1)	Excursion	Kiviranta (S4)	
15:40	Rodger (S4)	Clilverd (S2)	Excursion	Kyrölä (S4)	
16:00	Kero (S4)	Newnham (S2)	Guided tour 16-17	Kalakoski (S2)	
16:20	Marshall (S4)	Hendrickx (S2)	Guided tour 16-17	Mursula (S3)	
17:00	Icebreaker		Excursion	CCMI splinter	
19:00			Dinner		

	MONDAY	**13 JUNE**
9:20	Registration	Registration
9:40	Welcome	Welcome
10:15	Tea and coffee	Tea and coffee
10:45	Nesse Tyssøy (S1)	Energetic Electron Precipitation into the Middle Atmosphere - Constructing the Loss Cone Fluxes from MEPED POES (invited)
11:20	Kilpua (S1)	Dependence of magnetosphere-ionosphere storm-time response on large-scale solar wind structures
11:40	Asikainen (S1)	Solar wind drivers of energetic electron precipitation
12:00	Pettit (S4)	Comparison of two MEPED electron data sets with proton contamination corrections
12:20	Lunch	Lunch

13:20	Poster session 1	Poster session 1
14:50	Tea and coffee	Tea and coffee
15:20	van de Kamp (S4)	A model providing long-term datasets of energetic electron precipitation during geomagnetic storms
15:40	Rodger (S4)	Including "Typical" Relativistic Electron Precipitation in Representative Models
16:00	Kero (S4)	Lower mesospheric ionisation effect on the cosmic radio noise absorption spectrum
16:20	Marshall (S4)	Atmospheric Response to Energetic Electron Precipitation - Ionization, optical emissions, x-rays, and backscatter
17:00	Icebreaker	Icebreaker

	TUESDAY	**14 JUNE**
9:00	Partamies (S4)	Characterisation of pulsating aurora
9:20	Turunen (S2)	Modeled response of mesospheric ozone to a pulsating aurora event on 17 November 2012
9:40	Matthes and Funke (S3)	Solar forcing for CMIP6
10:15	Tea and coffee	Tea and coffee
10:45	Yeo (S1)	UV SSI variability - Why do measurements and models not agree? (invited)
11:20	Marsh (S2)	Aeronomic impacts of a revision to the solar irradiance forcing for CMIP6
11:40	Kunze (S2)	Effects of different spectral solar irradiance datasets on the chemistry and dynamics in the CCMs EMAC and WACCM
12:00	Misios (S2)	Sensitivity of the simulated stratospheric climatology to the specification of solar irradiance spectra
12:20	Lunch	Lunch
13:20	Poster session 2	Poster session 2
14:50	Tea and coffee	Tea and coffee
15:20	Ball (S1)	High solar cycle spectral variations inconsistent with stratospheric ozone observations
15:40	Clilverd (S2)	Substorm-induced energetic electron precipitation: Impact on atmospheric chemistry
16:00	Newnham (S2)	Mesospheric nitric oxide production by medium energy electrons above Halley station, Antarctica
16:20	Hendrickx (S2)	EPP-produced NO and its 27 day solar cycles in production and mesospheric descent

	WEDNESDAY	15 JUNE
9:00	Espy (S2)	Comparison between in-situ particle precipitation and NO_x production in the mesosphere
9:20	Verronen (S2)	Enhancement of odd nitrogen modifies mesospheric ozone chemistry during polar winter
9:40	Pérot (S2)	Energetic particle precipitation effects as observed by the Odin/SMR instrument (invited)
10:15	Tea and coffee	Tea and coffee
10:45	Thiéblemont (S3)	Solar influence on North Atlantic climate (invited)
11:20	Bender (S2)	Particle-induced NO production in the mesosphere and lower thermosphere from SCIAMACHY NO time series
11:40	Kuchar (S2)	Attribution of lower-stratospheric tropical temperature variations to the 11-year solar cycle
12:00	Shieferdecker (S2)	Is there a solar signal in lower stratospheric water vapor?
12:20	Lunch	Lunch
13:20	Poster session, all	Poster session, all
14:50	Excursion	Excursion
16:00	Guided tour 16-17	Guided tour 16-17
17:00	Excursion	Excursion
19:00	Dinner	Dinner

	THURSDAY	16 JUNE
9:00	Orsolini (S2)	Role of planetary waves, gravity waves and tides in the downward transport of nitrogen oxides during elevated stratopause events
9:20	Meraner (S2)	Sensitivity of the Simulated Mesospheric Transport of Nitrogen Oxides to Parameterized Gravity Waves
9:40	Chiodo (S3)	Reduction of climate sensitivity to solar forcing due to stratospheric ozone feedback (invited)
10:15	Tea and coffee	Tea and coffee
10:45	Coddington (S4)	Measurements of Solar Irradiance - How the future TSIS-1 mission will extend current understanding of solar irradiance variability (invited)
11:20	Lu (S2)	Does Wave-Mean Flow Interaction Amply the 11-Year Solar UV Signal?
11:40	von Clarmann (S3)	Another Approach to Stratospheric-Mesospheric Exchange: The Direct Inversion of the Continuity Equation
12:00	Duderstadt (S3)	Nitrate ion spikes in ice cores not suitable as proxies for solar proton events
12:20	Lunch	Lunch

13:20	Poster session 3	Poster session 3
14:50	Tea and coffee	Tea and coffee
15:20	Kiviranta (S4)	Empirical model of nitric oxide in the upper mesosphere and lower thermosphere based on 12 years of Odin-SMR measurements
15:40	Kyrölä (S4)	GOMOS measurements of O_3, NO_2 and NO_3 compared to specified-dynamics WACCM simulations
16:00	Kalakoski (S2)	Dynamical effects of EEP induced mesospheric ozone loss in WACCM
16:20	Mursula (S3)	Comparing the influence of sunspot activity and geomagnetic activity on winter surface climate
17:00	CCMI splinter meeting	CCMI splinter meeting

	FRIDAY	**17 JUNE**
9:00	Nieder (S2)	Solar particle impact on the middle atmosphere: results of global model studies
9:20	Andersson (S3)	Long-term atmospheric effects of medium-energy electron precipitation from chemistry-climate modelling
9:40	Turner (S4)	The success of CubeSats for providing inexpensive yet high-quality observations of energetic electron precipitation from Earth's radiation belts (invited)
10:15	Tea and coffee	Tea and coffee
10:45	Sinnhuber (S4)	Validation of the direct effect of mid-energy electrons in the mesosphere: Suggestion for a new HEPPA model-measurement intercomparison experiment
11:20	Arsenovic (S2)	The Influence of Middle Range Energy Electrons on Atmospheric Chemistry and Regional Climate
11:40	Maliniemi (S3)	QBO-dependent relation of geomagnetic activity and northern annular mode during the 20th century
12:00	Final Discussion	Final Discussion
12:20	Conclusion	Conclusion

Poster session 1	**Monday 13 June**
Artamonov (S2)	Model CRAC:EPII for atmospheric ionization due to precipitating electrons: Applications and comparison with parametrization model
Lavarra (S4)	Photoionisation characteristics in the polar summer mesosphere inverted from the ESR IPY data
Nedal (S2)	Investigate the effect of different solar phenomena on the high-latitude ionosphere
Oyama (S2)	Correspondence of evolution of EEP with auroral-patch morphological changes at the substorm recovery phase

Sandanger (S4)	Solar cycle variability in long term particle fluxes as measured by NOAA POES
Verronen (S2)	Contribution of proton and electron precipitation to the observed electron concentration in October-November 2003 and September 2005
Ødegaard (S1)	Energetic electron precipitation during geomagnetic storms driven by high-speed solar wind streams

Poster session 2	**Tuesday 14 June**
Feng (S2)	Effect of solar proton events and medium energy electrons on the middle atmosphere using a 3D WACCM with D region ion-neutral chemistry
Grandhi (S2)	Does the SPE of January 2005 produce a unique, identifiable signature in polar middle atmosphere dynamics?
Hackett (S2)	Elevated stratopause events and their effects on energetic particle precipitation
Peck (S2)	Whole atmosphere impacts by auroral EEP
Päivärinta (S2)	Effect of transport and energetic particle precipitation on Northern Hemisphere polar stratospheric odd nitrogen and ozone in January-March 2012
Smith-Johnsen (S2)	NO produced by energetic electron precipitation during a geomagnetic storm in April 2010
Thiéblemont (S2)	Sensitivity of tropical stratospheric ozone to rotational UV variations at different time scales: observations vs model
Zawedde (S2)	The Impact of Energetic Electron Precipitation on Mesospheric Hydroxyl during a Year of Solar Minimum

Poster session 3	**Thursday 16 June**
Andrews (S3)	Sub-seasonal influence of the solar cycle on the winter NAO
Asikainen (S3)	Modulation of the polar vortex by energetic particle precipitation and Quasi-Biennial Oscillation via ozone loss
Ball (S4)	Constraining solar irradiance changes using ozone: uncertainties and limitations
Garfinkel (S2)	Stratospheric Response to Intraseasonal Changes in Incoming Solar Radiation
Lu (S3)	Downward Wave Reflection as an Additional Mechanism for the Troposphere Response to the 11-year Solar Cycle
Meraner (S3)	Climate Effect of a Mesospheric Ozone Loss due to Energetic Particle Precipitation
Ringsby (S4)	Frequency Correction of CO Spectra from Odin/SMR
Verronen (S4)	WACCM-D - Whole Atmosphere Community Climate Model with D-region ion chemistry
Versick (S3)	Tests of a parameterization for auroral forcing in the CCM EMAC for CMIP6 simulations

1 Solar and particle variability

Solar wind drivers of energetic electron precipitation

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Disturbances of near-Earth space are predominantly driven by coronal mass ejections (CMEs) mostly originating from sunspots and high-speed solar wind streams (HSSs) emanating from coronal holes. Here we study the relative importance of CMEs and HSSs as well as slow solar wind in producing energetic electron precipitation. We use the recently corrected energetic electron measurements from the Medium Energy Proton Electron Detector instrument on board low-altitude NOAA/Polar Orbiting Environmental Satellites from 1979 to 2013. Using solar wind observations categorized into three different flow types, we study the contributions of these flows to annual electron precipitation and their efficiencies in producing precipitation. We find that HSS contribution nearly always dominates over the other flows and peaks strongly in the declining solar cycle phase. CME contribution mostly follows the sunspot cycle but is enhanced also in the declining phase. The efficiency of both HSS and CME peaks in the declining phase. We also study the dependence of electron precipitation on solar wind southward magnetic field component, speed, and density and find that the solar wind speed is the dominant factor affecting the precipitation. Since HSSs enhance the average solar wind speed in the declining phase, they also enhance the efficiency of CMEs during these times and thus have a double effect in enhancing energetic electron precipitation.

References

Asikainen, T., Ruopsa, M., Solar wind drivers of energetic electron precipitation, J. Geophys. Res., 121, doi:10.1002/2015JA022215, 2016

High solar cycle spectral variations inconsistent with stratospheric ozone observations

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Solar cycle changes are thought to have an impact on surface weather, particular over the North Atlantic, Europe and the United States. The pathway, initiated through heating of the equatorial stratosphere caused by solar ultraviolet radiation, is governed by the magnitude of ultraviolet solar cycle changes. Thus, quantifying this change is critical to our understanding of solar impacts on climate. Observations from the SORCE satellite, launched in 2003, have shown broadband, ultraviolet solar cycle changes two to three times larger than previous observations, and solar models. Using the larger changes in climate models leads to a larger regional surface climate response.

We combine information from a state-of-the-art climate model with several ozone composites of observations and find strong evidence that the changes in ozone do not support the large changes observed by SORCE (see Fig. 1). Further, our results support the lower forcing given by the solar models and, thus, our findings support the magnitude of solar cycle changes observed by the UARS/SUSIM instrument, which operated from 1991-2005. The use of a more realistic solar forcing in climate models will allow for a better understanding of the mechanism by which the Sun can influence surface climate.

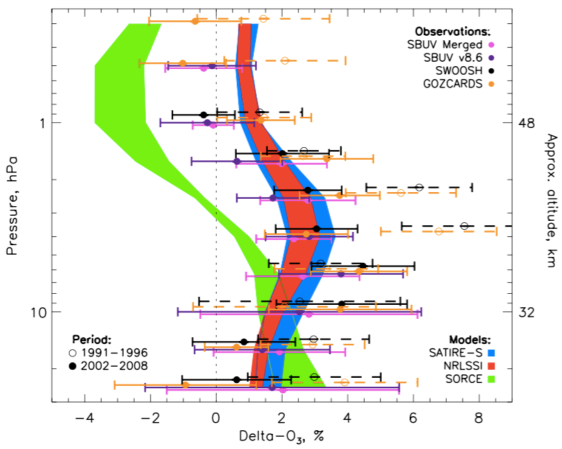

Figure 1: *The photolytic response to solar cycle changes extracted from ozone composites of observations (dot-bars), and chemsitry climate model simulations using a varying solar irradiance (shading). Extraction of signal was achieved by subtracting a chemistry climate model run with no varying solar component. Figure from Ball et al., 2016*

References

Ball, W.T., Haigh, J.D., Rozanov, E.V., Kuchar, A., Sukhodolov, T., Tummon, F., Shapiro, A.V., Schmutz, W., 2016. High solar cycle spectral variations inconsistent with stratospheric ozone observations, Nature Geoscience, 10.1038/ngeo2640

Dependence of magnetosphere-ionoshere storm-time response on large-scale solar wind structures

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The details of magnetospheric and ionospheric activity during geomagnetic storms depends strongly on the large-scale solar wind structure that interacts with the near-Earth space environment. The key drivers of geomagnetic storms are coronal mass ejections (CMEs), slow-fast stream interaction regions (SIRs) and fast streams. CMEs are further broken down to a sheath and a flux rope. In this presentation I will demonstrate that all the above mentioned structures have distinct solar wind properties and consequently are related to highly different magnetosphere-ionosphere responses and dynamics of the MeV electrons in the Van Allen radiation belts. For example, CME sheaths have high dynamic pressure and Alfvén Mach numbers and large-amplitude fluctuations of the magnetic field, while CME flux ropes have lower dynamic pressure and Alfvén Mach numbers and smooth magnetic fields. Hence, CME sheaths and flux ropes cause very different modes of solar wind forcing and solar wind – magnetosphere coupling efficiences. Due to their turbulent properties CME sheaths cause in particular intense variations of the auroral currents, while flux ropes tend to rather lead to enhanced large-scale convection and efficient ring current build-up. In addition, clear differences in characteristics of solar wind driving conditions and geospace responses, including radiation belts, for sheaths, flux ropes, SIRs and fast streams are expected to lead to different effects on the atmosphere.

Energetic Electron Precipitation into the Middle Atmosphere - Constructing the Loss Cone Fluxes from MEPED POES

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The impact of Energetic Electron Precipitation (EEP) on the chemistry of the middle atmosphere (50-90 km) is still an outstanding question as accurate quantification of EEP is lacking due to instrumental challenges and insufficient pitch angle coverage of current particle detectors. The MEPED instrument onboard the NOAA/POES and MetOp spacecraft has two sets of electron and proton telescopes pointing close to zenith (0^o) and in the horizontal plane (90^o). Using measurements from either the 0^o or 90^o telescope will underestimate or overestimate the bounce loss cone flux respectively, as the energetic electron fluxes are often strongly anisotropic with decreasing fluxes towards the center of the loss cone. By combining the measurements from both telescopes with electron pitch angle distributions from theory of wave-particle interactions in the magnetosphere, a complete bounce loss cone flux is constructed for each of the electron energy channels >50keV, >100keV,and >300keV. We apply a correction method to remove proton contamination in the electron counts. We also account for the relativistic (>1000 keV) electrons contaminating the proton detector at sub-auroral latitudes. This gives us full range coverage of electron energies that will be deposited in the middle atmosphere.

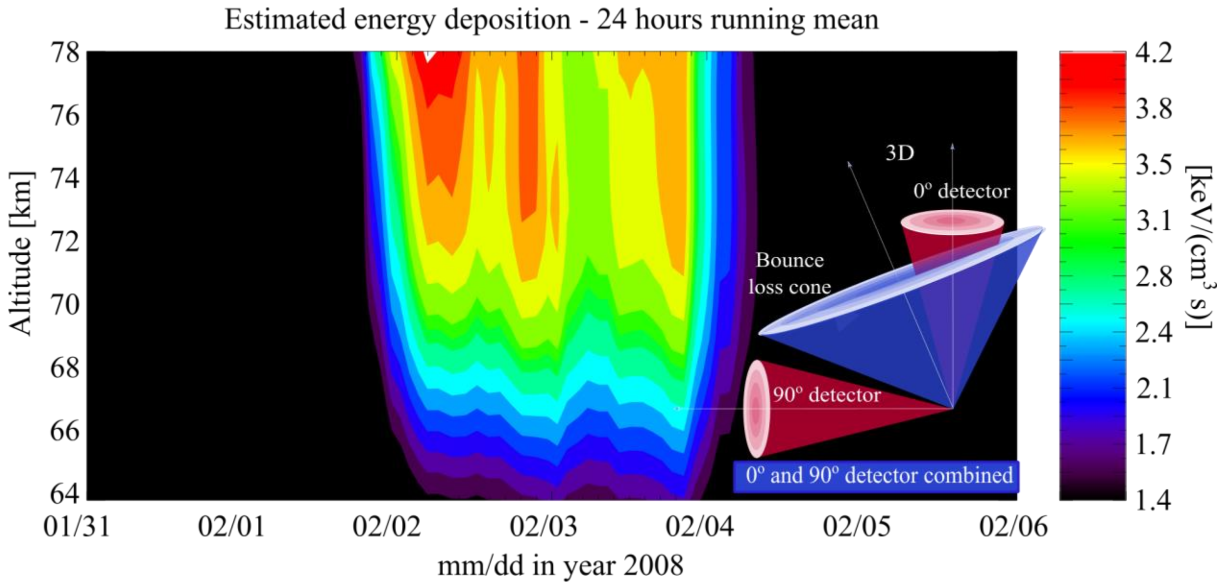

Figure: *Electron fluxes measured by the two MEPED telescopes are matched with pitch angle profiles derived from the theory of wave particle interaction. Complete bounce loss cone fluxes are constructed, and the electron energy deposition into the mesosphere is calculated.*

Finally, we demonstrate the method's applicability on strongly anisotropic pitch angle distributions during a weak geomagnetic storm in February 2008. We compare the electron fluxes and subsequent energy deposition estimates to OH observations from the Microwave Limb Sounder on the Aura satellite substantiating that the estimated fluxes are representative for the true precipitating fluxes impacting the atmosphere.

UV SSI variability - Why do measurements and models not agree?

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UV SSI has been monitored from space since 1978. This is accompanied by the development of models aimed at reconstructing UV SSI by relating the variability to solar magnetism. There is controversy between the various measurements and models in terms of the wavelength-dependence of the variation over the solar cycle, which see their application to climate models yield qualitatively different results. Here, we highlight the main discrepancies between available records and reconstructions, and discuss the likely causes.

Energetic electron precipitation during geomagnetic storms driven by high-speed solar wind streams

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The processes leading to acceleration or loss of relativistic electrons in the magnetosphere during geomagnetic storm time have yet to be fully understood, and whether a geomagnetic storm will lead to enhanced or depleted fluxes of relativistic electrons is not always evident. Relativistic Electron Precipitation (REP) can penetrate deep into the atmosphere and influence composition and dynamics. To study the effect of REP upon the atmosphere, the energy and intensity of the electrons need to be accurately represented. We use MEPED detectors on board the POES satellites to study the behaviour of electrons with energies E>50 keV, E>100 keV, E>300 keV and E>1000 keV during geomagnetic storms.

The MEPED vertical telescope measures precipitated flux, and the horizontal telescope trapped flux at satellite altitude (ca 850 km). Using a newly developed technique, we can derive the flux of electrons depositing their energy in the atmosphere from the pair of detectors on each satellite (bounce loss cone flux). 41 isolated CIR storms were identified in the period 2006-2010. By combining the measurements from several satellites, we obtain a close to global view of the relativistic electron fluxes, enabling us to study the relationship between the REP and different geomagnetic indices and solar wind drivers.

We perform a superposed epoch analysis with solar wind parameters, geomagnetic indices radiation belt fluxes and precipitated fluxes. The storms that lead to enhanced precipitating fluxes have in general high solar wind velocities over longer time periods compared to other storms. Geomagnetic indices show that these storms have longer lasting geomagnetic activity (AE index), but not necessarily stronger in magnitude.

2 Solar and particle effects on the stratosphere and above

The Influence of Middle Range Energy Electrons on Atmospheric Chemistry and Regional Climate

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We investigate the influence of Middle Range Energy Electrons (MEE or ring current; typically 30-300 keV) precipitation on the atmosphere using the SOCOL3-MPIOM chemistry-climate model with coupled ocean. Model simulations cover the 2002-2010 period for which ionization rates from the AIMOS dataset and atmospheric composition observations from MIPAS are available. Results show that during geomagnetically active periods MEE significantly increase the amount of NOy and HOx in the polar winter mesosphere, in addition to other particles and sources, resulting in local ozone decreases of up to 35 %. These changes are followed by an intensification of the polar night jet, as well as mesospheric warming and stratospheric cooling. The contribution of MEE also substantially enhances the difference in the ozone anomalies between geomagnetically active and quiet periods. Comparison with MIPAS NOy observations indicates that the additional source of NOy from MEE improves the model results, however substantial underestimation above 50 km remains and requires better treatment of the NOy source from the thermosphere. A surface air temperature response is detected in several regions, with the most pronounced warming occurring in the Antarctic during austral winter. Surface warming of up to 2 K is also seen over continental Asia during boreal winter.

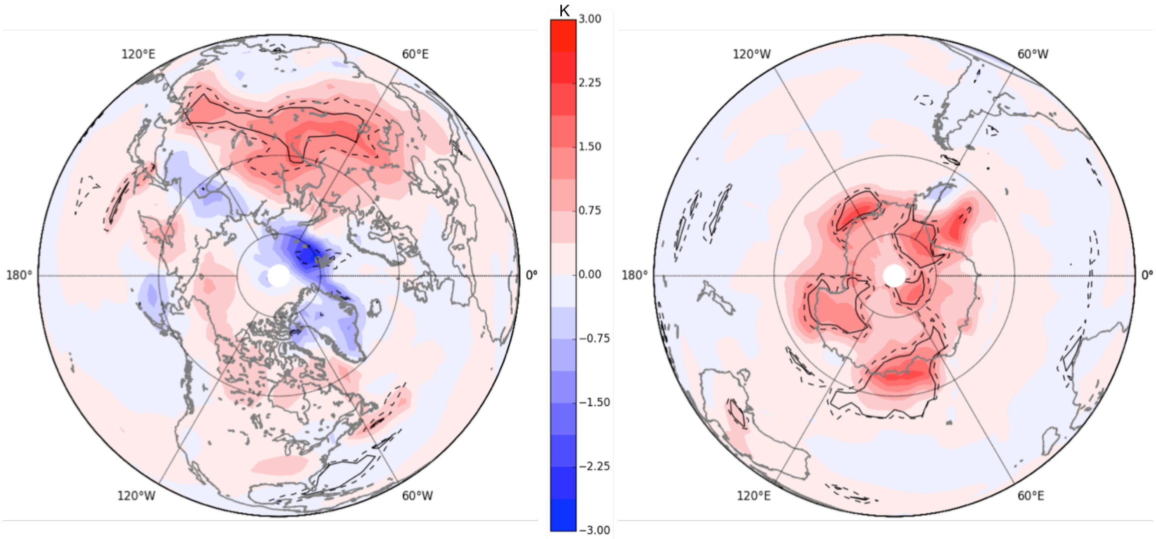

Figure 1: *Spatial distribution of 2 m temperature difference (MEE – NOMEE) in K for DJF (left plot) and JJA (right plot) averaged over 2002–2005. Dashed line circles the regions with 90% and solid line with the 95% confidence level. Adapted from Arsenovic et al., 2016.*

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Model CRAC:EPII for atmospheric ionization due to precipitating electrons: Applications and comparison with parametrization model

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A new model of the family of CRAC models, CRAC:EPII (Cosmic Ray Atmospheric Cascade: Electron Precipitation Induced Ionization), is presented. The model calculates atmospheric ionization induced by precipitating electrons. The CRAC:EPII is based on Monte Carlo simulation: Compton scattering, generation of bremsstrahlung high-energy photons, photoionization, annihilation of positrons, and multiple scattering. The results from the simulations are given as look-up table representing the ionization yield function. The CRAC:EPII allows one to compute ionization due to precipitating electrons for a given altitude (up to 100 km) considering a given electron spectrum. The ionization yields is compared with an analytical parametrization for various energies of incident precipitating electron.

Modulation of the polar vortex by energetic particle precipitation and Quasi-Biennial Oscillation via ozone loss

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Energetic particle precipitation (EPP) has been shown to cause ozone loss in the stratosphere during polar winter. This has been suggested to enhance polar vortex with the effect propagating even to ground level, where it is observed as a more positive phase of the Northern Annular Mode (NAM), the dominant ground circulation pattern in the winter time. Recent research has also shown that the quasi-biennial oscillation (QBO) modulates the relationship between the ground NAM and EPP so that the positive correlation between the two is more clearly seen in the easterly phase of QBO measured at 30 hPa height especially during the late winter season.
Here we aim to elaborate the QBO modulated connection between EPP and NAM by studying how the EPP affects the stratospheric polar vortex in the two phases of the QBO. Since the EPP presumably affects the polar stratosphere via indirect ozone loss we will study how the EPP modulates the amount of ozone, the stratospheric temperatures and zonal winds in the two QBO phases.

Particle-induced NO production in the mesosphere and lower thermosphere from SCIAMACHY NO time series

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During geomagnetic disturbances, enhanced amounts of solar-wind and radiation-belt particles (mainly electrons) enter the upper atmosphere (70–120 km) and produce nitric monoxide (NO). Large-scale circulation then transports this trace gas down to the stratosphere (below about 45 km). There NO catalytically reduces ozone, altering the stratospheric ozone layer. This further affects atmospheric dynamics, possibly all the way down to the surface. Eventually, this chain of processes relates space weather to the lower atmosphere and the climate system.

We analyse SCIAMACHY NO measurements in the mesosphere and lower thermosphere (MLT, 50–150 km) to link geomagnetically induced particle precipitation to NO production in the upper atmosphere. In particular observing the NO gamma emissions, we derive the NO number densities from 60 km to 160 km from the SCIAMACHY UV spectra. We use the UV spectra from two different limb scan types, the nominal mode from the ground to 90 km and the MLT mode from 50 km to 150 km. Combining both, we obtain an almost ten-year global daily data set of NO number densities from 60 km to 90 km, from August 2002 until March 2012.

We inspect this time series with respect to solar and geomagnetic activity using different statistical methods: superposed epoch analysis and multi-linear regression analysis. We use the UV Lyman-α emissions to model the long-term solar cycle effects and the auroral electrojet (AE) index to gauge the particle influx into the MLT. We find that in particular at polar latitudes, the NO number densities are in a statistically significant way linked to the solar Lyman-α flux and the geomagnetic AE index. In the future, starting from this analysis, we aim to construct a simple empirical model for NO in the MLT region to extend and constrain chemistry-climate models.

Substorm-induced energetic electron precipitation: Impact on atmospheric chemistry

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Abstract:

Magnetospheric substorms drive energetic electron precipitation into the Earth's atmosphere – this mechanism acts independently from previously reported radiation belt electron precipitation processes. Substorms cause energetic electron precipitation with energies of 100's of keV, affect a large range of geomagnetic latitudes, last about 1 hour, and can occur more than 2000 times/year depending on the phase of the solar cycle [*Rodger et al., 2016*]. To investigate the impact of substorm-driven electron precipitation on atmospheric chemistry we use the output from a recently developed substorm model [*Beharrell et al., 2014*] to describe electron precipitation forcing of the atmosphere during an active substorm period in April-May 2007. We provide an estimate of substorm impact on the neutral composition of the polar middle atmosphere.

Model simulations show that the enhanced ionization from a series of substorms leads to an estimated ozone loss of 5-50% in the mesospheric column depending on season [*Seppälä et al., 2015*]. This is similar in scale with small to medium solar proton events (SPEs). This effect on polar ozone balance is potentially more important on long time scales (months-years) than the impulsive but sporadic (few SPE/year vs. 3-4 substorms/day) effect of SPEs. Our results suggest that substorms should be considered an important source of energetic particle precipitation into the atmosphere and included in high-top chemistry-climate models.

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Comparison between in-situ particle precipitation and NOx production in the mesosphere

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The effects of moderate geomagnetic storms during the winters of 2008 and 2009 have been investigated using satellite and ground-based observations over the Antarctic station at Troll (72S, 2.5E). We compare simultaneous measurements of ozone and nitric oxide from a ground-based microwave radiometer at Troll, with local energy deposition derived from POES satellite. The integrated column abundance of NO between 60 and 80 km, when compared to the integrated column energy deposition or ionization density over the same altitude region at the instrument location, shows only moderate correlation and a significant lag between the ionization and the NO density. Similar results were obtained using the AE index. In an attempt to compensate for horizontal transport, the climatology of winds and tides from Rothera station (68S, 68W) was used to infer the daily transport of NO into the instrument field of view, and the energy deposition region expanded accordingly. While this had minimal effect on the correlation between the NO and ionization column, convolving an exponential decay curve with the AE index significantly improved the correlation and removed the lag between changes in the index and the NOx produced. Details of these results and their interpretation in terms of horizontal and vertical transport will be discussed.

Effect of solar proton events and medium energy electrons on the middle atmosphere using a 3D Whole Atmosphere Community Climate Model with D region ion-neutral chemistry

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Abstract:

It is crucial to understand the sources of odd nitrogen NOx (NO, NO_2) and odd hydrogen HOx (OH, HO_2) since they play important roles in the chemistry of stratospheric and mesospheric O_3. In the middle and upper atmosphere, NOx and HOx are produced directly through the interactions of ionizing particles with atmospheric gases. During solar proton events and geomagnetic activities, the enhanced ionizations produce a large amount of NO in the middle atmosphere by complex ion chemistry.

Recently we have developed a new coupled ion-neutral chemical model for the ionospheric *D* region (altitudes ~50 - 90 km) based on the Sodankylä Ion and neutral Chemistry (SIC) model and 3D Whole Atmosphere Community Climate Model (WACCM), termed as WACCM-SIC. In this poster, we will describe the WACCM-SIC model which now includes in WACCM an extra 306 ion-neutral and ion-recombination reactions of neutral species, positive and negative ions, and electrons. WACCM-SIC simulations have been performed to investigate the impact of a medium SPE of 15-17 January 2005, and the effect of Medium Energetic electrons (~ 1-30 MeV) of 2013-2014 on the middle atmospheric species (NOx, HOx, HNO_3 and ozone). The modelled simulations will also be compared with available satellite measurements (e.g., Aeronomy of Ice in the Mesosphere satellite) and a ground-based microwave radiometer observations at Halley station (75°S), as well as other model simulations including the standard WACCM and two reduced versions of SIC, WACCM-D and WACCM-rSIC.

Stratospheric Response to Intraseasonal Changes in Incoming Solar Radiation

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Superposed epoch analysis of meteorological reanalysis data is used to demonstrate a significant connection between intraseasonal solar variability and temperatures in the stratosphere. Decreasing solar flux leads to a cooling of the tropical upper stratosphere above 7hPa, while increasing solar flux leads to a warming of the tropical upper stratosphere above 7hPa, after a lag of approximately six to ten days. Late winter (February-March) Arctic stratospheric temperatures also change in response to changing incoming solar flux in a manner consistent with that seen on the 11 year timescale: ten to thirty days after the start of decreasing solar flux, the polar cap warms during the easterly phase of the Quasi-Biennal Oscillation. In contrast, cooling is present after decreasing solar flux during the westerly phase of the Quasi-Biennal Oscillation (though it is less robust than the warming during the easterly phase). The estimated composite mean changes in Northern Hemisphere upper stratospheric (~ 5hPa) polar temperatures exceed 8K, and are potentially a source of intraseasonal predictability for the surface. These changes in polar temperature are consistent with the changes in wave driving entering the stratosphere.

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Does the SPE of January 2005 produce a unique, identifiable signature in polar middle atmosphere dynamics?

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Investigations of Solar Proton Events (SPEs) impact on middle atmosphere have long history starts in the late 1960s. The SPE typically occur near solar maximum and are infrequent in nature. Typically, it lasts for a few days and lead to polar atmospheric changes through ionization, dissociation, dissociative ionization, and excitation processes. They are known to cause significant changes in chemical constituents such as HOx, NOy, and ozone, which in turn may cause changes in temperature. Changes in the temperature will impact the middle atmosphere residual circulation. While the chemical changes are evident in multiple SPEs and other geomagnetic disturbances, there are fewer observations supporting potential dynamical changes. This might partly be due to highly variable background winds. The SPE in January 2005 is a special event, it is the most powerful event that occurred in the solar minimum period and also accompanied by a powerful geomagnetic storm. In addition the polar vortex in the Northern Hemisphere is stable during this time that allows finding significant SPE impact on middle atmosphere. In this paper, we present the observed dynamical variations in the middle atmosphere during SPE. We used meteor radar winds and MERRA reanalysis winds to explore potential dynamical changes. We notice large zonal winds in comparison to climatological mean values and enhancements in the semidiurnal tides.

Elevated stratopause events and their effects on energetic particle precipitation

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The northern hemisphere polar winter exhibits extreme dynamical variability that affects temperature profiles, winds, and atmospheric chemistry in the middle atmosphere, with potential connections to long-term weather and climate in the troposphere. Extreme events known as elevated stratopause (ES) events occur during the winter after some sudden stratospheric warmings (SSWs). Such events have been shown to affect the transport of EPP-NO_x ($NO + NO_2$) into the stratosphere, and indicate that enhanced descent of NO_x has occurred through the EPP indirect effect (EPP-IE). Elevated stratopause events occur when the polar vortex breaks down completely, the stratopause becomes indistinct for a number of days, then the vortex recovers at higher altitudes than before the warming, around 20 km higher than the seasonal climatological mean height. The change in circulation results in enhanced descent of EPP-NO_x from the mesosphere into the stratosphere, where it then participates in catalytic cycles with ozone and results in enhanced ozone depletion. Many methodologies have been utilized to investigate ES events in observations and models, however identified years in the modern literature disagree significantly as a result of the use of different indicators. Here we investigate various indicators in an attempt to resolve discrepancies in the literature in documented ES events, and identify and apply the best indicator to older reanalyses in order to assess the occurrence of ES events in the historical data record. Future work will focus on applying the indicator to SD-WACCM in order to investigate the effects of ES events on EPP-$NO_{x.}$

EPP-produced NO and its 27-day solar cycles in production and mesospheric descent

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Energetic particle precipitation (EPP) produces nitric oxide (NO) in the Mesophere-Lower Thermosphere region (MLT), and during the polar winter, NO can reach down to stratospheric altitudes where it destroys ozone. Several case studies have shown a deficit in models' abilities to correctly represent the transport of NO from the lower thermosphere to the mesosphere and stratosphere, especially in connection with sudden stratospheric warmings.

We study by means of superposed epoch analyses, the general scenario of NO production due to energetic particles in the auroral region, see *Hendrickx et al.* (2015). NO observations are provided by the Solar Occultation For Ice Experiment (SOFIE) instrument onboard the Aeronomy of Ice in the Mesosphere (AIM) satellite. We focus on the downward transport from the lower thermosphere to mesosphere. The analysis clearly shows the effect of the 27 day solar cycle all the way down to 50 km during polar winter. Initially a rapid downward transport is noted during the first 10 days after EPP onset to an altitude of 82 km, which is then followed by a slower downward transport of approximately 1-1.2 km/ day to lower mesospheric altitudes in the order of 30 days. These results are compared to NO simulations of the Whole Atmosphere Community Climate Model (WACCM).

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Dynamical effects of EEP induced mesospheric ozone loss in WACCM

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The Climate and Solar Particle Forcing project (CLASP) is focused on studying the potential effects that the particle flux from the Sun can have on the Earth's climate. The project aims to clarify our understanding of natural climate forcing mechanisms. Project focuses on studying the role of atmospheric dynamics and dynamical coupling between atmospheric layers as a connection mechanisms between Solar particle flux and climate variability.

In this presentation we describe the results of model simulations using the Specified Chemistry Whole Atmosphere Community Climate Model (SC-WACCM), the atmospheric component of the Community Earth System Model (CESM). In our simulations we apply a polar ozone reduction of 30% in the upper mesosphere between 70-80 km during polar winter which corresponds to the ozone loss due to energetic electron (EEP) precipitation seen by satellites measurements in recent study by *Anderson et al.* (2014). Simulations are used to study chemistry-dynamics connections and wave-mean flow interactions potentially resulting from the observed EEP induced ozone losses.

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Attribution of lower-stratospheric tropical temperature variations to the 11-year solar cycle

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The double-peaked tropical temperature response to the 11-year solar cycle (SC) has been well documented. However, there are concerns about the origin of the lower peak due to potential aliasing with volcanic eruptions or ENSO. Here we explain how the solar signal can be misattributed to another signal, due to their collinearity, and how the amplitude of the signal may depend on the period and method of analysis. We attribute the SC using a statistically rigorous multiple linear regression (MLR) model. Sensitivity experiments with the chemistry-climate model (CCM) SOCOL show that the signal attributed to the SC is reduced by 60% when volcanoes are switched off. A further 20% reduction is attributed to interannual variations in sea surface temperature and sea ice content. We confront our reference simulation with other CCMs simulated within the Chemistry-Climate Model Initiative (CCMI) framework. Finally, we demonstrate that the correct identification of the solar signal from the historical record requires a period starting no later than in 1965 to prevent aliasing.

In addition, we provide a brief tutorial of open-source MLR tool available to the SOLARIS-HEPPA community for future model validation in terms of solar influences on climate.

Effects of different spectral solar irradiance datasets on the chemistry and dynamics in the CCMs EMAC and WACCM

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An updated reconstruction of spectral solar irradiance (SSI) derived by the Naval Research Laboratory Solar Spectral Irradiance (NRLSSI2) model (*Coddington et al.*, 2015) and the SSI reconstruction of the Spectral And Total Irradiance REconstruction for the Satellite era (SATIRE-S) model (*Yeo et al.*, 2014) both show stronger UV variability over the 11-year solar cycle than the previous NRLSSI1 dataset, which has been used widely in Chemistry-Climate model (CCM) studies and also within CMIP5. Besides solar cycle changes, there are also changes in the spectral distribution of the energy in NRLSSI2 and SATIRE-S compared to NRLSSI1. The aim of this study is to analyse the dynamical and chemical implications of using the most recent SSI reconstructions of NRLSSI2, SATIRE-S and the average of both, which is the recommended SSI dataset for the upcoming CMIP6, in comparison to NRLSSI1 (CMIP5 recommendation).
We employ the different SSI datasets in 45 years time slice simulations with the two CCMs EMAC (ECHAM/MESSy Atmospheric Chemistry) and CESM1(WACCM) (Community Earth system model(Whole Atmosphere Community Climate Model)). We apply two different setups for each SSI dataset, one with SSI for Nov. 1994 near the solar cycle 23 minimum and the second with SSI for Nov. 1989 during the solar cycle 22 maximum. All other boundary conditions, including greenhouse gases, ozone depleting substances, sea surface temperatures and sea ice concentrations are set to represent year 2000 conditions.
Using the most recent SSI datasets during solar minimum conditions leads to a significant decrease in short wave (SW) heating rates and related cooling in large parts of the middle atmosphere in the tropics. This decrease in heating rates is mainly caused by a decrease in SSI in the Herzberg continuum and Hartley bands. Related changes in ozone concentrations are negative in the middle stratosphere but positive around the stratopause. The 11-year solar cycle variability of the updated SSI datasets increases the solar signal in SW heating rates and temperatures around the stratopause and above. The positive solar signal in ozone is weaker around the stratopause and lower mesosphere, when using the most recent SSI datasets. The increased variability of updated Lyman-α and Schumann-Runge SSI is leading to a more negative solar signal in ozone in the upper mesosphere. In the lower stratosphere the differences in the positive ozone solar signal is related to the CCMs, with WACCM showing a stronger ozone solar signal, rather than caused by the usage of different SSI datasets.

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Does Wave-Mean Flow Interaction Amply the 11-Year Solar UV Signal?

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Planetary wave propagation, refraction and reflection depends critically on the zonal winds through which the wave propagates. When wave breaking occurs, it in turn induces irreversible changes in background zonal flow. Such wave-mean flow interaction can be highly non-linear, acting to amplify initially small external or internal forcing. It has been suggested that wave-mean flow interaction is responsible for the amplification of the 11-year solar cycle signals, especially those induced by the solar ultraviolet (UV) irradiance variability that is known to have a small but nevertheless direct photochemical and radiative effect in the upper atmosphere. However, exactly how the amplification occurs and to what extent the upper-level solar UV forcing is transferred downward to affect the near surface climate and variability remain imperfectly understood.

This study examines the 11-year solar cycle modulation of wave-mean flow interaction during northern winter with a special attention given to changes in the seasonal evolution. We find that the solar cycle signal in transient and quasi-stationary waves are generally of opposite sign and tend to cancel each other on average. Under normal conditions, the cancellation would result in weak, noisy and insignificant solar signal in either total wave forcing or the zonal mean circulation. However, when favorable conditions are met, solar modulation of transient waves can preferably lead to either a strong polar vortex via barotropical instability, or stratospheric sudden warming (SSWs) via nonlinear wave resonance. Whether or when those effects take place depends critically on background conditions, the vertical profile of the polar vortex, and the presence of other forcing. These results suggest that the solar modulation of wave-mean flow interaction is non-linear, involving both amplification and cancellation. The process is underpinned by multiple effects which would not necessarily lead to significant downward transfer of zonal mean westerlies. Based on these results, a plausible explanation is provided for the large scatter and weak solar signal obtained among the Coupled Model Intercomparison Project Phase 5 (CMIP5) model ensembles.

Aeronomic impacts of a revision to the solar irradiance forcing for CMIP6

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In preparation for the sixth phase of the Coupled Model Intercomparison Project (CMIP6), a revised solar forcing dataset has been the assembled as part of the Solar Influences activity of the Stratosphere-troposphere Processes And their Role in Climate (SPARC) project [*Matthes et al., in preparation*]. The new dataset differs significantly from the previous dataset used by CMIP5 models in the distribution of the mean solar spectral irradiance, particularly in the ultraviolet (UV). For example, in the 300-350 nm band the irradiance in the new model is reduced by approximately 0.75 Wm^{-2}. To put this in perspective, that change amounts to approximately 4 to 6 times the magnitude of the solar cycle variation in that band.

Using the NCAR Whole Atmosphere Community Climate Model (WACCM), we assess the impact on stratospheric composition and dynamics of this revision to the solar irradiance by comparing WACCM experiments that are forced by either the CMIP5 or CMIP6 solar forcing dataset. We find that ozone near the stratopause increases by over 1.6% in the experiments forced with the CMIP6 dataset. The primary cause of this increase is the ~2.5% decrease in odd-hydrogen species (HOx = {H, OH and HO_2}) above ~35 km. HOx reductions are caused by a decrease in the Hartley band irradiance that creates $O(^1D)$ from ozone photolysis; the reaction with $O(^1D)$ being the primary way in which H_2O is converted to HOx. The reduction in UV irradiance in the CMIP6 forcing dataset also leads to a cooling of the stratosphere and lower mesosphere of up to 1.6K.

Considering that smaller irradiance changes that occur over the solar cycle have been implicated in changes in surface climate, our study suggest that the mean state of climate models used in CMIP6 may be significantly different than those used in CMIP5, as a result of changes in the mean solar irradiance forcing.

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Sensitivity of the Simulated Mesospheric Transport of Nitrogen Oxides to Parameterized Gravity Waves

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Gravity waves strongly influence the mesospheric circulation and hence, the transport processes in the middle atmosphere. After particularly strong sudden stratospheric warming (SSW) event as in January 2009, satellite observations indicate an up to 50 times higher amount of nitrogen oxides in the stratosphere, which descended from the thermosphere, than under undisturbed conditions (*Randall et al., 2009*). However, the second phase of the HEPPA model – observation intercomparison study shows that the mesospheric descent of nitrogen oxides in models is in general too weak after the SSW in 2009. *McLandress et al., (2013)* showed that the non-orographic gravity wave drag determines the strength of the downward transport of atmospheric tracers after a sudden stratospheric warming. It also controls the descent of the elevated stratopause, which is known to be too quick in the Hamburg Model of Neutral and Ionized Atmosphere (HAMMONIA) and in other models covering this altitude region (*Pedatella et al., 2014*).

Here, we discuss how sensitive the dynamics of the middle atmosphere in HAMMONIA are to changes of the parameterized gravity wave sources. Discussed are both, changes in a homogeneous background source and a source related to frontal activity. We concentrate on the descent of nitrogen oxides and of the elevated stratopause for the winter 2009 including the major stratospheric warming in January 2009. We will show that a weakening of gravity wave sources enhances the downward transport and prevents the elevated stratopause to descend too quickly. The amount of descending nitrogen oxides is largely controlled by the altitude at which a considerable amount of horizontal momentum is deposited.

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Sensitivity of the mean state of the stratosphere to the specification of solar irradiance spectra

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The sensitivity of the stratospheric mean state to five reference solar irradiance spectra is investigated using the chemistry climate model EMAC. The model is forced with NRLSSI v1, NRLSSI v2, SATIRE-S, SORCE, SOLID and CMIP6 spectral solar irradiances describing a quite Sun (mean January-April 2008). Simulations show that the mean thermal state of the stratosphere depends considerably on the specified spectrum given that the annual mean temperature in tropical stratopause varies by more than 2.5 K, in some cases. Temperature anomalies are stronger in boreal winter and the polar night westerlies strengthen by about 15%. The simulated ozone climatology is also influenced by the choice of the reference spectrum and EMAC simulates concentration changes up to 6-7% in the middle stratosphere. Given that net effect of the ozone response is to dump temperature anomalies, we find an amplified temperature perturbation of about 20-30% in twin simulations without interactive chemistry coupling. Using the two dimensional chemical-radiative dynamical model SOCRATES we trace the spectral regions that contribute the most to the simulated changes in the stratosphere.

Investigate the effect of different solar phenomena on the high-latitude ionosphere

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In this work, we studied four of the most powerful events during the last and current solar cycles. The events were associated with two types of solar phenomena, Coronal Mass Ejections (CME) and Solar Flares. We used our data from SOHO/LASCO CME catalogue and Richardson & Cane list of ICMEs, in addition to the database of GOES satellite for X-ray solar flares. Her we traced these phenomena from the Sun until reaching the magnetosphere and interact with the ionosphere. We focused on the associated impacts on the high latitude ionosphere in both hemispheres for different speeds of CMEs and different classes of solar flares. By using the networks of Global Navigation Satellite System (GNSS) we extracted the vertical total electron content (TEC) in several stations at the high latitudes and we found approximately the same effect on high latitudes by the solar flare types, while the effect of the CME was more powerful.We saw the signature of these phenomena in the northern hemisphere is more the southern one.

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Mesospheric nitric oxide production by medium energy electrons above Halley station, Antarctica

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The effect of medium energy electrons (MEE) on the seasonal abundance and short-term variability of nitric oxide (NO) in the Antarctic middle atmosphere is investigated. Near-continuous measurements of the NO partial column at 73–105 km have been made by a 230–250 GHz passive microwave radiometer at Halley station (75°37'S, 26°14'W, L = 4.6, geomagnetic latitude -62°), Antarctica. Halley is directly under the region of radiation-belt electron precipitation and deep within the polar vortex during the austral winter. Geomagnetic activity close to solar maximum, during March 2013 to July 2014, was driven primarily by impulsive coronal mass ejections and led to MEE precipitation into the polar middle atmosphere. Superposed epoch analyses of the ground-based data, together with NO observations made by the Solar Occultation For Ice Experiment (SOFIE) onboard the Aeronomy of Ice in the Mesosphere (AIM) satellite, show enhanced mesospheric NO following moderate geomagnetic storms (Dst ≤ -50 nT). Measurements by co-located 30 MHz riometers indicate simultaneous increases in ionisation at 75–90 km directly above Halley when Kp index ≥ 4. NO production by MEE directly in the upper mesosphere, versus downwards transport of NO from the lower thermosphere, is evaluated using a new version of the Whole Atmosphere Community Climate Model incorporating the full Sodankylä Ion-Neutral Chemistry Model (WACCM-SIC). Model ionization rates are derived from the Polar-orbiting Operational Environmental Satellites (POES) second generation Space Environment Monitor (SEM-2) Medium Energy Proton and Electron Detector instrument (MEPED). The model data are compared with observations to quantify the impact of MEE on stratospheric and mesospheric odd nitrogen (NO_x), odd hydrogen (HO_x), and ozone.

Solar particle impact on the middle atmosphere: results of global model studies

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Solar energetic particles and short wave radiation are the main forcings that drive middle atmospheric chemistry. In a cascade of chemical processes, reactive species like NOx (N, NO, NO2) and short lived HOx (H, OH, HO2) are formed. Those species act as catalysts for the depletion of Ozone in the mesosphere and stratosphere.

Global model studies from three different atmospheric chemistry and transport models are presented (3dCTM, EMAC, KASIMA) and compared to MIPAS-measurements. The EPP indirect effect is investigated in detail, the downward transport of NOx and the depletion of ozone are quantified. For NOx, very good agreement is found between all models at 1Pa level, remaining with beginning downward transport. Contrarily, considerable differences in stratospheric ozone balance and ozone depletion are found. EPP induced ozone depletion between 5% and 30% in the stratosphere, depending on solar activity and the model used, are discussed.

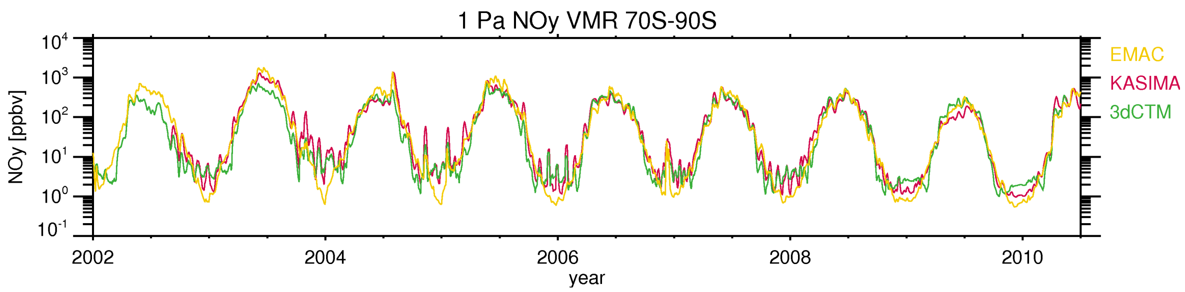

Figure 1: *Timeline of NOx VMR at 1Pa altitude, 70-90 South, from different atmospheric models*

ROLE OF PLANETARY WAVES, GRAVITY WAVES AND TIDES IN THE DOWNWARD TRANSPORT OF NITROGEN OXIDES DURING ELEVATED STRATOPAUSE EVENTS

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To represent the impact of energetic particle precipitation on the middle and lower atmosphere, a proper account of the downward transport of nitrogen oxides (NOx) produced in the mesosphere-lower thermosphere (MLT) region is needed. The occurrences of stratospheric sudden warmings accompanied by elevated stratopause events (ESEs) strongly modulate the inter-annual variability of the transport from the MLT into the polar stratosphere. During ESEs, the polar stratopause reforms at mesospheric altitudes before being brought down to its climatological position by a mean meridional circulation driven by planetary and gravity waves *(Limpasuvan et al., 2016)*. The latter descent can strongly enhance polar stratospheric NOx abundances.

We use the NCAR whole-atmosphere chemistry-climate model WACCM with nudged dynamics to examine dynamical processes during ESEs, with a particular focus on the event of January 2013, including the behavior of planetary waves, gravity waves and tides. We analyse the modelled transport of NO and the model defficiencies in quantitatively reproducing the very large NO descent observed by the SMR instrument aboard the Odin satellite. A brief reversal of the mean meridional circulation strongly affecting the transport in the MLT, and an enhancement of the semi-diurnal tide also follow the ESE onset. We further examine the impacts of enhancing eddy diffusion and of the tidal forcing. Ground-based meteor radar observations in Trondheim (64N) provide further insight on the behavior of tides and gravity waves during the event.

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Correspondence of evolution of EEP with auroral-patch morphological changes at the substorm recovery phase

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It is well known that visible auroral activity is well developed in association with the geomagnetic substorm. There are three stages in the substorm progress: growth, expansion, and recovery phases. The most intense aurora usually appears around local midnight coinciding with the substorm onset, which corresponds to a stage change from the growth to the expansion phases. With progressing toward the recovery phase, the emission intensity tends to be weaken, pulsating and forming the aurora into patches.

Aurora is a representative polar phenomenon of atmospheric emission, which is resulted from excitation by magnetospheric-origin precipitating particles (mainly electrons). Since typical aurora emits at altitudes of 100-300 km, it is considered that electrons in energy range from 100eV to 10keV largely contribute to the visible auroral activity according to the stopping height theory. These electrons also ionize the atmosphere coinciding with the emission. The electron-density increase at 100-300 km height is thus a typical feature, in particular at substorm onset and expansion phase.

Some cases of the recovery phase associate enhancements of the electron density at lower heights such as 70-90 km. This suggests precence of more energetic electron precipitations (EEP). Based on the previous studies of the substorm recovery phase, the auroral morphological changes and EEP are regarded as representative attitudes. However, it has not been well studied about the relationship between the two attitudes, in particular regarding correlation of the appearance. Then we analyzed data from EISCAT radar, KAIRA riometer, collocated cameras and photometer, ground-based magnetometers, particle and plasma-wave detectors on-board satellites, and AARDDVARK. This paper presents two events, and both events reveal that EEP is evolved coinciding with auroral patch formation in the late morning. Measurements of the EISCAT radar show ionization at 65 km height, corresponding to EEP at energy of ~500keV.

Effect of transport and energetic particle precipitation on Northern Hemisphere polar stratospheric odd nitrogen and ozone in January - March 2012

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A strong sudden stratospheric warming (SSW) that took place in early 2012 was accompanied by several medium scale solar proton events (SPEs). We use a chemistry transport model (CTM) in order to assess the relative contributions of indirect (intensified downward transport of odd nitrogen) and direct (in-situ production of NO_x by protons) effects on the stratospheric NO_x ozone in the Northern polar cap area during January-March 2012. The CTM is constrained by an upper boundary condition for reactive nitrogen (NO_y) species, based on satellite observations from Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on board Envisat, and includes a new parameterization of the SPE-caused effects on NO_y and odd hydrogen (HO_x) species. The results show that the amount of NO_x increased due to both, transport and in-situ production, but more pronounced stratospheric impact was caused by the intensified downward transport of NO_x after the mid-January SSW. The model results indicate NO_x enhancements of up to 3300 % (<48 ppbv) just below the stratopause level (around 50 km), and even up to 120 % (5 ppbv) as low as 38 km altitude. The SPEs increase NO_x by up to 820-1200 % (14-21 ppbv) at the same stratospheric altitudes. The effect on the stratospheric ozone is larger following the downward transport of NO_x, than during and after the SPEs. The model predicts ozone losses of up to 17 % and 9 % at around 40 km due to transport and SPE effects, respectively. The results emphasise the importance of both middle atmosphere dynamics and the geomagnetic activity on the chemical composition of the stratosphere, possibly propagating further down into the troposphere.

Whole atmosphere impacts by auroral EEP

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The effects of auroral (< 30 keV) energetic electron precipitation (EEP) on tropospheric and surface climate remain poorly understood. This is largely due to the short observational record, and missing parameterizations of EEP forcing in most state-of-the-art climate models. Here we examine the long-term atmospheric and surface impacts of EEP forcing, by comparing a set of simulations from the Whole Atmosphere Community Climate Model. This study improves upon past work by only changing auroral EEP between simulations, coupling with an interactive ocean model, and using long (300 year) model integrations. Results show 6% decreases in southern hemisphere upper stratospheric (~40 km) ozone caused by EEP-induced NO_x. No significant changes are seen in northern hemisphere stratospheric ozone. As a consequence, temperature and wind changes in the stratosphere are small and/or not significant. Surface temperature changes over selected periods of the simulations are consistent with previous modeling studies. However, it is shown that these results are not robust over a 300 year period. Lack of an EEP caused signal at the surface is attributed to internal model variability. This work suggests that there are no robust impacts on surface climate caused by auroral EEP. In contrast, there is a significant response found in the stratosphere and above. Effects on surface climate from other sources of energetic particle precipitation outside auroral EEP are not examined in this study. Given large internal variability, any surface signals from EPP will be difficult to attribute until mechanisms tying together polar stratosphere-troposphere coupling by upper stratospheric ozone loss are identified.

Energetic particle precipitation effects as observed by the Odin/SMR instrument

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The Sub-Millimeter Radiometer (SMR) on board the Odin platform, launched in 2001, is a limb emission sounder measuring trace gases in the stratosphere, mesosphere, and lower thermosphere. Odin is a Swedish-led satellite project funded jointly by Sweden (SNSB), Canada (CSA), Finland (TEKES), and France (CNES), with support by the 3rd party mission programme of the European Space Agency (ESA).

Energetic Particle Precipitation (EPP) refers to the process by which energetic protons and electrons affect the Earth's middle atmosphere. This is an important solar-terrestrial coupling mechanism.

In a first step, we will present the SMR products that can contribute to a better understanding of the effects of EPP on the atmosphere. Nitric oxide (NO), which is produced by EPP in the high latitude mesosphere / lower thermosphere (MLT), is retrieved from the measurement of its thermal emission line at 551.7 GHz. Water vapour (H_2O), which is a good tracer species in the middle atmosphere, and temperature can also be retrieved at 557 GHz. These data sets are available over a long period of time, covering more than a solar cycle. The recent improvements of the SMR products will be presented. The full reprocessing of the data sets is in progress, as part of an ESA project. Carbon monoxide (CO), which is a very good tracer for transport processes in the middle atmosphere as well, could not been retrieved up to now because of an instrumental failure that affected the corresponding frequency mode at the beginning of the mission. An algorithm is currently being developed, in order to fix this problem and make this data set available.

In a second step, we will show how these data sets have already been used to study the effects of EPP on the atmosphere. The evolution of NO and H_2O volume mixing ratio, as well as temperature, in the middle atmosphere during each Arctic winter from 2003 to 2016 shows that the downward transport of NO from the MLT to the stratrosphere (EPP indirect effect – EPP-IE) is strongly dependent on dynamical activity. A detailed comparison with the Whole Atmosphere Community Climate Model with Specified Dynamics (WACCM-SD) has been performed, focusing on the Arctic winter 2012/2013, when a high amount of NO has been transported down to the stratosphere according to SMR observations. The goal is to investigate why the EPP-IE is not well reproduced by the model. In addition, an empirical model of NO in the upper mesosphere and lower thermosphere is being developped, based on the empirical orthogonal function analysis of 12 years of NO measurements by SMR. This model will help us to better understand how the NO production varies with solar activity, and could be used as an input for global chemistry climate models to better reproduce the effects of EPP.

Is there a solar signal in lower stratospheric water vapor?

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A merged time series of stratospheric water vapor built from the Halogen Occultation Instrument (HALOE) and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) data between 60° S and 60° N and 15 to 30 km and covering the years 1992 to 2012 was analyzed by multivariate linear regression, including an 11-year solar cycle proxy. Lower stratospheric water vapor was found to reveal a phase-shifted anti-correlation with the solar cycle, with lowest water vapor after solar maximum. The phase shift is composed of an inherent constant time lag of about 2 years and a second component following the stratospheric age of air. The amplitudes of the water vapor response are largest close to the tropical tropopause (up to 0.35 ppmv) and decrease with altitude and latitude. Including the solar cycle proxy in the regression results in linear trends of water vapor being negative over the full altitude/latitude range, while without the solar proxy, positive water vapor trends in the lower stratosphere were found. We conclude from these results that a solar signal seems to be generated at the tropical tropopause which is most likely imprinted on the stratospheric water vapor abundances and transported to higher altitudes and latitudes via the Brewer–Dobson circulation. Hence it is concluded that the tropical tropopause temperature at the final dehydration point of air may also be governed to some degree by the solar cycle. The negative water vapor trends obtained when considering the solar cycle impact on water vapor abundances can possibly solve the "water vapor conundrum" of increasing stratospheric water vapor abundances despite constant or even decreasing tropopause temperatures.

NO produced by energetic electron precipitation during a geomagnetic storm in April 2010

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In April 2010 an energetic electron precipitation (EEP) event occurred. A coronal mass ejection (CME) caused the Dst-index to reach -80nT, followed by solar wind speeds of over 600 km/s lasting for three days. Electron fluxes measured by the NOAA POES satellites were increased by an order of magnitude and stayed elevated for three days. We investigate the atmospheric nitric oxide (NO) response to these incoming energetic electrons. By combining the low and medium energy electron fluxes from the Total Energy Detector (TED) and Medium Energy Proton and Electron Detector (MEPED) on the NOAA POES satellites we get a continuous energy spectrum ranging from 1-1000 keV, which corresponds to atmospheric altitudes of 60-150 km. The multiple NOAA satellites enables us to construct global maps of the precipitating electrons. The energy spectra of the incoming electron fluxes are compared to NO measurements from The Solar Occultation for Ice Experiment (SOFIE) on board the Aeronomy of Ice in the Mesosphere (AIM) satellite. The correlation between the incoming electrons and the increase of NO is strongly affected by NO's long lifetime when not exposed to sunlight. The EEP produced NO is not restrained to the region it is being produced. It will be transported both horizontally and vertically by background winds and waves. Winds from Whole Atmosphere Community Climate Model (WACCM) and the empirical Horizontal Wind Model (HWM07) are therefore used to take into account the horizontal transport of NO in order to understand the total direct impact of the incoming electrons.

Sensitivity of tropical stratospheric ozone to rotational UV variations at different time scales: observations vs model

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Solar spectral irradiance fluctuations associated with the Sun's 27-day rotational cycle can significantly modulate the ozone concentration in the upper tropical stratosphere. The magnitude of this ozone solar rotational signal exhibits large temporal variations, however. While the signal is well identified during periods of high solar activity (e.g. maximum phase of the 11-year solar cycle), it remains unclear to what extent the solar rotational signal can be estimated during periods of low solar activity and which time interval is required for an accurate estimation.

In the present study, we examine the sensitivity of the stratospheric ozone response to the Sun's 27-day rotational cycle using MLS satellite observations and numerical simulations performed with the LMDz-Reprobus chemistry-climate model. LMDz-Reprobus was used either (i) in its nudged configuration where transport and dynamics are forced with temperature and wind fields from ERA-Interim reanalysis (i.e. CTM configuration) or (ii) in its free-running model configuration (i.e. CCM configuration). While the CTM configuration allows focusing on the photochemical processes, the CCM one allows accounting for all the interactions between chemistry, dynamics and radiation. In the CCM configuration, we performed an ensemble of 5 simulations of 17 years (from 1991 to 2007).

We first analyze two 3-year periods corresponding to the declining phases of solar cycle 22 (10/1991-09/1994) and solar cycle 23 (09/2004-08/2007). While both observations and CTM results are consistent, they reveal that the tropical stratospheric ozone response to short-term UV variations markedly differs between the two periods, i.e. the rotational ozone signal is overall less well identified for the solar cycle 23. This is confirmed when examining the CCM results, showing a large spread between the different ensemble members, suggesting that the strong temporal variability in the rotational ozone signal is strongly influenced by non-solar dynamical variability.

We then used the CCM simulations ensemble to investigate the influence of (i) the level of the solar activity and (ii) the size of the time-window on the retrieved ozone rotational signal sensitivity (defined as the percentage change in ozone for 1% change in solar UV flux). The mean sensitivity profile is found to be rather independent to the level of solar activity but the sensitivity dispersion seems to be generally lower during high solar activity periods. Moreover, it is shown that the robustness of the solar rotational ozone signal retrieval is degraded when the UV forcing variance is low and inversely. We further show that the errors in the estimation of the solar rotational ozone sensitivity strongly depend not only on the level of solar rotational activity, but also on the size of the time-window. Not surprisingly, the most accurate estimation of the ozone rotational signal sensitivity is derived for the longest time-window (here 15 years).

Modeled response of mesospheric ozone to a pulsating aurora event on 17 November 2012

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Energetic particle precipitation into the upper atmosphere is known to create excess amounts of odd nitrogen and hydrogen. These in turn destroy mesospheric and upper stratospheric ozone in catalytic reaction chains, either in situ at the altitude of energy deposition, or indirectly due to transport to other altitudes and latitudes in the case of odd nitrogen, which has a long life-time in the absence of sunlight. Recent statistical analysis of satellite data on mesospheric ozone reveals that the variations during energetic electron precipitation from Earth's radiation belts can be tens of percent. Here we report evidence of ozone destruction due to a single event of pulsating aurora early in the morning local time on 17 November 2012. The presence of high energy component in the precipitating electron flux was detected as low-altitude ionization seen by the EISCAT VHF radar in Tromsø, Norway. Simultaneous observations by Van Allen probes satellite B show occurrence of rising tone lower band chorus waves, causing the precipitation in pulsating aurora. We model the effect of high-energy electron precipitation on ozone concentration using a detailed coupled neutral and ion-chemistry model. Due to a 30 minutes lasting recorded electron precipitation event we find 14 percent odd oxygen depletion at 75 km altitude. In general, for pulsating aurora events, we find depletions in the scale of tens of percent, depending on the precipitation characteristics used in modeling. The effect is notably maximized at the sunset time following the occurrence of the precipitation.

Enhancement of odd nitrogen modifies mesospheric ozone chemistry during polar winter

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Energetic particle precipitation (EPP) enhances odd nitrogen (NO_x) in the polar upper atmosphere. Model studies have reported a solar cycle response in mesospheric ozone (O_3) caused by EPP-related NO_x enhancements which are included by applying a vertical NO_x flux at around 80 km. However, it is not clear how O_3 can be affected when the main chemical catalyst of odd oxygen (O_x = O + $O(^1D)$ + O_3) loss in the mesosphere is odd hydrogen (HO_x). Here we use a 1-D atmospheric model and show how enhanced NO_x affects mesospheric chemistry and changes HO_x partitioning, which subsequently leads to increase in O_x loss through standard HO_x-driven catalytic cycles. Another, smaller increase of O_x loss results from HO_x storage in HNO_3 during night, and its release by daytime photodissociation. Our results suggest that EPP, through NO_x enhancements, could have a longer-term effect on mesospheric HO_x and O_x in polar winter.

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Contribution of proton and electron precipitation to the observed electron concentration in October-November 2003 and September 2005

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Understanding the altitude distribution of particle precipitation forcing is vital for the assessment of its atmospheric and climate impacts. However, the proportion of electron and proton forcing around the mesopause region during solar proton events is not always clear due to uncertainties in satellite-based flux observations. Here we use electron concentration observations of the European Incoherent Scatter Scientific Association (EISCAT) incoherent scatter radars located at Tromsø (69.58°N, 19.23°E) to investigate the contribution of proton and electron precipitation to the changes taking place during two solar proton events. The EISCAT measurements are compared to the results from the Sodankylä Ion and Neutral Chemistry Model (SIC). The proton ionization rates are calculated by two different methods, a simple energy deposition calculation and the Atmospheric Ionization Model Osnabrück (AIMOS v1.2), the latter providing also the electron ionization rates. Our results show that in general the combination of AIMOS and SIC is able to reproduce the observed electron concentration within ±50% when both electron and proton forcing is included. Electron contribution is dominant above 90 km, and can contribute significantly also in the upper mesosphere especially during low or moderate proton forcing. In the case of strong proton forcing, the AIMOS electron ionization rates seem to suffer from proton contamination of satellite-based flux data. This leads to overestimation of modelled electron concentrations by up to 90% between 75–90 km and up to 100–150% at 70–75 km. Above 90 km, the model bias varies significantly between the events. Although we cannot completely rule out EISCAT data issues, the difference is most likely a result of the spatio-temporal fine structure of electron precipitation during individual events that cannot be fully captured by sparse in-situ flux (point) measurements, nor by the statistical AIMOS model which is based upon these observations.

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The Impact of Energetic Electron Precipitation on Mesospheric Hydroxyl during a Year of Solar Minimum

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In 2008 a sequence of geomagnetic storms occurred triggered by high speed solar wind streams from coronal holes. Improved estimates of precipitating fluxes of energetic electrons are derived from measurements on board the NOAA/POES-18 satellite using a new analysis technique. These fluxes are used to quantify the direct impact of Energetic Electron Precipitation (EEP) during solar minimum on middle atmospheric hydroxyl (OH) measured form the Aura satellite. During winter, localized longitudinal density enhancements in the OH are observed over North Russia and North America at corrected geomagnetic latitudes poleward of +/-55^{o}. Although the North Russia OH enhancement is closely associated with increased EEP at these longitudes, the strength and location of the North America enhancement appear to be unrelated to EEP. This OH density enhancement is likely due to vertical motion induced by atmospheric wave dynamics that transports air rich in atomic oxygen and atomic hydrogen downward into the middle atmosphere, where it plays a role in the formation of OH. In the southern hemisphere, localized enhancements of the OH density over West Antarctica can be explained by a combination of enhanced EEP due to the local minimum in Earth's magnetic field strength, and atmospheric dynamics. Our findings suggest that even during solar minimum, there is substantial EEP driven OH production. However, to quantify this effect, a detailed knowledge of where and when the precipitation occurs is required in the context of the background atmospheric dynamics.

3 Solar and particle effects on the troposphere and climate system incl. atmosphere and ocean-atmosphere coupling

Long-term atmospheric effects of medium-energy electron precipitation from chemistry-climate modelling

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Medium energy electrons (MEE, 30-1000 keV) from the Earth's outer radiation belt continuously affects the chemical composition of the mesosphere in the polar regions. In particular, ionisation caused by MEE precipitation leads to the production of odd hydrogen and odd nitrogen species that affects ozone chemistry. By absorbing a great part of UV radiation, ozone plays an important role in the energy budget and dynamics of the middle atmosphere. However, understanding the long term effects from MEE and its potential role in the polar climate variability is a difficult task due to the limitations of the satellite measurements. Here we use the Whole Atmosphere Community Climate Model (WACCM) together with MEE flux characterised using a precipitation model driven by the magnetic Ap index to simulate the effects of MEE on the solar cycles time scale. We will present preliminary results from free running simulations for the period of time 1955-2005. We will contrast our results with those from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) in order to assess the role of MEE and its significance to the atmospheric dynamics and climate variability in the polar regions.

Sub-seasonal influence of the solar cycle on the winter NAO

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Observational analysis of the 11-year solar cycle influence on winter North Atlantic surface pressure patterns reveals a peak NAO-like Azores response at lags of 3-4 years (Gray et al., 2013). It has been shown that absorption of solar UV radiation by ozone in the equatorial upper stratosphere can lead to changes in the Arctic Oscillation through a top-down mechanism involving wave-mean-flow interaction (Kodera & Kuroda, 2002, Ineson et al., 2011). This mechanism operates on seasonal timescales but is unable to explain the observed multi-year lagged response in the North Atlantic mean sea level pressure (MSLP). To explain the lag Scaife et al. (2013) proposed that the solar cycle signals could be sequestered within the upper layers of the North Atlantic Ocean, allowing signals to persist from one winter to the next. This seasonal re-emergence mechanism has been demonstrated in contexts unrelated to solar variability (Taws et al., 2011). Using model simulations we demonstrate that ocean feedbacks can provide an explanation for the observed lagged response of the NAO to the solar cycle (Andrews et al., 2015).

Furthermore, analysis of the observed response of North Atlantic MSLP to the solar cycle shows that calculating averages over the December-January-February period masks differences between early- and late-winter responses (Gray et al., 2016, in press). Here we show that the simulated response to the solar cycle also possesses sub-seasonal variations. The early-winter response lags the solar cycle by several years, but the late-winter response shows greater sychronisation with the solar cycle. This finding is further evidence for the seasonal re-emergence mechanism playing a key role in determining the solar cycle response in North Atlantic climate.

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Reduction of climate sensitivity to solar forcing due to stratospheric ozone feedback

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An accurate assessment of the role of solar variability is a key step towards a proper quantification of natural and anthropogenic climate change. To this end, climate models have been extensively used to quantify the solar contribution to climate variability. However, owing to its large computational cost, the bulk of modeling studies to date have been performed without interactive stratospheric photochemistry: the impact of this simplification on the modeled climate system response to solar forcing remains largely unknown. Here we quantify this impact, by comparing the response of two model configurations, with and without interactive ozone chemistry. Using fully coupled long integrations, we first obtain robust surface temperature and precipitation responses to an idealized irradiance increase. Then, we show that the inclusion of interactive stratospheric chemistry significantly reduces the surface warming (by about one third) and the accompanying precipitation response. This behavior is linked to photochemically-induced stratospheric ozone changes, and their modulation of the surface solar radiation. Our results suggest that neglecting stratospheric photochemistry leads to a sizable overestimate of the surface response to changes in solar irradiance. This has implications for simulations of the climate in the Last Millennium and geoengineering applications employing irradiance changes larger than those observed over the 11-year sunspot cycle, where models often use simplified treatments of stratospheric ozone that are inconsistent with the imposed solar forcing.

Nitrate ion spikes in ice cores not suitable as proxies for solar proton events

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Nitrate ion spikes in polar ice cores are contentiously used to estimate the intensity, frequency, and probability of historical solar proton events. We use the Whole Atmosphere Community Climate Model to calculate how large an event would have to be to produce enough odd nitrogen throughout the atmosphere to be discernible as nitrate peaks at the Earth's surface. These hypothetically large events are compared with probability of occurrence estimates derived from measured events, sunspot records, and cosmogenic radionuclide archives. We conclude that the fluence and spectrum of solar proton events necessary to produce odd nitrogen enhancements equivalent to the spikes of nitrate ions in Greenland ice cores are unlikely to have occurred throughout the Holocene, confirming that nitrate ions in ice cores are not suitable proxies for historical individual solar proton events.

Downward Wave Reflection as An Additional Mechanism for the Troposphere Response to the 11-year Solar Cycle

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Using ERA-Interim reanalysis data from 1979-2014, we examine the seasonal evolution of the zonal mean flow, the meridional gradient of potential vorticity (PV), the Eliassen-Palm (E-P) fluxes and E-P flux divergence and the associated 11-year solar cycle modulation of northern winter. We analyze the extent to which the anomalies detected from these dynamical quantities may lead to a modification of the zonal mean circulation and wave coupling between the stratosphere and the troposphere via downward wave reflection. Special attentions is paid to the corresponding changes in tropospheric circulation especially those related to the North Atlantic Oscillation (NAO). We show that, in early winter during high solar activity years, a strengthening of the westerlies in the subtropical upper stratosphere leads to enhanced divergence of planetary wave activity at mid-latitudes. Upward propagating planetary waves are deflected poleward, causing enhanced wave breaking in the high-latitude lower mesosphere and upper stratosphere. A reflecting surface is consequently formed in the high-latitude upper stratosphere, leading to enhanced downward wave reflection. The combined effect of downward wave reflection at high-latitudes and development of a dipole pattern in synoptic wave anomalies in the extratropical mid- to upper troposphere leads to a poleward shift of the eddy-driven jet and a positive NAO in mid- to late winter. These results suggest that downward wave reflection may act as an additional 'top-down' pathway by which the effect of solar ultraviolet (UV) radiation in the upper stratosphere is transmitted downward directly from the upper stratosphere to the troposphere.

QBO-dependent relation of geomagnetic activity and northern annular mode during the 20th century

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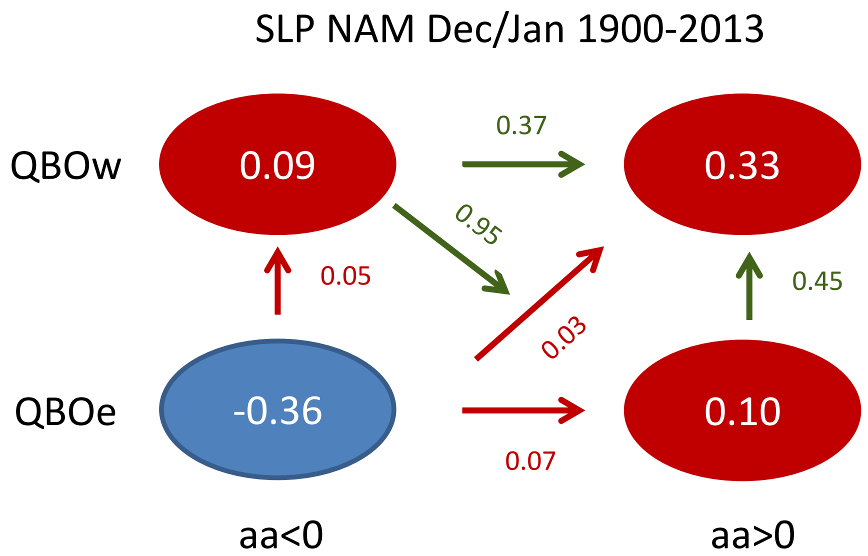
Mutually conflicting results have been presented in earlier studies on the long-term relation of geomagnetic activity (GA) and the winter northern annular mode (NAM) and its modulation by quasi-biennial oscillation (QBO). Some studies have found a stronger positive relation in the easterly phase of the QBO, while in other studies a stronger positive relation was found in the westerly phase of the QBO. Using QBO reconstruction from the beginning of the 20th century we find that the QBO modulation of the GA-NAM relation is temporally variable, which explains the earlier, seemingly differing results. Positive relation is found to be valid in the easterly QBO phase at 30 hPa for the whole 20th century. We also find that the QBO at 30 hPa better represents the Holton-Tan relation for the surface circulation, and that the Holton-Tan relation is only observed during early/mid winter, while an anti-Holton-Tan relation is found in the late winter for strong geomagnetic activity. These results emphasize the systematic response of NAM to particle precipitation during the entire 20th century, and underline the importance of considering the preconditioning of the atmosphere when studying the solar-related effects upon climate.



Solar Forcing for CMIP6

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We describe the recently generated solar forcing dataset for CMIP6 and highlight in particular changes with respect to the CMIP5 recommendation. The solar forcing is provided for radiative properties, i.e., total solar irradiance (TSI) and solar spectral irradiance (SSI), and F10.7cm radio flux, as well as particle forcing, i.e., geomagnetic indices Ap and Kp, and ionisation rates to account for effects of solar protons, electrons and galactic cosmic rays. This is the first time that a recommendation for solar-driven particle forcing is provided for a CMIP exercise. The solar forcing dataset is provided at daily and monthly resolution separately for the CMIP6 Historical Simulation (1850–2014), for the future (2015–2300), including an additional extreme Maunder Minimum-like sensitivity scenario, as well as for a constant and a time-varying forcing for the preindustrial control simulation. This paper provides an overview on the forcing dataset and how it was created, and discusses implications for climate modeling.

Climate Effect of a Mesospheric Ozone Loss due to Energetic Particle Precipitation

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Energetic particle precipitation (EPP) frequently produces nitrogen oxides and hydrogen oxides in the polar middle atmosphere. Both components deplete ozone in the polar stratosphere and mesosphere, which in turn influences the radiative balance of the middle atmosphere and subsequently the strength of the polar vortex. Recently, *Anderson et al. (2014)* showed that mesospheric ozone is reduced up to 34% between EPP maximum and EPP minimum due to hydrogen oxides induced by EPP. Those large changes raise the question of a potential impact of energetic particles on the tropospheric climate. While several studies have analyzed the potential impact of a stratospheric ozone loss on the tropospheric climate (e.g., *Seppälä et al., 2009*), the influence of mesospheric ozone loss has not yet been investigated.

Here, we analyze the influence of a polar mesospheric ozone loss on the climate in the coupled climate model MPI-ESM1. To rule out potential additional forcings, we perform two experiments where all boundary conditions except mesospheric ozone are identical and constant in time. First, we will discuss the influence of an idealized mesospheric ozone loss on the middle atmospheric dynamics and then the potential impact on the surface temperature in the Northern Hemisphere.

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Comparing the influence of sunspot activity and geomagnetic activity on winter surface climate

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We compare here the effect of geomagnetic activity (using the aa index) and sunspot activity on surface climate using sea level pressure dataset from Hadley centre during northern winter. Previous studies using the multiple linear regression method have been limited to using sunspots as a solar activity predictor. Sunspots and total solar irradiance indicate a robust positive influence around the Aleutian Low. This is valid up to a lag of one year. However, geomagnetic activity yields a positive NAM pattern at high to polar latitudes and a positive signal around Azores High pressure region. Interestingly, while there is a positive signal around Azores High for a 2-year lag in sunspots, the strongest signal in this region is found for aa index at 1-year lag. There is also a weak but significant negative signature present around central Pacific for both sunspots and aa index. The combined influence of geomagnetic activity and Quasi Biannual Oscillation (QBO 30 hPa) produces a particularly strong response at mid to polar latitudes, much stronger than the combined influence of sunspots and QBO, which was mostly studied in previous studies so far. This signal is robust and insensitive to the selected time period during the last century. Our results provide a useful way for improving the prediction of winter weather at middle to high latitudes of the northern hemisphere.

Solar influence on North Atlantic climate

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Quasi-decadal variability in solar irradiance has been suggested to have substantial effects on Earth's climate at regional scales. In the North Atlantic sector, the 11-year solar signal has been proposed to project onto a pattern resembling the Arctic Oscillation/North Atlantic Oscillation which maximizes by a lag of a few years due to ocean-atmosphere coupling processes. This relationship has however not yet been univocally supported by climate model simulations with realistic observed forcings. Its detection is further complicated since quasi-decadal fluctuations of the North Atlantic Oscillation can be intrinsically generated by the coupled ocean-atmosphere system.

In a recent study, we compared two fully coupled multi-decadal ocean-atmosphere chemistry-climate simulations which either included or suppressed solar forcing variability. While the North Atlantic Oscillation index displayed a quasi-decadal variability mode in both experiments, the one including the 11-year solar cycle showed a statistically significant solar/North Atlantic Oscillation index coherency lagged by 1-2 years. Atmospheric dynamical investigations further suggested that the 11-year solar cycle synchronizes the internally generated quasi-decadal North Atlantic Oscillation variability through the downward propagation of the solar signal from the upper stratosphere to the troposphere – or "top-down" mechanism.

I will further discuss the North Atlantic solar signal projection mechanisms in light of recent results derived from historical climate reconstruction and climate model numerical simulations.

Tests of a parameterization for auroral forcing in the CCM EMAC for CMIP6 simulations

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Energetic Particle Precipitation (EPP) is well known as a source of NOx in the middle atmosphere. Due to the quite long photochemical lifetime of NOx in the polarnight middle atmosphere transport effects have to be considered. Therefore NOx produced by EPP in the lower thermosphere can be transported downwards into the stratosphere where it contributes to the destruction of polar ozone. This process is also called the EPP indirect effect. Because of radiation feedbacks and stratosphere-troposphere interaction this effect can alter tropospheric climate. Here we show results for the recommendation for the implementation of this effect in chemistry-climate-models (CCM) for CMIP6 simulations.

Most of the used models in CMIP6 do not include the source region of NOx. Therefore the EPP indirect effect needs to be considered as an NOx upper boundary condition. Here, we use a parametrization in terms of Ap which is based on MIPAS observations. We show how to best implement the parameterization in models and how to avoid some general pitfalls. The effects in the used model EMAC (model top at 1 Pa) are compared to observations, generally showing a good agreement.

4 Tools for assessing solar and particle influences, incl. measurements, models, and techniques

Constraining solar irradiance changes using ozone: uncertainties and limitations

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The magnitude of ultraviolet flux changes over the solar cycle is uncertain, despite decades of observations from multiple instruments. Solar flux changes directly impact chemical concentrations and temperatures in the stratosphere. Stratospheric ozone has also been observed for multiple decades, and shows a clear solar cycle signal. Through our current understanding of how ozone concentration depends on solar ultraviolet irradiance, especially over the tropics, it is possible to constrain the solar irradiance variability using ozone observations.

However, there are large uncertainties that remain in such an approach, one of which depends strongly on the ozone data itself. We make comparisons of recently available ozone composites, discuss where they disagree, how difference may be accounted for, and consider the impact on the extraction of the solar cycle magnitude that results from the different ozone datasets. We report our findings and show what ozone can currently tell us about solar cycle irradiance changes.

Another Approach to Stratospheric–Mesospheric Exchange: The Direct Inversion of the Continuity Equation

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Solar terrestrial coupling via particle precipitation in the mesosphere and above and subsequent subsidence of this processed air into the stratosphere usually outweighs the direct solar particle impact in the stratosphere. Thus a thorough understanding and quantification of these mesospheric intrusions is essential. Traditionally, these subsidence processes are analyzed via the analysis of inert tracers, which allow determination of mesospheric–startospheric fluxes. To obtain a more detailed picture of mesospheric–stratospheric interaction, we propose to directly invert the two-dimensional continuity equation to obtain from global tracer measurements information on the advection vectors and mixing coefficients. This is, besides sequential or variational data assimilation or inverse modelling of sources, another independent category of inverse techniques. We have applied this method to global two-dimensional tracers fields measured by MIPAS. The resulting two-dimensional field of advection vectors has a spatial sampling of 4° in latitude and 5 km in altitude, and the time resolution of the current tests is one month. Results reproduce the expected atmospheric features like major warmings, overturning mesospheric circulation, mesospheric intrusions, the tropical pipe as well as the upper and lower branch of the Brewer-Dobson circulation. Furthermore, the results are roughly consistent with measurements of the mean age of stratospheric air, which all gives confidence in this novel method. We propose to use resulting advection vectors and mixing coefficients to diagnose atmospheric processes in a more detailed manner than it was possible with the conventional empirical methods. Both the method and results will be presented.

Measurements of Solar Irradiance – How the future TSIS-1 mission will extend current understanding of solar irradiance variability

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The Total and Spectral solar Irradiance Sensor (TSIS) is scheduled for launch to the International Space Station in August 2017. The overall goal of TSIS is the measurement of total solar irradiance (TSI) and solar spectral irradiance (SSI). The TSIS observations are the follow on to the instruments of the Solar Radiation and Climate Experiment (SORCE) and the TSI Calibration Transfer Experiment (TCTE) -that are currently carrying the record of TSI and SSI since 2003- with higher accuracy, increased precision, and improved stability. The improvements in accuracy, precision, and stability (i.e. the measurement requirements) are driven by the need to improve our understanding of Earth's climate response to solar variability, for separating natural from anthropogenic climate forcing effects, and for the proper monitoring and interpretation of the variability in spectrally dependent radiative processes induced by changes in Earth's surface and atmosphere.

Observing small signals of long-term global climate change places very specific requirements on satellite observing systems. For solar irradiance, variations of less than 0.1% per decade are typical. The TSIS TIM and SIM instruments have been designed and built with the requirements needed to detect possible long-term solar variability in mind. In this talk, I will focus on presenting the instrument design changes and pre-launch calibration approach that result in the improvements in accuracy and precision with respect to SORCE. I will also discuss the anticipated role of the future TSIS observations for constraining the Naval Research Laboratory solar variability model that is used to estimate past and future solar irradiance over multiple 11-year solar cycles in Earth climate studies.

A model providing long-term datasets of energetic electron precipitation during geomagnetic storms

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The influence of solar variability on the polar atmosphere and climate due to energetic electron precipitation (EEP) has remained an open question, largely due to lack of a long-term EEP forcing dataset that could be used in chemistry-climate models. Motivated by this we have developed a model for 30–1000 keV radiation belt driven EEP. The model is based on precipitation data from low-Earth orbiting satellites POES in the period 2002-2012, and empirically described plasmasphere structure, which are both scaled to a geomagnetic index which is either Dst or Ap. Because this geomagnetic index is the only input of the model, the model can be used to calculate the energy-flux spectrum of precipitating electrons over long periods with a time resolution of 1 day.

Results from the model compare well with EEP observations over the period of 2002–2012. Using the model avoids the challenges found in measured datasets concerning proton contamination and quiet-time noise floor. The model results can be used to produce the first ever long-term atmospheric ionization rate dataset for radiation belt EEP. The ionization rate dataset, which primarily describe the effect of precipitation at the altitude region between 60-110 km, will enable simulations of EEP impacts on the atmosphere and climate with realistic EEP variability. Still, due to limitations in this first version of the model, the results most likely still represent an underestimation of the total EEP ionization effect. Fig. 1 shows a comparison between the measured electron precipitation flux and the modelled one as a function of L-shell value (equivalent to a geomagnetic latitude) and Ap.

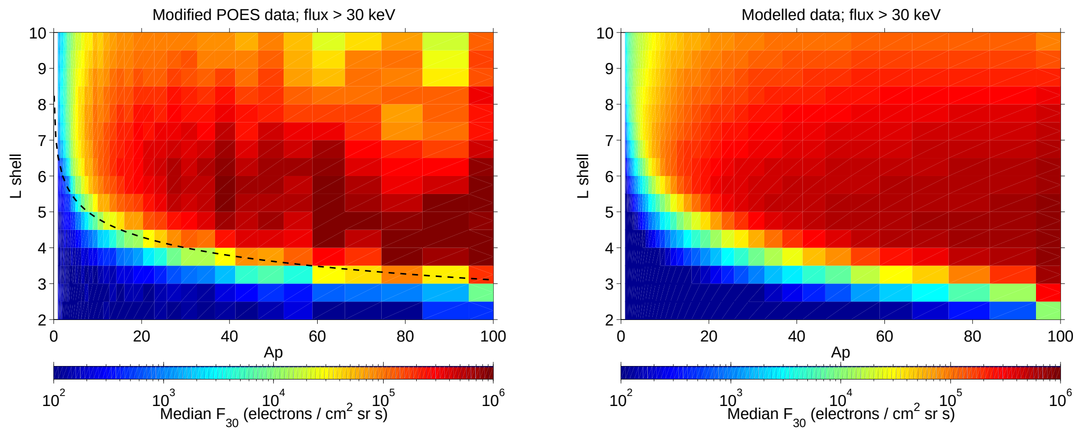

Figure 1: *Left: the median measured electron flux as a function of L-shell value and Ap-index. Right: the modelled electron flux for the same parameters.*

Lower mesospheric ionisation effect on the cosmic radio noise absorption spectrum

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Radio wave absorption taking place in the collisional plasma of the D-region ionosphere makes it possible to estimate the electron content, and hence the EPP (or solar X-ray) flux, by observing the cosmic radio noise absorption (CNA). In contrast to the traditional riometers observing the CNA at a single frequency, the novel so-called spectral riometers measure a wide band of the CNA spectrum (e.g., between 20–80 MHz) with a high frequency resolution. The main advantage of this approach is to have a better control over radio interferences and instrument+ground noise contributions, both causing biases to the CNA estimation. Moreover, a significant ionisation in the lower mesosphere (circa 60 km and below) can have an effect not only on the magnitude of the CNA but also on its spectral shape. This may provide extra information on the solar protons, relativistic electrons and X-ray irradiance. In this presentation, potential signatures of the spectral shape changes due to EPP events and solar flares are presented from the KAIRA radio telescope data.

Empirical model of nitric oxide in the upper mesosphere and lower thermosphere based on 12 years of Odin-SMR measurements

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Nitric oxide (NO) is produced by energetic particle precipitation (EPP) and soft solar X-rays in the lower thermosphere. NO is transported down to lower atmospheric regions during polar winter, where it can interact with ozone. A reliable model for the amount of thermospheric NO is needed as an input for chemistry climate models (the Whole Atmosphere Community Climate Model (WACCM) for instance) to accurately reproduce the effects of solar activity variations on climate variability. Such an empirical model was developed by Marsh and Solomon (2004) based on 2.5 years of measurements from the Student Nitric Oxide Explorer (SNOE).

We propose to develop the same kind of empirical model, but based on a much longer data set from the ODIN/Sub-Millimetre Radiometer (SMR), covering more than a solar cycle. The goal is to calculate the amount of NO as a function of altitude, magnetic latitude, and time. The Odin-SMR instrument has been measuring NO emission spectra at 551.7 GHz since 2003. Until 2007, only one measurement day per month was allocated for NO subsequent to which this amount was increased to 4 each month. The measurements range from the mid-stratosphere up to 115 km in tangent altitude and -82.5°S to 82.5°N in latitude. Following in the footsteps of Marsh & Solomon (2004), we use an eigenanalysis technique on daily zonal mean number density of NO to decompose the measured signal for each altitude and magnetic latitude in the lower thermosphere. We use Empirical Orthogonal Functions (EOF) for the decomposition of the time signal and as a result, the daily NO data set is represented as a time mean plus the sum of the orthogonal functions. These EOF's are ordered in descending order according to the amount of variance they capture from the original measurements. We then proceed to link these EOF's to physical processes. We find that the first and most influential EOF is associated with auroral activity, the second EOF varies with solar declination, and the third EOF depends on the varying 10.7 cm solar flux. These findings agree with those of Marsh & Solomon (2004). Finally, based on the links to the physical processes, we construct a model which is based on indices describing the auroral activity, declination, and the 10.7 cm solar flux.

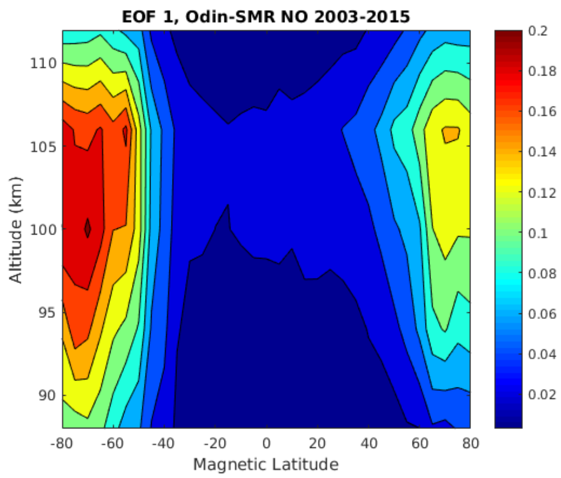

Figure 1: *First EOF from the Odin-SMR dataset.*

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GOMOS measurements of O_3, NO_2 and NO_3 compared to specified-dynamics WACCM simulations

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In this work we show results from a comparison where measurements of the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument are compared with the Whole Atmosphere Community Climate Model (WACCM) from the National Center for Atmospheric Research. The inter-comparison includes O_3, NO_2 and NO_3 vertical profiles and the comparison uses only those profiles from WACCM that are co-located with the GOMOS profiles.

GOMOS on board the European Space Agency's ENVISAT satellite measured 880 000 stellar occultations during 2002–2012. From UV-Visible and IR spectra of the horizontal transmission vertical profiles of O_3, NO_2, NO_3, H_2O, O_2 and aerosol extinction can be retrieved. Measurements cover altitude region from the cloud top up to 150 km. Atmospherically valid data for ozone are obtained generally in 15–100 km with 2–3 km resolution. For nitrogen species the altitude range is 2–50 km with resolution 4 km. In polar latitudes GOMOS NO_2 profiles can extend up to 75 km during elevated NO_2 conditions.

WACCM is a chemistry-climate model spanning the range of altitude from Earth's surface to the thermosphere (approximately 140 km) with 88 vertical levels of variable vertical resolution of 1.1 km in the troposphere to 3.5 km above 65 km. Horizontal resolution is 1.9 deg. in latitude by 2.5 deg. in longitude and the model time step is 30 minutes. In the present analysis version 4 of WACCM was run in 'specified dynamics' mode by constraining dynamical fields to Modern-Era Retrospective Analysis for Research and Applications (MERRA) meteorological reanalyses below 1 hPa.

This work utilizes newly developed WACCM variants with improved description of energetic particle precipitation and its middle atmospheric effects. An example of NO_2 comparison in Arctic is shown in Fig.1.

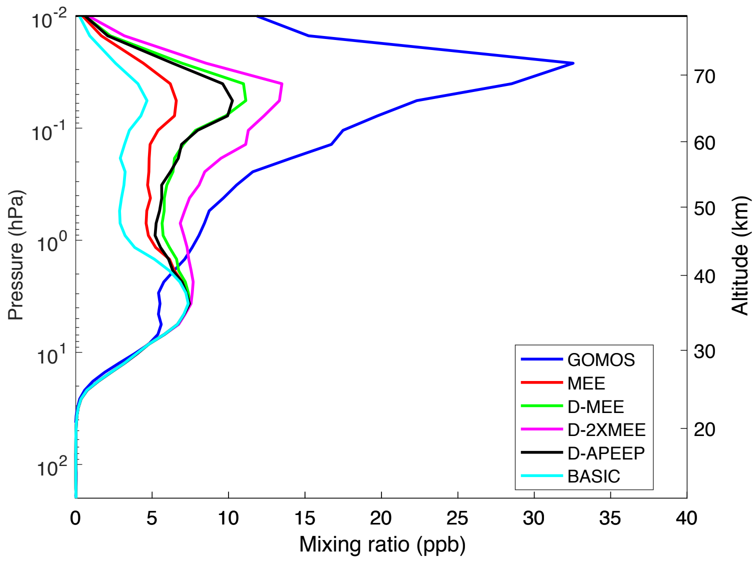

Figure 1: GOMOS NO_2 measurements over Arctic in 2002 compared with several WACCM simulations

Photoionisation characteristics in the polar summer mesosphere inverted from the ESR IPY data

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We investigated photoionisation in the polar summer mesosphere by interpreting the EISCAT Svalbard Radar (ESR, 78.2°N, 16.0°E) data by the Sodankylä Ion and neutral Chemistry model (SIC). The ionisation process expected to be dominant is the Lyman-alpha photoionisation of the nitric-oxide (NO). However, the data showed remarkably stronger diurnal variation between midday and "midnight" (i.e., the largest SZA in the midnight sun season), than any level of NO could reproduce in the model.

We found out that, in addition to NO, also photochemistry of O_2 plays a great role in the ionisation, depending on altitude. To be able to explain the observed electron density quantitatively, taking into account the complexity of the potential ionisation processes, we used the MCMC inversion for the NO and O_2 concentrations and the corresponding spectral lines of the solar flux. This approach reveals the importance of different ionisation sources for the D-region ionosphere and mutual coupling between photochemical processes involved. Preliminary analysis of the method is presented here.

Atmospheric Response to Energetic Electron Precipitation: Ionization, optical emissions, x-rays, and backscatter

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Collisions with the upper atmosphere provide one of the primary loss mechanisms for radiation belt particles; this process is known as energetic particle precipitation or EPP. The physical interaction between these energetic particles and the neutral atmosphere forms a natural example of basic particle physics. This interaction leads to effects that can be used as diagnostics of the interaction; these include i) secondary ionization, ii) excitation of optical emissions, iii) generation of x-rays via bremsstrahlung, and iv) energetic electron backscatter. These effects can be used to quantify the precipitating flux, provide quantitative inputs to upper atmospheric models, and estimate the effects of precipitation on radiation belt particle populations.

In this paper, we present a modeling framework which is used to quantify each of the four diagnostic signatures above for any given precipitating particle distribution. The model can simulate both electron and proton precipitation, but here we focus on electrons. We focus in particular on the backscattered electrons and x-ray generation as mechanisms of greatest value for diagnostics.

For electron backscatter, we provide a Green's function-like estimate of the backscattered electron distribution, in energy and pitch angle, for a given input electron energy and pitch angle. The resulting distributions can be used to build a backscatter distribution for any 2D input distribution. We show that for distributions with large populations inside, but near, the local bounce loss cone angle, a significant fraction of the precipitating electron energy is backscattered and not precipitated as is commonly assumed. This observation leads to a new, more complete interpretation of the bounce loss cone, one that is a function of electron energy.

For x-ray calculations, we similarly provide a Green's function interpretation of the expected x-ray fluxes and spectra for discrete precipitating input distributions. The generated x-rays are propagated down to a notional balloon platform, and up to a notional spacecraft platform. The simulations for balloon-observed x-rays are validated with observations from the BARREL campaign measurements. We observe that the resulting x-ray energy distributions at balloon altitudes show very little variation for different input distributions; as such it is difficult to infer the precipitating electron distribution from balloon-borne x-ray measurements. However, x-ray distributions at LEO spacecraft altitudes show a marked variation with input electron energy and pitch angle. Thus spacecraft measurements of x-rays may be more useful in inferring the precipitating electron and pitch angle distribution. Such measurements may provide a valuable measurement of precipitating electron fluxes, especially in cases where particle detectors in LEO are unable to resolve the loss cone angle for precipitating electrons.

Characterisation of pulsating aurora

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Pulsating aurora is an event of often irregular auroral shapes turning on and off with periods of about a second to a few minutes. A variety of different pulsation frequencies can be observed simultaneously and visual auroral intensities are weak. Pulsation within an auroral all-sky camera (ASC) field-of view leaves a distinct trace in the quicklook image data plots (keograms available at http://www.space.fmi.fi/MIRACLE/ASC/) making the events relatively easy to identify. In this study, MIRACLE ASC data from 5 Lapland stations in 1997–2007 (about 0.8 million images / station / season) have been used to build a picture of the typical properties of auroral pulsations. Traditionally, pulsating aurora has been related to substorm recovery phases and morning sector auroral activity, but according to our experience the pulsating aurora is much more common than that.

Based on about 400 pulsating auroral events over the Fennoscandian Lapland we outline the typical duration, extent, conditions and change in the peak emission height for the events. We show that the auroral peak emission height decreases by about 8 km on average at the start of the pulsation. For about 10% of the events this brings the soft auroral precipitation down to about 90 km suggesting electron precipitation energies of 10 keV and above, which are high enough to affect the chemical composition of the neutral atmosphere below. We further show that the median duration of auroral pulsations observed over Lapland is about 1.4 hours. This value, however, is only a lower limit of the true duration, since in many cases the end of event is limited by the end of auroral imaging for the night or the aurora drifting out of the camera field-of-view. The long lifetimes of pulsations and the related high precipitation energies make this type of aurora an important cumulative energy deposition process which is easy to identify from the ground-based image data.

Comparison of two MEPED electron data sets with proton contamination corrections

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During periods of high geomagnetic activity, significant electron precipitation into the atmosphere can occur from the radiation belts. These electrons can have large impacts on the chemistry in the middle and upper atmosphere, particularly odd nitrogen, odd hydrogen, and subsequently ozone. Precipitating electrons have a wide spectrum of energies. Low energy electrons that are responsible for the Aurora Borealis/Australis are highly correlated with geomagnetic indices such as the Kp-index. This makes geomagnetic indices a good proxy for low energy electron precipitation. Medium and higher energy electrons have more variability than low energy electrons and can penetrate deeper into the atmosphere, making them potentially more important for chemistry effects. Unfortunately, the MEPED instruments generally used to quantify higher energy electron precipitation suffer from proton contamination. Several attempts have been made to improve the data through proton removal algorithms. Two data sets that have used such correction algorithms are compared in this investigation. The data sets are described Rodger et al. [2013] and Peck et al. [2015].

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Frequency Correction of CO Spectra from Odin/SMR

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The Odin satellite is a joint astrophysics and aeronomy mission that was launched in 2001. In 2007, it became an ESA third party mission and it has been entirely dedicated to aeronomy since then. It is equipped with a Sub-Millimeter Radiometer (SMR) and an instrument combining an optical spectrometer and an infrared imager, called OSIRIS. The work presented here is solely based on measurements performed by the SMR instrument.

Since the launch in 2001, Odin/SMR has been measuring vertical profiles of various atmospheric trace gases, including carbon monoxide. Vertical profiles of CO can be retrieved from the measurement of a thermal emission line, centered at 576.268 GHz. This could be done correctly for one year, between October 2003 and October 2004. However, due to an instrumental failure during all other observation times, the local oscillator frequency of the corresponding radiometer is offset from the demanded frequency, resulting in a frequency shift of the entire spectrum. In order for the CO measurements to be useful, a frequency correction must be performed in the retrieval process. The observed center frequency of the CO line is compared to the theoretical value so the frequencies can be shifted accordingly. The main challenge lies in distinguishing the CO line from a nearby ozone line. A program has been developed to locate and distinguish the center frequency of the observed CO line and to shift the frequencies to coincide with the theoretical values. This is the first of two steps in the frequency correction procedure, where the second step is an inversion, which can fine tune the frequency adjustment within $\pm$2MHz. A robust frequency correction and retrieval methodology for SMR CO will be presented in the poster.

Carbon monoxide is a trace gas characterized by a long photochemical lifetime, which makes it a very good tracer for transport processes in the middle atmosphere. The correction method presented here will result in a large set of CO vertical profiles with a vertical resolution of 3 – 4 km, from 2001 until present day. This data set, which could not be used until now, will be very useful for studying solar influences on the atmosphere, especially the energetic particle precipitation (EPP) indirect effect. CO measurements can indeed be used to determine which fraction of nitric oxide (NO) measured in the stratosphere that has been produced in the mesosphere/lower thermosphere by EPP and has been brought down during the polar winter.

Including "Typical" Relativistic Electron Precipitation in Representative Models.

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In recent years there has been much progress towards providing representative empirical models of energetic electron precipitation for use in coupled climate calculations. Observation based models representing auroral electron precipitation have been available for more than a decade, and appear to do a reasonable job of predicting thermospheric changes. In the last 5 years the HEPPA community has worked together to produce empirical models of medium energy (30-1000 keV) electron precipitation, particularly originating from the radiation belts. A recent example of such a model is based on experimental satellite measurements that have at least been partially validated, and is sufficiently flexible to predict precipitation outside of the existing period of measurements [*van de Kamp et al.*, 2015]. This recent model has been recommended for use in CMIP-6.

While the medium energy electron precipitation models could be improved (for example, by incorporating magnetic local time), it seems time to identify the most important missing factors in our representations of energetic electron precipitation. One of these is precipitation from substorms, which are extremely common events that modelling suggests could have a significant impact - these are being discussed in a different presentation. Another important issue is relativistic electron precipitation. Satellite observations of HOx has indicated that significant increases can be observed as low as ~52 km altitude [*Andersson et al.*, 2012], suggesting a measurable influence of relativistic electrons with ~3 MeV energy.

While the POES/MEPED integral electron count observations include contributions from electrons with energies to at least 10 MeV, it is not clear how to characterise this precipitation. Some evidence has been presented suggesting that precipitating relativistic electron energy spectra are different than those for medium energies, and that the scattering process may often be less efficient for relativistic electrons than for medium energy electrons. Conversely there is also evidence for some strong local scattering processes for example, those which produce relativistic electron microbursts. In addition, it appears the timing of relativistic electron precipitation can be strongly offset from the timing of medium energy precipitation.

In this talk we will review our understanding of the differences between medium energy electron precipitation and relativistic electron precipitation. We will use measurements from the POES, SAMPEX, and DEMETER satellites to demonstrate the differences between the broad energy ranges, and the limitations of the existing datasets.

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Solar cycle variability in long term particle fluxes as measured by NOAA POES

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The Medium Energy Proton and Electron Detector (MEPED) onboard the Polar Orbiting Operational Environmental Satellites (POES) consists of two proton telescopes, one viewing nearly radially outward from Earth (the 0° detector) and the other viewing antiparallel (Space Environment Monitor-2) or perpendicular (SEM-1) to the satellite's velocity (the 90° detector). The detectors experience radiation damage and become degraded after a couple of years. The satellites operational period is often more than 10-15 years. In order to use the whole data set for quantitative studies it is mandatory to correct the energy thresholds. By comparing accumulated integral flux from a new and an old satellite at the same magnetic local time (MLT) and time period, *Sandanger et al.* (2015) established a set of correction factors for 4 of the SEM-2 satellites. Based on these correction factors, *Ødegaard et al.* (2016) found that the rate of degradation depended on both the solar cycle and the flux measured by the detector. Using this dependence, they established an important method that has the power of correcting the entire NOAA POES data set independent of comparable simultaneous satellites. More than 2 solar cycles of corrected proton flux data is here presented and compared to the ap index. The correction of the proton flux have also implications for the electron flux, as the measured electron flux is contaminated by protons [*Yando et al.*, 2011]. When correcting the electron data set for proton contamination, it is important to use the proton spectra that have been corrected with regard to degradation.

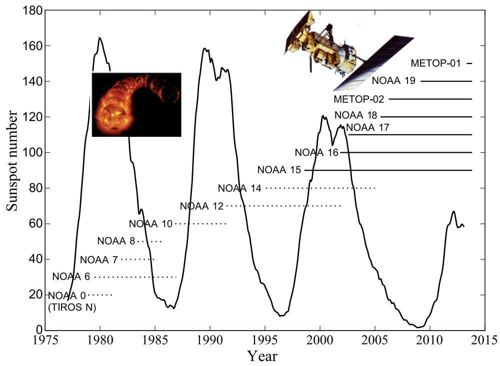

Figure 1: *NOAA POES and MetOp satellites cover more than three solar cycles. Satellites with the SEM-1 and SEM-2 instrument package are displayed using dotted and solid lines, respectively.*

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Validation of the direct effect of mid-energy electrons in the mesosphere: Suggestion for a new HEPPA model-measurement intercomparison experiment

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Mid-energy electron (MEE) precipitation caused by geomagnetic storms and substorms directly affects the chemical composition of the middle atmosphere by forming NO_x and HO_x, thus contributing to catalytic ozone loss. The direct effect of MEE in the mesosphere has been characterized by recent observations for NO, OH, and ozone and it has been suggested that the ozone response may play an important role in the Sun-Earth connection. Nitric oxides formed in the mesosphere by MEE contribute to the so-called EPP indirect effect, i.e. descent of particle-induced NOy from the mesosphere or lower thermosphere during polar winter, and a subsequent decrease in stratospheric ozone. The EPP effect from both auroral and MEE particles has already been included in several CCMs and is recommended as part of the solar forcing for ongoing climate model intercomparison activities.

We propose a new model-measurement intercomparison experiment evaluating the impact of MEE in models which already include MEE forcing by comparing to recently published observations of its effect on NO, OH, and ozone. In this contribution, we would like to explain and discuss the set-up of the proposed model experiment.

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The success of CubeSats for providing inexpensive yet high-quality observations of energetic electron precipitation from Earth's radiation belts

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CubeSats are small (1U is 10cm x 10cm x 10cm), fully-functional spacecraft that offer relatively inexpensive opportunities to conduct space-borne experimentation and/or flight-prove new technology and capabilities. The use of CubeSats for space science applications is of growing interest to the greater magnetospheric, solar, and planetary science communities, and to date, some of the most successful scientific CubeSat missions have studied electrons in Earth's radiation belts and how those electrons are lost (a.k.a., "precipitated") into the atmosphere. Here, we will focus on three such CubeSat missions, two that have already completed their prime science objectives on orbit plus another that is scheduled to launch in 2017, and how these are good examples of how CubeSats can be used to provide high-quality, cutting edge science for a very small fraction of the cost of traditional missions. We also discuss how CubeSats are not a solution to all of our spaceflight requirements but are a revolutionary new standard that is proving invaluable for space technology education, instrument and subsystem electronics miniaturization, and innovative and complementary science with existing missions and satellites.

The three missions that we highlight here include: Aerospace's AeroCube-6, University of Colorado's CSSWE, and the University of California, Los Angeles (UCLA) ELFIN. The AeroCube-6 (AC6) mission consisted of a pair of ½U CubeSats with deployable solar panels and magnetic torque coils for attitude control. Using attitude control and differential drag, the separation between the two AC6 satellites along their common orbit could be actively controlled. Along with the AC6 instrument suite, consisting of three energetic particle dosimeters calibrated to measure radiation belt electrons and protons, the two-point measurements from AC6 enable scientists to study the spatio-temporal nature of electron precipitation losses [e.g., Blake and O'Brien, 2016]. The Colorado Student Space Weather Experiment (CSSWE) is a 3U CubeSat that carried a solid-state detector telescope that provided observations of relativistic electron precipitation and solar energetic protons. During it's more than two year mission, CSSWE proved invaluable for several studies demonstrating how CubeSats can complement larger, more-expensive missions, such as NASA's Van Allen Probes [e.g., Li et al., 2013; Blum et al., 2013; Schiller et al., 2014]. Finally, the upcoming Electron Losses and Fields Investigation (ELFIN) is a 3U CubeSat that is currently in development at UCLA and scheduled for launch in 2017. ELFIN will provide the first observations of relativistic electron pitch angle distributions within the atmospheric loss cone, which should prove critical in understanding the types of waves that are scattering electrons and causing loss from Earth's radiation belts.

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WACCM-D – Whole Atmosphere Community Climate Model with D-region ion chemistry

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Energetic particle precipitation (EPP) and ion chemistry affect the neutral composition of the polar middle atmosphere. For example, production of odd nitrogen and odd hydrogen during strong events can decrease ozone by tens of percent. However, the standard ion chemistry parameterization used in atmospheric models neglects the effects on some important species, such as nitric acid. We present WACCM-D, a variant of the Whole Atmosphere Community Climate Model, which includes a set of lower ionosphere (D-region) chemistry: 307 reactions of 20 positive ions and 21 negative ions. We consider realistic ionization scenarios and compare the WACCM-D results to those from the Sodankylä Ion and Neutral Chemistry (SIC), the state-of-the-art 1-D model of the D-region chemistry. We show that WACCM-D produces well the main characteristics of the D-region ionosphere, as well as the overall proportion of important ion groups, in agreement with SIC. Comparison of ion concentrations shows that the WACCM-D bias is typically within $\pm 10\%$ or less below 70 km. At 70–90 km, when strong altitude gradients in ionization rates and/or ion concentrations exist, the bias can be larger for some groups but is still within tens of percent. We also evaluate the performance of EPP/ion chemistry modeling by comparing WACCM-D results for the January 2005 solar proton event (SPE) to those from the standard WACCM and observations from the Aura/MLS and SCISAT/ACE-FTS instruments. The results indicate that WACCM-D improves the modeling of HNO_3, HCl, ClO, OH, and NO_x during the SPE. For example, Northern Hemispheric HNO_3 from WACCM-D shows an increase by two orders of magnitude at 40-70 km compared to WACCM, reaching 2.6 ppbv, in agreement with the observations. Based on our study, WACCM-D provides a state-of-the-art global representation of D-region ion chemistry and improves modeling of EPP atmospheric effects considerably.

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