A three-dimensional ground-to-space understanding of sudden stratospheric warmings through a combination of numerical models, satellite and ground-based observations

Applicants: N. Pedatella (Coordinator), J. Chau, T. Fuller-Rowell, B. Funke, L. Goncharenko, L. Harvey, K. Hocke, H. Jin, S. Nozawa, H. Schmidt, C. Stolle, and C. Zülicke

Abstract

The lower atmosphere can generate disturbances in the ionosphere that reach magnitudes of 100-150%, and the lower atmosphere thus represents a source of variability that is comparable to moderate geomagnetic storms. Due to their large-scale and extended duration, sudden stratospheric warmings (SSWs) have proven to be ideal for studying vertical coupling between the lower, middle, and upper atmospheres. Considerable progress has been made in recent years on the coupling between atmospheric regions during SSWs. This has been primarily driven by focused research efforts making use of newly developed whole atmosphere models, and extensive ground-based and satellite observations. However, a comprehensive global view of atmospheric variability during SSWs has yet to be established. This is largely due to uncertainty in model simulations along with the spatial and temporal limitations of observations, respectively. These shortcomings can be overcome through an integrative approach that combines various numerical models with a diverse set of observations, and doing so will lead to vastly improved understanding of the processes responsible for coupling different atmospheric regions.

In an effort to establish a thorough understanding of atmospheric coupling during SSWs, we propose to bring together experts in middle atmosphere chemistry and dynamics with experts in the ionosphere-thermosphere system. Through combining ground-to-space whole atmosphere models with ground-based and satellite observations, we aim to develop an in-depth understanding of the three-dimensional global variability that occurs throughout the atmosphere during SSWs. The comparison of model simulations with a comprehensive set of observations will not only serve to validate the model simulations, but also allow for the model simulations to aid in the interpretation of the observations. This will significantly improve our understanding of the processes that drive vertical coupling.

Scientific Rationale

Within the past decade it has become increasingly recognized that dynamical processes in the troposphere and stratosphere profoundly influence the upper atmosphere [e.g., *Akmaev*, 2011; *England*, 2012]. Spatial and temporal variability in the mesosphere, thermosphere, and ionosphere can be directly connected to variability in the underlying atmosphere. The coupling between atmospheric regions occurs through gravity waves, tides, and planetary waves, and it thus occurs across a wide range of spatial and temporal scales. Though it is always present to some degree, the coupling between the lower and upper atmosphere is especially apparent during sudden stratospheric warmings (SSW) [*Chau et al.*, 2012]. SSWs consistently produce large disturbances in the mesosphere, thermosphere, and ionosphere, and the study of SSWs thus provides an ideal scenario for furthering our understanding of lower-upper atmosphere coupling.

Through the extensive study of SSWs significant progress in understanding the coupling between atmospheric regions has been made in the past several years. Recent progress has been facilitated by developments in: (1) whole atmosphere models, (2) distributed high-quality ground-based observations, and (3) global satellite observations. Important aspects in each area that are pertinent to the study of lower-upper atmosphere coupling during SSWs are summarized in the following.

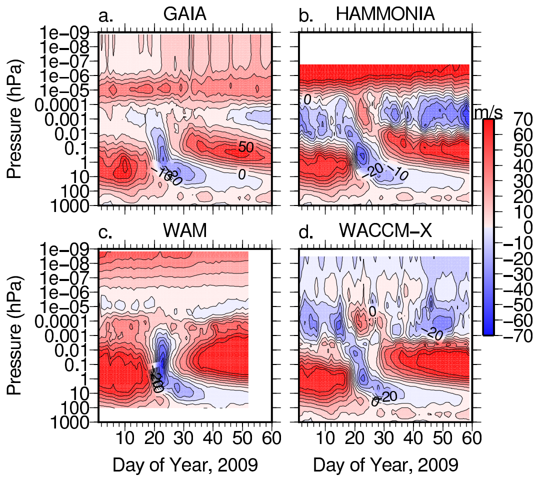

Figure 1. Zonal mean zonal wind at 60°N during the 2009 SSW from (a) GAIA, (b) HAMMONIA, (c) WAM, and (d) WACCM-X simulations (after Pedatella et al., 2014)

(1) It is only recently that whole atmosphere models have been able to simulate the chemical and dynamical variability from the surface to the thermosphere for specific time intervals. Such whole atmosphere model simulations are ideal for studying the mechanisms that couple variability in the lower and upper atmospheres. However, these models are still under development, and differences among simulations exist, particularly at high altitudes where the simulations are sensitive to model parameterizations. This fact is illustrated in Figure 1, which shows the zonal mean zonal wind at 60°N from four different model simulations of the 2009 SSW. Given the large differences in the simulations, one may question the fidelity of the model simulations in the mesosphere and thermosphere. Detailed model-data comparisons are therefore necessary to understand model performance and shortcomings. Furthermore, several models are now capable of simulating the ionosphere response to lower atmosphere disturbances, enabling more detailed exploration of how the lower atmosphere drives ionospheric variability.

(2) Local, ground-based observations afford the opportunity to understand dynamical variability on spatial and temporal scales that are currently unachievable by satellite observations. Ground-based observations have thus significantly contributed to the understanding of atmospheric wave activity during SSWs, especially for waves at sub-daily periods. The interpretation of this variability is, however, extremely difficult owing to known longitudinal differences that occur in the upper atmosphere response to SSWs. To fully realize the potential of ground-based observations it is thus necessary to place them into the broader global context through comparison with either numerical models or additional ground-based and satellite observations.

(3) Satellite observations are the only means for observing global variability in the upper atmosphere during SSWs, and are thus critical for understanding large-scale processes during SSWs. Satellite records from Aura MLS, CHAMP, COSMIC, Envisat MIPAS, and TIMED/SABER now consist of numerous SSWs. The three Swarm satellites launched in 2013 are also anticipated to contribute to understanding the role of vertical coupling on ionosphere variability in the coming years. Comparison of multiple SSWs based on different, and complimentary, satellite observations is now possible, permitting a more in-depth view of global-scale variability in the middle and upper atmosphere during SSWs. Satellite observations thus provide a valuable benchmark for model simulations as well as ground-based observations.

Whole atmosphere models, local, and global satellite observations have already led to considerable progress towards understanding the coupling between atmospheric regions. Nonetheless, there remain gaps in our knowledge of the entire chain of events that couples SSWs to middle and upper atmosphere variability. We propose to bring together experts in whole atmosphere modeling, ground-based, and satellite observations in an effort to perform model-data comparisons during SSWs. Extensive comparison of models and observations is required to fully realize the potential of each, and is a necessary step towards improved understanding of the processes that connect variability in the lower and upper atmospheric layers.

Scientific Goals

Motivated by the previously mentioned importance of whole atmosphere modeling and observations for investigating vertical coupling during SSWs, we have identified several key scientific questions that will be addressed by bringing together experts in different scientific disciplines. Addressing these topics will lead towards an improved understanding of coupling between atmospheric regions. The key questions to be addressed are:

(1) How do whole atmosphere model simulations of SSWs compare to observations in the mesosphere, thermosphere, and ionosphere? And, is this consistent across SSWs?

A comparison of the GAIA, HAMMONIA, WAM and WACCM-X whole atmosphere model simulations of the 2009 SSW revealed considerable discrepancies between the models for the zonal mean, planetary wave, and tidal variability in the mesosphere and lower thermosphere [*Pedatella et al.,* 2014]. However, a comprehensive comparison with observations has not been performed, and we will perform detailed comparison between the models and observations, with particular emphasis on short-term tidal variability. It is additionally unknown if the similarities and differences among model simulations for the 2009 SSW are consistent across SSWs. We therefore propose to extend this study to other events, such as the 2006, 2008, and 2013 SSWs. These investigations will shed light on the validity of underlying physical processes and assumptions used in the different models, and will therefore enhance understanding of observations.

With several models now capable of simulating the ionosphere variability during SSWs, we intend to extend model comparisons to the ionosphere. Direct comparison of the modeled ionosphere response to CHAMP, COSMIC, GPS total electron content (TEC), and Incoherent Scatter Radar (ISR) observations will be performed to determine the current capabilities of ionosphere models to simulate ionospheric variability during SSWs.

(2) Can a classification scheme of SSW-related disturbances in the upper atmosphere lead to better understanding the link between the drivers of SSWs and upper atmosphere variability?

SSWs are traditionally classified based on their characteristics in the stratosphere, typically at 10 hPa. Recent observations and model results have demonstrated that characteristic features also exist in the upper atmosphere response to SSWs. The occurrence of an elevated stratopause following some SSWs and not others is one example of different middle-upper atmosphere responses to different SSWs [*Chandran et al.*, 2013]. Using observations and model simulations we will extend the classification scheme for SSWs to include information from the upper atmosphere. Such a classification scheme can provide insight into the connection between variability in the stratosphere and upper atmosphere. That is, if observations and model simulations reveal that specific aspects of the upper atmosphere response consistently occur for certain types of SSWs, as defined by their stratospheric parameters, it will enhance understanding of the link between these two regions.

(3) What is the connection between local and global variability?

Local observations have proven to be essential for understanding the variability in the mesosphere, thermosphere, and ionosphere that occurs on time-scales ranging from hours to days. Interpreting the results is made difficult owing to the lack of spatial information. Here we seek to leverage the high temporal resolution of local observations with global satellite observations and model simulations to further understand how the global-scale variability influences local observations. A particular area of focus is on understanding the longitudinal variability in the

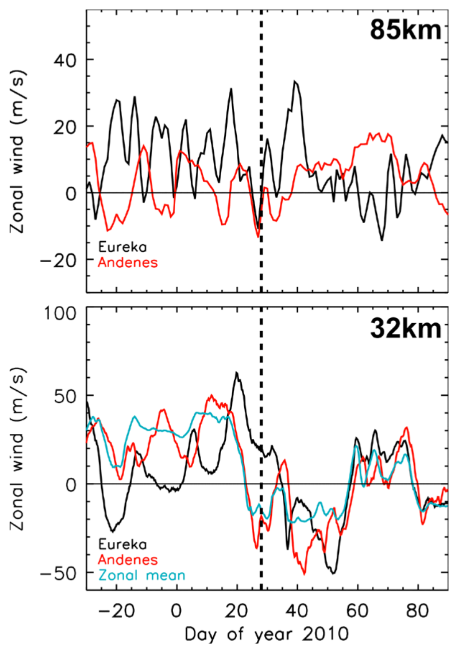

Figure 2. Zonal wind observations at Eureka, Canada (80°N, 86°W) and Andenes, Norway (69°N, 16°E) at 85 km (top) and 32 km (bottom). The zonal mean zonal wind at 32km from MERRA reanalysis is also included in the bottom panel.

mesosphere and ionosphere. Figure 2 shows an example of this variability, and it is clear that significantly different wave activity occurs in the stratosphere and mesosphere zonal wind observations at Eureka, Canada and Andenes, Norway. The temporal variability in the stratosphere at these two locations also departs significantly from the zonal mean variability deduced from atmospheric reanalysis. Comparison of local observations, such as those in Figure 2, with satellite observations and whole atmosphere model simulations will enhance understanding of the sources of the observed wave activity. This will provide new insight into the mechanisms leading to the longitudinal differences in the short-term variability.

Expected Outcomes

Results of the proposed project will be summarized in several papers. Comparison of the observed and modeled neutral atmosphere and ionosphere variability for several different SSWs will be the subject of two separate papers. Studies relating the local, or longitudinal, observed variability to the global dynamics will also be published. Given the significant progress in recent years since the last review paper [*Chau et al.,* 2012], we intend to prepare a review paper on atmospheric coupling during SSWs. A new SSW classification scheme including upper-atmosphere effects will be the subject of another paper. The results of the proposed project will also be presented at multiple national and international scientific conferences.

Added Value of ISSI

The proposed project brings together numerical modeling and observational experts in the middle, and upper atmospheres. Such a diverse group of experts is necessary due to the nature of this research, and it is difficult to assemble such a team through conventional funding platforms. ISSI thus provides a unique opportunity to bring together a group of experts that would not otherwise be able to comprehensively address the research topic. ISSI further provides a forum for establishing collaborations, and assures that the most current understanding of atmosphere coupling during SSWs will be published in a comprehensive review paper.

Participants

The project team is composed of an international group of scientists with expertise in the middle and upper atmosphere. It includes experts familiar with global numerical models (CTIPe, GAIA, HAMMONIA, KMCM, TIME-GCM, WAM, WACCM), satellite (Aura MLS, CHAMP, COSMIC, MIPAS, TIMED/SABER, Swarm), and ground-based observations (MF and meteor radars, ISR, GPS TEC, LIDAR). The team members have expertise in a broad range of disciplines, as required to undertake this multi-disciplinary project. Team members that have confirmed participation in the proposed project include:

- Nicholas Pedatella (Coordinator, COSMIC Program Office, UCAR, USA)
- Jorge Chau (Leibniz Institute of Atmospheric Physics, Germany)
- Timothy Fuller-Rowell (CIRES, University of Colorado, USA)
- Bernd Funke (Instituto de Astrofisica de Andalucia, Spain)
- Larisa Goncharenko (MIT Haystack Observatory, USA)
- Lynn Harvey (LASP, University of Colorado, USA)
- Klemens Hocke (Institute of Applied Physics, University of Bern, Switzerland)
- Hidekatsu Jin (National Institute of Information and Communications Technology, Japan)
- Satonori Nozawa (Solar-Terrestrial Environment Laboratory, Nagoya University, Japan)
- Hauke Schmidt (Max Planck Institute for Meteorology, Germany)
- Claudia Stolle (University of Potsdam, Germany)
- Christoph Zülicke (Leibniz Institute of Atmospheric Physics, Germany)

Project Schedule

We plan to have two weeklong meetings held around September-October 2014 and 2015. Prior to the first meeting we will agree upon 2-3 SSW events that will be the focus of our effort. Preliminary results from model simulations and observations will be presented and discussed at the first meeting. The second meeting will focus on a more detailed comparison between results from different numerical models and observations. This comparison will aid in understanding the coupling processes between the lower and upper atmosphere. Preparation of a review paper that summarizes the present understanding of atmosphere coupling during SSWs will also take place during the final meeting.

ISSI Support

Our team requires a single meeting room with a projector and internet access for laptops. We request per diem for the team members to cover expenses while in Bern. Additional support for 1-2 young scientists, to be identified at a later date, is requested. We also request round trip travel expenses for the team leader.

References

Akmaev, R. A. (2011), Whole atmosphere modeling: Connecting terrestrial and space weather, *Rev. Geophys.,* 49, RG4004, doi:10.1029/2011RG000364.

Chandran A., R. L. Collins, R. R. Garcia, D. R. Marsh, V. L. Harvey, J. Yue, and L. de la Torre (2013), A climatology of elevated stratopause events in the whole atmosphere community climate model, *J. Geophys. Res*., 118, doi:10.1002/jgrd.50123.

Chau, J. L., L. P. Goncharenko, B. G. Fejer, and H.-L. Liu (2012), Equatorial and Low Latitude Ionospheric Effects During Sudden Stratospheric Warming Events, *Space Sci. Rev.*, doi:10.1007/s11214-011-9797-5.

England, S. E. (2012), A Review of the Effects of Non-migrating Atmospheric Tides on the Earth's Low-Latitude Ionosphere*, Space Sci. Rev.,* doi: 10.1007/s11214-011-9842-4

Pedatella, N. M. et al. (2014), The neutral dynamics during the 2009 sudden stratosphere warming simulated by different whole atmosphere models, *J. Geophys. Res.*, 119, doi:10.1002/2013JA019421.