

Gravity Wave Effects on Polar Vortex Geometry During Split-Type Sudden Stratospheric Warmings

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Sudden stratospheric warmings represent one of the most compelling tests of our ability to explain and predict the dynamical circulation of the stratosphere. Yet despite significant recent progress in the classification of the geometric structure and evolution of sudden warmings (e.g. split versus displacement events), our understanding of the dynamics underlying these events remains elusive. This fact is especially glaring in light of the fact that stratosphere-troposphere coupling is particularly strong during and after sudden warming events, and therefore our ability to predict tropospheric climate and weather could be improved by gaining a more clear understanding of the dynamics underlying sudden warming events.

The traditional sudden stratospheric warming paradigm states that an anomalously strong pulse of planetary wave activity from the troposphere is required in order to trigger an event. However, the results of *Matthewman and Esler (JAS 2011)* contradict this hypothesis by pointing out that resonant excitation and vortex breakdown can occur for relatively weak wave forcing. With this idea in mind, we utilize reanalysis data to revisit and revise the traditional hypothesis of the necessary conditions for triggering a sudden warming.

In this study, reanalysis (JRA25) data, including parameterized gravity wave drag, which extends upwards into the lower mesosphere (~55 km) is used to explore the relationship between gravity wave and planetary wave variability and polar vortex geometry prior to sudden stratospheric warming events. In particular, an attempt is made to identify the key geometric features of the polar vortex that are common to the development of all split-type warming events. Comparison of planetary and gravity wave activity suggests that anomalous gravity wave drag prior to split-type sudden warmings plays an important role in 'tuning' the vortex towards its resonant, barotropic excitation point by minimizing the vortex area, elongating the vortex in the meridional-zonal plane, and aligning the vortex so that is barotropic throughout the stratosphere. The robustness of the role of gravity wave drag in vortex 'tuning' is examined by contrasting the results obtained via JRA25 reanalysis data versus analogous results obtained from the ERA-Interim and MERRA reanalysis data sets. The results presented in this study have important implications for stratosphere-troposphere research by providing an important new view on the geometric state of the polar vortex prior to split-type warmings that may help researchers attempting to understand and predict sudden stratospheric warming events and tropospheric weather and climate.

Citation:

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Missing Gravity Waves and Southern Hemisphere Wind Biases in Climate Models: What can observations tell us?

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Global satellite observations of gravity waves are used to examine the properties and variability of waves from different sources at high southern latitudes in the fall through spring season. Climate models have common wind biases in the Southern Hemisphere stratosphere (Butchart et al., 2011) that are associated with delayed breakdown of the winter vortex and extended cold temperatures in springtime. These biases are also related to the excessive persistence of the Southern Annular Mode in models (Gerber et al., 2010), and the seasonal cycle of ozone loss (Alexander et al., 2010). Ozone loss and recovery have affect climate at the surface on timescales from annual to decadal (Perlwitz et al., 2008; Son et al., 2008; Arblaster et al., 2011). Limited land areas and missing orographic gravity wave drag (McLandress et al., 2012) have long been associated with these wind biases since orographic gravity wave drag parameterizations alleviate the biases in the Northern Hemisphere (Palmer et al., 1986).

We report on observations from the Aqua satellite's Atmospheric Infrared Sounder (AIRS) and examine global properties of gravity waves in the Southern Hemisphere stratosphere at 30-40 km altitudes. Three possible origins for gravity waves missing in climate models are examined: Orographic waves from small islands in the southern oceans, horizontal propagation of orographic waves from continental regions, and non-orographic waves. We quantify limits on wave observability by AIRS and show how stratospheric winds exert a first-order control on this observability, with near-surface conditions exerting a second-order effect. The implications are that both island waves and non-orographic waves occur much more commonly at lower altitudes than we can observe with AIRS, increasing their potential importance on the Southern Hemisphere circulation. We use the observations from AIRS to estimate potential contributions from both orographic and non-orographic gravity wave sources to the general circulation of the Southern Hemisphere.

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Sources, variability and wave mean-flow interactions of tropospheric gravity wave activity at Davis, Antarctica (69S, 78E)

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Lower atmospheric sources of gravity wave activity in the high southern latitudes have been previously documented by radiosondes, high-altitude balloons and satellite observations. Ground-based instruments enable the continuous characterisation of the small-scale structure, variability and intermittency of gravity wave activity. Such observations include the high-frequency waves which are believed to carry a significant proportion of total momentum flux.

A Very High Frequency (VHF) wind-profiling radar located at Davis has collected lower tropospheric wind velocity data for around two years. We investigate the variability of the occurrence of high frequency gravity waves seen with the radar. Using composite analysis, we diagnose the orographic and mesoscale meteorological sources of the waves and the times when the largest wind velocity variances occur. We will discuss the seasonal variation of intense gravity wave activity and relate this to the background wind conditions. Lastly, we investigate the mean-flow interaction of these waves in the upper troposphere and lower stratosphere (UTLS) region using case studies.

Relations between tropospheric blocking and the stratospheric polar vortex in an ensemble of climate models

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The possibility of dynamical linkages between stratospheric sudden warmings and tropospheric blocking events has been of interest for some time. Both types of event involve dramatic and sustained disruptions of large-scale westerly flow, and in the troposphere such disruptions can lead to prolonged spells of anomalous weather such as those seen in Europe and North America during the recent cold winters of 2009-2010 and 2010-2011. Over the past fifty years, observations have suggested that these two types of event - tropospheric blocking and stratospheric warming - may be related. Tropospheric blocking events may act to force stratospheric warmings, with the geometric character of the warming - whether the stratospheric vortex is displaced away from the pole or is split into two separate vortices - depending on the location of the precursor blocking events. Conversely, distinct stratospheric precursors of blocking events may, if real, imply enhanced tropospheric predictability (with likely socio-economic benefits). Unfortunately the limited length of the observational record makes it difficult to determine the robustness of these associations based on observations alone. This difficulty is characteristic of efforts to understand and quantify the natural variability of the atmosphere, and it motivates the analysis of long model integrations in order to reduce statistical uncertainty and isolate causal factors. In this study we examine stratosphere-troposphere linkages related to blocking events by considering a large ensemble of coupled atmosphere-ocean general circulation model data, most of which is culled from the Coupled Model Intercomparison Project Phase 5 online archive. Daily geopotential height data from several thousand years' worth of historical and pre-industrial control integrations are analysed in order to robustly assess the nature of the troposphere-leading and stratosphere-leading relationships. The fidelity of both blocking and stratospheric polar vortex variability shows considerable variation amongst the models in this ensemble. Nevertheless, the results support the existence of distinct blocking precursors to displacements and splits of the stratospheric vortex, as well as the existence of stratospheric precursors to high-latitude blocking events.

Untangling the role of ozone versus GHGs in SH climate change

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Future climate change in the extratropics of the Southern Hemisphere (SH) is likely to be driven by two opposing effects, stratospheric ozone recovery and increasing greenhouse gases (GHGs). Poleward shifts in the extratropical westerly jet and associated positive trends in the Southern Annular Mode (SAM) are projected in almost all climate models under increasing CO₂, while ozone recovery leads to the opposite response, primarily in austral summer. The relative importance of each forcing to summer projections of the SAM varies across models and scenarios, with a large spread in the magnitude and even sign of the circulation response. With recent studies suggesting a significant influence of ozone on rainfall and carbon uptake, understanding and reducing this model spread is crucial for improving regional prediction.

The Coupled Model Intercomparison Project Phase Five (CMIP5) presents an unprecedented opportunity to explore the role of ozone recovery in future climate projections, with all participating models including some form of ozone forcing under multiple greenhouse gas emissions scenarios. However, without single forcing experiments of the future provided by the modelling groups it is difficult to untangle the impact of ozone recovery from the signal of other forcings. Additional single forcing experiments with the NCAR CCSM4 were undertaken to examine the individual role of GHGs, aerosols, land-use change and ozone recovery on future projections of the SH circulation, rainfall, ocean and sea-ice. The experiments suggest that the impact of ozone recovery and GHG forcings are not linearly additive, warranting further investigation into the physical mechanisms behind ozone and GHG forced change.

The relevance of blocking highs for stratospheric variability in a changing climate

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Major stratospheric warmings (MSWs) are preceded by an anomalously high injection of planetary wave (PW) activity into the stratosphere related to different factors such as the appearance of high-amplitude anticyclonic anomalies or blocking highs (BHs). However, not all BHs lead to an enhancement of PW activity, and their location is important for the modulation of climatological PWs. For example, Nishii et al. (2011) found in JRA-25 reanalysis data that BHs over the Euro-Atlantic sector tend to enhance the upward propagation of PWs, whereas the influence of BHs over the western Pacific on PWs is opposite, leading to a strengthening of the polar vortex. Thus, it is of scientific interest to study whether potential future changes in stratospheric variability are linked to potential changes in this relationship in the future.

In this study we first assess whether the EMAC Chemistry-Climate-Model is able to reproduce the geographical dependence of the influence of BHs on upward propagating PWs in recent past climate. In a second step we study possible future changes in this dependence. For that purpose, we use two transient simulations of the period 1960-2100 carried out with EMAC under the future climate change scenarios RCP4.5 and RCP8.5.

By applying the methodology of Nishii et al. (2011), EMAC is shown to reproduce qualitatively well the geographical dependence in the BH influence on PW injection and thus, on the stratospheric variability. Moreover, this dependence does not change in the future. However, BHs preceding MSWs in the future do not seem to be located in the preferred regions for the enhancement of PW as clearly as in the past, particularly under extreme climate change conditions (Fig.1). This might be an indication that the role played by BHs in the occurrence of future MSWs is less important than in the past.

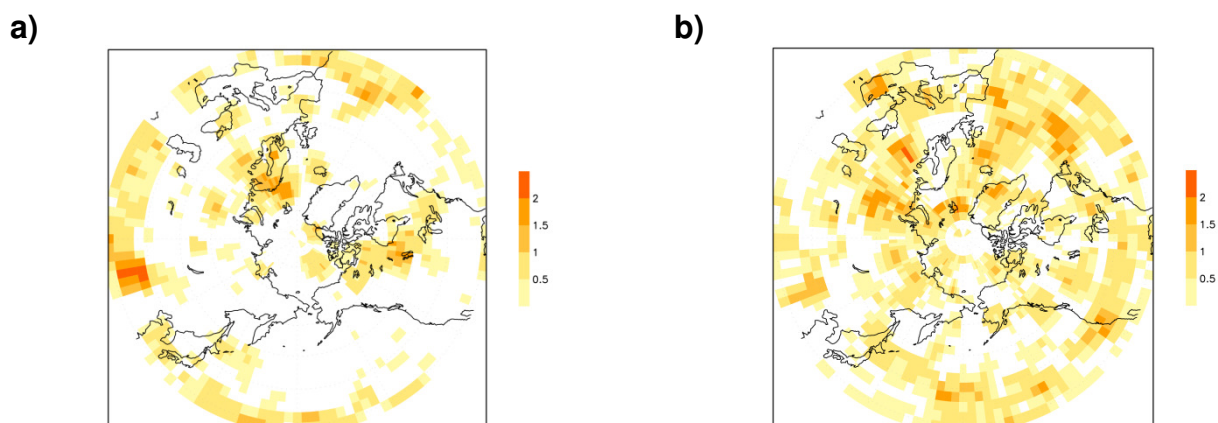


Figure 1. Probability of BH (%) in the period between lags -10 and -1 days before the central date of MSWs in: (a) 1960/61-1999/2000 and (b) 2060/61-2099/2100 of the RCP8.5 run.

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Influence of Sudden Stratospheric Warmings on the Indian Summer Monsoon

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The goal of this research effort is to assess the variability of sudden stratospheric warmings (SSWs) during northern winter along with some dynamical parameters of the middle atmosphere to examine their roles in determining the variability of rainfall over tropics in the forthcoming summer monsoon. The analysis is done using Reanalysis data of National Centers for Environmental Prediction (NCEP) for 32 years (1979-2010) and with model simulation output of EGMAM. The model (EGMAM) used is a middle atmosphere version of ECHO-G with 39 vertical levels (top level 0.01 hPa). The automated algorithm to identify SSWs uses 10hPa zonal mean zonal wind at 60° and the mean temperature gradient between 60° and the polar region. Each of the three experiments is carried out with an idealized sinusoidal solar forcing with a period of 11 years ranging over 21 solar cycles and 231 years respectively. During SSWs years, the forthcoming summer monsoon shows a positive precipitation anomaly over India from June to August for the ensemble of all the three experiments (Fig. 1) and also with observation (Fig. 2).

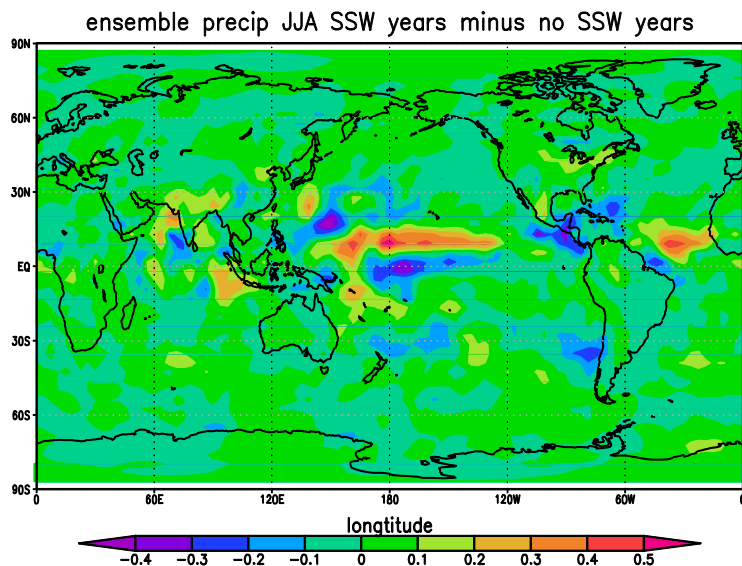


Fig. 1

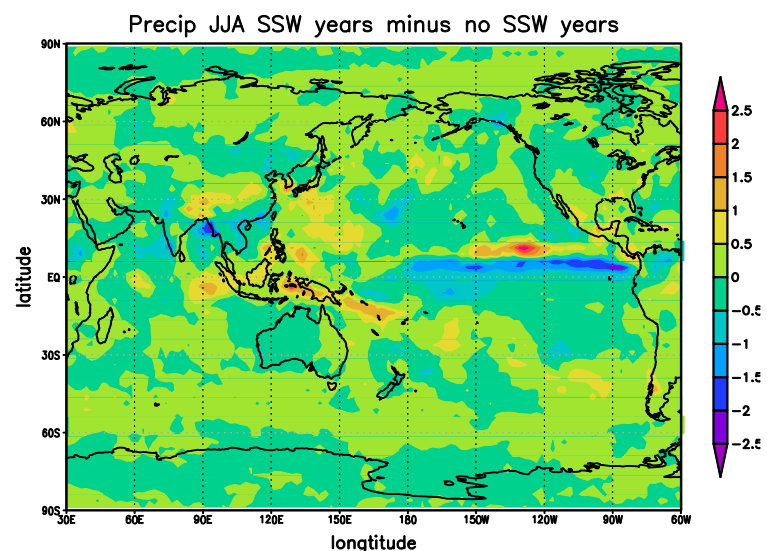


Fig. 2

Observational and Modelling Studies of the Short-Term Climate Influences of the Ozone Mechanism

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The relationship between the total ozone amount (TOA) field and global characteristics of air-masses distribution seems to be proved beyond any doubt. Analyses of observational studies of the ozone layer performed at the Voeikov Main Geophysical Observatory (MGO) suggest a distinct correlation between spatial-temporal TOA distribution, synoptic formations and air-masses boundaries in the upper troposphere and the temperature field of the lower stratosphere.

Ozone, being formed in the upper stratosphere (at altitudes of 30 to 50 km, where it is in a photochemical equilibrium) and then transported downwards by diffusion and turbulence, builds up at lower stratospheric levels (ozone density of ≈ 1 DU/km at 50 km altitude increasing up to 15-18 DU/km at 25 km). Observations demonstrate there is no particular dependence of ozone content at 25 km and higher on climatic air-masses location. Hence, we can assume that TOA at a given point is determined not by ozone formation rate but rather by the efficiency of its destruction in the lower stratosphere.

In this study we perform a series of numerical simulations of formation, evolution and decay of ozone anomalies on different spatial and temporal scales, comparing results of a global model with that obtained with regional and mesoscale modelling and verifying modelling results with vast observational data. Our main goal is to fully simulate processes both in the troposphere and the stratosphere with high model resolution. We use the standalone version of the CAM modeling system for global-scale modeling and a modified version of the WRF-Chem model for finer-scale stratospheric dynamics and mesoscale tropospheric processes simulation. We modify the WRF-Chem to improve simulation of stratospheric processes with ozone as an active tracer, allowing for the possible radiative feedback on ozone dynamics. By comparing results of global-scale and regional mesoscale simulations, we evaluate the role of different processes and scales in ozone anomalies. Furthermore, to investigate the interconnection between stratospheric ozone dynamics in ozone anomalies formation and tropospheric processes in weather phenomena, we introduce perturbations to the initial conditions. First, variable fields on stratospheric model levels are modified to see the propagation of this perturbation and its possible impact on weather phenomena. Then, in subsequent numerical experiments, disturbances are introduced into surface and tropospheric variable fields to follow their influence on the stratospheric ozone dynamics.

Radiative heating of the stratosphere resulting from the ozone cycle and thermodynamical vertical convection in the troposphere are two rival processes, the first pulling the tropopause level down and the second lifting it up. Thus, we assume that the interference of these two phenomena influences the circulation processes in the lower stratosphere and the troposphere, affecting tropopause height and location of the stationary atmospheric fronts. In particular, high TOA values in the northern hemisphere in 2013 lower the tropopause height over the Atlantic region creating a cold season in Europe. Furthermore, the tropopause depression leads to intensification of blocking processes.

Representation of convectively forced gravity waves and their impact on the upper troposphere and stratosphere of the Met Office GCM

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An activity is under way within European Union project EMBRACE (Earth system Model Bias Reduction and assessing Abrupt Climate change) to develop parametrization schemes for convective sources of non-orographic gravity waves to use in Earth System Models (ESM). One motivation for the work is that convection is a recognised source of gravity waves in the atmosphere and hence by including a process neglected by many current state-of-the-art gravity wave parametrizations, the physical realism of ESMs may be improved and a better match to observations obtained in cases where this process occurs. A second motivation relates to a characteristic tendency for the current generation of ESMs to underestimate tropical variability in the middle atmosphere with the quasi-biennial and semi-annual oscillations appearing to be more regular than observational evidence suggests they should be. Improved variability is relevant for detection and attribution of climate change signals against the 'natural' background of the ESM and for prediction of 'onset of threshold reached' diagnostics of interest to mitigation and adaptation. The variability of convective activity both spatially and over time raises an obvious prospect that the representation of gravity wave sources generated by convection is a 'missing' process that can help to address variability characteristics of the ESM. Moreover, in the context of climate change, alterations in pattern and occurrence of convection arising from global warming will have the potential to affect the generation of gravity waves and hence feedback on large-scale phenomena such as the Brewer-Dobson Circulation.

Preliminary investigations with a pre-existing convective gravity wave scheme (Kim et al., 2013) have been followed by installation of a new simple parametrization of convection sources within the Met Office model (MetUM). The impact due to such a scheme on the MetUM upper troposphere and stratosphere evolution will be examined, with particular attention paid to the tropical tropopause layer, forcing of the simulated quasi-biennial oscillation and interactions with explicitly resolved equatorial waves. Initially, the focus will be on performance assessment of schemes at the process level to characterize distribution patterns, seasonal responses and statistics of the fluxes generated and propagated both in the global model and off-line. Output will be evaluated against a combination of local (e.g. Balloon) and global (e.g. Satellite) observation derived data and output from high resolution simulations over the Indian Ocean. As variability at levels above the upper troposphere is influenced not just by variability in the original gravity wave sources but also by the effect of filtering by the wind shears encountered as the waves ascend in the vertical, the relative contributions of these two aspects will be explored.

Y.-H. Kim, A.C. Bushell, D.R. Jackson and H.-Y. Chun (2013). Impacts of introducing a convective gravity wave parametrization upon the QBO in the Met Office Unified Model. *Geophys. Res. Lett.*, 40, 1873-1877, doi:10.1002/grl.50353

Differences in Ozone Recovery and its Climate Impact under different Climate Change Scenarios.

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Recent observations and climate model studies have shown that ozone depletion and increases in greenhouse gases during the last few decades have affected stratospheric temperatures and the mean circulation over the Southern Hemisphere polar cap. These changes can propagate down into the troposphere and reach the surface, with important consequences for Southern Hemisphere climate.

In the future, the increase in greenhouse gases and the expected ozone recovery will have opposite effects on future trends in the SH. Here, we make use of 95year AR5 simulations made with the Whole Atmosphere Community Climate Model WACCM4, coupled to a deep ocean to investigate ozone recovery and its impact on Southern Hemisphere climate under three different climate change scenarios.

Results show a larger ozone recovery under RCP8.5. This is mainly due to the GHG-induced increase in ozone production in the upper tropical stratosphere and not to the intensification of the Brewer Dobson circulation. However, the RCP4.5 and RCP2.6 scenarios show very similar ozone trends, because of the competing effects of climate change and ozone recovery in RCP4.5. The behavior of ozone is reflected in temperature and zonal mean zonal wind from the stratosphere down to the surface. The largest trends occur in scenarios RCP2.6 and RCP8.5, while the impact of ozone recovery at the surface is negligible in RCP4.5.

The Stratospheric Network for the Assessment of Predictability (SNAP)

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During winter and spring the stratosphere is a dynamically exciting place, with intense and dramatic stratospheric major warming events occurring typically in two out of every three years in the Northern hemisphere and minor warming events occurring more frequently still. It is not surprising, therefore, that there has long been interest in understanding what role the stratosphere plays in tropospheric weather and climate. One particular aspect of this problem, is the idea that an enhanced representation of the stratosphere in models used for forecasting tropospheric weather on short to medium ranges might enhance the tropospheric skill in those models.

In this presentation, we describe a new emerging activity of SPARC designed to address issues of coupled stratosphere-troposphere predictability, SNAP. SNAP will seek to answer several outstanding questions about stratospheric predictability and its tropospheric impact, including:

- Are stratosphere-troposphere coupling effects important throughout the winter season or only when major stratospheric dynamical events occur?
- How far in advance can major stratospheric dynamical events be predicted and usefully add skill to tropospheric forecasts?
- Which stratospheric processes, both resolved and unresolved need to be captured by models to gain optimal stratospheric predictability?

We plan to answer these questions by conducting an international intercomparison of stratospheric forecasts. The presentation will describe this experiment, progress to date and how you can get involved in the network by analysing the results and/or participating in future SNAP workshops.

Solar Cycle Modulation of the ENSO Impact on the Winter Climate of East Asia

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Previous studies indicated that the El Niño-Southern Oscillation (ENSO) is an important impact factor for the East Asian climate anomalies. During an El Niño event the climate is warmer and wetter than normal, while Southeast Asia tends to experience less rainfall. In contrast, during a La Niña winter the aforementioned situations are generally reversed. Such differences can be regarded as being led by an anomalous Walker circulation and the related anomalous anticyclone over the subtropical western North Pacific (WNP), which is a key system that carries the impacts of ENSO to East Asia. Recent works documented that the responses of the climate system to peak solar years resemble La Niña events [e.g., Meehl *et al.*, 2003; van Loon *et al.*, 2007]. This study examines how the East Asian winter climate response to the ENSO varies with the 11-year solar cycle. The results indicate that the ENSO and East Asian climate relationship is robust and significant during winters with low solar (LS) activity, with evident warming in the lower troposphere over East Asia, which can be closely linked to the decreased pressure gradient between the cold Eurasian continent and the warm Pacific. Moreover, during the LS and El Niño winters there is a typical rainfall response in Southeast Asia, with wet conditions over South China and dry conditions over the Philippines, Borneo, Celebes, and Sulawesi, which can be explained by the anticyclone over the WNP. However, during high solar (HS) activity winters, both the surface temperature and rainfall anomalies are much less closely associated with the ENSO. The possible mechanism for this solar modulation of the ENSO-related East Asian climate anomalies may be the change in the tropospheric circulation with the ENSO in both tropical and extratropical regions. Particularly, in the LS cases an anomalous WNP anticyclone is intensified and a noticeable cyclone occupies northern Northeast Asia, resulting from the changing location and strength of the large-scale Walker circulation induced by the more pronounced sea surface temperature (SST) anomalies associated with the ENSO. Further investigation with long historic data confirms that the relationship between the ENSO and the East Asian winter climate anomalies depends on the phases of 11-year solar cycle, with enhanced East Asian climate variation during the LS winters. Therefore, our results imply that solar cycle variation should be taken into account when predicting the ENSO-based winter climate in East Asia.

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Determining the Date of the Polar-Vortex Breakup in the Stratosphere

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A new method is proposed to determine the timing of the polar-vortex breakup in the spring-time stratosphere. While all the previous definitions of the vortex breakup are to be applied to the lower stratosphere, this new method can be used for all the levels of the stratosphere. First the edge of the polar vortex near the time of breakup is defined by the value of potential vorticity (PV) averaged for 15 days at the largest latitudinal gradient of PV when the vortex significantly weakens. Secondly, the timing of vortex breakup is defined as when the vortex area decreases most rapidly. To test the validity of this new definition of the vortex breakup distributions of various trace species are analyzed including methane, nitrous oxide, water vapor, and ozone observed by Improved Limb Atmospheric Spectrometer (ILAS) and ILAS-II, and ozone observed by Polar Ozone and Aerosol Measurement (POAM) 2 and POAM 3. Distributions of trace species observed around the breakup time show that the new method is better than previous methods, particularly in the upper stratosphere.

Responsible mechanisms behind the short scale Stratosphere-troposphere exchange associated with cyclonic weather conditions

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Abstract.

Earlier studies have shown the stratospheric intrusion into the troposphere during the passage of tropical cyclone by characterizing the radar reflectivity and vertical velocity measured by Indian mesosphere-stratosphere-troposphere (MST) radar located at a tropical station Gadanki (13.5°N, 79.2°E). Moreover the spatio-temporal structure of stratospheric air intrusion associated with cyclone weather is also simulated using Advanced Research-Weather Research and Forecast (WRF-ARW) model. One of the causative mechanisms responsible to stratospheric intrusion is the tropopause weakening or break by impinging of updraft. However, due to the lack of simultaneous observations of temperature and ozone profiling, the exact causative mechanism is still unrevealed. In this context, a study has been carried out under the 'Climate And Weather of the Sun-Earth System (CAWSES)-India Phase-II' programme by simultaneously operating Indian MST radar at Gadanki and launching of GPS sondes (6 hourly) and ozonesondes (1-daily) from Gadanki and Trivandrum (8.5°N, 76.5°E) during the Bay of Bengal 'Nilam' cyclone. The study has brought out some unique features on stratosphere-troposphere exchange processes associated with tropical cyclone. Detailed results will be presented and discussed in the upcoming workshop.

Wave activity at ionospheric and tropospheric-stratospheric heights above the Andes Mountains detected from FORMOSAT-3/COSMIC GPS radio occultation data

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We analyze the possible relationship between propagating gravity waves detected in the troposphere-stratosphere and the lower ionosphere near and above the highest Andes mountains. Wave activity proxies given by relative neutral temperature and electron density variance respectively are calculated, from six years of FORMOSAT 3/ COSMIC GPS (Taiwan's Formosa Satellite Mission 3/Constellation Observing System for Meteorology - Global Positioning System) radio occultation data. Linear and rank correlation is tested for pairs of these indicators, corresponding to occultation events in the considered region. A systematic enhancement of wave activity at the eastern ionospheric side of the Andes range, with respect to the western side, is observed. The seasonal variability as well as differential effect introduced by the action of orography on the generation of mountain, deep convection or even secondary waves is discussed.

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Annular Modes and Stratosphere-Troposphere Coupling in Chemistry-Climate Models

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This study aims to assess the ability of climate models to reproduce observed stratosphere-troposphere coupling. Coupling between the stratosphere and troposphere is examined via the Southern and Northern Annular Modes (SAM and NAM). These modes, associated with the shifting of atmospheric mass between the poles and mid-latitudes, are the principal modes of atmospheric extra-tropical variability in their respective hemispheres. The modes have various effects on regional climate. For example, a positive SAM, representing atmospheric mass shifting towards mid-latitudes, is associated with anomalously strong westerlies over the Southern Ocean and a southward shift of the storm track. Baldwin and Dunkerton [2001] and Thompson et al. [2005] show that strong or weak NAM or SAM events, in the stratosphere are usually followed by an annular-mode anomaly of the same sign in the troposphere that can last for around 60 days. Such results show that the stratosphere can play an important role in extended-range weather prediction.

It is important for climate models to adequately reproduce the observed stratosphere-troposphere coupling in order to predict changes in regional climate based on changes in the stratosphere (such as the creation and recovery of the ozone hole). The models analyzed in this study include an atmosphere-ocean-chemistry coupled climate model with a well resolved stratosphere and comprehensive stratospheric chemistry (NIWA-UKCA) as well as models participating in the Coupled Model Intercomparison Project 5 (CMIP5) which handle changes in ozone with varying degrees of complexity. The accuracy of the stratosphere-troposphere coupling is assessed relative to the ERA-Interim reanalyses. Comparison of the different models as well as comparison of the NIWA-UKCA sensitivity simulations with and without changes in ozone depleting substance emissions, and with or without changes in greenhouse gases, allow us to investigate the influence of ozone and other greenhouse gases on changes in the annular modes.

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Cirrus, transport, and mixing in the tropical upper troposphere

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Understanding the transport and mixing induced by the radiative heating associated with cirrus clouds in the tropical upper troposphere is challenging because clouds are highly variable in space and time. In this work we investigate whether the time-mean radiative heating rate in cloudy air gives the correct transport timescale of air and tracers. The time-mean radiative heating rate is a Eulerian quantity, whereas the transport timescale is calculated in a Lagrangian framework by following trajectories in the model simulations.

We idealize heterogeneously distributed clouds in the atmosphere by a stochastic cloud ensemble surrounded by cloud-free regions in a 2D model. Clouds are represented as radiative heat sources distributed randomly in time over the simulation duration. Our calculations show that the mean age of air of the spectrum of time since crossing the base of the cloudy region is considerably longer than the timescale indicated by the time-mean radiative heating within the cloudy region. This is because the interaction between the “macroscale” circulation between the cloudy and cloud-free regions, and the “microscale” circulation around each cloud causes substantial mixing between cloudy and clear air. Also, the mean age of air does not scale as expected from the time-mean cloud radiative heating. More specifically, if the time-mean radiative heating rate in the cloudy region doubles, the transport timescale is reduced by a factor less than two. Stronger advective tendency represented by the time-mean radiative heating in the cloudy region is intrinsically coupled with stronger mixing.

Assessing seasonal predictability from stratospheric variability in a seasonal prediction system

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The predictability arising from stratospheric variability is analyzed in a seasonal prediction system including a high top atmosphere model and a full ocean. Stratospheric variability is suggested to enhance tropospheric predictive skill through the downward influence of Sudden Stratospheric Warmings as well as the remote influence of El Niño pathways through the stratosphere. Here, we aim to quantify predictive skill on seasonal timescales with a focus on the extratropical Northern Hemisphere. We use a seasonal prediction model based on the MPI-ESM coupled climate model system (as used for the CMIP5/IPCC-AR5 simulations) initialized from reanalysis data for the atmosphere, ocean, and for sea ice. Hindcast ensemble runs are performed for the satellite era 1981 to 2011, with start dates every May and November.

Stratospheric variability is reproduced well in the hindcast runs with a realistic frequency of sudden warmings, with the ensemble spread representing the variability of reanalysis data. ENSO variability is captured in the tropical Pacific with a high predictive skill for 5 months. The suggested relationship between El Niño and stratospheric polar cap temperatures is reproduced. We also investigate predictive skill in the North Atlantic / European sector as a function of stratospheric variability.

While the North Atlantic / Europe sector traditionally exhibits little skill in seasonal prediction models, our analysis of a seasonal forecast system presents a promising step towards assessing the influence of stratospheric variability on the predictability of tropospheric variability on seasonal timescales.

Quantifying the Uncertainty in Simulated Trends in the Stratospheric Circulation

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The atmospheric circulation is expected to respond to stratospheric ozone depletion and recovery, as well as the forcing due to anthropogenic greenhouse gases in the 21st century. However, the amplitude of the response varies widely from one simulation to the next. Additionally, the response within a single simulation is difficult to detect because the response is likely to lie within the bounds of natural variability, which makes it challenging to distinguish the anthropogenic signal from climate “noise”. The goal of this study is to quantify the uncertainty of the atmospheric circulation's response to anthropogenic warming and stratospheric ozone concentrations, with an emphasis on trends in the stratospheric circulation. This study uses the output from the National Center for Atmospheric Research (NCAR) Community Climate System Model Version 3 (CCSM3) 40-member ensemble climate change simulations and the 5th phase of the Coupled Model Intercomparison Project (CMIP5). Individual ensemble members from the NCAR CCSM3 model and different climate models from the CMIP5 archive are used to quantify the uncertainty in the projected trends in the tropospheric and stratospheric circulation, as well as distinguish the natural from the forced variability in the atmosphere. The results of the analysis will help constrain the uncertainty in predicted changes in the general circulation of the atmosphere, including those due to the Brewer-Dobson circulation.

Connections between the Spring Breakup of the Southern Hemisphere Polar Vortex, Stationary Waves, and Air-Sea Roughness

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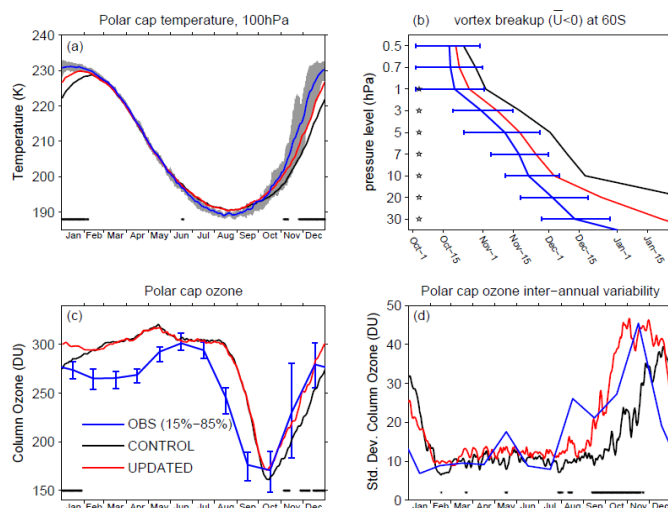
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A robust connection between the drag on surface-layer winds and the stratospheric circulation is demonstrated in NASA's Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM). Specifically, an updated parameterization of roughness at the air-sea interface, in which surface roughness is increased for moderate wind speeds (4m/s to 20m/s), leads to a decrease in model biases in Southern Hemispheric surface wind, ozone, polar cap temperature, stationary wave heat flux, and springtime vortex breakup. A dynamical mechanism is proposed whereby increased surface roughness leads to improved stationary waves. Increased surface roughness leads to anomalous eddy momentum flux convergence primarily in the Indian Ocean sector (where eddies are strongest climatologically) in September and October. The localization of the eddy momentum flux convergence anomaly in the Indian Ocean sector leads to a zonally asymmetric reduction in zonal wind and, by geostrophy, to a wavenumber-1 stationary wave pattern. This tropospheric stationary wave pattern leads to enhanced upwards wave activity entering the stratosphere. The net effect is an improved Southern Hemisphere vortex: the vortex breaks up earlier in spring (i.e., the spring late-breakup bias is partially ameliorated) yet is no weaker in mid-winter. More than half of the stratospheric biases appear to be related to the surface wind speed biases. As many other chemistry-climate models use a similar scheme for their surface layer momentum exchange and have similar biases in the stratosphere, we expect that results from GEOSCCM may be relevant for other climate models.

Garfinkel, C. I., L. D. Oman, E. A. Barnes, D. W. Waugh, M. M. Hurwitz, A. M. Molod (accepted), Connections between the Spring Breakup of the Southern Hemisphere Polar Vortex, Stationary Waves, and Air-Sea Roughness, J. Atmos. Sci.

Garfinkel, C.I., A. M. Molod, L.D. Oman, I-S. Song (2011), Improvement of the GEOS-5 AGCM upon updating the Air-Sea Roughness Parameterization, GRL, 38, L18702, doi:10.1029/2011GL048802.



Evolution of (a) polar cap temperature at 100hPa (b) the date on which 60S zonal wind reaches 0m/s (i.e. the vortex breakup), (c) evolution of polar cap column ozone, (d) evolution of variability in polar cap column ozone, in the UPDATED, CONTROL, and reanalysis data. The range of observational variability is indicated with gray shading or error bars. Days in which UPDATED and CONTROL are significantly different from each other at the 95% level are designated with a star below the curves or to the left of the curves.

A Lagged Response to the 11-year Solar Cycle in Observed Winter Atlantic / European Weather Patterns

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The surface response to 11-year solar cycle variations is investigated by analysing the long-term mean sea level pressure and sea surface temperature observations for the period 1870-2010. The analysis reveals a statistically significant 11-year solar signal over Europe and the North Atlantic provided the data are lagged by a few years. The delayed signal resembles the positive phase of the North Atlantic Oscillation (NAO) following a solar maximum. The corresponding sea surface temperature response is consistent with this. A similar analysis is performed on long-term climate simulations from a coupled ocean-atmosphere version of the Hadley Centre model that has an extended upper lid so that influences of solar variability via the stratosphere are well resolved. The model reproduces the positive NAO signal over the Atlantic / European sector but the lag of the surface response is not well reproduced. Possible mechanisms for the lagged nature of the observed response are discussed.

The Importance of the Stratosphere for Atlantic Climate Variability

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The North Atlantic Oscillation (NAO) is the leading mode of Northern Hemisphere winter weather and variability. It does not only modulate European weather but also influences the surface heat transfer between the ocean and the atmosphere in the North Atlantic. This influence is particularly interesting in the Labrador Sea as this region is known to play an important role in modulating the strength of the Atlantic Meridional Overturning Circulation (AMOC).

Via modulating the NAO, stratospheric polar vortex events might play a substantial role in Atlantic climate variability, including the strength of the AMOC.

We investigate the effects of different stratospheric polar vortex states on North Atlantic climate variability from 1955 to 2100. First, we use a high-top coupled global chemistry-climate model, the CESM1-WACCM from the National Centre of Atmospheric Research (NCAR). We will focus mainly on the stratospheric influence on the NAO, which in turn influences long-term variability of the Atlantic Ocean. The impact of increased greenhouse gases in the 21st century will be included in the analysis using the RCP 8.5 scenario from CMIP5. This enables us to investigate the broadly debated decrease in the strength of the AMOC under global warming and in particular the stratospheric impact. A comparison with a low-top GCM from NCAR (CCSM4) will provide information about the relative importance of the stratospheric representation in a climate model and its influence on Atlantic climate variability.

Quantifying the Effects of Natural and Anthropogenic Factors on the NH Polar Winter Stratosphere

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Variability in the strength and structure of the Northern Hemisphere (NH) stratospheric polar winter vortex also modulates the tropospheric circulation. A detailed knowledge of the vortex evolution can therefore contribute to improved surface weather forecasts. Various natural and anthropogenic forcings influence both the mean state and the variability of the stratospheric polar vortex. Natural forcings include the Quasi-Biennial Oscillation (QBO) of equatorial stratospheric winds, variations in sea surface temperatures (SSTs) where El Niño Southern Oscillation (ENSO) events play an important role, or the 11-year solar cycle. Beyond the anthropogenic factors, changes in greenhouse gases (GHGs) and ozone-depleting substances (ODs) have to be mentioned at first place. Natural and anthropogenic forcings effect the frequency and characteristics of Stratospheric Sudden Warmings (SSWs) by influencing the polar vortex.

In this study we aim to quantify the influence of the above mentioned forcings and give an estimate of their relative importance for the modulation of the polar vortex. We therefore analyze statistically a set of model simulations where the different forcings were systematically switched on and off to allow the investigation of the single factors. The experiments were performed with NCAR's Community Earth System Model (CESM), a coupled model system including an interactive ocean (POP2), land (CLM4), sea ice (CICE) and atmosphere (NCAR's Whole Atmosphere Community Climate Model (WACCM)) component. Our control experiment is a 145-year simulation with the fully coupled atmosphere-ocean version of CESM-WACCM. A second experiment is a 55-year simulation with only CESM's atmospheric component WACCM, a fully interactive chemistry-climate model extending from the Earth's surface through the thermosphere (about 140 km), with underlying climatological SSTs obtained from the coupled CESM control run. A third 55-year simulation is performed without the nudging of the equatorial QBO. All three simulations develop under conditions where GHGs are held constant at the 1960 level. In a fourth simulation, the GHGs follow the Representative Concentration Pathways (RCP) 8.5 scenario, a relatively strong scenario where the GHG concentrations and emissions increase considerably over time. From the individual simulations we can estimate the respective roles of natural and anthropogenic factors on the NH stratospheric polar vortex evolution.

The Interaction Between Stratospheric Sudden Warmings and Ozone

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Mid-winter stratospheric sudden warmings of the northern hemisphere polar vortex and the associated enhanced meridional circulation in the extratropics are known to influence ozone concentrations in the northern high latitudes. This phenomenon has been poorly studied over the past decade but has recently seen a renewed interest. The ERA-Interim reanalysis data suggests that ozone concentrations in the high latitude mid-to-lower stratosphere are increased by as much as 20% following a sudden warming. Furthermore, these ozone concentration anomalies outlast the more well known temperature anomalies that follow a sudden warming, remaining significant for up to a week longer. We investigate whether this signal is seen in current generation Earth System Models, and how accurately the structure of the associated ozone anomalies is simulated. Effects of both transport and rates of chemical destruction on ozone concentrations are considered. A preliminary study on the inverse question of whether anomalous ozone concentrations can trigger a sudden warming, and therefore dramatically alter a seasonal forecast, is presented.

The deterministic tropospheric response to a zonally-symmetrically induced stratospheric sudden warming

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We present a novel technique for efficiently generating a large ensemble of sudden-warming-like episodes in a comprehensive middle atmosphere model by a zonally-symmetric nudging technique. The influence on the troposphere over the several months following the stratospheric wind reversal is closely analogous to that expected from a warming produced by the internal dynamics of the model, and we show that the ensemble response closely resembles a composite of warmings in the free-running model.

Using such an ensemble generated with the Canadian Middle Atmosphere Model, we show that the equatorward shift of the tropospheric jet seen in the 'dripping paint' plots of Baldwin and Dunkerton can be reproduced in the absence of any initial tropospheric anomaly, confirming the downward influence of the stratosphere. A comparable tropospheric response is obtained when forcing towards the zonal mean evolution of either a split or a displacement event, suggesting that at lags of a week to several months the response is independent of the zonally-asymmetric component of the stratospheric circulation. Despite the zonal symmetry of the forcing in the stratosphere, the tropospheric response is highly zonally-asymmetric, and is consistent with zonal asymmetries in the response to sudden warmings found in reanalyses. The changes in near surface winds over the Atlantic are of the order of several meters per second and persist for sixty days, implying a non-negligible forcing of the ocean circulation.

The Surface Climate Response to 11-Yr Solar Forcing: Observational Analyses, Comparisons With GCM Simulations, and Tests of the Stratospheric (UV-Ozone) Forcing Mechanism

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The surface climate response to 11-yr solar forcing during northern winter is first re-estimated by applying a multiple linear regression (MLR) statistical model to Hadley Centre sea level pressure (SLP) and sea surface temperature (SST) data over the 1880-2009 period. In addition to a significant positive SLP response in the North Pacific found in previous studies, a positive SST response is obtained across the midlatitude North Pacific. Negative but insignificant SLP responses are obtained in the Arctic. The derived SLP response at zero lag therefore resembles a positive phase of the Arctic Oscillation (AO). Evaluation of the SLP and SST responses as a function of phase lag indicates that the response evolves from a negative AO-like mode a few years before solar maximum to a positive AO-like mode at and following solar maximum. For comparison, a similar MLR analysis is applied to model SLP and SST data from a series of simulations using an atmosphere-ocean general circulation model (EGMAM; Bal et al., 2011). The simulations differed only in the assumed solar cycle variation of stratospheric ozone. It is found that the simulation that assumed an ozone variation estimated from satellite data produces solar SLP and SST responses that are most consistent with the observational results, especially during a selected centennial period. In particular, a positive SLP response anomaly is obtained in the northeastern Pacific and a corresponding positive SST response anomaly extends across the midlatitude North Pacific. The model response versus phase lag also evolves from a mainly negative AO-like response before solar maximum to a mainly positive AO response at and following solar maximum.

To test whether the most successful model simulation is primarily a consequence of stratospheric (solar UV-ozone) forcing, MLR analyses of model zonal wind and temperature data are also carried out for individual months in northern winter. It is found that the simulation that produced a good agreement with the observationally estimated surface climate response is characterized by an unusually strong zonal wind anomaly in the northern midlatitude upper stratosphere during early winter at solar maximum relative to solar minimum (about 5.5 m/s). The centennial period of this simulation that produced the best agreement yielded an even larger zonal wind anomaly (7.5 m/s). This wind anomaly is a result of the stronger imposed solar cycle variation of ozone in the upper stratosphere for this simulation. It propagates poleward and downward during the winter, perturbing tropospheric circulation, and initiating ocean-atmosphere feedbacks that lead to the observed SLP and SST responses in the North Pacific. Overall, therefore, the results support the “top-down” mechanism originally described by Kodera and Kuroda (2002).

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The Boreal Spring Stratospheric Final Warming and Its Interannual and Interdecadal Variability

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Abstract:

Based on the daily NCEP/DOE reanalysis II data, dates of the boreal spring Stratospheric Final Warming (SFW) events during 1979-2010 are defined as the time when the zonal-mean zonal wind at the central latitudes (65°-75°N) of the westerly polar jet drops below zero and never recovers until the subsequent autumn.

It is found that the SFW events occur successively from the mid to the lower stratosphere and averagely from the mid to late April with a temporal lag of about 13 days from 10 hPa to 50 hPa. Over the past 32 years, the earliest SFW occurs in mid March whereas the latest SFW happens in late May, showing a clear interannual variability of the time of SFW. Accompanying the SFW onset, the stratospheric circulation transits from a winter dynamical regime to a summertime state, and the maximum negative tendency of zonal wind and the strongest convergence of planetary-wave are observed.

Composite results show that the early/late SFW events in boreal spring correspond to a quicker/slower transition of the stratospheric circulation, with the zonal-mean zonal wind reducing about 20/5 m s⁻¹ at 30 hPa within 10 days around the onset date. Meanwhile, the planetary wave activities are relatively stronger/weaker associating with an out-of-/in-phase circumpolar circulation anomaly before and after the SFW events in the stratosphere. All these results indicate that, the earlier breakdown of the stratospheric polar vortex (SPV), as for the winter stratospheric sudden warming (SSW) events is driven mainly by wave forcing; and in contrast, the later breakdown of the SPV exhibits more characteristics of its seasonal evolution. Nevertheless, after the breakdown of SPV, the polar temperature anomalies always exhibit an out-of-phase relationship between the stratosphere and the troposphere for both the early and late SFW events, which implies an intimate stratosphere–troposphere dynamical coupling in spring.

In addition, there exists a remarkable interdecadal change of the onset time of SFW in the mid 1990s. On average, the SFW onset time before the mid 1990s is 11 days earlier than that afterwards, corresponding to the increased/decreased planetary wave activities in late winter-early spring before/after the 1990s.

Key words: stratospheric final warming, onset date, wave activity, anomalous circulation

Reference: J. G. Hu, R. C. Ren, Y. Y. Yu, et al. 2013. The Boreal Spring Stratospheric Final Warming and Its Interannual and Interdecadal Variability. *Sci China Earth Sci*, in press.

Eastward phase-shift of Southern-Hemisphere planetary waves in the lower stratosphere

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Observational studies have shown that planetary waves in the Southern-Hemisphere stratosphere had shifted eastward in October in the past few decades, showing a wavenumber-1 spatial pattern of trends. Previous works suggested that the eastward phase-shift is linked to SST warming in the central Pacific, and that it is due to altered wave guide.

In the present work, using satellite observational data, we first show that the eastward phase-shift of planetary waves mainly exists in the lower stratosphere, while warming trends are located in the Antarctic polar cap in the middle and upper stratosphere, due to increasing wave activity. Second, we perform GCM simulations to demonstrate that stratospheric ozone changes can also result in longitudinal phase-shifts of planetary waves. As total ozone is decreased, the wave phase shifts eastward. By contrast, increasing total ozone leads to westward phase-shift. Our analysis reveals that stratospheric ozone changes alter atmospheric thermal structures and zonal flows, which consequently change the wave guide and cause longitudinal phase-shift of planetary waves.

An Improved Idealized General Circulation Model for the Study of Stratosphere-Troposphere Coupling and the Seasonal Cycle of Tropical Upwelling

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In their 1994 article in the *Bulletin of the American Meteorological Society*, Held and Suarez designed an idealized forcing to explore the impact of model numerics on the general circulation of the atmosphere. Their model setup, a simple recipe that replaces radiative and convective schemes with Newtonian relaxation towards a prescribed equilibrium temperature profile, has taken on new life as an idealized model of the atmosphere for research, and led to discoveries which have both increased our understanding of the atmosphere and facilitated improvements of comprehensive models. Polvani and Kushner (2002) extended the “Held-Suarez” forcing upward to create an idealized model of the stratosphere-troposphere system. Recent studies, however, have shown that these adjustments to improve the representation of the stratosphere inadvertently lead to a number of problems: biases in the position of the tropospheric jet streams, the presence of atmospheric flow regimes, and a low tropopause.

We trace all of these problems back to bias in the lower stratospheric temperatures, and correct them by adjusting the equilibrium temperature profile. The new blend between the “Held-Suarez” and “Polvani-Kushner” forcings preserves the coupling between the troposphere and stratosphere, and further permits one to create a more realistic seasonal cycle of the atmospheric circulation. In particular, the simple model can capture the seasonal cycle of the Brewer-Dobson Circulation and tropical upwelling. We strongly recommend that it be used for future idealized studies of the stratosphere-troposphere system.

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Extra–Tropical Atmospheric Response to ENSO in the CMIP5 Models

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The extra–tropical atmospheric response to El Niño/Southern Oscillation (ENSO) is assessed in the historical and pre–industrial control CMIP5 simulations. This analysis considers two types of El Niño events, characterized by positive sea surface temperature (SST) anomalies in either the central equatorial Pacific (CP) or eastern equatorial Pacific (EP), as well as EP and CP La Niña events, characterized by negative SST anomalies in the same two regions. Seasonal mean geopotential height anomalies in key regions typify the magnitude and structure of the disruption of the Walker circulation cell in the tropical Pacific, upper tropospheric ENSO teleconnections and the polar stratospheric response.

In the CMIP5 ensembles, the magnitude of the Walker cell disruption is correlated with the strength of the mid–latitude responses in the upper troposphere i.e., the North Pacific and South Pacific lows strengthen during El Niño events. The simulated responses to El Niño and La Niña have opposite sign. The seasonal mean extra–tropical, upper tropospheric responses to EP and CP events are indistinguishable. The ENSO responses in the MERRA reanalysis lie within the model scatter of the historical simulations. Similar responses are simulated in the pre–industrial and historical CMIP5 simulations.

Overall, there is a weak correlation between the strength of the tropical response to ENSO and the strength of the polar stratospheric response. ENSO–related polar stratospheric variability is best simulated in the “high–top” subset of models with a well–resolved stratosphere.

Modelling the Impacts of HFCs on Climate and Stratospheric Ozone: First Results

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Hydrofluorocarbons (HFCs) are strong greenhouse gases that can indirectly modify the ozone layer by changing the stratospheric climate. Rapidly increasing HFC emissions may lead to significant stratospheric change by the mid-21st century, potentially counteracting the ozone and climate benefits of the Montreal Protocol and Kyoto Protocol. Each HFC compound has different chemical and radiative properties, and emissions growth rates, and thus will have different stratospheric impacts. However, the full ozone and climate impacts of HFCs, as well as the chemistry and climate benefits of limiting future growth in HFC emissions, have not been quantified.

We will present the first results of a modelling study aiming to assess the impacts of HFCs on global climate and stratospheric ozone. This study will rely on two chemistry-climate models (CCMs): the NASA Goddard Space Flight Center (GSFC) two-dimensional (2D) atmospheric CCM and a three-dimensional (3D) fully-coupled ocean-atmosphere version of the Goddard Earth Observing System CCM (GEOSCCM). The computational efficiency of the NASA GSFC 2D model makes it ideal for model development and for performing multiple sensitivity simulations. We will present simulations highlighting the newly-integrated HFC chemistry in the NASA GSFC 2D model. Ground-based and satellite remote sensing datasets will be used to validate modelled HFC concentrations in the recent past.

The ocean-atmosphere GEOSCCM will be used to estimate the impacts of HFCs on both tropical and polar climate, and will provide an absolute estimate of the HFC contribution to both surface warming and stratospheric climate change. As a preliminary step, we will present simulations of the 2000-2050 period forced by various future emissions scenarios for the primary greenhouse gases and ozone-depleting substances.

Leading Modes of Variability in Antarctic Climate: Covariance of Ozone and Sea Ice in AO-UMUKCA Control Integration

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Changes in sea ice significantly modulate climate change because of its high reflective and insulating nature. While Arctic Sea Ice Extent (SIE) shows a negative trend, Antarctic SIE shows a weak but positive trend, estimated at $0.127 \times 10^6 \text{ km}^2$ per decade [Turner et al., 2013]. The trend results from large regional cancellations, more ice in the Weddell and the Ross seas, and less ice in the Amundsen - Bellingshausen seas. A number of studies have demonstrated that stratospheric ozone depletion has had a major impact on the atmospheric circulation, causing a positive trend in the Southern Annular Mode (SAM), which has been linked to the observed positive trend in autumn sea ice in the Ross sea. However, other modelling studies show that models forced with prescribed ozone hole simulate decreased sea ice in all regions comparative to a control run, [for a review see Thompson et al., 2011].

We investigate the relationship between anomalous Antarctic ozone years and the subsequent changes in Antarctic sea ice distribution in a 100 year pre-industrial control simulation using the AO-UMUKCA model. The model has a horizontal resolution of $3.75^\circ \times 2.5^\circ$ degrees in longitude and latitude; and 60 hybrid height levels in the vertical, from the surface up to a height of 84 km. The ocean component is the NEMO ocean model on the ORCA2 tripolar grid, and the sea ice model is CICE. We apply EOF analysis to the seasonal anomalies of sea ice concentration, MSLP, and Z 500, and identify the leading climate modes controlling the variability of Antarctic sea ice in each case. We also discuss regional differences in sea ice distribution and their relationship with ENSO, SAM, PSA, and wave 3 climate indices.

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Importance of the radiative base state for the dynamical variability of the stratosphere

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We will show how the thermodynamic equilibrium state in a dry GCM impacts the dynamics of the stratosphere and troposphere-stratosphere interactions. Such models represent efficient tools to analyze aspects of atmospheric dynamics. In dry primitive equation models, the atmosphere is relaxed against a predefined base state. Perturbation experiments may modify the relaxation temperature field, relaxation time scale, or the orography to force specific wave responses. In the past, the impact of the form of the base state has received only limited attention. We argue that nonlinearities in the dynamics require a careful construction of the base state. The presence of a polar night vortex (of radiative origin) is crucial for realistic troposphere-stratosphere interactions. Similarly, we show that a relaxation temperature field and time scale based on radiative transfer calculations improves the seasonality of upwelling in the tropical lower stratosphere. Here, we present an improved and fully analytically described base state and analyze the effects of perturbing the relaxation temperature, time scale, and tropospheric forcing. Specifically, we focus on nonlinear dynamical responses in experiments related to stratosphere-troposphere coupling, stratospheric circulation, and the nature and frequency of stratospheric sudden warmings.

Simultaneous Occurrence of Polar Stratospheric Clouds and Upper-tropospheric Clouds Caused by Blocking Anticyclones in the Southern Hemisphere

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This study statistically examines the simultaneous appearance of polar stratospheric clouds (PSCs) and upper tropospheric clouds (UCs) using the CALIPSO lidar observations for five austral winters of 2007-2011. The occurrence frequency of clouds in the height range of 15-25 km is significantly correlated with that in 9-25 km. From the analyses based on tropopause-relative altitude, the occurrence frequency of clouds at higher than 6 km above the tropopause (i.e. PSCs) is significantly correlated with that around and slightly above the tropopause. The UCs observed simultaneously with PSCs reported in previous case studies are possibly located around and slightly above the tropopause rather than in the troposphere. It is shown that the simultaneous occurrence of PSCs and UCs is frequently associated with blocking highs having large horizontal scales (several thousand kilometres) and tall structure (up to a height of ~15 km). The longitudinal variation of blocking high frequency accords well with that of the simultaneous occurrence frequency of PSCs and UCs. This fact suggests that the blocking highs provide a preferable condition for the simultaneous occurrence of PSCs and UCs. Moreover, PSC compositions are investigated as a function of relative-longitude of the anticyclones including blocking highs. It is seen that relatively high proportions of STS (super-cooled ternary solutions), Ice, and Mix2 (mixture of nitric acid trihydrate and STS) types are distributed to windward of, around, and to leeward of the anticyclones in the westerly background flows, respectively.

Reference: Kohma, M., and K. Sato (2013), Simultaneous occurrence of polar stratospheric clouds and upper-tropospheric clouds caused by blocking anticyclones in the Southern Hemisphere. *Atmos. Chem. Phys.*, 13, 3849-3864, doi:10.5194/acp-13-3849-2013.

Long term trends of middle latitude stratospheric winds from NCEP/NCAR

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NCEP/NCAR reanalysis provides us winds time series for period 1958 – 2010 in $2.5^\circ \times 2.5^\circ$ vertical resolution. That is why we can study long term trend of this important characteristic. We focus on two pressure levels (100 and 10 hPa) in middle latitude bands (52.5°N). We study wind direction and speed and their connection to the other tropospheric/stratospheric phenomena (NAO, QBO etc.). We can compare behaviour of wind characteristic in different sectors of middle latitude, study their sensitivity to these phenomena and study influence of wave propagation (planetary waves).

Modulation of the Southern Annular Mode through UV change

-a chemistry climate model simulation-

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Previous studies of the observation show that the Southern Annular Mode (SAM) tends to be modulated according to the 11-year solar cycle. In fact, late-winter SAM signal in the lower troposphere tends to be extended to the upper stratosphere and persist until the following summer in the solar-max years, whereas it is mostly restricted in the troposphere and disappears quickly in the solar-min years.

To examine the source of such solar cycle modulation of the SAM, three sets of 42-year runs of our chemistry-climate model had been performed. The only difference of these three runs is a small realistic change of the ultra-violet (UV) radiation.

Our model satisfactorily simulates the solar cycle modulation of the SAM signal; the stratosphere-troposphere coupling tends to be stronger with the increase of the UV. The result suggests that the source of observed solar cycle modulation comes from UV change.

To examine how the solar cycle modulation occurs with small change of the UV, lagged regression analysis is performed based on the dominant SVD mode of zonal-mean wind and vertical component of E-P flux on October for each run. We found that although signals of zonal wind and E-P flux are very similar in October, they develop to very different states according to the UV strength. In fact, clear downward propagation of stratospheric SAM signal to the troposphere is found on December in stronger UV run, but such downward signal is very unclear for weaker UV run. Analysis of wave propagation/forcing shows that such difference of downward propagation of stratospheric signal originates mostly from the wave propagation in the troposphere. In fact, wave propagation tends to more enhanced toward the tropical troposphere in stronger UV run, but vertical propagation is more enhanced for weaker UV run. Possible scenario of solar cycle modulation of SAM signal is discussed.

Impacts of Ocean-Atmosphere Coupling on Southern Annular Mode

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Climate in the Southern Hemisphere (SH) stratosphere and troposphere has undergone significant changes in recent decades, especially in the austral summer. These changes are strongly projected to a shift of the Southern Annular Mode (SAM) towards its positive polarity. The SAM variations drive coherent responses in the Southern Ocean circulation and sea surface temperature (SST). However, it is poorly understood whether and how the SAM-induced ocean anomalies might interact back with the atmosphere and impact the SAM. In this study we investigate the effects of ocean-atmosphere coupling on the structure, strength and trend of the SAM using the Goddard Earth Observing System – Coupled Atmosphere-Ocean-Chemistry Climate Model (GEOS-AOCCM).

We perform coupled ensemble simulations of the recent past (1960-2010) with the GEOS-AOCCM. We also conduct uncoupled simulations with the atmosphere-only version of the GEOS-AOCCM, using SSTs and sea ice concentrations produced by the coupled simulations as boundary conditions. The differences between these two ensemble simulations quantify the effects of ocean-atmosphere coupling.

The coupled and uncoupled simulations have very similar results on stratospheric climate change and ozone depletion. However, air-sea interactions act to reduce the stratospheric SAM variability during austral summer. Near the surface, the coupled simulations produce smaller SAM trends than the uncoupled simulations. The e-folding timescale of the SAM is shorter in the coupled experiments than in the uncoupled experiments. These results indicate that ocean-atmosphere coupling has a negative feedback on the SAM. Possible mechanisms responsible for the ocean negative feedback to the SAM will be discussed.

Investigation of Reflective and Absorptive Winters in Response to Natural and Anthropogenic Forcings in CESM-WACCM

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Vertical propagation of extratropical planetary waves with long horizontal wavelength plays a substantial role in controlling the dynamics of the northern hemisphere winter stratospheric vortex. During some winters, the stratospheric flow is characterized by strong wave absorption in the stratosphere, resulting in strong wave-mean-flow interaction (i.e. absorptive winters). The wave absorption induces a descending vortex-deceleration, which reaches the troposphere and affects the weather systems for a few weeks. During other winters, planetary waves are reflected back down to the troposphere, affecting the structure of tropospheric planetary waves and inducing the zonal-mean and eddy anomalies (i.e. reflective winters).

To examine what determines the type of winter dynamics using a combination of observational analysis, we investigate a number of experiments with the chemistry-climate model CESM-WACCM under various natural and anthropogenic forcings such as quasi-biennial oscillation (QBO), sea surface temperature (SST), green house gasses (GHGs) and ozone depleting substances (ODs). In order to characterize the evolution of vertical wave propagation over time, the DWC index is defined based on the PC of leading EOF mode of zonal-mean wave-1 eddy meridional heat flux between 30 and 100 hPa. Wave-mean flow diagnostics with slight modifications following Perlwitz and Harnik (2003) are also employed. Understanding what controls the type of stratospheric winter may lead to improvement of its representation in models, and thus to better predictions of ozone, climate, and even tropospheric weather.

Impact of the representation of the stratosphere on tropospheric weather forecasts

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The mid-winter polar stratosphere has great potential as a source of additional predictability for medium and extended-range weather forecasts. Several studies have demonstrated that during particularly dynamically active periods in the stratosphere known as stratospheric sudden warmings (SSW), tropospheric forecasts can be sensitive to the stratospheric evolution on timescales of 10 days. A key limitation of these studies has been their idealised nature. Similarly, there has been little investigation of how and why changes to the stratosphere influence tropospheric behaviour and what this means for the design of future numerical weather prediction systems.

This work addresses the above issues by performing a series of ensemble experiments using the Met Office Unified Model with a range of different vertical resolutions. These include a 'low top' model with an upper boundary in the mid-stratosphere and two 'high top' models with a similar upper boundary in the mesosphere, but with differing stratospheric vertical resolutions. The forecasts were run at these resolutions around the SSW of February 2010. The focus is on short to medium range timescales and so the forecasts are only out to 30 days. Statistically significant differences in surface fields, with mean differences in surface pressure of up to 3hPa are found between 'high top' and 'low top' simulations as soon as 5 days into the forecast. These tropospheric differences resemble a negative North Atlantic Oscillation pattern, and are likely related to the inability of the 'low top' model to effectively capture the SSW. No statistically significant differences are detected in surface fields between the two 'high top' models, suggesting that the extra vertical resolution does not influence the surface forecast at this timescale.

The second part of this study investigates whether the dynamical interaction between the stratosphere and the troposphere is mediated by changes to the development of baroclinic eddies. A wave breaking detection method is developed to assess Rossby wave breaking in the troposphere. Changes in wave breaking are detected between simulations containing a SSW and those without, suggesting that the stratosphere may affect the development of Rossby waves in the troposphere. The tropospheric changes are consistent with observed climatological influences of stratospheric conditions on tropospheric wave breaking.

Northern winter Climate Change: Uncertainty in CMIP5 projections related to Stratosphere - Troposphere coupling

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Future changes of the stratospheric circulation could have an important impact on tropospheric climate change in the Northern Hemisphere (NH), given that sea level pressure is known to respond not only to tropospheric circulation variations but also to vertically coherent troposphere-stratosphere circulation variations. Here, stratospheric climate change and its potential to influence surface climate change as simulated by the Coupled Model Intercomparison Project – phase 5 (CMIP5) model ensemble are assessed. We focus on Northern winter climate projections for the period 1961 to 2100, RCP8.5 scenario. It is found that for about 70% of the CMIP5 models, polar stratospheric zonal winds will weaken at high latitudes and strengthen at low latitudes by the end of the century. While the weakening of the polar stratospheric zonal winds is in agreement with previous single model studies carried out with models with tops above the stratopause, within the CMIP5 model set it is found that the location of the model top and better performance of stratospheric variability at all time scales are not good predictors of the polar stratospheric zonal wind response to anthropogenic climate change. A multiple linear regression analysis used to isolate the implications of the spread in the polar stratospheric wind response shows that there is a considerable inter-model spread in sea level pressure change that is likely to be associated with the inter-model spread of the Arctic winter stratospheric change.

Mechanisms mediating the 11-yr solar cycle influence on climate in the CMIP5 historical simulations

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The variation of the incoming solar irradiance over the course of the 11-yr solar cycle is a significant source of stratospheric variability. Dynamical mechanisms could amplify and transfer solar signals from the stratosphere to the troposphere and even the surface in a “top-down” pathway. In the opposite direction, “bottom-up” mechanisms could mediate solar signals from the surface to the troposphere via air-sea coupling. A robust identification and physical explanation of solar cycle signals in the troposphere may advance our understanding of the climatic response to the 11-yr solar cycle as brought about from “top-down” and “bottom-up” mechanisms, respectively. The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides an unprecedented opportunity towards this direction because for a first time different coupled models are driven by spectral solar irradiance changes. We here analyse archived “historical” simulations (1850-2009) with a lead/lag multiple linear regression model, focusing onto responses of the lower stratosphere, troposphere and oceans. Both the lower stratosphere and troposphere warms in solar maximum, whereas a significant warming is identified mainly over the western Pacific and Indian oceans. The stratosphere responds instantaneously to the solar forcing but in the troposphere lagged signals can be identified in some models. We further categorize models in “low- and high-top, depending on the inclusion or not of detailed stratospheric dynamics. This classification is found educative when the relative role of the “top-down” versus “bottom-up” forcing is investigated. The simulated solar signals are compared with those from the 20th century reanalysis project.

The Influence of Stratospheric Vortex Displacements and Splits on Surface Climate

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A strong link exists between stratospheric variability and anomalous weather patterns at the Earth's surface. Specifically, during extreme variability of the Arctic polar vortex termed a ``weak vortex event'', anomalies can descend from the upper stratosphere to the surface on time scales of weeks. Subsequently the outbreak of cold-air events have been noted in high Northern Latitudes, as well as a quadrapole pattern in surface temperature over the Atlantic and western European sectors but it is currently not understood why certain events descend to the surface while others do not. In this study we compare a new classification technique of weak vortex events, based on the distribution of potential vorticity, with that of an existing technique and demonstrate that the subdivision of such events into vortex displacements and vortex splits has important implications for tropospheric weather patterns on weekly-monthly time scales. Using reanalysis data we find that vortex splitting events are correlated with surface weather and lead to positive temperature anomalies over eastern North-America of more than 1.5K, and negative anomalies over Eurasia of up to -3K. Associated with this is an increase in high-latitude blocking in both the Atlantic and Pacific sectors and a decrease in European blocking. The corresponding signals are weaker during displacement events, although ultimately they are shown to be related to cold-air outbreaks over North America. Due to the importance of stratosphere-troposphere coupling for seasonal climate predictability, identifying the type of stratospheric variability in order to capture the correct surface response will be necessary.

Recent Antarctic Climate Change and Its Relation to Stratospheric Ozone Depletion and Increases on Long-lived Greenhouse Gases

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Antarctica has experienced some of the largest rates of both surface warming and cooling found anywhere on the planet. Unlike the Arctic, where sea ice has been declining, sea ice extent in the Southern Ocean has been increasing in recent decades despite some regional decreases. Stratospheric ozone depletion has generally been implicated in aspects of climate change in the Southern Hemisphere¹. Often such inferences are based on climate model simulations that exclude ozone chemistry. Trends in Antarctic sea ice are generally not reproduced in contemporary climate model simulations²; consequently, at present, the causes of sea ice trends in the Southern Ocean are poorly understood.

Here we present results using simulations by the NIWA-UKCA global atmosphere-ocean chemistry-climate model³; these simulations will contribute to the Chemistry-Climate Modelling Initiative (CCMI). We use an ensemble of three simulations following the “REF-C2” specification with all anthropogenic forcings operating, as well as sensitivity simulations in which ozone depletion, or alternatively increases in greenhouse gases (GHGs), have been suppressed⁴. In these simulations, we study the processes linking atmospheric and sea ice change. We find that the patterns of sea ice trends in some of the simulations are remarkably similar to observations for the post-1980 period. In the REF-C2 simulations and in the simulation with suppressed GHG increases, total sea ice extent declines markedly until around 1980 but increases or remains unchanged for a period thereafter. We present evidence based on ice-core data, supporting the notion that there has indeed been such a turn-around. By contrast, the simulation with suppressed ozone depletion does not exhibit this turn-around. There are also important differences in the geographic patterns of sea ice trends among the REF-C2 ensemble members. This suggests the presence of regional decadal-scale climate variations which may help explain the lack of agreement on patterns of sea ice change characterizing recent climate model simulations².

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Stratosphere key for wintertime atmospheric response to warm Atlantic decadal conditions

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The factors driving the multidecadal North Atlantic Oscillation (NAO) fluctuations and the associated trends remain unclear, especially after the last reversing of the NAO-trend seen after the mid of the 1990s. There is evidence that the observed low frequency changes in winter NAO drive a significant portion of Atlantic Multidecadal Variability (AMV). However, whether the observed decadal NAO changes can be forced by the ocean is controversial. In this work (Omrani et. al. 2013) we show, through observational analysis and atmospheric model experiments, that large-scale Atlantic warming associated with AMV drives a high-latitude precursory stratospheric warming in early to mid winter that propagates downward, resulting in a negative tropospheric NAO in late winter. The mechanism involves stratosphere/troposphere dynamical coupling and can be simulated to a large extent, but only with a stratosphere-resolving model (i.e., high-top). Further analysis shows that this precursory stratospheric response can be explained by the shift of the daily extremes toward more major stratospheric warming events. This shift cannot be simulated with the atmospheric (low-top) model configuration that poorly resolves the stratosphere and implements a sponge layer in upper model levels. While the potential role of the stratosphere in multi-decadal NAO and Atlantic meridional overturning circulation changes has been recognised, our results show that the stratosphere is an essential element of extra-tropical atmospheric response to the Atlantic ocean variability. Our findings suggest that the use of stratosphere resolving models should improve the simulation and prediction of extra-tropical climate in decadal time-scales, and lead to a better understanding of natural and anthropogenic climate change.

Reference:

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Impacts on SH tropospheric circulation predictability of incrementing stratosphere vertical resolution in climate models

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The study documents the predictability of seasonal means of 200-hPa and 850-hPa geopotential heights in the Southern Hemisphere (SH) during winter and summer. Ensembles of lead-1-month climate predictions outputs for DJF and JJA available from the WCRP/CHFP-SHFP Project are used. In particular, 4 different climate models with “high-top” versions, which resolve the stratosphere, and “low-top” versions, which do not, are considered. Predictability is defined as the ratio between the interannual standard deviation of the ensemble mean (S) and the ensemble spread (N). Predictability changes associated with changes in model vertical resolutions are described by computing the ratio between high-top model predictability and low-top model predictability.

The predictability analysis performed for each of the models considered, shows that for all of them, signal is larger over the Bellingshausen-Amundsen seas for all seasons and levels considered. Also, some models present at around 45°S significant signal values, but its zonal location is model dependent. In DJF, predictability at high levels is also large at tropical and subtropical latitudes in the South Pacific, likely related with the atmospheric response to ENSO. Nevertheless, that signal is not evident in JJA. At low levels, DJF signal is also large over northern Australia and, for some models, over the Maritime Continent too. On the other hand, noise is large at middle and high latitudes and, in general, is larger (smaller) in DJF than in JJA at high (low) levels.

Predictability changes between models resolving the stratosphere and those who do not, are model dependent for all seasons and levels considered. CMAM model presents in general alternating regions of increased and reduced predictability, concentrated at high latitudes of the South Pacific, and mainly associated with signal changes. On the other hand, ARPEGE model shows in general no improvement of SH circulation predictability with better resolution of stratosphere. Exceptions are the southern tip of South America at low levels and the vicinity of the Antarctic Peninsula at both levels, where predictability improvement is found for the ARPEGE high-top version. In addition, IFS high-top model clearly improves predictability at high levels in JJA, mainly associated with noise reduction. Although, at low levels and particularly in DJF, predictability provided by this model largely decreases at the tropics. Finally, predictability improvements provided by the HadGem high-top model, are larger in JJA than in DJF. Such changes, which are more evident at high levels, are mainly associated with noise reductions at tropical regions and signal increases at middle and high latitudes.

A Numerical Experiment on Formation of Tropopause Inversion Layer Associated with an Explosive Cyclogenesis: Possible Role of Inertia-Gravity Waves

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Tropopause Inversion Layer (TIL) is a persistent layer with high static stability (e.g., Birner et al., 2002). Although some formation mechanisms of the TIL have been proposed, details are not understood well (e.g., Wirth 2003; Randel et al. 2007). We perform a numerical experiment with a regional atmospheric model, the Japan Meteorological Agency Non-hydrostatic Model (JMA-NHM). The model has 200 layers in the vertical from the surface to 25 km in altitude, and the horizontal domain is 4140 km x 4000 km around Japan with a horizontal resolution of 20 km. The time integration period is 72 hours from 19th to 22nd in February, 2009, during which a typical explosive cyclogenesis was observed. For the initial and boundary conditions, we use NCEP FNL.

Although the TIL in the model is stronger in negative vorticity areas as observed (Birner et al., 2002), the relationship is clear only at the developing and mature stages of the cyclone, suggesting that the time evolution of the cyclone plays an important role in the formation of the TIL. In order to clarify dynamical formation processes of the TIL, a three-dimensional structure of the squared Brunt-Väisälä frequency, N^2 , is analyzed. An arc-shaped wave packet (Fig. 1) propagating northward from a jet streak associated with the cyclone satisfies the dispersion relation of inertia-gravity wave with a period of about 300 minutes. Histograms of N^2 at the TIL classified by d^2w/dz^2 and dw/dz at the TIL show that enhancement of d^2w/dz^2 by vertically-propagating gravity waves has a significant impact on the strength of the TIL. The effect of gravity waves on the TIL is clearer in the regions where relative vorticity at the tropopause is negative. This result implies that gravity waves may play an important role in making the negative correlation between the strength of the TIL and relative vorticity at the tropopause.

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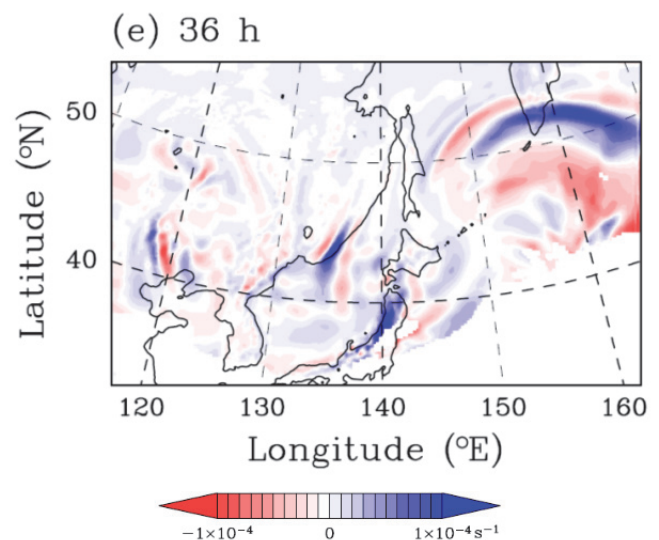


Figure 1 Horizontal maps of dw/dz at 260 hPa at $t = 36$ h.

A Climatological study on LiDAR observations of middle atmospheric gravity wave activity over Reunion Island (20.8°S, 55.5°E)

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Abstract

In this paper, climatological characteristics of the gravity wave activities are studied using temperature profiles obtained from Rayleigh lidar located at Reunion Island (20.8°S, 55.5°E) over a period of ~14 years (1994-2007). Gravity wave (GW) study has been performed over the height range from 30 to 65 km. The present study documents the GW characteristics in terms of time (frequency), height (wave number) and GW associated Potential Energy and their seasonal dependences. Generally, the temporal evolution of temperature profile illustrates the downward phase propagation indicating that the energy is propagating upward. The wave activity is clearly visible with the wave periods ranging from 260 min to 32 min. The dominant components have vertical wavelengths in the range of about ~4 km to 35 km. The potential energy over the height region from 30 km to 65 km are calculated and presented. It is found that the seasonal variation of potential energy is maximum during summer in the upper stratosphere and lower mesosphere. A semiannual variation is seen in the gravity wave activity over all height ranges in the months of February and August.

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An analysis of Double Tropopause formation and its relationship to the Tropopause Inversion Layer during Stratosphere-Troposphere Exchange events.

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Double tropopauses (DT) are a result of an overlap of the polar and tropical tropopauses poleward of the subtropical jet and are important because of their location in the Upper Troposphere Lower Stratosphere (UTLS). More precisely, DTs have been associated with the poleward transport of upper tropospheric air into the lower stratosphere [Homeyer et al., 2011], which redistributes radiatively active species and impacts Earth's radiative budget.

Recent studies of the DT have shown conflicting evidence for the origin of air within this structure [Homeyer et al., 2011; Wang and Polvani, 2011] and have found that the DT could not form within baroclinic low pressure systems without the presence of the tropopause inversion layer (TIL) [Wang and Polvani, 2011]. The analysis presented here seeks to address these issues by answering the following questions: Is the DT associated with high latitude stratospheric air or low latitude upper tropospheric air or both? Does the relationship found by Wang and Polvani [2011] occur in the real atmosphere and if so why?

In this study both satellite observations and model simulations are utilized. HIRDLS is a high resolution infrared satellite instrument with global coverage and a resolution of 1 km in the vertical and 100 km along track. CLaMS is a transport model which uses Lagrangian transport and is well suited for UTLS studies since it is designed to simulate transport in regions with strong transport barriers such as the tropopause. In the first part of this study the relationship between the DT and the TIL is analysed in the northern hemisphere using HIRDLS temperature data. Results show that DT frequency generally decreases/increases in the tropics/extratropics as the TIL above the first tropopause increases in strength. Further investigation using ECMWF ERA-Interim data reveals that DTs associated with a strong TIL coincide with anticyclonic circulations and strong upward vertical motion, suggesting the warm conveyor belt. A case study confirms this relationship. DT formation is studied further by examining transport within this structure using CLaMS. First monthly climatologies of CLaMS water vapor and ozone data are produced and then compared to data from HIRDLS. After close equivalence between these two datasets is verified CLaMS simulations are generated for a couple of regions in the northern hemisphere that are, in general, strongly associated with STE events. Transport within the DT as it forms is analysed for these two regions. This represents the first step of a larger analysis that will investigate DT formation and its impact on the UTLS.

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Stratospheric and tropospheric circulation changes in response to a zonally asymmetric ozone field (ERA40) of the boreal stratosphere

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We studied the inter-annual and intra-seasonal influence of stratospheric zonally asymmetric ozone on the stratospheric and tropospheric circulation by using the well-known GCM-ECHAM5. The control model simulation was run for 40 years with AMIP SSTs from 1960 until 1999 using a mean seasonal cycle of zonal mean ozone from climatology. A further simulation was carried out with the prescribed deviation from zonal mean ozone based on monthly means of zonally asymmetric ozone of each year in the boreal extra-tropics derived from ERA-40 reanalysis data set (1960-1999). In comparison with the control run the altitude-longitude cross section on 65°N of the polar vortex reveal an inter-decadal westward shift which is statistically significant, and is confirming the result of former similar studies for the 1990s. During the period of 1980 – 1999 the reanalysis data show an increase of the amount of ozone considering the zonal ozone anomaly. We found that the number of stratospheric sudden warming events increased significantly in the simulation. Furthermore, the inter-annual variability of the Northern Annular Mode (NAM) was significantly enhanced in the middle and upper stratosphere for midwinter and in the lower stratosphere for early winter but reduced during late winter - early spring. Under the action of zonally asymmetric ozone a weakening of the Arctic Oscillation (AO) was identified between the mid-1980s and the mid-1990s. The prediction skill of the mean AO by the daily stratospheric NAM increased in midwinter for a lead time of 10 days. Furthermore, we examined the influence of the zonally asymmetric ozone on Rossby wave breaking in the upper troposphere and found a significant westward shift of poleward Rossby wave breaking events over Western Europe in the winter time. The possible mechanisms will be discussed in more details. By this we show a strong influence of the stratospheric zonally asymmetric ozone on the stratospheric and tropospheric circulation due to enhanced dynamical coupling processes.

Using age to diagnose the stratospheric circulation and its trends

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Stratospheric climate models invariably predict an acceleration of the stratospheric diabatic circulation under conditions of increasing greenhouse gases (e.g., Butchart et al., 2006). Attempts to confirm this result by seeking evidence of decreasing mean age of stratospheric air (Engel et al., 2008; Stiller et al., 2012) have proved negative. Reasons for this lack of success may include the short data record, given the high degree of stratospheric interannual variability. However, there is the additional uncertainty of the relationship between the strength of the circulation and age; the latter is, in general, sensitive to the intensity of mixing and to the structure, and not just the strength, of the circulation,.

Nevertheless, some aspects of age bear a direct relationship to the strength of the diabatic circulation; in a “leaky tropical pipe” model, the age difference between tropics and extratropics on any isentropic surface is simply proportional to the strength of the tropical upwelling (Neu and Plumb, 1999). Here we extend this result to the more general case, in which case the gross age difference, defined as the average difference between downwelling and upwelling air, is again only dependent on the strength of mean upwelling across the isentrope; perhaps counter-intuitively, it is independent of isentropic mixing and on whether the circulation follows a low or high path.

This relationship is illustrated through diagnosis of a 3D “dynamical core” model, forced under a wide range of conditions to represent different stratospheric climates. We discuss both the reality of the result and its limitations. We conclude that, given a sufficiently long data record, age differences, but not age itself, can be used to diagnose circulation strength and its trends.

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Characteristic of gravity waves resolved in ECMWF analysis data

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Gravity waves (GWs) influence the circulation of the atmosphere on global scale. Because of insufficient measurements and the difficulty to involve all relevant scales in a single model run, they are one of the chief uncertainties in climate and weather prediction. More information, in particular on global scale, is required. Can we employ global models such as the ECMWF high-resolution GCM to infer quantities of resolved GWs? Does this give us insight for the characteristics and relative importance of real GW sources? And can we use such data safely for, e.g., planning measurement campaigns on GWs? Also trajectory studies of cloud formation (cirrus in the UTLS, PSCs) and related dehydration and denitrification rely heavily on realistic temperature structures due to GWs.

We here apply techniques developed for an ESA study proving the scientific break-through which could be reached by a novel infrared limb imager. The 3D temperature structure of mesoscale GWs is exploited to determine amplitudes and 3D wave vectors of GWs at different levels (25km, 35km and 45km altitude) in the stratosphere. Similar to real observations, GW momentum flux is largest in the winter polar vortex and exhibits a second maximum in the summer subtropics. Based on the 3D wavevectors backward ray-tracing is employed to characterize specific sources. For instance, we find for the northern winter strong GW momentum flux (GWMF) associated with mountain waves from Norway and Greenland as well as waves emitted in the lower troposphere from a storm approaching Norway. Waves from these sources spread up to several thousand km in the stratosphere. Together these three events form a burst in the total hemispheric GWMF of a factor of 3. Strong mountain wave events are also found e.g. at Tierra del Fuego and the Antarctic Peninsula, regions which are in the focus of observational and modeling studies for a decade. Gravity waves in the tropical region are associated with deep convection in the upper troposphere. They have significantly longer horizontal wavelengths but shorter vertical wavelengths than indicated by observations. They also exhibit lower phase speeds than waves simulated by mesoscale modeling of deep convection events. This difference is not due to the model resolution. Rather, GWs in ECMWF are excited aloft of the convection in the altitudes of largest wind-shear and least dynamical stability. GWs which are excited by latent heat release in the mid troposphere, however, seem to be missing in ECMWF. Likely, the reason is that the convective parameterization of ECMWF treats convection inside a single model cell and couples only the net effects to the global dynamical fields. For instance, ECMWF vertical winds do not exhibit any strong updrafts normally found in deep convection.

In summary, our study demonstrates that larger scale MWs and waves from storms are represented in ECMWF in a realistic fashion, while convective gravity waves are not. This is not a resolution problem, but depends on the convective parameterization. The day-to-day variability of GWMF (and GW drag) is huge, even for total hemispheric fluxes - and could be even underestimated by ECMWF. Finally, it is demonstrated that an infrared limb imager would provide novel insight into real GWs similar as this study did for the ECMWF model.

Southern Hemisphere circulation variability and Antarctic sea ice

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The atmospheric circulation in the Southern Hemisphere exhibits a near-zonally symmetric maximum in variability between 50°S and 65°S. However, the timescales of variability are very different between the eastern and western hemispheres (Figure 1). This presentation will discuss the character of Southern Hemisphere circulation variability and the implications for Antarctic sea ice variability.

Since the Antarctic continent is located largely in the eastern hemisphere, the meridional temperature gradient is stronger over the Indian Ocean sector than over the Pacific sector. Hence, the storm track and the eddy-driven jet are strongest over the Indian Ocean and synoptic-scale variability dominates there. Over the Pacific sector, the storm track and eddy-driven jet are weaker and lower-frequency variability (partly related to tropical forcing) is more important.

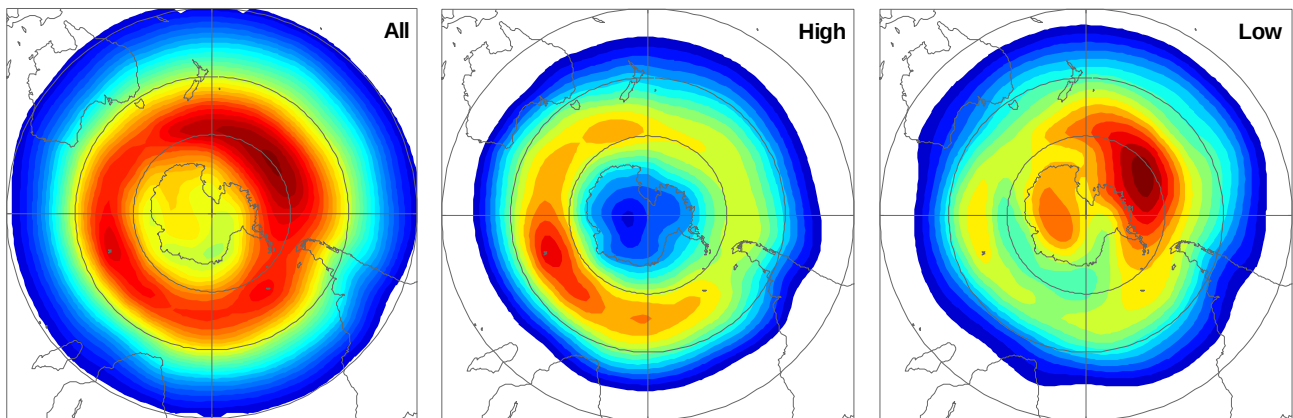


Figure 1: Standard deviation of daily 500hPa height anomalies (NCEP reanalyses, from 1979). Left panel shows the standard deviation over all time scales. The middle panel shows the standard deviation for synoptic-scale variability (8-day high-pass filter) and the right panel shows the standard deviation for monthly and longer-scale variability (30-day low-pass filter). Colour scale starts at 20m (blue) in all panels. The darkest shade represents 160m in the left panel, but 100m in the middle and right panels.

This presentation will review the nature of variability in the Southern Hemisphere circulation on synoptic to seasonal time scales, including the SAM and the dominant mid-latitude zonal wave patterns. It will also discuss how Antarctic sea ice concentration in different sectors of the hemisphere is related to circulation variability and how those relationships have varied on decadal time scales. Implications for the future of total Antarctic sea ice extent will be outlined.

Solar Variability Effects on Extratropical Surface Climate

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We present modelling studies of the response of the stratosphere-troposphere-ocean system to variations in solar UV. A clear and robust mechanism operates to transmit downward propagating signals from the upper stratospheric heating to the extratropical surface winter climate. The surface climate responds via a shift in the North Atlantic/Arctic Oscillation. In experiments with a fully dynamical and interactive ocean, the response produces a tripolar ocean heat and surface temperature signature. Long term ocean memory and ocean-atmosphere feedback then result in a lagged atmospheric response to variable solar forcing and peak atmospheric response a few years after the peak in solar forcing. On longer timescales, future multidecadal variability in solar forcing could also provide an important modification to regional climate scenarios in winter. Using a hypothesized future decline in solar variability, we show that regional climate impacts are comparable to the difference between different future greenhouse gas forcing scenarios.

While there is uncertainty in the strength of the surface climate response due to the size of UV forcing variations and also ocean-atmosphere feedback, our experiments suggest that solar variability can drive important regional surface climate anomalies on all timescales. Amplitudes in our current experiments are large enough to significantly affect the likelihood of cold and mild winters in the extratropics in seasonal, decadal and climate change predictions.

A new interpretation of the relation between QBO phase and stratospheric sudden warming frequency

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Dynamical coupling between the tropics and extra-tropics gives rise to an important source of atmospheric variability on interannual time scales. In the stratosphere, the most significant source of such coupling involves the tropical quasi-biennial oscillation and the winter polar vortex, and takes the form of an increase in the frequency of stratospheric sudden warmings during the easterly phase of the QBO, an effect noted originally by Holton and Tan¹. Explanations of the Holton-Tan effect typically invoke quasi-linear arguments, whereby a farther poleward zero-wind line during the easterly phase acts to reflect equatorward propagating planetary waves, focusing them into higher latitudes and increasing wave amplitudes there.

While quasi-linear wave dynamics offer a simple framework to understand the Holton-Tan effect, high resolution fields from models and meteorological reanalysis indicate a highly inhomogeneous background state and strongly nonlinear wave motions. Planetary waves reside on the wave guide of the polar vortex edge, while a well-mixed surf zone between vortex edge and subtropical barrier obscures the notion of lateral wave propagation.

In this talk, a new description of the Holton-Tan effect is offered based on the influence of background shear on the nonlinear Rossby wave critical layer that constitutes the surf zone. In essence, stronger shear during the easterly phase implies, for a given wave forcing, a narrower surf zone than during the westerly phase. Because the surf zone acts as a sink of wave activity for planetary waves on the polar vortex edge, amplitudes of the latter may be correspondingly decreased during the westerly phase. The proposed description is consistent with the observed correlations of forcings and net accelerations documented by Dunkerton and Baldwin² and suggest a leading role for the secondary circulation in producing the observed effect. Implications for tracer transport out of the tropics will also be discussed.

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² Dunkerton, T. J. and Baldwin, M. P., 1991 Quasi-biennial modulation of planetary-wave fluxes in the Northern Hemisphere winter, *J. Atmos. Sci.*, **48**, 1043–1061

A practical method to identify stratospheric polar vortex displacement and splitting events

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Extreme variability of the stratospheric polar vortex during winter can manifest as a vortex displacement event or a vortex splitting event. The influence of this vortex disruption can extend downwards and affect surface weather patterns. In particular, vortex splitting events have been associated with a negative Arctic Oscillation pattern. An assessment of the impacts of climate change on the polar vortex is therefore important and more climate models now include a well-resolved stratosphere. To aid this analysis, we introduce a new threshold-based method to distinguish between vortex splitting and displacement events. It requires only geopotential height at 10hPa to measure the geometry of the vortex using two-dimensional moment diagnostics. It captures extremes of vortex variability at least as well as previous methods when applied to reanalysis data, and has the advantage of being easily employed to analyse climate model simulations.

Reference:

Seviour, W. J. M., D. M. Mitchell, and L. J. Gray (2013), A practical method to identify stratospheric polar vortex displacement and splitting events. *Geophys. Res. Lett.* (submitted).

On the control of the residual circulation and stratospheric temperatures in the Arctic by planetary wave reflection

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It is well established that interannual variability of eddy (meridional) heat flux near the tropopause controls the variability of Arctic lower-stratospheric temperatures during spring via a modification of the strength of the residual circulation. While most studies focus on the role of anomalous heat flux values, here the impact of stratospheric wave reflection, identified as negative total (climatology plus anomaly) heat flux events, on the Arctic stratosphere is investigated. Utilizing ERA-Interim reanalysis it is found that negative total heat flux events coincide with a transient reversal of the residual circulation and cooling of the Arctic lower stratosphere. The negative events weaken the seasonally averaged adiabatic warming. The positive extreme events act to amplify the climatology.

The analysis provides a new interpretation of the winters of 1997 and 2011, which are known to have the lowest Arctic lower-stratospheric temperatures in the satellite era. While most winters involve positive and negative heat flux extremes, the winters of 1997 and 2011 are unique in that they only involved extreme negative events. This behavior contributed to the weakest adiabatic downwelling in the satellite era and suggests a dynamical contribution to the extremely low temperatures during those winters that could not be accounted for by diabatic processes alone. While it is well established that dynamical processes contribute to the occurrence of stratospheric sudden warming events via extreme positive heat flux events, the results show that dynamical processes also contribute to cold winters with subsequent impact on Arctic ozone loss. The results highlight the importance of interpreting stratospheric temperatures in the Arctic in the context of the dynamical regime they are associated with.

Stratospheric Final Warming Events and their Impact on the Troposphere

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In both hemispheres, stratospheric polar vortices form in the fall, reach maximum strength in midwinter, and break up in later winter-spring. This final breakup of the vortex is referred to as a stratospheric final warming event. Black and McDaniel (2007a and 2007b) used reanalysis data to study final warming events and reported coherent circulation changes associated with these events that extend to the surface in both hemispheres. We study stratospheric final warming events and their surface impact in a simplified GCM forced by specified equilibrium temperature distributions. We force the GCM with a seasonal cycle in equilibrium temperature that is confined to the stratosphere. Thus, any seasonal variations in tropospheric circulation are unambiguously of stratospheric origin. We investigate the effects of a range of topographic forcing amplitudes on the variability in timing of final warming events and study the impacts of these events on tropospheric circulation for each case. We find that earlier stratospheric final warming events are associated with larger wave activity and have more surface impact than later events. We also compare the tropospheric response to final warming events to the model's annular mode structure and analyse the role of planetary and synoptic scale eddy feedbacks in the model's troposphere.

The ozone hole is thought to be the primary cause of circulation changes in the Southern Hemisphere over the last several decades (e.g. Polvani et al. 2011 and Thompson et al. 2011). These changes are usually referred to as an increase in the positive phase of the SAM, which is associated with a poleward shift of the jet and storm tracks. The ozone hole cools the polar stratosphere, extending the persistence of the polar vortex and delaying final warming events. Thus, we also perform an observational analysis comparing Southern Hemisphere stratospheric final warming events in years with and without large ozone depletion, and study the tropospheric impacts of these changes. The surface impact of Antarctic ozone depletion and recovery is an important aspect of the assessment of current and future climate change.

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Zonal and Seasonal Variations in Future Predictions of the Mid-Latitude Circulation

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Global climate models predict that future increases in greenhouse gas concentrations will be accompanied by changes in the mid-latitude circulation of each hemisphere. It is often concluded based on zonal mean analysis, or basin wide analysis, that a general feature of the mid-latitude circulation response to climate change is a poleward shifting of the eddy driven mid-latitude jet streams and associated storm tracks. As yet, the mechanisms responsible for this change remain uncertain and it is thought that future stratospheric circulation changes may play some role in this tropospheric response.

Here, the CMIP-5 models are used to further investigate the mechanisms involved in the mid-latitude circulation response to anthropogenic forcing. Particular attention is paid to the seasonal and zonal variations in the response. While, the dominant change in the Southern Hemisphere is a relatively zonally symmetric poleward shifting of the mid-latitude jet stream, the Northern Hemisphere response is considerably more complex. In the Northern Hemisphere, the response varies considerably with season and longitude. Various features are identified that do not resemble a poleward shifting of the climatological circulation. For example, in the winter season, the Pacific jet stream shifts equatorward on the Eastern side of the basin with implications for the climate of the west coast of the USA. On the Eastern side of the Atlantic basin, the zonal wind anomalies represent more of an extension of the jet stream rather than a poleward shift, with implications for Mediterranean climate. These features are robust across the model simulations and were also present in the older CMIP-3 ensemble.

To aid in further understanding of the mechanisms involved in mid-latitude circulation changes as a function of longitude and season, the two-dimensional vertically integrated momentum budget is calculated for a subset of CMIP-5 models. This is used to identify which features of mid-latitude circulation change are associated with altered transient eddy momentum fluxes and which require additional interpretation through changes to the more quasi-stationary features of the circulation, with a view to a better understanding of mid-latitude climate change.

Understanding Climate Model Biases in Southern Hemisphere Mid-latitude Variability

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The Southern Annular Mode (SAM) represents a latitudinal shifting of the Southern Hemisphere (SH) jet stream and is the dominant mode of variability in the SH mid-latitude circulation. A common bias among global climate models is that they tend to exhibit SAM variability that is much too persistent, particularly in the summer season. Many climate forcings such as ozone depletion/recovery and increasing greenhouse gas concentrations result in tropospheric circulation changes that project strongly onto the SAM and therefore the inability of models to simulate natural SAM variability correctly is of concern for the ability of such models to accurately predict future circulation changes.

Here, a combination of analysis of the CMIP-5 models and specifically targetted experiments with one global climate model, the Canadian Middle Atmosphere Model (CMAM), are used to investigate the cause of this bias in SAM variability. The role of biases in stratospheric variability and climatological tropospheric jet structure are assessed. This reveals a bias in internal tropospheric dynamics that it not caused by either the climatological jet latitude bias or biases in stratospheric variability. An analysis of eddy-mean flow feedbacks reveals that the strength of the planetary wave feedbacks onto the SAM differ between models and the reanalysis, leading to the enhanced SAM persistence.

The role of the tropopause region in the wave forcing of sudden stratospheric warmings

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Sudden stratospheric warmings (SSWs) represent the dominant dynamical variability of the polar stratosphere. Recent studies of these events demonstrate linkage between their occurrence and subsequent tropospheric flow. This linkage has been shown to increase the predictability of tropospheric weather in medium-range numerical weather forecasts following SSWs. Yet without the use of advanced numerical weather prediction models supplied with precise initial conditions, predictability of sudden warmings themselves remains notably low. This suggests that our understanding of the dynamical forcing of such events is not complete.

SSWs are known to be forced by planetary waves originating in the troposphere. Our previous work has demonstrated that sudden warmings are preferentially forced by wave drag with time scales on the order of one week. It is further known that the meteorological state of the upper troposphere and lower stratosphere (UTLS) region greatly affects the propagation of these planetary waves. How the UTLS region affects the time scales of vertically propagating planetary waves has not been well detailed.

Here we show through reanalysis data and modeling how UTLS conditions relate to the wave forcing time scales associated with sudden stratospheric warmings. The modeling approach here is twofold in resolution: the first being a simple model following the 1-dimensional, beta-plane model of Holton and Mass (1976); the second being an idealized general circulation model initialized in perpetual January and forced with simplified bottom boundary topography. Initial results suggest that the stratification and zonal wind of the UTLS are pivotal to the organization of propagating waves onto longer time scales and larger amplitudes associated with SSWs. We demonstrate how this organization, in tandem with previous results on the forcing of sudden warmings, may be used to generate diagnostics for increasing predictability of sudden stratospheric warmings.

Investigating the stratospheric gravity wave response to storm characteristics over the US using WRF with validation by radar and satellite data

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Gravity waves are important for the momentum budget of the middle atmosphere and those generated by convection are prevalent in the tropics and summer mid-latitudes. Predominant westward winds in the summer middle atmosphere keep stationary planetary and mountain waves from invading the atmosphere aloft, causing it to be a rather calm region. Regarding the residual circulation of the summer mid-latitude middle atmosphere there is evidence that gravity waves play a role (Alexander and Rosenlof, Nonstationary gravity wave forcing of the stratospheric zonal mean wind, JGR, 1996; Scaife et al., Impact of a spectral gravity wave parameterization on the stratosphere in the Met Office Unified Model, JAS, 2002).

In a previous study we have demonstrated that the Weather Research and Forecasting Model (WRF) is suitable to realistically simulate gravity-wave-generating storms over the US. It was found that key variables for determining gravity wave properties in parameterizations such as the storm structure and evolution as well as the distribution of precipitation strength and cloud depth can be validated using radar measurements and are most sensitive to the microphysics parameterization. However, it was also found that the wave spectrum above the storm is not governed solely by the parameters that are used in parameterizations like the Beres scheme (Beres, Gravity wave generation by a three-dimensional thermal forcing, JAS, 2004). The interaction of convective cells with upper level wind shear appears to be also quite important. Additional validation and analysis methods are needed to disentangle the dynamic processes in the simulations and to optimize the choice of physics parameterizations.

Here, a modified version of the WRF model is presented. The new model is run without any microphysical processes. Instead the full four-dimensional latent heating field from a simulation that includes moist processes is used as input to force the waves. In addition the background wind profile can be specified. This allows us to discriminate between various possible wave generation mechanisms. Furthermore, it renders possible a direct comparison of the simulated waves to satellite measurements, as the improved computational efficiency allows to extend the model top to sufficiently high levels.

Using this new tool a detailed study is conducted on a storm case over the US but this investigation can be extended to multiple additional convective events over North America. The simulations are validated by using both radar and satellite data. We clarify which effects are important in determining the stratospheric wave properties, discuss the associated momentum flux spectra and compute the wave-driven force on the stratospheric winds. The aim is to learn more about the characteristics of mid-latitude gravity waves, especially how they are tied to the mean winds in the region of the storm and to properties of the latent heating field created within the convective rain cells. This latent heating field can be characterized by its horizontal and vertical scale, its frequency distribution and its local and domain-averaged magnitudes. These questions are important since the typical resolution of climate models is orders of magnitude too low to resolve these details.

The influence of different sensitivity factors on the 11-year solar signal representation in CESM-WACCM

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In order to better understand the influence of solar variability on climate, it is crucial to estimate and separate natural from anthropogenic climate variability. Observational and modeling studies have shown robust impacts of solar irradiance variability on the climate system. However, the established top-down and the proposed bottom-up mechanisms involve challenging feedback mechanisms arising from complex interactions between solar forcing and the atmosphere-ocean system.

In this work, we investigate the influence of external forcings such as the QBO, variable SSTs or increases in GHG concentrations (anthropogenic) on the 11-year solar cycle signal representation with NCAR's Community Earth System Model (CESM, version 1.0.2), a coupled model system including the Whole Atmosphere Community Climate Model (WACCM). We will use a couple of multi-decadal sensitivity experiments with different combination of various variability factors such as QBO, SSTs, or anthropogenic forcing. Results are presented from a composite analysis with respect to the maximum and minimum solar phases.

By comparing the stratospheric and tropospheric dynamical responses to the solar signal in these experiments, we find statistically significant discrepancies. These results will be then discussed to shed more light on the associated physical mechanisms.

Variability of tracer transport in spring/summer Arctic stratosphere simulated by CESM-WACCM

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Recent observational and modeling transport studies of Arctic stratospheric final warmings have shown that tropical/subtropical air can be transported to high latitudes and remain confined within a long-lived “frozen-in” anticyclone (FrIAC), embedded in the summer easterlies for several months. A climatology of these sporadic events has shown that their frequency of occurrence considerably increased over the last decade: among the nine cases detected over the period 1960-2011, five occurred between 2002 and 2011. Although a stratospheric favorable preconditioning for their occurrence were identified, the causes of such an increase are not yet understood.

In this study, a chemistry climate model is used for the first time to investigate FrIACs characteristics and variability. Simulations were performed with the NCAR's Community Earth System Model (CESM), a coupled model system including an interactive ocean (POP2), land (CLM4), sea ice (CICE), and atmosphere (NCAR's Whole Atmosphere Community Climate Model (WACCM)). To detect low-latitude air masses characterizing FrIACs, daily 3-D output of temperature, horizontal wind and pressure are used to calculate the potential vorticity equivalent latitude (PVEL) distribution onto various isentropic levels in the range 700 K - 1200 K. Additionally, anticyclones are identified by using an algorithm designed to detect systematically vortex edges. To classify an event as a FrIAC, we require that the intrusion contains air masses from low-latitudes (below PVEL=40°N), reaches the polar region (beyond 60°N), and is collocated with an anticyclonic eddy.

Among the 145 years analyzed (1955-2099), from a simulation with natural forcing conditions only, 20 FrIACs are found. They occur predominantly under a strong and abrupt winter-to-summer dynamical transitions which are driven by large planetary wave activity. FrIACs characteristics (i.e. spatial extent and duration), are overall consistent by comparing with FrIACs detected in ERA-Interim and ERA-40 meteorological reanalyses. However, CESM simulation reveals decadal clustering of FrIAC occurrences that we will discuss by applying our FrIAC detection method to three CESM-WACCM sensitivity experiments, i.e. simulations with (i) natural forcing without Quasi-Biennial Oscillation, (ii) natural forcing with fixed Sea Surface Temperatures, and (iii) anthropogenic forcing based on the RCP8.5 scenario.

A case study of Major Sudden Stratospheric Warming in January 2013

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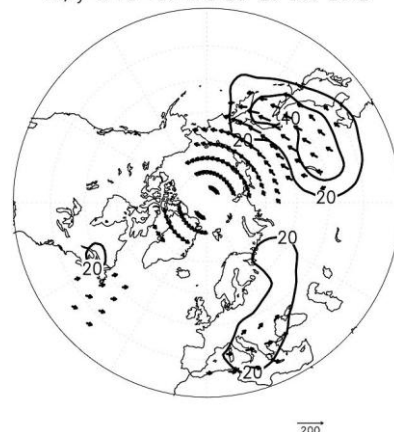
Recent Arctic winters exhibit a large interannual variability of polar stratosphere. Cold winter with stable, well isolated and long-lived polar stratospheric vortex resulted in record ozone loss in 2010/11 followed by winters 2011/12 and 2012/13 with Sudden Stratospheric Warming (SSW) and relative mellow ozone losses. The mechanism of this interannual variability is still unclear and its investigation is of interest particularly due to possible implication to the improvement of seasonal forecast of Arctic Oscillation in the troposphere.

Present study employed NCEP and Japanese Reanalysis daily data to analyze dynamics of tropo-stratosphere over the northern extratropics during the winter 2012/13 and compare it with some recent “cold” and “warm” in stratosphere Arctic winters.

The main feature of winter 2012/13 is the Major SSW started on 5-6 Jan. and propagated to the lower stratosphere. SSW was accompanied by splitting of polar vortex into two lobes in the lower-middle stratosphere and observed till 26-27 Jan. when both lobes merged. SSW maximized nearby 1 hPa and led to warming of the polar stratosphere on ~30 K and zonal wind reverse to easterlies. 3-4 days later the 2nd SSW occurred and led to additional increase of temperature on ~20 K. The strong cooling of the upper strato-mesosphere started on 14-15 Jan. but the lower stratosphere remained warm until March.

The propagation of wave activity (WA) in tropo-stratosphere was analyzed by calculation of 3-D fluxes according to Plumb (1985). The Major SSW was preceded on 10-12 days by strong increase of upward WA in the lower - middle stratosphere with the maximum over the southern Eastern Siberia – China (right Fig.) that accompanied by strong increase of wavenumber 1 over the middle-high latitudes in the troposphere - stratosphere. The 2nd maximum of upward propagation of WA before SSW observed on 1-2 Jan. and its strength and spatial structure were comparable with the 1st maximum.

Fx,Fy & Fz 100 hPa 23–25 Dec 2012



Strong decrease of wavenumber 1 in the next days (its amplitude averaged over 40-70°N dropped from 700 gpm on 23 Dec. to 200 gpm on 10 Jan. on 30 hPa) was accompanied by increase of wavenumber 2 (from 150 gpm on 1 Jan. to 400 gpm on 10 Jan.) that was caused by amplification of the tropospheric anticyclone over the Northern Atlantic that penetrated upward to the middle stratosphere and resulted in the polar vortex splitting during the Major SSW.

Analysis of WA in the middle-upper troposphere revealed a Rossby-wave train (RWT) propagating eastward from the northern Pacific to north-eastern Atlantic on 29 Dec. – 5 Jan. This RWT could contribute to amplification of tropospheric anticyclone and to the splitting of polar vortex during SSW (similar to SSW in January 2003 - Peters et al., 2010).

The nonlinear self-interaction of wavenumber 1 that could also contribute to increase of wavenumber 2 (Pogoreltsev, 2001) and to the splitting of polar vortex is discussed.

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The multi-scale nature of SAM influence on South America climate

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Southeastern South America (SESA) is one the continental regions in the Southern Hemisphere (SH) significantly influenced by the activity of the Southern Annular Mode (SAM), as it has been shown by previous works. However, little attention has been paid to the multi-scale nature of that influence. The objective of this work is then to describe and discuss SAM influence on climate variability in SESA from intraseasonal, to interannual and longer timescales. The study is motivated by the fact that a better understanding of such influence might contribute to improve climate predictions in that particular region. SESA encompasses the La Plata Basin, which is the fifth largest in the world and second only to the Amazon Basin in South America in terms of geographical extent, it includes one of the most agricultural productive regions of the world, it is home of more than 100 million people including the capital cities of 4 of five countries (Argentina, Brazil, Uruguay, Paraguay, and Bolivia), generating more than 70% of the five countries GNP.

Intraseasonal variability in SESA explains a significant percentage of variance all year around. In particular, during JJA, the leading pattern of intraseasonal variability, as described from band-pass filtered OLR anomalies, is characterized by a monopole centered over SESA with a northwest-southeast orientation. It has been found that 10 days before the leading pattern induces positive precipitation anomalies in SESA, a quasi-stationary anticyclonic anomaly develops over Antarctica Peninsula,. The stationary behavior of the anticyclonic center seems favored by a hemispheric circulation anomaly pattern associated with a negative SAM phase and a wavenumber 3-4 pattern at middle latitudes. Case studies have shown that such hemispheric pattern can be promoted by the early development of SAM negative phase at lower stratosphere, which in terms of weeks, promotes similar circulation anomalies at the troposphere.

Precipitation also exhibits over SESA considerable interannual variability, influenced mainly by the El Niño-Southern Oscillation (ENSO). However, during austral spring, SAM influence is also relevant. SAM positive (negative) phases are associated with decreased (increased) precipitation over SESA. Moreover, SAM activity can produce a large modulation of ENSO influence in climate variability over SESA. It was found that the joint occurrence of a warm ENSO event with a negative SAM phase induces larger precipitation anomalies in SESA.

However, SAM influence on SESA climate variability is not that stable as the ENSO influence is. Significant change in the spatial circulation anomaly pattern typically associated with SAM influence was found in the vicinity of South America between the 1960s–70s and 1980s–90s. In the first decades, SAM positive phase is associated with an anomalous anticyclonic circulation developed in the southwestern subtropical Atlantic that promotes precipitation increase over SESA. On the other hand, during the last decades the anticyclonic anomaly induced by the SAM's positive phase covers most of southern South America and the adjacent Atlantic, producing decreased precipitation over SESA. The origin of such multi-decadal changes is not clear yet.

Characteristics of lower stratospheric gravity waves during stratospheric sudden warmings from ray-tracing experiments and GPS radio occultation data

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Stratospheric sudden warmings (SSWs) are large-scale transient events in the winter polar middle atmosphere. They affect the atmosphere structure and general circulation profoundly and could also have significant impacts on weather in the troposphere. SSWs are the most dramatic example of dynamical coupling of the lower and middle atmosphere. Due to the dramatic change of the background atmosphere within a very short period of time, SSWs affect gravity wave (GW) propagation and transmission in the middle atmosphere profoundly. To date, our knowledge of how the characteristics of GWs vary during SSWs is still very limited, especially for information on wavelengths and propagation directions. In this study, detailed GW ray-tracing experiments will be performed to investigate the variations of GW parameters including amplitudes, wavelengths, and propagation directions, before, during, and after SSW events to elucidate the effects of different background conditions on GW characteristics in the winter polar lower stratosphere. The results will also be compared with GW characteristics determined from GPS radio occultation data using a sophisticated GW analysis algorithm.

The stratospheric response to applied extratropical torques

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Variability in the zonal mean stratospheric extratropical circulation associated with external factors such as the quasi-biennial oscillation (QBO) or tropospheric wave driving is often explained through these factors inducing an anomalous torque in the stratosphere, for example due to inducing anomalous divergence of the Eliassen-Palm (EP) flux. Analytical solutions using the primitive equations exist when the total EP flux is specified (e.g. Holton et al. 1995) but leave aside the question of how wave driving responds when the EP flux is perturbed but the total flux is allowed to respond to subsequent changes in the zonal mean flow. Studies of the effect of an applied torque in the troposphere have shown the response tends to resemble the Northern Annular Mode (NAM), illustrating that the response is dynamically complex (Ring and Plumb 2007; 2008). Understanding the response in the stratosphere will aid understanding of factors affecting variability of the polar vortex and stratospheric sudden warmings, and consequently also variability of the tropospheric NAM (e.g. Baldwin and Dunkerton 2001, Jung and Barkmeijer 2006), and also the effect of changing gravity wave parameterisations (e.g. Cohen et al., 2013).

We show the steady state and transient responses to an applied torque in the extratropics in the winter hemisphere of a primitive equation model of the stratosphere and mesosphere under both perpetual January conditions and with a realistic seasonal cycle. Under perpetual January conditions the circulation response to torques placed poleward of 60N is robust and closely resembles the NAM. However, counter-intuitively a positive torque causes the vortex to be weaker. The EP flux becomes more convergent in the region of an applied positive torque and nearly completely cancels the direct effect of the torque, and becomes more upward and convergent in the extratropical stratosphere causing deceleration. The EP flux response is qualitatively similar but weaker in runs with a realistic seasonal cycle, and the circulation response is less like the NAM, indicating there is sensitivity of the steady state response to the model climatology and tropospheric wave forcing.

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How does the quasi-biennial oscillation affect the polar vortex?

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The stratospheric polar vortex is weaker in the easterly phase of the quasi-biennial oscillation (QBO-E) than in the westerly phase (QBO-W) (Holton and Tan, 1980), but the mechanism behind the QBO's influence is not well understood. We argue firstly that the composite difference of the atmospheric state between QBO-E and QBO-W closely resembles the structure of the Northern Annular Mode (NAM), the leading empirical orthogonal function of stratospheric variability, including its wave components. Studies of dynamical systems indicate that many different forcings could give rise to this response, and therefore this composite difference does not provide much information about the forcing mechanism. The transient response of the vortex to forcing by the QBO is probably much more informative, particularly on time scales shorter than the dynamical time scale of vortex variability, which is about a week. This response in a general circulation model is consistent with the proposed mechanism of Holton and Tan (1980), indicating this mechanism has a role in the QBO modulation of vortex strength, in contrast to the conclusions of several recent studies. Our novel approach of examining the transient response to a forcing on short time scales may be useful in various other outstanding problems.

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The effect of climate change on transatlantic aviation turbulence in the UTLS region

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Atmospheric turbulence causes most weather-related aircraft incidents. Commercial aircraft encounter moderate or-greater turbulence tens of thousands of times each year world-wide, injuring probably hundreds of passengers (occasionally fatally), costing airlines tens of millions of dollars, and causing structural damage to planes. Clear-air turbulence is especially difficult to avoid, because it cannot be seen by pilots or detected by satellites or on-board radar. Clear-air turbulence is linked to atmospheric jet streams in the upper troposphere-lower stratosphere (UTLS) region, which are projected to be strengthened by anthropogenic climate change. However, the response of clear-air turbulence to climate change has not previously been studied.

Here we show using computer simulations that clear-air turbulence changes significantly within the UTLS transatlantic flight corridor when the concentration of carbon dioxide in the atmosphere is doubled. At cruise altitudes within 50-75N and 10-60W in winter, most clear-air turbulence measures show a 10-40% increase in the median strength of turbulence and a 40-170% increase in the frequency of occurrence of moderate-or-greater turbulence. Our results suggest that climate change will lead to bumpier transatlantic flights by the middle of this century. Journey times may lengthen and fuel consumption and emissions may increase. Aviation is partly responsible for changing the climate, but our findings show for the first time how climate change could affect aviation.

SST Forced Stratospheric Warming over Southern-Hemisphere High Latitudes

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Abstract

Satellite observations show significant stratospheric warming trends over Southern-Hemisphere (SH) high latitudes and large portion of the Antarctic polar region in spring season since 1970s. To investigate the relationship between the observed stratospheric warming and sea surface temperature (SST) increases, we performed simulations with a coupled chemistry-climate model (WACCM) forced by observed time-varying global and tropical (30S-30N) SSTs and global SSTs with increasing observed CO₂. For global SST forcing, ensemble simulations generate significant warming trends in the SH high-latitude stratosphere and cooling in the mesosphere over the Antarctic. The maximum warming of about 7-8 K over 1979-2006 is located in the middle stratosphere. The warming trends mainly occur in austral winter, different from the timing of observed warming trends that are in austral spring (September and October). For tropical SST forcing, the timing and spatial patterns are similar to that of global SST forcing, but with weaker magnitudes, about half of the global SST forcing. EP flux analysis shows that the stratospheric warming is resulted from increasing wave activity from the troposphere to the stratosphere, which enhances the Brewer-Dobson Circulation (BDC), causing warming in the high-latitude stratosphere. However, as the model is forced by both global SST and increasing GHGs, warming trends in the SH high-latitude stratosphere are weak and less significant, suggesting that the stratospheric cooling effect of GHGs would enhance the polar vortex and suppress upward propagation of planetary waves. Overall, the simulations here suggest that SST warming has major contributions to stratospheric warming in SH high latitudes.

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Idealized Simulations of Sudden Stratospheric Warmings with an Ensemble of Dry GCM Dynamical Cores

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Sudden Stratospheric Warmings (SSWs) are major events in the polar stratosphere and are characterized by the breakdown or wind reversal of the polar vortex in the winter hemisphere. This phenomenon is accompanied by a sudden rise of stratospheric temperature in the polar region. Such events are highly coupled with the troposphere and thereby significantly impact the lower tropospheric weather and climate regimes.

SSWs are mainly generated and influenced by vertically propagating planetary-scale waves and their interaction with the zonal flow. In particular, orographically generated planetary waves are believed to play a major role. However, orographic gravity waves are not enough to explain SSWs in their entirety, and our understanding of the details of SSW precursors and their predictability is still incomplete. Wave-blocking events in the troposphere and internal variability of the stratosphere can both contribute to the onset of SSWs. Our study sheds light on dynamical causes and effects. It discusses the onset and development of SSWs in idealized General Circulation Model (GCM) simulations that isolate the dynamical core from the physical parameterization package.

In particular, SSWs are simulated with an ensemble of four dynamical cores that are part of the Community Atmosphere Model (CAM version 5) at the National Center for Atmospheric Research (NCAR). These are the spectral transform semi-Lagrangian (SLD), spectral transform Eulerian (EUL), Finite-Volume (FV), and CAM5's newest default Spectral Element (SE) dynamical cores. The simulations are configured for a dry and flat earth, and thereby omit typical wave triggering mechanisms like moist convection or orographic forcing. The dynamical cores are driven by Rayleigh damping near the surface and the model top, and a prescribed Newtonian temperature relaxation as suggested by Held and Suarez (1994) and Williamson et al. (1998). We demonstrate that SSWs can be simulated in both hemispheres at an equal rate, even in the absence of convectively or orographically forced waves. Wave analysis is performed to understand the driving mechanisms of SSWs in the different dynamical cores. In particular, the Transformed-Eulerian-Mean (TEM) analysis is used to explore the relative roles of the forcing by the resolved waves, the TEM advection terms and unresolved waves. It is shown that the choice of the numerical schemes in the dynamical cores greatly impacts their ability to resolve waves, and thereby trigger the SSW phenomenon in the simulations.

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The impact of the tropopause inversion layer on the gravity wave activity

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The sharpness of the tropopause plays an important role in the propagation of the atmospheric waves (such as, planetary waves, Kelvin waves, gravity waves). The tropopause inversion layer (TIL) is a relatively new observational feature. It could affect the vertical propagation of tropospheric eddies, and thus could contribute to the changes in the tropospheric circulation observed in association with stratosphere-troposphere coupling. It may also influence the vertical propagation of atmospheric waves as well as suppress the stratosphere-troposphere exchange (STE) of chemical constituents.

In this study, we attempt to investigate the impact of TIL on the gravity wave activities by analysing the case study at a mid-latitude US station, Boise, Idaho (43.57N, 116.22W) from Stratospheric Processes and Their Role in Climate Data Center (SPARC) 1998 to 2008. The features of the TIL found in this study are similar to the previous studies. The TIL at the US mid-latitude station is stronger and deeper in winter and spring than that in summer and autumn. The TIL characteristics (depth and intensity) are better correlated with the gravity wave activities in the stratosphere than those in the troposphere. The gravity wave energies in the stratosphere show a statistically significant anti-correlation with TIL features. These results suggest that the profound impact of TIL on the gravity wave activities in the stratosphere.

Stratospheric Thermodynamics during the Seasonal Transition between Winter and Summer

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Abstract: This study applied the spatial similarity coefficient method to define the seasonal transition (ST) from winter to summer in the extratropical stratosphere. The thermodynamic features of the ST were examined in both hemispheres using the European Centre for Medium-Range Weather Forecasts Interim reanalysis data. The results show that the characteristics of the ST depend largely on both the geophysical locations and meteorological fields used to define it. The occurrence and duration of the ST are also affected by the activity of planetary waves in the stratosphere.

This study also investigated the interannual variation of ST in the extratropical stratosphere and its relationship with stratospheric sudden warming (SSW), the quasi-biennial oscillation (QBO), and El Niño and Southern Oscillation (ENSO). It was shown that SSW more commonly occurs in La Niña winters with a weak or easterly QBO phase, and most of these SSW events coincide with the beginning of the ST. SSW events that occur after 22 January were strongly correlated with the onset of zonal-wind-based ST. In the Northern Hemisphere (NH), the easterly (westerly) QBO hastens (delays) the onset of ST in high and low latitudes, whereas it delays (hastens) the ST in middle latitudes. The duration of the ST is significantly affected by the QBO. The ST begins earlier (later) in the lower stratosphere than in the upper stratosphere after El Niño (La Niña) winters in the NH. The influence of QBO and ENSO in the Southern Hemisphere (SH) is similar to that in the NH but much weaker.

Key words: Seasonal transition, stratosphere, SSW, QBO, ENSO.

Motivation and importance: This study provides a new definition of seasonal transition in both NH and SH, and interprets the influence of SSW, QBO and ENSO on ST. The process in this transition period is helpful to better understand how stratospheric change from disturbed winter to relatively stable summer. Based on this understanding, we further focus on how stratospheric ST affects troposphere, and distribution of stratospheric chemical traces such as O₃, CH₄ and NO₂ observed by satellites.

The Characteristics of Wintertime Tropospheric Blocking over Ural-Siberia and Its Implication for East Asia Winter Monsoon

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Abstract

Severe cold air outbreaks in East Asia are dynamically linked to the tropospheric blocking. This study investigates the climatological aspects and temporal characteristics of wintertime Ural-Siberian blocking (USB, centered over 30°–100° E), for the period 1980/1981–2009/2010. Sixty-eight events are identified and their physical structure is diagnosed using thermodynamic and geostrophic vorticity tendency equations. In climatology, horizontal advections play a fundamental role in constructing a USB event, in which the anticyclonic center is a warm core in the troposphere and a cold core in the lower stratosphere. The decay of the thermal structure is related to diabatic cooling along the vertical structure and warm advection in the lower stratosphere. Meanwhile, the collapse of the height structure is caused primarily by cyclonic vorticity advection. A strong interrelationship exists between the intensity and extension of USB events. The temporal characteristics of USB events are analyzed by examining strong and weak events, which are of high and low intensity. The strong events are probably preceded by an open ridge over Europe and a cyclogenesis over the Mediterranean Sea, and their formation is followed by the stronger amplification of a Rossby wave packet across Eurasia. On the other hand, the weak events are likely to be triggered by surface cold anomalies over Siberia. Overall, the evolution of a USB event forms a dynamic linkage with the Siberian high, in which the decay stage of the USB event is accompanied by a southeastward migration of the Siberian high and a subsequent cold air outbreak in East Asia. These results advance our understanding of USB and its relationship with East Asian winter monsoon activities.

Performance of a gravity wave parameterization with moist baroclinic wave life cycle simulations

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The life cycle of a moist baroclinic wave is often associated with the generation of upward-propagating gravity waves. The interactions of these wave types are studied with the mesoscale Weather Research and Forecasting model at different resolution and moisture. Several gravity wave packets are identified in the lower stratosphere with a characteristic structure and location above jets, fronts and convective regions. Relevant large-scale generation processes such as flow deceleration, frontogenesis and condensational heating are included in a state-dependent parameterization formula. It performed very well with the five different simulations – its use in global circulation models is discussed.