SPARC DynVar Workshop 2:
Modeling the Dynamics and Variability of the Stratosphere-Troposphere System

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Book of Abstracts

Pathways for Communicating Changes in Stratospheric Ozone to the Arctic Polar Vortex: Role of Zonally Asymmetric Ozone

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A mechanistic model that couples quasi geostrophic dynamics, radiative transfer, ozone transport, and ozone photochemistry is used to study the effects of zonal asymmetries in ozone (ZAO) on the model's polar vortex. The ZAO affect the vortex via two pathways. The first pathway (P1) hinges on modulation of the propagation and attenuation of a planetary wave by ZAO; the second pathway (P2) hinges on modulation of the flux convergences due to ZAO. In the steady state, P1 dominates over P2 in the dynamically controlled lower stratosphere and in the photochemically controlled upper stratosphere. P2 is of secondary importance in mid-stratosphere, where dynamical and photochemical time-scales are comparable. The relative importance of propagation and attenuation in P1 is diagnosed using an ozone-modified refractive index and an ozone-modified vertical energy flux. In the lower stratosphere, ZAO cause the wave propagation and wave attenuation to oppose each other. The result is a small change in PWD but a large reduction in wave amplitude. Thus ZAO in the lower stratosphere "precondition" the wave before it propagates into the upper stratosphere, where attenuation due to photochemical accelerated cooling dominates, causing a large reduction in PWD and thus a warmer polar vortex. The ability of ZAO within the lower stratosphere to impact the upper stratosphere and lower mesosphere is discussed in light of secular changes in stratospheric ozone and increasing greenhouse gas concentrations.

An intercomparison of observations and global models to assess gravity wave effects on circulation

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Recent intensification of effort in developing climate models with more realistic stratospheric circulations has in turn lead to an increased interest in modeling gravity wave mean-flow forcing effects in these models. We will describe plans and preliminary results of an intercomparison of gravity wave momentum fluxes and forcing in both observations and global models, which is an ongoing effort of an international team organized with the help of SPARC and the International Space Science Institute. We also invite participation from other models/groups/individuals involved in DynVar. The aim of the intercomparison is not only to assess the degree of agreement or disagreement among the various measures of wave effects on circulation; We also plan to eventually merge existing global observations into a coherent set of constraints that may be applied either to gravity wave parameterizations in global models or to resolved gravity waves in present and future high-resolution model simulations. This intercomparison of gravity wave momentum fluxes and momentum tendencies is organized under four scientific questions:

(1) What is the spectrum of absolute momentum flux carried by gravity waves in the lower stratosphere? The spectrum of momentum flux associated with gravity waves near the tropopause and in the lower stratosphere is of primary importance in determining the mean-flow forcing effects of gravity waves at higher altitudes in the middle atmosphere. Although the vector flux would be more desirable, observations can provide global estimates of the absolute value of the flux that can be used as constraints for parameterizations of gravity wave drag.
(2) What are the seasonal, geographical and interannual variations in momentum flux? Both observations and models show gravity wave momentum fluxes have large geographical variations that vary both seasonally and interannually. Geographic maps of the flux for each calendar month and year from both the observations and from climate models will be intercompared as a first step in developing a climatology.
(3) How intermittent is the momentum flux? Gravity waves with their small horizontal scales

and high frequencies are frequently observed in wave packets defined by a spatial and temporal envelope of finite amplitude. Conversely, the theoretical basis behind most parameterizations of non-orographic gravity waves assumes a uniformity of the wave spectrum in space and/or time, and although intermittency is recognized as important, it is generally treated by application of a scaling parameter. Is the atmospheric momentum flux delivered in a continuous stream of low-amplitude waves, or in highly sporadic large-amplitude wave packets? The answer can dramatically affect the wave breaking altitudes and the profile of the gravity wave driven force on the mean flow.
(4) What is the zonal-mean gravity wave zonal force as a function of height and latitude?

Currently, global models treat gravity wave effects on the global circulation in a variety of ways. Some models now explicitly resolve gravity waves without any parameterization, while in the past many climate models have treated gravity wave effects solely via parameterizations. Most models in use today will resolve some waves and parameterize the effects of others. A quantitative intercomparison of the zonal-mean gravity wave driven force in these various models may show general agreement and form the basis of a climatology. Clear differences with model resolution may point toward a set of resolution-dependent constraints for parameterizations. Other differences may point to differences in the gravity wave parameterizations, model physics, or model numerics.

Quasi-biennial oscillations in an atmospheric general circulation model

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We examine the simulation of the quasi-biennial oscillation (QBO) of tropical stratospheric winds in an atmospheric general circulation model. The vertical resolution of the model is varied in order to determine why spontaneous generation of realistic zonal-mean zonal wind oscillations in the lower stratosphere requires high vertical resolution of the order of 0.5 km (as found in a number of previous studies). In our model a combination of resolved and parameterized waves are required to generate a QBO, but it seems not to be possible to compensate for a lack of vertical resolution by increasing the driving due to parameterized waves. Simulation of a reasonably realistic QBO in the model allows for the examination of dynamical coupling between the QBO and the stratospheric winter polar vortex (also known as the Holton-Tan effect) as internal atmospheric variability, i.e. excluding the effects of other influences that occur in the real atmosphere such as ENSO and the 11-year solar cycle.

The GFDL CM3 simulations: results of a climate model including something for everyone

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Several thousand years' simulations have been completed with the GFDL climate model in preparation for CMIP5. The model is an updated version of the previous climate model and includes a coupled ocean as well as coupled aerosols. A particular strength is the incorporation of both detailed tropospheric and detailed stratospheric chemistry which operates seamlessly from the surface to the model upper boundary at 0.03 hPa. The presentation will focus on the simulation period 1860-2005. It is found that stratospheric ozone has only a small trend prior to the year 1970. As the CFC amounts increase from shortly after 1970, stratospheric ozone starts to decrease and continues until about 2000. The steadily increasing GHG concentrations cool the stratosphere from about the beginning of the 20th century at a rate which increases with height. During the early period the reducing temperatures leads to increased stratospheric ozone. The model results show a strong, albeit temporary, response to volcanic eruptions. For most of the period, while CFC concentrations remain low, the effect of eruptions is shown to increase the amount of HNO3, reducing the amount of ozone destruction by the NOx catalytic cycle. By contrast, the effect of El Chichon and Mt. Pinatubo is simultaneously to increase the chlorine radicals and decrease the chlorine reservoirs. The net volcanic effect on nitrogen and chlorine chemistry depends on

altitude and for the these two volcanoes leads to an ozone increase in the middle stratosphere and a decrease in the lower stratosphere. Model lower stratospheric temperatures are also shown to increase during the last three major volcanic eruptions, by about 0.6 K in the global and annual average, consistent with observations.

Stratospheric communication of ENSO teleconnection in European winter

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The Reading Intermediate General Circulation Model (IGCM) has been used to investigate the response of the stratosphere and the surface to ENSO-like SST forcing. We find an approximate doubling of stratospheric sudden warmings during El Nino winters. At the surface, the model response in the Euro-Atlantic region corresponds well to the canonical sea-level pressure signal of a negative NAO. We also perform sensitivity experiments in which the variability of the stratosphere has been degraded. We find evidence of a 'stratospheric bridge' mechanism in which stratospheric variability may play an important role in communicating the ENSO signal to Europe.

Impact of Stratospheric Dynamics on Global Tropopause Structure

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The height of the tropopause is often considered to be primarily set by the combined effects of a dynamically active troposphere and a stratosphere in near radiative equilibrium. Here, modifications of this picture due to stratospheric dynamics are quantified using a comprehensive chemistry-climate model (CCM) and simple idealized modeling. Stratospheric radiative equilibrium solutions are obtained using off-line radiative transfer calculations for given tropospheric climate as simulated by the CCM. That is, a hypothetical climate is obtained that has a realistic troposphere and a stratosphere in radiative equilibrium. The resulting tropopause height in these stratospheric radiative equilibrium solutions is reduced by several kilometers in the tropics but is increased by 1-2 km in the extratropics compared to the tropopause height in the (full-blown) CCM, reducing the equator-to-pole contrast in tropopause height by more than 50%. That is, more than half of the equator-to-pole contrast in tropopause height can be attributed to stratospheric dynamics. This is discussed in terms of the stratospheric residual mean meridional circulation which tends to lift the tropopause within its upward branch in the tropics and tends to lower the tropopause within its downward branch in the extratropics, especially during winter.

The Northern Annular Mode and large volcanic eruptions: a tropospheric/ stratospheric mechanism?

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Winters closely following explosive volcanic eruptions tend to show anomalous circulation and warm anomalies over northern Eurasia. On average, strong eruptions over the last 500 yrs caused significant winter warming in models and reconstructions, and lead to significantly detectable model fingerprints in reconstructions. However, the mechanism involved and the ability of models to simulate this mechanism fully is still uncertain. In this paper we study the role of the tropospheric circulation during the months preceding the volcanic winter season. Anomalous eddy heat flux during October and November is consistent with the wind and temperature anomaly observed during the mature stage of the winter and is linked to anomalous tropospheric circulation. The observations suggest that the volcanic forcing in the lower equatorial stratosphere forces changes in the tropical circulation leading to the

tropospheric anomalies during October and November which will then act as precursor of the anomalous volcanic winter.

The Brewer-Dobson Circulation in a changing climate

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The stratospheric part of the residual mean meridional circulation, which is also referred to as the Brewer-Dobson Circulation (BDC), is a main feature of stratosphere dynamics. Air parcels originating from the troposphere enter the stratosphere near the equator via tropical upwelling, and are then transported poleward. Having reached the mid-latitudes they start to sink, so that some of them re-enter the troposphere after a relatively short time. Other air parcels, however, proceed traveling to high latitudes, where they eventually sink back into the troposphere. Passive tracers can be used to visualize this transport pattern, and thus provide the opportunity to obtain a measure of the strength of the BDC by calculating the mean age of stratospheric air.

The BDC is expected to react to external forcing and in particular changes in the tropospheric state. In recent model simulations, increasing greenhouse gas (GHG) emissions were found to be a possible source for an intensification of extra-tropical planetary-wave forcing, leading to an increase in tropical upwelling and thus an acceleration of the BDC, as indicated by stratospheric age of air tracers. However, this result is not supported by measurements of the age of stratospheric air, which do not indicate any systematical change in the strength of the BDC over the past decades.

In this work we use the new general circulation model (GCM) ECHAM6 to simulate the BDC in a changing climate. The particular focus lies on the impact of the model configuration. For the stand- alone atmosphere version of ECHAM6 we use the model resolutions T63L31, T63L47 and T63L95. To analyze possible correlations of the strength of the BDC to a changing climate, the model is run in the time-slice mode using three different sets of boundary conditions with regard to sea surface temperatures (SSTs) and GHG concentrations: preindustrial (1860), present-day (2000) and future (2050, scenario-based) conditions. The results of this analysis will be compared to model simulations performed with the coupled atmosphere-ocean GCM ECHAM6/MPIOM. In the coupled version the model resolutions will be T63L31 and T63L47 for the atmosphere, and TP10L40 (three poles) for the ocean.

As a first step, we present our results obtained from three time-slice simulations performed with ECHAM6 in the T63L47 configuration. The three different simulations were run with the three different sets of boundary conditions mentioned above. Results with regard to the evolution of the BDC in a changing climate are compared to the findings of similar simulations performed with ECHAM5, the progenitor of ECHAM6. Climatologies and trends of the tropical upwelling as well as for the age of stratospheric air will be presented.

Evaluation of the Stratosphere in the Climate Forecast System (CFS)

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The NOAA Climate Forecast System (CFS) is the primary operational forecasting tool for weekly to seasonal forecasts. Coupling between the stratosphere and troposphere may offer a source of predictability at these time scales. To improve the stratosphere-troposphere coupling in the CFS, we first evaluate the biases in the model stratosphere using an AMIP-style simulation. We find that the Northern Hemisphere polar night jet is too weak and is accompanied by a negative North Atlantic Oscillation (NAO) bias in the troposphere. We also evaluate the ability of the CFS to capture the frequency of major stratospheric sudden warmings. Finally, we examine the impact of the El Nino Southern Oscillation (ENSO) on the Northern Hemisphere stratosphere in the CFS.

Role of Ozone Depletion and Recovery on the SH jet and tropospheric climate using WACCM4 simulations.

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Observations over the last few decades have shown an acceleration of the tropospheric westerly jet in the Southern Hemisphere. General Circulation Models corroborate this result and reveal that both the increase in greenhouse gases and polar ozone depletion are responsible for this trend which affects directly tropospheric climate. For the future, atmospheric-ocean coupled models for the Intergovernmental Panel of Climate Change Fourth Assessment Report (IPCC-AR4) and Chemistry Climate Models from the CCMVal2 (SPARC report) activity disagree. The first ones are coupled to an ocean model, do not fully resolved the stratosphere and do not always account for the expected ozone recovery. The second ones are fully chemistry coupled with the top of the model well beyond the stratopause, however they use observed sea surface temperatures as boundary conditions. While the IPCC models show, as in the past, an intensification of the polar jet in the SH although at a weaker rate, the CCMVal models predict a deceleration on the poleward side during the SH summer, which is attributed to the strong warming induced by the recovery of the ozone hole in the Antarctic lower stratosphere and not always considered in IPCC models.

The latest version of the Whole Atmosphere Community Climate Model WACCM4 coupled to a deep ocean model brings together the advantages of both IPCC and CCMVal models. New simulations have been run for the past and future as part of the CMIP5 activity. They are analyze here to investigate the role of ozone depletion and recovery on the SH jet and their implications for SH tropospheric climate. The results are compared to observations, low-top models and CCMVal models.

Solar signal propagation: The role of gravity waves and stratospheric sudden warmings

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We use a troposphere-stratosphere model of intermediate complexity to study the atmospheric response to an idealized solar forcing in the subtropical upper stratosphere during Northern Hemisphere (NH) early winter. We investigate two conditions that could influence the poleward and downward propagation of the response: 1) the representation of gravity wave effects, and 2) the presence/absence of Stratospheric Sudden Warmings (SSWs). We also investigate how the perturbation influences the timing and frequency of SSWs. Differences in the poleward and downward propagation of the response within the stratosphere are found depending on whether Rayleigh friction (RF) or a gravity wave scheme (GWS) is used to represent gravity wave effects. These are likely related to differences in planetary wave activity in the GWS and RF versions, as planetary wave redistribution plays an important role in the downward and poleward propagation of stratospheric signals. There is also remarkable sensitivity in the tropospheric response to the representation of the gravity wave effects. It is most realistic for GWS. Further, tropospheric responses are systematically different dependent on the absence/presence of SSWs. When only years with SSWs are examined, the tropospheric signal appears to have descended from the stratosphere, while the signal in the troposphere appears disconnected from the stratosphere when years with SSWs are excluded. Different troposphere-stratosphere

coupling mechanisms therefore appear to be dominant for years with and without SSWs. The forcing does not affect the timing of SSWs, but does result in a higher occurrence frequency throughout NH winter. Quasi-Biennial Oscillation effects were not included.

Role of the stratospheric ozone on the medium-range weather forecast: A case study of northern winter 2003-2004

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The role of the stratospheric ozone on the predictability of medium-weather forecast during the northern hemisphere winter 2003-2004 is examined using a chemistry-climate model of the Meteorological Research Institute (MRI-CCM2). The model is a climate model with a well-resolved stratosphere, including a full atmospheric chemistry from the surface to the middle atmosphere. An ensemble of 20 numerical forecasts was performed every 6 hours using the initial conditions determined from the objective analysis data of the Japan Meteorological Agency. In these runs, radiative feedbacks of chemical constituents such as ozone and methane predicted by the chemistry module were considered. We also performed another ensemble of the 20 runs using the same initial conditions, in which the radiative feedbacks of chemical constituents were not considered and the prescribed distribution of the chemical constituents were forced. The effects of the day-to-day variability of stratospheric ozone on the weather forecast were examined using the two ensemble runs.

The role of linear interference in the Annular Mode response to Tropical forcing

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Recent observational and modelling studies have shown that eastern tropical Pacific Ocean (TPO) warming associated with the El Nino-Southern Oscillation (ENSO) is linked to the negative phase of the wintertime NAM in the stratosphere and troposphere. The TPO-NAM link involves a Rossby wave teleconnection from the tropics to the extratropics and to the polar stratosphere. For a TPO warming, the Rossby wave teleconnection is associated with an increase in stratospheric wave driving that in turn induces a negative NAM anomaly in the stratosphere and troposphere. Previous work further suggests that tropical Indian Ocean (TIO) warming is associated with a positive NAM anomaly, which is of opposite sign to the TPO case. The TIO case is, however, difficult to interpret because the TPO and TIO are not independent. To better understand the dynamics of tropical influences on the NAM, the current study investigates the stratosphere-troposphere NAM response to imposed TPO and TIO warming in general circulation models (GCMs). The NAM responses to the two warmings have opposite sign, and can be of surprisingly similar amplitude even though the TIO forcing is relatively weak. It is shown that the sign and strength of the NAM response is often simply related to the phasing, and hence the linear interference, between the Rossby wave response and the climatological stationary wave.

Radiative heating/cooling variations due to solar activity changes of spectral irradiance

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One of the most important inputs that driving general circulation models is the solar irradiance spectrum; this energy is subsequently distributed and impacts the evolution and dynamics on multiple scales. The solar input is known to change on many time scales. The changes are small except at very short wavelengths. In the present work we choose to study the 11-year variations of the sunspot cycle (or magnetic activity cycle) using three states during the past

cycle 23, represented by spectra for: 2000/2001 (high-activity), 2005 (moderate-activity), 2008 (low-activity).
The calculated irradiance spectra are based on the Solar Radiation Physical Modeling (SRPM) of Fontenla, *et al.*, 2009. These data have shown remarkable agreement with the measurements of Solar Spectral Irradiance (SSI). In particular, the recent data from the Solar Spectral Irradiance Monitor (SIM) on board the SORCE satellite provides the first long-duration solar spectral irradiance measurements at limited resolution in the spectral range from 260 to 1600 nm and has been used to validate the SRPM results during the period 2004-2009.

The fine-spectral-resolution SRPM spectra is used as input to MODTRAN®5 (Berk, *et al.*, 2004), which is a 'soda straw' radiative transfer code, run at $0.2cm^{-1}$ spectral resolution and 1 km vertical resolution. This approach ignores both dynamics and chemistry and focuses on a very detailed treatment of radiative transfer and molecular spectroscopy. MODTRAN calculates the instantaneous energy balance (fluxes and cooling rates) across the spectrum, but it does not include any feedback due to changes of temperature or composition, relying only on the input specifications. However, the isolation of just the solar input, against the atmospheric and surface properties, within the altitude range from 100 km downward, permits the assessment of the magnitude of changes of solar-only contributions to the variations of vertical radiative fluxes and heating rates on the various atmospheric layers. Distinctions between the stratospheric and boundary layers, affected by solar variability as it impacts static ozone, water vapor bands, and land and ocean, provide a baseline metric for understanding the normal solar cycle perturbations to the Earth's atmosphere.

In the presentation we discuss the most important results found for the driving of stratospheric layers. Significant and interesting solar-induced variations of the radiative heating and flux are found in the Hartley-Huggins and Chappuis O3 bands that affect the stratospheric layers.

Fontenla, J.M., Curdt, W., Haberreiter, M., Harder, J., and Tian H., "Semiempirical models of the solar atmosphere. III. Set of Non-LTE Models for Far-Ultraviolet/Extreme-Ultraviolet Irradiance Computation", ApJ, 707, 482-502 (2009)

Berk, A., Anderson, G. P. ; Acharya, P.K. ; Bernstein, L.S. ; Fox, M., "MODTRAN®5: A reformulated atmospheric band model with auxiliary species and practical multiple scattering options", in Sensors, Systems, and Next-Generation Satellites VIII, edited by R. Meynart, S. P. Neeck, and H. Shimoda, Proc. SPIE Int. Soc. Opt. Eng., 5571, 78–85, (2004).

Impact of changes in transport on future Antarctic ozone

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The stratospheric ozone layer is expected to recover from the effects of ozone depleting substances over the next century as stratospheric halogen concentrations decline. However, ozone concentrations are also affected by changes in climate. The mass of stratospheric ozone over Antarctica is analysed using the E39C-A chemistry-climate model. In particular, a method is applied that allows the changes in ozone induced by chemical and dynamical processes to be disentangled. It is found that in the annual mean, the ozone mass in the Antarctic stratosphere (in the region 60°-90°S and 200 to 10 hPa) increases by 10% from the 2000s to the 2040s. Changes in chemical destruction rates imply an increase in ozone of +20%, while changes in transport lead to a reduction in ozone of about 10%. This reduction in ozone due to transport is caused by reduced import of ozone from southern mid- latitudes. The analysis of air mass fluxes shows that the mass flux from mid-latitudes to the polar region is inhibited in summer in the middle stratosphere (above 60 hPa). This leads to reduced ozone transport into high latitudes. The inhibited air mass flux is linked to a weakening of the strength of the southern hemisphere Brewer-Dobson circulation in summer. This weakening is in turn induced by ozone recovery, as increasing ozone concentrations lead to higher temperatures in the Antarctic stratosphere. This reduces the meridional temperature gradient leading to weaker zonal winds, which affects planetary wave propagation into the stratosphere. In this way the dynamical response to ozone recovery feeds back negatively on ozone recovery through a reduction in transport.

Tropospheric vs. Stratospheric Control of the Brewer Dobson Circulation

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Tracer analysis is blended with residual mean circulation and downward control calculations to explore the stratospheric overturning circulation, or Brewer-Dobson Circulation, in idealized general circulation models. In particular, I will focus on the role(s) of the troposphere and stratosphere in controlling the strength and depth of the circulation. I find that while the troposphere appears to largely set the input of planetary and synoptic waves into the stratosphere, subsequent propagation and dissipation of the wave activity is substantially affected by the state of the stratosphere. Thus the overturning circulation depends critically on coupling between the two layers of the atmosphere. As documented in earlier studies, tracer transport by the overturning circulation can be quite sensitive to model numerics and resolution. Systematic resolution sweep experiments with two numerical models subject to the same forcing enable us to set benchmarks for the net overturning circulation, and may provide guidance for comparing tracer transport in more comprehensive GCMs.

Radiative-Photochemical Damping of Equatorial Waves in the Middle Atmosphere

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Convection in the tropical equatorial troposphere spawns a broad spectrum of waves that propagate vertically into the middle atmosphere. The damping of these waves results in a body force that drives the zonal-mean circulation, including the two most striking features of the equatorial middle atmosphere: the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO). To faithfully represent these wave-driven circulation features requires a precise description of the damping processes operating on the waves. With this in mind, we examine the relative importance of Newtonian cooling (NC) and ozone heating (OH) on the damping of Kelvin, Rossby-gravity, inertia-gravity and equatorial Rossby waves using an equatorial beta-plane model of the middle atmosphere. The OH is comprised of contributions from ozone photochemistry and ozone advection (vertical and meridional). The model waves are forced from the lower boundary and propagate vertically on a steady, zonal-mean basic state. An analytical analysis yields explicit expressions for the (local) spatial propagation and spatial damping rate for each wave type. Guided by observed wave spectra, spatial damping rates are calculated for zonal-mean basic states consistent with the easterly and westerly phases of the QBO and SAO.

A simple parameterization is presented that accounts for effects of OH on the spatial damping rates of equatorial waves in the stratosphere. The parameterization specifically accounts for wave type, zonal scale, meridional structure, and propagation speed. The parameterization shows that irrespective of wave type, the OH due to vertical ozone advection dominates over meridional ozone advection. The vertical ozone advection may augment or oppose the damping due to NC, depending on altitude and meridional wave structure. Damping effects due to ozone photochemistry increase with height and always augment NC. In the vicinity of a critical layer, ozone photochemistry always dominates over advection. The effect of OH on the spatial damping rates is typically maximized in the mid to upper stratosphere. For Kelvin, Rossby-gravity, and equatorial Rossby waves corresponding with observations, the OH may contribute as much as 45% to the spatial damping rate. Because inertia-gravity waves span a wide range of zonal-wave scales and meridional structures, and may be of high or low

frequency, the effects of OH on their spatial damping rate are more complicated than for the other wave types. For inertia-gravity waves propagating with the mean current, OH may contribute as much as 35% to the spatial damping rate. Counter-propagating waves have damping rates that are typically about ~10% less than for waves that propagate with the current. The implications of these results for global climate modeling will be discussed.

The vertical profile of final warmings in the Northern Hemisphere

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The final warming of the stratospheric polar vortex is defined as the time when the zonal mean zonal wind at 60 degrees becomes easterly for the last time. In the Southern Hemisphere this warming occurs first at the top of the stratosphere and propagates downwards. However, in the Northern Hemisphere the final warming occurs first at around 10hPa suggestive of a more dynamical, rather than radiative, cause. ERA-Interim reanalysis and CCMVal-2 model data are used to investigate, and an attempt is made to split the forcing of the final warming into dynamical and radiative components.

Decadal changes in stratosphere-troposphere downward wave coupling in the Southern Hemisphere and the role of ozone changes

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Most of the previous studies on the impact of stratospheric ozone depletion on the tropospheric circulation have focused on changes in the zonal-mean circulation, i.e. changes in the Southern Hemisphere annular mode, which result from changes in zonal-mean stratosphere-troposphere coupling. Here we examine decadal changes in downward wave coupling between the stratosphere and troposphere in the Southern Hemisphere during winter and spring, in both the MERRA reanalysis and the Goddard Earth Observing System Chemistry-Climate Model (GEOS CCM). Wave-wave cross correlations applied to the MERRA reanalysis data set suggest stratosphere-troposphere downward wave coupling in the Southern Hemisphere has become stronger over the past three decades with more downward reflection during the September to December period. Wave geometry diagnostics indicate this increase is due both to an earlier onset of downward reflection in September and to reflection lasting longer into December as a result of the delay in vortex breakup.

We use the GEOS CCM to assess the impact of ozone changes on the observed increases in downward wave coupling. When forced with observed changes in halogens the ozone-induced changes in the wave geometry cause a delay in the vortex breakup date and downward wave coupling during late spring/early summer increases, as in the observations. During the period of ozone recovery downward wave coupling decreases. When the model was run with increasing greenhouse gases but without ozone changes there was no significant change in the downward wave coupling. The results reveal a new mechanism where in stratospheric ozone changes can affect the tropospheric circulation.

Stratosphere-troposphere Dynamical Coupling Through Blocking Phenomena During Recent Major Stratospheric Sudden Warmings

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Stratospheric sudden warmings (SSWs) are strong manifestation of stratosphere-troposphere dynamical coupling. Their possible relationship with blocking phenomena in the troposphere has been often pointed out. In the present study, such stratosphere-troposphere dynamical coupling is examined for typical cases of recent SSWs including vortex displacement and vortex-splitting SSWs by the use of the ECMWF re-analysis data. On the basis of the Plumb's (1985) wave activity flux, it is found for the vortex-splitting event in January 2009 that the warming was brought about by the amplification of wavenumber 2; this was associated with the upward propagation of wave packets originating from a clear blocking ridge over Alaska and their following eastward propagation leading to the intensification of a trough over eastern Siberia (Harada et al., 2010). Similar features can be commonly seen in other past events of the vortex-splitting type. On the other hand, for vortex displacement SSWs, e.g. the SSW in December 2001, blocking ridges over the Atlantic sector are found to play an important role in the evolution of the events. Moreover, the relationship with ENSO events is also discussed in the presentation.

The dynamical origin of long time scales in the Arctic lower stratosphere

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Stratosphere-Troposphere coupling is understood to be at its most active in boreal winter, during extended episodes of a weakened or strengthened polar vortex. Stratospheric time-scales are evidently extended in comparison to tropospheric time scales during these events, and the longer radiative time scales in the lower most stratosphere are an obvious candidate explanation.

We present a series of simplified GCM experiments which suggest that while the radiative time scales play a role, the slower dynamics are episodic in nature and depend upon the occurrence of anomalous zonal mean states which strongly suppress stratospheric wave activity.

Can the GEOS CCM Simulate the Temperature Response to Warm Pool El Niño Events in the Antarctic Stratosphere?

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“Warm pool” (WP) El Niño events are characterized by positive sea surface temperature (SST) anomalies in the central equatorial Pacific. During austral spring, WP El Niño events are associated with an enhancement of convective activity in the South Pacific Convergence Zone, provoking a tropospheric planetary wave response and thus increasing planetary wave driving of the Southern Hemisphere stratosphere. These conditions lead to higher polar stratospheric temperatures and to a weaker polar jet during austral summer, as compared with neutral ENSO years. Furthermore, this response is sensitive to the phase of the quasi-biennial oscillation (QBO): a stronger warming is seen in WP El Niño events coincident with the easterly phase of the quasi-biennial oscillation (QBO) as compared with WP El Niño events coincident with a westerly or neutral QBO.

The Goddard Earth Observing System (GEOS) chemistry-climate model (CCM) is used to further explore the atmospheric response to ENSO. Time-slice simulations are forced by

composited SSTs from observed WP El Niño and neutral ENSO events. The modeled eddy heat flux, temperature and wind responses to WP El Niño events are compared with observations.

A new gravity wave drag scheme has been implemented in the GEOS CCM, enabling the model to produce a realistic, internally generated QBO. By repeating the above time-slice simulations with this new model version, the sensitivity of the WP El Niño response to the phase of the quasi-biennial oscillation QBO is estimated.

Stratospheric impacts on the North Atlantic Ocean circulation

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Previous research has found significant dynamical linkages between stratosphere and troposphere on intra-seasonal time scales. However, whether stratospheric variability can also influence the ocean has not been addressed before, despite the fact that the low-frequency nature of stratospheric events should be particularly effective in driving and enhancing intrinsic oceanic variability. The existence of such an influence would have consequences for climate predictability on both decadal and climate time scales.

In order to investigate whether the stratosphere impacts the ocean, we study long control integrations with the coupled GFDL model and other low-top models from the CMIP3 archive, focusing on the North Atlantic sector where strong oceanic variability in association with the Atlantic Meridional Overturning Circulation (AMOC) is observed.

From these simulations we find clear evidence for an impact of long-lived stratospheric circulation anomalies on the AMOC. This impact is mediated through the North Atlantic Oscillation (NAO) and mostly associated with heat flux anomalies at the air-sea interface. The resulting temperature fluctuations modulate the deep convective part of the AMOC and lead to signals which over the course of several years propagate to the bottom of the ocean. We further find that these events drive intrinsic low-frequency variability in the AMOC that persists for several decades.
We discuss the significance of these results in light of the recent series of stratospheric sudden warming events and of long-term climate change. Our findings support the increasing body of evidence that resolving the climate prediction problem requires understanding the nature of stratospheric variability on all time scales.

Predictability of the stratospheric sudden warming and its impact on the tropospheric climate in January 2009 - Comparison with the warmings of 2004 and 2006

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Predictability of the stratospheric sudden warming (SSW) and its following Northern Annular Mode (NAM) variability in the troposphere is examined for the winter of 2009, and comparison is made with other warmings of 2004 and 2006. The predictability was examined using sets of ensemble runs of a climate model of our institute. The SSW of 2009 is very unusual in the sense that it is caused by almost pure planetary wave of zonal-wavenumber 2 and such SSW is the only one that appears in the past. So it will be interesting to see how extend can we predict the occurrence of the SSW and following impact on the troposphere with the climate model. The result shows that the occurrence of the SSW can be predicted if prediction is initialized within 8 days before the peaked day. The limit is rather short compared with the one found in the previous studies, which shows limit longer than about 2 weeks. The predictability of the downward propagating tropospheric NAM variability following the SSW shows that very long predictability of a few months cannot be obtained even if the forecast is performed before the occurrence of the SSW. Predictability is limited to almost half months regardless of the initial time of the prediction. The situation was very different to the typical PJO-type warmings of 2004 and 2006.

Impacts of the convection parameterization scheme on the Stratospheric Equatorial waves simulated by the GCM LMDz.

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Equatorial waves play an important role in the stratosphere and are a fundamental components of the interaction between physics and dynamics in the tropical atmosphere. Equatorial Kelvin waves and Rossby-Gravity waves are partly responsible for the quasi-biennal oscillation (QBO) and the semi-annual oscillation. These waves also contribute to the dehydration of the air when it crosses the Tropopause Tropical Layer. It is therefore important that they are well represented in General Circulation Models (GCMs).

Stratospheric equatorial waves are often considered to be forced by convection but other sources are plausibles like the interaction between the midlatitudes and the tropics. In model the direct effect of convection can also be hidden by the fact that the vertical resolution can become a strong dynamical filter for the slow and long equatorial waves that eventually enters in the stratosphere.

To adress these issues we compare two simulations with the LMDz GCM where two distinct convection schemes are used: the parameterization of Tiedke (1989) and the parameterization of Emanuel (1990). A wavenumber-frequency spectrum analysis of precipitations is then performed and compared with observations. The spectral characteristics of precipitations depend clearly on convective scheme with clearly underestimating the high frequences and the high wavenumbers of the precipitation. To evaluate the impact of these changes on equatorial waves, we performe an other wavenumber-frequency spectrum analysis of the zonal wind, the meridionnal wind, the temperature and the geopotential. We first note an important Kelvin waves activity in the model lower stratosphere despite the weak eastward activity in the precipitations. Moreover, the westward Rossby-Gravity waves seem even less affected by the convection scheme than the Kelvin waves: in both simulations they are not much different, despite the fact that the precipitation variability in both simulation is very different.

Stratospheric circulation in seasonal forecasting models: implications for seasonal prediction

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Accurate seasonal forecasts rely on the presence of low frequency, predictable signals in the climate system which have a sufficiently well understood and significant impact on the atmospheric circulation. In the Northern European region, signals associated with seasonal scale variability such as ENSO, North Atlantic SST anomalies and the North Atlantic Oscillation have not yet proven sufficient to enable satisfactorily skilful dynamical seasonal forecasts.

The winter-time circulations of the stratosphere and troposphere are highly coupled. It is therefore possible that additional seasonal forecasting skill may be gained by including a realistic stratosphere in models. In this study we assess the ability of five seasonal forecasting models to simulate the Northern Hemisphere extra-tropical winter-time stratospheric circulation. Our results show that all of the models have a polar night jet which is too weak compared to re-analysis data. It is shown that the models underestimate the number, magnitude and duration of periods of anomalous stratospheric circulation. Despite the poor representation of the general circulation of the stratosphere, the results indicate that there may be a detectable tropospheric response following anomalous circulation events in the stratosphere.

The study highlights some of the deficiencies of current seasonal forecasting models with a poorly resolved stratosphere. Alongside other studies which examine troposphere-stratosphere dynamical coupling, the results highlight a potential way to improve the skill of operational winter-time forecasts in the Northern hemisphere extra-tropics.

Could changes in stratospheric water vapour influence regional surface climate?

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Variability in stratospheric water vapour (SWV) can arise from a number of different mechanisms. Changes in SWV directly affect the thermal structure of the stratosphere. For instance, a uniform increase in SWV causes cooling which is largest in the extra-tropical lower stratosphere. The dynamical response to such a cooling pattern highlights a mechanism for influencing stratospheric variability on multi-annual timescales, which is the typical lifetime of a tropical SWV anomaly. Since changes in the winter-time stratospheric flow have been shown to influence the underlying tropospheric circulation, changes in SWV could therefore have a significant effect on the extra- tropical surface climate on multi-annual timescales.

This study investigates the tropospheric response to an idealised uniform increase in SWV from 3 to 6ppmv using a version of the HadGAM2 AGCM with a resolved stratosphere. We show that the strong radiative cooling in the extra-tropical lower stratosphere is associated with a westerly acceleration of the zonal wind on the upper poleward flanks of the subtropical jets. The surface response to the SWV increase shows positive North Atlantic Oscillation and Southern Annular Mode anomalies, which are largest in DJF in both hemispheres. We show evidence that the surface changes are associated with a poleward shift in baroclinic eddy activity.

The results suggest that transient changes in SWV, particularly in the extra-tropical lower stratosphere, may be important for seasonal to interannual variability of surface climate in the extra- tropics. Future experiments will test the relevance of the mechanisms presented for SWV anomalies with a more realistic amplitude and structure.

Sources of Annular Mode timescales

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Timescales derived from Annular Mode (AM) variability provide dynamical insight into stratosphere-troposphere coupling and are linked to the strength of AM responses to climate forcings. AM timescales reflect decorrelation times of geopotential height in the stratosphere and troposphere. But geopotential height involves a vertical integral via the hypsometric equation, and this makes ambiguous some aspects of the dependence of the timescales on vertical level. In this study, a methodology for decomposing AM variability into contributions from surface pressure and from temperature is presented that is based on a linearization of the hypsometric equation. The decomposition is then used to interpret stratosphere-troposphere coupling events and the seasonal variation of Annular Mode timescales in reanalysis products and in two versions of a general circulation model that have distinctly different stratospheric representation. It is shown that surface pressure variations best

account for tropospheric AM variability and timescales, while stratospheric temperature variations best account for stratospheric AM variability and timescales. The rapid phase speed of descent of AM anomalies into the troposphere during stratosphere-troposphere coupling events is related to the relatively weak variations of zonal mean temperature there. The analysis makes explicit the point that surface pressure and stratospheric temperature yield dynamically separable, but nevertheless coupled, contributions to AM variability. The time scales due to these separate contributions as well as their coupled effect may be isolated. The decomposition might serve as the basis for further theoretical analysis on the origins of stratosphere-troposphere coupling. For example, it is shown that the surface pressure contribution reflects the timescale of upper tropospheric eddy momentum fluxes while the stratospheric temperature contribution reflects the timescale of stratospheric eddy heat fluxes.

When chaos rules: evidence against a stochastic description of Northern Annular Mode high frequency variability

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An understanding of future climate change is dependent on two things: the prescription of external forcings (the 'scenarios'), e.g. future GHG emissions, solar irradiance, land-use etc; and modes of internal variability. Concerning the latter, the North-Atlantic Oscillation (NAO), and Northern Annular Mode (NAM) are key to describing low frequency internal variability on regional and hemispheric scales. Our understanding of these has relied, in part, on statistical descriptions of near-surface height and pressure fields. Specifically, seasonal NAM variability has been described using low order stochastic models, e.g. first order autoregressive (Marchov) processes, which are characterised by an exponential fall-off in the autocorrelation function. However, on timescales of days to weeks, it is not evident how applicable these models are. We assess the relevance of power-law representations of near-surface annular mode variability (1000hPa Z), with a particular critique of the AR-1 representation. We claim that power law behaviour does not and can not readily explain the wintertime NAM on timescales shorter than 40 days, but rather deterministic chaos provides a more suitable paradigm. We conclude by outlining the relevance of our results to NAM variability in the stratosphere

Diagnosis of stratospheric contribution to Northern Hemisphere wintertime variability using nudging AGCM experiments

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Besides ocean-atmosphere coupling, there is growing observational and numerical evidence that troposphere-stratosphere coupling also contributes to climate variability on a wide range of scales. The aim of the present study is to evaluate the stratospheric polar vortex influence on northern mid-latitude wintertime climate variability through the implementation of a grid point nudging technique in the ARPEGE-Climat atmospheric general circulation model (AGCM). Besides a control ensemble experiment where the model is only driven by observed sea surface temperature (SST), parallel ensembles have been performed in which an additional forcing has been accounted for through the nudging of the northern extratropical stratosphere towards the ERA40 reanalysis. Though idealized, this original experiment design allows us to compare the relative contribution of the lower and upper boundary forcings on the simulated tropospheric variability. Results show that the stratospheric nudging improves both the climatology and variability of the northern mid-latitudes. On a seasonal timescale, an EOF analysis reveals a major improvement of the Arctic and North Atlantic oscillations (AO and NAO) interannual variability. On a daily timescale, a cluster analysis of 500 hPa geopotential anomalies over the North-Atlantic Europe domain also indicates a more realistic intraseasonal variability of the four main weather regimes (NAO +/-, blocking, and Atlantic

Ridge), and primarily of the two NAO phases. Sensitivity experiments to vertical and/or horizontal resolution only show minor impacts on our results, suggesting that resolution is not the main limiting factor in the ARPEGE-Climat model and that a well resolved tropopause is not necessary for the nudging technique to be efficient. Case studies have been also carried out for winters 1976-1977 and 2009-2010, corresponding to extreme negative phases of the AO, and confirm the key role of the polar stratosphere for understanding and possibly predicting the wintertime variability in the northern mid-latitudes.

A dynamical mechanism for recent Southern Hemisphere Climate Change

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In recent decades there has been a marked strengthening of circumpolar westerlies around Antarctica in the lower stratosphere and troposphere during late spring and early summer, respectively. A state-of-the-art general circulation model simulation and ECMWF reanalysis are used to test the dynamical mechanism and forcing responsible for the downward descent of these zonal wind anomalies. The downward propagation is captured by the model in response to springtime ozone depletion in the lower stratosphere. The lifecycle of the response is described by onset, growth, maturation, decline, and decay phases. The onset and growth phases are characterized by a reduction in upward wave activity into the stratosphere, in response to the stronger lower stratospheric wind associated with diabatic cooling from ozone depletion, and consequently a wave driven acceleration of the mean zonal wind, that is, a strengthening of the stratospheric vortex. The induced mean meridional circulation acts to redistribute the wave driving downwards, resulting in the downward propagation of the zonal wind anomalies. The maturation, decline, and decay stages are marked by an increase in upward wave flux into the stratosphere, in response to the zonal wind anomalies reaching the surface and an increase in low-level baroclinicity, and consequently a wave driven deceleration of the mean zonal wind resulting in the gradual erosion of the anomalous vortex and a return to the climatological circulation. This wave driven dynamical mechanism is also apparent in linear trends in reanalysis data over the period since the appearance of the Antarctic ozone hole.

On the relationship between stratospheric resolution, annular mode persistence, and tropospheric climate change

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It is now well established that stratospheric climate change can impact the troposphere through the dynamical two-way coupling between the stratosphere and the troposphere. Sufficient vertical resolution in the stratosphere is needed in order for a model to correctly simulate this influence. Previous research has also shown that vertical resolution impacts the persistence of the annular mode and that longer persistence increases the climate response to the same external forcing. Together, these findings suggest that vertical resolution, annular mode persistence, and tropospheric climate response are related. However, it is still an open question how much stratospheric resolution is needed to correctly simulate such effects and to produce reliable simulations of tropospheric climate change.

Here, we address these issues and examine two versions of the GFDL climate model AM2 that only differ in terms of their vertical resolution and the location of the upper lid. The low-top version of the model has 24 vertical levels and a model lid at ~40 km, while the high-top version has 48 levels and a model lid at ~80 km. All other settings and parameterizations are identical. The two versions are used to produce long equilibrium simulations of climate change in response to various external forcings, including depletion and recovery of stratospheric ozone, various levels of greenhouse gases, and increases in sea surface temperatures.

We study the impact of vertical resolution on the tropospheric circulation response and find a significant sensitivity of this response to vertical resolution. We further find that vertical resolution impacts the annular mode persistence. As predicted by theory, differences in time scale and differences in circulation response are related. However, we demonstrate that the simple picture of an equivalency between increased vertical resolution and increased sensitivity to external forcings does not hold. Reasons and implications for this discrepancy are discussed.

Evaluation of downward wave coupling in the GEOS CCM Version I

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We investigate downward wave coupling between the stratosphere and troposphere in the southern hemisphere using the Goddard Earth Observing System chemistry-climate model (GEOS CCM) Version I. Downward wave coupling occurs when planetary waves reflected in the stratosphere impact the troposphere and is distinct from zonal-mean coupling, which results from wave dissipation and its subsequent impact on the zonal-mean flow. In the southern hemisphere, downward wave coupling dominates the dynamical coupling between stratosphere and troposphere on the intraseasonal time scale. The GEOS CCM captures the main features of the observed seasonal cycle of downward wave coupling in the southern hemisphere. Downward wave coupling occurs when there is a bounded wave geometry involving a high-latitude meridional wave guide bounded above by a vertical reflecting surface as in observations. However, there is a bias in the timing of the downward wave coupling. It begins too early and ends too late in the seasonal cycle. The late season bias is caused by a bias in the timing of vortex breakup.

Projection of future behavior of the quasi-biennial oscillation in the tropical stratosphere under the greenhouse gas increase

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Simulations on the past and future middle atmosphere were made for 140 years from 1960 to 2100 with the chemistry-climate model (CCM) of Meteorological Research Institute (MRI), MRI-CCM. Three different forcing runs were performed. The first run uses the SRES A1B GHG scenario and the adjusted A1 halogen scenario. The second uses the same SRES A1B GHG scenario with the halogens fixed at 1960 levels, and the third uses the same adjusted A1 halogen scenario with the GHGs fixed at 1960 levels. It is found that the QBO amplitude in zonal wind in the tropical stratosphere is decreased in future under the global warming due to the greenhouse gas increase, while the QBO amplitude is scarcely decreased under the fixed GHGs conditions.

Current status of MRI models for the CMIP5 simulation

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MRI will make the CMIP5 simulation with an earth system model, the complexities of which change from one simulation to another, depending on the scenarios/forcings/boundary-conditions. The current status of the MRI models for spin-up runs will be given in the presentation together with simulation plans.

Effects of stratospheric ozone depletion and increasing greenhouse gases on the Southern Ocean and Antarctic sea ice trends

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It has been well established that increasing greenhouse gases lead to changes in the strength and position of the tropospheric jet. Model experiments indicate that such changes induce changes in ocean temperatures, and the overturning and zonal circulation of the Southern Ocean. The importance of stratospheric ozone depletion for trends in the Southern Hemisphere tropospheric circulation has been acknowledged in more recent years. Previous studies have shown that the ozone influence maximizes in summer, and that its contribution to observed summer tropospheric circulation trends dominates that of increasing greenhouse gases, but the ocean circulation response to ozone changes alone has not been previously investigated. Due to the anticipated recovery of the stratospheric ozone layer opposite trends are expected for the next ~50 years, opposing the effects of increasing greenhouse gases.

In this study we employ comprehensive coupled Atmosphere-Ocean General Circulation Models with high vertical resolution to study the influence of greenhouse gases and stratospheric ozone on the Southern Ocean and Antarctic sea ice trends. We find that both greenhouse gases and ozone depletion induce changes in the Southern Ocean meridional overturning circulation, the Antarctic Circumpolar Current and the meridional ocean warming patterns, with ozone effects dominating before ~2020, and greenhouse effects dominating after ~2020. Long time-slice simulations forced with observed stratospheric ozone trends reveal that our model simulates a year-round decrease in Antarctic sea ice, in contrast to qualitative predictions made elsewhere. This suggests that processes not linked to stratospheric ozone depletion must be causing the observed increase in Antarctic sea ice extent.

The response of the tropical lower stratosphere to ENSO

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In response to anomalies in tropical pacific sea surface temperatures, both observations and models consistently show a temperature signal in the tropical lower stratosphere of the opposite sign to the SST anomaly. During warm ENSO conditions the tropical lower stratosphere is cooler and vice-versa. This temperature signal is associated with changes in tropical upwelling which also acts to alter stratospheric ozone and water vapour concentrations.

The exact mechanisms for the production of this lower stratospheric response remain uncertain. Here, SST perturbation experiments with the dynamical version of the Cana- dian Middle Atmosphere Model (CMAM) will be used to investigate the mechanisms responsible for the change in circulation of the tropical lower stratosphere in response to SST anomalies. While some recent evidence suggests that altered gravity wave drag in the northern hemisphere sub-tropics may be important, in these experiments changes in resolved wave drag in the summer hemisphere are found to dominate. The reason for this anomalous wave drag and why the summer hemisphere dominates will be discussed. Fur- thermore the mechanism for the production of the tropical upwelling response to ENSO will be compared and contrasted with that in response to global warming.

The role of transient tropospheric forcing in stochastic low-order models of sudden stratospheric warmings

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The amplitude of tropospherically forced planetary waves is known to be of first-order importance in producing sudden stratospheric warmings (SSWs). This forcing amplitude is observed to undergo strong temporal fluctuations. Characteristics of the resulting transient forcing leading to major stratospheric warmings are investigated in a highly truncated [zero dimensional] model of stratospheric wave-mean flow interaction, as well as the [one dimensional] Holton-Mass model. Modeled sudden warmings are shown to be highly sensitive to the time scale of the prescribed tropospheric forcing in both systems. Transient momentum forcing due to quasi-random gravity wave activity is also taken into account by means of an additive noise term in the zonal momentum equation. This small-scale forcing needs to be parameterized in climate models and is usually considered to be of little importance in driving SSWs. It is shown that this noisy small-scale forcing can strongly affect the nature of stratospheric wave-mean flow interaction and the occurrence of SSWs in the truncated models.

Why can't climate models capture the observed connection between seasonal snow cover and the Northern Annular Mode?

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The suite of general circulation models (GCMs) in the Coupled Model Intercomparison Project (CMIP3) have been found not to reproduce the observed relationship between October Eurasian snow cover anomalies and the wintertime Northern Annular Mode (NAM). This apparent deficiency is reexamined here based on analysis of observational data and GCM simulations with prescribed snow forcing. Previous work has shown that in a comprehensive GCM in which an autumnal Siberian snow forcing is prescribed, a vertically propagating Rossby wave train is generated that propagates into the stratosphere, drives dynamical stratospheric warming and induces a negative NAM response that couples to the troposphere. The wave response and background climatological stationary wave must interfere constructively to achieve wave activity amplification into the stratosphere and the zonal mean stratosphere-troposphere NAM response. Using observational data, it is shown that constructive interference also occurs in the observed October Eurasian snow cover-NAM connection. This constructive interference peaks in December, corresponding to strong wave activity flux into the stratosphere two months after the snow cover anomalies in October. By contrast, the CMIP3 GCMs typically show a negative correlation between October Eurasian snow cover and December wave activity flux, which is related to destructive interference between the wave train associated with the snow and the background stationary wave. This work suggests that differences in the horizontal phasing of regionally forced waves can have a significant effect on stratospheric variability.

Mesosphere-Stratosphere-Troposphere transport during and after a Major Stratospheric Sudden Warming in WACCM

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A stratospheric sudden warming (SSW) is a dramatic event that contributes significantly to the inter-annual variability of the middle atmosphere. While it has long been observed that some major SSWs are accompanied with a strong mesospheric temperature disturbances, recent re-analyses and satellite observations reveal that the zonal wind reversal that

characterizes SSWs can be initiated in the mesosphere, before propagating down into the stratosphere and troposphere. Furthermore, it now appears that, in addition to perturbing the tropospheric circulation, SSWs are dynamical disturbances affecting the entire middle atmosphere, as well as the thermosphere.

A realistic major stratospheric sudden warming (SSW) event is simulated in the National Center for Atmospheric Research (NCAR) Whole Atmosphere Community Climate Model (WACCM). The event is highlighted by a rapid branching of the polar stratopause, with one branch plunging down into the mid stratosphere, and another branch rapidly elevated to near 75km, at normal mesospheric altitudes. The SSW is accompanied by a strong equatorward and downward residual circulation between 40 and 60 km. The descent occurs mainly through the core of the highly displaced vortex during SSW and is accompanied by the apparent intrusion of carbon monoxide (CO) rich air (peeling away from the mesosphere as the mesospheric vortex collapses) into the mid-latitude, lower stratosphere.

Observed connection of the stratospheric quasi-biennial oscillation with El Niño-Southern Oscillation in radiosonde data

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Using a stratospheric zonal wind data archive of radiosonde observations at equatorial stations for 1953–2008, this study investigates whether or not signals of the quasi-biennial oscillation (QBO) vary with the El Niño-Southern Oscillation (ENSO) cycle. The signals of the QBO are represented by trajectories in a phase space spanned by time series of two leading modes of wind variability. Two properties of the trajectories, distance from the origin and time rate of change in argument, which are proxies for amplitude and phase progression rate of the QBO, respectively, are first examined in relation to seasons and QBO phases. The examination confirms known features of the QBO including the so-called seasonal locking and more regular phase propagation for the westerly phase. A further comparison of the properties between cold and warm ENSO conditions (La Niña and El Niño, respectively) reveals unprecedented evidence of clear variations of the QBO with ENSO: the QBO signals exhibit weaker amplitude and faster phase propagation for El Niño conditions. Such variations are also supported by a composite analysis of zonal wind anomalies. We also discuss a possible connection of the ENSO-associated changes in the QBO with those in equatorial wave activity.

Controls by the Zonal Mean Circulation on the Stationary Wave Response to Climate Change

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The stationary wave field, defined as the zonally asymmetric component of the time mean atmospheric circulation, exerts a strong control on regional climate and accounts for a significant fraction of the wave driving of the Northern Hemisphere extratropical zonal mean circulation. Climate models simulate a wide range of stationary wave responses to climate forcing, and previous work has debated whether the responses are dominated by changes in the zonal mean flow or in the zonally asymmetric forcing terms such as diabatic heating. This presentation will describe efforts to understand the stationary wave response to climate change in "high top" chemistry-climate models (CCMs) with well resolved dynamical stratosphere, using a recently developed weakly nonlinear stationary wave model with good stratospheric resolution. We first focus on the response of the Canadian Middle Atmosphere Model CCM to climate change. In this CCM, we use the stationary wave model to show that much of the extratropical stratospheric stationary wave response to climate change can be attributed to changes in the zonal mean flow. Remarkably, the acceleration of the subtropical upper tropospheric zonal mean jet in climate change, which is a robust radiatively driven zonal mean climate change response, can by itself drive a large fraction of the change to the

upper tropospheric and stratospheric stationary wave field from the subtropics to the polar latitudes. In addition, changes to the zonal mean basic state in the subtropics and extratropics are associated with enhanced stratospheric stationary wave driving (and by implication a negative Northern Annular Mode response). The analysis indicates that a positive feedback occurs between the high latitude wave response and zonal mean response. We then extend the analysis to a large group of CCMs analyzed in support of the SPARC CCMVal Report and WMO Ozone Assessments. In these models, it is also found that changes to the zonal mean also account for a significant fraction of the stationary wave response to climate change.

Abrupt circulation responses of the stratosphere-troposphere coupled system to climate change-like forcing in a relatively simple AGCM

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The circulation response of the coupled troposphere-stratosphere system to climate change-like thermal forcings is explored with a simple atmospheric general circulation model. The imposed forcing mimics the warming induced by greenhouse gasses and other anthropogenic factors in the low-latitude upper troposphere. We progressively increase the amplitude of the warming to study the changes in circulation, up to and beyond those projected by the IPCC models under the A1B emission scenario. For weak to moderate forcing amplitudes, the circulation response is remarkably similar to that found in comprehensive models: the Hadley cell widens, the tropospheric mid-latitude jets displace poleward, and the Brewer-Dobson Circulation (BDC) increases. However, when the warming of the upper tropical troposphere exceeds approximately 5 K, as projected by the end of the 21st century under the A1B scenario, an abrupt change of the whole atmosphere circulation is observed. In the troposphere the near surface jet jumps poleward by nearly 10 degrees, while in the stratosphere the polar vortex greatly intensifies, sudden warming events are severely reduced, the BDC weakens considerably, and the intra-seasonal coupling between the troposphere and stratosphere disappears. This abrupt transition is found to be robust to a doubling of either the horizontal or vertical resolution of the model.

MIROC-ESM: CMIP5 runs and QBO analysis

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We have mostly finished CMIP5 runs of MIROC-ESM, which includes a high-top T42L80 GCM. By using a non-orographic gravity wave drag parametrization, MIROC-ESM simulates the equatorial quasi-biennial oscillation (QBO). In CMIP5 runs, we gave a same constant gravity wave source near the equator. However, time-height structures of simulated QBO varies with global warming. Possible reasons will be discussed.

The EC-Earth high-top simulation in CMIP5

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The newly developed global climate system model, EC-Earth, have been applied to perform ensembles of CMIP5 experiments. The EC-Earth core system consists of the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF) as the atmosphere component and the Nucleus for European Modelling of the Ocean (NEMO) developed by Institute Pierre et Simon Laplace (IPSL) as the ocean component and the Louvain-la-Neuve sea Ice Model (LIM) embedded in the NEMO. The ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler. The standard configuration of EC-Earth runs at T159 horizontal spectral resolution and 62 vertical levels with the top of atmosphere at 1hPa for the atmosphere, and 1 x 1 degree horizontal resolution and 42 vertical levels for the ocean. Recently, a high top version of the EC-Earth of 91 vertical layers for the atmosphere is established which resolves well the stratosphere with the top at 0.01 hPa. In AMIP-type experiments the high-top model is shown to have a superior representation of the stratosphere. A CMIP5 experiment is now being performed.

In this study, the historical hindcast of the high-top EC-Earth CMIP5 experiment is analysed. The main characteristic of the troposheric and oceanic circulation are presented and compared with that of the low-top EC-Earth experiments. The possible influence of the stratosphere on the circulation is investigated.