Role of the Stratosphere in Seasonal and Decadal Predictions

D.Smith[1], A. Scaife[1], A. Arribas[1], E. Blockley[1], A. Brookshaw[1], R.T. Clark[1], N. Dunstone[1], R. Eade[1], D. Fereday[1], C.K. Folland[1], M. Gordon[1], L. Hermanson[1], J.R. Knight[1], D.J. Lea[1], C. MacLachlan[1], A. Maidens[1], M. Martin[1], A.K. Peterson[1], M. Vellinga[1], E. Wallace[1], J. Waters[1] and A. Williams[1]

[1]Met Office, Exeter, UK Ex1 3PB

There is emerging evidence that the stratosphere plays a key role in seasonal and decadal predictions. It has been demonstrated many times that anomalies in stratospheric winds subsequently propagate downwards and may impact the troposphere. Moreover, stratospheric winds are influenced by many potentially predictable processes including ENSO, solar variability, the QBO, and changes in Arctic sea ice cover. The most recent Met Office seasonal forecasting system, GloSea5, yields skilful hindcasts of the North Atlantic Oscillation, with correlations greater than 0.6. Analysis of these hindcasts will be presented illustrating the importance of stratospheric processes on seasonal timescales, and implications for decadal predictions will be discussed.

Interannual Variation of the Antarctic Ozone Hole and Its Implication for Seasonal Prediction

S.-W. Son[1], A. Purich[2], H. Hendon[3], B. Kim[4], L. M. Polvani[5]

[1]School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea; [2]CSIRO Marine and Atmospheric Research, Aspendale, Australia; [3]Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Australia; [4]Korea Polar Research Institute, Incheon, South Korea; [5]Department of Applied Physics and Applied Math, Columbia University, New York, U.S.A.

Southern Hemisphere (SH) climate change in the past has been attributed to the combined effect of greenhouse gas increase and Antarctic ozone depletion. Recent studies have shown that the latter has played at least a comparable role to the former in austral summer. Using observational datasets, here we show that the Antarctic ozone hole has affected not only the long-term climate change but also the inter-annual variation of the SH surface climate.

Springtime ozone concentration exhibits a large variation on interannual time scale, mainly due to extratropical wave driving in the upper troposphere and lower stratosphere during polar winter. This variation, which is quantified by removing slowly-varying component or non-linear trend from the observed ozone time series, is found to influence surface climate in a major way with a time lag. A significant negative correlation is found between the September Antarctic ozone concentration and the October Southern Annular Mode (SAM) index, resulting in systematic variations in precipitation and surface temperature throughout the SH. For instance, a high September ozone concentration, which leads to a low October SAM index, is associated with reduced precipitation and increased temperature in subtropical Australia, and reduced temperature in Patagonia and on the Antarctic Peninsula in October.

The surface response to the Antarctic ozone variation is further found to be comparable to but independent of that associated with El Nino-Southern Oscillation and Indian Ocean Dipole Mode, which have been traditionally viewed as the leading drivers of predictable climate variability in the SH. This result suggests that SH seasonal prediction could be improved by considering Antarctic stratospheric variability.

Inertial Gravity Waves in the Antarctic Stratosphere

D. J. Murphy[1], A. R. Klekociuk[1], S. P. Alexander[1], P. T. Love[1], R. A. Vincent[2]

[1]Australian Antarctic Division, Kingston, Australia, [2]University of Adelaide, Adelaide, Australia.

A decade of radiosonde observations of wind and temperature in the troposphere and lower stratosphere have made it possible to compile a climatology of low-frequency gravity waves above Davis, Antarctica (69ºS, 78ºE). Wave characteristics, extracted using wavelet analysis [Zink and Vincent, 2001], show strong seasonal and height variations. In particular, the high prevalence of down-going waves in the winter lower stratosphere previously identified at other Antarctic sites [Moffat-Griffin et al. 2011; Yoshiki and Sato, 2000] has been shown to exist at Davis.

The vertical structure and seasonal variation of down-going wave percentages are shown in Figure 1a, and a relationship with the background zonal wind structure (contoured) is suggested. Figures 1b and 1c show that the down-going waves replace up-going waves in the winter lower stratosphere.

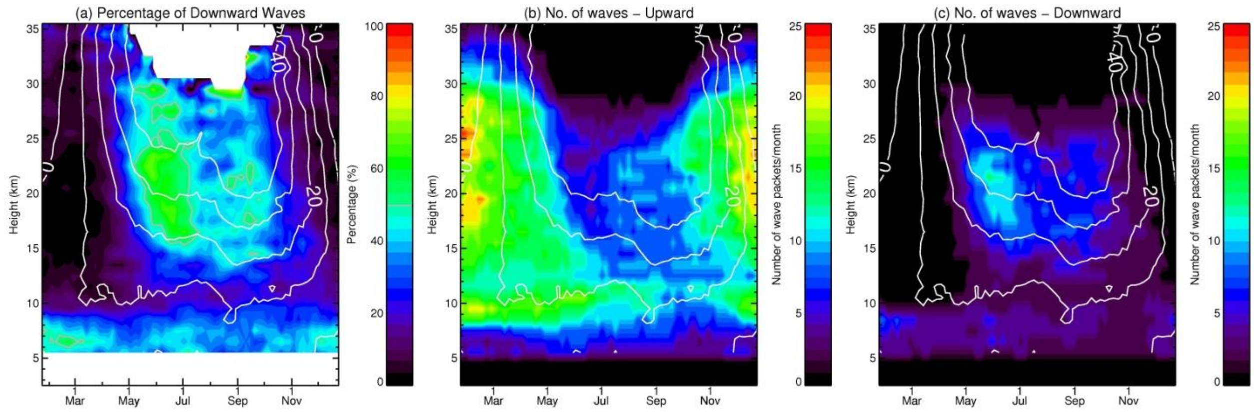

Figure 1. Vertical wave propagation statistics for Davis. The zonal mean wind is contoured .

Statistical distributions of the characteristics of the up and down-going waves show strong similarities suggesting a common source. It has been suggested [Sato and Yoshiki, 2008] that imbalance processes in the polar night jet may play a role in their production. This possibility is considered along with the propagation characteristics of the waves to explore their role in the dynamics of the polar stratosphere, and to examine the adequacy of their representation in atmospheric models.

References:

Moffat-Griffin, T., R. E. Hibbins, M. J. Jarvis and S. R. Colwell, Seasonal variations of gravity wave activity in the lower stratosphere over an Antarctic Peninsula station, *J. Geophys. Res.*, 116, D14111, doi:10.1029/2010JD015349, 2011.

Sato, K. And M. Yoshiki, Gravity wave generation around the polar vortex in the stratosphere revealed by 3-hourly radiosonde observations at Syowa station, J. Atmos. Sci., 65, 3719-3735, 2008.

Yoshiki, M. And K. Sato, A statistical study of gravity waves in the polar regions based on operational radiosonde data, *J. Geophys. Res.*, 105, D14, 17995-18011, 2000.

Zink, F. and R. A. Vincent, Wavelet analysis of stratospheric gravity wave packets over Macquarie Island 1. Wave parameters, *J. Geophys. Res.*, 106, 10275-10288, 2001.

Dynamical coupling between the stratosphere and troposphere

T. Shaw[1]

[1]Dept. of Earth & Environmental Sciences and Applied Physics & Applied Mathematics, Lamont-Doherty Earth Observatory, Columbia University, New York, NY, USA

This talk will review our current understanding of dynamical stratosphere-troposphere coupling. Specific focus will be given to recent research linking extreme stratospheric wave propagation (upward and downward) to North Atlantic weather and climate. Extreme wave propagation events characterized by the tails of lower stratospheric-high latitude eddy heat flux distribution are found to significantly impact the residual circulation in the stratosphere and to be connected to North Atlantic Oscillation-like anomalies in the troposphere. Furthermore it will be shown that CMIP5 models that do not properly represent the distribution of extreme stratospheric heat flux events exhibit a biased climatological planetary wave structure in the Northern Hemisphere troposphere. Finally, the talk will provide a summary of some outstanding questions and potential future research directions.

The Stratospheric Plunger

Mark P. Baldwin[1], Thomas Birner[2]

[1]University of Exeter, UK; [2]Colorado State University, Fort Collins, CO, USA

At mid-to-high latitudes, the stratosphere contains >25% of the column of atmospheric mass. As large-scale waves propagate upward from the troposphere—predominantly during northern winter and southern spring—the strength of the stratospheric polar vortex undergoes large fluctuations lasting from weeks to months. These changes are not confined to the stratosphere. They appear to propagate downward to Earth's surface, where they have substantial effects on surface weather and climate, especially on the Northern and Southern Annular Mode (NAM, SAM) patterns, with substantial, long-lasting shifts in the jet streams, storm tracks, precipitation, and likelihood of blocking events. Despite unambiguous observations of this phenomenon, as well as numerical simulations, the primary dynamics of this downward coupling are not understood. Here we show that the day-to-day thickness of the troposphere is controlled primarily by the vertical displacement of the column of air above the Arctic—which is directly related to the strength of the polar vortex above—like a plunger controlling the movement of water in a pipe. We demonstrate that this mechanism is consistent with the observed changes to jets, storm tracks, and the NAM/SAM, as well as the observed timescale of the tropospheric changes. Our conceptual model points to the importance of the Arctic tropopause layer for assessing the fidelity of stratosphere–troposphere coupling in climate and weather forecast models.

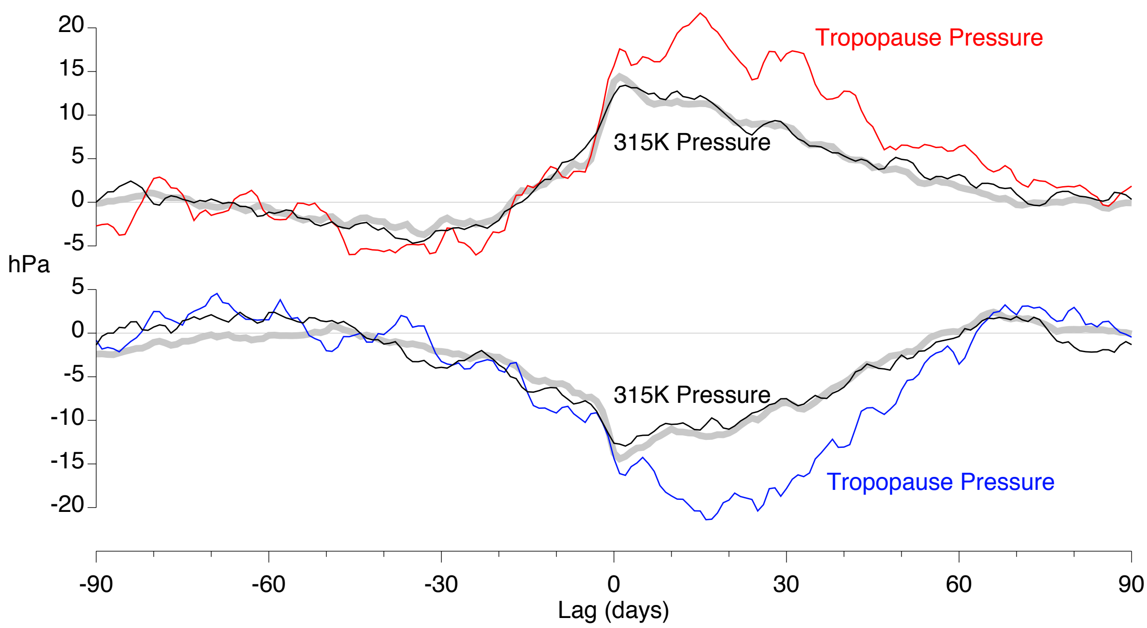

Figure 1. Lag composites of the tropopause region for (top) extreme negative events, and (bottom) extreme positive events, based on an index of polar cap 530K PV. The grey curves are the (scaled) PV530K index. The black curves represent the 315K isentropic surface (near the tropopause) pressure anomaly over the polar cap. The red and blue curves are pressure anomalies for the thermal tropopause over the polar cap. This figure shows that the 315K surface tracks the strength of the polar vortex, and that the thermal tropopause appears to amplify the signal, compared to nearby isentropic surfaces.

Understanding and Predicting the Brewer-Dobson Circulation

E. P. Gerber and N. Y. Cohen

Center for Atmosphere Ocean Science, Courant Institute of Mathematical Sciences, New York University, New York NY, USA

A hierarchy of idealized general circulation models allows us to explore the impact of tropospheric and stratospheric processes on the Brewer-Dobson Circulation, both in terms of the residual mean (or diabatic) circulation and the transport of tracers. The residual mean circulation is understood through the lens of the "downward control principal" (Haynes et al. 1991), where the circulation, at least in the steady state, is explained as a response to mechanical wave driving, effected primarily by planetary-scale Rossby waves and small-scale gravity waves. The use of interactive models, however, allows us to explore reverse "control" by the circulation and stratospheric diabatic forcing on the wave driving. Our findings suggest that the Brewer-Dobson Circulation can be more fully understood as a result of interactions between Rossby waves, gravity waves, and the mean flow.

We first focus on the role of planetary-scale Rossby waves. We find that while tropospheric wave driving sets the overall amplitude of the residual mean circulation, the diabatic forcing of the stratosphere (in particular, the strength of the polar vortex) sets its structure and depth. For tracer transport in the mid to upper stratosphere, both of these controls can be equally important. The relative independence of these processes suggests the potential for structural changes in the circulation. For example, an increase in tropospheric wave driving coupled with a warming of the polar vortex can increase upwelling in the lower stratosphere (and so cool the tropical cold point) while simultaneously decreasing it above, increasing the age of air at height.

We next introduce gravity wave parameterizations to the idealized model to explore the role of gravity wave driving in the Brewer-Dobson Circulation. Perturbations of the orographic scheme reveal a remarkable degree of compensation between the parameterized and resolved wave driving: when the gravity wave driving is changed, the resolved wave driving tends to change in the opposite direction, so there is little net impact on the residual mean circulation. This compensation between resolved and unresolved waves suggests that the commonly used linear separation of the Brewer-Dobson Circulation into components (i.e. resolved vs. parameterized wave driving) provides a potentially misleading interpretation of the role of different waves. It may also, in part, explain why comprehensive models tend to agree more on the total strength of the Brewer-Dobson circulation than on the flow associated with individual components, particularly when diagnosing changes of the circulation driven by anthropogenic forcing.

Haynes, P. H., C. J. Marks, M. E. McIntyre, T. G. Shepherd, and K. P. Shine, 1991: On the "Downward Control" of Extratropical Diabatic Circulations by Eddy-Induced Mean Zonal Forces. *J. Atmos. Sci.*, **48**, 651-678.

Reconsidering the traditional definition for stratospheric sudden warmings

A.H. Butler[1], D.J. Seidel[2], S. Hardimann[3], and N. Butchart[3]

[1]CIRES/NOAA, Boulder, CO, USA; [2]NOAA Air Resources Lab, College Park, MD, USA; [3]Met Office, Hadley Centre, UK

The current classification and detection of stratospheric sudden warmings (SSWs) is largely based on a definition developed by the World Meteorological Organization in the decades after their discovery by Richard Scherhag in 1952. While the definition evolved over that time period, in general the classification of a major mid-winter SSW includes two things: (1) the reversal of the 10 mb zonal mean zonal winds at 60N; and (2) an increase of the latitudinal mean temperature gradient at 10 mb and poleward of 60N. This definition was likely based largely on the extant observational system during the pre-satellite era. Comparing this traditional definition with more recent diagnostics in current literature (e.g., annular modes, polar cap geopotential heights, vortex moments, zonal winds at 70N) suggests that the classification of SSWs can be quite sensitive to the chosen definition. For example, the traditional definition detects no major SSWs during the 1990s, while every other diagnostic detects several substantial breakdowns of the polar vortex during that decade. We suggest criteria for a new definition and pose the questions: if the current observational network were available when SSWs were first discovered, what would the WMO have chosen for the definition? Should the WMO definition be updated?

Fast and slow response of sea ice and the Southern Ocean to ozone depletion

Cecilia M. Bitz[1], David Ferreira[2], and John Marshall[3]

[1]University of Washington, [2]University of Reading, [3]Massachusetts Institute of Technology

Interannual variability in the Southern Annular Mode (SAM) and sea ice covary such that an increase and southward shift in the surface westerlies coincides with an expansion of the sea ice cover, as seen in observations and models alike. Yet, the sea ice extent decreases in response to similar sustained wind anomalies driven by 20th century ozone depletion in modeling studies. Why does sea ice appear to have opposite responses to SAM-like variability on interannual and multi-decadal timescales? We demonstrate explicitly that the response of sea ice and the Southern Ocean to ozone depletion is a two timestep problem. The interannual variability of sea ice and the SAM parallels the fast response of sea ice to ozone depletion. The fast response is dominated by an enhanced northward Ekman drift, which transports heat northward and causes negative SST anomalies in summertime, earlier sea ice freeze-up, and increased sea ice concentrations and northward expansion of the sea ice edge year round. The enhanced northward Ekman drift causes a region of Ekman divergence south of the Antarctic polar front, which results in upwelling of warmer waters from below the mixed layer. With sustained westerly wind enhancement, the energy balance of the upper ocean is dominated by the upwelling heat flux from of the anomalous upwelling of warm waters over the northward heat flux from the anomalous Ekman drift. Hence, the slow response is positive SST in summertime and a reduction in the sea ice cover year round. We demonstrate this behavior in two models: one with an idealized geometry and another a sophisticated global climate model. We discuss the controls on the transitions of fast to slow response.

Changes in the ventilation of the southern oceans due to stratospheric ozone depletion

D.W. Waugh[1],

[1]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD, USA.

Surface westerly winds in the Southern Hemisphere have intensified over the past few decades, primarily in response to the formation of the Antarctic ozone hole. There is intense debate on the impact of this on the ocean overturning circulation and carbon uptake. Here, we use measurements of CFC-12 made in the southern oceans in the early 1990s and mid- to late-2000s to examine changes in ocean ventilation. Our analysis reveals a decrease in the age of subtropical mode waters and an increase in the age of circumpolar deep waters at similar depths. Simulations with coupled and ocean-only models are used to examine the mechanisms causing this change and to examine possible future changes as ozone hole recovers. This research suggests that the formation of the Antarctic ozone hole has caused large-scale coherent changes in the ventilation of the southern oceans, with potential implications for the ocean uptake of heat and anthropogenic carbon.

Do Large Tropical Volcanic Eruptions influence the SAM?

Kirstin Krüger[1], Matthew Toohey[1], Doreen Metzner[1,2]
[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
[2]LUBW (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg), Karlsruhe, Germany

(Contact: kkrueger@geomar.de)

Large tropical volcanic eruptions have a significant influence on the atmospheric large-scale circulation patterns of the Northern Hemisphere, through mechanisms related to the radiative effects of volcanic sulfate aerosols resulting from the direct injection of SO_2 into the stratosphere. While no such confirmed volcanically induced anomalies in the Southern Hemisphere (SH) circulation have yet been observed, we find that general circulation model simulations of eruptions with SO_2 injections larger than that of the 1991 Mt. Pinatubo eruption (~15 Mt SO_2) do result in significant atmospheric circulation changes in the SH, specifically an enhanced positive phase of the Southern Annular Mode (SAM). We explore the mechanisms for such a volcanically induced SAM response, as well as the corresponding changes at the surface (i.e. temperature, precipitation, sea ice). The anomalous strong and poleward shift of the westerly wind band in mid-latitudes, characterizing the positive SAM phase, has potential impacts on the Southern Ocean as well as on the deposition of volcanic sulfate to the Antarctic ice-sheet, and hence ice-core based reconstructions of past volcanic activity. This study has relevance for better understanding SAM forcing mechanisms, interpreting observed SAM time series, and predicting future SAM changes after large explosive volcanic eruptions in the tropics.

Blockings and Upward Planetary-Wave Propagation into the Stratosphere

K. Nishii[1], H. Nakamura1, Y. J. Orsolini[2]

[1]RCAST, University of Tokyo, Tokyo, Japan; [2]Norwegian Institute for Air Research, Kjeller, Norway

The connection between tropospheric blockings and stratospheric variability, especially major stratospheric sudden warming (SSW), has been shown to depend on location of blocking development (e.g. Martius et al. 2009; Woollings et al. 2010). Through composite analysis applied to high-amplitude anticyclonic anomaly events observed around every grid point over the extratropical Northern Hemisphere, we quantitatively reveal distinct geographical dependence of blocking influence on upward propagation of planetary waves (PWs) into the stratosphere (Nishii et al. 2011). Tropospheric blockings that develop over the Euro-Atlantic sector tend to enhance upward PW propagation, leading to the warming in the polar stratosphere and, in some occasions, to major SSW events. In contrast, the upward PW propagation tends to be suppressed by blocking developing over the western Pacific and the Far East, resulting in the polar stratospheric cooling, which is consistently with Nishii et al. (2010). By decomposing a poleward eddy heat flux term into linear interference and non-linear terms (e.g. Nishii et al. 2009), this dependence is found to arise mainly from the sensitivity of the interference between the climatological PWs and upward-propagating Rossby wave packets emanating from blockings to their geographical locations. This study also reveals that whether a blocking over the eastern Pacific and Alaska can enhance or reduce the upward PW propagation is case-dependent.

Not only blockings, tropospheric persistent cyclonic anomalies, especially over the Northwestern Pacific, also have potential to affect the stratospheric circulation. We will discuss further on the role of tropospheric anticyclonic and cyclonic anomalies in the stratospheric variability.

References:

Martius, O., L. M. Polvani, and H. C. Davies, 2009: Blocking precursors to stratospheric sudden warming events. Geophys. Res. Lett., 36, L14806, doi:10.1029/2009GL038776.

Nishii, K., H. Nakamura and T. Miyasaka, 2009: Modulations in the planetary wave field induced by upward-propagating Rossby wave packets prior to stratospheric sudden warming events: A case study, Q. J. R. Meteorol. Soc., 135, 39-52.

Nishii, K., H. Nakamura, Y. J. Orsolini, 2010: Cooling of the wintertime Arctic stratosphere induced by the Western Pacific teleconnection pattern, Geophys. Res. Lett, 37, L13805, doi:10.1029/2010GL043551.

Nishii, K., H. Nakamura, Y. J. Orsolini, 2011: Geographical dependence observed in blocking high influence on the stratospheric variability through enhancement and suppression of upward planetary-wave propagation, J. Climate, 24, 6408-6423.

Woollings, T., A. J. Charlton-Perez, S. Ineson, A. G. Marshall, and G. Masato, 2010: Associations between stratospheric variability and tropospheric blocking. J. Geophys. Res., 115, D06108, doi:10.1029/2009JD012742.

Modeling Tropospheric Impacts of the Arctic Ozone Depletion 2011

A. Karpechko[1], J. Perlwitz[2], E. Manzini[3]

[1]Finnish Meteorological Institute, Helsinki, Finland; [2]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boudler, USA; [3]Max-Planck-Institut für Meteorologie, Hamburg, Germany

Unusually strong Arctic stratospheric polar vortex and low polar stratospheric temperatures in winter-spring 2011 led to massive chemical ozone depletion. Estimated ozone chemical loss reached 80% at 18-20 km by late March and the estimated deficit of total ozone column due to chemical loss reached 47% at 80°N by early April. The observed pattern of the tropospheric circulation in April following the ozone depletion event was characterized by a strongly positive phase of the Northern Annular Mode (NAM). In the Southern Hemisphere, the Antarctic ozone depletion has been recognized as an important driver of climate change with impacts possibly extending into the subtropics. However the impacts of the Arctic ozone loss on the tropospheric climate remain poorly quantified. In this study we analyze the impacts of the Arctic ozone depletion 2011 on the troposphere by using the atmospheric general circulation model ECHAM5. Sea surface temperature and sea ice concentration (SST/SIC) and atmospheric ozone (O3) anomaly fields based on the observational data are used to force the model. By performing a set of 50-years long simulations we analyze the response of the model to SST/SIC and O3 forcings separately and also to the combined SST/SIC and O3 forcing (ALL). We find that in all three experiments the tropospheric response is characterized by an increased probability of the positive NAM events between mid-March and mid-April. The largest increase of the probability is simulated in the ALL experiment. In all three experiments the tropospheric response is preceded by a strengthening of the stratospheric westerly winds, consistent with the canonical pattern of downward anomaly propagation. We find that the average response of the tropospheric circulation to the O3 forcing alone is weak compared to the internal variability, and that the circulation changes in the ALL experiments are mostly consistent with the SST/SIC forcing. However the combined effect of the two forcing on the circulation is not additive suggesting that non-linear interaction between ozone-induced stratospheric cooling and a tropospheric forcing associated with the SST/SIC anomalies contributed to the large atmospheric climate anomalies observed in spring 2011.