FESD-1338814 Marshall (PI) 09/01/13 to 08/31/18

Second year Report (June, 2015)

NSF Award Title: FESD Proposal Type I - The impact of the ozone hole on the climate of the Southern Hemisphere
NSF Award number: OCE-1338814
Project Lead: John Marshall, MIT

ACCOMPLISHMENTS

Overview of project

The dramatic depletion of the Antarctic ozone since the late 1970s has introduced a major perturbation to the radiative balance of the stratosphere with a wide range of consequences for climate. There is strong evidence that ozone loss has significantly altered the climate of the southern hemisphere troposphere, including the surface, with implications for ocean circulation, the cryosphere and coupled carbon cycle. As ozone depletion recovers in the next half-century or so, a corresponding reversal of these changes can be expected, providing an unprecedented opportunity to observe how the climate system relaxes from a known perturbation.

The overarching question we are attempting to address in our project is:

What are the mechanisms, impacts and indicators of the Antarctic stratospheric ozone hole and its recovery on the climate of the atmosphere-ocean-ice-carbon system?

To tackle this problem an interdisciplinary team of researchers from MIT (John Marshall, Alan Plumb and Susan Solomon), Columbia University (Lorenzo Polvani), Johns Hopkins University (Darryn Waugh, Tom Haine and Anand Gnanadesikan) and NCAR (Marika Holland, Doug Kinnison and Dan Marsh) has been funded by NSF for a 5-year period.

Major Activities

(i) *Drivers of the recent tropical expansion in the Southern Hemisphere*. (JHU)

We have performed a quantitative analysis of single-forcing model integrations to isolate the role of different factors on southward shift of the southern edge of the Hadley Cell (HC). Observational evidence indicates that the southern HC edge has shifted southward during austral summer in recent decades, but there is no consensus on the cause of this shift, with several studies reaching opposite conclusions as to the relative role of changes in sea surface temperatures (SSTs) and stratospheric ozone depletion in causing this shift. Our analysis of published studies and a new suite of integrations with the Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM) show that the weight of the evidence clearly points to stratospheric ozone depletion as the dominant driver of the tropical summertime expansion over the period in which ozone hole was formed (1979 to late 1990s). SSTs are not a major factor over this period, but SST trends have contributed to HC trends since then. Studies that have claimed SSTs as the major driver of tropical expansion since 1979 have used prescribed ozone fields that significantly underrepresent the observed Antarctic ozone depletion.

(ii) Southern Hemisphere extratropical circulation: Recent trends and natural variability. (JHU) We have examined the natural variability and trends in several different diagnostics of the SH extratropical circulation using Coupled Model Intercomparison Project Phase 5 (CMIP5) model runs and reanalyses. Specifically we quantify the natural variability of the SH extra tropical circulation by using CMIP5 pre-industrial control model runs and compare with the observed trends in Southern Annular Mode (SAM), jet magnitude, and jet location. We show that trends in SAM are due partly to external forcing, but are not outside the natural variability as described by these models. Trends in jet location and magnitude, however, lie outside the unforced natural variability but can be explained by a combination of natural variability and the ensemble-mean forced trend. These results indicate that trends in these three diagnostics cannot be used inter-changeably.

(iii) Isopycnal mixing and oceanic anthropogenic carbon uptake. (JHU)

We have examined the possible role that differences in lateral mixing plays in the variation in anthropogenic carbon dioxide uptake across Earth System Models (ESMs). We have varied the lateral eddy mixing coefficient A_{Redi} used in a single model (GFDL ESM2Mc) and produced a range of anthropogenic carbon dioxide uptake that is similar to the range across different ESMs. The highest uptake, resulting from a simulation with a constant A_{Redi} of 2400 m^2/s, simulates 15% more historical carbon uptake than a model with $A_{\mathrm{Redi}} = 400\ m^2/s$. A sudden doubling in carbon dioxide produces a 21% range in carbon uptake across the models. Two spatially dependent representations of A_{Redi} produce uptake that lies in the middle of the range of constant values despite predicting very large values in the subtropical gyres. One-dimensional diffusive models of the type used for integrated assessments can be fit to the simulations, with A_{Redi} accounting for a substantial fraction of the effective vertical diffusion. Such models, however, mask significant regional changes in stratification and biological carbon storage.

(iv) Robustness of simulated tropospheric response to ozone depletion (JHU)
We have examined the tropospheric response to the stratospheric ozone hole in a range of models. The magnitude of the shift in the mid-latitude tropospheric jet to the formation of the ozone hole varies substantially in published modeling studies, indicating sensitivity to model specifics. However we show that the shift in the jet latitude per degree cooling in the polar stratosphere is statistically the same in suite of models ranging from an atmosphere only model using specified stratospheric ozone to a couple atmosphere-ocean model with interactive stratospheric chemistry. This result indicates that differences in jet shifts among some published studies is due to the amount of ozone depletion in the models and not model numeric or processes included in the models.

(v) Ozone-hole climate response function simulations (JHU)
We have performed an ensemble of Ozone-hole climate response function simulations using the JHU version of the GFDL ESM2Mc. Preliminary analysis shows a two-timescale response in the southern ocean SST response to an abrupt ozone hole with a cooling over initial ~20 years following by warming in subsequent years. This similar to that found in the MITgcm but differs from that in NCAR CESM model (which has a much shorter cooling period). There are indications that the response in the JHU-GFDL model that the timescales of the response to the ozone perturbation dependent on the state of the southern ocean (which varies naturally from warm to cold phases, with differing stratification).

(vi) Natural variability in Antarctic sea ice. (NCAR)

An improved understanding of the internal variability of Antarctic sea ice provides a means to better quantify the relative importance of ozone forcing on the system. Additionally, since ozone loss projects onto the naturally occurring Southern Annular Mode (SAM), assessing the relationships between natural variability in the SAM and sea ice can provide insights on the sea ice response to ozone loss. We are exploring the internal variability of sea ice from these various perspectives. This includes analysis of simulations from a large ensemble (currently at 38 members) of 20^{th}-21^{st} century Community Earth System Model (CESM) experiments and within the CMIP5 multi-model ensemble. This has included an assessment of both pre-industrial and 20^{th} century simulations. Whereas most previous work has analyzed variability and trends of the total Antarctic region, we are assessing the spatial characterization of variability in sea ice. We are also analyzing the influence of modes of variability (including the SAM) on sea ice variability at a number of timescales. A manuscript is currently in preparation on sea ice trends in the late 20^{th} century.

(vii) Support for Fixed Ozone experiments (NCAR)

In addition to analysis of existing simulations, we have also performed a set of integrations for the 1955-2005 time period with fixed ozone concentrations. These integrations are consistent with the CESM Large Ensemble and so by comparing across these ensembles we can further quantify the role of ozone loss on Antarctic climate conditions. Analysis of integrations are currently underway.

(viii) Simulation of Polar Ozone (MIT & NCAR)

Recent studies have raised questions about the chemical processes responsible for Antarctic ozone losses, in particular whether or not equivalent ozone depletion could occur without polar stratospheric clouds or temperatures below 195K. The chemical roles of nitric acid trihydrate solid PSCs versus supercooled ternary solutions have also been questioned. Understanding this chemistry is essential to ensure that coupled chemistry climate models simulate the vertical and horizontal profiles of ozone loss – and hence stratospheric cooling and dynamical responses in an accurate fashion. Our study provides a detailed analysis of the processes driving ozone loss in SD-WACCM, and demonstrates that formation of polar stratospheric clouds and temperatures below 192K are required if the observed depletion is to be simulated. Another key finding of this research is that transport of ClONO2 from southern subpolar regions near 55-65°S to higher latitudes near 65-75°S is important for the activation of chlorine, linking higher latitudes to regions exposed to more sunlight, and increasing the need to fully understand stratospheric transport if the ozone hole is to be accurately modeled.

(ix) Southern Ocean cooling in a warming world: reassessing the role of westerly winds (MIT)

In contrast to the global warming trend and the loss of Arctic sea ice, the Southern Ocean has exhibited a gradual decrease in sea surface temperatures (SSTs) and a net expansion of the sea ice cover over recent decades. Moreover, historical simulations with CMIP5 global climate models do not reproduce the observed cooling around Antarctica and, instead, predict slow but steady warming and sea ice loss. We identify enhanced wind-driven Ekman transport as a possible dynamical mechanism allowing the Southern Ocean to cool. We further discuss the discrepancy between observations and CMIP5 historical simulations. The latter underestimate the strengthening and the poleward shift of the Southern

Hemisphere surface westerlies – due either to an inadequate representation of ozone forcing or, perhaps, internal variability contributing to the observed wind trends. We propose that under a realistic evolution of surface winds, CMIP5 models can produce cooling trends around Antarctica with magnitudes and spatial patterns similar to observations. To that end we consider the unforced preindustrial control runs of CMIP5 models and examine periods with multidecadal trends in the speed and position of the Southern Hemisphere surface westerlies that are comparable to the 1979-2014 trends. Strengthening and southward displacement of surface winds produce an SST dipole around Antarctica: cooling south of 50S and warming in a zonal band along 30-50S, similar to observed patterns. These wind-induced cooling trends in the Southern Ocean are large enough to locally overwhelm the effect of greenhouse gas forcing and allow the sea ice cover to expand in a warming world. We compare our findings to those of recent modeling studies which suggest that ozone depletion results in warming around Antarctica.

(x) The effect of ozone depleting substances of the Southern Ocean in last half century (Columbia)

Observations show robust changes in the circulation, temperature and salinity of the Southern Ocean in recent decades. To what extent these changes are related to the formation of the ozone hole in the late 20th Century is an open question? Using a state-of-the-art comprehensive chemistry-climate Earth system model, we contrast model runs with varying and with fixed surface concentrations of ozone depleting substances (ODS) from 1955 to 2005. In our model, ODS cause the majority of the summertime changes in surface wind stress which, in turn, induce a clear poleward shift of the ocean's meridional overturning circulation. In addition, more than 30% of the model changes in the temperature and salinity of the Southern Ocean are caused by ODS. These findings offer unambiguous evidence that increased concentrations of ODS in the late 20th Century are likely to have been been an important driver of changes in the Southern Ocean.

(xi) Extreme stratospheric heat flux events and the surface signatures in the Southern high latitudes (Columbia)

We have been examining the link between stratospheric heat flux and anomalous climate and weather patterns in the troposphere, as a way of analyzing high-latitude troposphere-stratosphere planetary wave coupling in the Southern Hemisphere, and notably around Antarctica. Instantaneous connections are found in ERA-Interim reanalysis data between extremes in the meridional heat flux distribution at 50hPa and wave-1 patterns in geopotential height, temperature, zonal wind and mean sea level pressure during Sept-Nov (the period of highest wave activity). The surface connection of the extremes is particularly prominent around the Amundsen Sea, clearly affecting the Amundsen Sea low. A metric based on the ERA-Interim extremes is then used to assess the performance of CMIP5 models and compare performance across hemispheres. Tropospheric differences between models that perform well and those that perform poorly are masked by large biases in the mean state.

(xii) Wind Driven Oscillations in the Southern Ocean and the Relationship between Forced and Internal (Columbia)

We study the response of the Southern Ocean response to oscillating wind stress forcing at the surface, through a hierarchy of models, starting with an analytical framework and testing the results with a high resolution isopycnal channel ocean model. It is hypothesized that the transient ocean response to variable winds lies between the two limits of Ekman response (high frequency limit) and “eddy saturation” (low frequency limit). The Ekman response is characterized by the isopycnals adjusting to the wind forcing quickly. In the eddy saturated limit, all of the wind energy goes into mesoscale eddies and this occurs over long time scales. The response of circumpolar transport, eddy kinetic energy, and potential energy to oscillating winds is quantified. A robust analytical framework derived for the ocean response in the high frequency limit. Both the phase and amplitude response predicted by the linear analytic framework is verified using ensemble experiments performed with an isopycnal layered coordinate model (GOLD). The results from the numerical experiments show qualitative agreement with the theory for high frequency response and throws valuable insight into low frequency and transient response as well. The results from the numerical simulations in the low frequency limit is in accord with previous dynamical arguments and modeling studies of eddy saturation.

(xiii) Using stratospheric and ozone-hole studies in outreach (MIT)

A collaboration between Tomas Saraceno, visiting artist at the Center for Arts, Science and Technology (CAST) at MIT and Lodovica Illari of EAPS is focusing on the “Becoming Aerosolar” project. “Becoming Aerosolar” explores the use of high altitude solar balloons bringing together art and science in a manner designed to engage the public and raise awareness of the environment and sustainability. In particular we are in the process of developing (i) associated teaching material on the web, exploring the dynamics and chemistry of the stratosphere and the ozone hole in the context of Aerosolar and balloon flights and (ii) visualizations of stratospheric processes and balloon data using an I-globe which projects data on to a sphere.

Specific Objectives

(i) How does interactive chemistry modify the coupling between the stratosphere and the rest of the climate system?
(ii) What are the resulting changes in ocean circulation, ice-cover, heat and carbon uptake, and ocean biogeochemistry?
(iii) What are the impacts and observable indicators of the ozone hole on the global climate.

Significant Results

(i) The response of the Southern Ocean to a repeating seasonal cycle of ozone loss has been found to comprise both fast and slow processes – see Marshall et al, 2014 and Ferreira et al (2015). The fast response is similar to the inter-annual signature of the Southern Annular Mode (SAM) on SST, on to which the ozone-hole forcing projects in the summer. It comprises enhanced northward Ekman drift inducing negative summertime SST anomalies around Antarctica, earlier sea ice freeze-up the following winter, and northward expansion of the sea ice edge year-round. The enhanced northward Ekman drift, however, results in upwelling of warm waters from below the mixed layer in the region of seasonal sea ice. With sustained bursts of westerly winds induced by ozone-hole depletion, this warming from below eventually dominates over the cooling from anomalous Ekman drift. The resulting slow-timescale response (years to decades) leads to positive SST anomalies around Antarctica and ultimately a reduction in sea-ice cover year-round.

(ii) Response of Southern Ocean Circulation and Ventilation to changes in SH winds. Analysis of CFC-12 and SF6 measurements made in the southern oceans over the past three decades reveals large-scale coherent changes in the ventilation, with a decrease in the age of subtropical sub Antarctic mode waters and an increase in the age of circumpolar and polar deep waters – see Waugh (2014). We have shown that the decrease in subtropical age is consistent with the observed intensification of the zonal wind stresses and subtropical gyre strength over the same period. Furthermore, this is also consistent with response in Community Climate System Model version 4 (CCSM4) to a strengthening of the zonal wind stress.

(iii) The ozone-hole not only influences the climate of the Antarctic but also impacts that of the middle-latitudes and the tropics. For example in Bandoro et al (2014) we find that the intensity of summer temperatures in Australia and elsewhere in the Southern Hemisphere may be better predicted as early as the previous spring by monitoring stratospheric ozone levels. Observational evidence indicates that the southern Hadley Cell edge has shifted southward during austral summer in recent decades. An analysis led by JHU is showing that the weight of evidence clearly points to stratospheric ozone depletion as the dominant driver of the tropical summertime expansion over the period in which ozone hole was formed (1979 to late 1990s).

What opportunities for training and professional development has the project provided?

Seven graduate students, Jordan Thomas, Aditi Sheshadri, Olga Tweedy, Justin Bandoro, Mark England, Anirban Sinha and Yavor Kostov have worked on the project. Postdoctoral researchers Ute Hausmann, Ari Solomon and Will Seviour are being supported full-time on the project.

How have the results been disseminated to communities of interest?

The results of the above research have been presented at several scientific meetings. Oral presentations have been given at the AMS Middle Atmosphere Conference (Rhode Island, June 17-20, 2013), and SPARC General Assembly (New Zealand, January 2014); and posters presented at the 2014 Ocean Sciences Meeting (Hawaii, February 2014) and The Latsis Symposium (Zurick, June 2014). These meetings cover a wide range of communities, including the middle atmosphere and oceanography communities.

PRODUCTS

Conference Papers and Presentations

Thomas, J. L.; Waugh, D.; Gnanadesikan, A.; Pradal, M. A.; (2014).
Quantifying Surface And Subsurface Natural Variability In The Southern Ocean.
2014 Ocean Sciences Meeting. Hawaii.
Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Tweedy, O., D.W. Waugh, L. Oman, F. Li, 2014

Impact of Antarctic ozone asymmetries on tropospheric climate
The Latsis Symposium, Atmospheric and Climate Dynamics, 18-21 June 2014, Zurich.
Acknowledgement of Federal Support = Yes.

Journals

Waugh, D.W. (2014). Changes in the ventilation of the southern oceans, Philosophical Transactions A. **372**: 20130269. http://dx.doi.org/10.1098/rsta.2013.0269; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Smith, K., R. Neely, D.R. Marsh, L.Polvani (2014), The Specified Chemistry Whole Atmosphere Community Climate Model (SC-WACCM), submitted to J. Adv. Model. Earth Syst. Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Bandoro, J., S. Solomon, A. Donohoe, D. Thompson, and B. Santer, (2014): Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change. J. Climate. doi:10.1175/JCLI-D-13-00698.1, in press. Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Marshall J, Armour K.C., Scott J.R., Kostov Y., Hausmann U., Ferreira D, Shepherd T.G, Bitz C.M. (2014) The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing.Phil. Trans. R. Soc. A372: 20130040. http://dx.doi.org/10.1098/rsta.2013.0040 Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Ferreira, D., Marshall, J., Bitz, C., Solomon, S., and Plumb, A., (2015) Antarctic Ocean and Sea Ice Response to Ozone Depletion: A Two-Time-Scale Problem. *Journal of Climate*, vol. 28, pp. 1206–1226, 2015 http://dx.doi.org/10.1175/JCLI-D-14-00313.1 Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Gnanadesikan, A., M.-A. Pradal, and R. Abernathey (2015), Isopycnal mixing by mesoscale eddies significantly impacts oceanic anthropogenic carbon uptake, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL064100. Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Thomas J.L., D. W. Waugh, A Gnanadesikan (2015), Southern Hemisphere extratropical circulation: Recent trends and natural variability. *Geophys. Res. Lett.*, *42*, 10.1002/2015GL064521 Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Waugh, D.W, C.I. Garfinkel, L.M. Polvani (2015), Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? J Climate, to appear, 2015. Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Solomon, S., D. Kinnison, J. Bandoro, and R. R. Garcia, Simulation of Polar Ozone: An Update, submitted to J. Geophys. Res. (2015).

Solomon, A., L.M. Polvani, K.L. Smith and R.P. Abernathey: The impact of ozone depleting substances on the circulation, temperature and salinity of the Southern Ocean: An attribution study with CESM1(WACCM), submitted to GRL (2015)

Hausmann, H, A. Czaja and J. Marshall, 2015: Observational estimates of air-sea feedbacks and damping time scales of sea surface temperature anomalies in the Southern Ocean. Submitted to J. of Climate

PARTICIPANTS

What individuals have worked on the project?

Darryn Waugh, Jordan Thomas, Olga Tweedy, Rolando Garcia, Dan Marsh, Doug Kinnison, Marika Holland, John Marshall, Susan Solomon, Ari Solomon, David Ferreira, Ute Hausmann, Lodovica Illari, Jason Bandoro, Alan Plumb, Lorenzo Polvani, Will Seviour, Tom Haine, Anand Gnanadesikan, Aditi Sheshadri, Mark England, Anirban Sinha, Omar Mahmood, Yavor Kostov

What other organizations have been involved as partners?

Scientists at the NASA Goddard Space Flight Center have been involved in ozone asymmetry study.

Have other collaborators or contacts been involved?

Feng Li and Luke Oman (NASA GSFC).

Chaim Garfinkel (Hebrew University, Jerusalem, Israel)

IMPACTS

What is the impact on the development of the principal discipline(s) of the project?

Development of WACCM, a leading and widely used chemistry climate model, benefits a multitude of scientists working in areas adjacent to our project.

Our project is helping to resolve a major puzzle in understanding the influence of the southern annular mode (SAM) on sea ice and the Southern Ocean. The response of the Southern Ocean (and sea ice) comprises distinct short and long timescale characteristics in response to ozone depletion. This has possibly wide implications for our understanding of how the SH climate responds to the ozone hole and its recovery.

Our recent observational and modeling results confirming coherent changes in the ventilation of the southern oceans due ozone-induced changes in the wind stress is potentially a very significant result. The ventilation of the southern oceans accounts for a large fraction of the global ocean uptake of heat and anthropogenic carbon, and is of critical importance for global climate and ocean biogeochemistry. The SH westerly winds have strengthen and shifted poleward over recent decades, and modeling studies suggest that this has caused changes in the ocean’s overturning circulation and in carbon uptake. However, the sensitivity of the ocean overturning to decadal changes in wind stresses has been under debate. Our results present observational and modeling evidence for changes in the ventilation, which has potentially important implications for global climate as well as ocean biogeochemistry.

The link between springtime ozone and summertime temperatures has possibly major impacts on our understanding of SH climate and its prediction. Ozone levels will likely rise in the coming decades and our work suggests severe summers in places like Australia may become more frequent. This is the first time the community has looked at the variation of ozone as a way to forecast/predict the next summer's temperature. This could be especially important for farmers, and for areas like southeastern Australia, where most of that nation's population resides.

What is the impact on other disciplines?

As described above our work on the development of WACCM, a leading and widely used chemistry climate model, benefits a multitude of scientists working in areas adjacent to our project. Our research on ocean ventilation has potentially important implications for ocean biogeochemistry, as well as other aspects of the climate system (including changes in Antarctic sea ice). The use of ozone as a way to forecast/predict the next summer's temperature could be especially important for farmers, and for areas like southeastern Australia, where most of that nation's population resides.

What is the impact on the development of human resources?

This project has provided opportunities for graduate students and post-doctoral scientists to perform research in atmosphere and ocean sciences.