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

First year Report (June, 2014)

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 and Tiffany Shaw), 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) Impact of zonal asymmetries in ozone on tropospheric climate. We have analyzed simulations of three versions of the Goddard Earth Observing System Chemistry Climate Model (GEOS CCM) that differ in their representation of stratospheric ozone, to examine the impact on SH tropospheric trends.
(ii) Response of Southern Ocean Circulation and Ventilation to changes in SH winds. We have used measurements of CFC-12 and coupled atmosphere-ocean model simulations to examine changes in the southern ocean circulation and transport, and connections with ozone depletion and changes in the surface winds. We have examined the variability of the southern ocean in pre-industrial simulations from coupled atmosphere-ocean climate model, and compared with observations for the last 30 years.
(iii) Development of WACCM. We are documenting improvements in the Whole Atmosphere Community Climate Model (WACCM) that specifically impact polar stratospheric ozone. This

includes a model description paper (Kinnison et al., 2014) that documents the chemistry updates for the Chemistry Climate Model Initiative (CCMI) simulations that will be used in future FESD work. The dynamical updates to the WACCM CCMI version will be discussed in another paper (Garcia et al., 2014), which will discuss an extension of the WACCM gravity wave parameterization that includes a spectrum of inertia gravity waves. This additional spectrum provides increased wave forcing over the southern polar cap and leads to a better representation of the temperature structure of the polar stratosphere. We have completed development and validation of the specified chemistry (SC) version of WACCM in collaboration with team members at Columbia University and documented it in Smith et al. (2014). A second paper contrasting the effects of the ozone hole on tropospheric climate between WACCM-SC and the fully-interactive model is in preparation. We have further developed a version of WACCM-SC that implements an ozone tracer that is relaxed to the specified zonal mean ozone with a 3-day time constant. This model will be used to understand the importance of non-zonally symmetric polar stratospheric ozone on tropospheric climate. This work is led by Dan Marsh and will be presented at the FESD working group meeting (July 2014).

(iv) Computing ozone-hole response functions. A key approach being pioneering in our FESD project is to characterize the response of the climate to ozone-hole perturbations using the concept of Climate Response Functions (sometimes called Green's functions). Here the forcing is switched on impulsively at t = 0 and the evolution of the coupled system monitored and studied. The Green's function enables one to probe the relative roles of atmosphere and ocean in the response to impulsive GHG and/or ozone hole forcing and the inherent spatial patterns and times-scales, so important for detection in the observational record. Moreover the approach readily and very cleanly facilitates comparison across models. Finally, when convoluted with the observed time history of forcing, the Green's function yields the time history of response to the extent that the system is linear. Two papers (Marshall et al, 2014; Ferreira et al, 2014) set out the ideas and present some early calculations. Our goal is to repeat such calculations in a number of coupled climate models to assess the sensitivity of results.

(v) Tropospheric impacts and signatures of the ozone hole using the instrumental record. Susan Solomon and collaborators have found 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 (Bandoro et al, 2014). In years with high springtime ozone, we find that winds shifted, bringing hotter summer temperatures to much of Australia and parts of southern Africa and South America. Lower ozone levels reversed this behavior, with winds leading to cooler summertime temperatures to these same regions.

Specific Objectives

(i) how does interactive chemistry modifies 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) Our new calculations confirm early calculations showing the simulations with zonal-mean ozone underestimate SH stratospheric and tropospheric trends. This bias is reduced if a parameterization is used where ozone is relaxed with a 3 day time scale towards a zonal-mean state. This parameterization can be included in models without stratospheric chemistry.

(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 subantarctic mode waters and an increase in the age of circumpolar and polar deep waters. 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 response of the Southern Ocean to a repeating seasonal cycle of ozone loss has been found to comprise both fast and slow processes. 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.

(iv) We have found 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. The study, published in the Journal of Climate, suggests that as the springtime ozone hole's severity varies from year to year, the temperatures in Australia and southern regions of Africa and South America reveal correlations: years with higher springtime ozone experience hotter summers, and vice versa. The results suggest that ozone levels may help meteorologists predict the severity of summertime temperatures months in advance.

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

Three graduate students, Jordan Thomas, Olga Tweedy and Justin Bandoro, have worked on our project. A postdoctoral researcher Ute Hausmann has also been supported and others are being recruited.

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., (2014) Antarctic ocean and sea ice response to ozone depletion: a two timescale problem. submitted to Journal of Climate. Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

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, David Ferreira, Ute Hausmann, Jason Bandoro, Alan Plumb, Lorenzo Polvani, Tiffany Shaw, Tom Haine and Anand Gnanadesikan

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).

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.