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

Third year Report (July, 2016)

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 Ryan Abernathey), 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

Major activities and themes running through our proposal over the past year are highlighted in the following numbered paragraphs. A complete list of publications emanating from our project can be found in the 'Products' section.

(i) *Southern Hemisphere extratropical circulation: Recent trends and natural variability*. (JHU)

In Waugh et al (2015) we 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.

(ii) Ozone-hole climate response function simulations (JHU)

Recent studies (Ferreira et al, 2015) have suggested that the response of the Southern Ocean to stratospheric ozone depletion is nonmonotonic in time; consisting of an initial cooling followed by a long-term warming. This result may be significant for the attribution of observed Southern Ocean temperature and sea ice trends, but the time scale and magnitude of the response is poorly constrained, with a wide spread among climate models. Furthermore, a long-lived initial cooling period has only been observed in a model with idealized geometry and lacking an explicit representation of ozone. In Seviour et sl (2016) we calculated the transient response of the Southern Ocean to a step-change in ozone in a comprehensive coupled climate model, GFDL ESM2Mc. The Southern Ocean responds to ozone depletion with an initial cooling, lasting 25 years, followed by a warming. We extend previous studies to investigate the dependence of the response on the ozone forcing as well as the regional pattern of this response. The response of the Southern Ocean relative to natural variability is shown to be largely independent of the initial state. However, the magnitude of this response is much less than that of natural variability found in the model, which limits its influence and detectability.

(iii) Natural variability in Antarctic sea ice. (NCAR and MIT)

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 on to SAM, assessing the relationships between natural variability in the SAM and sea ice can provide insights on the sea ice response to ozone loss. In Holland et al (2016) we assess the sea ice response to Southern Annular Mode (SAM) anomalies for preindustrial control simulations from CMIP5. Consistent with work by Ferreira et al (2015), the models generally simulate a two-timescale response to positive SAM anomalies, with an initial increase in ice followed by an eventual sea ice decline. However, the models differ in the cross-over timescale at which the change in ice response occurs, in the overall magnitude of the response, and in the spatial distribution of the response. Late 20th century multidecadal Antarctic sea ice trends in CMIP5 simulations are related in part to different modeled SAM responses, as diagnosed from pre-industrial runs, acting on different time-varying transient SAM conditions. This explains a significant fraction of the spread in simulated late 20th century southern hemisphere sea ice extent trends across the model simulations. Applying the modeled SAM response to the observed record suggests that variations in the austral summer SAM, which has exhibited a significant positive trend, have driven a modest sea ice decrease.

(iv) Simulation of Polar Ozone and the healing of the Ozone Hole (MIT & NCAR)

CFCs that cause ozone depletion have been phased out under the Montreal Protocol. A chemically-driven increase in polar ozone (or "healing") is expected in response to this historic agreement. Observations and model calculations taken together indicate that the onset of healing of Antarctic ozone loss has now emerged (Solomon et al, 2016). Fingerprints of September healing since 2000 are identified through (i) increases in ozone column amounts, (ii) changes in the vertical profile of ozone concentration, and (iii) decreases in the areal extent of the ozone hole. Along with chemistry, dynamical

and temperature changes contribute to the healing, but could represent feedbacks to chemistry. Volcanic eruptions episodically interfere with healing, particularly during 2015 (when a record October ozone hole occurred following the Calbuco eruption).
See: http://news.mit.edu/2016/signs-healing-antarctic-ozone-layer-0630

(v) Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models (MIT & NCAR)

In Kostov et al (2016) we investigate how sea surface temperatures (SSTs) around Antarctica respond to the Southern Annular Mode (SAM) on multiple timescales. To that end we examine the relationship between SAM and SST within unperturbed preindustrial control simulations of GCMs included in CMIP5. We develop a technique to extract the response of the Southern Ocean SST (55◦S−70◦S) to a hypothetical step increase in the SAM index. We demonstrate that in many GCMs, the expected SST step response function is nonmonotonic in time. Following a shift to a positive SAM anomaly, an initial cooling regime can transition into surface warming around Antarctica. However, there are large differences across the CMIP5 ensemble. In some models the step response function never changes sign and cooling persists, while in other GCMs the SST anomaly crosses over from negative to positive values only three years after a step increase in the SAM. This intermodel diversity can be related to differences in the models' climatological thermal ocean stratification in the region of seasonal sea ice around Antarctica. Exploiting this relationship, we use observational data for the time-mean meridional and vertical temperature gradients to constrain the real Southern Ocean response to SAM on fast and slow timescales.
see: http://oceans.mit.edu/news/featured-stories/southern-ocean-cooling-in-a-warming-world

(vi) Atmospheric and Ocean circulation in the Southern high latitudes (Columbia)

The group at Columbia University has continued work on several aspects of the atmospheric and ocean circulation in the Southern high latitudes, and the impact of ozone depletion. First, using the WACCM model, they have quantified the relative importance of ozone depletion and increasing GHG on the temperature, salinity and meridional circulation of the Southern Ocean: in that model ozone depletion was found to be responsible for over 80% of the circulation changes, and 30% of the temperature and salinity changes between 1955 and 2005 (Solomon A. et al, 2015). Second, they have examined stratosphere-troposphere coupling in Southern Hemisphere, and found that extreme negative (positive) heat flux events are linked to a westward (eastward) shift in the Amundsen Sea Low, and anomalous warming (cooling) over the Amundsen Bellingshausen Seas in both models and reanalyzes (England et al, 2016). Third, they have explored the predictability of changes in the position and strength of the midlatitude jet in the Southern Hemisphere, using the recent Large Ensemble project, and determined that both past and future trends (due, roughly, to ozone depletion and greenhouse gases, respectively) are highly predictable (Solomon and Polvani, 2016). Fourth, they have demonstrated, using two different climate models (with and without coupled ozone chemistry) that ozone depletion has impacted the Amundsen Sea Low (ASL), the key driver of variability around Antarctica, over the period 1955-2005 (England et al, 2016 - submitted). Fifth, they have contrasted several metrics of tropical expansion in the Southern Hemisphere, and shown that upper tropospheric metrics (e.g. the height of the tropopause) correlate very poorly, over a wide range of time scales, with more traditional metrics of the size of the tropical belt (e.g. the latitude where precipitation equals evaporation) (Solomon et al, 2016 - submitted). Sixth, they have investigated how the competition between westerly wind driven upwelling and baroclinic eddy transport on the Stratification in the Southern Ocean varies across different the time scales, contrasting eddy-resolving model simulations with theoretical predictions (Sinha and Abernathey, 2016 - submitted). Finally, L.M. Polvani has been involved in several papers led by John Hopkins University.

(vii) 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. The sculptures float without burning fossil fuels or using solar panels and batteries; and without helium, hydrogen and other rare gases. We are 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.

A demonstration of the Aerocene recently made a big splash at Solutions COP21, the exhibition of scientific and educational innovations at the Grand Palais du Paris held in conjunction with the historic UN Paris Climate Summit during December 2015, as described in recent articles published in the New York Times and on the MITNews web site. Illari also exhibited during MIT's Open House on April 23, 2016 in celebration of 100 hundred years at its Cambridge campus.

See:

https://paocweb.mit.edu/index.php?q=about/spotlights/cop21-finding-hope-climate-aerocene

http://oceans.mit.edu/news/featured-stories/the-value-of-community-engagement-with-climate-science

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 (inter-annual) and slow (decadal) processes. This framework has been used to interpret how both Southern Ocean SST and sea-ice extent respond to trends in the SAM and how these processes are represented in climate models (Ferreira et al, 2015; Kostov et al, 2016; Holland et al, 2016).
(ii) Observations and model calculations indicate that the onset of healing of Antarctic ozone loss, resulting from the phasing out of CFCs under the Montreal Protocol, has now emerged – see Solomon et al (2016). Fingerprints of September healing since 2000 are identified through:

(1) increases in ozone column amounts, (2) changes in the vertical profile of ozone concentration, and (3) decreases in the areal extent of the ozone hole. Along with chemistry, dynamical and temperature changes contribute to the healing, but could represent feedbacks to chemistry. Volcanic eruptions episodically interfere with healing, particularly during 2015, when a record October ozone hole occurred following the Calbuco eruption.

(iii) Observational evidence indicates that the southern Hadley Cell edge has shifted southward during austral summer in recent decades. Waugh et al (2015) show 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 have been supported on the project.

How have the results been disseminated to communities of interest?

Over the past year, results of the above research have been presented at numerous scientific meetings including: AGU, 2015, AMS New Orleans 2016; Ocean Scinces, 2016, NAS Workshops in Woods Hole (2015) and Boulder (2016), ASOF meeting in Lerici, 2016. These meetings cover a wide range of communities, including the middle atmosphere and oceanography communities.

A new ‘Ozone and Climate’ website has been developed that draws together our FESD group and presents the project to the outside world.
see here: http://ozoneandclimate.squarespace.com/

A growing list of news stories, targeted at the general public, have been written:
see here - http://ozoneandclimate.squarespace.com/news/

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.
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.
Seviour, W., D.W. Waugh, A. Gnanadesikan, A Two-Timescale Response of the Southern Ocean to Ozone Depletion: Importance of the Background State , AGU Fall 2015 meeting, San Francisco, 14-18 December 2015
Pradal, M-A. S, A. Gnanadesikan, J.L Thomas, How ocean lateral mixing changes Southern Ocean variability in coupled climate models 2106 Ocean Sciences, New Orleans, 21-26 February 2016.

Pradal, M-A. S, A. Gnanadesikan, RP Abernathey, Impact of space dependent eddy mixing on large ocean circulation, 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Ragan S., A. Gnanadesikan , Impact Of Parameterized Lateral Mixing On The Circulation Of The Southern Ocean , 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Russell, A., S, A. Gnanadesikan, Pradal, M-A. RP Abernathey Impact of Lateral Mixing in the Ocean on El Nino in Fully Coupled Climate Models, 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Seviour, W., D.W. Waugh, A. Gnanadesikan, A Two-Timescale Response of the Southern Ocean to Ozone Depletion: Importance of the Background State, 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Thomas, J.L, Ocean carbon and heat uptake in response to an ozone perturbation, 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Waugh, D.W., Variability in ocean ventilation from three decades of transient tracer measurements, 2106 Ocean Sciences, New Orleans, 21-26 February 2016.
Stewart, K. D, T.W.N Haine, Thermobaricity in the Transition Zones between Alpha and Beta Oceans, Workshop on: Response of Global Climate to the Antarctic Ozone Hole, MIT, MA, 2016.
Stewart, K. D. and T. W. N. Haine, Mode and Intermediate Water Formation Processes Captured by the ARGO Array, 2016 Ocean Sciences Meeting, New Orleans, LA, 2016
Stewart, K.D., and T. W. N. Haine, Thermobaricity in the Transition Zones between Alpha and Beta Oceans, 13th Arctic-Subarctic Ocean Fluxes (ASOF) Meeting, Lerici, Italy, 2016.
Kinnison, D., S. Solomon, D. J. Ivy, M. J. Mills, R. R. Neely III, A. Schmidt, Polar ozone depletion and trends as represented by the Whole Atmospheric Community Climate Model (WACCM), EGU2016-9101, European Geosciences Union General Assembly 2016, Vienna Austria, 17-22 April 2016.
Marshall, J, Ute Hausmann and David Ferreira. AGU, 2015 Observational constraints on the response function of Southern Ocean SST to SAM forcing.
Marshall, J AMS meeting, New Orleans, 2016. Bernhard Haurwitz Memorial Lecture

<u>Journals</u>

MIT

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.

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

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, http://dx.doi.org/10.1175/JCLI-D-14-00313.1

Solomon, S., D. Kinnison, J. Bandoro, and R. R. Garcia, (2015): Simulation of polar ozone depletion: An update. Journal of Geophysical Research-Atmospheres, 120, 7958-7974, doi:10.1002/2015JD023365.

Solomon, S., D. J. Ivy, D. Kinnison, M. J. Mills, R. R. Neely III, A. Schmidt (2016): Emergence of Healing in the Antarctic Ozone Layer. Science. 15 Jul 2016: Vol. 353, Issue 6296, pp. 269-274. DOI: 10.1126/science.aae0061

Hausmann, U., A. Czaja, and J. Marshall (2016): Mechanisms controlling the SST air-sea heat flux feedback and its dependence on spatial scale. Climate Dynamics. First Online: 04 May 2016. http://dx.doi.org/10.1007/s00382-016-3142-3

Hausmann, U., A. Czaja, and J. Marshall (2016): Estimates of air-sea feedbacks on sea surface temperature anomalies in the Southern Ocean, J. Climate. http://dx.doi.org/10.1175/JCLI-D-15-0015.1. Published online on 7 January 2016.

Armour, K.C., J. Marshall, J. R. Scott, A. Donohoe, and E. R. Newsom (2016): Southern Ocean warming delayed by circumpolar up-welling and equatorward transport. Nature Geoscience 9, pp. 549-554. DOI: 10.1038/ngeo2731.

Kostov Y., J. Marshall, U. Hausmann, K. C. Armour, D. Ferreira, and M. M. Holland (2016): Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models. Climate Dynamics. DOI:10.1007/s00382-016-3162-z. First Online: 17 May 2016

NCAR

Holland, M.M, L. Landrum, Y. Kostov and J. Marshall (2016): Sensitivity of Antarctic sea ice to the Southern Annular Mode in coupled climate models. submitted to Climate Dynamics.

Columbia

Neely, R.R., D.R. Marsh, K.L. Smith, S.M. Davis and L.M. Polvani (2014): Biases in Southern Hemisphere climate trends induced by coarsely-specifying the temporal resolution of stratospheric ozone, Geophys. Res. Lett., 41, 8602-8610. doi:10.1002/2014GL061627

Smith, K.L. , R.R. Neely, D.R. Marsh and L.M. Polvani (2014): The Specified Chemistry Whole Atmosphere Community Climate Model (SC-WACCM), J. Adv. Model. Earth. Syst., 6, 883-901 doi:10.1002/2014MS000346.

Solomon, A., L.M. Polvani, K.L. Smith and R.P. Abernathey (2015): The impact of ozone depleting substances on the circulation, temperature and salinity of the Southern Ocean: An attribution study with CESM1(WACCM), Geophys. Res. Lett., 42, 5547-5555. doi:10.1002/2015GL064744.

Waugh, D.W., C.I. Garfinkel and L.M. Polvani (2015): Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? J. Climate, 28, 6581-6586. DOI: http://dx.doi.org/10.1175/JCLI-D-15-0138.1.

England, M.R., T.A. Shaw and L.M. Polvani (2016): Troposphere-stratosphere dynamical coupling in the Southern high latitudes, and its linkage to the Amundsen Sea, J. Geophys. Res., 121, 3776-3789. doi:10.1002/2015JD024254.

Solomon, A. and L.M. Polvani (2016): Highly significant responses to anthropogenic forcings of the midlatitude jet in the Southern Hemisphere. J. Climate, 29, 3463-3470. DOI: http://dx.doi.org/10.1175/JCLI-D-16-0034.1

England, M.R., L.M. Polvani, K.L. Smith, L. Landrum and M.M. Holland: Robust response of the Amundsen Sea Low to stratospheric ozone depletion, submitted to Geophys. Res. Lett. (2016)

Solomon, L.M. Polvani, D.W. Waugh and S. Davis: Contrasting Upper and Lower Atmospheric Metrics of Tropical Expansion in the Southern Hemisphere, submitted to Geophys. Res. Lett. (2016)

Sinha, A., and R. Abernathey: Timescales of Southern Ocean Eddy Equilibration, submitted to J. Phys. Oceanog. (2016)

JHU

Waugh, D.W., (2014): Changes in the ventilation of the southern oceans, Phil. Trans. R. Soc. A. DOI: 10.1098/rsta.2013.0269.

Gnanadesikan, A., M.-A. Pradal, and R. Abernathey (2015): Isopycnal mixing by mesoscale eddies significantly impacts oceanic anthropogenic carbon uptake. Geophys. Res. Lett., 42, 4249–4255. doi: 10.1002/2015GL064100.

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Gnanadesikan, A., M.A Pradal, R Abernathey (2015): Exploring the isopycnal mixing and helium–heat paradoxes in a suite of Earth system models. Ocean Science 11 (4), 591-605 doi:10.5194/os-11-591-2015

Stewart, K. D, T.W.N Haine, (2016): Thermobaricity in the Transition Zones between Alpha and Beta Oceans. J. Phys. Ocean, DOI: 10.1175/JPO-D-16-0017.1.

Seviour, W.J.M, A. Gnanadesikan, D.W. Waugh (2016): The Transient Response of the Southern Ocean to Stratospheric Ozone Depletion, J. Climate. DOI: http://dx.doi.org/10.1175/JCLI-D-16-0198.1

Seviour, W.J.M, A. Gnanadesikan, D.W. Waugh, 2016: The Transient Response of the Southern Ocean to Stratospheric Ozone Depletion, J. Climate, submitted.

Seviour, W.J.M, D. W. Waugh, L. M. Polvani, G.J. P. Correa, 2016: Robustness of the simulated tropospheric response to ozone depletion, Climate Dynamics, submitted.

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?

Feng Li and Luke Oman (NASA GSFC).
Chaim Garfinkel (Hebrew University, Jerusalem, Israel)
Natassa Romanou and Max Kelley (Goddard Institute for Space Sciences)

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.

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.