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

Fourth year Report (July, 2017)

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) Response of the Southern Ocean to Ozone Depletion. (JHU)

A major research focus has been on understanding the reason for large differences between models in their SO response to ozone depletion. In Seviour et al. (2017), we showed that the cooling response to the ozone hole in the GFDL model was significantly driven both by cloud feedbacks and by a decrease in entrained heat from the mixed layer. Motivated by this result we have run an additional ensemble of ozone response simulations with the GFDL model with increased lateral mixing. These simulations have a much shorter-lived cooling of the SO because the higher stratification makes it much more difficult to entrain heat from below. Hence, we have been able to produce responses that look both like the MITgcm response (~25 year cooling) and the CCSM response (~5 year cooling) in a single model by simply varying a single mixing parameter-one which varies significantly across climate models. We are currently putting together a paper which analyzes these runs together with runs down with other models. [*With MIT, Reading, GISS*]

We have continued work on tropical expansion in the southern hemisphere. Work in Solomon, A. et al. (2017) showed that some recently used metrics for the tropical width (e.g. OLR or tropopause height based metrics) correlate poorly with traditional metrics based on stream function or precipitation-evaporation. We have continued to examine this issue focusing on differences between changes in width defined by stream function or P-E, and how this varies with forcing driving the changes and among models. [*With Columbia.*]

Following up on the work of Seviour et al. (2016) which showed that an important part of the response to ozone in the GFDL model was due to modulating ocean convection, we have further examined the role of convection in two studies. In Cabre et al. (2017) we show that open-ocean convection in the GFDL model has global impacts on the energy budget, resulting in more shortwave absorption, followed by transport across the equator in the ocean and atmosphere. However, while the transport in the atmosphere is radiated to space, the transport in the ocean largely shows up in an excess of stored heat. In Thomas et al. (subm.) we examine the co-variation of carbon and heat content associated with convective variability, showing that the variations in carbon content are primarily driven by the Southern Ocean with lower carbon content during convective periods, while the heat content increases during convective periods as a result of heat uptake in the tropics.

We are continuing to work on examining the impact of the ozone hole on the uptake of anthropogenic carbon and are discussing a possible paper showing that this impact is small across models [*with GISS, Reading, MIT, and NCAR/UC-Boulder*]

Work continues on the role of sea ice in the southern ocean climate system and its secular change. This includes a study of the seasonality of sea ice, in comparison to the northern hemisphere sea ice system (Haine & Martin, 2017), a diagnosis of the upper ocean stratification in relation to sea ice (Stewart & Haine, 2016), and the role of nonlinearities in the seawater equation of state for the ocean mixed layer (Stewart et al., 2017).

(ii) Variability in Antarctic sea ice. (NCAR)--

Observed changes in Antarctic sea ice exhibit large and partly compensating regional trends, resulting in a small overall increase during the satellite record. In order to better understand the observed record, we have been assessing factors that drive regional sea ice change, including the role of ozone loss. Two primary research projects have resulted from this work. The first is an observational analysis to assess ice changes in the Ross Sea since 1979. This region exhibits the largest increasing ice trends, which are not captured by the internal variability or forced change within climate models. We find that variability during the austral fall in this region is driven by westerly wind anomalies five months prior in the austral spring. Based on these relationships, observed trends in springtime winds could explain a considerable fraction of the ice increases that have occurred in the western Ross Sea. The second project has targeted the role of ozone loss in driving regional ice trends using a set of climate model experiments with fixed ozone for the 20th century. Comparing these to standard 20th century simulations elucidates that ozone loss does indeed drive a regional pattern of sea ice change due to its influence on deepening the Amundsen Sea Low.

(iii) Southern Hemisphere polar stratospheric temperature trends (NCAR)

In the polar lower stratosphere of the Southern Hemisphere (SH), observations show a long-term cooling in the last decades of the twentieth century [e.g., Thompson and Solomon, 2002], which has been reproduced in general circulation models. Idealized simulations have attributed most of the trend in austral spring to ozone depletion. The decrease in ozone leads to stratospheric cooling, which enhances the meridional gradient of temperature in the SH polar cap and leads to an intensification of the zonal-mean zonal winds which propagates from the stratosphere to the troposphere. It is well established that the long-term cooling leads to a poleward shift and strengthening of the tropospheric jet in austral summer, which in turn affects storm tracks, precipitation, and the ocean circulation. Therefore, accurate modeling of past ozone and temperature changes in the SH polar lower stratosphere is key for understanding their impacts on present SH climate and for predicting future changes. In Calvo et al. [2017], we have evaluated the latest version of the Whole Atmosphere Community Climate Model (WACCM), used in many FESD-Ozone related studies. This new version of WACCM includes a new polar chemistry scheme [Solomon et al., 2015] and an updated parameterization of orographic gravity waves [Garcia et al., 2017]. The temperature trends in the Antarctic lower stratosphere have been found to be in excellent agreement with radiosonde observations for 1969–1998 as regards magnitude, location, timing, and persistence.

(iv) Southern Hemisphere circulation in austral fall (MIT & NCAR).

Much research has focused on trends in the Southern Hemispheric circulation in summer (Dec-Jan-Feb) in the troposphere and stratosphere, while changes in other seasons have received less attention. In Ivy et al. [2017a], we examined the seasonality and structure of observed changes in tropospheric and stratospheric winds, geopotential height, and temperature of the Southern Hemisphere over the satellite era since 1979. This work found that statistically significant trends similar to those of the Antarctic summer season are also observed in austral fall, particularly May. Evidence for a significant shift in the position of the May jet is shown. Further, this work showed observational evidence for significant austral fall ozone depletion in the lowermost stratosphere and demonstrated using radiative calculations that the associated lower stratospheric May polar cooling is consistent with the ozone losses.

(v) Volcanic aerosols and Antarctic ozone depletion (MIT & NCAR).

We have continued our analysis of the impact of volcanic aerosols on Antarctic ozone depletion. In 2015, the Antarctic ozone hole reached a record average size for the month of October. WACCM simulations with specified dynamics and temperatures based on reanalysis suggested that the record size was likely due to the eruption of Calbuco, but did not allow for dynamical or thermal feedbacks (Solomon et al., Science, 2016). In Ivy et al. [2017b], we presented simulations of the impact of the Calbuco eruption on the stratosphere using the WACCM with interactive dynamics and temperatures. Comparisons of simulations with and without volcanic aerosols suggested that the eruption of Calbuco indeed played a key role in establishing the record ozone hole of 2015. Furthermore, comparisons of the interactive and specified dynamics simulations indicated that chemical ozone depletion due to volcanic aerosols is the primary mechanism for the enhanced ozone depletion in 2015, while temperature and dynamical feedbacks had a minimal influence. Additional work on this topic has been submitted for peer review (Stone et al., 2017). In the latter study, the WACCM impact of the Calbuco volcanic aerosols on

South Polar ozone depletion is extensively evaluated with observations, specifically comparing model results to Aura MLS and OMI ozone anomalies, polar ozonesondes stations, and volcanic aerosol extinction based on CALIOP.

(vi) Changes in Antarctic Ozone and Stratospheric Temperature in the late 20th versus early 21st Centuries (MIT & NCAR).

Here observed and modeled patterns of seasonal trends in Antarctic ozone and temperature in the late 20th (1979-2000) and the early 21st (2000-2014) centuries are compared. Patterns of pre-2000 observed Antarctic ozone decreases and stratospheric cooling as a function of month and pressure are followed by opposite-signed (i.e., "mirrored") patterns of ozone increases and warming post-2000. An interactive chemistry-climate model (WACCM) forced by changes in anthropogenic ozone depleting substances produces broadly similar mirrored features. Statistical analysis of unforced model simulations suggests that internal and solar natural variability alone is unable to account for the pattern of observed ozone trend mirroring, implying that forcing is responsible for this behavior. This work has been submitted for peer review (Solomon et al., 2017).

(vii) 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

(viii) Research at Columbia on the impact of the ozone hole of Atmosphere and Ocean

In this past year, 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. With team members Laura Landrum and Marika Holland at NCAR, using the WACCM model, they have demonstrated that ozone depletion causes a deepening of the Amundsen Sea Low (England et al, 2016); they are now expanding this work and studying the effect of ozone depletion on regional aspects of observed sea ice trends around Antarctica. They have also demonstrated the importance of ozone changes upon quadruling of CO_2: specifically, they have shown that such changes result in a considerable negative feedback on the polar jet shift that accompanies CO_2 increases (Chiodo and Polvani, 2017). In collaboration with colleagues at Princeton, the group at Columbia has also carefully contrasted the Southern Hemisphere circulation response to ozone depletion in two different models, and showed how such response sensitively depends on the models' ability to capture the observed climatological evolution of the stratospheric circulation (Lin et al 2017). Finally, the Colubia group had completed a paper contrasting metrics of tropical expansion in the Southern Hemisphere (stratospheric ozone having been one of the early metrics used to report such expansion) and shown that upper tropospheric/lower stratospheric metrics, in general, have very poor correlation with more traditional metrics of the size of the tropical belt (Solomon et al 2016). This raises important issues as to which metrics are better suited to capture the expansion of the tropical belt, notably in the Southern Hemisphere where a large fraction of the observed trends have been attributed to ozone depletion.

(ix) 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.

One product of the outreach activity has been the development of EsGlobe, an interactive display for rendering environmental or model data onto a sphere (either a physical sphere, a virtual sphere on a flat screen display or indeed one's cell phone). It can be tilted and rotated to facilitate ease of viewing, as shown in Fig.1 and described in the legend. More importantly, it will enable interactive work with the underlying data sets. We envisage that EsGlobe will also be a valuable resource for outreach in informal settings such as lab visits, museums and libraries and can even be used to enliven professional lectures and seminars. A prototype exists and is already being used in outreach and educational activities. Projects that target stratospheric dynamics is a priority.

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, Will Seviour, Ed Doddridge, Gabriel Chiodo and Kane Stone have been supported on the project.

How have the results been disseminated to communities of interest?

Since the start of the project, 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, 2017), ASOF meeting in Lerici, 2016. These meetings cover a wide range of communities, including the middle atmosphere and oceanography communities – see detailed list below.

An ‘Ozone and Climate’ website has been developed and maintained 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
Holland, M.M. and L. Landrum, Factors influencing regional changes in Antarctic sea ice, Los Alamos National Lab Frontiers in Geoscience Colloquia, Los Alamos, NM, May 15, 2017
Holland, M.M. and L. Landrum, Towards understanding regional variability and trends in Antarctic sea ice, National Snow and Ice Data Seminar, Boulder, CO, April 26, 2017
Holland, M.M. and L. Landrum, Factors influencing regional changes in Antarctic sea ice, NCAR Southern Ocean Workshop, Boulder, CO April 10, 2017

Holland, M.M., L. Landrum, M. Raphael, S. Stammerjohn, Factors influencing sea ice variability and trends in the Western Ross Sea, International Glaciological Symposium, Wellington, NZ Feb 16, 2017
Holland, M.M. and L. Landrum, Influence of winds on Ross Sea ice cover: Seasonal lags and explained trends, AGU Fall Meeting, San Francisco, CA, Dec 2016.
Landrum, L., M.M. Holland, L. Polvani, and M. Raphael, Antarctic Sea Ice Response to Late 20th Century Ozone Changes: a Modeling Perspective on Regional and Seasonal Trends and Variability, AGU Fall Meeting, San Francisco, CA, Dec 2016.
Holland, M.M., Investigating Antarctic sea ice variability using experiments with a hierarchy of ocean models, WCRP Model Hierarchy Workshop, Princeton, NJ, November 2016
Seviour, W. J. M., A. Gnanadesikan, D. W. Waugh, and M.-A. Pradal. The transient response of the Southern Ocean to stratospheric ozone depletion, AMS AOFD meeting, Portland, OR, 2017.
Seviour, W. J. M., A. Gnanadesikan, D. W. Waugh, and M.-A. Pradal. A Two-Time Scale Response of the Southern Ocean to Ozone Depletion: Regional Responses and Physical Mechanisms, AGU Fall Meeting, San Francisco, CA, 2016.
Seviour, W. J. M., A. Gnanadesikan, and D. W. Waugh. The transient response of the Southern Ocean to stratospheric ozone depletion, Quadrennial Ozone Symposium, Edinburgh, UK. 2016.
Seviour, W. J. M., D. W. Waugh, L. M. Polvani, G. J. P. Correa, and C. I. Garfinkel. Robustness of the simulated tropospheric response to ozone depletion, Quadrennial Ozone Symposium, Edinburgh, UK. 2016.
Thomas, J.L, Ocean carbon and heat variability in an earth system model, 2016 AGU Fall Meeting, San Francisco, CA, December 12-16 2016.
Waugh, D.W., Contrasting Upper and Lower Atmospheric Metrics of Tropical Expansion in the Southern Hemisphere, US CLIVAR working group meeting, October 2016.
Waugh, D.W., Contrasting Upper and Lower Atmospheric Metrics of Tropical Expansion in the Southern Hemisphere, ISSI Tropical Width Diagnostics meeting, Bern, March 2017
K. Stewart and T. W. N. Haine, Thermobaricity in the transition zones between alpha and beta oceans, CLIVAR Open Science Conference, Qingdao, China, 2016
K. D. Stewart and 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
T. W. N. Haine and T. Martin, The Arctic-Subarctic sea ice system is entering the seasonal regime , 5th FAMOS Meeting, Woods Hole Oceanographic Institution, Woods Hole, MA ,2016
K. D. Stewart and T. W. N. Haine and A. McC. Hogg and F. Roquet, On Cabbeling and Thermobaricity in the Surface Mixed Layer, EGU General Assembly 2017.
T. Martin and T. W. N. Haine, Does the Arctic Amplification peak this decade? EGU General Assembly 2017
Calvo, N., R. R. Garcia, and D. E. Kinnison, 2017: Revisiting Southern Hemisphere polar stratospheric temperature trends in WACCM: The role of dynamical forcing, Chemistry Climate Initiative Meeting, Toulouse France, 13 June, 2017.
L Landrum, M Holland, LM Polvani: Antarctic Sea Ice Response to Late 20th Century Ozone Changes: a Modeling Perspective on Regional and Seasonal Trends and Variability. AGU in San Francisco, December 2017
P Lin, D Paynter, LM Polvani, G Correa, Y Ming and V Ramaswamy: Circulation response to ozone depletion depends on the zonal wind Climatology. AGU in San Francisco, December 2017
A Solomon, LM Polvani, DW Waugh and S Davis: Contrasting upper and lower atmospheric metrics of tropical expansion. AGU in San Francisco, December 2017

G. Chiodo and LM Polvani: Robust impact of coupled stratospheric ozone chemistry on the response of the Austral circulation to increased greenhouse gases. AGU in San Francisco, December 2017
Doddridge, E., "Impact of SAM on the seasonal cycle of sea ice extent around Antarctica", Southern Ocean Workshop, 10-13 April 2017, NCAR, Boulder, Colorado
Doddridge, E., webinar to virtual meeting of Frontiers in Earth System Dynamics: Ozone and Climate Project, 19 May 2017

Journals

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.

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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.

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Ivy, D. J., C. Hilgenbrink, D. Kinnison, R. Alan Plumb, A. Sheshadri, S. Solomon, and D. W. J. Thompson, Observed changes in the southern hemispheric circulation in May, *Journal of Climate*, 30, 527-536, doi:10.1175/JCLI-D-16-0394.1, 2017a.

Ivy, D. J., S. Solomon, D. Kinnison, M. J. Mills, A. Schmidt, and R. R. Neely, the influence of the Calbuco eruption on the 2015 Antarctic ozone hole in a fully coupled chemistry-climate model, *Geophys. Res. Lett.*, doi:10.1002/2016GL071925, 2017b.

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Stone, K. A., S. Solomon, D. Kinnison, M. C. Pitts,, L. R. Poole, M. J. Mills, A. Schmidt, Ryan R. Neely III, D. Ivy, M. J. Schwartz, B. J. Johnson, M. B. Tully, A. R. Klekociuk, G. König-Langlo, and S. Hagiya, Observing the impact of Calbuco volcanic aerosols on South Polar ozone depletion in 2015, in review, *J. Geophys. Res*., 2017.

Doddridge, E. and J. Marshall: Impact of the Southern Annular Mode on the seasonal cycle of Antarctic sea ice extent. Under review in Geophysical Research Letters, 2017

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.

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Landrum, L., M.M. Holland, L. Polvani, and M. Raphael, 2017: Antarctic sea ice response to Late 20th Century ozone changes, In preparation for submission to Geophys. Res. Lett.

Calvo, N., R. R. Garcia, and D. E. Kinnison, Revisiting Southern Hemisphere polar stratospheric temperature trends in WACCM: The role of dynamical forcing. *Geophys. Res. Lett.*, 44, 3402-3410, doi:10.1002/2017GL072792, 2017a.

Garcia, R. R., A. K. Smith, D. E. Kinnison, A. de la Cámara, and D. J. Murphy, Modification of the gravity wave parameterization in the Whole Atmosphere Community Climate Model: Motivation and results, *J. Atmos. Sci*., 74, 275–291, doi:10.1175/JAS-D-16-0104.1, 2017.

Columbia

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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.