WORLD CLIMATE RESEARCH PROGRAMME SPECIAL WORKSHOP ON CLIMATIC EFFECTS OF OZONE DEPLETION IN THE SOUTHERN HEMISPHERE

BY P. O. CANZIANI, A. O'NEILL, R. SCHOFIELD, M. RAPHAEL, G. J. MARSHALL, AND G. REDAELLI

A World Climate Research Programme (WCRP) Special Workshop titled the "Climatic effects of ozone depletion in the Southern Hemisphere: Assessing the evidence and identifying gaps in the current knowledge" focused on the current understanding of Southern Hemisphere (SH) ozone depletion, in particular high-latitude ozone depletion, with regards to its impacts on hemispheric climate and its role relative to greenhouse gas (GHG)–induced climate changes. The 2010 United Nations Environment Programme (UNEP)/World Meteorological Organization (WMO) Scientific Assessment of Ozone Depletion, and research published since, provided the starting point for discussion. The workshop was supported by WCRP, the National Science Foundation (NSF; United States), the National Aeronautics and Space Administration (NASA; United States), Agencia Nacional de Promoción Científica y Técnica (Argentina), and the Pontificia Universidad Católica Argentina (Argentina).

CLIMATIC EFFECTS OF OZONE DEPLETION IN THE SOUTHERN HEMISPHERE: ASSESSING THE EVIDENCE AND IDENTIFYING GAPS IN THE CURRENT KNOWLEDGE

WHAT: Fifty researchers from 11 nations met to examine our understanding of the links between stratospheric ozone depletion and recovery and the climate of the Southern Hemisphere, including the Southern Ocean as well as the interaction of ozone depletion with processes driven by the concentration of greenhouse gases. Attribution of current, recognized climate changes in the Southern Hemisphere was discussed in order to assess the relative contributions of ozone depletion and greenhouse gases.

WHEN: 25 February–1 March 2013

WHERE: Buenos Aires, Argentina

WORKSHOP AIMS. There is overall consensus in the stratospheric and climate communities that the current state of our understanding of SH ozone has to be thoroughly evaluated and discussed in order to consolidate current views of the issues at hand. This is necessary to identify future research needs, both in light of the expected ozone layer recovery and ongoing climate changes being driven by sustained increases in GHGs and other environmental processes (deforestation, desertification, and land use changes) that impact climate. Furthermore, different WCRP core projects also agreed that given the scope of issues, the discussion had to be interdisciplinary, bringing together Stratospheric Processes and Their Role in Climate (SPARC), Climate Variability and Predictability of the Ocean–Atmosphere System (CLIVAR), and Climate and Cryosphere (CLiC) WCRP core projects' communities.

The driving questions were as follows:

1) How well do we understand the mechanisms relating Antarctic ozone loss to tropospheric climate in the Southern Hemisphere?

2) How will GHG increases and ozone depletion/recovery interact in the future, and what will be their impacts on the polar vortex and tropospheric climate?
3) What do we not know, and what observing or research actions are required?

To foster an environment for such an exchange of ideas and interdisciplinary interaction, the Scientific Organizing Committee[1] determined that the workshop dynamics should return to the essence of scientific meetings, that is, the famed Solvay Conferences. A strong emphasis was placed on rigorous discussion following each invited keynote presentation, with sessions being organized around specific topics:

1) Stratospheric ozone variability and impact on climate;
2) Processes I: Tropospheric climate and weather events;
3) Processes II: Cryosphere, ocean circulation, and carbon uptake; and
4) Modeling and predictions.

For each topic, two to three keynote speakers were invited to deliver a review talk, followed by an extended period of discussion and debate. In practice, the exchange of views started within the keynote speaker presentations, leading to excellent results. Session chairs conducted the debates, while session rapporteurs registered all proceedings. Keynote speakers were as follows:

- Session I: Sophie Godin, Darryn Waugh, and Steve Rintoul;
- Session II: Edwin Gerber and Ryan Fogt;
- Session III: Marilyn Raphael, Gareth Marshall, and Wenju Cai; and
- Session IV: Michael Sigmond and Nathan Gillett.

Research presentations were possible through a parallel poster session. Over 30 posters were presented and displayed for the duration of the workshop (PDF versions of the posters can be accessed through www.uca.edu.ar/index.php/site/index/es/uca/programa-para-el-estudio-de-procesos-atmosfericos-en-el-cambio-global/wcrp-special-workshop/poster/). The 50 participants from Australia, New Zealand, South Africa, the United States, France, Germany, Italy, Russia, the United Kingdom, Japan, and Argentina attended the workshop.

A special session, chaired by early career scientists and Ph.D. students, many of whom were able to attend thanks to WCRP, NSF, and NASA support, was held prior to the concluding session: they presented and discussed early career perspectives on the issues and included their views on the future of the field. During the final plenary, rapporteurs presented session summaries. Thus, final workshop conclusions were actively discussed and approved during this final session.

AFFILIATIONS: Canziani—Equipo Interdisciplinar para el Estudio de Procesos Atmosféricos en el Cambio Global, Facultad de Ciencias Fisicomatemáticas e Ingeniería, Pontificia Universidad Católica Argentina, and Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; O'Neill—National Centre for Earth Observations, NERC, Reading, United Kingdom; Schofield—School of Earth Sciences, University of Melbourne, Melbourne, Victoria, Australia; Raphael—Department of Geography, University of California, Los Angeles, Los Angeles, California; Marshall—British Antarctic Survey, Cambridge, United Kingdom; Redaelli—CETEMPS, and Department of Physical and Chemical Sciences, University of L'Aquila, L'Aquila, and Istituto di Acustica e Sensoristica, CNR, Rome, Italy
CORRESPONDING AUTHOR: Pablo O. Canziani, PEPACG-UCA, Edificio San José 3er p., Alicia Moreau de Justo 1600, C1107AFF Capital Federal, Argentina
E-mail: pocanziani@gmail.com

DOI:10.1175/BAMS-D-13-00143.1

In final form 26 December 2013

MAIN WORKSHOP CONCLUSIONS. *Session I: Stratospheric ozone variability and impact on climate.* State of knowledge. *Ozone observations and modeling.* Severe ozone depletion has occurred in the Antarctic spring stratosphere caused by human-produced ozone-depleting substances—the Antarctic ozone hole. The Montreal Protocol has been successful in reducing the amount of ozone-depleting substances (ODSs) in the atmosphere, but the return to pre-1980 levels will take decades. The ozone hole should return to 1980 values by 2050–70. By 2100, models predict an ozone "super recovery" in the SH mid-latitudes as a result of 1) an increase in the strength of the Brewer–Dobson circulation and 2) a decrease in ozone loss rates in the upper stratosphere due to

[1] Marilyn Raphael, Robyn Schofield, Anne Thompson, Gareth Marshall, Thando Ndarana, Paul Newman, Manuel Pulido, Gianluca Redaelli, James Renwick, David Thompson, Darryn Wauch, and Shigeo Yoden, and also co-chairs Alan O'Neill and Pablo Canziani.

stratospheric cooling. Increasing levels of GHGs drive both of these effects.

SH climate. There have been large changes in the SH summer climate over the last 30 yr, from the surface through to the stratosphere, and from polar regions to the subtropics. Many of the recent SH climate changes have been attributed to the ozone hole causing an increasingly positive trend in the southern annular mode (SAM) or a poleward shift in the jet during austral summer.

Other changes in climate in recent decades, which appear to be ozone driven, have been noted: 1) a winter reversal of the jet in the stratosphere has been delayed from late spring to summer; 2) through impacts on the SAM, the jet changes have affected Antarctic surface temperatures, with a warming over the Antarctic Peninsula and a cooling in East Antarctica, especially in austral summer; 3) in conjunction with GHG increases, the jet changes have likely induced changes to the pattern of regional midlatitude drying and mid- to high-latitude moistening observed in the SH; and 4) changes in the Hadley and Ferrel cells' circulation patterns have been observed.

Models (ranging from idealized atmospheric models to climate models with interactive chemistry) indicate that the ozone hole is the primary cause of the observed changes, which lie outside the range of SH extratropical summer climate natural variability.

Ozone loss and GHG increases have both driven the recent positive trend in the SAM during austral summer. Ozone recovery over the next decades will impose a negative forcing on the SAM, thus dampening the positive influence of a continuing rise in GHG concentrations. Therefore, while increasing GHGs are expected to cause an overall SH warming, SAM-related past trends in summer climate will likely weaken, and maybe even reverse, contingent on the extent of changes in GHG forcing. The cause of SAM's recent positive trend during austral autumn is not currently understood and may simply be the result of natural climate variability.

Impacts on the SH ocean. The wind stress curl is changing, with the zero line shifting poleward, inducing an intensification of the super gyre. Observations support this intensification (ocean temperature trends are consistent for 1960–2007). The tropospheric jet's position is a significant driver of oceanic changes in response to the ozone losses of the past decades, through 1) the ocean's thermal response to the position of the atmospheric jet and 2) the ocean's dynamical response to changes in tropospheric temperature.

How well these two ocean response processes are represented within models explains, to a large extent, the spread among current climate models. There are different potential mechanisms to drive these processes, which are not yet understood. A key necessity for reducing uncertainty is to improve current understanding of model tropospheric variability for a given stratospheric ozone perturbation.

Future research questions. Some questions for future research are as follows:

1) Can observations be prioritized? At what sampling rates do we need the different observations: subdaily, daily, weekly, or monthly? Are more ocean measurements needed?
2) Are the observed changes in the various components of the Earth system coherent with current understanding?
3) Is ozone behaving like we think it is supposed to? What is the effective equivalent stratospheric chlorine (EESC) doing? Are chlorine and bromine declining as we think they should?
4) What will be the relative roles of ozone and GHGs in future SH climate?
5) Linearity of the response to GHG and ODS changes: How linear/nonlinear and uncorrelated/synergistic is the atmospheric response to their changes?
6) How should the Hadley cell be defined?
7) Can reanalysis products be trusted? How should variability and trend studies be tackled with reanalysis?

Session II: Processes I: Tropospheric climate and weather events. State of knowledge. West Antarctic temperatures have risen, and these temperatures are sensitive to the strength and position of the Amundsen Sea low (ASL). A minority of climate models suggest that ozone depletion has contributed to the deepening of the ASL.

Although the SAM is a hemispheric-scale mode of variability, its impact varies significantly at regional scales. Predominant spatial patterns in the relationship between SAM and elements of the Southern Hemisphere surface climate exist, but can reverse sign on decadal time scales. Such sign changes could be due to the internal climate variability, related to planetary wave-3 phase and amplitude over the Southern Ocean. This has implications for identifying a robust methodology for using the Antarctic ice core record to generate a proxy for SAM, and on the level of certainty with which we can ascribe future projections of Antarctic climate and related projections of sea level rise.

Future SAM trends are likely to be much weaker or even opposite in austral summer (negative) compared to other seasons (positive). This may lead to increased summer melting for regions with a current predominant negative SAM temperature relationship (East Antarctica), while over the Antarctic Peninsula there is likely to be greater winter accumulation.

FUTURE RESEARCH QUESTIONS. Some questions for future research are as follows:

1) What is the natural variability of SAM? What are the causes of the positive SAM trends in austral autumn?
2) What is causing the variability/deepening trend of the ASL? Is there a possible contribution from asymmetric modes of variability?
3) How do zonal-mean ozone asymmetries affect climate?
4) Is there a need for further regional variability and trend studies to better assess the climate response to ozone forcing? If so, which studies?

Session III: Processes II: Cryosphere, ocean circulation, and carbon uptake. STATE OF KNOWLEDGE. On average, observed sea ice extent around Antarctica has been increasing. This increase has not been uniform—some large regions show significant increase, others significant decrease. The causes for sea ice extent changes are not fully understood; however, they appear to be mediated by changes in surface wind speed and direction, as well as ocean currents. The changes in winds may be associated with the strength of the ASL, as well as the strength and polarity of the SAM. The mixed layer depth response to the SAM shows zonal asymmetry.

Observed changes in the Southern Ocean have been linked to changes in near surface winds. These changes include the subtropical super gyre, the meridional overturning circulation, and the ocean becoming a less effective sink of CO_2.

While sea ice extent observations indicate Antarctic sea ice extent enhancements, almost all available model studies for twentieth-century climate simulate a decrease. This includes models that explicitly simulate stratospheric ozone depletion, which indicate that stratospheric ozone depletion should have driven a hemispheric total sea ice extent decrease.

FUTURE RESEARCH QUESTIONS. Some questions for future research are as follows:

1) What is the cause for the discrepancy in sea ice trends between observations and models over the twentieth century? Are differences due to model deficiencies or unknown processes affecting sea ice variability? For example, does freshwater input play a major role? From a modeling perspective, how important are stratospheric resolution and ocean–atmosphere coupling for sea ice modeling?
2) What is the intrinsic model variability of sea ice properties?
3) How will the ocean circulation and carbon uptake evolve as ozone recovers?
4) Where is the heat derived to support ocean heat content changes associated with ocean circulation changes induced by wind stress?
5) How will the ocean circulation and wind changes affect carbon uptake?

Session IV: Modeling and predictions. STATE OF KNOWLEDGE. Models show that the relative role of ozone and GHGs in forcing past climate trends, particularly of SAM, varies seasonally, while being comparable in the annual mean.

A bias remains in the simulation of the midlatitude jet position when compared to reanalysis data. The jet latitude bias appears to be positively correlated with the simulated jet shift size in response to ozone and GHG depletion. The future evolution of jet trends remains unclear and depends on the relative role of ozone versus GHG forcing.

A well-resolved stratosphere and a high upper boundary are required to simulate a proper tropospheric response. The response to prescribed ozone depletion is significantly larger in models with finer vertical resolution in the lower stratosphere compared to models with low-top and coarser vertical resolution in the stratosphere. This may be related to a lack of momentum conservation at the top of the model, leading to an unrealistic dynamical response in the stratosphere. Many Coupled Model Intercomparison Project phase 5 (CMIP5) models probably have high enough stratospheric resolution to resolve this response. The stratospheric temperature response varies by a factor of 2 or more over the pole for a given ozone forcing, adding to the spread of model responses in the troposphere.

Zonal-mean ozone is usually prescribed in models, but ozone exhibits zonal asymmetries in spring when the ozone hole is often centered off the pole. The use of zonal-mean ozone distributions underestimates the climatic response, leading to a weaker and warmer vortex in austral spring, an overall reduction in the stratospheric response, and an underestimation of the SAM changes. At present, most CMIP5 models likely underestimate the tropospheric impacts of ozone changes.

Climate models consistently fail to reproduce Antarctic sea ice variability and trends. This is probably at least partially caused by the insufficient representation of processes related to sea ice formation and ocean–atmosphere interactions. Furthermore, Antarctic ozone depletion's contribution to the recent Antarctic sea ice trends is unclear, even if several recent model studies regarding ocean–atmosphere coupling seem to indicate that this may not be the case.

Future research questions. Some questions for future research are as follows:

1) Are natural variability mechanisms adequately understood in order for models to reproduce it properly? How significant is the current representation of natural variability in models, and what is its contribution compared to ozone and GHG forcing? How do we improve tropospheric variability in models? Do we need to better differentiate long-term trends from seasonal to interannual variability when analyzing model outputs?
2) What are the mechanisms for stratosphere–troposphere coupling? Which mechanisms need to be included in models?
3) What is the cause of the bias in midlatitude jet position?
4) How well do the models represent change in the Hadley cell? Why, while reanalyses suggest the trend in the Hadley cell extension is larger in austral summer than in austral autumn, do models fail to reproduce this seasonality?
5) Do current GCMs underestimate the tropospheric response to ozone due to a lack of vertical resolution or momentum conservation? Do they overestimate the tropospheric response to ozone due to the jet bias?
6) How important a shortcoming is the use of zonal-mean ozone for the interpretation of CMIP5 results? What is the best design for future GCM experiments without coupled chemistry to account for the effects of the zonal asymmetry of ozone?
7) What are the heat sources causing the surface warming pattern in the SH, and do the models capture them?
8) How important is stratospheric resolution for sea ice modeling?
9) The coupling between the important Earth systems (atmosphere, ocean, land, and cryosphere) remains a major modeling challenge. What should be done to meet this challenge?

CONCLUDING REMARKS. This workshop allowed a thorough analysis of the current understanding of the coupling between ozone depletion and SH surface climate, leading to the formulation of a large number of issues that need to be addressed, through observations, analysis, and modeling, in a shared, strong interdisciplinary approach, so as to provide appropriate answers.

One frequent issue refers to reanalyses, regarding their quality and applicability for climate studies. The community is concerned about their use, given the differences between the various versions, which can lead to widely different results. This is a fundamental issue that needs to be discussed beyond the sphere of issue-oriented workshops.

Regarding models, there was an overall view that much work needs to be carried out to improve models, including the coupling between submodels representing the various Earth subsystems involved. This is crucial to improving the relationship between model outputs and observations so that a better understanding of the coupling and physics involved can be reached, for example, regarding the effect of ozone-related atmospheric processes on ocean circulation and carbon uptake.

Given the climate system's intrinsic variability, the workshop emphasized that using models to establish causal links between stratospheric ozone changes and tropospheric climate changes (e.g., trends) must be based on the use of ensemble simulations. While this approach is standard practice, there is further scope for work with larger numbers of ensemble members, as well as multimodel ensembles, to ensure results are indeed robust.

The workshop methodology provided an optimal environment for the exchange of views and debate about future research directions. Active participation of early career scientists and Ph.D. students provided new perspectives, views, and concerns to this debate.