WCRP Special Workshop on Climatic Effects of Ozone Depletion in the Southern Hemisphere:
Assessing the evidence and identifying Gaps in the current knowledge.
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**Introduction**

A WCRP Special Workshop on the ‘Climatic Effects of Ozone Depletion in the Southern Hemisphere: Assessing the evidence and identifying gaps in the current knowledge’, was convened at the Pontificia Universidad Católica Argentina, Buenos Aires, Argentina, from 25 February to 1 March, 2013. The workshop aims were to discuss our current understanding of Southern Hemisphere ozone depletion, in particular high latitude ozone depletion, its impacts on hemispheric climate and relative role with respect to greenhouse gas (GHG) induced climate changes. Discussions were initiated from results published in the last 2010 UNEP/WMO Scientific Assessment of Ozone Depletion and research published since. The workshop was supported by WCRP, the Agencia Nacional de Promoción Científica y Técnica (Argentina), the National Science Foundation (USA), NASA (USA) and the Pontificia Universidad Católica Argentina.

The main conclusions from the last Ozone Assessment, relevant to the workshop topics, can be summarized as follows:

1. There is new and stronger evidence for radiative and dynamical links between stratospheric change and specific surface climate changes.
2. Changes in stratospheric ozone, water vapour and aerosols all radiatively affect surface temperature.
3. Observations and model simulations show that the Antarctic ozone hole caused much of the observed southward shift of the Southern Hemisphere mid-latitude tropospheric jet during summer since 1980.
4. This southward shift has been linked to a range of observed climate trends in the Southern Hemisphere mid- and high latitudes during summer.
5. The influence of stratospheric changes on climate will continue even after ozone is no longer affected by emissions of ozone depleting substances.
6. Future recovery of the Antarctic ozone hole and increases in GHGs are expected to have opposing effects on the Southern Hemisphere mid-latitude jet.

**Workshop aims**

There was overall consensus in the stratospheric and climate communities that the current state of our understanding of Southern Hemisphere ozone had to be thoroughly evaluated and discussed in order to consolidate our views on the issues at hand. This was necessary to identify future research needs, both in light of the expected ozone layer recovery over the coming decades and ongoing climate changes being driven by sustained increases in greenhouse gases and other environmental processes, such as 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 the SPARC, CLIVAR and CLiC communities.

The driving questions of the workshop were:
1. How well do we understand the mechanisms relating Antarctic ozone loss to tropospheric climate in the Southern Hemisphere?
2. How will greenhouse gas increases and ozone depletion/recovery interact in future, and what will their impacts be on the polar vortex and on tropospheric climate?
3. What don’t we know, and what observing or research programs need to be undertaken?

In order to foster an environment for the much required exchange of ideas and interdisciplinary interaction, the Scientific Organizing Committee (Gareth Marshall, Thando Ndarana, Paul Newman, Manuel Pulido, Marilyn Raphael, Gianluca Redaelli, James Renwick, Robyn Schofield, David Thompson, Anne Thompson, Darryn Waugh, Shigeo Yoden, with Alan O’Neill and Pablo Canziani co-chairs) determined that the workshop dynamics should return to the historical roots of scientific meetings, following the concept of the famed early 20th Century Solvay Conferences. A strong emphasis was thus placed on rigorous discussion after each invited keynote presentation. The oral sessions were organized around specific topics:

I Stratospheric ozone variability and impact on climate
II Processes I: tropospheric climate and weather events
III Processes II: cryosphere, ocean circulation and carbon uptake
IV Modelling and predictions

For each topic, two or 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 tended to start within the keynote speaker presentations, leading to excellent results. The session chairs did a wonderful job of conducting the debates, while session rapporteurs took note of all proceedings.

Close to 50 participants from Australia, New Zealand, South Africa, USA, France, Germany, Italy, Russia, United Kingdom, Japan and Argentina attended the workshop. The keynote speakers were:

Session I: Sophie Godin, Darryn Waugh, Steve Rintoul (rapporteur: Peter Braesicke)
Session II: Edwin Gerber, Ryan Fogt (rapporteur: Ulrike Langematz)
Session III: Marilyn Raphael, Gareth Marshall, Wenju Cai (rapporteur: Darryn Waugh)
Session IV: Michael Sigmond, Nathan Gillett (rapporteur: James Renwick)

Research presentations were facilitated through poster sessions, held in an adjoining room, where coffee breaks and food were served for extended viewing. Over 30 posters were presented and displayed for the duration of the workshop. PDF versions of the posters presented can be viewed at:
Furthermore, a special session, chaired by early career scientists and PhD students, was held before the concluding session. During this session they presented and discussed early career perspectives on the topics discussed, as well as the future of the field. These perspectives are also reported below.

During the final session the rapporteurs presented summaries of each session. The final conclusions of the workshop were also actively discussed during this final plenary session, providing further interesting insights by allowing all different aspects to be viewed together.

**Main Workshop Conclusions**

**Session I: Stratospheric ozone variability and impact on climate**

**State of Knowledge**

*Ozone observations and modelling:*

- 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 in the 2050-2070 period.
- 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 stratospheric cooling. Both of these effects are driven by increasing levels of GHGs.

*SH climate:*

- There have been large changes in the SH summer climate over the last thirty years, from the surface all the way through to the stratosphere, and from Polar Regions to the sub-tropics.
- 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 and autumn.
- Other important changes in climate, which appear to be ozone driven, have been noted, in particular: (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 mid-latitude drying and mid- to high-latitude moistening observed in the Southern Hemisphere, 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 natural variability of the SH extratropical summer climate.

The cause of the recent positive trend in the SAM during austral autumn is not currently understood and may simply be the result of natural climate 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 warming of the Southern Hemisphere, SAM-related past trends in summer climate will likely weaken, and maybe even reverse, contingent on the extent of changes in GHG forcing.

Impacts on the SH Ocean

The wind stress curl is changing, with the zero line shifting poleward, which induces an intensification of the super gyre.

Observations support this intensification (ocean temperature trends are consistent from 1960-2007).

The position of the tropospheric jet 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 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, but these are not yet understood. A key necessity for reducing uncertainty is to improve our understanding of the tropospheric variability within models for a given stratospheric ozone perturbation.

Future Research Questions

Can we prioritize observations? On what sampling rates do we need the different observations: sub-daily, daily, weekly, monthly? Do we need more ocean measurements?

Are there coherent changes in all quantities in the Earth system?

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 do?

What will the relative roles of ozone and GHGs be in future?

Linearity of the response to GHG and ODS changes: how linear/non-linear and uncorrelated/synergistic is the atmospheric response to their changes?

How do we define the Hadley Cell?

Can we trust reanalysis products? How should we tackle variability and trend studies 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-Bellingshausen Seas low (ABSL). A minority of climate models suggest that ozone depletion has contributed to the deepening of the ABSL.
- Although the SAM is a hemispheric-scale mode of variability, its impact varies significantly at the regional level.
- Predominant spatial patterns in the relationship between the SAM and elements of the Southern Hemisphere surface climate exist, but can reverse sign on decadal time scales. Such sign changes appear to be due to internal climate variability, which in particular could be related to the phase and amplitude of planetary wave-3 over the Southern Ocean.
- This has implications for identifying a robust methodology for using the Antarctic ice core record to generate a proxy of the SAM, and on the level of certainty with which we can ascribe future projections of Antarctic climate and related predictions of sea level rise.
- In future, there are likely to be opposite SAM trends in austral summer (negative) compared to other seasons (positive). This may lead to increased summer melting for regions with a predominant negative SAM temperature relationship (East Antarctica), while over the Antarctic Peninsula there is likely to be greater winter accumulation.

Future Research Questions

- What is the natural variability of SAM? What are the causes for SAM trends in austral autumn?
- What is causing the variability/deepening trend of the ABSL? Is there a possible contribution of asymmetric modes of variability?
- How do zonal mean ozone asymmetries affect climate?
- There is a need for further regional variability and trend studies to better assess the climate response to ozone forcing.

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 - there are large regions of significant increase and significant decrease. The causes of the changes in sea ice extent 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 Amundsen Sea Low, as well as the strength and polarity of the SAM.
- Although observations of sea ice extent indicate that Antarctic sea ice extent has been increasing, all available model studies of 20th century climate simulate a decrease. This includes models that explicitly simulate stratospheric ozone
depletion, which also indicate that stratospheric ozone depletion should have driven a hemispheric total sea ice extent decrease.

- Observed changes in the Southern Ocean have been linked to changes in near surface winds. These changes include the sub-tropical super gyre, the meridional overturning circulation and the ocean becoming a less effective sink of CO2.
- Links to SAM: the mixed layer depth response to the SAM shows zonal asymmetry.

**Future Research Questions**

- What is the cause of the discrepancy in sea-ice trends between observations and models over the 20th century? Are differences due to model deficiencies or unknown processes affecting sea ice variability?
- What is the intrinsic model variability of ice and ice core properties? What are the implications when this variability is simulated?
- How will the ocean circulation and carbon uptake evolve as ozone recovers?
- Where is the heat derived to support ocean heat content changes associated with ocean circulation changes induced by wind stress?
- How will the ocean circulation and wind changes affect carbon uptake?

**Session IV: Modelling and predictions**

**State of Knowledge**

- Models show that the relative role of ozone and GHGs in forcing past climate trends, particularly of the SAM, varies seasonally, while being comparable in the annual mean.
- A bias remains in the simulation of the mid-latitude jet position when compared to reanalysis data. The bias in jet latitude appears to be positively correlated with the size of the simulated jet shift in response to ozone and GHG depletion. The future evolution of jet trends remains unclear, and depends on the relative role of ozone vs. 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 high vertical resolution in the lower stratosphere compared to models with low-top and low 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 CMIP5 models probably have high enough stratospheric resolution to resolve this response.
- Zonal mean ozone is usually prescribed in models, but ozone exhibits zonal asymmetry in spring when the ozone hole is often centred 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.
The stratospheric temperature response varies by a factor of two or more over the pole for a given ozone forcing, adding to the spread of model responses in the troposphere.

Climate models consistently fail to reproduce Antarctic sea-ice trends. This is probably caused by the insufficient representation of processes related to sea-ice formation and ocean-atmosphere interactions. Furthermore, the contribution of Antarctic ozone depletion 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

- How important is the representation of natural variability in models? How do we improve tropospheric variability in models?
- What are the mechanisms for stratosphere-troposphere coupling? Which mechanisms need to be included in models?
- What is the cause of the bias in mid-latitude jet latitude?
- How important is simulated natural variability and what is its contribution compared to ozone and GHG forcing? Do we need to better differentiate long-term trends from seasonal to interannual variability when analysing model outputs?
- How well do the models represent the 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?
- 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?
- 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?
- What are the heat sources causing the surface warming pattern and do the models capture them?
- Models disagree with sea-ice observations. Why has total Antarctic sea-ice extent increased and why don’t current models capture this? What should we do to solve this major issue? For example, does freshwater input play a major role? How important is stratospheric resolution and ocean-atmosphere coupling for sea-ice modelling?
- How important is stratospheric resolution for sea-ice modelling?
- The coupling between the important Earth systems (atmosphere, ocean, land and cryosphere) remains a major modelling challenge.

Early Career Scientists and PhD Students Special Session

The young scientists attending the workshop met to discuss what, in their view, were the most relevant topics driving research development. Their foremost concern was how they, as early career scientists, could progress their careers...
while continuing interesting and relevant science. Major concerns in this area were model and instrument development, and the lack of high-impact publications that come with this area of research. They did, however, recognise the importance of relevant and frequent observations. The broad issues raised by the early career scientists were as follows:

**Observations**
They recognised the need for a robust global observational network, which has research-relevant measurements (not only ozone, but also precipitation and other variables). Particular care should be taken regarding the timescales on which these observations are made, for instance, surface wind observations over the ocean do not capture many high frequency variations - ideally these observations need to be made on sub-daily timescales. They also noted that more reanalysis data sets could be output at higher frequency, and more inter-comparison of such reanalyses could be implemented so that issues such as trends in reanalyses can be better constrained.

There was a general consensus that a reduction in the observational uncertainty associated ozone measurements is needed, and that this would lead to a better and more consistent implementation of ozone fields in model comparison projects. Specifically, the use of a zonally symmetric stratospheric ozone data set may not be sufficient for the detection and attribution of surface climate change and variability.

**Physical Understanding**
It was recognised that there was a need to revisit the fundamental dynamics of some models (*i.e.* the dynamical cores) instead of continuously adding and expanding on current models. This may allow for less ‘tuning’, and a better understanding of currently parameterized processes.

As a community, the early career scientists felt that to further research on ozone-related topics, a zonally asymmetric view must be adopted, both in terms of the evolution of stratospheric ozone and the corresponding surface response. This may involve employing new (or less used) diagnostics other than the SAM. They also note that the use of the SAM can be misleading, both in terms of its trend and variability. The need to focus on the seasonal response is of particular importance, especially over the March-May period.

Finally, the issue of coupling in models was raised. They noted that testing coupling mechanisms at all scales, from the large-scale, such as between the stratosphere and troposphere, down to the small-scale, is important. They concluded by noting that the co-variability between different climate systems is key to understanding the tropospheric circulation response to stratospheric ozone changes.

**On Communication and Interdisciplinary Research**
The importance of framing relevant scientific issues was raised, not just to policy makers, but also to us as an atmospheric community. This will help focus research, as well as improve chances of obtaining funding.

Of particular importance was the necessity of networking, in terms of developing cross-disciplinary research (i.e. oceanographers talking with atmospheric scientists, or modellers talking with observational scientists). This will also help make the community aware of older or less well-known studies, and prevent unnecessary duplication of such studies. They also mentioned it may also help to have a central location with relevant links to different observational or reanalysis data sets.

**Concluding Remarks**

This workshop provided a space for solid scientific discussion and exchange of ideas. It permitted a thorough analysis of our current understanding of the coupling between ozone depletion and SH surface climate. The discussions resulted in a large number of issues that need to be addressed, both from the analysis of observations and from modelling, preferably in a joint approach. The issues at hand require strong interdisciplinary interaction to provide appropriate answers.

One issue that came up frequently refers to reanalysis - their quality and applicability to use in climate studies. The community is concerned about their use, given the differences observed between the various versions, which can lead to widely different results depending on the aim of the study. This is a particularly crucial 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 sub-models that represent the various Earth sub-systems involved. This is crucial to improving the relationship between model outputs and observations so that we can better understand the coupling and physics involved, for example, in understanding the effect of ozone-related atmospheric processes on ocean circulation and, in particular, 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. Though such an approach is now standard practice, there is further scope for work with larger numbers of ensemble members, as well as multi-model ensembles, to ensure that results are indeed robust.

The workshop structure, by returning to the roots of scientific debate and discussion following the concept of the original Solvay Conferences, provided an optimal environment for the exchange of views and debate about future research
directions. Furthermore, the active participation of early career scientists and PhD students - thanks to the support received from WCRP, NSF and NASA - provided new perspectives, views and concerns to this debate. In addition, the poster session provided both an opportunity for the presentation of current research and an informal atmosphere for sustained exchanges during coffee, lunch breaks and even at the end of the day - exchanges that made an essential contribution to the aims, spirit and outcomes of the workshop.