A. Project Information

Title: The impact of the ozone hole on the climate of the Southern Hemisphere
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
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B. Overview of the 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?

The numerical simulations for which we seek support here are designed to help us answer this question. In so doing we will be better prepared to maximize the learning experience represented by the future healing of the ozone hole. The problem presents a fascinating intellectual and modeling challenge involving interdisciplinary study of the coupling of the stratosphere, troposphere and ocean; coupling of chemistry, radiation and dynamics in the stratosphere; coupling of the ocean, ice and atmosphere at the earth's surface; the coupling of the carbon cycle to ocean dynamics.

To tackle this problem an interdisciplinary team of researchers from MIT (John Marshall, Alan Plumb and Susan Solomon), Columbia University (Lorenzo Polvani and Gabriel Chiodo), Johns Hopkins University (Darryn Waugh, Tom Haine and Anand Gnanadesikan) and NCAR (Marika Holland, Laura Landrum, and Doug Kinnison) have been funded by NSF. This is an application for computer time on Cheyenne over a **1.5 year** period during which time key numerical experiments that are at the heart of our project will be carried out. It extends our initial allocation of 3.2M core hours granted in October 2013 and 8.3M core ours granted in March 2015. We have currently used **97%** of this allocation.

C. Science Objectives

Models will be deployed to explore the mechanisms, impacts and indicators of the Antarctic stratospheric ozone hole and its recovery on the climate of the atmosphere-ocean-ice- carbon system. Our numerical experiments are designed to explore the following three themes:

A. the coupling between the stratosphere and the rest of the climate system induced by ozone perturbations
B. resulting changes in ocean circulation, ice-cover, heat and carbon uptake, and ocean biogeochemistry
C. the impacts and observable indicators of the ozone hole on the global climate.

Our approach involves integration of coupled atmosphere-seaice-ocean models in which perturbations to stratospheric ozone concentrations are introduced and the resulting response of the climate studied.

D. Computational Experiments and Resource Requirements

Computational Experiments

• Numerical Approach

A range of models will be deployed in the project because model climates and their response to anthropogenic forcing, and particularly ozone-hole forcing, are model dependent. The models we propose to use for this computational allocation announcement are:

CESM1 (WACCM4): The Community Earth System Model **(CESM)** version 1**,** Whole Atmosphere Community Climate Model, version (WACCM) version 4. This is a state-of-the-art climate model, which in addition to the common atmosphere, land, ocean and sea-ice components, includes fully interactive atmospheric chemistry (*Marsh et al*., 2013). In this proposed work, we will designate this version as **CESM1 (WA)** and is based on **CAM4** physics. Such a model allows us to address highly complex questions, such as how increasing GHGs interact with ozone recovery, or how the non-zonal nature of the SH stratospheric ozone hole affects the climate system below, particularly when a coupled ocean response is included. CESM1 (WA) can also be run in a "specified chemistry" (**SC)** mode by supplying ozone and upper atmosphere heating rates from a previous CESM1 (WA) simulation. This version of the model is designated as **CESM1 (SC-WA).** Both approaches are used in this proposed work.

CESM1 (LE): The CESM1 large ensemble (**LE**) version, standard ~1-degree resolution is based on **CAM5** physics and is run in a specified chemistry mode. This model is part of a large ensemble project at NCAR. This proposed work would utilize the control simulation from this LE effort.

CESM2 (WACCM6): This version is an update to CESM1 (WACCM) using **CAM6** physics and enhanced chemistry. It will be released as community model by Spring/Summer 2017. Details on the updates and improvements to this model can be found at: http://www.cesm.ucar.edu/models/cesm2.0/. This version of the model is designated below as **CESM2 (WA).**

MITgcm: The MIT General Circulation model is a widely-used modeling infrastructure developed at MIT for the study of the role of the ocean, ice and biogeochemical cycles in the coupled climate. John Marshall is the leader of the MITgcm modeling group, with a particular interest and expertise in ocean circulation and its coupling to other parts of the climate system.

• Computational Experiments

The computational resources request (see summary table below) is divided up into four connected, but unique experiments aimed at examining the impact of Antarctic stratospheric ozone depletion on tropospheric climate:

1. Constrained Ocean

The surface climate response to Southern Annular Mode (SAM) wind variability differs greatly across climate models. *Kostov et al.* (2016) suggest that this is due in part to the simulated ocean climatology and more specifically to how changing ocean circulation acts on a biased sub-surface vertical temperature gradient to influence the upwelling of heat. We propose to further explore this hypothesis with a set of CESM1 simulations in which the high latitude Southern Ocean is partially constrained by nudging the sub-surface temperature and salinity towards observations. Through comparisons with existing fully coupled CESM1 simulations, we will then be able to assess how the influence of SAM variability differs depending on the ocean vertical stratification. These experiments will require multiple centuries of integration to determine the most effective experimental design, to provide model spin up, and to allow enough years for robust statistics. We will use the CESM Large Ensemble **(CESM1-LE)** code base because of the large number of existing simulations that will provide control conditions for this study.

2. Antarctic Ozone Loss and Surface Climate Predictability.

The ozone hole's influence on the circulation patterns of the southern hemisphere has been established, and in the proposed work we will seek to quantify the extent to which ozone information can improve predictions of surface climate in regions such as Australia and South America (*Bandoro et al*., 2014). We plan to first conduct a series of test runs (2005-2015) of heterogeneous chemistry in **CESM2 (WA),** from the tropopause to the 10 hPa level, to ensure that the representations of cirrus clouds, liquid sulfate aerosols, and PSCs in the model yield realistic ozone depletion profiles when compared with observations, under both volcanic and non-volcanic conditions. We propose to then run an ensemble of 10 runs under low concentrations of ozone depleting substances (1960-1975), and compare these to an ensemble of 10 runs under high concentrations of ozone depleting substances (1995-2020). This will provide a rich database for quantitative analysis of predictability. For example, one approach will be to use about 6 runs to characterize the seasonality and structure of tropospheric climate changes in WACCM (including temperature and rainfall patterns), and then examine whether the climate changes in target locations in Australia, South America, etc. within the other four can be skillfully predicted using that information. A key goal will be to characterize the latitudinal extent to which predictability is expected based on WACCM, which will then be used to guide examination and comparison with observations.

3. Climate Sensitivity to Prescribed Ozone

3a. Spatial and Temporal. Recently, it has been shown that while interactive ozone chemistry does not affect the modeled surface temperature response to increased GHG levels, it significantly reduces the Southern Hemispheric circulation response. The reported ozone changes in these WACCM integrations occur in the absence of changes in Ozone Depleting Substances (ODS), and thus represent a feedback (*Chiodo and Polvani*, 2016). This work suggests that more effort is needed in producing CO_2-scenario specific ozone data sets from models with interactive ozone chemistry. An important follow-up activity is needed to investigate whether imposing the ozone changes induced by increased CO_2 levels in a model without chemistry would capture the effects of ozone chemistry on the SH jet. Preliminary results reveal that imposing the *zonal mean* ozone climatology obtained from the 4xCO_2 runs from **CESM1 (WA)** in the specified chemistry version of **CESM1 (SC-WA)** would not fully capture the SH jet response. This points at a possible role of ozone asymmetries. Therefore, the scenarios list in the **Summary Table** will examine a combination of the specifications options for ozone under a 4xCO_2 forcing.

3b. Ozone Depletion Substances (ODS) Sensitivity. So far, the impact of ozone chemistry has been investigated using 1850 levels of ODS (e.g., *Chiodo and Polvani*, 2016). It is conceivable that the pattern of ozone response to 4xCO_2 - and sign of the feedback - could significantly change in present-day ODS concentrations. Indications of a possible basic-state dependency of the chemistry feedback also come from the non-linearity of precipitation trends (*Marvel et al.*, 2016). To complete this work, we will first need to run a **CESM1 (WA)** version with 4xCO_2 under present-day conditions. The ozone taken from this simulation will then be used in a **CESM1 (SC-WA)** simulation. This simulation will be compared to an additional CESM1 (SC-WA) simulation for 1xCO_2 under present day conditions.

3c. Ozone Forecast (FC) Sensitivity. One final question to be addressed within this section is the importance of the time-resolution of the ozone forcing in simulating the effects of the Montreal Protocol (**MP**) on 21st century ozone recovery. Specifying daily ozone concentrations was found to be key for proper simulation of the Antarctic ozone hole and the tropospheric circulation response (*Neely et al.,* 2014). However, the impact of temporal resolution of the ozone forcing on the simulation of the effects of ozone recovery has not been explored yet. The **Summary Table** show two sets of **CESM1 (SC-WA)** ensembles to examine this question. These simulations will be compared to two additional CESM1 (SC-WA) simulations where the specified ozone is derived from a Fixed year 2000 ODS (**FixODS**) condition. Contrasting these simulations will address the importance of time resolution of ozone forcing in predicting the effects of ozone recovery on climate.

4. Ocean Response to Impulsive Wind Changes. A key insight stemming from the FESD project thus far is that the response of the ocean to an impulsive wind change is a two-timescale problem. An initial rapid (weeks and months) Ekman-layer process stemming from a strengthened zonal wind stress (resulting in cooling) is followed by a slow (years to decades) warming process as warm waters from beneath are upwelled to the surface. The slow timescale response involves ocean dynamics mediated by the strong mesoscale eddy field in the Southern Ocean. These are currently parameterized rather than resolved in climate models. The numerical experiments we propose to carry out involve highly resolved unstable jets (analogues of the Antarctic Circumpolar Current - ACC) in the presence of seasonal sea ice. They are designed to address the two-timescale problem in an idealized setting.

The eddying channel has a domain size of 1200 km x 3200 km x 4 km with a horizontal resolution of 4km yielding a grid-point number of 300 x 800 x 50. A zonally-symmetric and re-entrant channel with a continent shelf at the Southern boundary will be run with Temperature and Salinity relaxation at the Northern boundary. Seaice will be included (both dynamics and thermodynamics) with a KPP vertical mixing scheme. The model is forced using bulk-formulae.

Experiments shown in the **Summary Table** will examine **sensitivity experiments** by modifying north boundary conditions, surface forcing, and model internal parameters at 4 km resolution. Several **higher horizontal** resolution experiments (2x2 km) are proposed to test and verify model convergence with resolution and time step. In addition, multiple configurations of the **non-zonally uniform bathymetry** (e.g., Antarctic peninsula, ridges or embayment at Southern edge) which require a larger domain (x2) in zonal direction, will be examined.

- ### Code Performance

CESM1 (LE): This version of the model has been run extensively (*Kay et al*., 2014), therefore, core hours per simulation year, HPSS and project space needs are well known. See summary table below.

CESM1 (WA): The interactive version of WACCM was run for CMIP5 (*Marsh et al*., 2013). The SC version has also been used in multiple scientific publications (e.g., *Neely et al*., 2014). The core hours per simulation year, HPSS and project space needs are well known. See summary table below.

CESM2 (WACCM): The 2-degree version will be used in this study. The timings for CESM2 (WACCM) are only currently available for the 1-degree version. The one degree version costs ~23K core hours per year on Yellowstone. We estimate the cost of the 2-degree version by dividing the cost of the 1-deg version by the resolution factor to get **5800 core hours / sim year**. Based on prior experience of running 2-degree CESM1 (WA) we estimate **200Gb per model year of HPSS** will be needed. We also assume that the project space needed for analysis will be 10% of this total (**20Gb/year**).

MITgcm: The large computational domain (2800x800 in the horizontal by 50 vertical levels), required in the channel configuration with MITgcm, including its seaice component (both thermodynamics and dynamics seaice) demands substantial computational resources. Used in hydrostatic mode, the MITgcm scales well on thousands of processors as long as the tile size (individual processor domain fraction) remains large enough (generally around 10K grid points). This is clearly the case in the channel setup on Yellowstone computers, running on 1,400 cores with a tile size of 40x40x50 vertical levels. The HPSS and project space is different for each experiment/simulation type based on resolution and variable selection. See summary table.

Resource Requirements

SUMMARY: To facilitate carrying out and analysis of the proposed experiments, we request **94152K** core processor hours on **Cheyenne** and **~260TB** of HPSS storage and **~35Tb** of additional project space (on "GLADE" disks). Much of the proposed work involves comparative analysis of multiple simulations with fully resolved 3-D fields. The FESD project currently has 30 Tb of project space. We will use this "30Tb" of project space for reference simulations that will be compared to the new simulation results under this proposed work. We will work with CISL to maximize our data analysis across multiple users, while minimizing the project space used during the remaining period of this proposal.

JUSTIFICATION OF ENSEMBLE MEMBERS: In all experiments discussed above and summarized in the table below, we asked for multiple ensemble members per experiment simulations (or perpetual simulations run out for >100 years). This use of ensemble members is justified by recent work of *Polvani et al*., "Stratospheric ozone depletion: the main driver of 20th Century atmospheric circulation change in the Southern Hemisphere, 2011; and *Kay et al*., "The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability", 2014. These studies highlighted the need to complete multiple ensemble members to detect climate signals in simulations with large variability in regions affected by ENSO and QBO.

DATA ANALYSIS NEEDS: There will be approximately 10 users total for each of the four projects described above. There will be data analysis needs, however we do not see any additional needs over the default 5000 core hours per user. Therefore, we request up to 10x5000 = **50K core hours** on data analysis machines (e.g., Caldera) for this work.

MULTI-YEAR PLAN: Our NSF FESD proposal was funded for 5 years. This is our third request for computing resources and we have 1.5 years remaining with the project. Our simulation plan is that these calculations will be carried out in the coming 1.5 years and so our request is for the remaining funding period.

Summary Table of Proposed Simulations

Experiment	Type / Details	Model Configuration	Sim period	# Sim Yrs	Mem-bers	Total Years	Core hours (Khr)	Proj. Space (Tb)	HPSS (Tb)
1) Constrained ocean	Pre-Industrial (PI) Control	CESM1 (LE)	1850	500	1x	500	**1150**	**0.5**	**5**
2) Antarctic O3 Loss and Surface Climate Predictability	Sensitivity to het chem.	CESM2-(WA)	2005-2015	10	10x	100	580	2	20
	High ODS	CESM2-(WA)	1995-2020	25	10x	250	1450	5	50
	Low ODS	CESM2-(WA)	1960-1975	15	10x	150	870	3	30
	Sub Total						**2900**	**10**	**100**
3) Climate Sensitivity to Prescribed Ozone (O_3). a) Spatial and temporal	$4xCO_2$, with 2D climatology (CLIM) O_3	CESM1 (SC-WA)	1850	200	1x	200	120	0.4	4
	$4xCO_2$, with 3D CLIM O_3	CESM1 (SC-WA)	1850	200	1x	200	120	0.4	4
	$4xCO_2$, with 2D transient (TRANS) O_3	CESM1 (SC-WA)	1850	200	1x	200	120	0.4	4
	$4xCO_2$, with 3D transient (TRANS) O_3	CESM1 (SC-WA)	1850	200	1x	200	120	0.4	4
b) ODS Sensitivity	$4xCO_2$, Present-Day ODS (PD-ODS)	CESM1 (WA)	2000	200	1x	200	240	0.8	8
	$4xCO_2$, with 3D O_3 from PD-ODS	CESM1 (SC-WA)	2000	200	1x	200	120	0.4	4
	$1xCO_2$, with 3D O_3 from PD-ODS	CESM1 (SC-WA)	2000	200	1x	200	120	0.4	4
c) Ozone Forecast (FC) Sensitivity	RCP4.5, monthly-3D-TRANS O_3	CESM1 (SC-WA)	2000-2100	100	3x	300	180	0.6	6
	RCP4.5, daily-3D-CLIM O_3	CESM1 (SC-WA)	2000-2100	100	3x	300	180	0.6	6
	RCP4.5, FixODS at 2000, monthly-3D-TRANS O_3	CESM1 (SC-WA)	2000-2100	100	3x	300	180	0.6	6
	RCP4.5, FixODS at 2000, daily-3D-TRANS O_3	CESM1 (SC-WA)	2000-2100	100	3x	300	180	0.6	6
	Sub Total						**1680**	**5.6**	**56**
4) Ocean response to impulsive wind change	Sensitivity Experiments	MITgcm(1)	2000	100	20x	2000	1152	3	30
	Higher Resolution	MITgcm(2)	2000	100	5x	500	2300	10	30
	Non-zonally uniform bathymetry.	MITgcm(3) 2km zonal	2000	100	20x	2000	2300	6	60
	Sub Total						**5752**	**19**	**100**
Total (Yellowstone)							11482		
Total (Cheyenne)	**Yellowstone*0.82**						**94152**	**35.1**	**261**

CESM1 (LE):	CAM5 Large Ensemble, ~1.0 deg, 26 levels.	2300 core hours/yr;	1Gb/yr project;	10Gb/yr HPSS
CESM1 (SC-WA):	WACCM4, ~2 deg, 66 levels,	600 core hours /yr;	2Gb/yr project;	20Gb/yr HPSS
CESM1 (WA):	WACCM4, ~2 deg, 66 levels, 60 species,	1200 core hours/yr;	4Gb /yr project;	40Gb/yr HPSS
CESM2 (WA):	WACCM6, ~2 deg, 70 levels, 228 species,	5800 core hours/yr;	20Gb/yr project;	200Gb/yr HPSS
MITgcm(1):	4x4km, 50 levels (300x800x50 grid-points)	562 core hours /yr;	1.5Gb/yr project;	15Gb/yr HPSS
MITgcm(2):	2x2km, 50 levels (600x1600x50 grid-points)	4600 core hours/yr;	20Gb/yr project;	60Gb/yr HPSS
MITgcm(3):	4x4km, 30 levels (600x800x50 grid-points)	1150 core hours/yr;	3Gb/yr project;	30Gb/yr HPSS

E. Data Management Plan.

Project members have extensive experience with shared modeling activities at NCAR, Columbia University, and MIT. All of this knowledge and experience will be harnessed by the project.

The specialized data produced by our project has a relatively short expected lifetime, as new developments and increased computational capability tend to make them obsolete within a few years. Therefore, there are no plans for long term archival (i.e., > 5 years). However, the capability will be maintained to re-run any numerical experiment and re-generate data that are requested after the project, provided the computational resources can be found. A subset of these results will be placed on the NCAR Earth System Grid for public use. This data subset will also meet the needs of most scientific journals who now request that any published results be made publically accessible.

In addition, if supported by CISL project space availablity, we would like to keep our project space (30 Tb current and 35Tb requested in this proposal) for one year after the completion of the Marshall et al. NSF FESD project. This will allow us to finish writing up scientific results for peer review.

Relevant policy statements are:

- CESM Experiment data shall be available to members of any CESM Working Group no later than six (6) months following the conclusion of the Experiment Simulation.
- CESM Experiment data shall become Public as soon as a scientific paper on the results has been submitted by the PIs who originated the model run or one year after the end of the simulation, whichever comes sooner.

F. Accomplishment Report.

Significant results made possible by CISL resources include:

(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). Numerical calculations involved taking coupled models and perturbing them with a 'step' perturbation to the prescribed ozone distribution in the model representing a perpetual ozone hole (but with a seasonal cycle).

(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:
  (a) increases in ozone column amounts
  (b) changes in the vertical profile of ozone concentration, and
  (c) 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

These calculations were carried out using WACCM.

(iii) While interactive ozone chemistry does not affect the modeled surface temperature response to increased GHG levels, it significantly reduces the Southern Hemispheric circulation response. The reported ozone changes in these WACCM integrations occur in the absence of changes in ODS, and thus represent an important feedback (*Chiodo and Polvani*, 2016).

More comprehensive reports on our 'Ozone and Climate' FESD project can be obtained here:
http://ozoneandclimate.squarespace.com/reports/
Seven graduate students and 4 postdoctoral students have been supported in part or in full on the project.

G. References.

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