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# Capturing the Stratosphere's Influence on Seasonal and Intraseasonal Predictability in a State-of-the-Art Navy Global Environmental Model (NAVGEM)

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## LONG-TERM GOALS

The long-term goals of this project are to tap the potential of an improved stratosphere and mesosphere for seasonal prediction by developing and testing new stratospheric and mesospheric modeling, prediction and data assimilation capabilities, all specifically designed to improve long-range prediction capabilities of the Navy Global Environmental Model (NAVGEM).

## OBJECTIVES

The overarching objective of this proposal is to gain an improved understanding of how the stratosphere and mesosphere in a state-of-the-art numerical weather prediction (NWP) system affect atmospheric prediction on time scales from days to months. To achieve this, our research focuses on the following scientific questions:

1. What are the fundamental dynamics and dominant physical coupling pathways governing the stratosphere-troposphere interaction that are most relevant for atmospheric prediction on time scales from days to months?
2. Which physical and dynamical processes in the forecast model are important in controlling this deep vertical coupling, and how sensitive is forecast skill to details in their numerical implementation?

## APPROACH

Our approach is guided by panel recommendations of WCRP (2008) and NAS (2010) to address knowledge gaps in our current understanding of coupled troposphere-stratosphere predictability:

R1. Models *must* extend to *at least* 0.01 hPa (~80 km altitude) with a full range of appropriate physical parameterizations, so as to properly predict stratospheric and mesospheric variability;
R2. Research should then focus on the extended system's ability to reproduce and delineate the poorly understood connections between stratospheric and tropospheric circulations.

***R1 Tasks***

To address R1, our project is progressively augmenting the NAVGEM SL forecast model and DAS to predict the integrated troposphere-stratosphere-mesosphere system, as outlined in tasks (a)-(e) below.

(a) SL model tests using additional vertical layers and resolution

(b) Improved radiative heating and cooling rates for the SL model's stratosphere and mesosphere

(c) Improved ozone and water vapor photochemisty for the upper stratosphere and mesosphere

(d) Parameterizations of subgrid-scale gravity-wave drag for the stratosphere and mesosphere

(e) Assimilation of stratospheric and mesospheric satellite observations

***R2 Tasks***

To address R2, we perform the following component tasks using the augmented NAVGEM model.

(a) Bias identification and parameterization correction/improvement

(b) Forecast-assimilation experiments supporting international research projects on predictability

(c) Realistic tropical QBO (quasi-biennial oscillation) and SAO (semiannual oscillation)

(d) Prediction of stratospheric sudden warmings (SSWs) and stratospheric NAM/SAM anomalies

(e) Tropospheric influences of stratospheric NAM/SAM anomalies

(f) Tropospheric coupling to the stratospheric QBO

## WORK COMPLETED

***R1 Tasks***. Very detailed reports on progress on these individual tasks was provided in last year's report, and so briefer updates to those progress reports are provided this year.

Major aspects of Task R1a were completed and published in the peer-reviewed scientific literature by Eckermann et al. (2014). This paper documented statistically significant reductions in NAVGEM model errors in the stratosphere though the use of an optimized hybrid sigma-p vertical coordinate. The sensitivity to vertical resolution was also investigated by McCormack et al. (2014), who found that accurate prediction of the quasi-biennial oscillation (QBO) of the tropical lower stratosphere required significant increases in model vertical resolution in the lower stratosphere.

Progress on Tasks R1b and R1c was achieved through the creation of a new T119L74 NAVGEM prototype extending to ~115 km altitude. We implemented and tested an initial lookup-table-based parameterization of exothermic chemical heating of the upper mesosphere based on output from the extended Whole Atmosphere Community Climate Model (WACCM-X). The scheme partially alleviated cold biases at uppermost model levels. Work also continued on tests of a new diurnal extension of the NRL linearized ozone photochemistry scheme in this same high-altitude NAVGEM system (Eckermann and McCormack 2014), which should reduce temperature biases at the stratopause and lower mesosphere when fully implemented and tuned.

Task R1d has been leveraged by work on a related ONR DRI to develop a new unified gravity-wave drag parameterization for NAVGEM. This work has led to immediate and significant reductions in

extratropical upper stratospheric temperature biases (Hogan et al. 2014b), and this year also led to the first simulation of a realistic QBO in the tropical lower stratosphere (McCormack et al. 2014).

Task R1e was completed via the peer-reviewed publication of Hoppel et al. (2013), which has documented the impacts of assimilation of upper atmosphere sounding (UAS) channel radiances acquired by the Special Sensor Microwave Imager/Sounder (SSMIS) on the operational F16, F17 and F18 satellites of the Defense Meteorological Satellite Program (DMSP). The work documented significantly reduced temperature biases and standard deviations in the stratosphere and mesosphere. The work also provided an additional capability to assimilated limb temperature retrievals from the SABER and MLS sensors on NASA research satellites.

## RESULTS

**R2 Tasks**. Progress on the R2a task proceeded along several lines. First, we documented a secular decrease in stratospheric temperatures in the NAVGEM SL dynamical core that was associated with small potential energy losses within the semi-Lagrangian semi-implicit (SLSI) dynamical core. This led to develop of an adiabatic correction formulation that identified and corrected these small mean temperature drops at each time step, leading to stable (rather than secularly increasing) stratospheric temperature biases that can be corrected via parameterization physics. Upper-level temperature increments from SSMIS channels (Task R1e) defined these mean temperature biases in the extratropics, and the gravity-wave drag scheme (Task R1d) was tuned to reduce these biases.

Progress in Task R2b was summarized in the peer-reviewed publication of Tripathi et al. (2014), which reviewed the impacts of a model stratosphere on predictability in global models of the international Stratospheric Network on Assessment of Predictability (SNAP) of the World Climate Research (http://www.sparcsnap.org/).

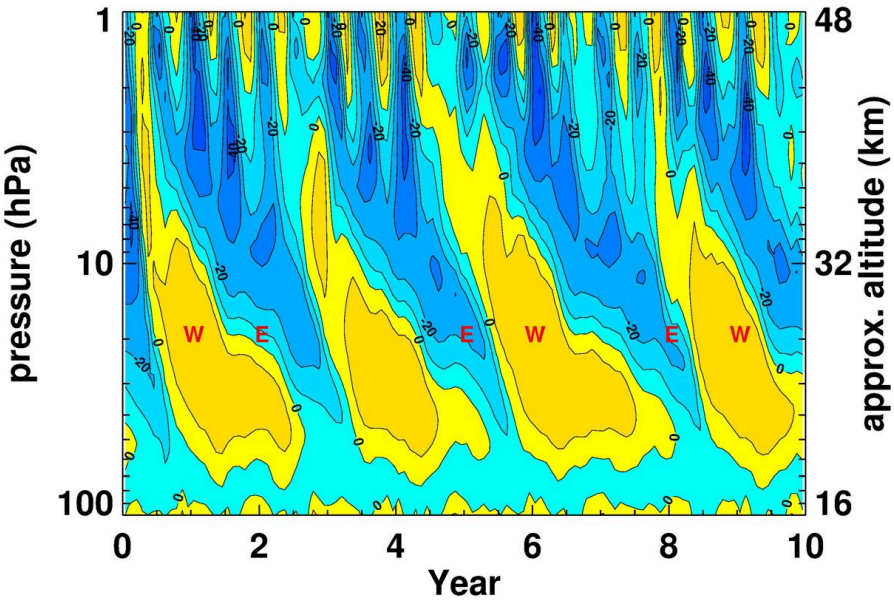


***Figure 1. Mean zonal winds (m s$^{-1}$, red/yellow is eastward, blue is westward) from 5$^o$S-5$^o$N from a 10-year nature run at T79L139 using stochastic gravity-wave drag parameterization with reduced vertical mixing and a new tropical wave source (McCormack et al. 2014). Note the quasi-two-year QBO-like wind oscillation in the lower stratosphere and the realistic SAO at higher altitudes.***

We made significant progress on Task R2c by adding tropical features to the gravity-wave drag parameterization and modifying other properties of the global model, work written up and submitted to the peer-reviewed scientific literature (McCormack et al. 2014). The necessary model changes to generate a realistic QBO were: (a) increasing vertical resolution in the stratosphere to ~500m; (b) producing a small tropical enhancement in parameterized gravity-wave momentum flux; (c) changing the dominant horizontal wavelength of the parameterized tropical gravity waves from 100 km to 500 km; (d) reducing the horizontal spectral diffusion in the stratosphere, and; (e) reducing vertical diffusive mixing in the stratosphere. In a 10-year T79L139 nature run, the model was able to reproduce without additional tuning a very realistic QBO in lower stratospheric tropical winds, with a realistic period of ~28 months and realistic descending easterly and westerly QBO shear zones, as shown in Figure 1. Furthermore, above these QBO winds the nature run also reproduced a realistic upper stratospheric semiannual oscillation (SAO) as well.

Aspects of Task R2d were completed with the peer-reviewed publication of Coy and Reynolds (2014). This work summarized the growth of leading singular vectors (SVs) in the stratosphere and how their growth accelerated or decelerated the evolution of the 2009 major stratospheric sudden warming. Ongoing work is studying the descent of these growing modes into the troposphere through deep descending anomalies in the northern annular mode (NAM), which addresses Task R2e. Physical mechanisms for stratospheric SV growth are being studied through identification of unstable potential vorticity gradients and growing particle trajectory divergences at SV epicenters. We are trying to understand and quantify these perturbation dynamics better in terms of Lyapunov exponents and lobe dynamics. We are also studying the global dynamics of these intense SV events in greater detail, using isentropic potential vorticity maps to study the three-dimensional dynamics of the wave breaking that seed early perturbation growth, as well as the fundamental dynamical mechanisms that initially support growth of these perturbations.

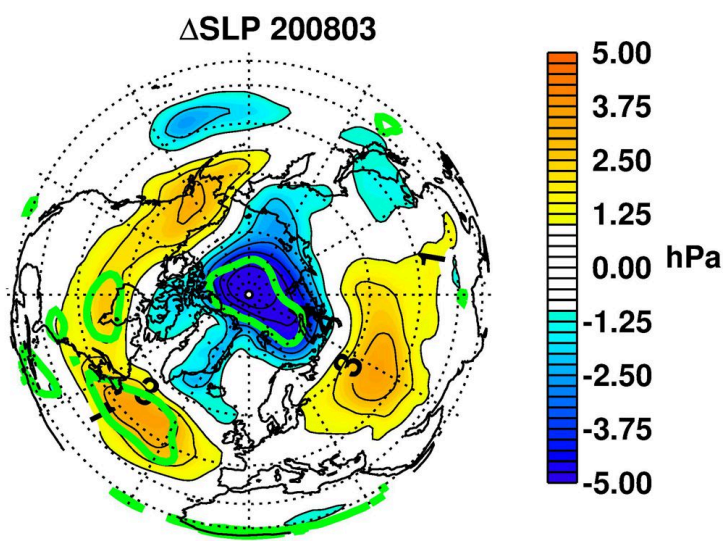


***Figure 2. Ensemble-mean Arctic sea-level pressure differences (hPa, see color bar on right) for March 2008 between QBO and non-QBO 120-day ensemble forecast model runs. Green contours enclose SLP contours that are significant at >99%.***

Aspects of Tasks R2e and R2f have been studied with the new self-generated QBO now in the model (see Figure 1), preliminary work also reported by McCormack et al. (2014). We performed ensembles of 120-day seasonal predictions during the boreal winter period of 2007-2008.

One set of ensembles used the forecast model with an ability to simulate the QBO as in Figure 1, while the other set of ensembles deactivated the tropical gravity-wave drag, so that the model produced no internal QBO or SAO.

In the ensemble runs containing the QBO, equatorial stratospheric winds were westerly throughout the winter, consistent with observations for the 2007-2008 winter. In the ensemble of runs without the QBO, weak easterly flow persisted in the equatorial stratosphere throughout the winter. Ensemble mean differences in sea level pressure (SLP) over the Arctic during March, plotted in Figure 2, show lower polar-cap SLP and higher mid-latitude SLP when the QBO is included in the model. Green contours in Figure 2 enclose regions where these SLP differences are statistically significant at the 99% confidence level. The results in Fig. 2 demonstrate that the westerly phase of the QBO acts to reinforce the positive high-latitude NAM teleconnection pattern throughout boreal winter that penetrates all the way to the surface. The result reveals a statistically significant coupling between NAM-like SLP anomalies in the Arctic and the QBO of the tropical stratosphere, which has also been derived from observations. Thus the model now incorporates a realistic tropical-extratropical teleconnection relevant for seasonal prediction.

## IMPACT/APPLICATIONS

The Oceanographer of the Navy (Naval Meteorology and Oceanography Command: CNMOC) has selected NAVGEM to be the Navy's bridging technology from its existing NWP capability at the time (NOGAPS) to a future Earth System Prediction Capability (ESPC) predicting the atmosphere seamlessly across time scales from days to decades. The improved NAVGEM seasonal prediction capabilities provided by this project are moving the Navy closer to a future operational ESPC generating ensemble forecasts on a continuum of time scales spanning weather and climate.

## TRANSITIONS

We transitioned a series of new code options to the NAVGEM "trunk" and "development" code repositories, including new L60 vertical layers, SSMIS UAS data assimilation code, adiabatic corrections, and unified gravity-wave drag parameterization code.

## RELATED PROJECTS

Doyle, J. D., and S. D. Eckermann, *The Boundary Paradox*, NRL 6.1 Accelerated Research Initiative, 1 October 2010-30 September 2015.

Eckermann, S. D, and collaborators, *New Approaches to the Parameterization of Gravity-Wave and Flow-Blocking Drag due to Unresolved Mesoscale Orography Guided by Mesoscale Model Predictability Research*, ONR Award Number: N0001411WX21220, 1 October 2011-30 September 2015.

Hoppel, K. W., *High Altitude Data Assimilation for NWP*, NRL 6.2 Work Unit, 1 October 2009-September 2013.

## REFERENCES

NAS (2010), Assessment of intraseasonal and interannual climate prediction and variability, Committee on Assessment of Intraseasonal to Interannual Climate Prediction and Predictability, National Research Council, The National Academies Press, 192pp (http://www.nap.edu/catalog.php?record_id=12878).

WCRP (2008), Position paper on seasonal prediction, First WCRP Seasonal Prediction Workshop, 4-7 June 2007, Barcelona, Spain, Report No. 3/2008, ICPO Publication No. 127, 23pp.

(http://www.wcrp-climate.org/documents/WCRP_SeasonalPrediction_PositionPaper_Feb2008.pdf).

## PUBLICATIONS

Coy, L., and C. A. Reynolds (2014), Singular vectors and their nonlinear evolution during the January 2009 stratospheric sudden warming, Quart. J. Roy. Meteorol. Soc., 140, 1013-1024, doi: 10.1002/qj.2181.

Eckermann, S. D., J. P. McCormack, J. Ma, T. F. Hogan, and K. A. Zawdie (2014), Stratospheric analysis and forecast errors using hybrid and sigma coordinates, Mon. Wea. Rev., 142, 476-485.

Eckermann, S. D. and J. P. McCormack (2014), Extension of linearized parameterizations of gas-phase stratospheric ozone photochemistry through the upper stratosphere, mesosphere and lower thermosphere, (paper in preparation).

Hogan, T. F., M. Liu, J. A. Ridout, M. S. Peng, T. R. Whitcomb, B. C. Ruston, C. A. Reynolds, S. D. Eckermann, J. R. Moskaitis, N. L. Baker, J. P. McCormack, K. C. Viner, J. G. McLay, M. K. Flatau, L. Xu, C. Chen, and S. W. Chang (2014a), The Navy Global Environmental Model, Oceanography, 27(3), 116--125, dx.doi.org/10.5670/oceanog.2014.73.

Hogan, T., M. Peng, N. Baker, C. Reynolds, B. Ruston, M. Liu, J. Ridout, S. Eckermann, J. Moskaitis, T. Whitcomb, K. Viner, J. McLay, P. Pauley, L. Xu., R. Langland, M. Flatau, J. McCormack, and S. Chang (2014), The Navy Global Environmental Model, NRL Review 2013, NRL/PU/3430--14-577, RN:14-1231-1938, June 2014, pp 138-140.

Hoppel, K. W., S. D. Eckermann, L. Coy, G. E. Nedoluha, D. R. Allen, S. D. Swadley, and N. L. Baker (2013), Evaluation of SSMIS upper atmosphere sounding channels for high-altitude data assimilation, Mon. Wea. Rev., 141, 3314-3330.

McCormack, J. P., S. D. Eckermann, and T. F. Hogan (2014), Generation of a quasi-biennial oscillation in an NWP model using a stochastic gravity wave drag parameterization, Mon. Wea. Rev., submitted.

Tripathi, O. P., M. Baldwin, A. Charlton-Perez, M. Charron, S. D. Eckermann, E. Gerbere, G. Harrison, D. Jackson, B.-M. Kim, Y. Kuroda, A. Lang, C. Lee, S. Mahmood, R. Mizuta, G. Roff, M. Sigmond, and S.-W. Son (2014), Review: The predictability of the extra-tropical stratosphere and its impacts on the skill of tropospheric forecasts, Quart. J. Roy. Meteor. Soc., in press.

**HONORS/AWARDS/PRIZES**

1. Stephen Eckermann received the 2013 Sigma-Xi Award for Applied Science from the NRL Edison Chapter for foundational contributions to the Navy's high-altitude forecasting and analysis capabilities.
2. Stephen Eckermann was awarded the 2013 American Meteorological Society's Editor's Award of the Journal of the Atmospheric Sciences for "thorough and detailed reviews with well-informed, well-posed and carefully argued questions for authors": see http://www.ametsoc.org/awards/2013awardrecipients.pdf
3. Stephen Eckermann was one of ten NRL awardees of the Navy Acquisition Excellence Award for Technology Transition, for the Navy Global Environmental Model (NAVGEM): see http://www.nrl.navy.mil/media/news-releases/2013/nrl-receives-navy-acquisition-excellence-award-for-global-weather-prediction-model