Final Report

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Title: "Dynamics of Arctic and Sub-Arctic Climate and Atmospheric Circulation: Diagnosis of Mechanisms and Biases Using Data Assimilation"

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Objectives:

The overall goal of work performed under this grant is to enhance understanding of simulations of present-day climate and greenhouse gas-induced climate change. The examination of present-day climate also includes diagnostic intercomparison of model simulations and observed mean climate and climate variability using reanalysis and satellite datasets. Enhanced understanding is desirable 1) as a prerequisite for improving simulations; 2) for assessing the credibility of model simulations and their usefulness as tools for decision support; and 3) as a means to identify robust behaviors which commonly occur over a wide range of models, and may yield insights regarding the dominant physical mechanisms which determine mean climate and produce climate change. A further objective is to investigate the use of data assimilation as a means for examining and correcting model biases. Our primary focus is on the Arctic, but the scope of the work was expanded to include the global climate system.

Activities and Results:

Research activities fall into five main areas:

1) Role of diabatic cooling anomalies in generating ENSO circulation anomalies:

Research on teleconnections of El Nino/Southern Oscillation (ENSO) events was conducted as a completion of the research tasks of the last funding cycle, which emphasized the representation of modes of natural variability in climate model simulations. ENSO teleconnections were originally regarded as a single train of stationary Rossby waves generated by a compact region of enhanced (reduced for cold events) equatorial convective heating. While more recent studies have greatly enhanced this dynamical picture, the dominant conceptual model of the teleconnections still identifies this monopolar convective heat source as the ultimate driver of the teleconnections.

Our results suggest that the regions of diabatic cooling which surround the equatorial Pacific heating anomaly during warm phase ENSO events are just as important as the equatorial heating in producing teleconnections. In simulations with a steady linear diagnostic model, heating and cooling anomalies derived from the NCEP/NCAR reanalysis make comparable contributions to the upper-level eddy height anomalies for ENSO events. In particular, remote cooling is just as important as local heating in determining the central longitude of the subtropical El Nino anticyclones

The same diagnosis was performed on model output from the NASA Seasonal to Interannual Prediction Project. Despite some differences between the modeled and observed circulations, heating and cooling played essentially the same role for the modeled ENSO as for the ENSO anomalies in the reanalysis. Thus the paper carries out the diagnostic strategy outlined in the proposal, in which model and reanalysis data are compared not only in terms of their structures, but in terms of the underlying dynamics responsible for the structure.

In the course of the above research, it became apparent that the tendency of the steady linear model to produce solutions with weak amplitude is a serious liability. The usual explanation for this deficiency is that linear models require large amounts of damping in order to prevent the solutions from being corrupted by resonance. A time-marching primitive equation model was developed in part to circumvent the need for such dissipation. In this modeling framework we examine solutions at an early stage before they are overwhelmed by dynamical instabilities and/or resonant interactions. These models can, moreover, offer insight into the time evolution of circulation anomalies. Finally, the model can be run with only modest computer resources, since the time-marching model sidesteps the memory issues involved in solving the matrix-based steady linear model. The model was adapted from the dynamical core of NASA's ARIES AGCM, obtained from Dr. Max Suarez, NASA/GSFC.

2) Arctic sea ice and atmospheric circulation in the NCAR climate model:

This subproject examines the dynamics of Arctic atmospheric circulation and the role of circulation in shaping Arctic climate, both in observations and model simulations. The bulk of our recent effort has been devoted to an examination of atmospheric circulation and its effect on sea ice thickness in the new version of NCAR's Community Climate System Model (CCSM3). Arctic sea ice plays an important role in the climate system, and an accurate representation of Arctic surface winds is a prerequisite for a credible sea ice simulation.

The starting point for the study is the fact that simulated Arctic sea ice and surface winds change substantially when CCSM3 resolution is increased from T42 (a 64x128 global grid) to T85 (a 128x256 grid). At T42 resolution, Arctic sea ice is too thick off the Siberian coast and too thin along the Canadian coast. Both of these biases are reduced at T85 resolution. For the surface winds, the most prominent difference is an erroneous North Polar summer anticyclone which is present at T42 but absent at T85.

We used an offline sea ice model, written and integrated by Dr. C. M. Bitz at the University of Washington, to study the effect of the surface winds on sea ice thickness. In this model, the surface wind stress is calculated from prescribed geostrophic surface winds, and and all other forcing inputs (e.g. surface air temperature) are calculated from fixed observational data. The offline model thus provides a means of isolating the mechanical effects of atmospheric circulation on sea ice, while ignoring the influence of biases in simulated air temperature, cloudiness, precipitation, etc.. Detailed comparisions were made between the ice thickness distributions generated by geostrophic surface winds from NCEP/NCAR reanalysis and CCSM3 at T42 and T85 resolution.

In the offline model, CCSM3 surface wind biases have a dramatic effect on sea ice distribution: sea ice produced by reanalysis surface winds is thickest along the Canadian coast, while CCSM3 winds produce the thickest ice on the Siberian side. In offline simulations using CCSM3 surface winds, the T85 winds produce thicker ice than their T42 counterparts along the Canadian archipelago -- a result which is consistent with the sea ice thickess differences found in the CCSM3 output.

Seasonal forcing experiments were also conducted, in which the offline model was forced with CCSM3 winds in the spring and summer and reanalysis winds in fall and winter. Using this methodology, we were able to relate Canadian-side thickness differences to the spring and summer differences between the T85 and T42 surface winds. The experiments also show that the excessive ice build up on the Siberian coast at both resolutions is related to the fall and winter surface wind biases.

A second part of the study looked at the structure and dynamics of the CCSM3 atmospheric circulation, both at the surface and at upper levels. In this part of the study we sought links between the CCSM3 surface wind biases over the Arctic Ocean and the large-scale tropospheric circulation. For the winter season, we focused on the Beaufort High, which dominates the surface circulation over much of the Arctic. At both resolutions the Beaufort high in CCSM3 is quite weak, weaker at higher resolution. In the reanalysis, eddy geopotential heights show that the wintertime Beaufort high has a barotropic vertical structure. But in CCSM3, high SLP in Arctic winter is associated with cold lower-tropospheric temperatures and a baroclinic vertical structure. The dependence of high Arctic SLP on cold low-level temperatures is thus an erroneous feature of the simulated dynamics of Arctic climate.

For the summer season, when zonal asymmetries of the Arctic circulation are small, we examined the structure and dynamics of the zonally averaged high-latitude circulation. In reanalysis, the summertime Arctic surface circulation is dominated by a polar cyclone, which is accompanied by surface inflow and a deep Ferrel cell north of the traditional polar cell. The Arctic Ferrel cell is accompanied by a northward flux of zonal momentum and a poleward lobe of the zonal-mean jet. These features do not appear in the CCSM3 simulations at either resolution. The notion of an Arctic Ferrel cell appears to be somewhat novel, and we plan to do more work to understand its dynamics

3) Changes in extratropical circulation and the hydrological cycle in global warming simulations:

In collaboration with Dr. David Lorenz, a UCAR postdoc hosted by the PI, we examined the changes in the extratropical circulation and hydrological cycle under global warming. The consensus prediction of the IPCC models is a strengthening and poleward shift of the tropospheric zonal jets in response to global warming. The change in zonal jets is also accompanied by a strengthening and a poleward and upward shift of transient kinetic energy and momentum flux. Similar jet changes in climate are simulated by a simple dry general circulation model (GCM) when the height of the tropopause is raised. The similarity between the simple GCM and the IPCC models suggests that the changes in mid-latitude circulation are predominantly driven by a rise in the height of the tropopause, and that other factors such as changes in increased moisture content and the reduction of the low-level pole-to-equator temperature gradient low-level meridional temperature gradient, for example, play a secondary role. In addition, the variability of about the ensemble-mean of the zonal wind response is significantly correlated with the variability of the tropopause height response over the polar cap, especially in the Southern Hemisphere.

In addition to the jet shifts, we examined the warming-induced changes in the extratropical hydrological cycle in the AR4 simulations. The changes in hydrological quantities are analyzed with respect to the increases expected from the Clausius-Clayperon equation, which describes the rate of increase of a hydrological quantity per temperature increase. The column-integrated water vapor increases at a rate close to the C-C rate, which is expected if relative humidity remains nearly constant. The poleward moisture transport and the precipitation increase with temperature at a rate less than the C-C rate with the precipitation increasing the least. In addition, the inter-model variance of poleward moisture transport and precipitation is explained significantly better when the zonal-mean zonal wind change as well as the temperature change is taken into account. The percent increase in precipitation per temperature increase is smallest during the warm season when the energy constraints on the hydrological cycle are more important. In contrast to other hydrological quantities, the changes in evaporation in the extratropics are not explained well by the temperature or zonal wind change. Instead, a significant portion of the inter-model spread of evaporation change is linked to the spread in the poleward ocean heat transport change. In addition, a significant amount of the inter-model spread in the relative humidity change in the subtropics is linked to the zonal wind change in the mid-latitudes.

4) Research on the use of the DART Ensemble Kalman Filter data assimilation system:

We began work on a project in which a data assimilation system (called DART) was used with the NCAR Community Atmosphere Model (CAM) to study Arctic circulation and circulation bias. The data assimilation research considered the effect on Arctic circulation of data assimilated over limited regions and layers of the atmosphere. Our first data assimilation experiment involved assimilating data in the region of the Arctic tropopause, where CAM (and most other global atmospheric models) has a pronounced cold bias. According to our results with the simple dry model, warming at the tropopause level should lower the tropopause, which in turn should reduce the eddy activity and shift the jet equatorward. Such indirect consequences of data assimilation would be in addition to the direct local effect of correcting the temperature bias and producing zonal-mean zonal winds in thermal wind balance with the temperature change. The results of the data withholding experiments were generally in keeping with this expectation, and were presented at the NCAR CCSM meeting by Justin Bagley, a graduate students funded by this grant. In addition, Justin performed a one-month data assimilations with DART/CAM incorporating refractivity observations from the Constellation Observing System for Meteorology, the Ionosphere, and Climate (COSMIC).

5) Research on the extent to which global warming poses a threat to polar bears:

We conducted a collaborative research effort with the U. S. Geological Survey (USGS) to assess the credibility of climate models for understanding the threat to polar bears posed by global warming over the 21st century. The research was undertaken to provide guidance to the U. S. Fish and Wildlife Service (FWS) in deciding whether to list the polar bear as a threatened species under the Endangered Species Act (ESA). Under the ESA, a species is "threatened" if it is "in danger of becoming endangered" in the "foreseeable future", which in this case was judged to be roughly 45 years. The USGS-led research combined data from fieldwork, radio telemetry from collared bears, satellite observations of sea ice concentrations, and climate model output to make projections of polar bear habitat and demographics over the 21^{st} century. This project supported the effort in two ways: 1) by choosing a set of 10 most credible climate models to use in making projections of future sea ice decline; and 2) by advising team members and federal government decision makers on the use and limitations of climate models. The conclusion of the research is that, given the geenhouse gas increases expected from the A1B “business as usual” emission scenario, polar bears will likely disappear from about two thirds of their current habitat by the middle of the 21^{st} century. Outcomes for the end of the century are considerably worse, with extinction probable throughout the entire range.

Deliverables:

Monographs, Reports, and Papers

DeWeaver, E. T., C. M. Bitz, and B. Tremblay, eds., 2007: Arctic Sea Ice Decline Grant: observations, projections, mechanisms, and implications. AGU Monograph, in preparation.

DeWeaver, E, 2007: Uncertainty in climate model projections of Arctic sea ice decline: an evaluation relevant to polar bears. Administrative Report, USGS Alaska Science Center, Anchorage, Alaska.

Lorenz, D. J., and E. DeWeaver, 2007: The response of the extratropical hydrological cycle to global warming. J. Climate, 20, 3470-3484.

Lorenz, D. J., and E. DeWeaver, 2007: Tropopause height and the zonal wind response to global warming in the IPCC scenario integrations. J. Geophys. Research, 112, D10119, doi:10.1029/2006JD008087.

DeWeaver, E., and C. M. Bitz, 2006: Atmospheric circulation and Arctic sea ice in CCSM3 at medium and high resolution. J. Climate, 19, 2415-2436.

DeWeaver, E., and S. Nigam, 2004: On the forcing of ENSO teleconnections by anomalous heating and cooling. J. Climate, 17, 3225-3235.

Presentations

Amstrup, S. C., and E. T. DeWeaver: Summary of Results: USGS science to inform U.S. Fish and wildlife decision-making on polar bears. Briefing presented to the White House Office of Science and Technology Policy, Old Executive Office Building, January 16, 2007.

Amstrup, S. C., H. Caswell, C. Hunter, I. Stirling, E. Regehr, D. Douglas, B. Marcot, G. Durner, 2007, and E. T. DeWeaver, 2007: Briefing on Results: USGS science strategy to support U. S. Fish and Wildlife Service polar bear listing decision. Briefing presented at the U. S. Department of the Interior, September 7, 2007.

Lorenz, D. J., and E. T. DeWeaver, 2006: The response of extratropical precipitation and moisture transport to increased CO2. 18th Conference on Climate Variability and Change, 86th AMS Annual Meeting, Atlanta, GA. February 2, 2006.

DeWeaver, E.T., 2006: Stability and climate sensitivity of seasonal sea ice: a theoretical framework. Eos Trans. AGU 87(52), 2006 Fall Meet. Suppl., Abstract C33B-1262.

Bagley, J., and E. T. DeWeaver, 2006: Applications of DART to climate model development: Arctic climate experiments and plans for a parameter estimation project. CAM Data Assimilation workshop, June 21, 2006.

DeWeaver, E. T., 2006: Stability analysis of the sea ice edge. 7th Summer Institute of the NOAA Postdoctoral Program in Climate and Global Change, 10-13 July 2006, Steamboat Springs, CO.

DeWeaver, E.T., 2006: Climate change and the stability of the sea ice edge, CCSM Polar Climate Working Group Meeting Report, Breckenridge, CO, Jun 21, 2006.

DeWeaver, E. T., 2005: Atmospheric circulation and its effect on Arctic sea ice in CCSM3 simulations at medium and high resolution. Seminar presented at the NASA Global Modeling and Assimilation Office (GMAO), November 15, 2005.

DeWeaver, E. T., 2005: Arctic and sub-Arctic atmospheric circulation in the CCSM3 simulations. Poster presented at the NCAR Junior Faculty Forum on Future Scientific Directions, July 27-29 2005.

DeWeaver, E. T., 2004: Arctic and sub-Arctic atmospheric circulation in observations and CCSM3 simulations. Poster presented at the NOAA Climate Diagnostics and Prediction Workshop, Madison, WI, October 21 2004.

Collaborators

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Cecilia M. Bitz, Atmospheric Science Department, University of Washington, Seattle, Washington.

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Graduate Students Supported

Justin Bagley (MS 2008), Erica Bickford (MS 2008).

Project Continuation

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