Final Report

Contract number: NA10OAR4310168

PI: Ming Cai
Co-PI: Huug van den Dool

Dynamical Climate Predictability of the NCEP CFS in the Stratosphere and the Statistical Downscaling for Climate Prediction in the Troposphere

PI Contact Information: Professor Ming Cai, Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, FL 32306. Email: mcai@fsu.edu. Tel. (850)-645-1551.

1. List of publications that acknowledge the CPO grant

1) Yu, Y-Y, **M. Cai**, R-C Ren, H. M. van den Dool, 2014: Relationship of Warm Air Mass Transport into Upper Polar Atmosphere and Cold Air Outbreaks in Winter. ***J. Atmos. Sci.***, (under review).

2) Sejas, S., O. S. Albert, **M. Cai**, and Y. Deng, 2014: Feedback Attribution of the Land/Sea Warming Contrast in NCAR CCSM4 Global Warming Simulations. ***Geophys. Res. Lett.*** (submitted).

3) **Cai, M.**, C. Barton, C-S Shin, and J. M. Chagnon, 2014: The Continuous Mutual Evolution of Equatorial Waves and the Quasi-Biennial Oscillation of Zonal Flow in the Equatorial Stratosphere**.** ***J. Atmos. Sci.***, DOI: 10.1175/JAS-D-14-0032.1.

4) Sejas, S., **M. Cai**, A. Hu, J. Meehl, W. Washington, and P. C. Taylor, 2014: Individual Feedback Contributions to the Seasonality of Surface Warming. ***J. Climate***, DOI: 10.1175/JCLI-D-13-00658.1.

5) **Cai, M.**, and C-S Shin, 2013: A Total Flow Perspective of Atmospheric Mass and Angular Momentum Circulations: Boreal Winter Mean State. ***J. Atmos. Sci.***, DOI:10.1175/JAS-D-13-0175.1.

6) Zhang, Q., C-S Shin, H. van den Dool, and **M. Cai**, 2013: CFSv2 Prediction Skill of Stratospheric Anomalies. Clim. Dyn. DOI:10.1007/s00382-013-1907-5.

7) Zhang, G., **M. Cai**, and A. Hu, 2013: Energy Consumption and the Unexplained Winter Warming over Northern Asia and North America. ***Nature Climate Change***. DOI: 10.1038/nclimate1803.

8) **Cai, M.**, and Bohua Huang, 2013b: A Dissection of Energetics of the Geostrophic Flow: Reconciliation of Rossby Wave Energy. ***J. Atmos. Sci.***, DOI: 10.1175/JAS-D-12-0249.1

9) **Cai, M.**, and Bohua Huang, 2013a: A New Look at the Physics of Rossby Waves: A Mechanical-Coriolis Oscillation. ***J. Atmos. Sci.***, DOI:10.1175/JAS-D-12-094.1.

10) Taylor, Patrick C., **M. Cai**, A. Hu, J. Meehl, W. Washington, and G. Zhang, 2013: A Decomposition of Feedback Contributions to Polar Warming Amplification. ***J. Climate***. DOI: 10.1175/JCLI-D-12-00696.1.

11) **Cai, M.**, and K-K Tung, 2012: Robustness of Dynamical Feedbacks from Radiative Forcing: 2% Solar versus 2xCO_2 Experiments in an Idealized GCM. ***J. Atmos. Sci.***, **69**, 2256-2271. DOI: 10.1175/JAS-D-11-0117.1.

2. Highlight of Major Accomplishments

The publications #1, #5, and #6 are on the core objectives of the funded research.

2.1 Coupling of warm air and cold air branches of the atmospheric general circulation (publication # 5)

This work builds the theoretical foundation from the observations for the dynamical linkages between the tropics and extratropics and between the stratosphere and troposphere. We follow the theoretical framework of Johnson and his collaborators and extend their diagnostic analysis that was based on seasonal mean data. Based on the comprehensive diagnostic analysis of diabatic and adiabatic mass and angular momentum fluxes and the source/sink terms of atmospheric angular momentum of the total flow, we have proposed **a conceptual model that substantiates Hadley's original view on the atmospheric general circulation**. *The conceptual model delineates the roles of instantaneous and continuous couplings among diabatic heating, adiabatic mass and its angular momentum transport, the pressure torque, the surface frictional torque, and the mountain torque in giving rise to the meridional mass and angular momentum circulations.* The conceptual model attempts qualitatively to explain 1) how the diabatic heating/cooling is coupled with adiabatic mass and its angular momentum transport in the tropical Hadley cell, 2) how the tropical Hadley mass circulation maintains the subtropical jet, 3) how the diabatic heating/cooling, adiabatic mass and its angular momentum transport, and the pressure torque are coupled in giving rise to the extratropical tropospheric Hadley cell, 4) how the intensification and movement of the tropospheric mid-latitude jet is associated with the extratropical Hadley mass circulation, 5) how the stratospheric mass circulation and its associated meridional angular momentum transport, driven by diabatic heating/cooling and the pressure torque, are responsible for the intensification and movement of the stratospheric polar jet, 6) what are the roles of the pressure torque, the surface frictional torque, the mountain torque, and the diabatic heating in the equatorward returning flow, and 7) what are the origins of the surface westerly wind in the extratropics and easterly wind in the tropics.

2.2 Assessment of the CFSv2 Prediction Skill of Stratospheric Temperature Anomalies (publication #6).

One of the key components of the funded research is to systematically evaluate the prediction skill for stratospheric anomalies in the retrospective seasonal climate predictions made by NCEP's Climate Forecast System (CFS). We have completed a comprehensive evaluation of the CFSv2 (reforecast) prediction skill of stratospheric temperature anomalies over the period of 1999-2010. The goal is to explore if the CFSv2 forecasts for the stratosphere would remain skillful beyond the inherent tropospheric predictability time scale of at most 2 weeks. The anomaly correlation (AC) between observations and forecasts for temperature field at 50 hPa (T50) in winter seasons remains above 0.3 at the lead time of 30 days whereas its counterpart in the troposphere at 500 hPa drops very quickly and below the 0.3 level at 12 days. We also prove that the CFSv2 has a high prediction skill both in an absolute sense and in terms of gain over persistence except in the equatorial region where the skill mainly comes from the persistence of the QBO signal. Based on the mass circulation theory, we conjecture that as long as the westward tilting of planetary waves in the stratosphere and their overall amplitude can be captured, the CFSv2 forecasts would still be very skillful in predicting zonal mean anomalies even though it cannot do so for the exact locations of planetary waves and their spatial scales. This explains why the CFSv2 has a high skill for the first EOF mode of T50, the intraseasonal variability of the annular mode associated with poleward propagation of zonal mean anomalies, despite that its skill degrades rapidly for higher EOF modes associated with stationary waves. This also explains why the CFSv2's skill closely follows the seasonality and its interannual variability of the meridional mass circulation and stratosphere polar vortex. In particular, the CFSv2 is capable of predicting mid-winter polar stratosphere sudden warming events in the Northern Hemisphere and the timing of the final warming polar stratosphere warming in both hemispheres 3-4 weeks in advance.

2.3 Relationship of warm air mass transport into upper polar atmosphere and cold air outbreaks in winter (publication #1).

The third key component of the funded research is to systematically evaluate the relation between warm air mass transport into upper polar atmosphere and cold air outbreaks in winter. The primary objective of this component of the study is to develop meridional mass circulation indices on daily basis that enable us to directly and physically link atmospheric circulation anomalies to individual cold air outbreak events in mid-latitudes in winter **with statistically robust and temporally lead information**. Towards this goal, we have constructed indices that measure the intensity of the meridional mass circulation crossing a latitude circle between mid-latitudes and the polar region using daily ERA_Interim data from 1979 to 2011. Mass circulation indices are constructed to measure the day-to-day variability of mass transport into the polar region by the warm air branch aloft and out of the polar region by the cold air branch near surface. It is shown that a lack of warm air mass transport into the polar region is accompanied by weaker equatorward advancement of cold air. As a result, the cold air mass is largely imprisoned within the polar circle, responsible for anomalous warmness in mid-latitudes and anomalous coldness in high latitudes. Conversely, a stronger warm air mass transport into the upper polar atmosphere is synchronized by a stronger equatorward discharge of cold polar air near surface, resulting in massive cold air outbreaks in mid-latitudes and anomalous warmth in high latitudes. There are two dominant geographical patterns of cold air outbreaks during the cold air discharging period (i.e., 1-10 days after a stronger mass circulation cross 60°N). One represents massive cold air outbreaks over both North America and Eurasian continents and the other is the dominance of cold air outbreaks only over one of the two continents with the abnormal warmness over the other continent. The first pattern mainly corresponds to the first and fourth leading EOFs of daily surface air temperature anomalies in winter seasons whereas the second pattern is related to the second leading EOF mode.

2.4 Highlights of other significant publications that acknowledge the CPO grant.

Zhang et al. (2013, publication #7) in an article published in *Nature Climate Change* studied the impact of energy consumption on the winter warming over Northern Asia and North America. Here is the abstract of that article: "*The worldwide energy consumption in 2006 was close to 498 exajoules. This is equivalent to an energy convergence of 15.8 terawatts (1.58×10^{13} W) into the populated regions, where energy is consumed and dissipated into the atmosphere as heat. Although energy consumption is sparsely distributed over the vast Earth surface and is only about 0.3% of the total energy transport to the extratropics by atmospheric and oceanic circulations, this anthropogenic heating could disrupt the normal atmospheric circulation pattern and produce a far-reaching effect on surface air temperature. We identify the plausible climate impacts of energy consumption using a global climate model. Results show that the inclusion of energy use at 86 model grid points where it exceeds 0.4 W/m^2 can lead to remote surface temperature changes by as much as 1 K in mid- and high latitudes in winter and autumn over most part of North America and Eurasia. These regions correspond well to areas with large differences in surface temperature trends between observations and global warming simulations forced by all natural and anthropogenic forcings. We conclude that energy consumption is likely a missing forcing for the additional winter warming trends in observations.*"

Cai and Huang (2013a, publication #9) studies a classic atmospheric dynamics problem: the physics of Rossby waves. Rossby waves play a fundamental role in large-scale atmospheric and oceanic motions that affect weather and climate. Rossby waves owe their existence to the meridional gradient of planetary vorticity. It is straightforward to derive the dispersion relation of Rossby waves from the quasi-geostrophic potential vorticity conservation equation without referencing to ageostrophic flow. This is possible because the net effect of ageostrophic flow to Rossby waves has been already incorporated into quasi-geostrophic potential vorticity dynamics. The oscillation mechanism of Rossby waves is generally understood through the conservation of potential vorticity, although it is not clear what is its physical restoring, as in other types of waves in fluid mechanics. According to Cai and Huang (2012), the β-induced convergence/divergence in the direction parallel to isobars results in an unbalanced flow that crosses isobars. The β-induced unbalanced flow is subject to a half-cycle Coriolis restoring force that can turn the unbalanced flow to the direction parallel to isobars but cannot continue to turn it back to its opposite direction because of the balance nature of the flow parallel to isobars. The new balanced flow resulting from the half-cycle restoring force has the same pattern as that on its right when facing the planetary vorticity gradient direction. The β-induced convergence/divergence and its restoration by the half-cycle restoring force on the unbalanced flow form a complete oscillation cycle, responsible for wave motions propagating to the left of planetary vorticity gradient. This oscillation is referred to as a mechanical-Coriolis oscillation (the first half-cycle oscillation is due to a mechanical deflection and the second half is due to the Coriolis deflection). The β-induced unbalanced flow is proportional to the ratio of β to the Coriolis parameter. As a result, the restoration time scale of the balanced flow by the half-cycle inertial restoring force depends on β only. The mechanical-Coriolis oscillation frequency is also inversely proportional to *k*, the wavenumber in the direction along planetary vorticity contours. The mechanical-Coriolis oscillation frequency can be succinctly expressed as $\omega = -\beta_{effective} / k$, where $\beta_{effective} = \beta \cos^2 \lambda \cos^2 \alpha$, λ and α are the angles of constant surfaces of total energy of Rossby waves with the vertical and planetary vorticity gradient, respectively.

Cai and Huang (2013b, publication #8) carried out a follow-up study on the physics of Rossby waves by Cai and Huang (2013a). In the new study, we have demonstrated that there is no ambiguity in the final form of the governing equations of a quasi-geostrophic (QG) model after partitioning the total flow into the geostrophic, balanced ageostrophic, and unbalanced ageostrophic components. The uniqueness of the QG model formulation ensures that the energetics of a QG model is the same as that derived from the QG potential vorticity equation. Particularly, the well-known but somewhat mysterious “missing term” in the energetics of Rossby waves, identified in the literature as the difference between the pressure work and the energy flux transported at the group velocity, can be easily recovered. The “missing term” is the pressure work on the convergence of the balanced ageostrophic flow, representing a “hidden” conversion between kinetic and potential energy of the geostrophic flow that excites the unbalanced flow. This energy conversion equals the convergence of a one-directional energy flux that always transports energy westward at the zonal phase speed of Rossby waves. The pressure work on the divergence of the unbalanced flow does the actual conversion between kinetic and potential energy of the geostrophic flow and the pressure work on the unbalanced flow causes energy propagation in other directions. Therefore, it is the pressure work on the unbalanced flow that causes Rossby waves to be dispersive, leading to the downstream development. The sum of the energy transported at the zonal phase speed of Rossby waves and the pressure work on the unbalanced flow exactly equals the energy transported at the group velocity of Rossby waves.

Cai et al. (2014, publication #3) diagnosed properties of (resolved) waves at instantaneous times. As such, we are the first to reveal the continuous temporal evolution of wave properties (effective ground-relative or intrinsic phase speed, wave length, vertical tilting) as the background zonal wind QBO evolves. Our finding of the smallness of the ground-relative phase speed of dominant waves at all times complements the well-established fact that dominant waves associated with the QBO always propagate in the opposite direction of the background zonal flow (in the literature, the information of wave propagation direction is derived based on space-time spectral analysis, which represents the average phase speed of waves in each of the QBO regimes, whereas ours shows continuously evolving instantaneous phase speed). We are the first to show that there exists a QBO-variation of the vertical tilting of (resolved) equatorial waves in the stratosphere. This independently assures that the QBO-variation of the intrinsic phase speed obtained in our study is in accordance with the QBO theory, namely that westward propagating waves have to have westward tilting and vice versa (in order to have upward energy propagation). We are also the first to show the driving mechanism of the QBO regime change and its downward propagation via pressure torque, by the waves whose vertical tilting alternates as the background QBO. This driving mechanism adds on to the well-established wave breaking/absorption mechanisms for the QBO. Furthermore, the QBO-variation of pressure torque term is exactly consistent with the QBO-variation of the independently diagnosed vertical tilting, namely that downward transfer of westerly angular momentum is associated with westward tilted waves and vice versa.

Taylor et al. (2013, publication #10) studied the feedback contributions to polar warming amplification in NCAR CCSM4 climate simulations. Here is the abstract of this article: "*Polar surface temperatures are expected to warm 2-3 times faster than the global mean surface temperature; a phenomenon referred to as polar warming amplification. Therefore, understanding individual process contributions to the polar warming is critical to understanding global climate sensitivity. The coupled feedback response analysis method (CFRAM) is applied to decompose the annual and zonal mean, vertical temperature response within a transient 1% yr^{-1} CO_2 increase simulation of the NCAR CCSM4 into individual radiative and non-radiative climate feedback process contributions. The total transient annual mean polar warming amplification (amplification factor) at the time of CO_2 doubling is +2.12 K (2.3) and +0.94 K (1.6) in the northern and southern hemisphere, respectively. Surface albedo feedback is the largest contributor to the annual mean polar warming amplification accounting for +1.82 K and +1.04 K in the northern and southern hemisphere, respectively. Net cloud feedback is found to be the second largest contributor to polar warming amplification (about +0.38 K in both hemispheres) and is driven by the enhanced downward longwave radiation to the surface resulting from increases in low polar water cloud. The external forcing and atmospheric dynamic transport also contribute positively to polar warming amplification: +0.29 K and +0.32 K, respectively. Water vapor feedback contributes negatively to polar warming amplification because its induced surface warming is stronger in low latitudes. Ocean heat transport storage and surface turbulent flux feedbacks also contribute negatively to polar warming amplification. Ocean heat transport and storage terms play an important role in reducing the warming over the Southern Ocean and Northern Atlantic Ocean*."

Sejas et al. (2014, publication #4) examined the individual contributions of the CO_2 radiative forcing and climate feedbacks to the magnitude, spatial pattern, and seasonality of the transient surface warming response in a 1% per year CO_2 increase simulation of the NCAR CCSM4. The main findings are summarized as follows: The CO_2 forcing and water vapor feedback warm the surface everywhere throughout the year. The tropical warming is predominantly caused by the CO_2 forcing and water vapor feedback while the evaporation feedback reduces the warming. Most feedbacks exhibit noticeable seasonal variations; however their net effect has little seasonal variation due to compensating effects, which keeps the tropical warming relatively invariant all year long. The polar warming has a pronounced seasonal cycle, with maximum warming in fall/winter and minimum warming in summer. In summer, the large cancelations between the shortwave and longwave cloud feedbacks and between the surface albedo feedback warming and the cooling from the ocean heat storage/dynamics feedback lead to a warming minimum. In polar winter, surface albedo and shortwave cloud feedbacks are nearly absent due to a lack of insolation. However, the ocean heat storage feedback relays the polar warming due to the surface albedo feedback from summer to winter, and the longwave cloud feedback warms the polar surface. Therefore, the seasonal variations in the cloud feedback, surface albedo feedback, and ocean heat storage/dynamics feedback, directly caused by the strong annual cycle of insolation, contribute primarily to the large seasonal variation of polar warming. Furthermore, the CO_2 forcing, and water vapor and atmospheric dynamics feedbacks add to the maximum polar warming in fall/winter

Cai and Tung (2012, publication #11) reports a modeling study that compares the climate response to 2% solar and $2xCO_2$ forcing. Previously radiative forcing, RF, at the tropopause is commonly used to characterize climate forcing. While useful for the vertical column, it masks differences in forcing at the surface and troposphere. We have applied "pattern-amplitude projection" metrics a quantitative analysis on how various radiative and non-radiative feedback processes redistribute energy spatially (both vertically and horizontally) in such a way that the final response to the two types of forcing is quite similar despite the differences in the spatial patterns of the two types of external forcing. At the surface, solar radiative forcing is stronger in the tropics than at the high latitudes, while greenhouse radiative forcing is stronger at high latitudes compared to the tropics. Also solar forcing is positive everywhere in the troposphere and greenhouse radiative forcing is positive mainly in lower troposphere. The water vapor feedback strengthens the upward decreasing radiative heating profile in the tropics and the poleward decreasing radiative heating profile in the lower troposphere. The "evaporative" and convective feedbacks play an important role only in the tropics where they act to reduce the warming at the surface and lower troposphere in favor of upper troposphere warming. Both water vapor feedback and enhancement of convection in the tropics further strengthen the initial poleward decreasing profile of energy flux convergence perturbations throughout the troposphere. As a result, the large-scale dynamical poleward energy transport, which acts on the negative temperature gradient, is enhanced in both cases, contributing to a polar amplification of warming aloft and a warming reduction in the tropics. The dynamical amplification of polar atmospheric warming also contributes additional warming to the surface below via downward thermal radiation.