SIMULATIONS OF WINTERTIME ARCTIC AIR SURGES INTO MIDDLE LATITUDES

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1. INTRODUCTION

Influxes of extremely cold air adversely impact large areas of the heavily populated middle latitudes during most winters. In addition to causing human suffering and fatalities, temperatures during severe cold outbreaks can kill vegetation and fall below the thresholds for which buildings and other infrastructural components were designed. Since 1989, when the National Weather Service began keeping statistics of cold wave fatalities, approximately 30 deaths per year have been directly attributed to extreme cold. Worldwide, the toll is even greater. During the recent winter of 2002-2003, for example, widespread cold in Eurasia caused over 500 fatalities in Bangladesh, over 600 fatalities in northern India, and widespread suffering in western Russia, including the Moscow area.

In the United States, the greatest economic losses from severe cold result from damage in the agricultural sector. During the cold outbreaks of 1983 and 1985, Florida citrus growers suffered losses of $3.6 billion and $2.9 billion, respectively, contributing to a significant shift from citrus growing to other types of land use in central Florida. The economic losses from such outbreaks are also high from broken water pipes, road damage and commercial slowdowns, especially in southern areas such as Florida and the Gulf Coast.

The incidence of extreme cold outbreaks is intertwined with climate variability in several ways. First, the atmospheric circulation patterns conducive to the build-up and southward migration of extremely cold airmasses show intra-seasonal to inter-decadal variability that is a fundamental characteristic of climate. Second, climate changes, especially changes of mean temperature, can be expected to affect the intensity of cold air outbreaks. One of the apparent climatic paradoxes of the past several decades is that the northern continental regions (northwestern North America, northern Asia) have shown the greatest warming during winter, a pattern not inconsistent with model-derived projections of greenhouse warming ---- but also a pattern that is consistent with natural variability over seasonal to decadal timescales. However, the incidence of extremely cold outbreaks has been at least as great in the 1980s and 1990s as in earlier decades of the century (Walsh et al., 2001, Fig. 2). In support of the latter finding, we note that, in the United States, 16 of the 50 state records for the lowest measured temperature have been set during the recent two-decade period 1979-1999, despite the widely reported warmth of the Northern Hemisphere during this period. Also somewhat paradoxical is Thompson et al.'s (2002, p. 1426) finding that extreme cold events are less common over the south-central United States during the warm phase of the ENSO cycle, even though mean temperatures are below-normal in this region during winters in which ENSO is in its warm phase.

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Similarly intriguing findings related to trends of temperature have been recently reported, apparently independently, by Michaels et al. (2000) and Kalkstein et al. (1990). While both groups found that the coldest and driest airmasses over subarctic land areas have warmed significantly in recent decades, Michaels et al. contend that the Northern Hemisphere warming since the mid-1940s "is almost exclusively confined to the dry, cold anticyclones of Siberia and North America". Since outbreaks of cold polar air into middle latitudes of North America have not lessened in the period since the 1940s, atmospheric dynamics and the large-scale circulation must play a key role in cold air outbreaks.

Among the atmospheric circulation patterns that have been associated with cold air outbreaks over North America are the Arctic Oscillation or its regional counterpart, the North Atlantic Oscillation; the Pacific-North American anomaly pattern; and ENSO, as noted above. In the case of the Arctic Oscillation, the negative phase (characterized by a weakened annular mode of the Northern Hemisphere circulation) is associated with increased cold outbreaks over much of the United States as well as parts of Europe and Asia (Thompson and Wallace, 2001). This tendency is consistent with an amplified longwave pattern in the troposphere; there are indications that a breakdown of the polar vortex in the stratosphere precedes the amplification of the tropospheric wave pattern by several days to a week or more (Thompson et al., 2002). The Pacific North American (PNA) teleconnection pattern has long been known to be associated with cold outbreaks over central and eastern North America through a build-up of an upper-air ridge over western North America, surface anticyclogenesis over the northwestern part of the continent, and a northwest-to-southeast steering flow aloft that facilitates the equatorward transport of cold airmasses. The PNA pattern shows some correlation with ENSO and with the Quasi-Biennial Oscillation (Thompson et al., 2002).

Cold outbreaks over Europe are associated with a breakdown of the North Atlantic Oscillation or its larger counterpart, the Arctic Oscillation. Walsh et al. (2001) have shown that surface airmasses of Siberian origin migrate westward when the onshore flow from the Atlantic Ocean weakens during the negative phase of the North Atlantic or Arctic Oscillation. The correlation between wintertime surface air temperature and the Arctic Oscillation extends well eastward into northern Asia, as shown by the correspondence between recent decadal-scale trends of the Arctic Oscillation and surface air temperature (Thompson and Wallace, 1998). The linkage to conditions over the southern part of the Asian landmass, such as the cold outbreak of the winter of 2002-2003, is less apparent, although it is likely that factors affecting the intensity of the Siberian anticyclone must be included in a diagnostic evaluation of such outbreaks.

2. OBJECTIVES

The linkage of cold outbreaks to climate, and the likelihood of climate changes over the coming decades to a century, gives climate models a potentially valuable role in (1) the diagnosis of the variability of extreme cold outbreaks in terms of dynamical and physical processes, and (2) a sound basis for projecting future changes in the characteristics (i.e., frequency, intensity, geographical distribution) of cold outbreaks over the decade-to-century timescale. However, climate models' handling of cold-air outbreaks has yet to be examined systematically in a climatic context. We are investigating the capabilities and limitations of global climate models with respect to diagnoses and projections of cold wave characteristics. The impacts of changes in the characteristics of extreme events, of which cold outbreaks are prime examples, are likely to be at least as important as changes of climatic averages.

3. RESULTS

A first step in the application of models to the study of cold waves is an evaluation of their simulations of cold outbreaks in the present climate, i.e., in control simulations. A model that successfully reproduces the temporal, spatial and intensity characteristics of cold outbreaks can shed light on the mechanisms that drive cold outbreaks, e.g., the relative roles of thermodynamic and dynamical processes in the evolution of a cold outbreak. An examination of the synoptic-scale heat budget variations in the NCEP/NCAR reanalysis, for example, shows that horizontal advection and vertical motion (subsidence) make the largest contributions to local changes of temperatures during a cold air outbreak in the middle latitudes of North America. However, diabatic processes appear to predominate in the northern regions of the continent, especially in areas where insolation is minimal. We are examining whether unconstrained models (vs. reanalyses) show similar patterns.

In a preliminary assessment of the extreme cold episodes simulated by several global climate models, we have examined the frequencies with which low-temperature thresholds and high-pressure thresholds have been exceeded over North America during winter in several state-of-the-art models. These models, which are being used in the Arctic Climate Impact Assessment (http://www.acia.uaf.edu/), include recent-generation models of the Canadian Climate Center (CCC), Geophysical Fluid Dynamics Laboratory (GFDL), The U.K. Hadley Centre (HadCM3), the Max-Planck-Institute (ECHAM4), and the NCAR Climate System Model (CSM1). Figure 1 shows that the frequencies with which the cold-airmass thresholds were exceeded in "control" climate simulations (for 1980-1999) are generally similar in the NCEP reanalysis and four of the leading GCMs used in ACIA. In other words, the models appear to be capturing the broad statistics of cold air outbreaks (CAOs) over North America in the present climate. This finding suggests that the models may be viable tools for addressing the possible changes in cold air outbreaks in greenhouse scenarios of climate change.

The highly episodic behavior of CAOs indicates that many years of climate model output are required to accurately evaluate their simulated behavior, both under modern radiative forcing and enhanced greenhouse gases. Such long records can be obtained either from an ensemble of simulations by a single model or from a set of simulations by different models. Our large collection of climate model output allows us to utilize both approaches. The GCM simulations in the ACIA archive (CSM1, GFDL, HadCM3, ECHAM, and CCC) provide a useful suite of control simulations and 21st-century projections forced by the IPCC's B2 greenhouse scenario. This archive, compiled at the University of Illinois as part of the ACIA activity, includes monthly as well as daily output (cf. http://zubov.atmos.uiuc.edu/ACIA/).

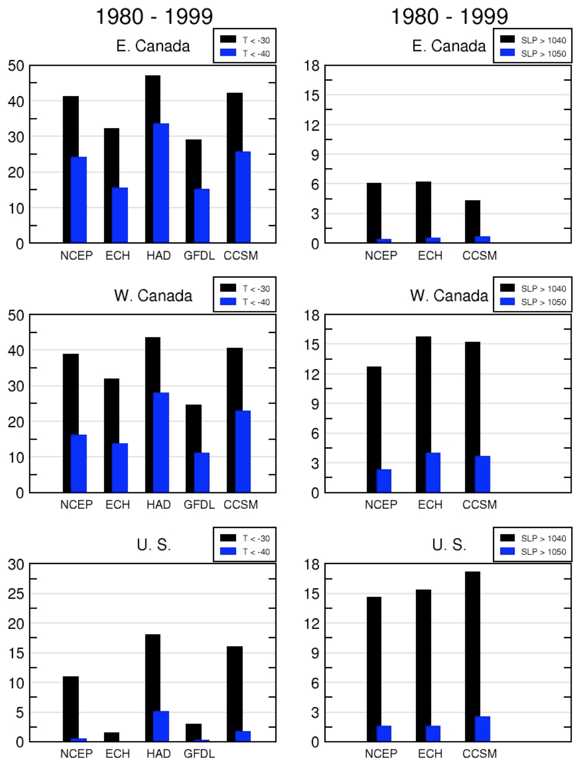

Figure 1. Frequencies of low-temperature (^{o}C), high-pressure (hPa) threshold exceedences in the NCEP/NCAR reanalysis and GCMs.

The large horizontal scales of most CAOs should allow climate models to simulate them, without resorting to higher resolution than today's typical global model. The preceding discussion and Figure 1 show that frequencies of extreme temperatures and pressures over North America during winter are, in a broad sense, captured by today's models. More specifically, our preliminary work indicates that the CSM1 (at its standard T42 resolution) is able to simulate realistically the formation and evolution of a CAO in its control run (modern boundary conditions). Figure 2 illustrates the synoptic pattern at the surface and aloft (500 hPa) during the life cycle of a CAO that affected the eastern U.S. In this instance, the model produces a classic CAO, in which an Arctic air mass is advected into the U.S. by a strong northwesterly flow aloft that develops due to blocking over Alaska. The surface air temperatures over the Midwest and eastern U.S. resemble those observed during extreme cold-air outbreaks over these regions.

Another important result from our ongoing research is the strong relationship between CAOs and the skewness of wintertime temperature distributions across North America. At many locations the variations of daily mean surface temperature show a pronounced negative skew (many more extreme cold days than extreme warm days), indicative of occasional incursions of Arctic air masses. Furthermore, both observations and simulations show that there is regional structure to the skewness pattern, as locations in the northern U.S. and western Canada tend to experience very negatively skewed distributions, whereas less negative and positive skewness prevails over the southern U.S. (Fig. 3). Because skewness provides a measure of the relative frequency and magnitude of extreme cold days, we are finding that it serves as an accurate quantitative proxy for CAOs. This is a very useful discovery, since we can then characterize the behavior of cold waves in terms of an index that consolidates large sets of observational data and model output. One of the aspects we are analyzing is the pronounced north-south gradient in skewness across the U.S., with large negative skew to the north and moderate positive skew to the south. This feature agrees qualitatively with observations, but the meridional variation of skewness simulated by the CSM1—and the newer Community Atmospheric Model, CAM3--is too pronounced compared with observations. This bias suggests that the simulated Arctic air masses may not be penetrating far enough into the southern U.S.

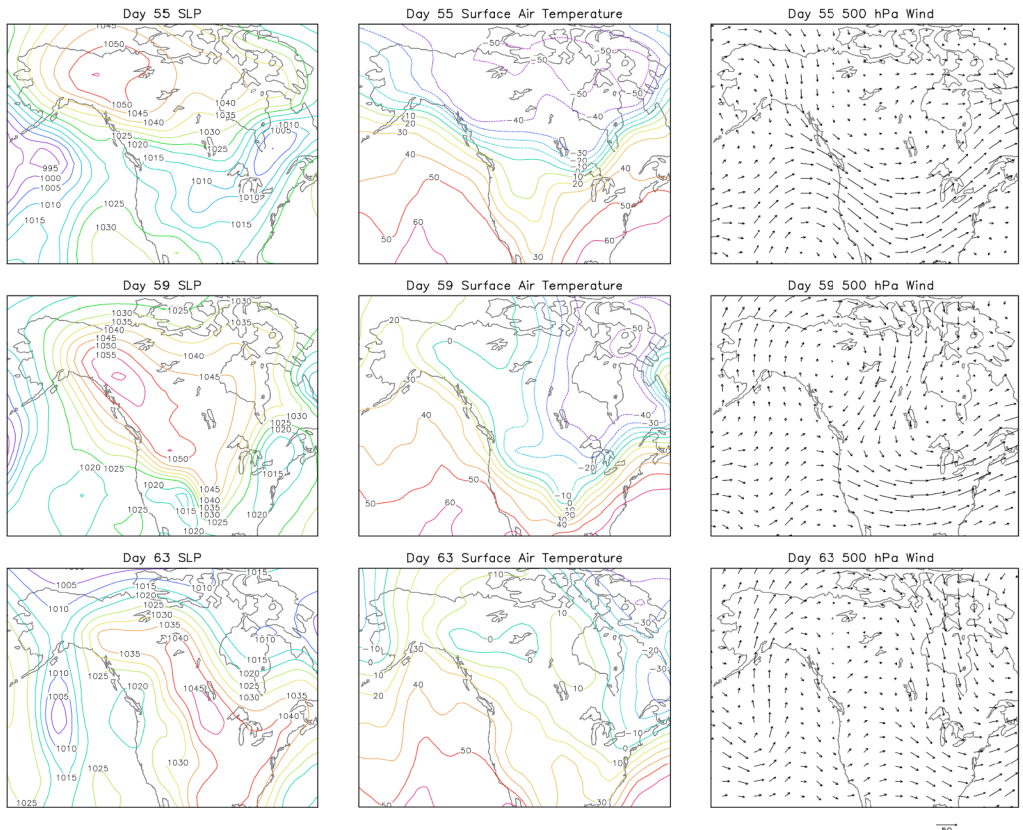

Figure 2. Arctic outbreak over the Midwest and eastern North America as simulated by the CSM1 in its control run. Maps display the evolution of a CAO every fourth day from day 55 (February 24) (top panel) to day 63 (March 4). Shown are (left) sea level pressure (hPa), (middle) daily mean surface air temperature (^{o}F), and (right) 500 hPa wind vectors (m/sec).

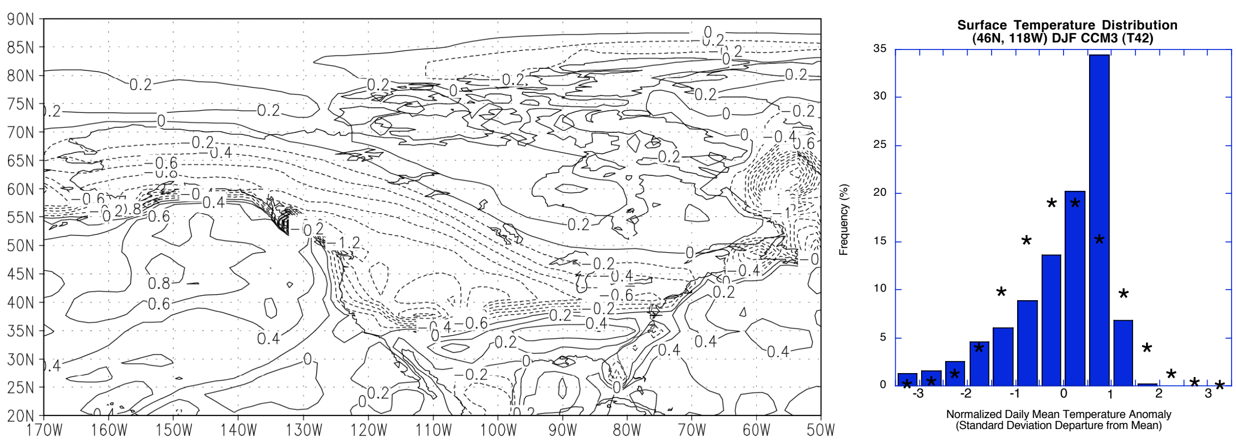

Figure 3. (left) Skewness of wintertime distribution of daily mean surface temperature simulated in a 19-year Community Climate Model (CCM3) run driven by observed SSTs from 1979-1998, (right) histogram of simulated wintertime daily mean surface temperatures in the Pacific Northwest (46^{o}N, 118^{o}W) in the same simulation (solid bars), compared with a Gaussian distribution (asterisks).

Another way of evaluating climate model simulations of CAOs is to compare their simulated characteristics with observations at a specific location. The following table shows such a comparison for the grid point corresponding to Madison, WI, in terms of the frequency, duration, and seasonal timing of CAOs. The table illustrates that the CCM3 model accurately reproduces the observed frequency and duration of these events. Simulated and observed CAOs occur at a rate of 1 per winter and typically last 2-3 days, although they may persist for a week to 10 days. The model captures the fact that January is the most common month for CAOs, but both model versions produce too many events late in the winter (February-March).

Madison, WI (43N, 90W)

	Observed (1940-2002)	T42 (19-year run)	T85(19-year run)
Frequency	0.9 CAO/winter	1.1 CAO/winter	1.1 CAO/winter
Duration			
2 Days	55%	67%	57%
3 Days	23%	19%	24%
4 Days	12%	9%	9%
5 Days	4%	0%	5%
6 Days	2%	0%	0%
7 Days	2%	5%	5%
8 Days	0%	0%	0%
9 Days	0%	0%	0%
10 Days	2%	0%	0%
Timing			
November	0%	0%	0%
December	20%	19%	9%
January	71%	43%	57%
February	9%	33%	29%
March	0%	5%	5%

Frequency, duration, and timing of CAOs at Madison, WI, as observed and as simulated in the CCM3.6 at T42 and T85 resolution (model output provided by Cecilia Bitz). In this study, CAOs are defined as at least two consecutive days during which the daily mean temperature is at least two standard deviations below the DJF wintertime mean temperature. These results suggest that the model adequately reproduces the frequency and duration of CAOs but has more difficulty simulating their timing during winter.

Although one might expect much less frequent and/or severe cold waves in a warmer climate, this supposition may not be correct. The occurrence of CAOs during the observational record is highly variable, and their frequency and magnitude are often independent of the mean background climate. As noted in Section 1, the pronounced wintertime warming of the anticyclones in Siberia and northwestern North America (Michaels et al., 2000), the source regions for CAOs, did not translate into a reduction in the frequency or strength of CAOs. We are analyzing the response of our collection of models to increased CO_2 to determine the relative roles of large-scale circulation changes and thermodynamic warming. We are comparing the characteristics of simulated CAOs in the modern climate (frequency, duration, intensity, etc.) with those of the enhanced-CO_2 experiments. A preliminary evaluation based on simple frequencies of various threshold exceedences in B2-scenario simulations by the ACIA models, shows that the occurrences of extremely low temperatures and high pressures over North America do not always decrease monotonically. For example, during the period from the mid-21st century (2040-2059) to the late 21st-century (2070-2089), CSM1 shows an increase in the frequency of temperatures below –30ºC over Canada, while the Hadley GCM shows an increased frequency of sea level pressures above 1040 hPa over the United States and Canada (Figure 4).

The type of circulation change underlying possible increases in CAO events over North America is shown in Figure 5 (derived from another 21st-century simulation by CSM). Notice the implied tendency for enhanced northerly flow aloft over the U. S. Midwest and enhanced northwesterly flow at the surface over the northeastern quarter of the U. S., both of which would mitigate the thermodynamic warming signal from increased CO_2. We are extending this evaluation of model output to include other models, including those in the IPCC AR4 collection. We will also evaluate temporal changes in the occurrence of the teleconnections found to be associated with CAO events. To the extent that changes in these teleconnection patterns are consistent with projected changes in CAO events, we will be able to conclude that changes in atmospheric dynamics may over-ride the direct radiative effects of increasing greenhouse gas concentrations.

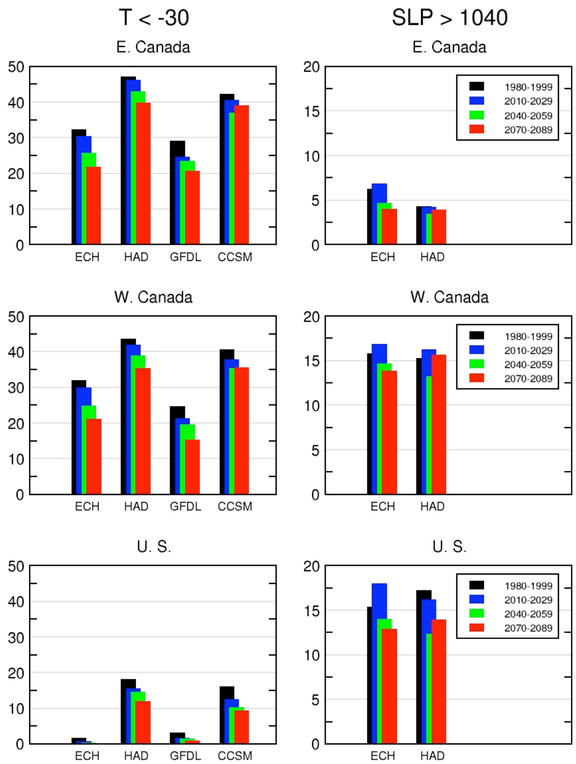

Figure 4. Time-slice values of low-temperature (^oC) and high-pressure (hPa) threshold exceedences in 21st-century simulations under scenario B2.

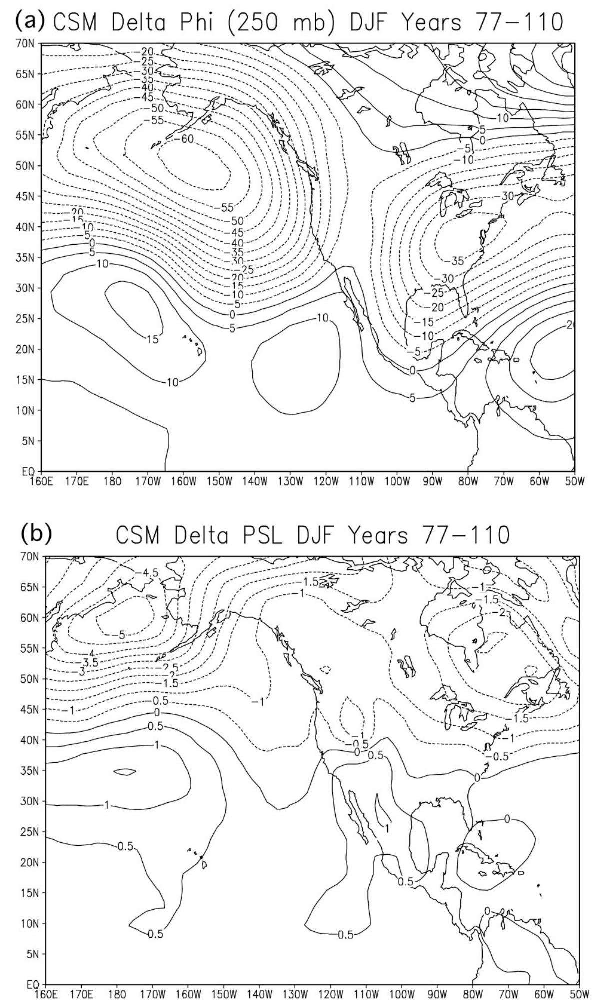

Figure 5. Simulated mean changes from modern control during the last few decades of CSM1's transient CO_2 experiment (negative contours dashed). Shown are differences in wintertime (a) 250 hPa geopotential height (meters) minus the global average anomaly and (b) sea level pressure (hPa).

ACKNOWLEDGMENTS

This project is supported by collaborative NSF grants ATM-0332099 and ATM-0332081: "Global Climate Model Simulations of Extreme Cold-Air Outbreaks".

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