On the regulation of minimum mid-tropospheric temperatures in the Arctic

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Received 13 October 2003; revised 9 February 2004; accepted 19 February 2004; published 20 March 2004.

[1] Observations indicate a minimum mid-tropospheric Arctic winter temperature of about −45°C at 500 hPa. This minimum temperature coincides with that predicted for moist adiabatic ascent over a sea surface near its salinity-adjusted freezing point. NCAR/NCEP Reanalysis data show that convective heating maxima averaged over the 50–70°N latitude band coincide both in longitude and altitude with total horizontal energy flux maxima entering the Arctic, indicating the significance of convection over open water on the winter Arctic energy budget. NCAR CCM single column model experiments simulating convective warming of a cold airmass moving over open water and radiative cooling as it moves again over cold land/sea ice support the hypothesis that the −45°C threshold can be maintained for 10–14 days after convective warming occurs. We speculate on the implications of this regulatory mechanism on surface temperatures. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4504 Oceanography: Physical: Air/sea interactions (0312); 9315 Information Related to Geographic Region: Arctic region; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature. **Citation:** Tsukernik, M., T. N. Chase, M. C. Serreze, R. G. Barry, R. Pielke Sr., B. Herman, and X. Zeng (2004), On the regulation of minimum mid-tropospheric temperatures in the Arctic, *Geophys. Res. Lett.*, *31*, L06112, doi:10.1029/2003GL018831.

1. Introduction

[2] Observational evidence for an Arctic temperature regulation mechanism operating on minimum winter temperatures was provided by *Chase et al.* [2002]. That analysis, performed for a 50-year period, showed that at 500 hPa Arctic temperatures reach −45°C in November of each year but seldom fall below this value despite continued net radiative loss in winter. The −45°C threshold corresponds to moist adiabatic ascent over a sea surface at −2°C—the approximate salinity-adjusted freezing point of seawater. It was hence hypothesized that Arctic airmasses maintain enough contact with unfrozen sea surfaces so that minimum sea surfaces temperatures (SSTs) are able to control minimum temperatures in the middle troposphere over the course of long winter season through convective warming. The 500 hPa level was chosen to capture unambiguous signal of convective warming. It is not influenced by the stratosphere, nor is it greatly affected by radiative cooling from below. Examination of daily weather charts confirmed that Arctic airmasses dip far enough south to come into contact with open ocean surfaces on a regular basis allowing the column to become moist adiabatic. As the airmass returns over cold land/sea ice, cooling should occur slowly from the surface upward, allowing 500 hPa temperatures to remain more or less constant for long periods until further excursions of air occur over warm water.

[3] We examine the two processes: convective warming and radiative cooling of the airmasses, which act together as a temperature regulation mechanism. The temperature regulation mechanism is examined with respect to the minimum possible SST values of −2°C, which can be viewed as the "critical" value. Higher SSTs would result in 500 hPa temperature above the observed minimum value of −45°C. Our analysis of data from the National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR) reanalysis focuses on the significance of convective activity in the northern high latitude oceans. Our modeling study simulates the processes of convective warming and radiative cooling, which occur over unfrozen waters and land/sea ice respectively, and proposes timescales for Arctic airmasses.

2. Methods and Results

2.1. Observational Study

[4] The NCEP/NCAR assimilation and forecast model [*Kalnay et al.*, 1996] produces two variables as a part of its convective parameterization: shallow [following *Tiedtke*, 1983] and deep convection [following *Grell*, 1993] that represent dry and moist convection respectively. Convective heating rate is a modeled variable. Figure 1 shows the spatial pattern of the convective heating rates at 800 hPa averaged over winter months for the period 1950–2002. The Norwegian Sea and northern North Atlantic in general have the strongest convective heating rates and are therefore implicated as the main source regions for convective heating of Arctic airmasses. The Bering Sea and northern North

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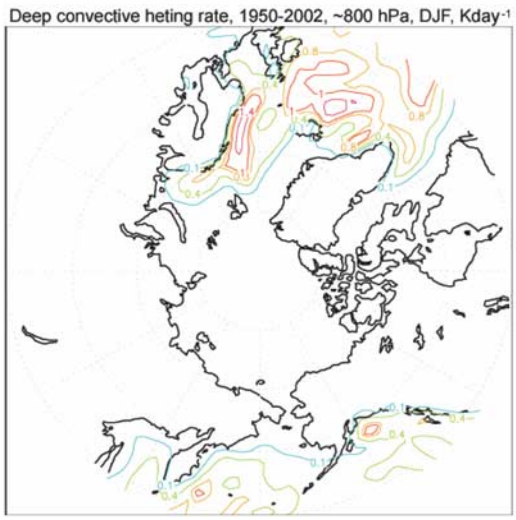

Figure 1. Deep convective heating rate (in K/day) north of 50°N computed from NCAR/NCEP monthly dataset averaged over 52 winters (1950–2002, DJF) for the 800 hPa level (approximated from sigma levels).

Pacific are interpreted as secondary source areas. Significant values are found over all open high latitude sea surfaces.

[5] *Overland and Turet* [1994] analyzed horizontal energy fluxes across the 70°N wall (reproduced in Figure 2). Positive (northward) fluxes are located mainly over open water regions (Norwegian Sea 40°W–30°E; Bering Sea 170°E–170°W) with maximum transports at 700–800 hPa. *Overland and Turet* [1994] found little interannual variability in the observed horizontal energy flux, suggesting strong control by "semi-permanent" areas of high-latitude convection over open water areas of the northern North Atlantic and northern North Pacific. They suggested that the upper ocean absorbs the solar energy during the summer season and is net energy source during the long winter season.

[6] We computed total (dry and moist) convective heating rates along several latitude bands from 50°N to 70°N. The maxima of convective activity averaged through 50–70°N and meridional energy fluxes incoming through the 70°N wall reveal similarities in both latitude and altitude

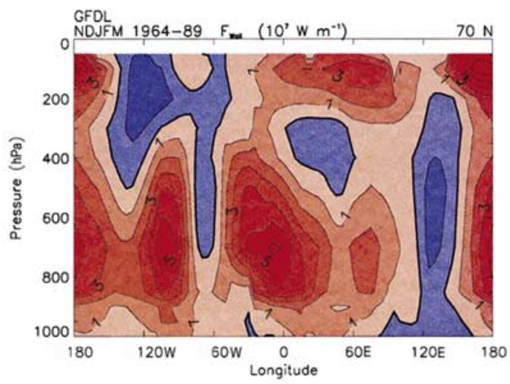

Figure 2. Variability of the atmospheric energy flux across 70°N computed from the GFDL dataset by *Overland and Turet* [1994].

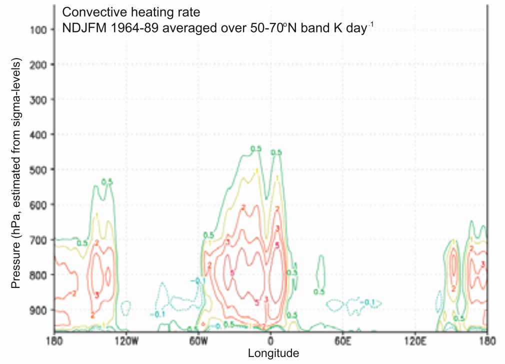

Figure 3. Convective heating rate longitudinal average for 50–70°N in K/day. The vertical axis is approximated from sigma-levels.

(compare Figures 2 and 3), lending support to the idea that energy transported into the Arctic is associated with convective warming over open waters. That there are differences is not surprising. The pattern of meridional transport across 70°N represents the combined transports of sensible heat, latent heat, and potential energy by transient eddies, standing eddies and the mean meridional circulation [*Overland and Turet*, 1994]. Convective heating over high-latitude open water areas, which injects heat into the troposphere, should be viewed as an integral part of the overall energy transport process.

[7] NCAR archives monthly vertically integrated mass, moisture, heat and energy budget products derived from NCEP/NCAR data. Also provided are estimates of the net surface heat flux computed as a residual from the vertically integrated energy tendencies, flux divergences and the top-of-atmosphere radiation budget (http://www.cgd.ucar.edu/cas/catalog/newbudgets/). In support of our results the winter data show that in the Norwegian and Bering seas, the mean upward net surface flux exceeds 200 Wm^{-2}.

2.2. Modeling Study

[8] The NCAR CCM single-column model (SCM) Version 3.6 [*Hack et al.*, 1999] is used to test the temperature regulation hypothesis. We divided the temperature regulation mechanism into two idealized processes: convective warming—occurring when a cold and dry continental airmass moves over open ocean, and radiative cooling—occurring when a heated and moistened airmass moves back over cold land/sea ice. The model uses an improved *Slingo* [1987] cloud parameterization scheme, which depends on relative humidity, vertical velocity, atmospheric stability and the convective mass flux associated with the parameterized moist convection. Deep (moist) convection is simulated by the mass flux scheme of *Zhang and McFarlane* [1995], shallow (dry) convection follows the triplet convective scheme of *Hack* [1994]. We eliminated the horizontal flux divergence for model boundary condition, assuming our airmass to be horizontally uniform. Hence we are examining vertical processes only.

[9] The first set of simulations represents convective warming. We use monthly averaged NCEP/NCAR data to create an average cold and dry Arctic winter sounding that is placed over unfrozen waters with prescribed SST and allowed to warm. As seen in Figure 4a, warming starts

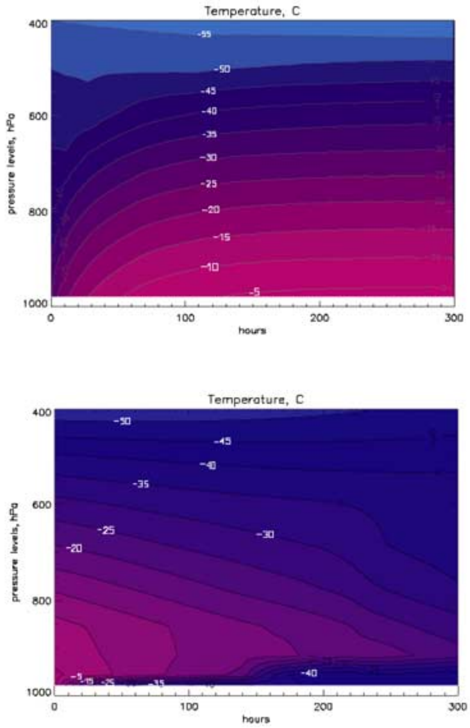

Figure 4. (a) Typical output from the convective warming simulation in the SCM (see text for further details), temperature °C. (b) Typical output from the radiative cooling simulation in the SCM model (see text for details), temperature °C.

quickly and propagates throughout the mid-troposphere over the order of several hours/days. The simulation reaches approximate equilibrium after about 4 days with temperatures close to moist adiabatic throughout the mid-troposphere (i.e., up to 500 hPa) indicating a dominance of convective processes. This was further confirmed by examining modeled convective heating rates and vertical motion (not shown). The 500 hPa equilibrium temperature is defined by the SST (−2°C SST on Figure 4a) as well the initial saturation level and therefore differs slightly from the values calculated by *Chase et al.* [2002]. Sensitivity tests showed that SST is the most important factor in determining the vertical temperature profile, which is consistent with the proposed regulatory mechanism. The convective heating process is fast enough to heat up the troposphere in several hours even over the lowest possible SSTs. Higher SSTs (such as occur in the Norwegian and Bering seas) would provoke even more vigorous convection. We also performed sensitivity tests for different initial temperature and moisture profiles. The low sensitivity to both profiles indicates that convective warming is likely to occur under many different conditions (relatively dry/moist, cold/warm airmasses).

[10] The second set of simulations represents the radiative cooling of the convectively warmed airmass as it moves over cold land/sea ice. Output from the warming simulation is used for an initial condition and is placed on either a snow/ice covered region or land with a prescribed surface temperature. Modifications also include prescribed stratospheric and tropospheric subsidence [following *Traub et al.*, 1995; and *Curry*, 1983 respectively]. Figure 4b depicts the radiative cooling simulation with a prescribed surface temperature of −23°C, stratospheric subsidence of -0.052 cm s^{-1} and a tropospheric subsidence of -0.1 cm s^{-1}.

[11] The cooling process is much slower than that of warming (compare with Figure 4a), mostly due to the stability associated with the development of surface-based temperature and moisture inversions. Variations in the initial moisture profile reveal the importance of a moisture inversion for isolating the troposphere from the surface: moister soundings with weaker inversions cool faster (8–12 days) than drier soundings (10–14 days) with strong inversions. Variations in prescribed surface temperature and initial vertical temperature profiles have only small effects on the cooling process. As expected the presence of subsidence leads to slower cooling rates, but is not dominant in maintaining the vertical temperature structure. The mid-troposphere remains near its original temperature until ~12 days into this simulation. The rate of cooling at 500 hPa averaged after several different simulations implies a 10–14 day timescale for Arctic airmass before the cooling reaches 500 hPa. This timescale agrees with *Curry* [1983], who found that continental polar airmasses evolve from maritime airmasses over approximately 14 days, but contrasts with shorter timescale proposed by *Fultz* [1986], who evaluated cold winter airmasses originating over land.

3. Summary and Implications

[12] *Chase et al.* [2002] proposed that the rarity of 500 hPa temperatures falling below −45°C in the Arctic can be explained by an SST regulation mechanism. This temperature threshold matches that predicted for moist adiabatic ascent over a sea surface near its salinity-adjusted freezing point. The present study provides further support for this hypothesis:

[13] 1. Convective activity is frequent over unfrozen water bodies in northern high latitudes. The Northern North Atlantic and the Northern North Pacific regions experience the most convection. As observed temperatures over Arctic land areas [*Chase et al.*, 2002] suggest an SST regulation, these high latitude ocean areas are proposed to be source areas for Arctic winter airmasses.

[14] 2. There is an agreement in both altitude and longitude between the peak convective activity and peak poleward energy transports into the winter Arctic [*Overland and Turet*, 1994]. This suggests that convection is an important energy source for Arctic airmasses in winter. Temporal agreement of the convective activity and poleward energy transport is currently under investigation.

[15] 3. SCM simulations indicate a 10–14 day timescale for airmasses to spend over land/ice before cooling down at 500 hPa.

[16] 4. If the main energy source is derived from the ocean surface, it would be difficult to significantly raise Arctic winter minimum mid-tropospheric temperatures without a corresponding rise in SSTs.

[17] The proposed mechanism has implications for changes in Arctic surface temperatures. *Kahl et al.* [2001] show that 500 hPa temperatures in the Arctic have not experienced any trend over the past 50 years, while surface air temperatures experienced a less than expected warming

trend [*Polyakov et al.*, 2002; *Przybylak*, 2002]. General circulation models (GCMs) predict the surface warming in the Arctic to be 3.5–5°C by the year 2100, i.e., 3–5°C/100 years [*IPCC*, 2001]; while the observed rates of Arctic warming over the 20th century are 0.5°C/100 years [*Polyakov et al.*, 2002]. Furthermore, the temporal and spatial expression of observed surface Arctic warming is not uniform, nor is it consistent with GCM simulations. Winter and spring seasons experience the most surface warming [*Serreze et al.*, 2000; *Przybylak*, 2002]. Spatially, winter Arctic surface warming appears to be confined to the cold dry anticyclonic regions [*Michaels et al.*, 2000], but model simulations of Arctic winter conditions do not reflect this.

[18] The connection between minimum mid-tropospheric temperatures and minimum surface temperatures over land during the Arctic winter has been discussed previously by *Chase et al.* [2002]. The regulation of mid-tropospheric temperature by convective processes implies a possible damping mechanism on surface temperature trends, particularly on the increase of minimum surface temperatures - one way for a warming climate to express itself. Assuming that IR balance in the Arctic winter conditions consists of upward (near black-body emission of the surface temperature) and downward (emission of the troposphere as a function of temperature) IR, and taking into account an SST control over the minimum mid-tropospheric temperatures, one can establish an indirect link of between SSTs and minimum surface temperatures. Considering the evidence above, a substantial increase in the minimum surface temperatures may depend on having warmer mid-troposphere. A change in minimum mid-tropospheric temperatures is complicated by the required preceding large increase in the SST and melting of sea ice, which thermal inertia makes difficult. That there is no observed trend in observed 500 hPa temperatures [*Kahl et al.*, 2001; *Chase et al.*, 2002] may explain the limited changes in the observed surface temperatures, compared to model predictions.

[19] **Acknowledgments.** The NCAR/NCEP Reanalysis data was obtained from the NCAR SCD Data archives. The NCAR CCM SCM 3.6 is obtained from NCAR. This research was supported by NSF Grants No. 0229973 001 and OPP-0240948. We thank anonymous reviewers for their thorough comments and suggestions.

References

Chase, T. N., B. Herman, R. A. Pielke Sr., X. Zeng, and M. Leuthold (2002), A proposed mechanism for the regulation of minimum mid-tropospheric temperatures in the Arctic, *J. Geophys. Res.*, *107*(D14), 4193, doi:10.1029/2001JD001425.

Curry, J. (1983), On the Formation of Continental Polar Air, *J. Applied Meteorol.*, *40*, 2278–2292.

Fultz, D. (1986), Residence Times and Other Time-Scales Associated with Norwegian Air Mass Ideas. *Namias Symposium*, Scripps Institution of Oceanography, Reference Series, 86-17, 82–102.

Grell, G. A. (1993), Prognostic Evaluation of Assumptions Used by Cumulus Parameterizations, *Mon. Wea. Rev.*, *12*, 764–787.

Hack, J. J. (1994), Parameterization of moist convection in the National Center fro Atmospheric Research community climate model (CCM2), *J. Geophys. Res.*, *99*(D3), 5551–5568.

Hack, J. J., J. A. Pedretti, and J. C. Petch (1999), *SCCM User's guide*, Version 1.2.

IPCC (2001), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the "Intergovernmental Panel on Climate Change* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson] Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 99–123, 525–575.

Kahl, J. D., M. Jansen, and M. A. Pulrang (2001), A. Fifty-year record of North Polar Temperatures Shows Warming, *Eos*, *82*(1), 1-1.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, Jenne, Roy, Joseph, and Dennis (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Michaels, P. J., P. C. Knappenberger, R. C. Balling Jr., and R. E. Davis (2000), Observed warming in cold anticyclones, *Clim. Res.*, *14*, 1–6.

Overland, J. E., and P. Turet (1994), Variability of the Atmospheric Energy Flux across 70°N Computed from the GFDL Data Set, *The polar Oceans and Their Role in Shaping the Global Environment*, geophysical monograph, AGU, 313–325.

Polyakov, I. V., G. V. Alekseev, R. V. Bekryaev, U. Bhatt, R. L. Colony, M. A. Johnson, V. A. Karklin, A. P. Makshtas, D. Walsh, and A. V. Yulin (2002), Observationally base assessment of polar amplification of global warming, *Geophys. Res. Lett.*, *29*(18), 1878, doi:10.1029/2001GL011111.

Przybylak, R. (2002), Changes in seasonal and annual high-frequency air temperature variability in the Arctic from 1951 to 1990, *Int. J. Climatol.*, *22*, 1017–1032.

Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry (2000), Observational evidence of recent change in the northern high-altitude environment, *Clim. Change*, *46*, 159–207.

Slingo, J. J. (1987), The development and verification of a cloud prediction scheme for the ECMWF model, *Q. J. R. Meteorol. Soc.*, *113*, 899–927.

Tiedtke, M. (1983), The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. ECMWF Workshop on Convection in Large-Scale Models, 28 November–1 December 1983, Reading, England, 297–316.

Traub, W. A., K. W. Jucks, D. G. Johnson, and K. V. Chance (1995), Subsidence of the Arctic stratosphere determined from thermal emission of hydrogen fluoride, *J. Geophys. Res.*, *100*(D6), 11,261–11,267.

Zhang, G. J., and N. A. McFarlane (1995), Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Centre Circulation Model, *Atmos.-Ocean*, *33*, 407–446.

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