JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D14, 10.1029/2001JD001425, 2002

A proposed mechanism for the regulation of minimum midtropospheric temperatures in the Arctic

T. N. Chase,[1] B. Herman,[2] R. A. Pielke Sr.,[3] X. Zeng,[2] and M. Leuthold[2]

Received 25 October 2001; revised 26 November 2001; accepted 30 November 2001; published 19 July 2002.

[1] This paper documents an observed lower extreme of midtropospheric (500 mbar) temperatures in the Arctic of approximately −45°C during the winter season in several data sets. Each data set shows that the coldest air masses in the Arctic reach −45°C during the fall months but seldom get much colder even into late winter despite a continued net radiative loss. We demonstrate that midtropospheric temperatures are significantly skewed toward warmer temperatures, indicating a regulatory mechanism at work. We further provide evidence that minimum Arctic midtropospheric temperatures are regulated by moist convective processes and that minimum 500 mbar temperatures are controlled to a large extent by high-latitude sea surface temperatures. The temperature −45°C is the expected 500 mbar temperature in an atmosphere regulated by moist adiabatic ascent from a surface temperature of 1°–2° below 0°C, the approximate freezing point of seawater. This implies that Arctic air masses are regularly in contact with unfrozen seawater to the south, an easily verified observation. Climate model simulations of the effects of increased greenhouse gasses hypothesize that high, northern latitude regions should warm at a faster rate than the globe as a whole, a hypothesis which does not appear to have strong observational support. We discuss the implications of this result for the accelerated Arctic warming hypothesis. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3314 Meteorology and Atmospheric Dynamics: Convective processes; 1699 Global Change: General or miscellaneous; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; *KEYWORDS:* Arctic convection, temperature regulation, atmosphere-ocean interactions

1. Introduction

[2] Figure 1 presents changes in the monthly averaged area of the −40°C, −42°C and −44°C, 500 mbar isotherm between 60° and 90°N since 1950 from the NCEP reanalysis [*Kalnay et al.*, 1996]. The main features which stand out from Figure 1 are that Arctic temperatures usually fall below −40°C by November. At temperatures much below −40°C, the overall area enclosed by the isotherm in question decreases precipitously. For example, the area of the −42°C isotherm is substantially smaller than the −40°C isotherm while the area enclosed by the −44°C isotherm approaches zero in all years. Seldom, during these months, do any points reach below −45°C and never during this time period was there a value less than −46°C in the monthly average. Because temperatures typically get colder than −40°C by late fall (November) it might be expected that much colder values would be reached in December, January or February as net radiative cooling continues. As demonstrated in Figure 1, this is not the case indicating a relatively consistent control over midtropospheric temperature during this season.

[3] Interestingly, this observed lower limit of approximately −40 to −45°C is in the range of what would be predicted for an atmosphere in moist adiabatic equilibrium with a surface temperature at, or slightly below, 0°C (Table 1). For example, at −2°C, the approximate absolute minimum temperature of an unfrozen sea surface during winter (e.g., given a salinity of 35%, sea ice would form at −1.9°C [*Holland et al.*, 1997; *Kiehl et al.*, 1996]), the 500 mbar temperature resulting from moist adiabatic ascent from the surface is slightly below −45°C. This is the observed annual lower limit in the monthly averaged data.

[4] A second feature of Figure 1 is that, over the last half-century, there is a weak, but statistically insignificant, decrease in the area of these coldest Arctic temperatures in these data. Table 2 gives linear regression trends and significance values by month for the period 1950–1998. All winter months (DJF) show small, insignificant decreases in the area enclosed by the coldest temperatures (i.e., a warming trend). This is, to some degree, consistent with other studies of Arctic temperature trends, which show some northern winter season warming since about 1950 [e.g., *Serreze et al.*, 2000; *Kahl et al.*, 2001].

[5] Given the observed association between 500 mbar and sea surface temperature and assuming it is unlikely to be a purely coincidental relationship, because it has been

---

[1] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.

[2] Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona, USA.

[3] Department of Atmospheric Science, Colorado State University, Ft. Collins, Colorado, USA.

0148-0227/02/2001JD001425$09.00

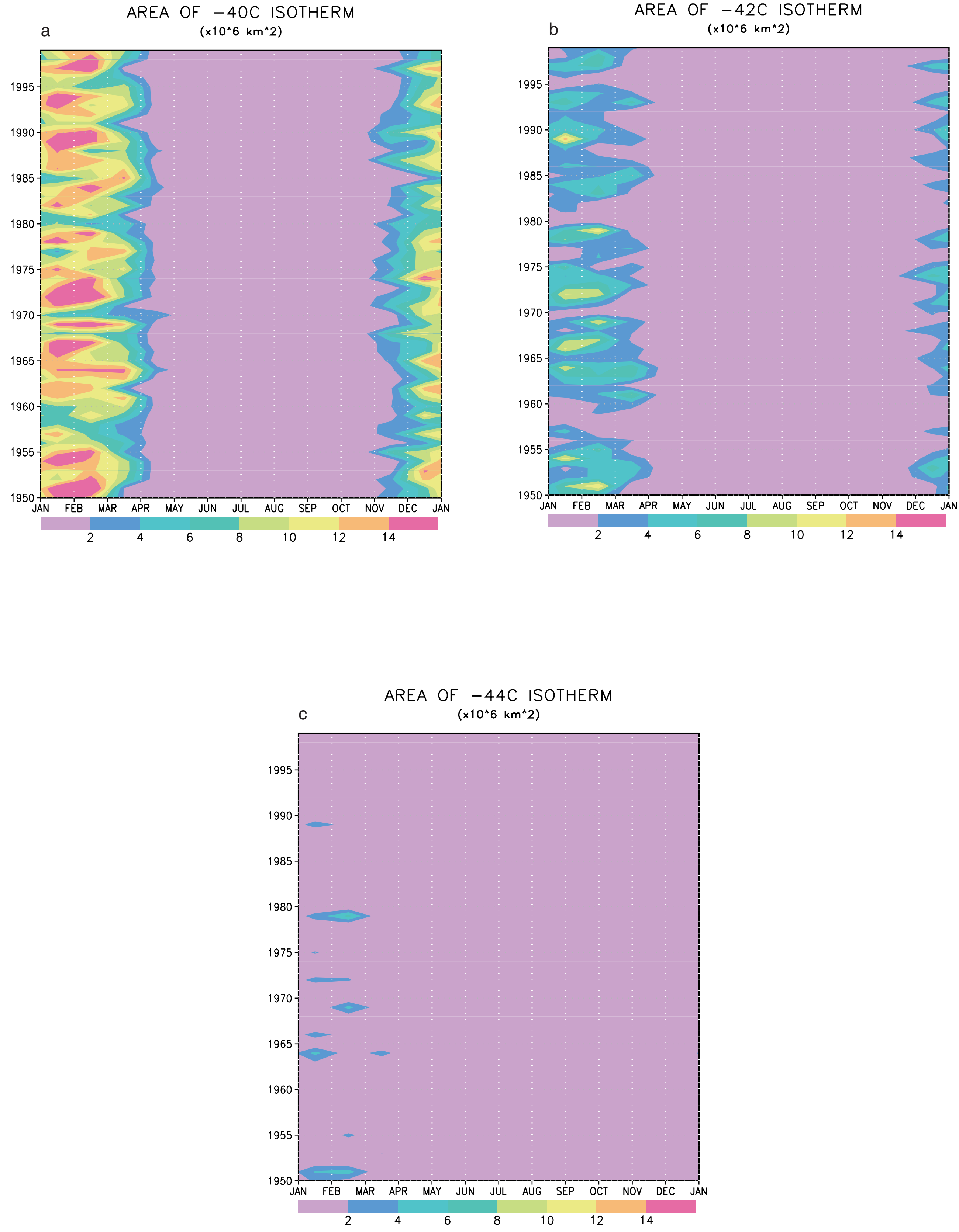

Figure 1. Reanalysis monthly averaged area enclosed by indicated isotherm during the period 1950–1998 north of 60°N. (a) −40°C isotherm, (b) −42°C isotherm, and (c) −44°C isotherm.

Table 1. Predicted Values of 500 mbar Temperatures Based on Moist Adiabatic Ascent of a Saturated Sea Level (1015 mbar) Parcel From Various Surface Temperatures

Surface Temperature (1015 mbar)	500 mbar Temperature
2°C	−39.9
1°C	−41.4
0°C	−42.5
−1°C	−43.8
−2°C	−45.2

robustly maintained over the course of half a century, a simple and appealing hypothesis is that Arctic air masses maintain enough contact with unfrozen sea surfaces in boreal winter that sea surface temperatures (SSTs) are able to maintain a control on midtropospheric temperatures throughout the Arctic. This implies that midtropospheric Arctic air masses (usually but not necessarily accompanied by very cold surface air) are dipping far enough south so that surface air beneath them is in contact with unfrozen seawater on a regular basis, an implication which can be easily verified by casual examination of daily Arctic weather charts. This contact allows quick warming of the coldest air masses through the depth of the lower troposphere by convective heating. Air masses so heated cool again once over sea ice or land, but this process is relatively quite slow, as the fastest cooling would occur from the extremely cold surface upward. This leaves midtropospheric temperatures relatively unaffected by the cooling process for long periods of time and does not generally allow cooling up to the 500 mbar level before another excursion over unfrozen water. We further investigate this hypothesis below.

2. HARA Rawinsonde Data

[6] While monthly averaged values give us a long-term view of the relationship between surface and 500 mbar temperatures, the NCEP reanalysis data at these high latitudes are not subject to as many observational constraints as in lower latitudes and are therefore less certain. Monthly averaging can also smear out real detail, particularly in extreme values. We therefore also examined twice-daily radiosonde observations from the Historical Arctic Rawinsonde Archive (HARA; *Kahl et al.* [1992]) for the years 1948–1991 as a second, quasi-independent data source. As a quality control measure in these data, soundings which had an established error in any field (not only temperature) according to the HARA documentation were removed from this analysis, as were any soundings which did not have information at at least 8 levels (presumably the mandatory levels). The total number of examined soundings for each month are as follows: January, 107,103; February, 98,605; March, 108,632; April, 106,061; May, 109,612; June, 103,742; July, 105,086; August, 105,915; September, 102,627; October, 106,065; November, 103,081; and December, 106,734. Table 3 gives the total number of soundings colder than the indicated temperature value at 500 mbar during the 1948–1991 time period and the percentage of all soundings for that month in parentheses. For example, in January, a total of 43,978 soundings were colder than −40°C at 500 mbar. Of these soundings, 29,171 were colder than −42°C, and so on.

[7] Table 3 corroborates the Arctic temperature picture derived from the reanalysis data as seen in Figure 1, though with more extremes, as would be expected from subdaily data relative to those averaged over a month. Table 3 shows 500 mbar temperatures first dipping below −40°C for more than isolated measurements in October, with large numbers of soundings first reaching this point in November. Again and most importantly, the proportion of the coldest soundings reached very early in the cold season (November and December) is barely exceeded in the later winter months, contrary to what might be expected in a region with no solar input for several months. In an average over the three coldest months (DJF), approximately 39% of soundings have temperatures below −40°C. This number again drops steeply for lower temperatures so that approximately 25% of soundings were colder than −42°C, 14% were colder than −44°C, 6% were colder than −46°C, and this percentage drops to near zero for temperatures less than −50°C. Again, a strong control on midtropospheric temperatures appears to be working, which limits minimum Arctic temperatures from falling much below −45°C for more than isolated periods.

[8] While not common, isolated observations significantly colder than −45°C do occur in the subdaily sounding data, as indicated in Table 3. For example, 2318 of the 312,442 measurements made at 500 mbar in December, January and February for the 1948–1991 period were below −50°C (i.e., less than 1% of the time). These atypical situations appear to arise primarily in areas where stationary upper level lows over high-latitude land areas allow air to stagnate for long periods without passing over open water and therefore to cool upward to the 500 mbar level.

[9] Figure 2 shows a histogram of December, January and February temperature measurements at 500 mbar in the HARA data. The distribution clearly deviates from normal and is skewed toward warmer values (skewness = 0.50) as would be expected should a control on minimum temperatures be active. Three statistical tests on the normalcy of the distribution (Kolmogov-Smirnov test, Cramer Von Mises test and the Anderson-Darling test) all show a deviation from normalcy at the 99% confidence level or greater.

[10] We next investigated the vertical structure of the coldest air masses in the HARA data as these are the soundings most likely to exhibit the thermal structure associated with a control on minimum temperatures. Table 4 shows the average vertical temperature structure of the coldest Arctic soundings (defined as soundings where the 500 mbar temperature is colder than −42°C) over land from 1948–1991. The presence of the air mass over land exerts a strong cooling influence over an air mass recently warmed over open water and this cooling from the

Table 2. Linear Trend and p Value in Parentheses by Month for the Areas Depicted in Figure 1[a]

Month	−40°C	−42°C	−44°C
Dec.	−36,192 (0.27)	−14,192 (0.27)	−622 (0.90)
Jan.	−1425 (0.97)	−10,122 (0.75)	−17,707(0.14)
Feb.	−9934 (0.79)	−30,752 (0.29)	−14,525 (0.29)

[a] Linear trends are given in units of 10^6km^2/yr. No seasonally averaged (DJF) trend is statistically significant at the 90% level or higher.

Table 3. Total Number of Sounding Measurements Colder Than Indicated Temperature at 500 mbar Among 183 HARA Land Stations During 1948–1991, North of 60°N[a]

Month	−40°C	−42°C	−44°C	−46°C	−48°C	−50°C
Jan.	43,978(41)	29,171(27)	16,286(15)	7169(7)	2432(2)	654(1)
Feb.	39,869(40)	26,352(27)	14,905(15)	6876(7)	2587(3)	751(1)
March	36,868(34)	22,637(21)	11,757(11)	4795(4)	1524(1)	341(0)
April	16,523(16)	7763(7)	2888(3)	868(1)	232(0)	69(0)
May	1177(1)	361(0)	103(0)	48(0)	26(0)	17(0)
June	70(0)	39(0)	28(0)	25(0)	22(0)	20(0)
July	38(0)	36(0)	30(0)	23(0)	16(0)	11(0)
Aug.	41(0)	32(0)	22(0)	17(0)	9(0)	6(0)
Sept.	415(0)	156(0)	79(0)	47(0)	28(0)	24(0)
Oct.	6305(6)	2378(2)	720(1)	180(0)	73(0)	34(0)
Nov.	24,752(24)	13,128(13)	5612(5)	1848(2)	458(0)	106(0)
Dec.	37,943(36)	23,616(22)	12,131(11)	4829(5)	1461(1)	346(0)

[a] Percentages of total soundings for the month (from the list in section 2) are given in parentheses. (Note that the coldest categories are subsets of all warmer categories.)

surface upward should be evident in this average sounding as should a moist adiabatic structure in the midtroposphere. The 500 mbar temperature is indeed approximately −44.5°C as would be predicted from moist adiabatic ascent. However, between the surface and 500 mbar, the sounding is substantially colder for the moist adiabat with a surface temperature of approximately −2°C, with the deviation from moist adiabatic increasing towards the surface. This is consistent with a process whereby cooling from the surface upward is affecting air masses warmed over oceans. By 400 mbar, the average sounding is warmer than expected by moist adiabatic ascent, though this level would be expected to regularly be above the tropopause during boreal winter and so subject to stratospheric thermal processes.

[11] The data in Table 4 are consistent with a cooling of a moist adiabatic profile once an air mass has moved over land. We therefore also examined all Arctic soundings for indications of convective control in the low troposphere to midtroposphere. Table 5 shows the total number of all soundings which are colder than indicated temperature thresholds. Table 5 indicates that at about 550–500 mbar, it is very unlikely for a temperature to ever drop much below that predicted by moist adiabatic ascent from a surface temperature of approximately −2°C. Below 550 mbar, temperatures begin to drop below this threshold and this becomes more common as the surface is approached. This feature is also consistent with the proposed idea that soundings over land are cooled slowly, relative to convective heating rates over open oceans, from the surface upward.

3. Arctic Marine Sounding Data

[12] We also examined data from the NCAR/NCEP Arctic Marine Rawinsonde Archive data set [*Kahl et al.*, 1992] which is available for the years 1976–1996 and represents ocean and iced-over stations north of 65°N. Metadata on the surface condition (iced over or open ocean) is not available for each individual sounding. For our discussion it is important to differentiate between sea ice and open ocean. In these data we assume that stations with a

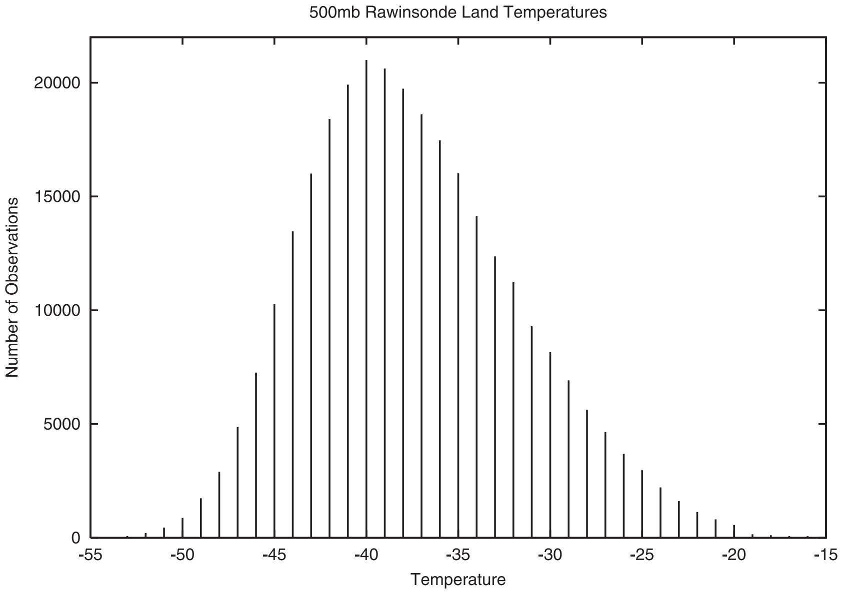

Figure 2. Histogram of the HARA rawinsonde 500 mbar temperature observations for December, January, February 1948–1991.

Table 4. Average of 75,891 of the Coldest Arctic Land Soundings (Soundings Where 500 mbar Temperature is Colder Than −42°C)[a]

	Surface	900 mbar	850 mbar	700 mbar	600 mbar	500 mbar	400 mbar	300 mbar
Temperature	−32.1	−28.0	−26.3	−30.8	−37.2	−44.0	−51.4	−58.2
Deviation		−20	−15	−8	−4	0	8	17

[a] The second row gives the deviation of the observed temperature from the moist adiabat from 1015 mbar and −2°C to the nearest whole number.

surface temperature of less than −3°C are completely iced over and so are representative of conditions on sea ice. While it is possible for surface air temperatures to be somewhat different than ocean temperatures on short timescales, this threshold should minimize that possibility and ensure that these soundings are representative of ice-covered regions. Stations with surface temperatures warmer than −1.5°C are considered as representative of open ocean.

[13] We examine DJF soundings over open ocean for consistency with the proposed regulation mechanism. Supporting evidence would include measurements at 500 mbar which almost never went below the moist adiabatic temperature at 500 mbar of −45°C and additionally, a moist adiabatic thermal structure for the coldest soundings reflecting recent moist adiabatic adjustment as cold air masses moved out over open water.

[14] At 500 mbar, 2390 soundings were taken over open water for DJF in the years 1976–1996. Of these, four were colder than −45°C at 500 mbar, indicating a strong threshold on minimum temperature. In contrast, of 875 marine soundings over sea ice in this season, 76 (9%) of them were colder than −45°C at 500 mbar.

[15] Our second test was performed by identifying the coldest soundings over open water at 500 mbar. These soundings should have recently been convectively adjusted and therefore should exhibit a moist adiabatic structure from the surface at least to 500 mbar. Table 6 gives results from averaging 299 soundings where the 500 mbar temperature was below −38°C. Using −38°C allows us to account for the fact that some soundings are adjusting from surface pressures of considerably less than 1015 mbar (used in the calculations for Table 1) and may therefore be warmer at 500 mbar than a sounding adjusting from 1015 mbar. The use of a colder cutoff point has little effect on the result, however.

Table 5. DJF Arctic Land Surface Soundings for 1948–1991[a]

Level, mbar	*T* Average	SOUND	MA	MA-2	MA-4
300	−57.0	29,4496	15(0)	10(0)	7(0)
350	−52.4	129,638	44(0)	21(0)	9(0)
400	−47.6	292,321	441(0)	144(0)	90(0)
425	−44.3	14,646	127(1)	27(0)	9(0)
450	−42.2	112,872	3325(3)	735(1)	102(0)
475	−39.0	15,651	844(5)	310(2)	65(0)
500	−37.8	296,381	33,558(11)	13,655(5)	4401(1)
525	−34.7	16,648	1729(10)	924(6)	398(2)
550	−33.4	117,942	25,569(22)	13,432(11)	6252(5)
575	−30.8	17,825	4018(22)	2367(13)	827(5)
600	−30.2	118,275	44,623(38)	30,552(26)	18,166(15)
650	−26.5	110,043	51,431(47)	38,741(35)	26,658(24)
700	−23.6	298,151	158,977(53)	124,619(42)	90,057(30)
750	−21.8	123,347	82,262(67)	71,449(58)	59,139(48)
800	−20.7	118,846	90,915(76)	82,960(70)	73,872(62)
850	−18.6	320,529	251,574(78)	229,042(71)	204,071(64)
900	−20.3	112,648	99,306(88)	95,597(85)	91,129(81)
950	−21.2	129,590	119,258(92)	116,267(90)	112,635(87)

[a] Columns are as follows: column 1, pressure level; column 2, average temperature; column 3, total number of measurements at that level; column 4, number of soundings where temperature was colder than moist adiabatic (starting from a surface of approximately −1.5°C) at that level (MA); column 5, number of soundings where temperature was 2° colder than moist adiabatic (MA-2); and column 6, number of soundings where temperature was 4° colder than moist adiabatic (MA-4). The percentages of total soundings are given in parentheses in columns 4, 5, and 6.

[16] From Table 6 it is clear that the average sounding is within 2.5° at every level to that predicted except above 500 mbar. The average sounding is slightly colder than moist adiabatic which can be accounted for by shallow dry ascent near the surface for a convectively adjusting parcel.

4. High-Latitude Convective Activity

[17] We also examined monthly averaged convective heating rates from the NCEP reanalysis in high northern latitude ocean regions for evidence of strong convective heating. While not a directly observed field in the NCEP reanalysis, Arctic precipitation patterns appear realistic [*Serreze and Maslanik*, 1997]. Convective heating rates, however, should be considered a reasonable estimate in these data. Table 7 gives average heating rates over the indicated regions covering the North Atlantic and North Pacific in February 1990. This table indicates that convective heating is indeed an important heating process throughout the lower troposphere when averaged over both ocean basins at high latitudes, even in the monthly average, and are comparable to longwave cooling rates.

[18] However, convective activity, and therefore convective heating, will be strongest in the coldest air masses as they move out over open water and occurs in limited regions at any one time. The convective heating term in these cases can, therefore, be significantly larger than in a large area average given in Table 7. This point is demonstrated in Figure 3 which shows the actual convective

Table 6. DJF Arctic Marine Soundings for 1976–1996[a]

Level	*T* Observed	*T* Predicted
300	−56.6	−71.0
400	−50.2	−54.0
450	−46.0	−47.0
500	−40.0	−40.0
550	−35.1	−34.0
600	−29.6	−29.0
650	−24.8	−23.5
700	−21.1	−19.0
750	−17.4	−15.0
850	−10.3	−8.0
900	−7.0	−4.5
995	2.1	1.0

[a] Columns are as follows: column 1, pressure level; column 2, observed average temperature; and column 3, predicted temperature from skew *T* from moist adiabat intersecting the average observed 500 mbar temperature.

Table 7. February 1990 Convective Heating Rate Averaged Over the North Pacific Region (135°E–120°W, 50°–62°N) and North Atlantic Region (55°W–30°E, 50°–75°N) Combined[a]

Pressure	Convective Heating, K/d	LW Heating, K/d
314	0.00	−0.65
374	0.01	−0.88
438	0.06	−1.27
504	0.12	−1.38
571	0.21	−1.40
636	0.37	−1.51
697	0.57	−1.45
754	1.06	−1.45
805	1.19	−1.49
850	0.95	−1.56
888	0.60	−1.11
920	0.43	−1.10
947	0.11	−1.10
969	−0.63	−0.72
987	−1.06	−0.68
1000	−0.93	−0.63

[a] Convective heating over land in this season is negligible. (Note that convective heating data are originally on sigma levels and pressure levels are estimated from sigma levels using climatological surface pressure data.)

heating rate at approximately 500 mbar averaged over the month of February, 1990. As can be seen in this figure, 500 mbar convective heating rates can be quite substantial, exceeding 2.5 K/d in some North Atlantic locations averaged over this month. We emphasize that monthly averages tend to smooth out the largest day-to-day values, so some instantaneous convective heating rates would be expected to be substantially larger.

5. Discussion and Conclusions

[19] We examined the hypothesis that Arctic air masses maintain enough contact with unfrozen sea surfaces in boreal winter so that sea surface temperatures (SSTs) are able to maintain a control on midtropospheric temperatures throughout the Arctic. That midtropospheric air masses dip far enough south on a regular basis to come into contact with open seawater can be confirmed by the examination of daily weather charts and is not examined in detail here. We did, however, examine the consequences for tropospheric thermal structure expected from such contact and have given evidence consistent with a warming of the coldest Arctic air masses through the depth of the lower troposphere by convective heating when air masses move out over open water and the cooling from the surface upward as the air mass moves over sea ice or land. This cooling from the surface upward is relatively quite slow allowing the midtroposphere to remain generally unaffected by cooling except in unusually stagnant air masses. A fundamental convective control is therefore established on the temperatures of midtropospheric Arctic air masses limiting 500 mbar cooling to approximately −45°C in northern winter. This regulatory mechanism is, by itself, of interest and requires further documentation and comparison with model simulations. Furthermore, this midtropospheric temperature regulation may also have implications for surface air temperature trends in the Arctic winter, a region and season where accelerated warming trends are simulated by greenhouse gas model scenarios.

[20] Observed trends in Arctic surface temperatures appear largely distinct from those simulated by anthropogenic greenhouse gas warming scenarios which suggest that Arctic surface temperatures should be highly sensitive to the radiative effect of rising levels of greenhouse gasses and should exhibit accelerated warming relative to the rest of the globe. Recent observations show that, contrary to this hypothesis, Arctic surface temperatures are rising at a significantly lesser rate (2–3 times) than those of the planet as a whole [*Kahl et al.*, 1996; *Przybylak*, 2000].

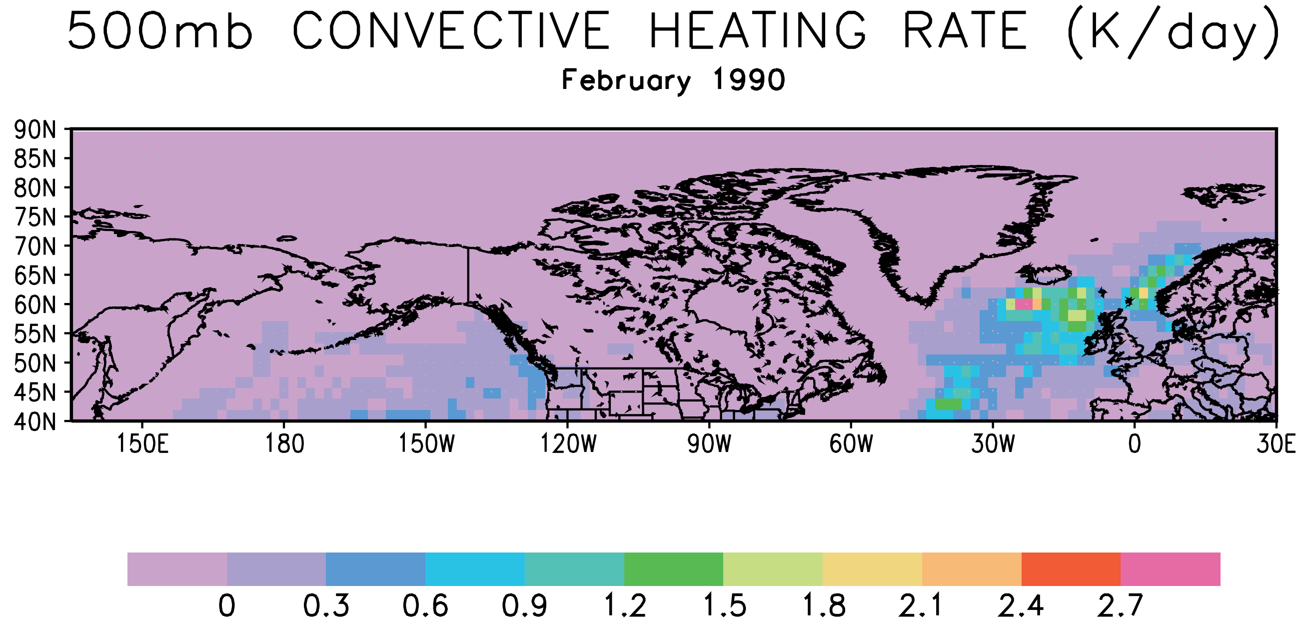

Figure 3. Convective heating rate in K/d averaged over the month of February 1990 at approximately 500 mbar.

Additionally, there is little observational evidence for an enhanced warming occurring mostly in winter: another hypothesis based on results from greenhouse gas simulations. For example, *Przybylak* [2000] showed that most of the recent, significant Arctic surface warming has occurred in the warm season. Perhaps more importantly, the observed Arctic surface warming trend in the past few decades follows an unusually cold period. Arctic surface temperatures are now approximately the same as earlier in the century and little, if any, surface warming is indicated in the Arctic as a whole since the 1930s [*Serreze et al.*, 2000, Figure 3].

[21] The evidence presented here indicates that midtropospheric temperatures in the Arctic are primarily controlled by moist adiabatic processes determined by open ocean temperatures rather than by direct heating from the surface. The midtroposphere contributes a substantial fraction of downward infrared radiation during the winter months, a period when incoming solar radiation and conduction from the surface (due to thermal insulation of snow cover and sea ice) can be considered negligible. Therefore surface air temperatures must be in quasi-radiative equilibrium with the midtroposphere during the winter months. Because downward radiation arriving at the surface is a strong function of midtropospheric temperatures, the coldest Arctic surface temperatures experienced must also be a strong function of midtropospheric temperature. We have shown several lines of evidence that extremes in Arctic, wintertime, midtropospheric temperatures are regulated by SST, rather than by other factors, such as changes in atmospheric CO_2. Future warming in this region would then require that large amounts of sea ice melt and the significant warming of SSTs. Minimum temperatures in the Arctic would then be free to rise allowing a significant overall warming. Such a regulatory mechanism as proposed here may therefore help explain the disparity between model simulations and observations in the Arctic if, for instance, the details of Arctic convection or the migration of Arctic air masses was incorrectly simulated.

[22] **Acknowledgments.** This work was supported by a grant from the Cooperative Institute for Research in Environmental Sciences. The National Snow Ice Data Center (NSIDC) provided the HARA data and the NCAR/NCEP Arctic Marine Rawinsonde Archive. NCAR/NCEP reanalysis monthly averages were obtained from the National Center for Atmospheric Research (NCAR) which is sponsored by the National Science Foundation. We thank both NSIDC and NCAR for making these data freely and easily accessible. We also thank Steven Pawson and two anonymous referees for their helpful comments.

References

Holland, M. M., J. A. Curry, and J. L. Schramm, Modeling the thermodynamics of a sea ice thickness distribution, 2, Sea ice/ocean interactions, *J. Geophys. Res.*, *102*, 23,093–23,108, 1997.

Kahl, J. D., M. C. Serreze, S. Shiotani, S. M. Skony, and R. C. Schnell, In situ meteorological sounding archives for arctic studies, *Bull. Am. Meteorol. Soc.*, *73*, 1824–1830, 1992.

Kahl, J. D. W., D. A. Martinez, and N. A. Zaitseva, Long-term variability in the low-level inversion layer over the Arctic ocean, *Int. J. Clim.*, *16*, 1297–1313, 1996.

Kahl, J. D. W., M. Jansen, and M. A. Pulrang, Fifty year-record of North Polar temperatures shows warming, *Eos Trans. AGU*, *82*, 1, 2001.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Kiehl, J. T., B. Boville, B. Briegleb, J. Hack, P. Rasch, and D. Williamson, Description of the NCAR Community Climate Model (CCM3), *NCAR Tech. Note NCAR/TN-420+STR*, Boulder, Colo., 1996.

Przybylak, R., Temporal and spatial variation of surface air temperature over the period of instrumental observations in the Arctic, *Int. J. Clim.*, *20*, 587–614, 2000.

Serreze, M. C., and J. A. Maslanik, Arctic precipitation as represented in the NCEP/NCAR reanalysis, *Ann. Glaciol.*, *25*, 429–433, 1997.

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, Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207, 2000.

T. N. Chase, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA. (tchase@cires.colorado.edu)

B. Herman, M. Leuthold, and X. Zeng, Department of Atmospheric Sciences, University of Arizona, Tucson, AZ 85721, USA. (herman@air.atmo.arizona.edu)

R. A. Pielke Sr., Department of Atmospheric Science, Colorado State University, Ft. Collins, CO 80523, USA. (pielke@snow.atmos.colostate.edu)