JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, XXXXXX, doi:10.1029/2008JD009799, 2008

Update on a proposed mechanism for the regulation of minimum midtropospheric and surface temperatures in the Arctic and Antarctic

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Received 8 January 2008; revised 28 August 2008; accepted 12 September 2008; published XX Month 2008.

[1] This paper is an update from our earlier paper to include data through July 2008. In our earlier paper, which included data through 1998, a mechanism which generally limits Arctic minimum 500 mb temperatures to the −40°C to −45°C range was presented. The current paper is in agreement with those earlier findings and also shows some evidence of later autumn onset dates of the initial appearance of these temperatures, in agreement with the recent reduction of Arctic sea ice cover in the summer and fall. In the southern hemisphere, little change can be seen for the seasonal onset and end of the temperatures reaching −40°C area, while the appearance of temperatures reaching −44°C area seems to show a later onset date beginning about 1998, but this time period is too small to define a clear trend. The limiting of the minimum of these midtropospheric temperatures has important implications for minimum surface temperatures that can occur over land during the Arctic winter.

Citation: Herman, B., M. Barlage, T. N. Chase, and R. A. Pielke Sr. (2008), Update on a proposed mechanism for the regulation of minimum midtropospheric and surface temperatures in the Arctic and Antarctic, *J. Geophys. Res.*, *113*, XXXXXX, doi:10.1029/2008JD009799.

1. Introduction

[2] *Chase et al.* [2002] presented a proposed mechanism for the regulation of minimum midtropospheric temperatures in the Arctic (here taken to be the region of the Earth north of 60°N latitude) in observational data which were later supported by model simulations [*Tsukernik et al.*, 2004]. The data set used in the original observational paper covered the period from 1950 to 1998. This paper extends the data set through July 2008. The purpose of the original work and the current paper is to document the apparent lower limit of midtropospheric (here the 500 mb level is used to represent the midtroposphere) temperatures to about −45°C during the winter season. Temperatures of −40°C or lower are usually first reached near the end of October or early November in the Northern Hemisphere but rarely get lower than −45°C through the rest of the winter season. A similar regime is present in the Antarctic, as shown in the earlier paper. It appears that some process is preventing this air from further cooling in spite of the continued net radiative loss as winter continues. The additional data provided here shows similar results but it appears that there is a slight trend for the first appearance of the −40°C temperatures to be later in the fall. We have, however, not seen any evidence that our original hypothesis as to the controlling mechanism is invalid.

2. Background

[3] Data was presented in the earlier paper [*Chase et al.*, 2002] to substantiate the claim that once 500 mb temperatures in high latitudes reach the −40°C level, usually in late October or early November, they rarely fall below −45°C for the rest of the winter. Figure 1 is an updated version of Figure 2 of the earlier paper including data through December 2007 using daily mean National Centers for Environmental Prediction (NCEP) Reanalysis data [*Kalnay et al.*, 1996]. The Reanalysis data are most reliable in the Arctic for the period since 1979 when satellite observations were included. Winter data at high latitudes prior to 1979 are most suspect as few ship observations were taken at this time of year. A lack of winter observations prior to 1979 mostly affects Antarctica [*Bromwich et al.*, 2007]. However, the pre-1979 isotherm climatology is similar to the post-1979 climatology so we included the entire period in our analysis.

[4] This histogram in Figure 1 shows the total area encompassed within a ΔT of 1°C centered about the abscissa value. For example, the −40°C accumulated area is the area encompassed by the −40°C ± 0.5°C isotherms for the reanalysis period 1948–2007. This histogram shows the same rapid drop-off of temperatures below −40°C compared to those in the radiosonde data in the earlier paper. Thus, the encompassed area of −50°C is about 0.4 ×

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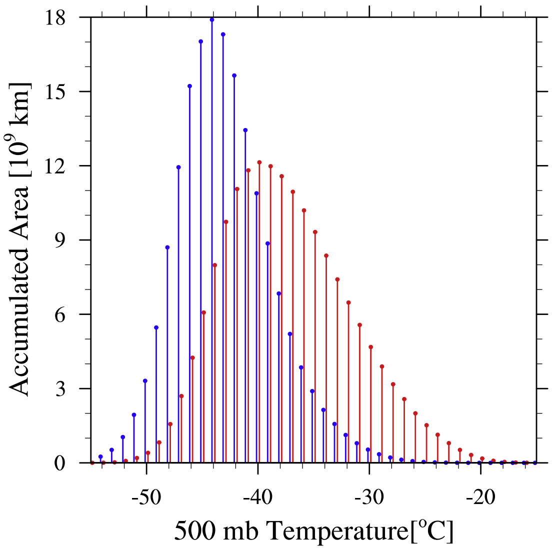

Figure 1. The accumulated area of 500 mb air having temperature centered on a 1°C bin from January 1998 to December 2007 using daily National Centers for Environmental Prediction Reanalysis data. Arctic data is shown in red, and Antarctic data is shown in blue.

10^9 km^2 compared to about 4.7 × 10^9 km^2 at −30°C. The same −40°C to −45°C limit appears to be in effect in the Antarctic also, although the peak is at about −44°C. Clearly, there must be some mechanism preventing further cooling in spite of a continuing net radiative loss throughout the winter season.

[5] That mechanism is hypothesized to be convectively transported heat from unfrozen ocean surfaces combined with latent heating due to moist adiabatic ascent. Cold continental air in winter that passes over unfrozen water is rapidly heated from below, causing convection to occur, usually within hours after passing over the water. Moist adiabatic ascent from the surface to 500 mb will yield 500 mb temperatures from about −38°C to −42°C for surface temperatures ranging from +2°C to −2°C. Upon passing once again over land, the air rapidly cools near the ground creating a very stable vertical temperature profile, inhibiting vertical mixing. Thus, the only way for cooling to extend up to the 500 mb level is by conduction or radiation by the atmosphere, both very slow processes. In the work of *Tsukernik et al.* [2004], calculations of radiative cooling for a variety of conditions were presented. These calculations showed that about 8–14 days are required for radiative cooling to be significant at the 500 mb level under a range of typical high-latitude winter conditions over land. In most instances, the air will have once again passed over open water before appreciable cooling at the 500 mb level can occur. The stronger zonal circulation in the Southern Hemisphere (SH) may allow air to remain over the icecap somewhat longer than in the Northern Hemisphere (NH), thus allowing for slightly lower temperatures to be reached there. This may account for the peak in the SH histogram to be at a slightly lower temperature. This periodic passing over unfrozen ocean is an effective way to limit how cold the midtropospheric air can get.

[6] Figure 2 illustrates the transformation of a very cold air mass passing over unfrozen ocean. In Figure 2, a series of soundings is generated from the reanalysis data along an offshore flow pattern. The soundings have been chosen to be along the path of a nearly constant westerly airflow and therefore closely represent the changes of the air parcels as they move along with the wind. The first sounding is over the bay of Ungava along the north coast of Labrador. The bay is typically frozen at this time of the year and the sounding shows a strong surface inversion, also typical for this time of the year. As the air passes over unfrozen water in the north Atlantic, the surface temperature begins to increase. By longitude 302.5°E, the low-level inversion is almost totally destroyed. At longitude 315.0°E, the surface warming has totally destroyed the inversion, the surface temperature has increased to about +4°C, and a nearly dry adiabatic lapse rate exists up to about 900 mb. Above this level the air is nearly saturated up to about 400 mb with a nearly moist adiabatic lapse rate from 900 mb up to that level.

[7] A very significant secondary result of this process is its effect on surface temperatures over land in the winter. To a first approximation, conduction of heat from below to the surface air can be neglected due to the poor conductivity of snow. Under clear, calm conditions, minimum night surface temperatures, also to a close approximation, will be reached when there is a balance between incoming and outgoing IR radiation. To a large extent, the incoming (downward) radiation will be determined by the vertical temperature distribution of the atmospheric column. Assuming the surface emits as a blackbody while each layer of the atmosphere emits at only a fraction of that of a blackbody, it is clear that equilibrium will be reached when the ground is significantly colder than the effective radiating tempera-

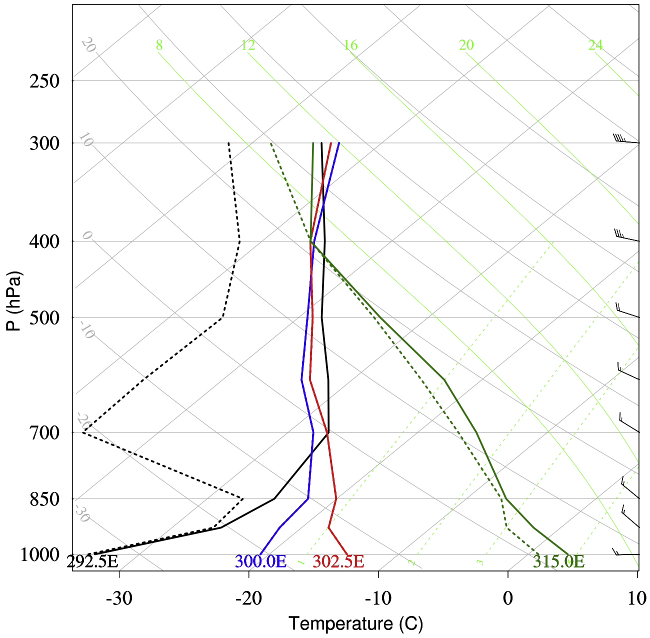

Figure 2. Longitudinally adjacent profiles at 60°N from 13 January 2005 showing temperature (solid line), dewpoint (dotted line), and mean wind barbs of the four profiles.

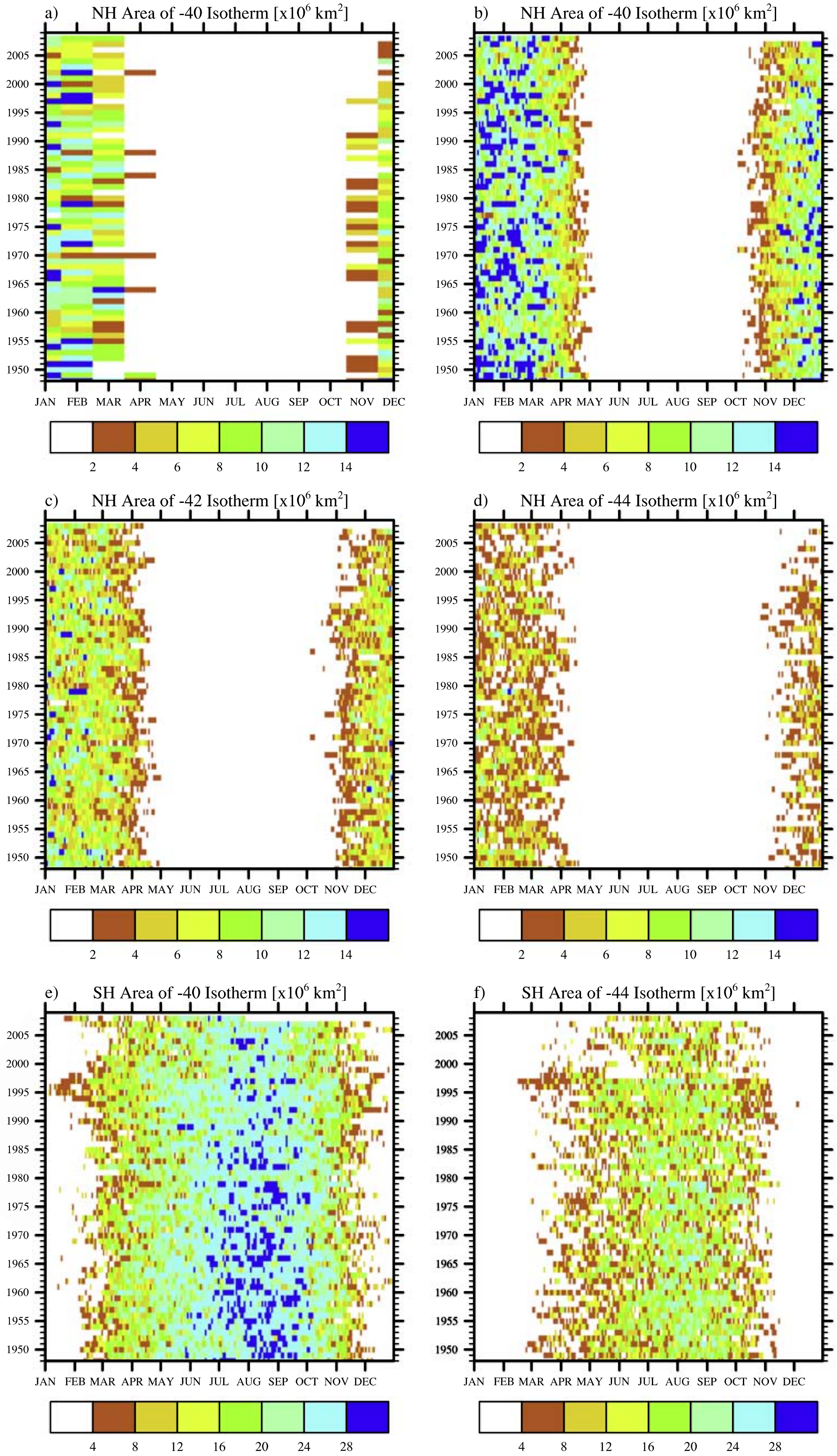

Figure 3. Arctic area in 10^6 km^2 enclosed by the 500 mb (a) monthly mean -40°C isotherm, (b) daily mean -40°C isotherm, (c) daily mean -42°C isotherm, and (d) daily mean -44°C isotherm. Antarctic area in 10^6 km^2 enclosed by the 500 mb (e) daily mean -40°C isotherm, and (f) daily mean -44°C isotherm. All plots use Reanalysis data for the period January 1948 to July 2008.

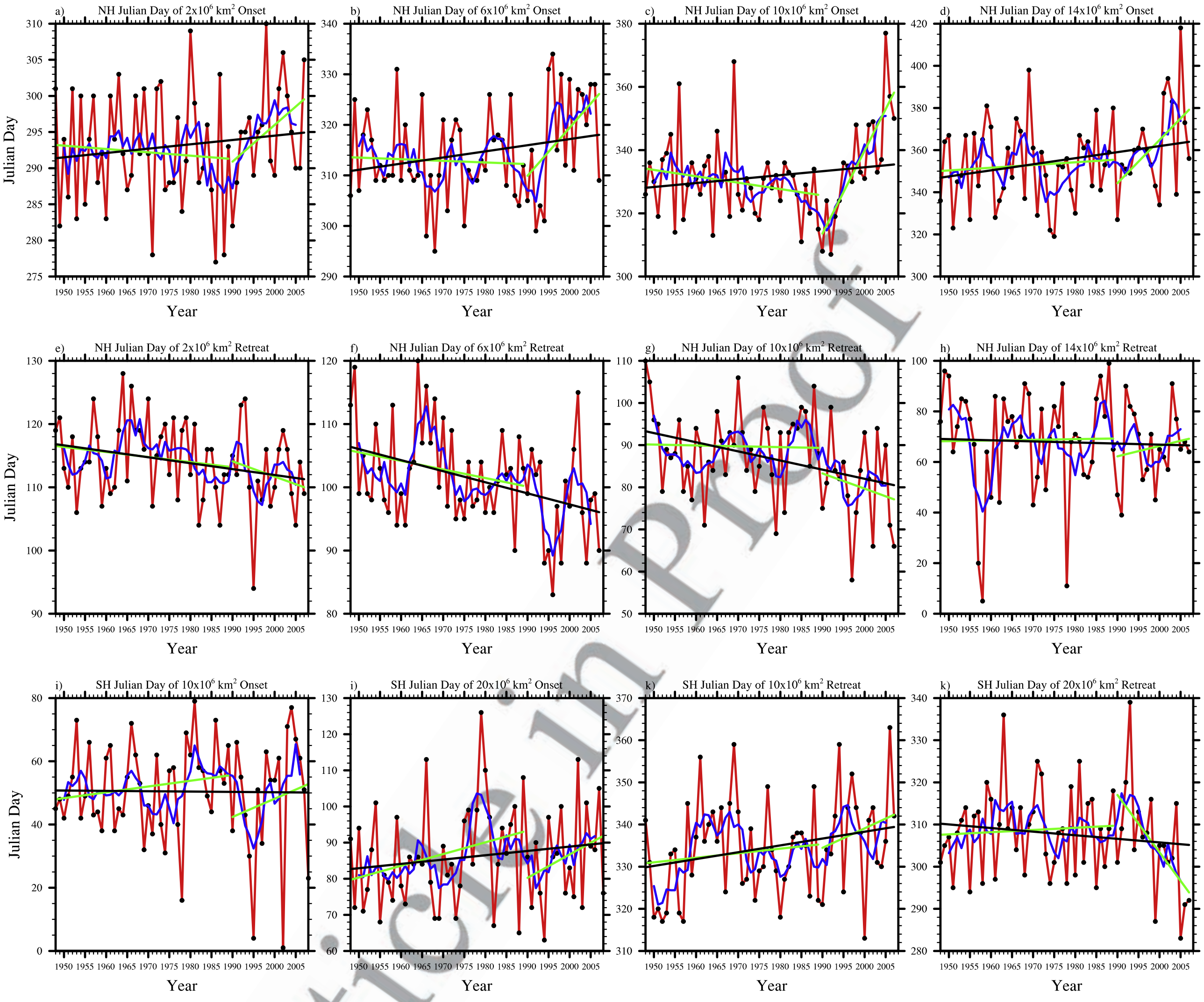

Figure 4. (a–d) First date in autumn and (e–h) last date in spring when 2, 6, 10, and 14 × 10^6 km^2 of the Northern Hemisphere has 500 mb air temperature of −40°C or lower. (i and j) First date in autumn and (k and l) last date in spring when 10 and 20 × 10^6 km^2 of the Southern Hemisphere has 500 mb air temperature of −40°C or lower. Reanalysis data are in red, 5-year running mean is in blue, full time series trend line is in black, and pre- and post-1990 trend lines are in green.

ture of the overlying atmosphere. Here we have assumed the 500 mb temperature is indicative of the effective radiating temperature of the atmosphere. Thus, the higher the 500 mb temperature, the higher the minimum surface temperature will be at radiative equilibrium. Conversely, the lower the 500 mb temperature, the lower the minimum surface temperature will be. This can readily be confirmed by casual examination of the 500 mb temperatures directly over the coldest surface air over land in the winter. The end result of this argument is that apparently the lowest winter temperatures over land are not primarily limited by greenhouse effects but in fact may very well be mainly controlled by sea surface temperatures. As long as there is sea ice cover, the lowest sea surface temperatures will be found bordering the ice and will be in the −2°C to +2C° range limiting minimum 500 mb temperatures to the −40°C to −45°C range, as indicated earlier, with extreme minimum surface temperatures similar to what are currently observed. If the extent of the ice-covered region continues to diminish, then the area of −40°C to −45°C at 500 mb will diminish, restricting the area where the lowest surface temperatures

Table 1. Trends for the Fall Onset Date of Selected Spatial Areas of −40°C 500 mb Temperature Shown for the Entire Time Series and for the Time Series Before and After 1990[a]

Onset Area (10^6 km)	Trend (day/year)	p	Pre-1990 Trend (day/year)	Post-1990 Trend (day/year)	p
2	0.06	0.71	−0.05	0.51	0.90
6	0.12	0.92	−0.03	0.95	0.94
10	0.12	0.78	−0.20	2.62	1.00
14	0.29	0.95	0.13	2.05	0.94

[a] For the entire time series trend, p values from a statistical t-test show the probabilities that the trend is different from zero. For the pre- and post-1990 trends, p values show the probability that the trends are statistically different. The mean onset Julian days for the four areas are 292, 313, 325, and 338, respectively.

Table 2. Same as Table 1, but for Spring Retreat Date[a]

Retreat Area (10^6 km)	Trend (day/year)	p	Pre-1990 Trend (day/year)	Post-1990 Trend (day/year)	p
2	−0.09	0.95	−0.08	−0.24	0.37
6	−0.18	0.99	−0.14	−0.07	0.05
10	−0.22	0.99	−0.02	−0.36	0.49
14	−0.04	0.23	0.03	0.41	0.39

[a] The mean retreat Julian days for the four areas are 114, 103, 91, and 79, respectively.

can occur. Carrying this argument to an extreme, if the ice caps were to totally disappear by the end of this century as some are predicting [e.g., *Holland et al.*, 2006] then the minimum surface temperatures will start to rise, controlled by minimum sea surface temperatures, as discussed above. In fact, there may be some evidence already that the area of −40°C at 500 mb is starting to diminish, at least during the onset period in late October or November as will be shown in section 3. This could be due to the reduction of ice cover in the Arctic during the fall, probably itself a result of the greatly reduced ice cover in summer. It will take more years of observation to confirm the hypothesis that the delay of onset of −40°C temperatures in the fall are due to reduced ice cover at that time, but the evidence to date is supportive. In the following section, updated data on the extent of −40°C or lower temperatures at 500 mb will be presented, as well as other related data.

3. Discussion

[8] Figure 3a shows the NH 500 mb areas enclosed by the −40°C isotherm as obtained from the monthly NCEP Reanalysis data. Figure 3a extends the data shown in Figure 1 of the earlier paper [*Chase et al.*, 2002] by over 10 years. Similar results are seen in ECMWF Reanalysis (not shown). Figures 3b–3d also show the daily areas enclosed by the −40°C, −42°C, and −44°C isotherms with better resolution than the monthly averages shown in Figure 3a. In the following, onset date is defined as the first date of the ice season when an isotherm enclosing a specified spatial area occurs. Likewise, retreat date is the last date when the spatial area exists. The fall onset dates for all temperature limits show a trend toward later onset times beginning about 1990. Retreat dates, especially for the −40°C and −42°C isotherms, show a trend toward occurring earlier in the season. Whether or not these will be long-term trends remains to be seen. Figures 3e–3f show the SH areas for the −40°C and −44°C isotherm. Little change can be seen for the onset and end of the −40°C area, while the −44°C area seems to show a later onset date beginning about 1998, but this time period is too small to draw any conclusions. Owing to the paucity of data prior to 1958, data and conclusions from this period may be less accurate than post-1958 results.

[9] Figures 4a–4d show least squares fits to the NH onset dates of −40°C areas of 2, 6, 10, and 14 × 10^6 km^2 (see Table 1 for trend magnitudes and statistical significance). These plots show that the fall onset dates for all but the largest area show a small trend toward earlier onset from 1948 to 1990, after which the trend shifts toward later onset dates. For the full reanalysis period, all NH areas show a small trend toward later onset dates. Figures 4e–4h show the NH spring retreat dates for the same areas (see Table 2 for trend magnitudes and statistical significance). For the full reanalysis period, all areas show a trend toward an earlier retreat date. The two smaller areas show trends toward earlier retreat dates both for the period before and after 1990. The 10 × 10^6 km^2 area shows little trend before 1990 and earlier retreats after 1990, with the entire period showing a trend toward earlier retreat. The 14 × 10^6 km^2 area shows little trend before 1990 with slightly later trend after 1990; however, taken as one time series, the trend is nearly zero. All areas indicate the possibility of a delay in spring retreat dates from about 1995 on, but this trend is too short to be significant. In the SH onset shown in Figures 4i–4j, there is no significant overall trend in the 10 × 10^6 km^2 onset date for the reanalysis period, but the area is trending toward a later date before and after 1990. There is a significant trend toward later onset for larger areas, such as 20 × 10^6 km^2. The SH retreat in Figures 4k–4l shows a trend toward slightly later retreat of the small areas and slightly earlier retreat of the large areas, with a majority of the large area trend contribution coming after 1990.

4. Summary

[10] We have updated the data from an original paper, which terminated with 1998 data, to go through July 2008. The apparent limit on minimum 500 mb temperatures to about −45°C is still quite apparent. Our original explanation of this being due to moist adiabatic lifting of very cold air parcels after being rapidly heated from below when passing over unfrozen water still appears to be a valid explanation of the mechanism responsible for this control. The updated data seems to indicate an earlier NH onset date for areas of 2, 6, and 10 × 10^6 km^2 of −40°C until 1990. After that time the onset dates have become noticeably later. The retreat dates in the spring are now earlier for all encompassed areas when considering the entire period from 1948 to 2008 but with some minor changes in the trend sign over shorter time periods.

[11] **Acknowledgments.** R.A. Pielke Sr. was supported on this study through the University of Colorado in Boulder (CIRES/ATOC). T. Chase was supported under NSF grant ATMO 531973. M. Barlage was partially supported under NSF grant ATM-0634763. We thank Dallas Staley for her standard excellent support in finalizing the paper.

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