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Comment on "Recent changes in the North American Arctic boundary layer in winter" by R. S. Bradley et al.

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Introduction

Near-surface temperature inversions are common in the Arctic and Antarctic, especially in winter. An early, comprehensive study of Arctic inversions was done by *Belmont* [1957]. More recently, Kahl et al. [*Kahl,* 1990; *Kahl et al.,* 1992a, 1993a b; *Serreze et al.,* 1992; *Skony et al.*, 1994] have investigated the characteristics of Arctic inversions and have also constructed a database of Arctic radiosonde data [*Kahl et al.,* 1992b]. Antarctic inversions have been examined by *Stone and Kahl* [1991]. Inversions on the Arctic coast of North America have been characterized by *Bradley et al.* [1992], who restricted their study to surface-based inversions. In their subsequent work, *Bradley et al.* [1993] (hereinafter referred to as BKD) showed that the average height of wintertime surface-based inversions (average of the 4 months December to March) had decreased by about one third from 1967 to 1990 at all the stations they analyzed (three in Alaska and six in Canada). This was true regardless of whether the average surface air temperature, for days with surface-based inversions, increased (e.g., Inuvik, Canada and Barrow, Alaska) or decreased (Eureka, Canada) as shown in Figures 2 and 3 of BKD. They were unable to find a physical explanation for this dramatic trend in inversion height.

We find that BKD's conclusion is sensitive to their particular definition of average inversion height, in which the lowest inversion height is first found in each individual profile, and those heights are then averaged for a season. As shown below, when we instead first average all the temperature profiles for a season and then find the inversion height in the seasonal average profile, we find no significant climatological trend over the past few decades. Our conclusion is to recommend the use of monthly or seasonal average profiles in climatological studies of inversions for the following reasons:

1. The various definitions of "inversion height" often lead to different diagnostic heights when applied to a single profile, but they usually all agree when applied to the much smoother monthly or seasonal average profile.

2. Nonclimatic causes, such as improvement in thermistor response time, reduction of balloon ascent rate, and increase in the sampling rate of radio transmission, can cause an apparent decreasing trend in the height of the lowest inversion in individual soundings by adding detail and therefore reducing the smoothness of the profile. Such changes in operational procedures have much less effect on the seasonal average profile.

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Average Temperature Profiles at Barrow and Eureka

We have analyzed radiosonde data from Barrow and Eureka, the stations with the lowest and highest frequencies of wintertime surface-based inversions (61% and 84%, respectively, on average, according to Table 1 of BKD). The period of record analyzed by BKD was 38 years at Barrow and 24 years at Eureka. Soundings were made at 0000 and 1200 UT; we have analyzed all of the 1200 UT soundings for the four winter months December to March, as did BKD. (At Barrow, the soundings prior to 1958 were made at other times, usually 0300 and 1500 UT. We use the sounding closest to 1200 UT for those years, as did BKD; it was usually at 1500 UT.)

Although the radio transmissions from each radiosonde to its ground station are sampled at intervals of a few seconds, only a small subset of the data is sent out to the Global Telecommunications System (GTS) to be archived: the "mandatory" levels (surface, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 7, 5, 3, 2, and 1 mbar) and "significant" levels, where the lapse rate or humidity changes significantly [*National Weather Service*, 1976].

Figure 1 shows the multiyear monthly average temperature profiles at Barrow and Eureka at 1200 UT, from the surface to 3000 m, for the four winter months. (The profiles for 0000 UT are nearly identical to those for 1200 UT except in March when surface warming is apparent in the afternoon.) There is an inversion in the monthly average profile in each of these months, and the average profiles are sufficiently smooth that all definitions of inversion height (such as the various definitions reviewed by *Bradley et al.* [1992]) are likely to agree; i.e., isothermal layers and multiple inversions are unlikely, so the height of maximum temperature is usually the same as the height at which the lapse rate (-dT/dz) first becomes positive.

Figure 1 shows that the inversion strength (difference between maximum temperature and surface air temperature) is greatest in December at Eureka (12 K) and in Janu-

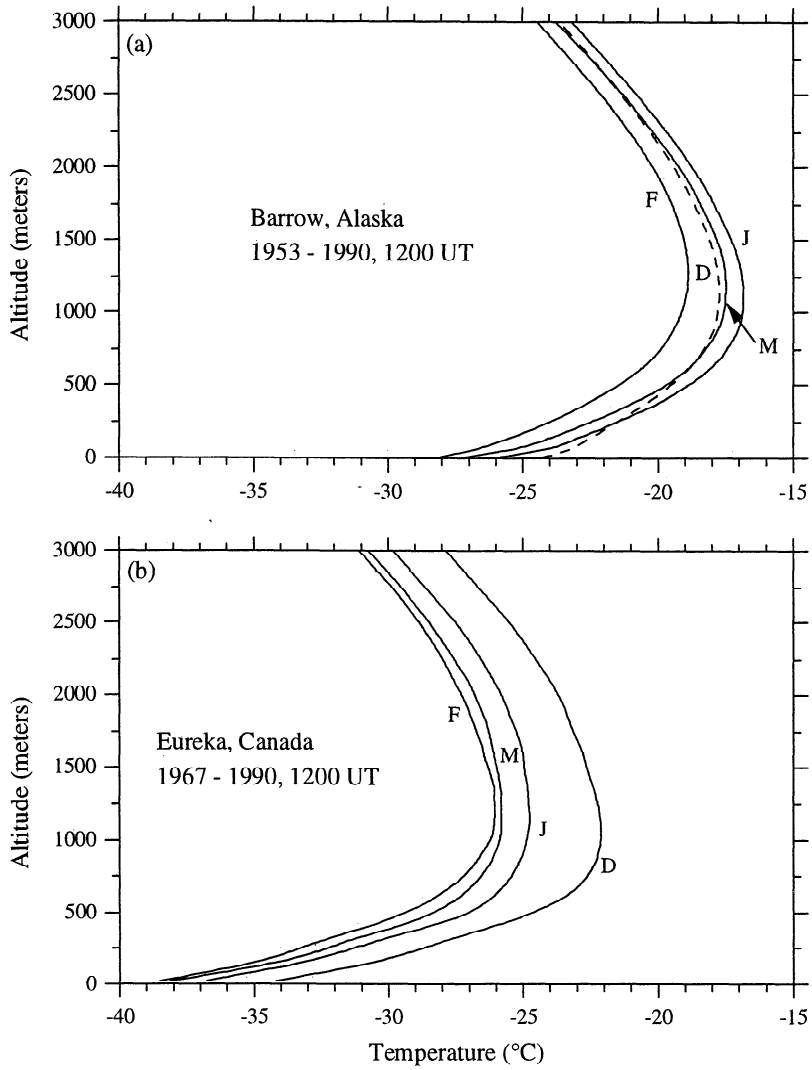

Figure 1. Multiyear monthly average temperature profiles (December, January, February, March) at 1200 UT for (a) Barrow (71°N, 157°W) and (b) Eureka (80°N, 86°W). Individual months are marked by their initials. The data at Barrow are for 1953-1990, and those for Eureka are for 1967-1990. (The Barrow soundings prior to 1958 were mostly at 1500 UT, not 1200.) Average temperature profiles are generated by linearly interpolating the individual daily soundings onto a 10-m grid and then averaging the gridded profiles.

ary at Barrow (9 K) and that the lowest 3 km of the troposphere is coldest in February at both locations. The average inversion height (height of maximum temperature) is about 1200 m at both Barrow and Eureka.

Recent Trends in Arctic Inversions

We now investigate multiyear trends in the wintertime inversion. BKD's method was to locate the top of the lowest inversion in individual soundings that exhibited surface-based inversions and then to average those heights. BKD rejected all soundings that did not contain inversions and also rejected soundings that did contain inversions unless there was a surface-based inversion (i.e., temperature increasing from the surface to the first above-surface reporting level). The fraction of soundings rejected varied by 20 - 50% from year to year.

The result of BKD's analysis is shown as the lower solid line in Figures 2a and 2b (copied from their Figures 2 and 3). Our analysis of the same radiosonde observations, using their procedure, gives similar results (dashed line). The small differences may mean that we have misinterpreted some subtleties of their criteria for rejecting erroneous soundings given in the appendix of *Bradley et al.* [1992].

However, when we instead first average all the temperature profiles for a season and then find the inversion height in the seasonal average profile, we find no significant trend at these two stations. These inversion heights are plotted as the upper lines in Figures 2a and 2b. Our average temperature profiles are found by linearly interpolating the individual daily soundings onto a 10-m grid and then averaging the gridded profiles. Most months have approximately 30 soundings, giving about 120 per season. The individual

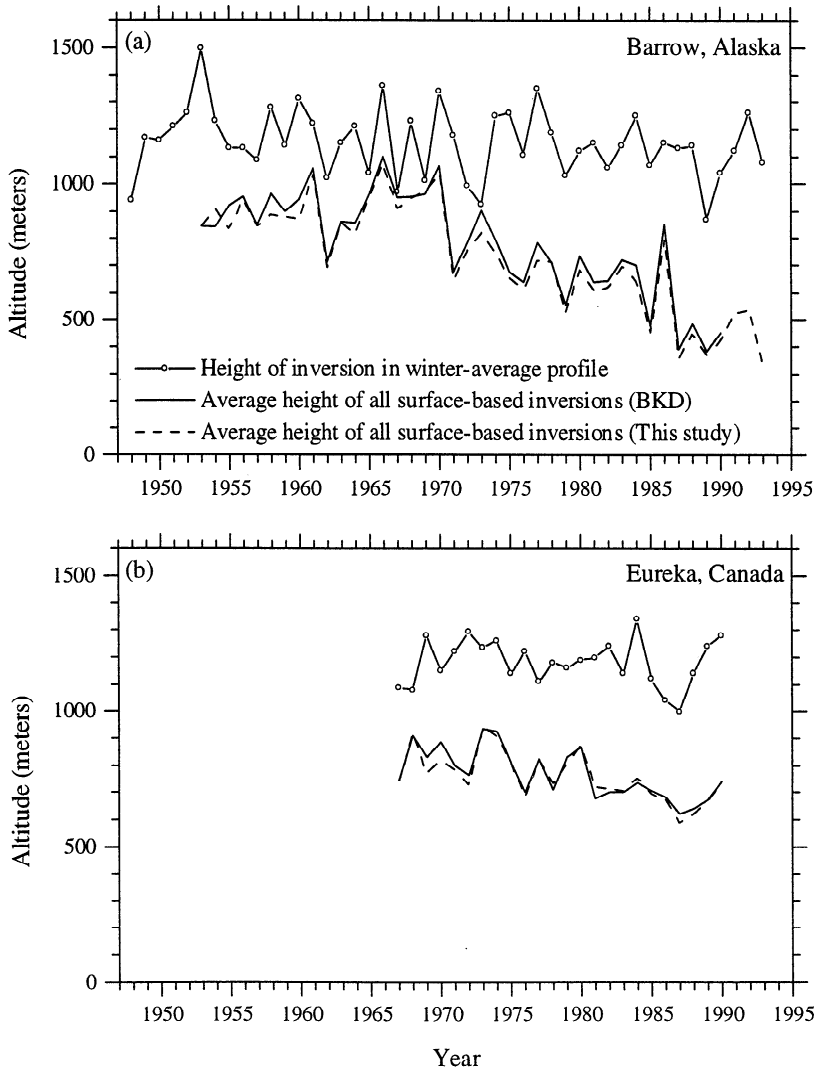

Figure 2. Winter-average inversion height at (a) Barrow and (b) Eureka, as determined by two different methods. Each point is the average for December-January-February-March, plotted in the year of January. The lower solid lines are copied from Figures 2 and 3 of *Bradley et al.* [1993]. The dashed lines are what we obtain when we apply their procedure to the soundings from these stations. The upper lines with open circles give the inversion height of the winter-average profiles. Least squares linear fits to the time series of winter-average profiles give slopes of -0.6±2.5 m/yr (Eureka, 1967-1990); -2.0±1.4 m/yr (Barrow, 1948-1993); and -3.8±1.8 m/yr (Barrow, 1953-1990). The slope obtained is sensitive to the choice of starting and ending years [cf. *Karl*, 1994].

months are not weighted by the number of days per month; this lack of weighting introduces very little bias. An exception is 1973, which may be biased since it is missing data from January and most of February.

Figures 2a and 2b show that our diagnosed height for the top of the inversion is higher than those determined using BKD's method. At Barrow, where BKD reported the winter seasonal average of inversion height to drop from about 900 m to 400 m in 37 years, we find that the inversion height of the seasonal average profile fluctuated around 1200 m with no significant trend. There are slight negative trends at both Barrow and Eureka, but these trends do not differ significantly from zero at the 2σ level. The slope obtained is sensitive to the choice of starting and ending years [cf. *Karl*, 1994].

Another important measure is the inversion strength. The inversion strength of the winter average profiles (Figure 3) shows no trend at Barrow and a possible positive trend at Eureka. The results are insensitive to the temperature uncertainties in the average profiles.

BKD also reported trends in the seasonal average surface air temperature, which we are not discussing in this comment. However, those trends are for the same subset of data used for their inversion height analyses, i.e., only those soundings with surface-based inversions.

Explanations

To explain long-term trends in climatic variables, it is useful to classify the causes as "climatic" and "nonclimatic"

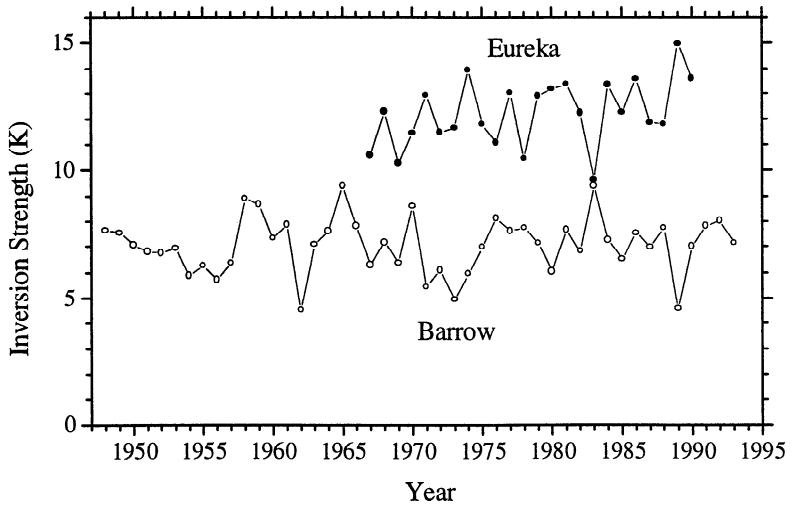

Figure 3. Inversion strengths at Barrow and Eureka determined from the winter-average temperature profiles. Least squares linear fits to these data give slopes of 0.00±0.01 K/yr at Barrow and +0.08±0.04 K/yr at Eureka.

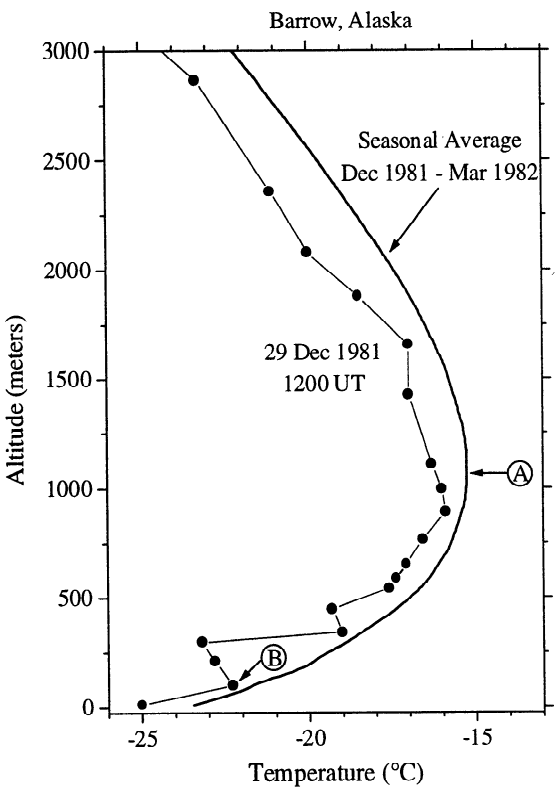

Figure 4. Illustration of the different results from two procedures used for assessing inversion height. The bold line is the average profile of the temperature in the lower troposphere at Barrow during December 1981 to March 1982. The thin line with reporting levels marked is one individual sounding taken during that winter. The method of *Bradley et al.* [1992] picks point B as the top of the surface-based inversion on that day. In the seasonal average profile, the top of the inversion is at point A.

[*Jones et al.*, 1986]. BKD suggest some possible climatic causes; here we investigate some possible nonclimatic causes, using the Barrow station as an example. Figure 4 shows the temperature profile at Barrow for a single sounding on December 29, 1981, together with the mean profile for that winter. The inversion height for the average profile is marked A; the height of the surface-based inversion is marked B, according to the criterion of BKD as the first point at which the lapse rate (-dT/dZ) becomes positive. BKD's reported average inversion height is the average of all points B on individual profiles that contained a surface-based inversion.

Thermistor Response Time

Our first thought was that improvements in radiosonde technology had allowed a more rapid response of the thermistor in more recent years, thus increasing the resolution of small-scale temperature fluctuations in the profile. This would result in the identification of a greater number of "significant" levels, and BKD did indeed find an increase over the years in the number of significant levels at all nine stations they studied. Soundings from earlier years, assuming a slower thermistor response, would be relatively smoother and also lagged relative to the true temperature profile, both factors causing the apparent height of the inversion to decrease with time. This is indeed what happened with Vaisala radiosondes. *Huovila and Tuominen* [1989] (quoted also in Table 2 of *Parker and Cox* [1995]) showed that the thermistor's *e*-folding response time τ at 1000 mbar pressure decreased from 10.5 s (1938-1959), to 5.1 s (1960-1975), 3.5 s (1976-1980), and 2.3 s (1981-1989), causing an apparent downward trend to the height of wintertime inversions in Finland. (Thermal lag was also shown by *Skony et al.* [1994] to cause the temperature profiles measured by radiosondes to differ from those measured by dropsondes.)

However, this effect turned out not to be relevant for the Barrow record. The response time of the temperature element in U.S. radiosondes was reduced in 1949 [*Elliott and Gaffen,* 1991, Table 1; *Jenne and McKee,* 1985, p. 1198] but was not changed subsequently. The radiosondes used at Barrow were made by Bendix-Friez prior to 1958 and by VIZ Corporation since 1958 (A. Brewington, personal communication, 1994). Both sondes have the same 5 to 6 s response time (M. Friedman, VIZ Corporation, personal communication, 1994). This is the radiosonde type used at most U.S. Weather Service stations. The Army radiosondes have a shorter response time of 3 to 4 s because they are thinner; the response time is proportional to the square of the radius of the thermistor rod [*Ney et al.*, 1961]. In conclusion, although thermistor response time did shorten over the past few decades in Europe and may have shortened in the Soviet Union (*Zaitseva* [1993] gives the response time as 5-6 s only for the new thermistor introduced in 1984), it did not change at Barrow.

Ascent Rate of Balloon

In interviews with past and present weather observers at Barrow, we learned that the balloons had been inflated with hydrogen or helium in the 1940s and 1950s but have been inflated with natural gas since March 1967. The balloon ascent rate with helium was 6 m s^{-1}; with natural gas, it is only 3 m s^{-1}. This change would have the same effect on the temperature profile as reducing the thermistor response time by half.

Radio Transmission Rate

Over the years, the data transmission rate of radiosondes has increased and reporting policies have changed. Together, these modifications would be expected to change the number of levels reported in individual soundings. The increase in the number of levels over time seen at Barrow, excluding data from 1965-1970 (Figure 5), indicates that the soundings contain more detailed structure, increasing the likelihood of detecting the first inversion top (point B in Figure 4) lower in the atmosphere. This, in turn, may contribute to the decreasing trend in the average height of surface-based inversion reported by BKD. An increase in the frequency of heights of surface-based inversions below 100 m is indeed seen in the Barrow record (Figure 6).

For VIZ radiosondes, the radio transmission rate for 1950-1986 was controlled by a "baroswitch" which transmitted approximately every 12 mbar in the lower atmosphere; i.e., about 100 m or 20 s (M. Friedman, personal communication, 1994). During this period, the radiosonde data were recorded onto a strip chart recorder. A major instrumentation revision occurred with the introduction of the Automatic Radio Theodolite (ART) systems around 1986, when the use of the strip chart was eliminated and the transmission rate was no longer controlled by the baroswitch. The ART system radiosondes report data at high frequency, which are then averaged by a ground station computer to produce a raw sounding with points every 6 s during the radiosonde flight.

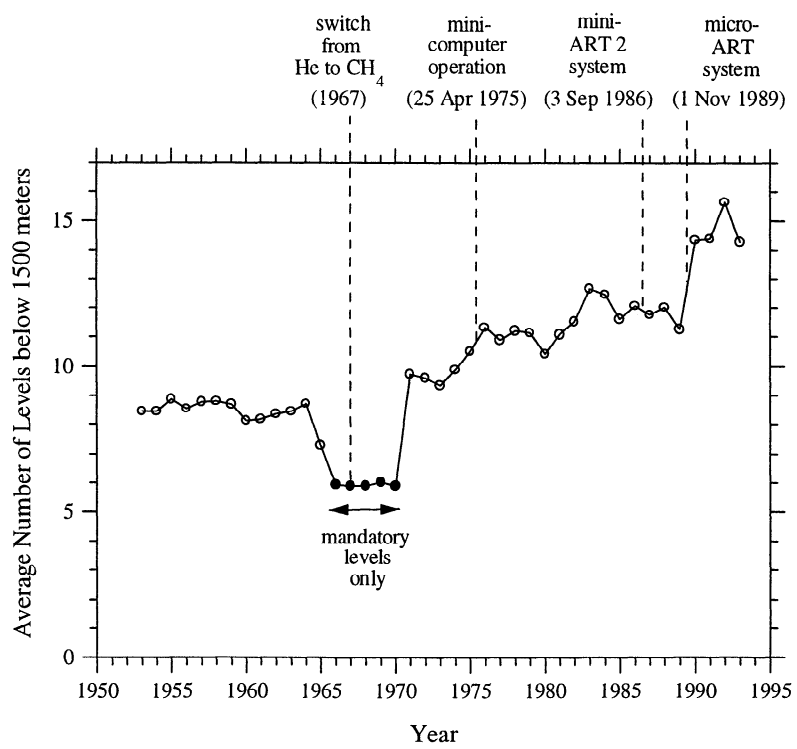

Figure 5. Average number of levels (mandatory plus significant) below 1500 m in winter season radiosonde reports at Barrow. Dates are marked at which changes were made in balloon ascent rate, radiosonde data transmission rate, and computer processing procedures. Some of these dates were given by *Schwartz and Wade* [1993] and *Schwartz and Govett* [1992].

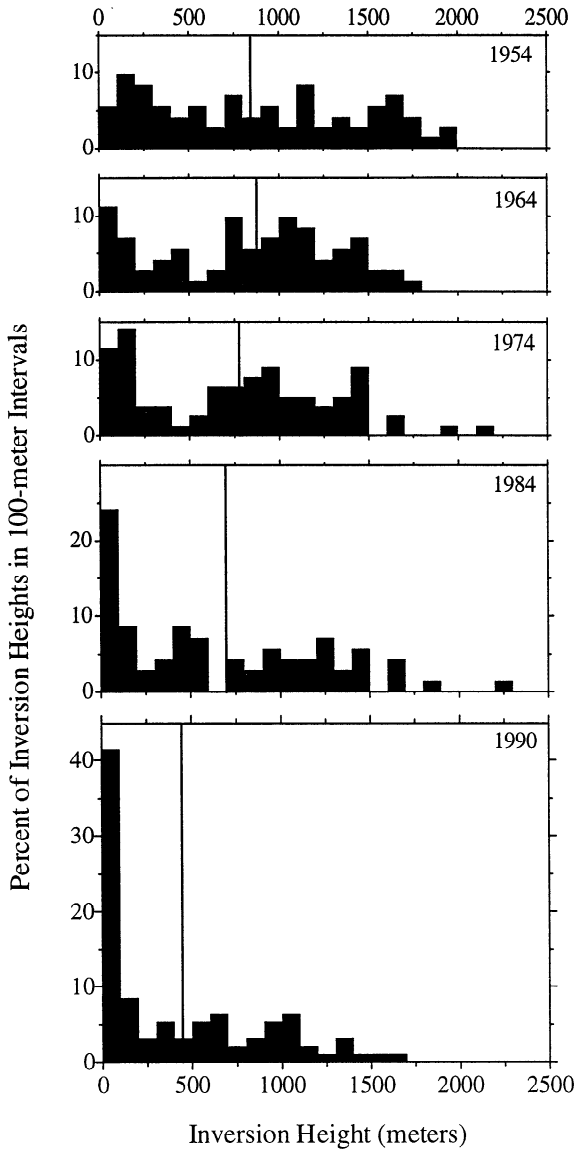

Figure 6. Frequency distribution of heights of surface-based inversions, found using BKD's method for a sample winter season in each of five decades. The vertical solid lines indicate the winter average inversion heights as determined by BKD. The distribution changes over time, showing an increasing number of inversion heights below 100 m.

Reporting Policy

The method for processing the raw sounding data has changed due to modifications in reporting policy. An example was noted by BKD in the Barrow record for the years 1965-1970, when only data from mandatory levels were available (Figure 5). The absence of significant levels caused the temperature profile to contain less structure and therefore the height of the first detected inversion to be higher on average (Figure 2a). The designation of mandatory levels has also changed in time; recently, another level was added at 925 mbar.

Other policy changes were instituted at the time of instrumentation upgrades. The introduction of the mini-computer system around 1975 eliminated the need to manually convert values from the strip chart to atmospheric temperatures and significantly reduced the amount of manual calculation performed by human observers. The switch to the mini-ART 2 system (in 1986 at Barrow) was the first fully automated system to determine significant levels without the strip chart recorder.

The criterion for defining significant levels has also changed in time. Prior to 1989 and the introduction of the micro-ART system, significant levels below 100 mbar were determined based on a departure of the temperature from linearity of greater than 1°C; the actual significant level is the point of maximum departure. The micro-ART system lowered the temperature criterion to 0.5°C; its introduction thus resulted in a greater number of significant levels (Figure 5).

Other Nonclimatic Factors

The last three nonclimatic factors discussed above are probably the ones most likely to have affected the radiosonde record at Barrow. Other factors that may affect the record at Arctic stations of other countries are all four of those discussed above, as well as the following factors.

Correcting for thermal lag. A simple correction procedure, recommended by *Jensen* [1958], is to take the temperature measured at time t but assign it to the pressure measured at time (t-τ). This procedure, or something similar, has been used at many stations, as reviewed by *Gaffen* [1994] and *Parker and Cox* [1995]. Implementation of this correction would cause a decrease in the derived inversion heights.

Pressure sensor. The response time τ to be applied in the correction for thermal lag is actually the difference between response times of the thermistor and the pressure sensor. Changes in the response time of the pressure sensor could therefore affect the reported profiles. We have been unable to obtain information about the response time of the pressure sensor.

Insertion of surface air temperature. The radiosonde report is augmented before it is sent to the GTS, by insertion of the surface air temperature as the first temperature in the profile. Details of how this is done can affect the diagnosis of a surface-based inversion. At Barrow, it was done in three ways: (1) by measuring the temperature at the balloon launch site, (2) by measuring the temperature at a fixed "screen" location, or (3) by extrapolation of the radiosonde transmissions down to ground level (C. Doran, personal communication, 1994). Depending on which procedure is used at a particular station, spurious surface-based inversions would appear if the balloon inflation tower (BIT) is significantly warmer or colder than the surface air, because the balloon is normally released immediately after opening the tower doors. We observed this effect in our experiments at South Pole Station, where the BIT is heated. The first temperature in the report is the surface air temperature; the second temperature is the first radiosonde transmission, which can be artificially high because of its memory of the warm room. The third temperature is colder again, so there

is an apparent but spurious surface-based inversion whose top is at the second level of the report [*Walden and Warren,* 1993, Figure 2]. At Barrow, the BIT is not heated, but it is sometimes warmer (colder) than the surrounding air because of recent cold (warm) synoptic-scale air advection.

Recommended Procedure for Analysis of Inversions

In an individual profile such as in Figure 4, the diagnosed height of the top of the inversion differs depending on which definition is used. BKD reviewed several definitions and chose one, which diagnoses point B as the inversion height in this particular profile. This choice is sensitive to the vertical resolution of the radiosonde data, which is affected by the factors listed above. However, even if the plotted profile is taken to be a true representation of the atmosphere, we think that point B may not be a particularly significant feature of the atmosphere. The small-scale structure in the temperature profile is due to interleaving (incomplete mixing) of adjacent air parcels and could be quite different in detail if measured by a second radiosonde launched just a few hours later.

We think it is probably more useful to study the monthly or seasonal average profile, in which the erratic fluctuations of individual profiles are averaged out, and all definitions of inversion height then agree. Furthermore, the inversion strength of the average profile is less ambiguous, and thus may be a more useful indicator of climate change. A further advantage to studying average profiles is that they are less sensitive to the changes in radiosonde technology and changes in operational procedures described above. In regional and global climatic studies, it may not be practical to investigate the details of operational procedure at each station as we have done for Barrow, so it is therefore useful to choose an analysis method that is relatively insensitive to nonclimatic factors. Monthly average or seasonal average profiles may be more useful than individual profiles for other purposes as well, such as in comparison with climate-model simulations.

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