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Recent Changes in the North American Arctic Boundary Layer in Winter

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Analysis of significant level radiosonde data from a network of Arctic stations reveals a systematic reduction in midwinter surface-based inversion depths over the past few decades, accompanied by a rise in surface temperature. Similar trends are observed over a wide sector, from 62°W to 162°W and from 70°N to 83°N. Possible causes for these changes include increases in warm air advection, cloud cover, ice crystals, aerosols, and greenhouse gases, but the specific reasons are difficult to identify, due to strong interactions between many potentially important factors. Nevertheless, the changes are significant for studies of Arctic haze, since the midwinter stable boundary layer has been decreasing in depth over time.

INTRODUCTION

Low-level temperature inversions (in which air temperature increases with elevation) are a characteristic feature of the Arctic troposphere, particularly in winter months [*Belmont*, 1957; *Vowinckel and Orvig*, 1967; *Busch et al.*, 1982; *Serreze et al.*, 1992]. In the Canadian high Arctic (>70°N) surface-based inversions occur on >70% of winter (December to March) days and range in depth from 650 to ~800 m [*Bradley et al.*, 1992; *Kahl et al.*, 1992]. Temperatures at the top of the inversion layer average 8°-10°C higher than at the surface but may be >30°C higher on individual days. Computer models of future climate associated with increased levels of greenhouse gases point to the lower troposphere of polar regions as the location of maximum warming [*Schlesinger and Mitchell*, 1987; *Walsh and Crane*, 1992]. The projected warming in this region is especially pronounced in winter months [*Manabe and Stouffer*, 1980]. As this is the location and time of year when the strongest surface temperature inversions develop, an analysis of instrumentally recorded variations in inversion structure, spanning the last 30-40 years, has been undertaken to determine if any significant changes in this zone have occurred. Pronounced changes in midwinter inversion structure have indeed occurred, consistent with those expected from increased levels of greenhouse gases. However, other factors may be responsible for the observed changes, reflecting the complex interactions which occur in the lower troposphere of the Arctic.

DATA ANALYSIS

Significant level radiosonde data, along a transect from Alaska to the Canadian high Arctic (Figure 1) for the period 1966 to 1990, were analyzed using 1200 UT soundings for the months of December to March. Data sources and periods of missing data are described in the appendix to *Bradley et al.* [1992]. The study focused on inversions which are surface based; elevated inversions were not considered. Henceforth, the term "inversion" refers to surface-based inversions (SBIs) only. The top of the inversion was defined by the height above which temperature first decreased with elevation. Thus embedded isothermal layers, when they occurred, were included as part of the overall inversion. The mean depth of all inversions in the months December to March was then calculated [cf. *Bradley et al.*, 1992]. Table 1 gives the frequency of occurrence of days with inversions, mean inversion depth and surface temperature (on days with SBIs) together with the mean rate of temperature change within the inversion ($\Delta T/\Delta Z$), and the mean temperature difference between the surface and the inversion top (ΔT). Inversions occur on 66-84% of winter days and range in mean depth from 419 to 812 m. Figure 2 shows the mean winter inversion depths and mean surface temperatures at the time of each sounding (1200 UT) over the last 24 years. Almost without exception, stations along a transect from Alert (83°N) to Kotzebue (67°N), a distance of >2000 km, show a consistent pattern of increasing surface temperature and declining inversion depths. (Very similar trends are observed if median inversion depths are used instead of means.) Only surface temperature at Eureka does not fit this pattern. The decrease in inversion depth ranges from 6 to 16 m yr^{-1}, since 1966-67, while surface temperatures have increased from +0.035°C to +0.244°C yr^{-1} (Table 2). Significant level data prior to 1966 are not available for most stations, but at Point Barrow, Alaska (71°N), the record can be extended back to 1952-53. (From February 1965 to June 1970, only mandatory levels are available for Point Barrow, leading to higher estimates of SBIs in winters during this interval.) A similar trend is also apparent when this longer period is examined (Figure 3). There are no systematic changes in inversion frequency or in missing data which can account for these trends. However, there has been an increase in the number of significant levels between 1000 and 850 mbar reported at all stations. This increase is steady and does not involve any abrupt discontinuities which might indicate inhomogeneities in the data due to changes in recording protocols or instrument changes. Indeed, we have found no evidence that such factors have played a role in the observed changes of inversion depth. We believe that the increase in number of significant levels recorded reflects real changes in the fine structure of the lower troposphere which have accompanied the decline in inversion depths.

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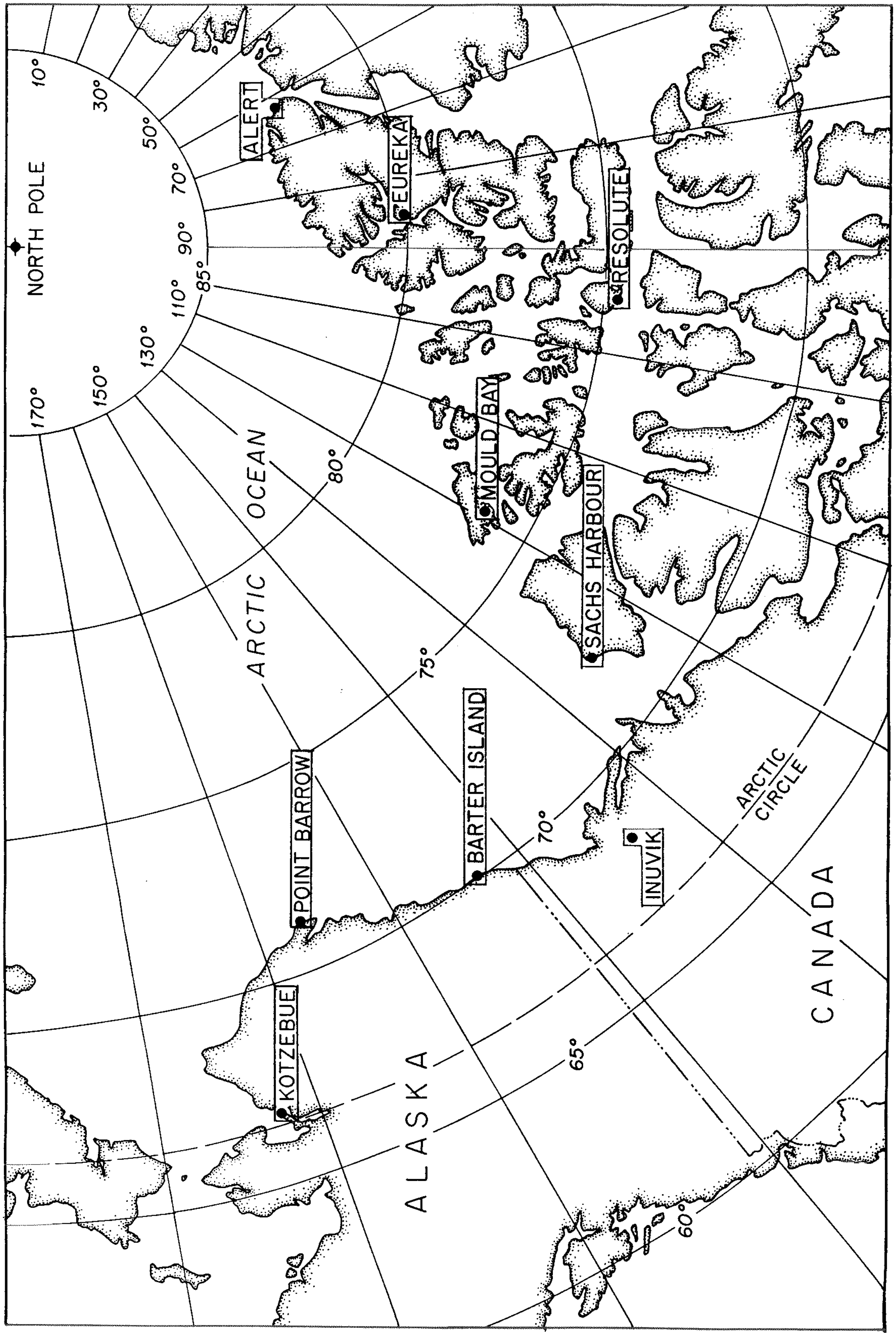

Fig. 1. Location of upper air stations in the study.

TABLE 1. Mean December to March Inversion Statistics (1967-1986) Based on Days With Surface-Based Inversions

	Depth, m	Freq,* %	ΔT/ΔZ, °C/100 m	ΔT, °C	Sfc Temp, °C
Alert	655	80	1.7	8.0	-32.7
Eureka	783	84	2.1	13.8	-38.2
Resolute	620	69	1.9	8.3	-32.3
Mould Bay	812	80	1.5	10.1	-33.1
Sachs Harbour	655	81	1.9	8.5	-29.7
Inuvik	671	70	1.9	9.5	-27.4
Barter Island	645	66	2.1	10.2	-27.5
Point Barrow	765	61	1.8	9.5	-27.1
Kotzebue	419	77	2.3	6.9	-18.8

Sfc Temp, surface temperature.

*Frequency of days with surface-based inversions, as a percentage of all days.

Significant level radiosonde data from several stations in northern and northeastern Siberia have also been examined, though data were only available from 1975 and a lot of data are missing. Nevertheless, of the eight stations studied, from Cape Chelyuskin (77.7°N, 104°E) to Wrangel Island (71°N, 178.5°W) all showed an increase in December to March mean surface temperature (1975-1976 to 1985-1986) and two stations showed pronounced downward trends in inversion depth. Similar trends in midwinter inversion depths and surface temperatures have thus been observed over a large sector of the Arctic, from 62°W to 162°W, with some indications that the pattern may extend to 104°E (Cape Chelyuskin). With few exceptions this corresponds to the region which *Stone et al.* [1992] determined had experienced a warming trend in the 850- to 700-mbar level during the period 1958-1986. However, in northwestern Russia, Fennoscandia, and Greenland a cooling trend was recorded between these levels.

DISCUSSION

The surface net radiation balance at a site is given by

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad (1)$$

where Q^* is net all-wave radiation flux, $K\downarrow$ and $K\uparrow$ are incoming and outgoing short-wave radiation fluxes, and $L\downarrow$ and $L\uparrow$ are incoming and outgoing long-wave radiation fluxes. Since short-wave radiation inputs in the Arctic are negligible during the winter, equation (1) can be simplified to $Q^* = L^*$, where L^* is the net long-wave radiation flux. Low-level warm air advection (within the boundary layer) is very uncommon at these latitudes in midwinter, so the surface energy balance can be considered as a simple function of the local long-wave radiation balance. Surface-based inversions develop when outgoing radiation from the surface exceeds incoming radiation from the atmosphere. Cooling of the overlying atmosphere

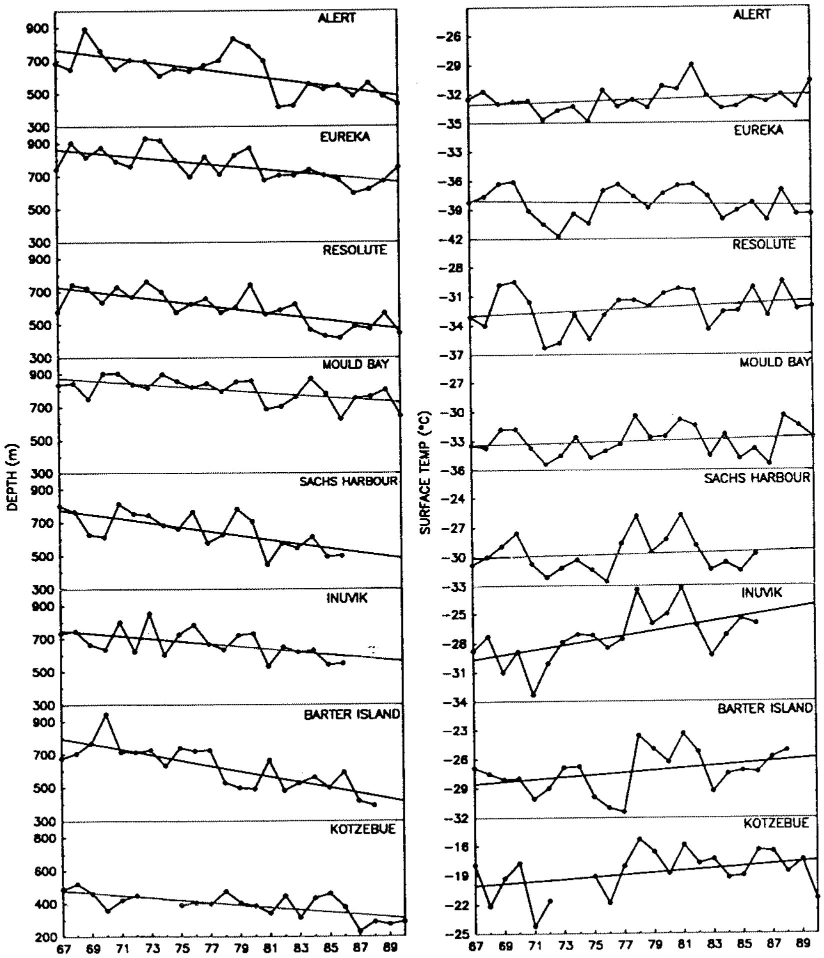

Fig. 2. Mean December to March surface-based inversion depths and mean surface temperatures at the time of each sounding (1200 UT) for the stations indicated. Year given is for each January (i.e., 1953 is December 1952 to March 1953).

TABLE 2. Trends in Surface Temperature (°C yr^{-1}) and Inversion Depths (m yr^{-1}) for North American Stations (1966-67 to 1989-90) for Days With Surface-Based Inversions

	Temperature, (°C yr^{-1})	Depth (m yr^{-1})
Alert	0.045	-12.2*
Eureka	-0.026	-8.7*
Resolute	0.065	-11.0*
Mould Bay	0.037	-6.3*
Sachs Harbour	0.035	-12.6*
Inuvik	0.244†	-8.2†
Barter Island	0.116	-16.4*
Point Barrow‡	0.109*	-12.9*
Kotzebue§	0.112	-7.2*

* Statistically significant at <0.01 level.
† Statistically significant at <0.05 level.
‡ Trends for 1952-1953 to 1989-1990.
§ Data missing for winters of 1972-1973 and 1973-1974.

causes the inversion to progressively increase in thickness. Lowest surface temperatures are thus associated with the deepest inversion layers [*Bradley et al.*, 1992]. Synoptic conditions which lead to strong surface cooling (clear sky, anticyclonic conditions with low wind speeds) are generally associated with the development of the deepest SBI layers, and may also produce elevated inversions, due to subsidence aloft [*Busch et al.*, 1982]. During those occasions when warm air is advected into the region, it tends to override the cold denser air near the surface. However, the main cause of the polar surface temperature inversion in winter is the negative energy balance [*Vowinckel and Orvig*, 1970].

If the atmosphere becomes more opaque to long-wave radiation emissions from the surface, due to higher levels of greenhouse gases (CO_2, CH_4, H_2O etc), there will be an increase in the effective emissivity of the atmosphere, leading to increased downward long-wave radiation [*Yamanouchi and Kawaguchi*, 1984]. This will result in an increase in net long-wave radiation, warming of the lower atmosphere, and a reduction in the thickness of the inversion layer. Similar effects would be expected as a result of increased atmospheric turbidity, increased occurrence of ice crystals, or of increases in low cloud amount, which would be especially effective in changing the long-wave radiation balance. For example, at Mizuho Station, Antarctica, monthly mean downward long-wave flux increased by ~77 W m^{-2} for middle and low cloud, and ~40 W m^{-2} for upper clouds, compared to clear sky conditions. As a result, on days with no cloud, net long-wave radiation was 30-40 W m^{-2} lower than on overcast days [*Yamanouchi and Kawaguchi*, 1984].

The difficulty in determining which of these various factors are responsible for the observed changes is made more complex by the strong feedbacks between them. For example, increased temperatures may result from increased levels of water vapor in the atmosphere. But higher temperatures may result in higher mixing ratios. Similarly, increased Arctic haze (increased atmospheric turbidity) might lead to more trapping of long-wave radiation and a consequent reduction in inversion thickness. But a reduction in inversion thickness would concentrate atmospheric contaminants over a shallower stable layer, and this itself could enhance downward long-wave radiation. In the following section we have attempted to determine which factors are most important in the observed changes.

Changes in Warm Air Advection

Surface temperatures may have increased, and inversions may have become shallower, due to a systematic increase in warm air advection into the region. We have investigated this possibility by examining sea level, 850 mbar and 700 mbar height fields for December to March in two periods (1966-1967 to 1977-1978 and 1978-1979 to 1988-1989). Pressure difference maps reveal the net change in circulation between the two periods (Figure 4). During the second period the Aleutian low was much stronger than in the preceding decade resulting in strong advection of warmer southerly air into western Alaska [*Trenberth*, 1990]. However, the geopotential height changes are relatively minor (~-6 gpm at 850 mbar) over the Canadian Arctic archipelago, and for several stations (Sachs Harbour, Mould Bay, and Inuvik) the net effect would have been to increase northerly airflow.

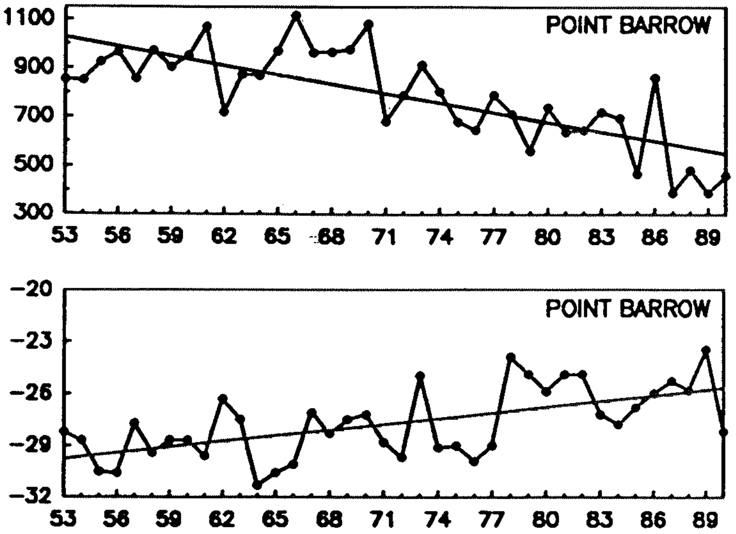

Fig. 3. Mean December to March surface-based inversion depths (top) and mean surface temperatures (bottom) at the time of each sounding (1200 UT) at Point Barrow, Alaska (71°N). From February 1965 to June 1970, only mandatory levels were available, leading to higher estimates of surface-based inversions (SBIs) in winters during this interval.


Sea Level Pressure Difference


850 mb Height Difference

Fig. 4. Difference in (top) December to March mean sea level pressure (millibars); (bottom) 850-mbar geopotential heights (meters) (December 1978 to March 1989 minus December 1966 to March 1978); negative values indicate a fall in pressure, or height, in the later period.

Yet these stations exhibit just as strong a change in surface temperature and inversion thickness as stations which may have been more directly affected by increased advection of southerly air (e.g., Kotzebue, Point Barrow). Another point argues against advection as a complete explanation for the observed changes. Trenberth has shown the relative strength of the Aleutian low over the last 20 years [*Trenberth*, 1990]; if advection was a primary factor in the trends of decreasing inversion depth and increasing surface temperature, years with the deepest Aleutian low and strongest warm air advection along its eastern flank should show especially high surface temperatures and low inversion depths. However, no such relationship can be discerned. Also, there have been no systematic changes in mean wind speed in the lower troposphere which might have caused turbulent disturbance of the SBI layer.

Increases in Atmospheric Turbidity

Increased levels of particulates in the lower troposphere of the Arctic (Arctic haze) could increase the flux of downward radiation, increase surface temperatures, and reduce inversion depth [*MacCracken et al.*, 1986; *Blanchet*, 1989]. There are numerous studies which indicate that pollutant levels are higher than in the past [e.g., *Stonehouse*, 1990]. The conductivity of ice (a proxy of Arctic air pollution) in a core from northern Ellesmere Island, Northwest Territories, Canada, increased 75% between 1956 and 1977 [*Barrie et al.*, 1985]. However, even in the absence of any systematic increase in anthropogenic pollutants, the observed changes in inversion depth would result in increased levels of "Arctic haze," due to particulates being concentrated within the inversion layer, over a shallower depth of the atmosphere. This in turn would provide a feedback to the midwinter radiation balance, increasing the downward long-wave radiation flux to the surface. To what extent increased levels of particulates have contributed to the changes in surface temperature and inversion depth, or are a result of these changes, is not clear at the present time. However, we note that the decline in inversion depth at Point Barrow has been greater in February than in December or January (Figure 5). This might be related to increasing particulate concentrations over the course of each winter, though the decline in March inversion depth (when pollutant levels are highest) is not as great as in February.

Increases in Cloudiness

Increased low-level cloud cover would have a profound effect on the surface radiation budget, by making net longwave radiation less negative. For example, *Stone et al.* [1989] measured downward long-wave radiation in winter during cloud-free and cloudy conditions at the south pole. Cloudy conditions increased L↓ by up to 50% on days with complete cloud cover. However, cloud observations in the midwinter darkness are difficult and any temporal variations in observed clouds must be viewed with caution, since observational acuity doubtless varies considerably with observer. Data from the six Canadian stations (Table 1) have been examined in detail to determine if any changes in overall winter cloud cover have occurred. In terms of total cloud cover, no significant trend has been recorded over the last 25 years.

Increases in Ice Crystal Occurrence

There has been a significant increase in the frequency of reports of ice crystals, as a percentage of "observed weather"

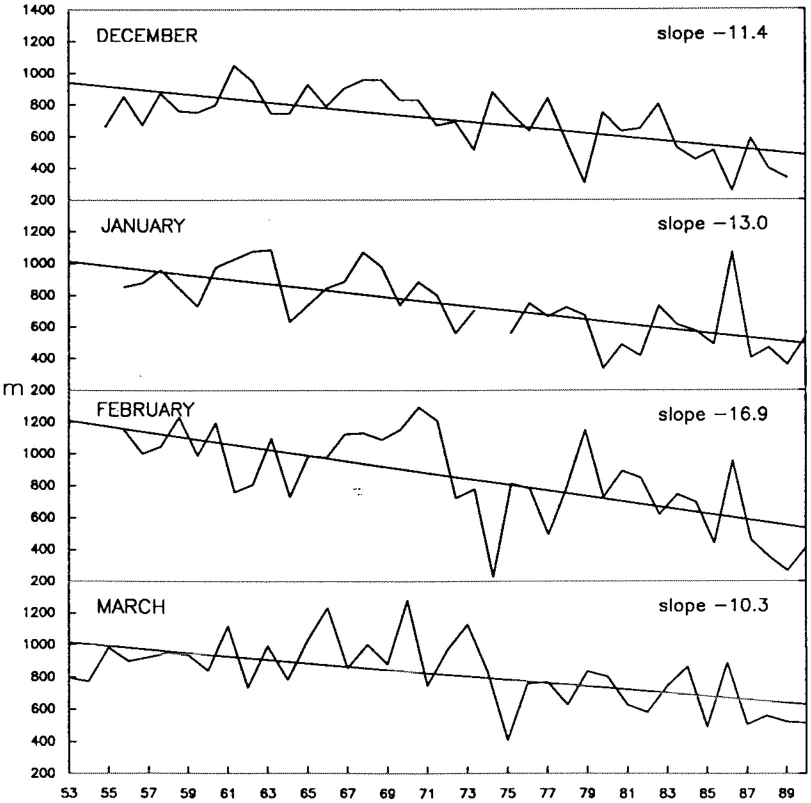

Fig. 5. Mean monthly surface-based inversion depths at Point Barrow, Alaska. Least squares linear trend lines have been fitted to each series and the slope of each is given in the graph (meters per year).

observations at the Canadian stations examined (Figure 6). These trends appear to be unrelated to large interannual changes in the number of "observed weather" records during this period. Ice crystals are extremely important to the surface energy balance in winter. For example, *Curry et al.* [1990] found net long-wave radiation losses decreased by ~79 W m^{-2} when ice crystals were present in the lower troposphere. It is not known if the apparent change in ice crystal occurrence is directly or indirectly related to a systematic increase in Arctic haze over this period, or if the increased frequency of reported ice crystals is simply an artefact of changes in observational practices. *Hoff and Leaitch* [1989] discuss the difficulties observers face in recording surface-based ice crystal clouds, which casts considerable doubt on whether these "observed" changes represent meaningful changes in atmospheric conditions. Nevertheless, the magnitude of the changes and their potential significance clearly warrants further investigation.

Increases in Greenhouse Gases

Changes in greenhouse gas concentrations would increase atmospheric opacity to outgoing long-wave radiation and increase downward long-wave radiation, resulting in higher surface temperatures and a reduction of the surface-based inversion layer thickness. Greenhouse gases may be particularly relevant in this environment since the entire midwinter energy balance is largely a function of long-wave radiation exchanges. Water vapor may be a factor, since increases in mixing ratio have been observed over the last 20 years at most stations, particularly in Alaska, but the levels of water vapor are nevertheless extremely low (for example, in the Canadian Arctic islands, mean winter mixing ratios within the inversion layer are <0.5 g/kg and in Alaska <0.8 g/kg). Increasing trends of 0.0008 to 0.008 g/kg/yr occurred in the surface to 900 mbar layer at all stations except Eureka and Barter Island, which showed small decreases. At Point Barrow, which showed the most consistent trends over the last ~40 years, mean mixing ratio in the 1950s averaged ~0.26 g/kg at the surface, whereas in the 1980s this had increased to ~0.39 g/kg, an increase of 50%, though still small in absolute terms. As noted earlier, such changes could well be the result of higher temperatures, rather than a cause, since an increase in temperature from -28° to -24°C (the approximate mean winter surface temperature change observed over the same period at Point Barrow) increases saturation vapor pressure by ~60%. Furthermore, at the low temperatures prevailing in winter in these regions, very low humidity readings are not very reliable and are highly dependent on sensor type and protocols employed in data reduction [*Elliott et al.*, 1991]. Thus the mixing ratio data may not be homogeneous over time; overall, we do not believe that increases in water vapor are the likely cause of the observed changes.

What about other greenhouse gases? Carbon dioxide levels have increased about 10% over the main period of study (1966-1990); other greenhouse gases (CH_4, CFC11, CFC12) have

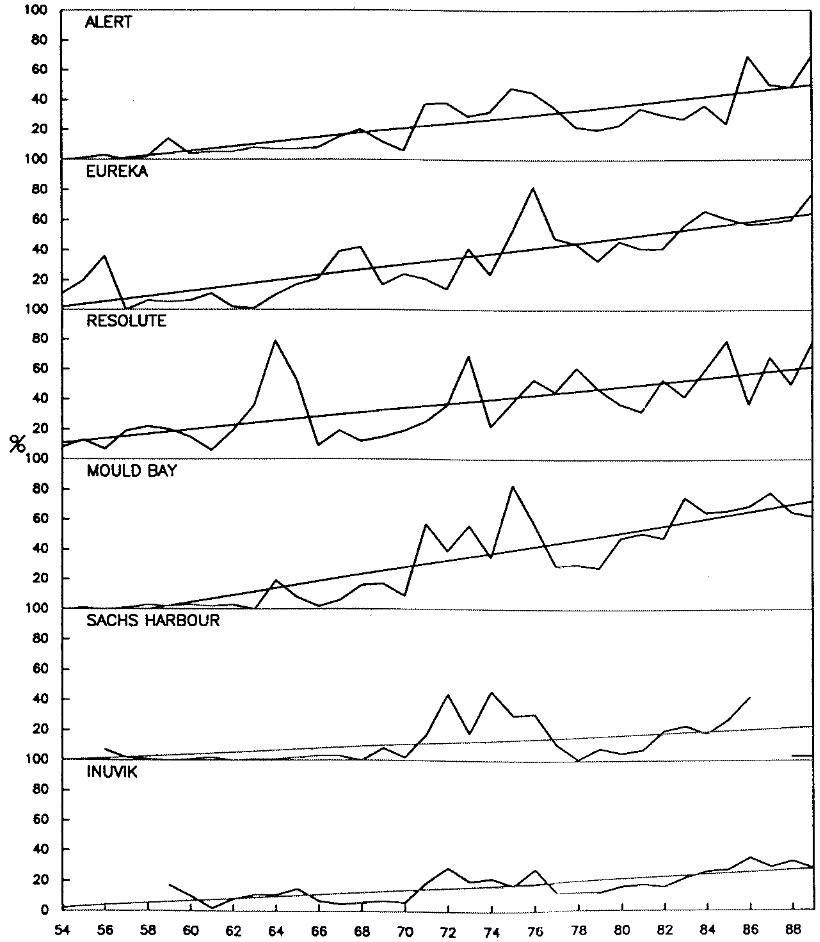

Fig. 6. Percentage of hourly "observed weather" observations in which ice crystals were reported, at six Canadian Arctic stations. Values plotted are for each December to March period.

increased in concentration at a faster rate over this period [*Watson et al.*, 1990]. Methane concentrations reach their highest levels in the Arctic, which is a major source region for this greenhouse gas and wintertime levels of CH_4 are 3-5% higher than in summer [*Nisbet*, 1989]. In spite of atmospheric mixing, methane levels are 15-20% higher in the Arctic compared to low latitudes [*Rasmussen and Khalil*, 1984; *Steele et al.*, 1987]. The radiation balance in midwinter would be influenced by increased levels of all greenhouse gases, but CH_4 may be of particular significance. We are not able to unequivocally relate the observed changes in inversion structure and surface temperature to greenhouse gases alone and can only point to the possible connection as worthy of further study and modeling. However, if anthropogenic greenhouse gases are involved in the observed changes of midwinter SBIs and surface temperature, we note that similar patterns might be expected in Antarctica (if the strong influence of katabatic winds over the continent [*Parish and Bromwich*, 1990] do not mask systematic changes). We have only been able to obtain long-term midwinter radiosonde data for two sites (South Pole and McMurdo). Of these, McMurdo shows exactly the same trends as at the Arctic stations, South Pole does not. Further studies of Antarctic inversions are needed to establish what the predominant pattern has been in this region.

CONCLUSIONS

Significant reductions in surface-based inversion depths in midwinter have been recorded over a wide sector of the Arctic, from 105°E to 62°W, accompanied by increased surface temperatures. The changes may be caused by (1) shifts in atmospheric circulation over the last 20-40 years, (2) increased cloudiness or ice crystal occurrence, (3) Arctic haze, (4) higher levels of greenhouse gases, or (5) some combination of these factors. Many of these factors are interrelated in complex ways, making it difficult to isolate cause from effect. Boundary layer structure in polar regions during the midwinter period of darkness may be especially sensitive to changes in greenhouse gas concentrations, but modeling studies are needed to determine the relative importance of each factor discussed. Regardless of the reason for the changes, they are especially significant for studies of Arctic haze, since the stable layer within which pollutants are mainly confined has been getting progressively shallower over the last few decades.

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