Differences between Radiosonde and Dropsonde Temperature Profiles over the Arctic Ocean

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ABSTRACT

The boundary layer structure measured by 402 pairs of approximately collocated radiosonde and dropsonde temperature profiles over the Arctic Ocean during the period 1957–61 is examined. The radiosonde profiles were obtained at the Russian drifting ice camps "North Pole 7" and "North Pole 8," and the dropsonde profiles were measured during the United States Air Force "Ptarmigan" series of weather reconnaissance flights. The boundary layer structure is characterized by the features of the low-level tropospheric temperature inversion.

The results indicate that the dropsonde soundings, although containing relatively few measurement levels, contain sufficient vertical resolution to characterize the temperature inversion. Systematic differences were noted in wintertime inversion features and near-surface temperatures as measured by dropsondes and radiosondes. These differences are attributed to contrasting temperature lag errors accompanying ascending and descending sensors.

1. Introduction

Atmospheric measurements over sea ice have historically been extremely difficult to obtain due to logistical problems arising from inaccessibility and harsh climates. This is especially true for upper-air measurements, for which automated sampling is particularly challenging and costly. Despite these difficulties, however, significant numbers of vertical soundings have been made over the Arctic Ocean during the past several decades. These historical upper-air datasets consist primarily of radiosondes released at drifting ice camps in the Arctic Ocean during 1954–90, and dropsondes released from aircraft during 1950–61. The radiosonde releases were included in the meteorology component of the "North Pole" expeditions, a series of Russian drifting ice stations established in 1937 (Voskresensky et al. 1983). The dropsonde measurements were part of the United States Air Force "Ptarmigan" weather reconnaissance program (Kahl et al. 1992b). In all, approximately 27 000 meteorological soundings over the Arctic Ocean during the period 1954–90 are available for analysis (Kahl et al. 1993).

These profile measurements are of great value because they comprise the only long-term, in situ observational records over the Arctic Ocean, an otherwise data-sparse region with an area approximately equivalent to that of the continental United States. The Arctic is thought to be a sensitive indicator of global climate change, thus diagnostic analyses of these data may reveal important insights on climate change processes. Indeed, a number of recent studies have utilized these measurements to investigate various features of the northern high-latitude climate (Kahl et al. 1993; Serreze et al. 1992a; Serreze et al. 1992b; Skony 1992; Nagurnyi et al. 1991; Timerev and Egorov 1991). Efforts are currently under way to include these measurements in global upper-air data archives (Eskridge and Sterin 1993) where they may be utilized for model reanalysis (e.g., Kalnay and Jenne 1991) and verification studies.

We have noted two potential problems that may affect analyses using these datasets, particularly with respect to the temperature structure in the lowest few kilometers of the atmosphere. The first problem concerns the vertical resolution. The dropsonde data contain an average of seven measurement levels between the surface and 700 hPa, about half the number usually present in archived radiosonde data. To what extent does the reduced vertical resolution limit the ability of the dropsonde data to describe the boundary layer temperature structure? The second problem concerns

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a possible systematic bias caused by lag errors. Temperature profiles measured by radiosonde and dropsonde are subject to systematic lag errors caused by the failure of the instrument to respond instantaneously to changes in temperature during ascent or descent. Lag errors corresponding to ascending and descending temperature sensors are expected to be of opposite sign (all other factors being equal). In this paper we investigate these problems by comparing approximately collocated temperature profiles over the Arctic Ocean measured by radiosonde and dropsonde instruments.

2. Data and methods

a. Temperature profile data

Two independent sets of temperature profile data over the Arctic Ocean were utilized. The first consists of 16 850 radiosonde ascents conducted at the "North Pole" series of Russian drifting ice stations during the period 1954–90. The radiosondes were released one to two times daily at locations along the drift path, mostly in the central Arctic Ocean (Fig. 1a). The data were obtained from the State Hydrometeorological Committee, Moscow, Russia.

The second set utilized is the "Ptarmigan dropsonde archive" (Kahl et al. 1992b). This database contains over 10 000 lower-tropospheric temperature profiles over portions of the Beaufort Sea and western Arctic Ocean (Fig. 1b). The dropsondes were released by United States Air Force weather reconnaissance aircraft during the period 1950–61. Temperature profiles from both sounding datasets were subjected to quality control procedures as described by Skony (1992).

b. Determination of temperature inversion features

A central feature of the Arctic boundary layer is the low-level temperature inversion (Serreze et al. 1992a; Bradley et al. 1992; Kahl 1990; Kahl et al. 1992a). The boundary layer structure may be characterized by the features of the low-level temperature inversion—specifically, the height of the inversion base, the inversion depth, and the temperature difference between the top and base of the inversion.

Low-level temperature inversions, that is, those with a base below the 700-hPa level, were objectively identified using the algorithm developed by Kahl (1990). The procedure is to scan each sounding from the surface upward, defining the inversion base as the bottom of the first layer in which temperature increases with altitude. The inversion top is defined as the bottom of the first subsequent layer in which the temperature decreases with altitude. Since Arctic temperature inversions often exhibit a complicated vertical structure (e.g., Belmont 1957), lapse layers are frequently encountered in the lower levels of the sounding. If these layers are thin (<100 m), they are considered to be embedded within the overall inversion layer. The inversion depth was then computed as the difference in altitude between

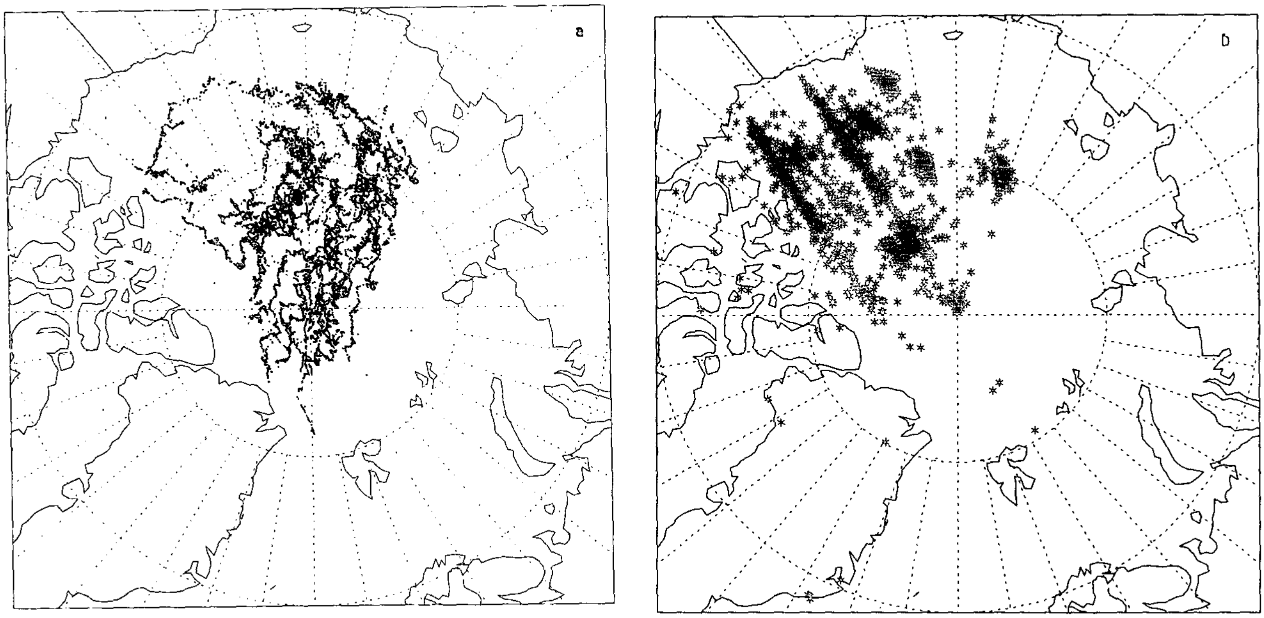

Fig. 1. (a) Locations of 16 850 temperature profiles measured by radiosonde at Russian drifting ice stations during 1954–90. The stations drift with the prevailing winds and surface currents in the Arctic Ocean, typically moving about 100 km each month. (b) Locations of 10 326 temperature profiles measured by dropsonde from United States Ptarmigan weather reconnaissance aircraft during 1950–61. The aircraft typically flew diamond-shaped patterns extending from central Alaska to the North Pole. Portions of the flight paths are visible as "streaks" of dropsonde positions. Drops were often made at predetermined locations, with as many as 500 soundings made at a few specific points. Over 100 soundings were made at the North Pole.

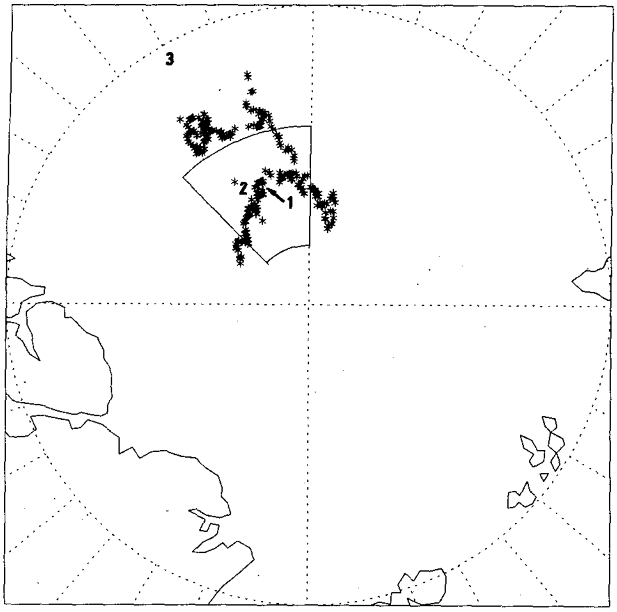

FIG. 2. Positions of matched Russian ice station and Ptarmigan dropsonde profiles. The asterisks denote the 402 ice-station positions that were determined to be approximately collocated with Ptarmigan soundings. Most of the collocated Ptarmigan soundings occurred at three specific locations: 85.9°N, 156.2°W (247 points, symbol "1"); 85.6°N, 149.9°W (103 points, symbol "2"); and 80.6°N, 149.9°W (30 points, symbol "3"). The 84°–88°N, 135°W–180° sector, used for the mean profiles in Fig. 3, is also shown.

inversion top and inversion base. The temperature difference across the inversion was similarly computed as the difference in temperature between inversion top and inversion base.

c. Calculation of mean monthly temperature profiles using dropsonde data

Using the entire dropsonde archive we computed mean monthly soundings for various subregions within the Ptarmigan area (Fig. 1b). Each sounding was first interpolated to 50-m increments from 0 (surface) to 6000 m. The interpolated soundings were then averaged to obtain a mean sounding for each month.

d. Comparison of inversion features determined from radiosonde and dropsonde profiles

We searched the two datasets for spatially and temporally collocated temperature profiles. As can be seen in Fig. 1, most of the ice-station soundings lie outside of the Ptarmigan region. Furthermore, the overlap in reporting periods is only 8 years: 1954–61. Determination of paired soundings was therefore limited to ice stations "North Pole 7" and "North Pole 8." The drift paths of these stations traversed the western Arctic Ocean region from May 1957 to December 1961, a period coinciding with the Ptarmigan reporting period.

An acceptable match between a Ptarmigan dropsonde profile and an ice-station radiosonde profile was defined if the two reports were separated by less than 300 km and taken within 12 h of each other. These criteria were established through an iterative process in which we tried to maximize the number of matches while keeping the distance (in space and time) between the two profiles as small as possible. If these criteria did not yield a unique match between the two datasets, the pair of soundings taken closest in time was retained and all others discarded. A total of 466 matches were identified, but this number was reduced to 402 after

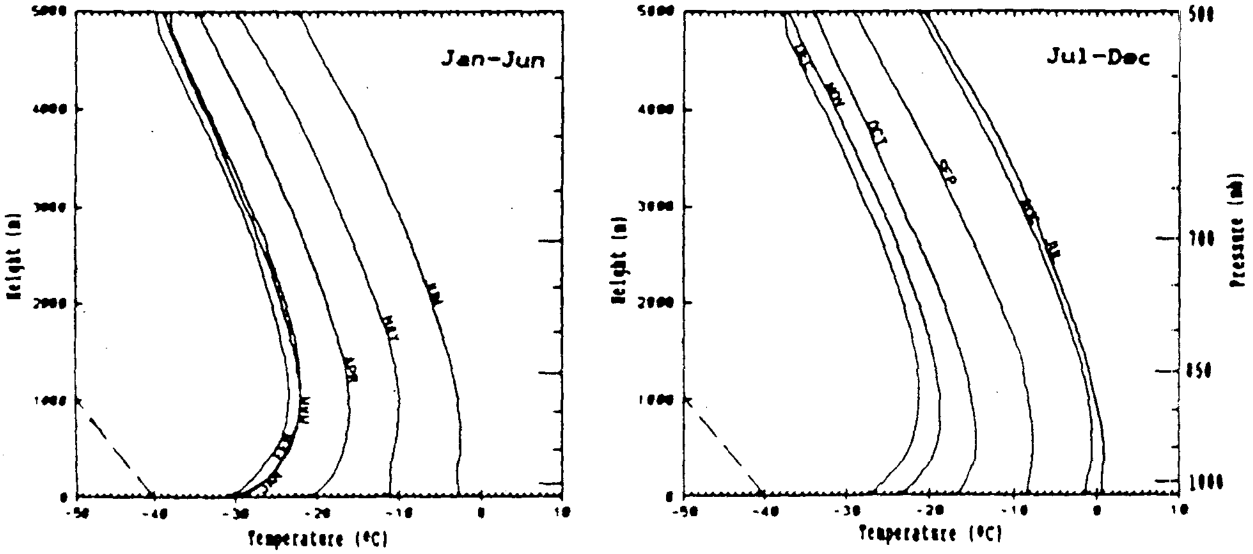

FIG. 3. Mean monthly temperature profiles for the region extending from 84° to 88°N and 135°W to 180° (shown in Fig. 2), computed from 1638 dropsonde soundings during 1950–61. The dry-adiabatic lapse rate is shown in the lower left corner for reference.

TABLE 1. Summary of temperature inversion features as determined from approximately collocated ice-station radiosonde ("Ice") and Ptarmigan dropsonde ("Ptarm") temperature profiles.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Both surface based	13	21	21	27	4	5	6	1	6	6	9	30	149
Both elevated	0	0	1	3	19	17	3	4	2	6	1	2	58
Ice surface based Ptarm elevated	6	8	2	5	7	2	5	0	1	1	4	10	51
Ice elevated Ptarm surface based	1	3	0	0	8	11	4	1	0	4	3	6	41
Inversion in both	20	32	24	35	38	35	18	6	9	17	17	48	299
Ice surface based Ptarm no inversion	2	0	4	3	1	0	2	1	0	1	2	0	16
Ice elevated Ptarm no inversion	0	0	0	0	1	1	1	0	0	1	0	0	4
Ice no inversion Ptarm surface based	2	1	0	1	3	5	4	1	0	1	0	1	19
Ice no inversion Ptarm elevated	0	0	0	0	6	15	21	5	2	0	0	0	49
Inversion in one	4	1	4	4	11	21	28	7	2	3	2	1	88
Both no inversion	0	0	0	0	2	4	5	1	3	0	0	0	15
Total	24	33	28	39	51	60	51	14	14	20	19	49	402
Ice station													
Total inversions	22	32	28	38	40	36	21	7	9	19	19	48	319
Surface based	21	29	27	35	12	7	13	2	7	8	15	40	216
Elevated	1	3	1	3	28	29	8	5	2	11	4	8	103
Inversion frequency	92%	97%	100%	97%	78%	60%	41%	50%	64%	95%	100%	98%	79%
Percent surface based	95%	91%	96%	92%	30%	19%	62%	29%	78%	42%	79%	83%	68%
Percent elevated	5%	9%	4%	8%	70%	81%	38%	71%	22%	58%	21%	17%	32%
Ptarmigan													
Total inversions	22	33	24	36	47	55	43	12	11	18	17	49	367
Surface based	16	25	21	28	15	21	14	3	6	11	12	37	209
Elevated	6	8	3	8	32	34	29	9	5	7	5	12	158
Inversion frequency	92%	100%	86%	92%	92%	92%	84%	86%	79%	90%	89%	100%	91%
Percent surface based	73%	76%	88%	78%	32%	38%	33%	25%	55%	61%	71%	76%	57%
Percent elevated	27%	24%	13%	22%	68%	62%	67%	75%	45%	39%	29%	24%	43%

eliminating soundings with poor vertical resolution (four or fewer levels) or a missing surface report. The locations of the paired soundings are shown in Fig. 2. Inversion characteristics were determined for all paired soundings.

3. Results

a. *Mean dropsonde temperature profiles*

Mean monthly soundings for the region extending from 84° to 88°N and 135°W to 180° are shown in Fig. 3. This region contained 1638 soundings including over 100 of the matches shown in Fig. 2. The low-level inversions can easily be seen during the winter months, with the coldest temperatures and deepest inversions occurring from December to March. Summertime profiles are nearly isothermal in the lowest kilometer, with a transition to wintertime conditions beginning in September.

The annual progression of the temperature inversion as depicted in the mean monthly soundings is in good agreement with earlier analyses of Arctic sounding data (Serreze et al. 1992a; Bradley et al. 1992; Kahl 1990; Kahl et al. 1992a; Nagurnyi et al. 1991; Timerev and Egorov 1991). The vertical resolution of the dropsonde profiles, an average of seven levels between the surface and 700 hPa, thus appears to be sufficient to identify the gross characteristics of the inversion layer. Similar results (not shown) were obtained for mean monthly soundings in other regions within the Ptarmigan measurement area.

b. *Frequency of inversion types*

A summary of the percentage of inversion types found in the paired soundings, by month, is given in

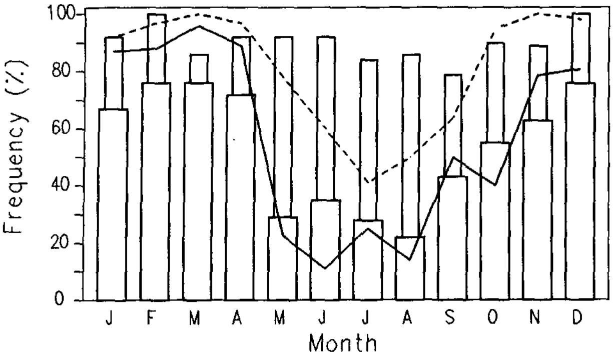

FIG. 4. Monthly inversion frequencies as determined from paired ice-station radiosonde and Ptarmigan dropsonde soundings. The boxes give inversion frequencies for the dropsonde soundings: wide boxes represent surface-based inversions, narrow boxes represent elevated inversions, and the sum of both box types gives the total inversion frequency. The lines give inversion frequencies for the ice-station radiosonde soundings: the dashed (upper) line represents total inversion frequency, the solid (lower) line gives surface-based inversion frequency, and the difference between the two lines represents the frequency of elevated inversions.

Table 1. An inversion was present in both the ice-station radiosonde and Ptarmigan dropsonde profiles in 299 cases (74% of the total number of sounding pairs). In 15 cases (4%) no inversion was present in either sounding, and for the remaining 88 pairs (23%) an inversion was present in one of the two soundings.

The annual progression of the frequencies of different inversion types is shown graphically in Fig. 4. During the winter months the frequency of surface-based inversions in the Ptarmigan soundings is 10%–20% less than the corresponding frequencies over the ice stations. During summer the total inversion frequencies for the ice-station soundings are considerably less than the corresponding frequencies for the Ptarmigan soundings (Fig. 4). This difference reaches 43% in July. The minimum in the ice-station total inversion frequency, 41% in July, is inconsistent with previous analyses of inversions over the Arctic Ocean. Serreze et al. (1992a) reported a summer total inversion frequency of 89%, Belmont (1957) reported a frequency of 90%, and Vowinckel and Orvig (1970) reported a June minimum total inversion frequency of 61% (partly based on North Pole 7 soundings). The summertime inversion frequencies given by the Ptarmigan soundings, however, are in good agreement with the previous studies.

In an attempt to determine the reasons for the surprisingly low frequency of summertime inversions depicted by the ice-station soundings, we looked more closely at the summer cases. There were 68 cases year-round in which inversions were identified in the Ptarmigan soundings but not in the ice-station soundings; of these, 62 cases occurred in the months May–September (Table 1). There were 106 cases during these same months in which inversions were identified in both soundings. Examination of the Ptarmigan inversions corresponding to these groups of cases revealed the following. For the 62 summer cases with inversions in the Ptarmigan but not in the ice-station soundings, the median inversion base height, depth, and temperature difference was 357 m, 433 m, and 2.9°C, respectively. For the 106 summer cases with inversions identified in both soundings, the corresponding median

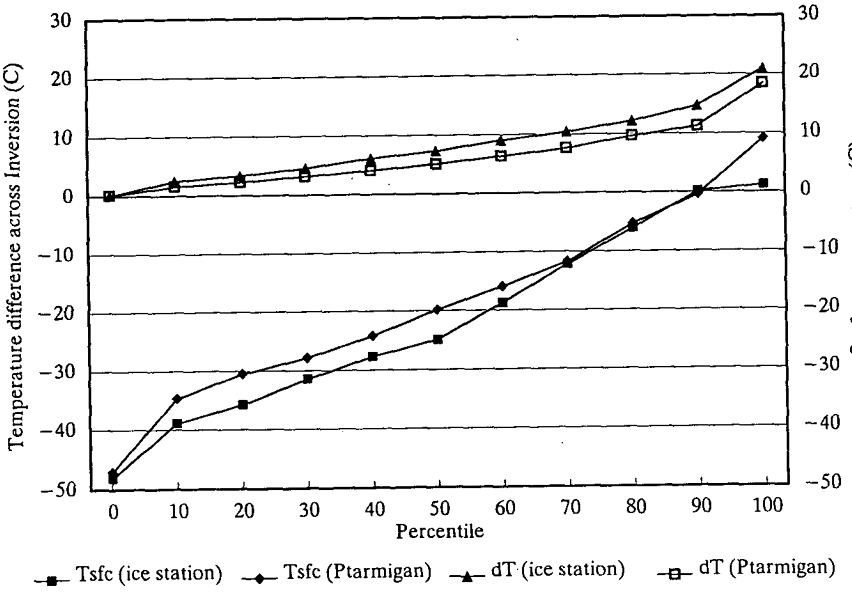

FIG. 5. Cumulative frequency distributions of surface temperature (Tsfc; right scale) and temperature difference across the inversion (dT; left scale) for the 299 cases for which inversions are present in both ice-station radiosonde and Ptarmigan dropsonde profiles.

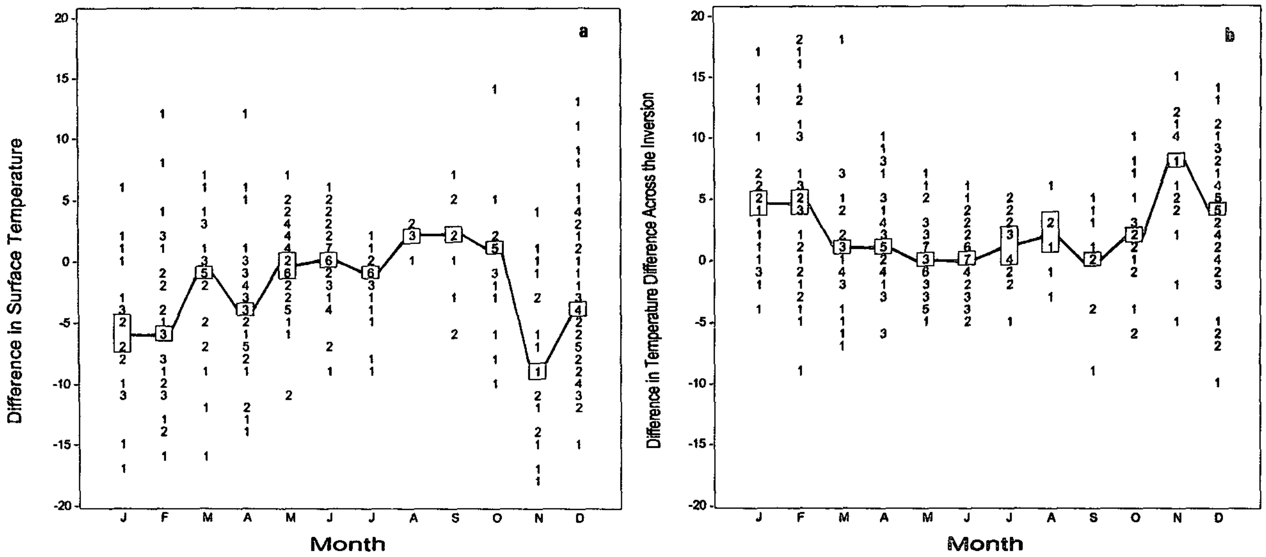

FIG. 6. Monthly distributions of differences in (a) surface temperature and (b) temperature difference across the inversion for the 299 cases for which inversions were present in both ice-station radiosonde and Ptarmigan dropsonde profiles. Differences are computed as ice-station value minus Ptarmigan value. The plotted numbers denote the number of paired soundings, and the line connects the median value for each month.

inversion base height, depth, and temperature difference was 116 m, 421 m and 3.6°C, respectively. This comparison indicates that the ice-station radiosonde soundings tend not to contain inversions when the corresponding Ptarmigan inversion is elevated and weak (i.e., with a small temperature difference across the inversion). In addition, of the 62 summertime cases in which inversions were present in the Ptarmigan but not in the ice-station soundings, 33 of the ice-station soundings depicted an elevated isothermal layer with depth greater than 100 m. This raises the possibility that weak, elevated inversions are being "missed" by the ice-station soundings and instead are incorrectly reported as elevated isothermal layers. This possibility is discussed further in section 4b.

c. Inversion features and temperatures

We prepared cumulative frequency distributions of temperatures (surface, 850 and 700 hPa) and inversion features (base height, depth, and temperature difference) for the 299 cases in which inversions were present in both the ice-station and dropsonde soundings. Distributions for most variables were similar for both sounding types, but systematic differences were evident for surface temperature and temperature difference across the inversion (Fig. 5). As shown in Fig. 5, Ptarmigan soundings consistently depicted higher surface temperatures and weaker inversions (smaller temperature differences) than their ice-station counterparts.

Monthly distributions of the differences in these variables (ice-station value minus Ptarmigan value) are given in Fig. 6. The largest differences and variances in surface temperature occurred in winter (Fig. 6a), with Ptarmigan surface temperatures about 6°–12°C warmer than the ice-station surface temperatures. The differences in the temperature difference across the inversion (Fig. 6b) is anticorrelated with the differences in surface temperatures (Fig. 6a), indicating that weaker inversions tend to accompany the warmer Ptarmigan surface temperatures. This relationship is also evident in Fig. 7, which confirms that warmer Ptarmigan surface temperatures tend to accompany weaker Ptarmigan inversions (smaller temperature differences). We note that warmer Ptarmigan surface temperatures are also observed in 75% of the 149 cases in which both sounding types indicate surface-based inversions. These pairs of surface-based inversions occur primarily in the winter months (Table 1).

4. Discussion

a. Temperature lag errors

Temperature profiles measured by radiosonde and dropsonde are fundamentally different in that the radiosonde measurements are made while the instrument travels upward, and the dropsonde measurements are made while the instrument travels downward. Both measurement types are subject to systematic lag errors caused by the failure of the temperature instrument to respond instantaneously to changes in temperature during ascent or descent. Temperature lag errors, though well understood in principle (e.g., Middleton 1943), have often been ignored in inversion analyses (Houvilla and Touminen 1990).

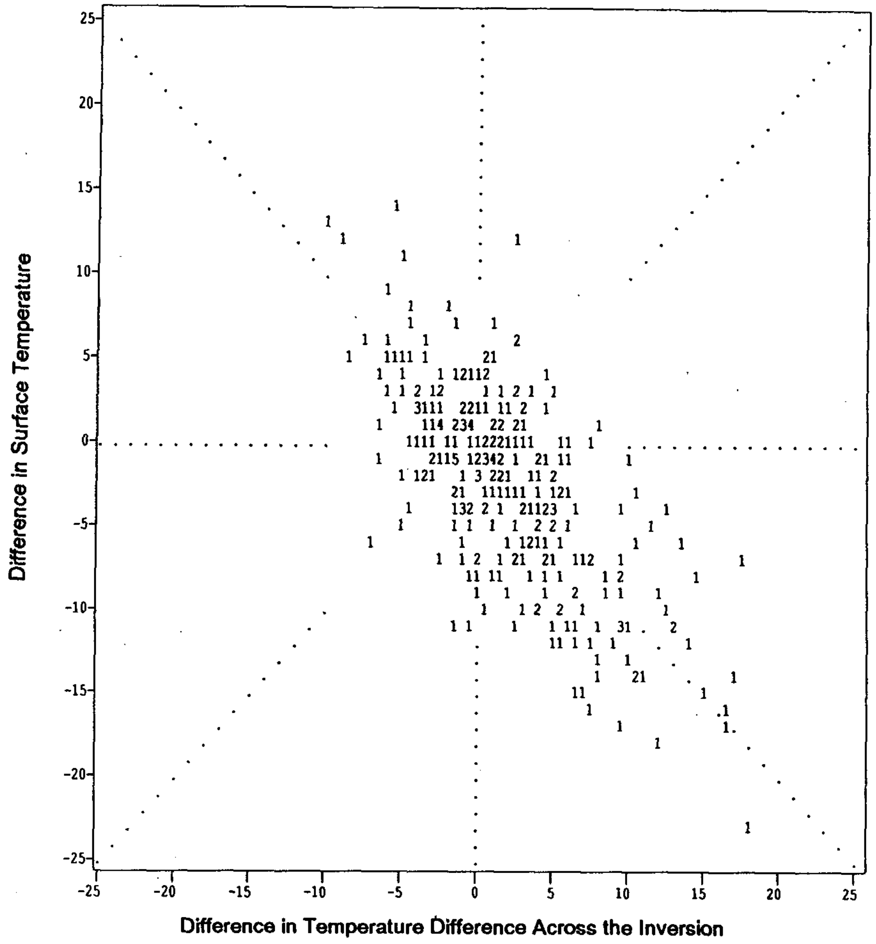

FIG. 7. Relationship between difference in surface temperature vs difference in temperature difference across the inversion for the 299 cases for which inversions were present in both ice-station radiosonde and Ptarmigan dropsonde profiles. Differences are computed as ice-station value minus Ptarmigan value. The plotted numbers denote the number of paired soundings.

The expected effects of temperature lags on dropsonde and radiosonde instruments traveling through a surface-based inversion are illustrated in Fig. 8. The descending dropsonde instrument will "remember" the cooler temperatures above the inversion, thus artificially lowering the inversion top and decreasing the inversion depth. As the instrument responds to the warmer temperatures in the inversion layer it will artificially increase the surface temperature, thus decreasing the temperature difference across the inversion. The expected systematic lag error of an ascending radiosonde instrument, on the other hand, has the opposite effect. The warmer temperatures sensed within the inversion layer tend to raise the inversion top and increase the temperature difference, artificially producing a deeper and stronger inversion. In the presence of an elevated inversion, the temperature lag could result in either a positive or negative bias, depending on the lapse rates within and above the inversion layer.

The magnitude of the temperature lag error in any actual dropsonde or radiosonde is dependent on a number of factors including sensor type, ventilation, humidity, and radiation corrections. Operational methods for correcting early Ptarmigan soundings for temperature lag errors have been documented (AWS 1952); however, we do not know whether any such corrections were incorporated into the raw data used to assemble the Ptarmigan dropsonde archive. An analysis of early Ptarmigan data by Poage (1954) suggested that errors introduced by temperature lag would typically be less that 1°C.

Our analysis presents conflicting evidence on the presence of a systematic lag bias in boundary layer temperatures measured by ice-station radiosondes. While the wintertime Ptarmigan soundings depict warmer surface temperatures and weaker inversions than their ice-station counterparts, they do not consistently depict smaller inversion depths and lower temperatures at 850 hPa, a level that roughly corresponds

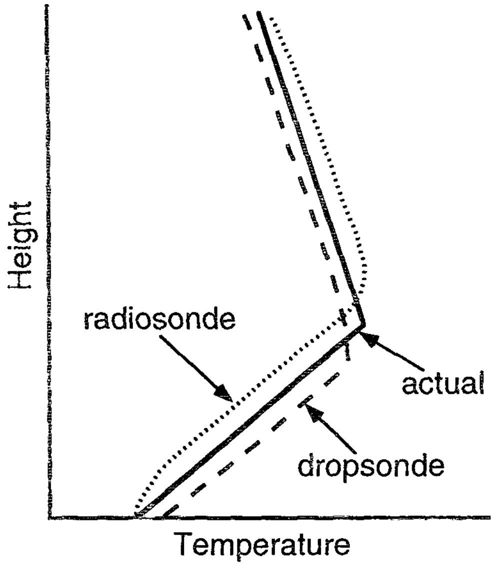

FIG. 8. Effect of temperature lag errors on a descending dropsonde (dashed line) and an ascending radiosonde (dotted line). The solid line represents the actual temperature profile.

to the top of the inversion layer. Based on the information available, we estimate that systematic temperature lag errors are responsible for a portion of the differences in surface temperatures and inversion features as measured by Ptarmigan dropsondes and ice-station radiosondes. Lag or calibration errors in pressure sensors could also contribute to the bias, as the measured pressure is used in the hydrostatic determination of geopotential height.

b. Possible instrumental problems associated with North Pole 7 and North Pole 8 radiosondes

The unexpectedly low frequency of summertime inversions depicted by the ice-station radiosonde sounding lacks an obvious physical explanation. Rather, it may reflect a systematic failure of the radiosonde instrument to detect weak elevated inversions. The first Soviet radiosondes, model RS-049, were used at ice stations North Pole 7 and North Pole 8 (Zaitseva 1990). The bimetal temperature sensor supplied with this early radiosonde instrument was evidently not able to respond quickly to temperature changes experienced while ascending through elevated inversion layers. As discussed earlier, this problem apparently caused weak inversion layers to be incorrectly recorded as isothermal layers. By 1963 the RS-049 instrument had been superseded at virtually all Soviet radiosonde stations (Zaitseva 1990). This apparent problem should not affect surface temperatures, as standard measurement protocol requires acclimating the instrument with the ambient air temperature prior to release. We were unable to ascertain the specific instrument types carried by the Ptarmigan dropsondes during the comparison period (1957–61).

5. Summary and conclusions

We examined 402 pairs of approximately collocated radiosonde and dropsonde temperature profiles over the Arctic Ocean during the period 1957–1961. The radiosonde profiles were obtained at the Russian drifting ice camps North Pole 7 and North Pole 8, whereas the dropsonde profiles were measured during the United States Air Force "Ptarmigan" series of weather reconnaissance flights.

Our principle results are as follows.

1) The relatively small number of lower-tropospheric measurement levels reported in the Ptarmigan dropsonde soundings provides sufficient resolution to detect the main features of the Arctic temperature inversion. The ice-station radiosonde data contain approximately twice as many levels in the lowest few kilometers; however, many of these levels appear to have been interpolated and do not necessarily provide better vertical resolution.

2) Wintertime surface temperatures measured by dropsondes are typically 6°–10°C larger than corresponding temperatures measured by ice-station radiosondes.

3) Dropsonde soundings consistently depict weaker inversions during winter. Median temperature differences across the inversion were 5°C less than those depicted by the corresponding ice-station soundings.

4) The frequency of summertime elevated temperature inversions depicted by ice-station radiosondes was up to 50% lower than similar frequencies found in the dropsondes and in previous studies.

Our results suggest that the systematic differences in wintertime inversion features and near-surface temperatures are partially attributable to contrasting temperature lag errors from ascending and descending sounding instruments. Unfortunately, it is impossible to quantify this bias because our paired soundings were not truly collocated (the match criteria specified that the two soundings be within 300 km and 12 h of each other). Other possible factors contributing to these differences include spatial and temporal inhomogeneities on scales smaller than 300 km and 12 h and differences in sounding data reduction algorithms (e.g., Elliott and Gaffen 1991).

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