

Surface Temperature of the Arctic: Comparison of TOVS Satellite Retrievals with Surface Observations

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ABSTRACT

Surface temperature is a fundamental parameter for climate research. Over the Arctic Ocean and neighboring seas conventional temperature observations are often of uncertain quality, however, owing to logistical obstacles in making measurements over sea ice in harsh environmental conditions. Satellites offer an attractive alternative, but standard methods encounter difficulty in detecting clouds in the frequent surface-based temperature inversion and when solar radiation is absent. The Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder Polar Pathfinder (TOVS Path-P) dataset provides nearly 20 yr (1979–98) of satellite-derived, gridded surface skin temperatures for the Arctic region north of 60°N. Another dataset based on surface observations has also recently become available. The International Arctic Buoy Program/Polar Exchange at the Sea Surface (IABP/POLES) project provides a gridded near-surface air temperature dataset based on optimally interpolated observations from Russian drifting ice stations, buoys, and land stations from 1979 to 1997.

In this study these two datasets are compared and areas with large differences (4 to 6 K) are found in both winter and summer. Over the ice-covered Arctic Ocean in both seasons TOVS temperatures are substantially colder than POLES and over the Greenland–Iceland–Norwegian (GIN) Seas TOVS is warmer. Using point measurements from manned ice stations and ships it is found that POLES is too warm (~2 K on average) in January. The bias is larger (~4 K) in regions where the primary source of data is buoys, which contain warm biases in winter owing to the insulation effect of snow covering the sensors. The difference between skin and 2-m temperatures accounts for approximately 1 K of the January discrepancy between POLES and TOVS. Over the GIN Seas in both seasons POLES is much too cold (~7 K) where values are based primarily on analyses from the National Centers for Environmental Prediction (NCEP). In July the TOVS temperatures are approximately 6 K too cold over ice-covered regions owing to poor retrievals when cloud cover exceeds 95%. When overcast retrievals are removed, this difference is reduced to 2 K. Therefore it is recommended that TOVS retrievals be rejected in summer when the retrieved cloud cover is over 95%. Decadal trends also differ greatly between POLES and TOVS primarily owing to the discontinuation of ice station data in the POLES dataset after 1991. Large positive trends in POLES over the central Arctic during spring are absent in TOVS in part because POLES relies on buoy data during the latter third of the data record.

1. Introduction

Surface air temperature is a fundamental variable in characterizing the climate system. This quantity has been measured for decades over the inhabited regions of the world and is most often analyzed for evidence of global warming. Over sea ice the surface temperature gains additional importance relative to other surface types because it can be considered an integrator of surface energy fluxes—radiation and turbulent fluxes from above and conductive fluxes from below. Because snow/ice surface temperature responds to a number of environmental conditions—such as ice and snow thickness, cloud cover, and surface melting—it also plays an important role in several feedback mechanisms that are

believed to exert a strong influence on climate sensitivity to change. Over sea ice-covered areas, however, the surface temperature in both a daily and climatological sense is poorly known owing to its temporal and spatial inhomogeneity, logistical obstacles in establishing a suitably dense observing network, and difficulties in measuring it from space.

Disagreement is rampant among the many climate models being used to simulate the present climate system. A comparison of 31 GCMs as a part of the Atmospheric Model Intercomparison Project (AMIP) shows the largest intermodel differences in surface air temperature occurring in high latitudes, with over 20 K separating the annual-mean values for the Arctic region (Gates et al. 1999). One aspect in which the models do agree is that the polar regions, the Arctic in particular, are more sensitive to anthropogenic modifications to the environment than any other zone; the so-called polar amplification. Models predict that global warming will

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be significantly larger in the high-latitude north, particularly in winter. Surface air temperature measurements from the past few decades are consistent with this forecast; significant warming trends ($\sim 0.5^{\circ}\text{C decade}^{-1}$) have been observed over much of Eurasia and North America (Serreze et al. 2000), particularly in winter and spring. Trends in data for the central Arctic Ocean, however, are much less certain owing to contradictions among available measurements and uncertainties in data quality. The most reliable measurements are from Russian meteorological stations (so-called NP data) that were positioned on thick ice floes and drifted with the ice pack between 1954 and 1991. These measurement records are invaluable for establishing temporal variability, but spatial variability is probably not well represented, as only two stations on average existed within the entire Arctic Ocean at any one time. Rigor et al. (2000) augment the dataset by blending the NP values with measurements from coastal meteorological stations and from buoys that were placed onto the ice as a part of the International Arctic Buoy Program (IABP). The blended dataset is generally considered the state of the art in Arctic Ocean surface air temperatures. However, while a concerted effort was made to remove effects of solar heating and snow insulation from buoy temperatures, their accuracy remains uncertain.

Satellites provide an appealing opportunity to measure surface skin temperature over the entire region, as polar-orbiting platforms view the high latitudes frequently. Several attempts have been made to use infrared imager data, such as those from the Advanced Very High Resolution Radiometer (AVHRR), but because of difficulties in distinguishing clouds from a background covered by snow and ice, temperatures are usually limited to clear-sky areas (Key and Haefliger 1992; Lindsay and Rothrock 1994; Yu et al. 1995). An experimental all-sky product has recently been derived from AVHRR imagery by modeling the effects of clouds and wind speeds on the surface temperature (Wong 2000), but validation of the results is limited.

In this paper we evaluate the accuracy of surface skin temperature fields in the Arctic region derived from the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) radiances by comparing them to near-surface air temperatures from three sources. One is the gridded product generated by interpolating data from meteorological stations and buoys (Rigor et al. 2000), and the other two are direct point measurements from Russian NP stations and from ships in open water. The next section describes the datasets used in this study, section 3 explains the methodology used to interpolate and compare the various sources of temperatures, section 4 presents the results of the comparisons and discusses probable causes of observed differences, and the final section summarizes our results and conclusions.

2. Datasets

Four sources of surface temperature data are used in this study: satellite retrievals from the National Aeronautics and Space Administration–National Oceanic and Atmospheric Administration (NASA–NOAA) TOVS Polar Pathfinder dataset (hereafter TOVS), the IABP/Polar Exchange at the Sea Surface (POLES) product (hereafter POLES), Russian North Pole ice station measurements (hereafter NP), and the Comprehensive Ocean–Atmosphere Data Set (COADS). Each dataset is described in some detail, along with its known or probable strengths and weaknesses.

a. NASA–NOAA TOVS Polar Pathfinder skin temperature

The TOVS instrument has flown continuously on NOAA polar-orbiting satellites since 1979 and consists of three radiometer arrays, of which we use two: the High Resolution Infrared Radiation Sounder (HIRS), and the Microwave Sounding Unit (MSU). Satellite radiances are processed with a modified version of the Improved Initialization Inversion (3I) algorithm developed by the Atmospheric Radiation Analysis group at the Laboratoire de Météorologie Dynamique (LMD). The algorithm has been modified to improve results over snow and ice surfaces (Francis 1994). A brief summary of the algorithm is provided here, and more detailed descriptions of 3I can be found in Chédin et al. (1985), Francis (1994), Stubenrauch et al. (1999), and Scott et al. (1999). The MSU and HIRS level-1b radiances are first calibrated using the standard procedure outlined in the NOAA Polar Orbiter Data User's Guide (Kidwell 1998), and data are interpolated to $(100\text{ km})^2$ retrieval boxes. Further corrections are applied based on a large number of comparisons between observed brightness temperatures and model-calculated values using collocated radiosonde data. When the TOVS dataset was created, corrections for only three of the NOAA polar-orbiting satellites were available. Available bias corrections were applied to satellites for which we did not have sensor-specific values, which may result in small biases.

Each retrieval box is then associated with one of five airmass types, ranging from tropical to polar winter, based on brightness temperatures of channels that are not affected by clouds. Various cloud tests are performed to determine whether individual HIRS pixels (with approximately 18-km resolution at nadir) are clear or cloudy. Subsequently the retrieval boxes are designated either as clear, partially cloudy, or overcast depending on the fraction of clear HIRS pixels within the box. The cloud tests have been modified since the original implementation of 3I to improve cloud detection over polar surfaces (Francis 1994; Stubenrauch et al. 1999; Scott et al. 1999). The effects of clouds on cloud-sensitive HIRS channels are removed using regressions

between pairs of microwave and infrared channels that have similar weighting functions. Cloud-cleared radiances are then used to search a library of profiles for a first-guess solution. The final temperature profile is obtained by minimizing differences between the first guess and the observations. Moisture profiles and surface skin temperature are retrieved only for 3I boxes that have been diagnosed with an effective cloud fraction (i.e., the product of cloud emissivity and coverage) below 90%, which typically eliminates about 5% of the retrieval boxes. Skin temperature is retrieved using different methods depending on whether the box is classified as clear, partly cloudy, or overcast, and whether it is located over land, open ocean, or sea ice. For clear and partly cloudy retrieval boxes, a combination of HIRS window channels (channels with central wavelengths of 11.1, 4.0, and 3.7 μm) is used in the clear HIRS pixels within the box. For boxes in which all HIRS pixels have some cloud but the effective cloud fraction is less than 90%, skin temperature and humidity are retrieved simultaneously using cloud-cleared window-channel radiances.

To create the TOVS dataset, the orbital swath retrievals are gridded in space and time onto the equal-area Special Sensor Microwave Imager (SSM/I) Earth grid (EASE; Armstrong and Brodzik 1995) north of 60°N and presented in hierarchical data format (HDF). Daily fields centered on 1200 UTC are provided for nearly 2 decades from 1979 until 1998. The dataset, which includes a variety of atmospheric and surface products, and further documentation can be obtained from the National Snow and Ice Data Center (NSIDC; online at <http://www.nsidc.org>). The TOVS products in the Arctic have been validated extensively with data from Russian NP stations in the ice-covered Arctic Ocean and from the Surface Heat Balance of the Arctic (SHEBA) field experiment (Francis and Schweiger 2000; Schweiger et al. 2002), which was conducted on thick sea ice approximately 200 km north of the Alaskan coast. Skin temperatures were not measured continuously during SHEBA, thus we compare 2-m air temperatures with TOVS skin temperatures (Fig. 1). The difference between the temperature of the surface skin and the air 2 m above is usually less than 1 K except in prolonged calm, clear conditions in the polar night (CEAREX Drift Group 1990; Guest and Davidson 1994).

While standard image-based methods can be used only in clear-sky conditions, the TOVS skin temperature product very nearly represents all-sky conditions. The 3I algorithm retrieves skin temperature except when the effective cloud fraction (the product of cloud coverage and cloud emissivity) is greater than 90%, which occurs infrequently in the Arctic owing to the low moisture content of the atmosphere. During the nonmelt season, the skin temperature over snow- and ice-covered surfaces can differ by several degrees depending on whether the area is clear or cloud covered (e.g., Wong 2000; Guest and Davidson 1994). This difference is largest

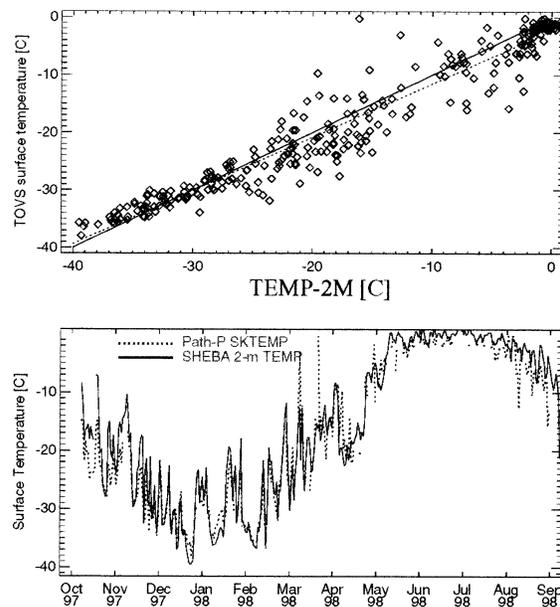


FIG. 1. Daily mean surface skin temperature from the TOVS Polar Pathfinder dataset compared with near-surface air temperature measured during the SHEBA field program. (top) A scatterplot showing lines of 1:1 correspondence and the least squares fit; (bottom) a time series of daily values. The bias is near zero, the rmse is 3 K and the correlation coefficient is 0.97 (from Schweiger et al. 2002).

when winds are calm and when solar radiation is absent. Under an isolated, small hole in the clouds, however, skin temperature is not expected to differ substantially from nearby cloud-covered areas because the clouds are generally moving over the surface. Consequently, the skin temperature will have little time to respond to reduced surface longwave radiation fluxes in a hole on the order of 20 km in diameter (approximate size of a HIRS pixel). Because a TOVS grid box is an average of all orbital swaths during a 24-h period (~ 14 views per day) and each 3I box represents an average of between 6 and 9 HIRS pixels, the effect of a few clear holes will be small. The comparison with SHEBA measurements supports this contention, as a clear-sky bias, which would manifest itself as TOVS values being lower on average than SHEBA measurements, is not evident. On the contrary, at the lowest temperatures it appears that TOVS temperatures are a few degrees too high. This bias is expected given that TOVS retrievals represent an average over a $(100 \text{ km})^2$ region that may include small areas of relatively warm thin ice or open water, while the SHEBA values are for thick ice only. It may also result from clouds embedded in the surface-based temperature inversion that may have been overlooked by the cloud detection algorithm. During the warm season there is no difference between clear and cloudy surface temperatures, as the surface is melting and therefore constant at 0°C. The TOVS values in summer are, however, slightly too cold, which may be caused by errors in cloud detection (cloud tops are gen-

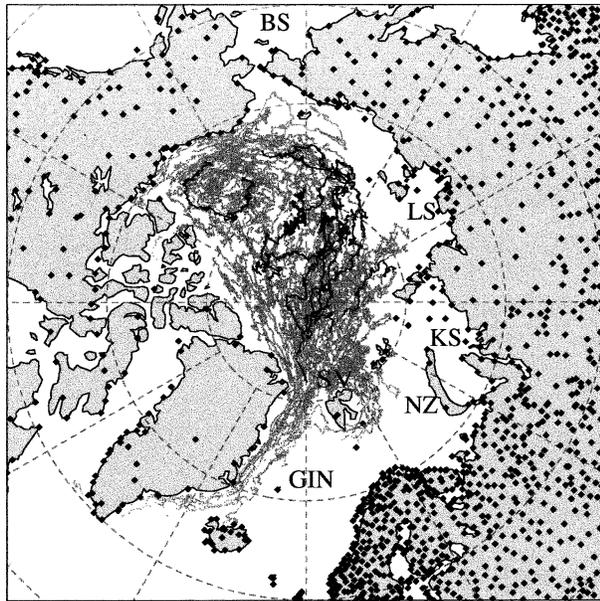


FIG. 2. Locations of observations used to produce the POLES dataset of near-surface air temperature fields. Black trajectories are the Russian North Pole meteorological ice stations (1979–91), gray trajectories are the drifting buoys of the IABP dataset (1979–97), and black diamonds are meteorological stations on land (1979–97). The following locations are marked: Novaya Zemlya (NZ), Kara Sea (KS), Laptev Sea (LS), Bering Sea (BS), Svalbard (SV), and Greenland–Iceland–Norwegian Seas (GIN). From Rigor et al. (2000).

erally colder than the surface in summer) or because a retrieved temperature is not allowed to exceed the melting point when sea ice is detected (Schweiger et al. 2002). Overall these results are encouraging, but further validation is needed to determine whether the level of accuracy is maintained in other regions of the Arctic and in other years.

b. IABP/POLES air temperature

The POLES dataset was created by combining 2-m air temperature measurements from Russian NP ice stations and meteorological stations located along the Arctic coast with temperature measurements from automated buoys positioned on the sea ice as a part of the IABP (Martin and Munoz 1997; Rigor et al. 2000). Data from the three sources are interpolated using objective analysis to a twice-daily, gridded product extending from 1979 to 1997, north of 60°N, at an approximate resolution of $(100 \text{ km})^2$. Each of the three sources of data have characteristics that may affect their representativeness of the Arctic Ocean. The Russian NP data are standard 2-m air temperature measurements made by trained human observers. The data are believed to be of high quality, but only one or two NP stations existed in the Arctic Ocean at any given time and they tended to be located in the eastern Arctic (Fig. 2). Measurements from coastal stations are plentiful and are also believed to be of high quality, but there are often large

horizontal temperature gradients between coastal land areas and the sea ice. Data from automated buoys are prone to a number of errors, including warming caused by absorption of solar radiation and insulation caused by snow covering the buoy and temperature sensor (Rigor et al. 2000). Beginning in 1992 about a quarter of the buoys were equipped with ventilated temperature sensors, which should reduce these effects. Before this time, many steps were taken to correct buoy temperatures, but residual effects are suspected. Further corrections were applied to the dataset in early 2002 (I. Rigor 2002, personal communication), and this updated version was used in this study.

The spatial distribution of data from these three sources is presented in Fig. 2. There are numerous regions where no data are available to the POLES interpolation scheme, notably most of the Greenland–Iceland–Norwegian (GIN) Seas and most of the peripheral seas north of the Asian continent. The NP data are also sparse in the Beaufort Sea, with only one station trajectory in that region. In areas where observations are sparse, the POLES dataset includes in its optimal interpolation procedure monthly mean values from the National Centers for Environmental Prediction (NCEP) analysis.

c. Russian NP station air temperature

From 1954 through early 1991 a continuous series of meteorological stations was established by the Soviet Union on ice floes drifting with the pack ice in the Arctic Ocean. It is extremely unfortunate that this program was discontinued, particularly in the early 1990s when disturbing changes have been observed in the Arctic region. These data were recently made available to the global scientific community by the Russian Arctic and Antarctic Research Institute (AARI). Weather observers at the stations made high-quality measurements of standard atmospheric variables, including 2-m air temperature (Kahl 1998). Between one and four stations existed in any year and tended to be located in the eastern half of the Arctic Ocean. We use 2-m air temperatures from stations that existed between 1979 and 1991. The dataset and documentation can be obtained from NSIDC.

d. COADS air temperature

The Comprehensive Ocean–Atmosphere Data Set contains individual meteorological observations over the global ocean from a variety of marine platforms, including ships, buoys, and ice stations. The NSIDC, in cooperation with the NOAA Climate Diagnostics Center (CDC), and the National Center for Atmospheric Research (NCAR), assembled an Arctic subset of surface marine observations from the global COADS dataset (Serreze 1997). Data for the ice-covered Arctic Ocean were obtained from this dataset, buoy observations excluded. For the GIN Seas region we selected from the global dataset the lowest-level temperatures from ra-

diosondes launched by ships in the area. These temperatures are daily average values.

3. Methodology

The primary objective of this study is to evaluate the accuracy of the TOVS surface skin temperature retrievals using surface-based measurements. To achieve this goal, surface temperatures during winter (January) and summer (July) from the various data sources are collocated by interpolating them to the TOVS grid. For both POLES data and point measurements we use a simple “nearest neighbor” method to collocate data in space, as the distance between any location and a TOVS gridpoint is less than 71 km. A more sophisticated interpolation technique is not warranted, as often the individual observations are so sparse that no relationship between two measurements would be expected. Temporally we average the 0000, 1200, and 2400 UTC POLES values to 1200 UTC to be consistent with TOVS products, which are averaged to 1200 UTC over a 24-h period. We performed a similar procedure on NP data, averaging temperatures at 0600, 1200, and 1800 UTC to 1200 UTC. The COADS data in the central Arctic are too irregular to calculate averages, so all values during a particular day were used. The COADS data obtained for the GIN Seas are already daily averages.

Standard statistical tools are used to compare temperature values. We consider only retrievals over ice and ocean, as over land the horizontal inhomogeneity of surface temperature is so large that any spatial separation of measurements and retrievals usually results in large differences that overwhelm actual discrepancies among observations.

The analysis begins with the calculation of decadal-mean temperatures for January and July for both TOVS and POLES. The difference between these mean fields shows whether significant discrepancies exist and where additional analysis is needed. We then use near-surface air temperature measurements from NP stations and COADS to identify the sources of and reasons for observed differences.

4. Results

a. Decadal means

Figure 3 shows the spatial distribution of decadal-mean differences between TOVS and POLES surface temperatures for January and July for the decade from 1980 to 1989. In January (Fig. 3a) the differences are primarily negative (TOVS colder than POLES) over the sea ice-covered regions except in the Laptev Sea (indicated by LS on Fig. 2). There are three primary lobes of large values: 1) the central Arctic Ocean north of the Alaskan coast, 2) a large area between Svalbard and the North Pole, and 3) just east of Novaya Zemlya in the western Kara Sea (NZ and KS in Fig. 2). Over open

water areas in the GIN and Bering Seas the differences are similar in magnitude but opposite in sign: TOVS retrievals are several degrees warmer than POLES values. In July (Fig. 3b) a bull’s-eye of negative difference (TOVS colder) centered on the North Pole exceeds -6 K, while TOVS is again warmer over the GIN Seas. The pattern of differences for both months in the following decade (1990–98) is very similar (not shown).

b. Intersatellite bias correction

As a first step toward understanding discrepancies between TOVS and POLES, we investigated the issue of intersatellite biases in the TOVS data. The TOVS instrument was originally designed to provide soundings for operational weather forecasting, and consequently did not undergo a climate-quality calibration procedure. As a part of the 3I processing algorithm for the TOVS dataset, satellite-specific corrections (so-called deltas) were applied to *NOAA-10*, *-11*, and *-12*, but deltas were not available for the other satellites. The procedure for calculating deltas is a tedious one requiring numerous high-quality, collocated radiosondes and forward radiative transfer modeling, which was beyond the scope of the TOVS effort. Consequently, the deltas for *NOAA-10* were applied to *NOAA-6* through *-9*, and deltas for *NOAA-12* were applied to *NOAA-14*.

Not surprisingly, remaining intersatellite differences are apparent in a 20-yr time series of monthly anomalies in retrieved skin temperature calculated over the entire TOVS domain (Fig. 4a). In an effort to remove the majority of the intersatellite bias, we applied a simple empirical correction method (Wang and Overland 2001). Assuming the *NOAA-10* period is the baseline, mean anomalies over the satellite life span for *NOAA-6*, *-7*, and *-8* are calculated, and any difference from the *NOAA-10* value is applied to those satellites as a correction. Resulting corrections are as follows: *NOAA-6* is -0.5 , *NOAA-7* is -1.1 , and *NOAA-9* is -0.9 . The correction for *NOAA-14* (-0.5) is calculated in the same way, except we compare the mean of the anomalies to that for 1979 to 1997 and *NOAA-11* is the standard instead of *NOAA-10*. While this simple procedure appears to eliminate much of the intersatellite difference (Fig. 4b), a more comprehensive effort is underway to remove biases in the TOVS radiance dataset. The decadal-mean discrepancies change only slightly after applying this correction, but trends calculated from TOVS retrievals should be interpreted with this uncertainty in mind.

c. Ice-covered Arctic Ocean: January

To investigate the source of decadal-mean differences in January over the ice-covered Arctic Ocean, we compare TOVS and POLES temperatures to 2-m air temperatures from the Russian NP drifting meteorological stations. The NP measurements are believed to be the

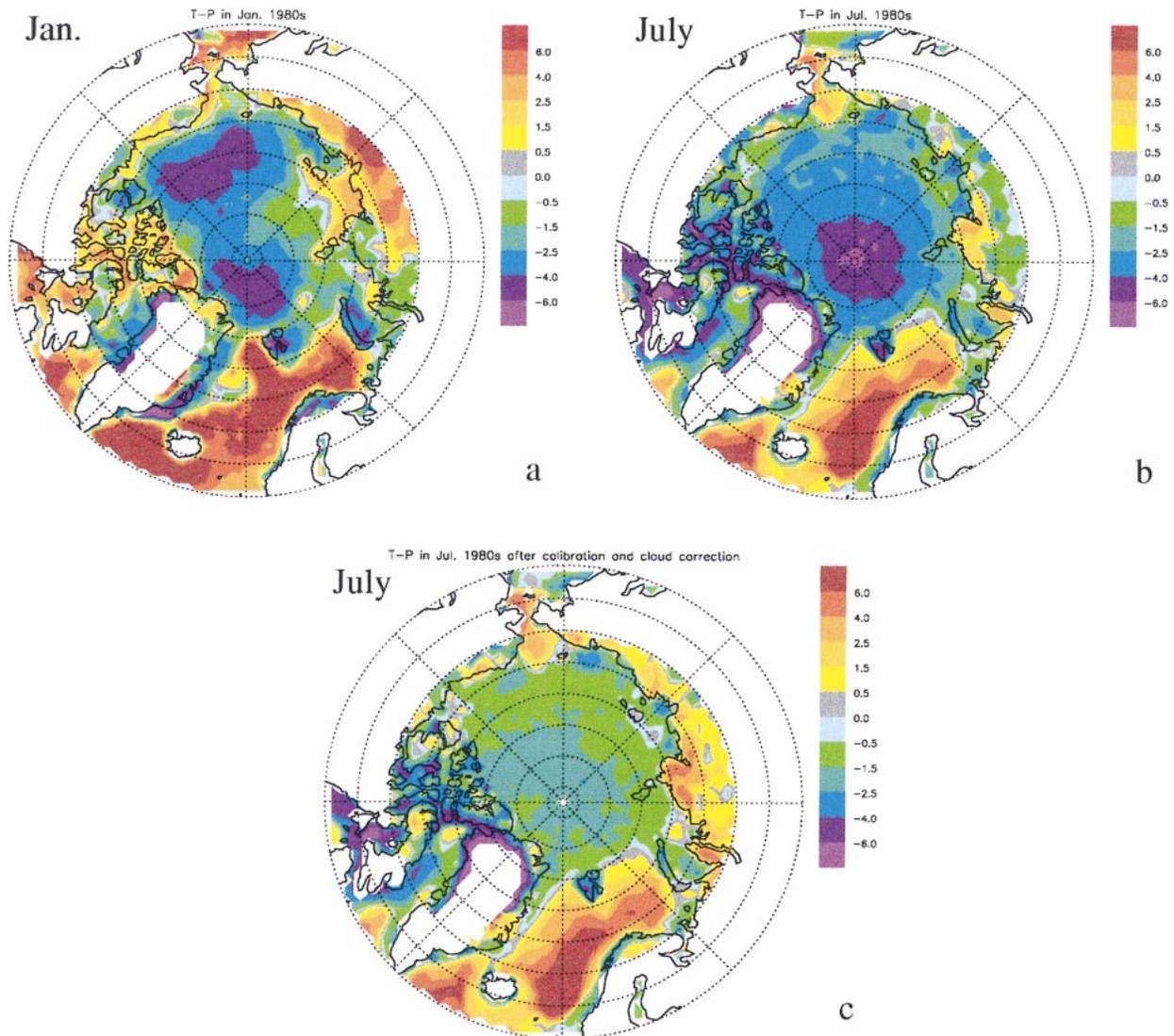


FIG. 3. Differences between decadal-mean (1980–89) TOVS skin temperatures and POLES near-surface air temperature (TOVS – POLES) in (a) Jan and (b) Jul. (c) Decadal-mean differences for Jul include corrections for cloud cover >95% over sea ice and for intersatellite biases.

most accurate available, and even though they are included in the POLES dataset, they are interpolated together with buoy data and coastal stations, sometimes over large distances.

Figure 5a shows a time series of differences in January-mean temperatures between collocated TOVS, POLES, and NP station data. The record begins in 1980, the first complete year of TOVS data, and ends in 1991 when the NP stations were discontinued. In every January the POLES data are as much as 5 K warmer than the NP measurements, with a mean difference of 2.0 K. TOVS retrievals are about 0.5 K cooler than NP data on average, which combined with the POLES difference, accounts for approximately 2.5 K of the discrepancy evident in Fig. 3a.

One source of the discrepancy is the inherent differ-

ence between skin and 2-m air temperatures in winter over sea ice. Typically this difference is less than 1 K (surface colder) except in prolonged clear, calm conditions (Guest and Davidson 1994).

Differences may also result from the density of different types of data used in the POLES dataset. In areas with relatively plentiful NP data, one would expect POLES temperatures to be more accurate than in regions where buoy measurements are the primary source of information for the interpolation. To test this hypothesis, we compare January temperatures from POLES and TOVS in two locations: 1) four points between the North Pole and Svalbard where NP data are sparse, and 2) along the tracks of 4 NP stations (stations 26, 27, 28, and 29) in the Pacific sector of the Arctic Ocean where NP data are relatively plentiful. The data-sparse area is

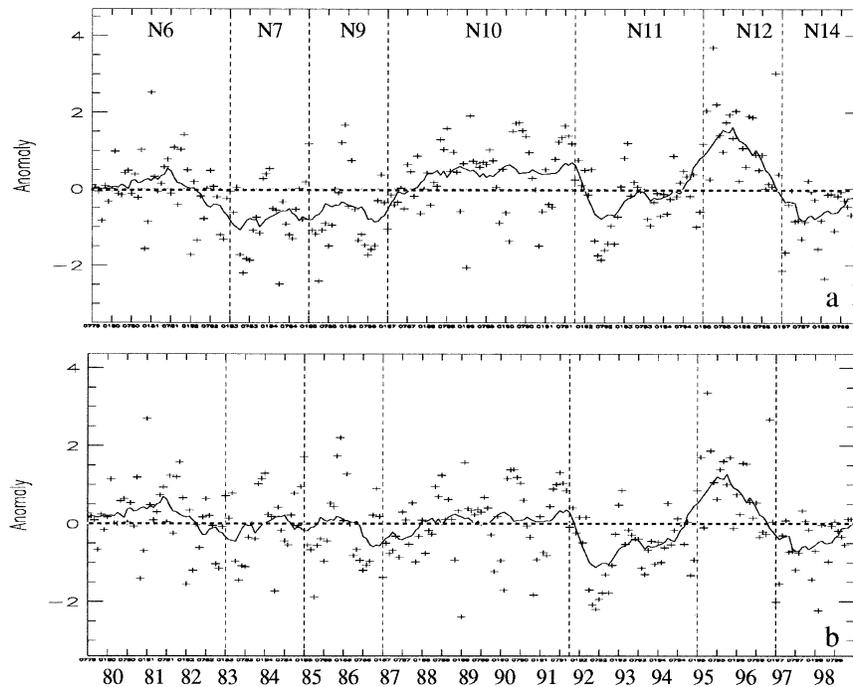


FIG. 4. Time series of monthly anomalies of surface skin temperature from the TOVS dataset during the entire data record from 1979 to 1998 (a) before and (b) after the application of empirical corrections. Solid line is the 1-yr running mean. Vertical lines mark transitions between NOAA polar-orbiting satellites, which are numbered at the top. Year labels correspond to 1 Jan.

also where the difference between TOVS and POLES in the comparison of January decadal means is largest (Fig. 3a). We find that the difference between POLES and TOVS along the NP tracks is small (TOVS colder) while in the NP data-sparse region the difference is over 3 K (Table 1). This result suggests that in areas where there are few NP measurements available for interpolation by the POLES procedure, two factors contribute to POLES data being too warm. First, the insulation effect of snow on buoys contributes to a warming of

the sensor (Rigor et al. 2000). Second, the interpolation process reduces the extremes in the temperature distribution, thereby causing coldest temperatures to be biased warm and warmest temperatures to be biased cool (I. Rigor 2001; personal communication).

Based on these findings as well as the validation results presented in Fig. 5a, it appears that the POLES data contain a warm bias of varying amounts in winter conditions and that TOVS skin temperatures represent actual conditions well. In the area immediately east of

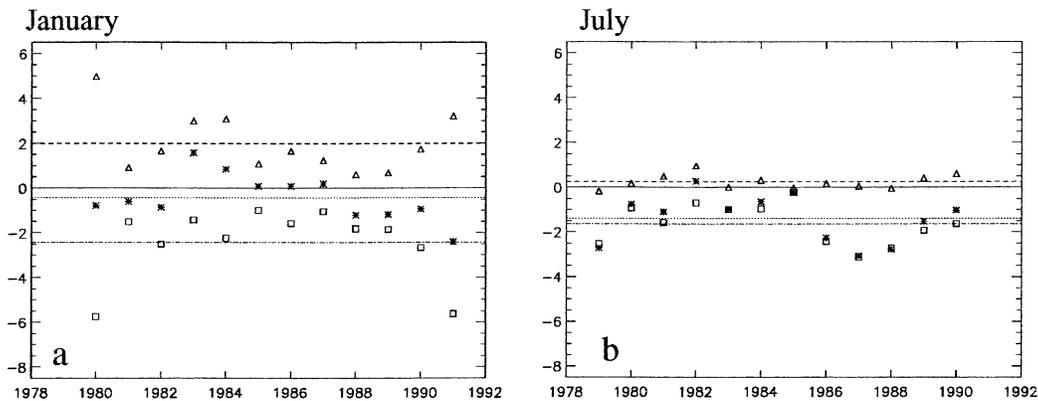


FIG. 5. Comparison of monthly mean differences among TOVS, POLES, and NP station surface temperatures in the ice-covered Arctic Ocean for each (a) Jan and (b) Jul along the track of the NP stations existing during each month. Dotted line (overall mean difference) and asterisks are TOVS - NP, dashed line and triangles are POLES - NP, and dash-dot line and squares are TOVS - POLES.

TABLE 1. Means of Jan temperatures from TOVS and POLES in two areas of the Arctic: 1) four points in the Atlantic sector of the Arctic Ocean where NP data are sparse, and 2) along NP drifting station trajectories in the Pacific sector.

Location	TOVS (°C)	POLES (°C)
85°N, 35°E	-32.5	-27.7
86°N, 0.0°	-34.0	-29.3
84°N, 25°E	-32.1	-27.3
87°N, 10°W	-34.5	-30.1
Mean of points in data-sparse area (A)	-33.3	-28.6
Mean temp from NP-26, -27, -28, -29 (B)	-32.9	-31.8
B - A	-0.4	3.2

Novaya Zemlya TOVS is colder than POLES and it is believed this is due to the warm bias in POLES because of insufficient data. In the Laptev Sea TOVS is warmer because some years have thinner than normal ice resulting in warmer surface skin temperatures. POLES cannot capture this feature because no NP stations nor buoys were located in the area.

d. Ice-covered Arctic Ocean: July

In July the surface of the sea ice has warmed to the melting point of freshwater and is close to 0°C everywhere across the Arctic. A time series of NP station data for July (not shown) confirms this statement. It is clear, therefore, that the TOVS retrievals are in error, as POLES data are nearly constant at 0°C during the melt season (Rigor et al. 2000). After considering several possible reasons for the bull's-eye over the pole where TOVS temperatures are more than 4 K too cold (Fig. 3b), we discovered that the erroneously cold retrievals occur when the retrieved cloud cover is high and at large satellite-view angles. Figure 6 shows the relationship between retrieved cloud cover (*not* effective cloud fraction) from TOVS and the difference between TOVS and POLES temperatures. There is a distinct increase in the difference for conditions when the cloud cover exceeds 95%. The summer Arctic is typically covered with extensive decks of low stratus clouds, which are notoriously difficult to differentiate from clear, ice-covered pixels using satellite observations (e.g., Curry et al. 1996). We find that by eliminating TOVS grid points that have a retrieved cloud cover greater than 95%, the error in July temperatures is drastically reduced from about 6 to 2 K too cold near the North Pole.

Figure 3c displays the July decadal-mean difference between POLES air temperatures and TOVS skin temperatures that have been corrected for both overcast conditions and the intersatellite biases (see section 4b). The TOVS retrievals over sea ice are still too cold, but the difference is generally less than 2 K and the spatial pattern is more homogenous, as expected for July. Figure 5b compares July-mean differences among TOVS, POLES, and NP data for the ice-covered Arctic Ocean after applying corrections to the TOVS retrievals. Based

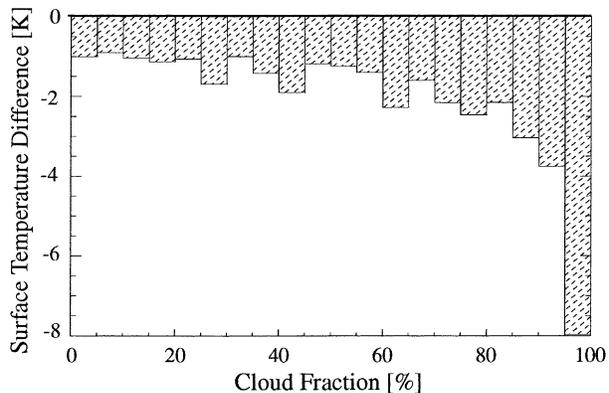


FIG. 6. Bar chart of the actual cloud fraction from TOVS vs the difference in surface temperature between TOVS and POLES along NP station trajectories at all available collocations in Jul.

on these findings, we recommend that TOVS retrievals of skin temperature during the melt season be rejected if the retrieved cloud cover exceeds 95%. In addition, surface temperatures of summer Arctic sea ice are known to be close to freezing, so accurate retrievals in this season are not needed.

e. GIN Seas: January and July

In both winter and summer seasons the TOVS skin temperatures are markedly warmer than POLES near-surface air temperatures in the GIN Seas region. Because POLES ingests little data in this area (Fig. 2), the interpolation scheme relies heavily on monthly climatologies from the NCEP analysis (Rigor et al. 2000). This is also a region of large horizontal temperature gradients owing to the close proximity of the warm Norwegian Current to the ice edge. Note that the largest differences between TOVS and POLES in Fig. 3 are located in the area where data ingested by POLES are most sparse. To evaluate POLES and TOVS fields in this region we use measurements from ships contained in the global COADS dataset. Locations of points used in the analysis are shown on maps in Fig. 7. Following the procedure we used for the ice-covered Arctic Ocean in January, except that all cloud conditions are included, we calculate differences between the COADS observations, POLES, and TOVS along the ship tracks in January and July between 1980 and 1995 (Fig. 8).

In both months it is clear that the POLES temperatures are too cold by approximately 7 K on average, which accounts for the differences between TOVS and POLES exhibited in all three plots in Fig. 3. The average difference between TOVS and COADS measurements, in contrast, is close to zero. The results of this comparison suggest that TOVS retrievals of surface skin temperature over open water regions of the Arctic (GIN Seas and Bering Strait) are more realistic than those included in the POLES dataset. If POLES included

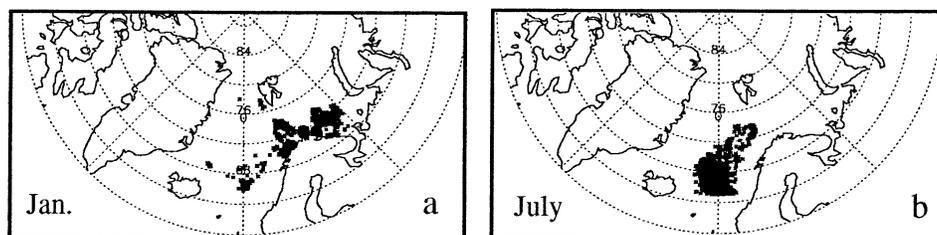


FIG. 7. Locations of COADS data in (a) Jan and (b) Jul used in comparisons to TOVS and POLES surface temperatures shown in Fig. 8.

COADS data in their interpolation scheme, their results in the GIN Seas would likely improve dramatically.

f. Comparison of decadal trends

In Fig. 9 we present decadal temperature trends in spring [March–April–May (MAM)] calculated from POLES and TOVS data for the same time period: 1980–97. We selected spring rather than winter because the trends in POLES from Rigor et al. (2000) are statistically significant over the Arctic Ocean during spring but not in winter. Our calculations using POLES data are different from those shown in Fig. 9 of Rigor et al. (2000) because we exclude 1979, we average their fields for 1200 UTC to be consistent with available data from TOVS, and the POLES dataset has been updated since Rigor et al. (2000) was published. The inclusion or not of data from 1979 makes a surprisingly large difference to the trends for all seasons, particularly in winter. The extensive areas of both positive and negative (albeit statistically insignificant) trends in the central Arctic during winter shown in Rigor et al. (2000) almost disappear if 1979 is excluded from the calculation.

The comparison of decadal trends from POLES and TOVS in our Fig. 9 should be considered with two caveats: TOVS retrievals over high elevation are not reliable, so only values over sea ice and open ocean

areas should be considered. It should also be noted that remaining intersatellite biases in TOVS radiances (see section 4b) introduce uncertainty into the TOVS-derived trends, thus we compare general patterns and not absolute values.

Despite these limitations, Fig. 9 shows some interesting and revealing contrasts between trends in POLES and TOVS temperatures. Overall the patterns are substantially different, except for the predominance of warming. In the central Arctic Ocean we find a large area of statistically significant positive trends in the POLES data (with and without 1979), but this feature is completely absent in TOVS. This is also the region where NP station data are most numerous (Fig. 2). The NP data, however, were discontinued in 1991; thus, the last third of the POLES dataset contains no NP data and relies solely on buoy data in this area. Because buoy data have been shown to be biased warm, the temperatures in the latter portion of the POLES record are biased warm. This leads to the apparent positive trend in the central Arctic. Another area of substantial disagreement between POLES and TOVS is located west of Novaya Zemlya where an area of significant positive trend is evident in TOVS but not in POLES. As already noted POLES ingested no data in this area, hence we speculate that the TOVS trend is realistic. The pattern is also consistent with changes in sea ice extent detected

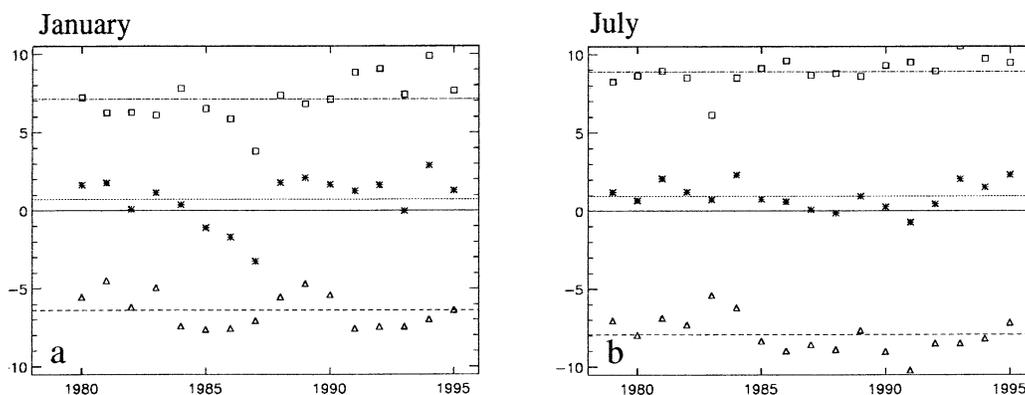


FIG. 8. Comparison of monthly mean differences among TOVS (all cloud conditions), POLES, and COADS station surface temperatures in the GIN Seas for each (a) Jan and (b) Jul along the track of COADS ships. Dotted line (overall mean difference) and asterisks are TOVS – COADS, dashed line and triangles are POLES – COADS, and dash-dot line and squares are TOVS – POLES.

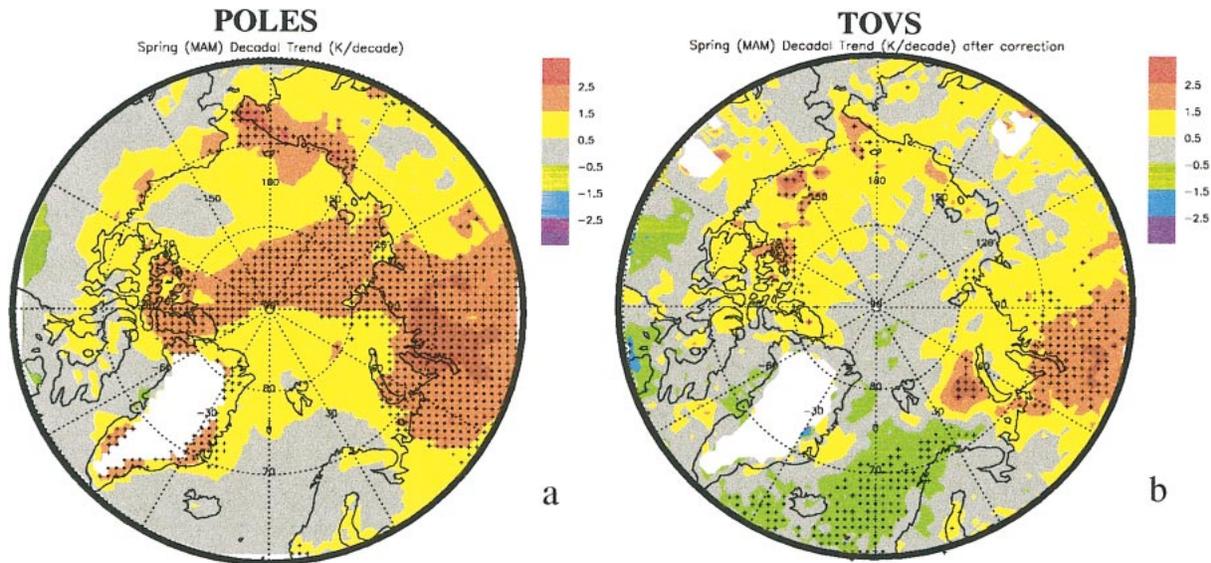


FIG. 9. Comparison of decadal trends (K decade^{-1}) in surface temperature during spring (MAM) from 1980 to 1997 calculated with a least squares fit to (a) daily POLES data and (b) TOVS retrievals. Trends with 95% confidence are indicated with plus signs, and with 99% confidence by a filled dot.

with passive microwave satellite data (Cavalieri et al. 1997), which show a large decrease in ice extent in this same area.

5. Conclusions

Comparisons between two recently available datasets of Arctic temperatures—the POLES near-surface air temperature dataset derived from surface observations and the TOVS skin temperature dataset derived from TOVS satellite retrievals—reveal large differences in both January and July. We compare these two sources of information over sea ice and open ocean with measurements of near-surface air temperature from meteorological stations on the sea ice and ships in the GIN Seas to determine the source of the observed discrepancies. Our findings are sorted by season and region.

a. Ice-covered Arctic Ocean in January

The decadal-mean TOVS skin temperatures are colder than POLES near-surface air temperatures by up to 6 K. By comparing TOVS and POLES temperatures to measurements from NP stations, we find that this discrepancy is caused by a combination of three factors. 1) The surface skin temperature averages approximately 1 K colder than the 2-m air temperature in the polar night, thus contributing about 1 K to the TOVS–POLES difference. 2) In areas where NP data are sparse and POLES relies primarily on buoy data, the POLES values are too warm owing to the insulation effect of snow on the buoy temperature sensors. 3) The interpolation procedure used by POLES to fill areas with no data reduces the extremes in the temperature distribution. The com-

bined effect of factors (2) and (3) is approximately 3 K. One exception to this pattern is in the Laptev Sea where TOVS temperatures are warmer than POLES. The POLES dataset has no data to ingest in this area, thus we speculate that TOVS temperatures are realistic and reflect the thin ice, and consequently warmer surface temperatures, that commonly exists in this area.

b. Ice-covered Arctic Ocean in July

The decadal-mean TOVS skin temperatures are colder than POLES near-surface air temperatures by more than 4 K in a nearly circular region north of 84°N . It is well known that the surface is melting and therefore near 0°C during July. The POLES temperatures are nearly constant at 0°C during the melt season, hence the TOVS retrievals are in error. We find that under heavily overcast conditions, according to TOVS satellite retrievals, the skin temperatures are much too cold. Removing TOVS grid points when the cloud cover exceeds 95% eliminates most of the observed error. A cold bias of approximately 2 K remains in the TOVS data over sea ice, however, probably caused by uncertainties in detecting stratus clouds over summer sea ice. We recommend that TOVS skin temperatures be rejected when the retrieved cloud cover exceeds 95%.

c. GIN Seas in January and July

The TOVS skin temperatures are substantially warmer than POLES near-surface air temperatures in both seasons south of the ice edge in the GIN Seas region. The POLES dataset includes very few observations from this area (Fig. 2), thus the NCEP analysis is the

primary source of information. Comparisons of TOVS and POLES temperatures to measurements aboard ships in the region clearly show that POLES values are consistently 5–7 K too cold and that TOVS temperatures are realistic. We recommend that the POLES dataset include COADS ship measurements in their interpolation scheme if possible.

d. Decadal trends

A comparison of decadal temperature trends in spring (MAM) calculated from both POLES and TOVS data for the same time period show large discrepancies over the central Arctic Ocean. A region of large, statistically significant positive trends in the POLES data is absent in the corresponding TOVS calculation. The NP station data are most dense in this area and provide relatively good coverage for the POLES interpolation scheme, but the NP data are absent from the latter third of the POLES record. Warm biases in buoy data, which are all that remain for POLES to ingest, cause an apparent positive trend. TOVS data show a strong, positive trend west of Novaya Zemlya that the POLES data do not, but no data are available in this area for POLES to ingest. While absolute magnitudes of TOVS trends are uncertain owing to remaining intersatellite calibration biases, we believe the patterns may be more realistic over the Arctic Ocean, particularly where trend magnitudes greatly exceed those of intersatellite biases.

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