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Upper-air temperatures around Greenland: 1964–2005

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[1] A 42-year collection of 12h balloon soundings from six sites surrounding Greenland reveal distinct patterns of tropospheric and stratospheric temperature variability. Seasonal mean upper-air temperatures exhibit statistically significant correlations with surface air temperature records. Over the full 1964–2005 record, patterns of statistically significant tropospheric warming and stratospheric cooling are evident. Overall, the magnitude of warming decreases with height, becoming cooling in the mid-stratosphere. During the recent 12-year period (1994–2005) lacking major volcanic forcing, statistically significant warming (+2.5 K to +5 K) is evident throughout the troposphere at all sites, with seasonal changes in the +3 K to +9 K range near the surface at 1000 hPa. The recent (1994–2005) tropospheric warming has dominated the 1964–2005 lower troposphere temperature change, despite 1964–1982 upper-tropospheric cooling. **Citation:** Box, J. E., and A. E. Cohen (2006), Upper-air temperatures around Greenland: 1964–2005, *Geophys. Res. Lett.*, *33*, L12706, doi:10.1029/2006GL025723.

1. Introduction

[2] Understanding the climate of Greenland is critical, for, due to an apparent mechanism of melt water induced ice flow acceleration [*Zwally et al.*, 2002] in response to recent Arctic climate warming [e.g., *Overland et al.*, 2004; *Stroeve et al.*, 2005], the Greenland ice sheet has been losing mass in recent years [*Velicogna and Wahr*, 2005], contributing significantly to global eustatic sea level rise [*Rignot and Kanagaratnam*, 2006].

[3] Long-term Greenland surface air temperature records are available from coastal weather stations [e.g., *Cappelen et al.*, 2001]. Greenland surface air temperature variability has been linked with seasonal variations in circulation intensity, the North Atlantic Oscillation (NAO), sea ice extent, and volcanism [*Box*, 2002]. Previous studies have examined long-term Arctic weather balloon temperature soundings [e.g., *Bradley et al.*, 1992, 1993; *Kahl et al.*, 1992, 1993]. However, the linkage of surface and upper air temperatures around Greenland (and elsewhere) remains unclear. How deep in the atmosphere the recent warming extends is unclear. Also uncertain in this region is the correlation between stratospheric and tropospheric temperature variability. This study benefits from more than four decades of data to address these questions. Of particular interest has been the recent decade, which spans a time of record-setting global and regional temperatures [*World Meteorological Organization*, 2005].

[4] In this study, we check data temporal homogeneity, and then determine the extent that surface air temperature variability is linked with upper air temperature variability. Using statistical regression, we measure temporal temperature trends and statistical significance around Greenland at fixed levels throughout the troposphere and stratosphere. We discuss potential causes of the observed variability.

2. Data and Methods

[5] The primary data set used in this study comes from operational weather balloon soundings, that is, *radiosondes,* made 12-hourly since at least 1964. Pre-1964 data available from the Historic Arctic Rawinsonde Archive (HARA) [*Kahl et al.*, 1992] exhibit a large (8 K) step at Aasiaat, Danmarkshavn, and Tasiilaq, apparently due to changing measurement practices. To avoid this temporal in-homogeneity, we consider only post-1963 data in this study. Data used in this study were obtained from the U.S. National Climate Data Center Integrated Global Radiosonde Archive (IGRA) [*Durre et al.*, 2006]. We selected the most continuous records available (Table 1) that surround the Greenland ice sheet (Figure 1). Changing measurement practices, that is, different instruments, and their sensitivity to environmental factors, such as solar over heating [*Santer et al.*, 2005; *Sherwood et al.*, 2005], present potential data homogeneity problems that can confound identification of climate signals [e.g., *Gaffen et al.*, 2000, *Lanzante et al.*, 2003a, 2003b]. Two tests suggest no post-1963 data homogeneity problems. First, the time series of upper air versus surface temperature difference exhibited no suggestion of step-changes. Nor did a running correlation of upper and surface records suggest correlation changes.

[6] Surface air temperature is usually measured at 1.5–2.0 m above the ground and has been recorded at coastal sites around Greenland. These data were obtained from the NASA Global Historical Climatology Network database [*Peterson and Vose*, 1997; *Hansen et al.*, 1999] to compare with upper air temperatures.

[7] Analyses are made for the following 15 ‘mandatory’ pressure levels in hPa units with mean annual altitudes in km, respectively, i.e., 1000 (0.1), 850 (1.1), 700 (2.8), 500 (5.3), 400 (7.0), 300 (8.8), 250 (9.9), 200 (11.1), 150 (13.3), 100 (16.0), 70 (18.2), 50 (20.2), 30 (23.0), and 20 (26.1). The Arctic troposphere exists on average in the 1013–400 hPa pressure range, corresponding to altitudes between sea level and 7 km. Thus, the 1000 hPa level represents the ‘surface’, but can be 100 m above the surface, that is, under high sea level pressure conditions. The upper limit of the troposphere, i.e., the *tropopause*, fluctuates seasonally and interannually in altitude. Consid-

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Table 1. Summary of Coastal Upper-Air Sounding Site Data Used in This Study

Site Name	WMO Station ID	Latitude, deg N	Longitude, deg W	Completeness (1964–2005), %
Pituffik/Thule Air Force Base	4202	76.53	68.75	73
Aasiaat/Egedesminde	4220	68.70	52.75	90
Narsarssuaq	4270	61.20	45.40	87
Danmarkshavn	4320	76.77	18.77	88
Illoqqortoormiut/Scoresbysund[a]	4339	70.48	21.97	90
Uunarteq/Kap Tobin[a]	4340	70.42	21.97	90
Tasiilaq/Angmagssalik	4360	65.60	37.63	73

[a]Illoqqortoormiut/Scoresbysund and Uunarteq/Kap Tobin are separated by 7 km and are taken to represent same region.

ering the mandatory levels only, in 1964–2005 means, the tropopause always occurs at 250 hPa (9.9 km). Only post-1992 data have sufficient vertical resolution in the IGRA compilation to monitor tropopause and surface inversion depths variations.

[8] The maximum number of samples per season for a given site and level is 186, with 744 possible annual samples at each level. Seasonal averages were excluded from statistical analyses for cases when the total number of samples was less than 80% of that potentially available.

[9] Given twice-daily radiosonde launches, we evaluated uncertainty due to the diurnal temperature cycle given that the calculation of trends may be sensitive to the time of the observations, i.e. 0z versus 12z. This uncertainty can be measured by calculating average absolute seasonal mean and median differences, and the standard deviation of the bias, between 0z and 12z, for each level and season, by site. For example, at 850 hPa, we found average absolute seasonal mean 0z to 12z differences as large as 0.35 K, for all sites and seasons, with standard deviations in the 0.3–0.5 K range. Median bias was 0.18 K. That the standard deviation exceeds the mean or median suggests that the bias are mostly random, and cancel. Sampling uncertainties were up to 0.2 K larger at 1000 hPa and in the stratosphere than in the mid troposphere. Larger sampling error in the lower troposphere is likely due to greater diurnal temperature variability near the surface that is not captured by twice-daily samples. The decreasing number of samples with height, caused by increasing balloon failure with increasing altitude, reduces the number of samples with height, especially above 100 hPa. Taking these sampling considerations together, we conclude that seasonal temperature changes greater than 0.4 K would exceed these sampling errors.

[10] Radiosonde data from each level are compared with the surface air temperature records to establish the vertical profile of thermal co-variability between the planetary boundary layer and the 'free atmosphere'.

[11] A set of linear regressions was computed for seasonal temperatures for each pressure-level. The data were not consistently skewed to require non-parametric statistics. Linear regression produced estimates for the temporal trend slope as well as significance test statistics, with the latter calculated from two-sided T-tests. We arbitrarily chose 90% as a reasonably high 'statistical significance' threshold. The temperature 'change' over regression periods is here defined as the linear regression slope (K y^{-1}) multiplied by the time-span in years, leaving temperature units. Our aim in trend analysis is to identify significant first-order changes in average temperature over some period of time, i.e. trends.

3. Results and Discussion

3.1. Correlations

[12] Figure 1 shows trends in correlations between surface temperatures at temperatures at the mandatory pressure levels for each Greenland site. A negative trend in correlation between the surface and upper-air temperatures with increasing height is evident (Figure 1). The correlation maximum is found at or near the surface. For half the sites, this correlation remains statistically significant on the annual basis up to 7 km (400 hPa), The correlation becomes negative and statistically significant *above* the lower strato-

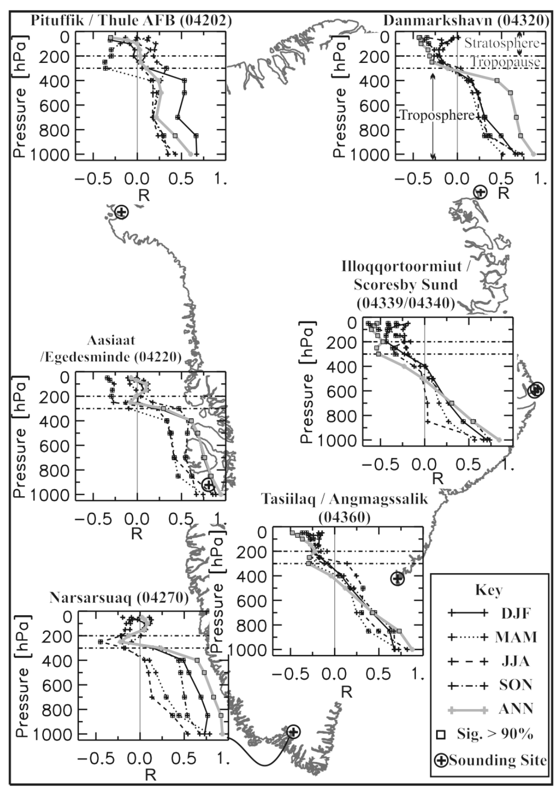

Figure 1. Greenland map with observation locations and height profiles of seasonal and annual correlations (R) between radiosonde-derived temperatures and long term ground-based surface air temperature records over the 1964–2004 period; points that are boxed indicate statistical significance at the 90% level.

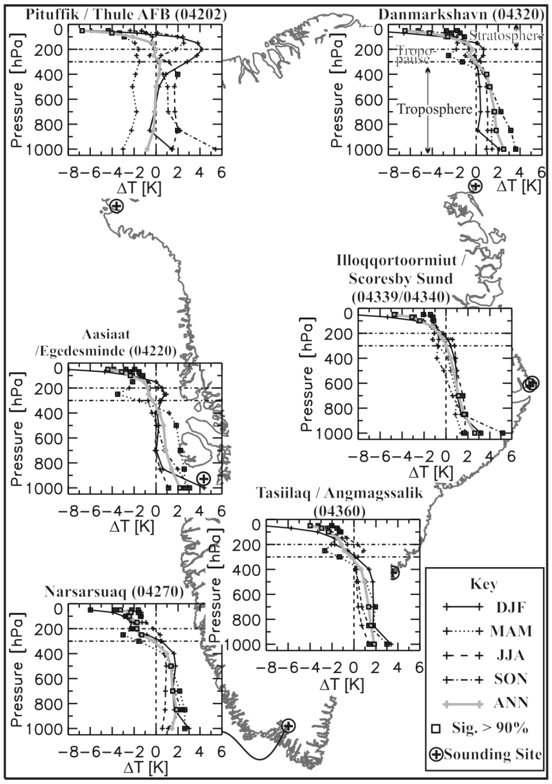

Figure 2. Greenland map with observation sites and seasonal height distribution of 1985–2005 temperature change (ΔT); points that are boxed indicate statistical significance at the 90% level.

sphere, that is, above 11 km. This asymmetry between tropospheric and stratospheric variability has earlier been noted [e.g., *Liu and Schuurmans*, 1990; *Wong and Wang*, 2000]. No consistent seasonal pattern correlation decay with height is evident among the stations. The pattern of high correlations near but not always at 1000 hPa (0.0–0.1 km) suggests that the upper air observational data are similarly reliable as surface records in assessing temperature variability over annual to inter-decadal time scales. We confirmed that the occasionally higher annual correlations results from annual aggregates averaging out high-frequency variability not captured by the twice daily radiosonde observations.

3.2. Air Temperature Trends

[13] Cooling associated with spring 1982 El Chichón and summer 1991 Pinatubo volcanic eruptions is evident during 1983–84 and 1992–1994 winter anomalies, respectively, at all but east and northeast Greenland sites (not shown), consistent with results from surface station data analyses [e.g., *Robock and Mau*, 1995]. These two eruptions caused −10 K and −7 K, respectively, monthly surface air temperature anomalies [*Box*, 2002]. In order to assess recent warming and avoid volcanic forcing bias, we investigated the 1994–2005 (12-year) period, in which a pattern of winter warming (+2.5 K to +5 K) is evident throughout the troposphere and is concentrated near the surface at all sites, with values in the +3 K to +9 K range at 1000 hPa (not shown). Over the 1985–2005 period, which straddles the Pinatubo cooling, a pattern of lower tropospheric warming is evident (Figure 2) at all but one northwestern site, i.e., Pituffik/Thule AFB). At south and eastern sites, there widespread statistical significance of this trend on the annual basis. Seasonally, the only statistically significant tropospheric trends are of warming, particularly in spring and autumn, again concentrated near the surface, but statistically significant up to heights from 800 hPa to 400 hPa, varying by site. Overall, the magnitude of tropospheric warming decreases with height. Stratospheric cooling (above 150 hPa) is evident at all stations, particularly in winter. Autumn tropospheric warming during this period over the three northernmost sites is large in comparison with other seasonal trends over this period, i.e. +1 K to 5.5 K at 1000 hPa.

[14] Lower and middle tropospheric warming and mid-stratospheric cooling is a dominant feature of the entire 42-year upper air temperature record (1964–2005) (Figure 3). However, a significant upper tropospheric cooling phase in the early portion of the record, i.e. 1964–1981, counteracts the impact of recent (post 1980s) winter warming. As a result, the only statistically significant tropospheric trends in the 1964–2005 period that are common among the sites surrounding Greenland are warming trends that occur in spring and autumn. Considering cooling evident in the earliest half of the data, with the exception of winter, the most recent warming phase (1994–2005) appears to have nonetheless dominated the long term annual temperature change.

[15] Important impacts of warming on glaciers and permafrost are worth mention in context of these findings.

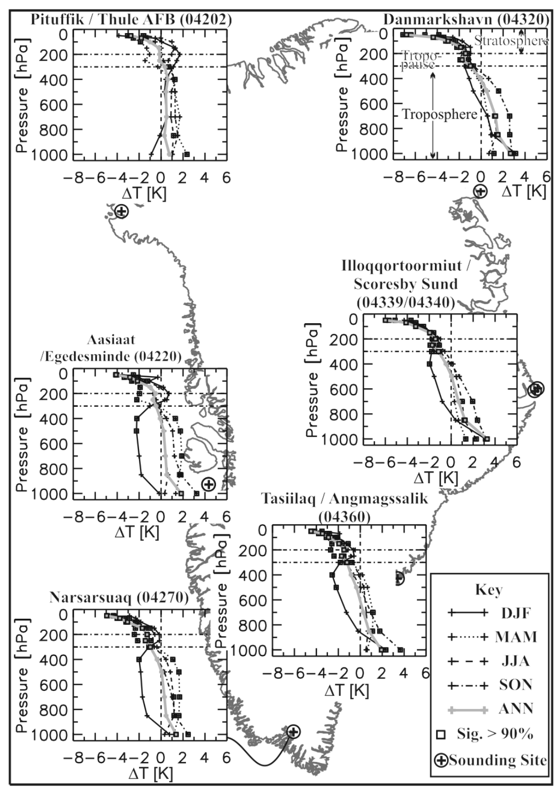

Figure 3. Greenland map with observation sites and seasonal height distribution of 1964–2005 temperature change (ΔT); points that are boxed indicate statistical significance at the 90% level.

Winter warming affects summer melt rates via erosion of snowpack and land surface 'cold content', resulting from increasing downward infrared and sensible heat fluxes, increases in fraction of liquid precipitation, changing cloud properties, probable increase in downward infrared irradiance, and changing surface temperature inversion strengths. Furthermore, summer water mass loss via evaporation is more efficient than via sublimation and is less of a latent heat sink, promoting amplified summer melt. Investigating these links should be pursued in subsequent research.

4. Conclusions

[16] Systematic patterns of tropospheric and stratospheric temperature change around the Greenland ice sheet are evident in weather balloon (radiosonde) data spanning the 1964–2005 period, with most variability occurring in winter. The recent 21-year period (1985–2005) is marked by statistically significant lower to mid tropospheric warming and mid-stratospheric cooling. The asymmetry between lower tropospheric and middle stratospheric temperature variability is clearly evident at all stations and in the vertical profile of correlation between surface and upper air seasonal and annual variability. The recent 1994–2005 warming period has strongly influenced the longer term (1964–2005) temperature variations, resulting in a pattern of overall tropospheric warming in the +1.5 K to +3.5 K range. Pre-1980s winter tropospheric cooling dominates the 1964–2005 period, at or above 500 hPa. Volcanic cooling episodes strongly affect winter temperatures both in the lower- to mid-troposphere and the mid-stratosphere, confounding trend analysis. By choosing periods free of volcanic forcing, e.g., 1994–2005, a clearer picture of regional temperature changes is evident.

[17] The radiosonde data do not seem to suffer from data homogeneity problems for three reasons: 1. Consistent spatial and temporal patterns are evident among six sites surrounding Greenland; 2. Decay and ultimate reversal in correlation of upper air with surface temperature observations are evident throughout the depth of the atmosphere at all sites, with statistically significant correlations near the surface and near the upper limit of the soundings, that is, in the mid-stratosphere (11–26 km altitude); and 3. No step-changes were found evident in the post-1963 temperature correlations between the upper air and surface station data. Pre-1964 data are marked by large step changes in temperatures, suggesting changing measurement practices and data homogeneity problems.

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