1.19 SATELLITE-OBSERVED CHANGES IN ENERGY ADVECTION WITHIN THE ARCTIC

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1. INTRODUCTION

The tropical regions of the Earth receive more solar radiation than they lose to space as longwave energy, while high latitudes emit more longwave radiation than they receive as insolation. To maintain a balance between the surplus in the tropics and the deficit at the poles, energy must be transferred poleward by the atmospheric and oceanic circulation systems. This lateral advection of heat and moisture into polar regions constitutes the primary source of energy for the high-latitude climate system [e.g., Nakamura and Oort, 1988]. On annual average the advection of sensible heat across 70°N is approximately equal to the net loss of radiation to space at the top of the atmosphere (TOA) within that latitude circle. In winter the advected energy is approximately two-thirds that lost to space (surface fluxes contribute the remainder), while in summer, owing to the increased incoming solar radiation, the advected energy is about 5.5 times larger than the net flux at the TOA.

Several investigators have studied this sink of Earth's "heat engine" using available rawinsonde data [e.g., Oort, 1971; Oort, 1974; Nakamura and Oort, 1988] and using soundings assimilated and interpolated with a general circulation model [Overland and Turet, 1996]. Because these studies were conducted before meteorological data from Russian ice stations were widely available, the validity away from the coasts is limited by the void of soundings over the Arctic Ocean, especially after 1990 when Russian meteorological stations on drifting ice islands were discontinued. Effects of the data void in the central Arctic Ocean have been demonstrated in several studies [e.g., Francis, 1994; Groves, 2001].

A new data set derived from satellite observations offers an unprecedented opportunity to diagnose lateral advection at $(100\text{-km})^2$ spatial and daily temporal resolution across the entire Arctic region. The NASA/NOAA TOVS Polar (Arctic) Pathfinder (so-called "Path-P") data set [Francis and Schweiger, 2000; Schweiger *et al*, 2001] contains fields of atmospheric and surface properties for 18 years extending from 1979 to 1996. This period in time appears to be an extremely interesting one, as near to its midpoint dramatic changes in a wide variety of atmospheric, cryospheric, oceanic, and biological variables have been observed by numerous investigators [e.g., Dickson, 1999; Serreze *et al*, 2000].

In this study, we use the new Path-P data set and NCEP Reanalysis winds to compute fields of heating caused by the convergence of advected sensible heat. Values are presented for three tropospheric layers (1000 to 700, 700 to 500, and 500 to 300 hPa) at daily temporal and $(100\ \text{km})^2$ spatial resolution. Coverage over the Arctic Ocean is much improved over data used in previous studies of Arctic advection, and Path-P products present an opportunity to analyze not only temporal and spatial advection patterns, but also the reasons for changes in these patterns and their relationships to a host of other atmospheric and surface properties and processes.

In this study we first evaluate the accuracy of upper-level wind velocities from NCEP and ECMWF Reanalyses by comparing them with independent rawinsonde data from the CEAREX (Coordinated Eastern Arctic Experiment, Sept. to Dec. 1988) and LeadEx (March/April 1992) field experiments. Data from these field experiments were not ingested into the reanalyses. We then present results from calculations of sensible heat convergence (SHC) over the Arctic basin using Path-P temperature profiles and NCEP upper-level wind fields.

2. DATA SETS

NASA/NOAA TOVS Polar Pathfinder Data Set (Path-P)

The TIROS Operational Vertical Sounder (TOVS) has flown on NOAA polar-orbiting satellites since late 1978 and has generated one of the longest and most complete global satellite data records in existence. To create Path-P, 18 years of TOVS radiances were subsetted for the Arctic region north of 60°N and processed with a version of the Improved Initialization Inversion ("3I") algorithm [Chedin *et al*, 1985; Scott *et al*, 1999; Francis and Schweiger, 2000; Schweiger *et al*, 2001] that has been modified to enhance accuracy over snow- and ice-covered surfaces [Francis, 1994]. Orbital retrievals were averaged in space to $(100\ \text{km})^2$ grid boxes, and in time to produce one Arctic-wide field per 24-hour period centered on 12 UTC. Fields are presented in the Hierarchical Data Format (HDF) on the Equal-Area SSM/I Earth (EASE) grid; [Armstrong and Brodzik, 1995], which facilitates combining Path-P products with others. In this study we use Path-P temperatures, which are provided at 10 levels: surface, 900, 850, 700, 600, 500, 400, 300, 100, and 70 hPa. Additional information about the Path-P dataset can be obtained in references cited above and at the Path-P website (http://psc.apl.washington.edu/pathp/pathp.html).

The 18-year Path-P record is composed of data from a non-identical set of sensor arrays flying on several polar-orbiting satellite platforms. The instrument package was originally designed for real-time weather prediction, not for climate research, and consequently relatively little attention was originally paid to climate-quality calibration among the various sensors. The results of this

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investigation are not sensitive to these issues, however, because advection is computed from horizontal thickness *gradients*, which effectively eliminates biases and trends that may exist owing to calibration problems.

Path-P products have been extensively validated with measurements from the Russian "North Pole" data set and from the Surface Heat Balance of the Arctic (SHEBA) field experiment. Validation results are presented in Schweiger *et al.* [2001] and at http://psc.apl.washington.edu/pathp/pathp.html. The r.m.s. errors in retrieved upper-level temperatures generally decrease with height and are less than 3 K, except near the tropopause where they increase to about 4 K. Biases are less than 1.5 K at all levels, and are generally slightly negative (retrievals too cold) in the upper troposphere and slightly positive in the lower troposphere [Schweiger *et al*, 2001]. Because of the small biases and relatively high spatial and temporal resolution of the Path-P data set, we believe that advection values computed from Path-P-derived thickness gradients will be superior to values obtained from reanalyses that ingest few data in the central Arctic. The accuracy of wind fields with which we advect these gradients, however, is not well known.

Reanalysis data Upper-level winds from the NCEP Reanalysis data set are used to advect Path-P-derived thickness fields. We evaluate the accuracy of both NCEP and ECMWF Reanalysis (ERA) winds. NCEP data were obtained from the online data base at the National Centers for Environmental Prediction, and ERA data were kindly provided by NCAR. Both data sets are optimally interpolated to Path-P's horizontal grid and to its vertical levels using pressure-weighted averages. For comparisons to rawinsonde winds, the nearest NCEP point is used, and for ECMWF we average the nearest 4 points.

Rawinsonde data from field experiments To evaluate the quality of upper-level wind fields in NCEP and ECMWF Reanalyses, we compare them to rawinsonde data that were not assimilated by the numerical models. The only independent data from the Arctic that we are aware of are from two field experiments: the Coordinated Eastern Arctic Experiment [CEAREX Drift Group, 1990] conducted in fall/winter 1988 northeast of Spitsbergen, and the Lead Experiment [LeadEx Group, 1993] conducted in the Beaufort Sea in spring 1992. Rawinsondes were launched approximately every 6 hours during both of these programs.

3. METHODOLOGY

Upper-level wind velocity We compare rawinsonde wind measurements from the CEAREX and LeadEx field programs to NCEP and ERA winds. Mean-layer values are computed in 5 layers bounded by 1000, 850, 700, 500, 400, and 300 hPa, the same layers used in advection calculations.

Sensible heat convergence Geometric thicknesses of layers defined above are computed from Path-P temperature profiles. Daily layer-mean wind velocities from the NCEP Reanalysis are used to advect thickness gradients in each Path-P grid box according to the standard temperature advection equation:

$$\frac{\Delta T}{\Delta t} = \frac{g}{R_d} \ln\left(\frac{p_1}{p_2}\right)(\vec{V} \bullet \nabla Z_T)$$

where $\Delta T/\Delta t$ is the change in mean-layer virtual temperature with time (due to dryness of the polar atmosphere, we use dry air temperature), g is the force of gravity, R_d is the dry gas constant, p_1 and p_2 are the pressure levels bounding the layer, V is geostrophic wind, and Z_T is the thickness of the layer. The heating is expressed either as K day^{-1} or W m^{-2} and is averaged to three layers bounded by 1000, 700, 500, and 300 hPa. We also compute the poleward, zonal, and seasonal components of SHC. Advective heating is difficult to validate owing to the poor spatial resolution of radiosonde data from the Arctic Ocean, but comparisons of transport across the 70°N latitude circle with calculations from coastal soundings are in good agreement [Francis, 1994]. Trends over the 18-year data set are computed using an IDL linear regression routine, and their significance is ascertained using the F-ratio statistic.

4. RESULTS

Winds Figure 1 shows statistics of comparisons between wind data from rawinsondes and values from the NCEP reanalysis. The biases in *u* and *v* at all levels are significant (> 95%) except for the *u* component in layer 5 (1000 to 850 hPa). The NCEP values exhibit the largest biases in the *u* component, while comparisons with ERA values (not shown) reveal large negative biases in the *v* component: in layers 1 - 5 they are -4.7, -4.0, -3.0, -2.4, and -1.2. In other respects the ERA statistics are similar. These apparent errors are even more striking when expressed as a percent of the total mean wind speed (bottom left of Fig. 1). To understand the sources of these differences, we examined the frequency distributions of positive and negative *u* and *v* winds, and found that both reanalysis data sets had the wrong sign for *u* approximately 20% of the time (30% in the lowest layer), and slightly less frequently for the *v* component. The implications for this are that advective heating computed with NCEP winds will likely be too small in the poleward sense, as the meridional wind is too strong from the north, and heating would be too large in the zonal direction owing to the wind being too strong from the west on average. If ERA winds were used, the same biases would occur, but much more strongly in the poleward direction and less so zonally. We further note that the comparisons are point measurements to grid-box means, so one would expect that the rawinsonde values would exhibit higher absolute maxima. This is generally true, as indicated in Fig. 2, but the cloud of points in this case is negatively biased. Our conclusion, therefore, is that for lack of better wind fields at present, and based on this limited set of independent wind measurements, it appears that the NCEP reanalysis is a better source for wind fields than is the ERA data set.

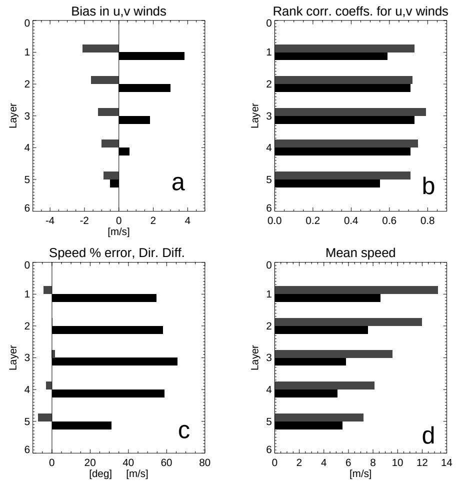

Figure 1: Statistics for NCEP upper-level winds compared with rawinsonde measurements. Layers are bounded by 300, 400, 500, 700, 850, and 1000 hPa. In (a) and (b) dark and light shaded bars are for u and v components, and in (d) dark and light bars are for raob and NCEP values. Approximately 300 collations were used.

<ins>Sensible heat convergence</ins> The18-year calculation of SHC confirms that the Arctic is warmed advectively on average, particularly in winter (not shown). In winter the heating is strong near Svalbard where storminess is frequent, and cooling occurs over the area south of Svalbard, as a predominant northward flow transports heat away from the Gulf-Stream-warmed lower atmosphere.

The 18-year record also reveals that significant changes in SHC have occurred. Figure 3a displays the trends in total annual SHC [K day^{-1} decade^{-1}] in the 1000-to-700 hPa layer, and Fig. 3b shows the significance of those trends expressed as confidence levels determined using an F-ratio test. Significant warming trends are evident in the Fram Strait, over the N. Barents Sea, off the north and east coasts of Greenland, in much of the Kara Sea, and near the North Pole. Areas of significant cooling are evident in the Laptev and Beaufort Seas, as well as in the GIN Sea. Figure 4 presents an indication of how temperature changes in the 1000-to-700 hPa layer affect the downward longwave flux at the surface and the outgoing longwave radiation at the top of the atmosphere. Calculations were performed

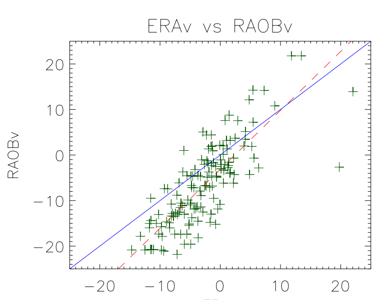

Figure 2: Scatter plot of ECMWF v winds versus rawinsonde winds in the 500 to 400 hPa layer. Lines of 1:1 correspondence and least-squares linear fit are also shown.

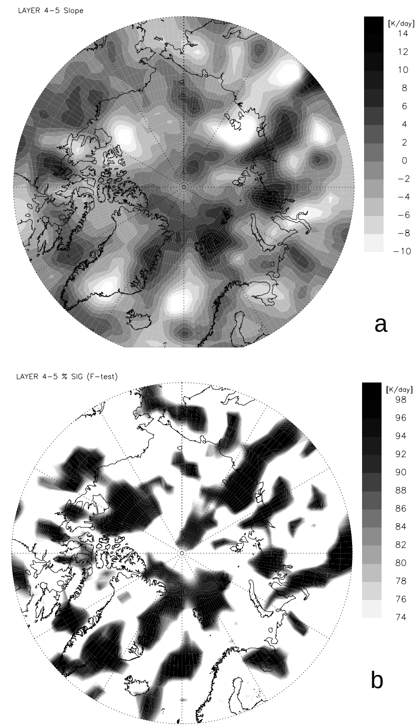

Figure 3: Trends in sensible heat convergence [K day^{-1} decade^{-1}] in the 1000-to-700 hPa layer (a), and the significance of those trends (b) expressed as a confidence limit. 10 K/day/decade is approximately 350 W/m^2/decade.

with the Streamer radiative transfer model [Key and Schweiger, 1998] assuming clear skies and winter Arctic conditions. Regions exhibiting large warming trends correspond closely with areas of largest ice thickness decreases shown in Rothrock *et al.* [1999].

Figure 5 illustrates the difference between the two decades in the poleward component of the winter SHC for the upper layers of the troposphere (500 to 300 hPa). Cooling predominates over the continents (i.e., the ‘90s are characterized by less poleward advective heating), while warming is strong near the straits connecting the Arctic Ocean with lower latitude basins. Strengthened warming in these areas suggests more active cyclones near the Iceland and Bering Sea low pressure centers, which corroborates observations by Key and Chan [1999]. The patterns are cohesive, and suggest a shift in

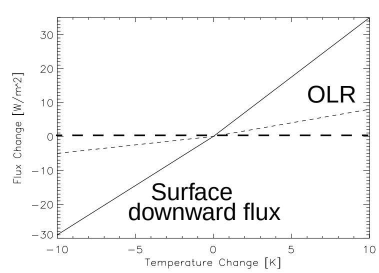

Figure 4: Simple forward RT calculation of the effect of warming in the 1000-to-700 hPa layer on the downward IR flux at the surface (solid) and the OLR (dashed) during typical clear-sky Arctic winter conditions.

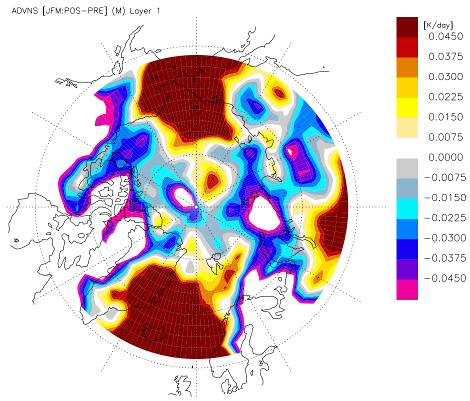

Figure 5: Difference between the 1980s and the 1990s in heating [K day^{-1}] caused by the convergence of poleward transported sensible heat in the 500-to-300 hPa layer.

a wave number 2 circulation pattern, especially in the upper layer. Further work will ascertain whether apparent trends can be attributed to changes in the strength and/or orientation of thickness gradients and/or changes in wind fields over time.

5. SUMMARY

We know the Arctic plays a central and complex role in the climate system, and that horizontal energy transport is the dominant link between the Arctic and the rest of the globe. We employ a new satellite-derived, Arctic data set with high spatial and temporal resolution to diagnose atmospheric heating resulting from the convergence of horizontally transported sensible heat. While these calculations are preliminary, they suggest that during the past 2 decades, a period in which numerous changes in a variety of geophysical and climate-relevant variables have been observed, significant changes have occurred in the SHC in both the lower and upper layers of the troposphere. Areas exhibiting significant warming trends in the lower layer correspond with areas of largest ice thickness decreases, and warming trends in the upper troposphere are consistent with observed increases in cyclone activity. Much work remains to ascertain the sources of these changes (strength or orientation of thickness gradients? wind strength or direction?), to investigate seasonal differences, and relate changes in heating to changes in other atmospheric and surface variables, such as cloud cover, sea ice extent, and surface temperature.

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