1. INTRODUCTION

The tropics absorb more solar radiation than they radiate to space as terrestrial radiation and constitute the source region for the global heat engine. Poleward of 35° there is a net annual energy deficit; the magnitude of the deficit increases with latitude. High latitudes, consequently, are the primary heat sink in this cycle. The surplus of heat in the tropics is transported poleward by the atmosphere and ocean, where it is then radiated to space to maintain the Earth's radiative equilibrium. A recent modeling study by Thorndike (1992) suggests that the equilibrium of the global climate system is particularly sensitive to the poleward energy flux; changes of 20 to 30 W m\(^{-2}\) may make the difference between an ice-covered and an ice-free Arctic Ocean. The flux into the Arctic has been quantified in terms of its components -- sensible heat, latent heat, potential energy, and kinetic energy -- and its seasonal variability by Oort (1971), Oort (1974), Nakamura and Oort (1989), and Overland and Turrell (1994). All of these studies, however, suffer from the same sampling limitations of the conventional observation network. Because the rawinsonde data are from land stations only and very few are located north of 80°N, the accuracy of the computed disposition of poleward advected energy is questionable. In light of this uncertainty and the potentially alarming consequences, it is important that we monitor not only the magnitude of the poleward flux, but also how it varies in space and time; where the energy is deposited within the Arctic; and how this energy is used (e.g., to melt ice, warm the ocean, radiate to space or to the surface).

Almost all of the geophysical variables required for computing the lateral advection of energy can be obtained from radiances measured by the TIROS-N Operational Vertical Sounder (TOVS). TOVS has flown on NOAA polar-orbiting continuously since 1978. One of the primary advantages of using these data to analyze patterns and estimate fluxes of poleward-advected energy is that retrievals are available at a 100 km x 100 km resolution across the entire Arctic basin every day. One can compute \( F_{\text{wall}} \) at any latitude, as well as its variation with longitude. The objective of the effort described here is to demonstrate the potential for using this information to investigate the spatial and temporal variability of horizontal energy fluxes in the Arctic Basin, which has not been possible before owing to the lack of upper-air data from sea-ice-covered regions. Two of the three components of the moist static energy flux in the 1000-to-700 mb layer are considered: the sensible heat flux and the water vapor flux. This layer of the troposphere was chosen for demonstration purposes because, as shown in previous studies, it contributes the majority of the poleward flux of moist static energy and the geostrophic wind is an adequate estimate of the mean wind in this layer. Three months of TOVS data (October 1987 and 1988 and March 1988) have been used to compute horizontal fluxes; in the future a more extensive analysis is planned with all three components of the moist static flux (including the flux of potential energy), in the entire troposphere, and using the 20-month TOVS Pathfinder Benchmark data set. Eventually, when the entire 16-year TOVS data record is available, the analysis can be extended through this period.
2. METHODOLOGY

The northward flux of moist static energy through an imaginary wall extending along a latitude circle and upward to the top of the atmosphere $F_{wall}$ comprises three components: the flux of sensible heat, latent heat (water vapor), and potential energy (Nakamura and Oort, 1988):

$$F_{wall} = \iint c_p \nu [\nu T] \frac{dx dp}{g} + \iint L_r [\nu q] \frac{dx dp}{g} + \iint g [\nu z] \frac{dx dp}{g}$$

Specific heat at constant pressure is denoted by $c_p$, $\nu$ is the northward component of the wind, $T$ is temperature, $x$ is distance along the latitude circle, $p$ is pressure, $g$ is gravity, $L_r$ is the latent heat of evaporation, $q$ is specific humidity, $z$ is height, square brackets indicate a zonal mean, and an overbar indicates a temporal mean.

Layer-average temperatures and humidities are obtained from TOVS radiances using the Improved Initialization Inversion ("3I") algorithm developed by the Laboratoire de Météorologie Dynamique (Chedin et al., 1985). The algorithm includes modifications to improve its performance over snow- and ice-covered surfaces (Francis, 1994). Retrievals from approximately seven orbits per 12-hour period (centered on 12Z) are optimally interpolated to a high-resolution subset of the NMC octagon grid. This process constitutes the temporal averaging for $T$ and $q$ in Eqn. (1). The northward wind $\nu$ is approximated by the meridional component of the geostrophic wind $G$. The geostrophic wind is derived from surface pressure analyses produced by the National Meteorological Center (NMC).

To obtain the zonal averages for any given latitude circle (or segment of one), values of $Tv$ and $qv$ at grid points within $2^\circ$ latitude of the specified latitude are summed and divided by the number of points that are located in this belt. The fluxes of sensible and latent heat are then computed as the first two terms in Eqn. (1).

The flux divergence [K sec$^{-1}$] at each grid point is computed directly from the temperature advection equation, which combines the horizontal gradients in the 1000-to-700 mb layer thickness $\nabla Z_T$ with the geostrophic wind vector $G$:

$$\left[ \frac{\Delta T}{\Delta t} \right]_S = \frac{g}{R_d} \ln \left[ \frac{p_1}{p_2} \right] (G \cdot \nabla Z_T)$$

where $\Delta T$ is the change in mean-layer temperature during time interval $\Delta t$, $R_d$ is the ideal dry gas constant, and $p_1$ and $p_2$ are the pressure levels bounding the layer of interest ($p_2 > p_1$). The difference between the temperature and virtual temperature for the dry polar atmosphere is neglected. Values of $(\Delta T/\Delta t)_S$ represent the heating resulting from a convergence of sensible heat.

The "poleward advective activity" (PAA), the flux divergence due to advection in the meridional direction only, has also been computed. A positive value represents either a northward advection of heat or a southward advection of cold. The purpose of this parameter is to identify regions of the Arctic that contribute most to achieving a balance between the low-latitude energy surplus and the high-latitude energy deficit. While the importance of PAA cannot be determined from only a few months of analysis, it is possible that the most active regions may be more sensitive to change, and therefore should be monitored for signs of change in the global circulation.
3. RESULTS

Figure 1 presents the TOVS-derived, zonal-average, poleward fluxes of sensible heat and latent heat ($F_S$ and $F_L$) averaged over October 1987, October 1988, and March 1988. Fluxes have been normalized by dividing the total net flux across the wall by the surface area north of the latitude circle under consideration. Both sensible and latent heat fluxes generally decrease with increasing latitude because energy is continually dissipated (e.g., by warming the atmosphere and/or radiating to space) as it travels northward from its source to the south. The fluxes across 70°N are in general agreement with those computed by Nakamura and Oort (1988) and by Overland and Turet (1994) given that their fluxes are for the entire atmospheric column to 50 mb while this calculation is for the 1000-to-700 mb layer only. October fluxes tend to be larger than those in March, possibly because horizontal temperature and moisture gradients are stronger in autumn than in spring.

The following discussion and figures describe and demonstrate TOVS-derived fields of the sensible heat flux divergence and the PAA parameter for the month of October 1988 (Fig. 2) and one particular day in October 1987 (Fig. 3).

Monthly-averaged fields of sensible heat convergence, PAA, and water vapor convergence for October 1988 are presented in Fig. 2. The NMC surface pressure analysis is also provided for reference. Convergence fields are noisy but are generally positive in the entire Arctic, as would be expected if the polar regions are, in fact, acting as a heat sink. In this month, as well as in October 1987 and March 1988 (not shown), there is an area of maximum heating north of eastern Siberia, which agrees with results of Overland and Turet (1994). This feature probably results from the preferred northward path of energy in the Bering Strait region. In the Barents Sea

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**Figure 1:** TOVS-derived monthly-mean fluxes of sensible (a) and latent (b) heat [W m$^{-2}$] across imaginary walls on latitude circles in the Arctic. Fluxes have been normalized by dividing by the surface area north of the latitude circle.
where the dominant energy path was located by Overland and Turet (1994), a heating maximum is present in October 1987 and in March 1988, but the region cools advectively in October 1988.

The plot of PAA (Fig. 2c) highlights the Fram Strait and Barents Sea as regions where the energy transfer between low and high latitudes is most active. This feature persists in October 1987 and March 1988 (not shown). A high degree of month-to-month variability is apparent, but the field is generally positive, indicating that poleward advection throughout the region is counteracting the global energy imbalance.

Monthly-averaged water vapor convergence in mm day$^{-1}$ is shown in Fig. 2d. As with sensible heat convergence, the values are predominantly positive. The climatic ramifications of water vapor convergence are difficult to ascertain, however, because of local sources and sinks of moisture and the various possible fates of latent heat. In regions where the convergence of water vapor is relatively large, for example, the impact on the local conditions may be minor unless the water vapor condenses. If no condensation occurs, the only effect may be to increase in the downward longwave flux (DLF) at the surface and alter the OLR owing to emission by the water vapor. If the water vapor does condense, its latent heat will be released into the atmosphere. Not only will the DLF increase because of the warmer atmosphere, but the cloud particles are more efficient emitters and will add substantially more to the DLF than would the same moisture in its vapor form. Finally, the condensed water

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**Figure 2:** Monthly average surface pressure from NMC (a), sensible heat flux convergence (b), “poleward advective activity (PAA)” (c), and water vapor convergence (d) for October 1988.
vapor may be advected to another area where it can evaporate and cool the local atmosphere, or it can fall to the surface as precipitation, adding mass to the sea ice below. One possibility for removing some of the ambiguity from this problem is to combine the water vapor convergence fields with observed water vapor changes over a time interval. If the water vapor convergence is positive, for example, but the change in total water vapor from one day to the next is less than the convergence, the difference may be attributable to cloud formation, or even to E-P (evaporation minus precipitation) at the surface. If the day-to-day change is smaller than the convergence, the difference may be attributable to evaporation of an existing cloud or of surface water (or ice). Given the almost complete void of information about precipitation in the central Arctic, this application may be of value.

Figure 3 presents the fields of surface pressure, 1000-700 mb thickness, sensible heat flux convergence, and PAA on 12 October 1987. This day was selected because a strong frontal system was advancing through the Kara and Laptev Seas (near 80°N, 80°E) and the associated advective pattern is clearly evident. The location of the front is indicated by steep thickness gradients and a deep trough in the pressure field extending from near the pole toward the Kara Sea. A strong southwesterly flow precedes (to the east) and strong northerly flow follows (to the west) the front. A cold front is usually characterized by warm advection ahead of and cold advection

Figure 3: Fields of NMC surface pressure (a), 1000-700 mb thickness (b), sensible heat flux convergence (c), and PAA (d) for 12 October 1987.
behind it, which can be clearly seen in the plot of sensible heat convergence. The storm system is also conspicuous in the field of PAA. Because the flows on both sides of the front are contributing positively to restoring the energy balance between low and high latitudes, the PAA is positive in the entire region around the storm system, even in regions of cold advection.

Errors in these calculations are difficult to assess. Retrieved temperature profiles have errors of approximately 3 K and NMC pressure gradients in the central Arctic are often too weak (Francis, 1994). Absolute values of retrieved water vapor from the 3I algorithm may be too large in dry, polar air masses, but the gradients in water vapor appear to be reliable (C. Claud, personal communication, 1992). This should not have a large impact on the meridional flux of water vapor because it is the gradients of water vapor, not the absolute values, that enter the calculation. It is difficult to validate moisture content and fluxes in the Arctic because measurements from radiosondes are notoriously unreliable in extremely cold, dry air masses. Finally, because the 3I algorithm rejects heavily clouded retrievals, results will be biased toward dry, clear-sky conditions.

In summary, the errors in these calculations cannot yet be quantified with any certainty. This effort will be pursued further in the future.

4. SUMMARY

Atmospheric variables derived from the satellite-based TOVS instrument are used to compute horizontal fluxes of sensible heat, water vapor, flux convergence, and the poleward advective activity. Examples for a monthly average and for a single day illustrate the potential for using satellite sounders to study atmospheric circulation systems on a variety of space and time scales. Future efforts will be devoted to extending these calculations to 50 mb, which will require information about upper level winds. TOVS-derived thickness fields will be used to compute thermal winds, which when combined with the geostrophic wind field, will provide an estimate of winds in upper layers. More accurate surface pressure data will be obtained from the Arctic Buoy Program (Colony et al, 1991), rather than from NMC whose analyses contain no information from the central Arctic Basin. Several years of TOVS data will be processed and analyzed to determine patterns of advection, advective heating, and PAA in the Arctic.

Because information about the cloud cover, temperature profiles, and surface conditions are also available from TOVS, the simultaneous analyses of these variables with advection patterns should provide a powerful tool for understanding weather systems and air-sea-ice interaction processes over the central Arctic Ocean where the lack of data has prevented studying these phenomena in the past.

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5. REFERENCES


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