SATELLITE DERIVED CLOUD-TRACK POLAR WINDS FROM 1981-2004

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ABSTRACT

Recent studies have shown that the Arctic climate has changed significantly over the past 20 years. Unfortunately, two important tools for studying recent climate change, the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis products, have been shown to have relatively large errors in the wind field over the Arctic where there is little or no radiosonde data available for assimilation. Can satellites be used to fill the spatial gaps? At least eight numerical weather prediction centers worldwide have demonstrated that satellite-derived polar winds have a positive impact on global weather forecasts. The impact on climate reanalyses should be similar. Therefore, a polar wind data set spanning more than 20 years is being generated using Advanced Very High Resolution Radiometer (AVHRR) data. Wind speed, direction, and height are estimated for the Arctic and Antarctic, poleward of approximately 65 degrees latitude, by tracking the movement of cloud features in the 11 μm window channel. Validation of the satellite-derived winds is being performed with winds from radiosondes, the ECMWF reanalysis, and thermal winds from the TIROS Operational Vertical Sounder (TOVS). Results indicate that the AVHRR-derived winds have lower speed biases than ECMWF reanalysis when compared radiosondes. It is recommended that the historical AVHRR polar winds be assimilated in future versions of the reanalysis products.

1. INTRODUCTION

In the early 1960s, Tetsuya Fujita developed analysis techniques to use cloud pictures from the first TIROS polar orbiting satellite for estimating the velocity of tropospheric winds (Menzel, 2001). Throughout the 1970s and early 1980s, cloud motion winds were produced from geostationary satellite data using a combination of automated and manual techniques. During 1989 J. Turner and D.E. Warren from the British Antarctic Survey developed a manual and automatic based technique for deriving Infrared (IR) cloud track winds in the polar regions from sequences of AVHRR (Advanced Very High Resolution Radiometer) images from the polar orbiting TIROS-N series of satellites (Turner and Warren , 1989). In 1992, the U.S. National Oceanic and Atmospheric Administration (NOAA) began using an experimental automated winds software package developed at the University of Wisconsin Space Science and Engineering Center that made it possible to produce a full-disk wind set without manual intervention. Fully automated cloud-drift and water vapor motion vector production from the Geostationary Operational Environmental Satellites (GOES) became operational in 1996, and now wind vectors are routinely used in operational numerical models of the National Centers for Environmental Prediction (NCEP) (Nieman et al., 1997; Velden et al., 2005).

However, a major gap in the global observing system exists over the polar regions because no routine measurements of tropospheric winds are made over most of the Arctic Ocean and the Antarctic continent (Figure 1). Therefore, satellite-derived wind fields from polar orbiting satellites, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on-board Terra and Aqua satellites and AVHRR on-board NOAA satellites, are most valuable. Previous research has shown that the inclusion of MODIS winds has a positive impact on numerical weather forecasts (Key et al., 2003; Velden et al., 2005). For the purpose of climate reanalysis the AVHRR would be more useful than MODIS due to AVHRR having a longer record - 25 years (1981-2006) - compared to the much shorter 6-year (2000-2006) record of MODIS. With a lack of observational data over the polar regions, numerical weather prediction model forecasts and climate reanalysis products will be less accurate over those regions. For example, Francis (2002) showed that both the NCEP and ECMWF climate reanalyses exhibited significant errors over the Arctic, being too strong by as much as 25-65% from the north and south directions when compared to radiosondes that were not assimilated into the reanalysis field (Francis 2002; Francis et al., 2005).

Recent studies have shown that the Arctic climate has changed significantly over the past 20 years. Examples of significant climate change over the polar regions include increased surface temperature over the Antarctic peninsula (Vaughan et al., 2001; Thompson and Solomon 2002), significant tropospheric warming over much of the Antarctic during the winter (Turner et al., 2006), increasing temperatures over most of the Arctic (Serreze et al. 2000; Rigor et. al., 2000; Cosimo 2003), decreased surface pressure (Walsh et al., 1996), and increased cyclonic activity in the Arctic (Zhang et al., 2004) and surrounding seas of the Antarctic (Fyfe 2003). As a result there has been decrease in sea ice concentration in the in the western Antarctic (Jacobs and Comiso 1997) and over much of the Arctic Ocean (Lindsay and Zhang 2005 and Rigor et al., 2002). Changes in these properties are a function of large-scale circulation patterns that affect surface-atmosphere interactions and feedback mechanisms. For example, an increase in cyclonic activity over the Arctic that has been observed since the 1980s has been a major influence in the thinning of sea ice and a decrease in ice concentration. It is therefore very important to improve any deficiencies in the reanalysis fields that are used for climate studies. Furthermore, improved wind reanalysis from satellite-derived winds will most likely improve future short-term climate studies on trends in regional atmospheric wind and circulation patterns in the polar regions.

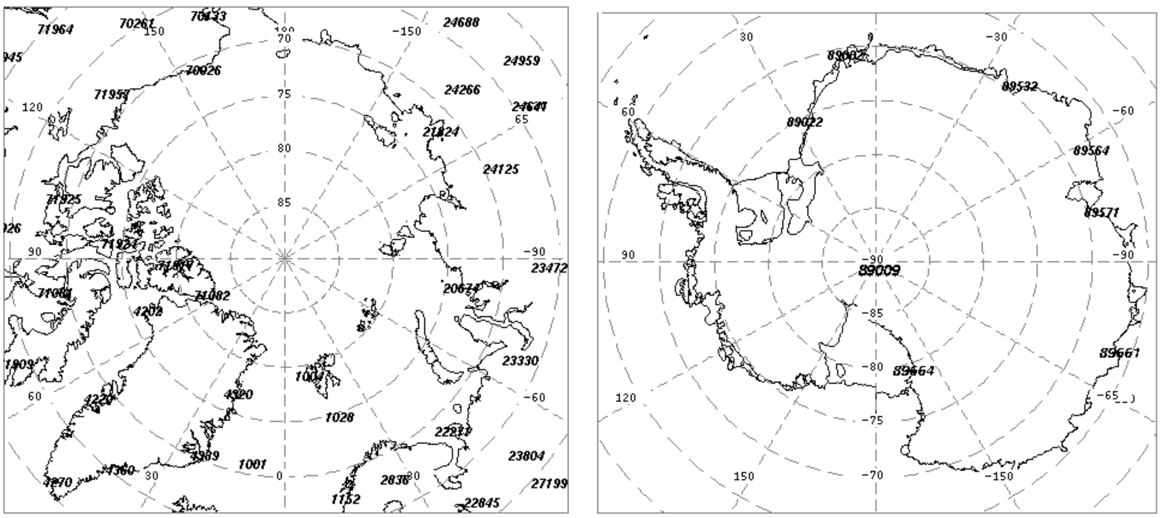

Figure 1: WMO stations across the Arctic and Antarctic. Only those stations that provide regular daily wind data are shown.

2. METHODOLOGY

Cloud tracking with AVHRR data is based on the established procedure used for the Geostationary Orbiting Environmental Satellites (GOES), which is essentially that described in Nieman et al. (1997) and Velden et. al. (1998). After remapping the orbital data to a polar stereographic projection, potential tracking features are identified. The lowest (coldest) brightness temperature in the infrared window band, generally indicating cloud, within a target box is isolated and local gradients are computed. Gradients that exceed a specified threshold are classified as targets for tracking.

Because AVHRR doesn't contain a water vapor channel, the wind vector heights are currently assigned by the infrared window method, which assumes that the mean of the lowest (coldest) brightness temperature values in the target sample is the temperature at the cloud top. This temperature is compared to a numerical forecast of the vertical temperature profile to determine the cloud height (Nieman et al., 1993). The method is reasonably accurate for opaque clouds, but inaccurate for semitransparent clouds (Nieman et al., 1993). In our research, the ECMWF ERA-40 reanalysis product with 2.5 degree spatial resolution and 13 vertical levels was used as the background field.

In order to calculate the wind vectors, a guess position of the target between images is determined and a search box of 32 by 32 pixels around the guess position is created. The target is then identified, if possible, in the search box of the subsequent image. The tracking method searches for the minimum of the sum of squared radiance difference between the target location and the region inside the search box (Key et al., 03). This is done for two image overlaps in three consecutive orbits, with the average of the two vectors taken as the initial calculated wind vector centered at the position of target in the middle image.

After wind vectors are determined and heights are assigned, the resulting data set is subjected to a rigorous post-processing, quality-control step. A 3-dimensional objective recursive filter is employed to re-evaluate the tropospheric level that best represents the motion vector being traced, to edit out vectors that are in obvious error, and to provide end users with vector quality information (Hayden and Purser 1995; Velden et al., 1998; Holmlund et al., 2001). An example of the final AVHRR graphical output product is given in Figure 2. When compared to the radiosonde network in Figure 1, it is obvious that the AVHRR winds can fill the gaps that are in the observational networks over the polar regions.

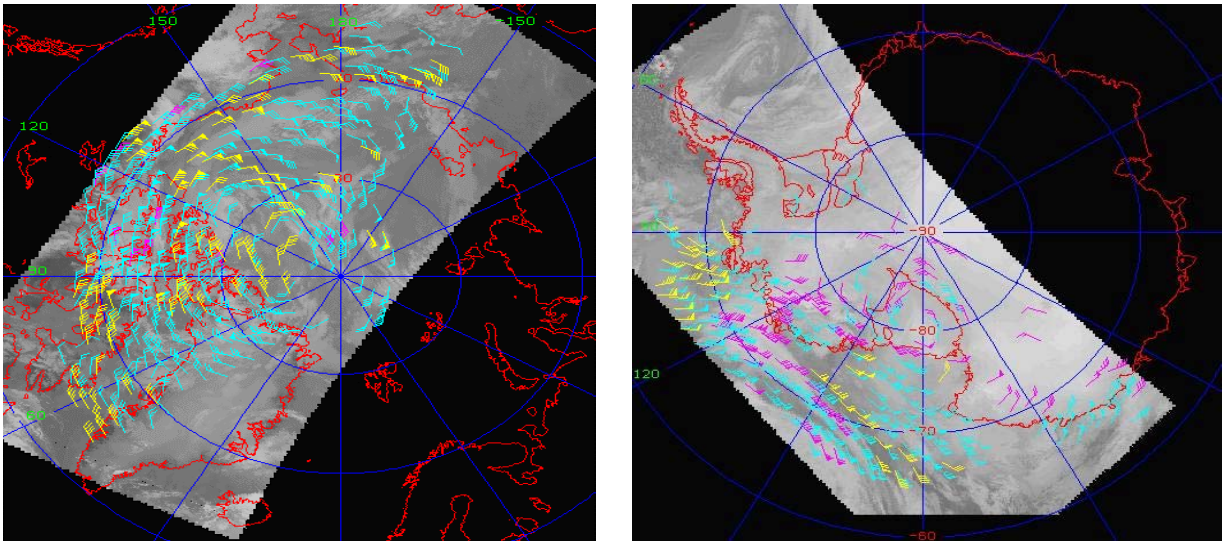

Figure 2: Example of AVHRR cloud-drift winds over the Arctic and Antarctic. The Arctic example (left) was taken from 1800 UTC on August 5, 1993. The Antarctic example was taken from 0600 UTC on April 25, 2001.

3. RESULTS

Statistical comparisons between AVHRR and ECMWF winds over the Arctic for random cases from 1992 through 2000 (Table 1) are given for three layers in terms of the wind speed root mean squared difference (RMS), the average speed and direction differences, and the mean wind speeds. The speed RMS is defined as the square root of the sum of the squared differences divided by the number of cases. The statistical comparisons between AVHRR and ECMWF indicate that the average speed differences change sign from negative (AVHRR being slower than ECMWF) in the lower and mid-levels to positive (AVHRR being faster than ECMWF) in the upper-levels, with the smallest speed differences occurring at mid-levels (400-700 hPa). The average direction differences, on the other hand, are negative (AVHRR counter-clockwise of ECMWF) for all layers and increasing with height. The speed RMS difference is about 44% of the mean ERA-40 wind speed. A statistical comparison of ERA-40 and AVHRR winds with radiosonde winds (“raobs”) from the Leads Experiment (LeadEx, Beaufort Sea, 1992), showed similar results (Table 2). LeadEx radiosonde observations were not assimilated into the climate reanalysis and therefore provide an excellent measure on the accuracy of the two wind sets. The comparison to LeadEx indicated that the winds derived from AVHRR have overall lower speed bias and RMS difference than ECMWF, but a slightly higher direction bias than ECMWF. However, when compared by atmospheric layer, the AVHRR has a much lower direction bias than ECMWF at low levels. When compared to TOVS thermal derived winds (not shown), it was found that the correlation coefficient was in the range of 0.7 to 0.8 between AVHRR and TOVS winds. These results indicate that the AVHRR cloud-track winds have the potential to improve reanalysis products. However, more validation will be done in the near future to verify that AVHRR outperforms ERA-40.

***Table 1*. Statistics for AVHRR IR Winds Over the Arctic Compared to ECMWF.**

Low-level(below 700 hPa)	
Number of cases	12,084
Speed rms	3.71 m/s
Average speed difference	-0.92 m/s
Average direction difference	-0.10 degrees
Mean ECMWF speed	8.56 m/s
Mean AVHRR speed	7.65 m/s
Mid-level (400-700 hPa)	
Number of cases	72,542
Speed rms	4.91 m/s
Average speed difference	-0.46 m/s
Average direction difference	-0.70 degrees
Mean ECMWF speed	11.01 m/s
Mean AVHRR speed	10.55 m/s
High-level (above 400 hPa)	
Number of cases	9,993
Speed rms	8.64 m/s
Average speed difference	1.71 m/s
Average direction difference	-1.53 degrees
Mean ECMWF speed	19.27 m/s
Mean AVHRR speed	21.07 m/s

***Table 2*. Statistical Comparison of AVHRR and ECMWF to Raob Winds from LEADEX.**
No collocations were found above 400 hPa.

All levels combined	
Total collocations	137
Speed rms ECMWF	5.99 m/s
Speed rms AVHRR	5.39 m/s
Speed bias ECMWF	1.64 m/s
Speed bias AVHRR	0.71 m/s
Direction bias ECMWF	2.02 degrees
Direction bias AVHRR	3.55 degrees
Mean ECMWF speed	8.81 m/s
Mean AVHRR speed	7.88 m/s
Mean raob speed	7.17 m/s
Low-level (below 700 hPa)	
Total collocations	70
Speed rms ECMWF	5.65 m/s
Speed rms AVHRR	5.04 m/s
Speed bias ECMWF	1.02 m/s
Speed bias AVHRR	-0.37 m/s
Direction bias ECMWF	10.16 degrees
Direction bias AVHRR	-0.26 degrees
Mean ECMWF speed	7.70 m/s
Mean AVHRR speed	6.31 m/s
Mean raob speed	6.68 m/s
Mid-level (400-700 hPa)	
Total collocations	67
Speed rms ECMWF	6.35 m/s
Speed rms AVHRR	5.77 m/s
Speed bias ECMWF	2.29 m/s
Speed bias AVHRR	1.85 m/s
Direction bias ECMWF	-6.45 degrees
Direction bias AVHRR	7.51 degrees
Mean ECMWF speed	9.97 m/s
Mean AVHRR speed	9.53 m/s
Mean raob speed	7.68 m/s

4. SUMMARY AND CONCLUSIONS

Previous research has shown that the reanalysis wind fields over the Arctic have significant errors that can have negative impacts on climate studies. MODIS satellite-derived winds have been proven to improve numerical weather forecasts, but satellite-derived winds have not yet been used to improve climate reanalysis products. With the climates over the Arctic and parts of the Antarctic changing significantly over the past twenty-five years, it is important to have very accurate wind fields for studying the mechanisms that gave rise to these changes.

The AVHRR on board NOAA satellites provides a 25-year dataset that can be used to derive cloud-drift winds. Statistical analyses of the AVHRR winds have shown that overall the ECMWF ERA-40 wind speeds are faster than AVHRR, which is indication of the reanalysis being too strong as described by Francis (2002). Comparisons to LeadEx radiosonde data demonstrates that the ERA-40 has a significant higher speed bias than AVHRR winds. We therefore recommend that the AVHRR cloud-drift winds be used in future reanalysis products.

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