P2.5 AN INVESTIGATION OF STRATOSPHERIC WINDS IN SUPPORT OF THE HIGH ALTITUDE AIRSHIP

George D. Modica[1], Thomas Nehrkorn[1], and Thomas Myers[2]

[1]Atmospheric and Environmental Research, Inc., Lexington, Massachusetts
[2]Systems Technology, Inc., Hawthorne, California

1. INTRODUCTION

This paper presents the results of a study of the climatology and predictability of the winds in the lower stratosphere. The information is intended to support the risk reduction phase of the High Altitude Airship (HAA). An understanding of the wind environment will assist HAA engineers in the design of onboard control systems that exploit the meteorological environment. Some background information on the HAA is presented next, followed by a discussion of the data and analysis procedures in Section 2, a presentation of the results in Section 3, and concluding remarks in Section 4.

1.1. The High Altitude Airship

The HAA is an unmanned, lighter-than-air vehicle being developed by the Lockheed-Martin under the program direction of the Missile Defense Agency. The prototype system is expected to be about 152 m long and 46 m in diameter. It will be equipped with four solar-powered electric motors and vectorable large twin-bladed propellers. This will provide a maximum airspeed of approximately 15-20 ms^{-1} (30-40 kt). An artist's rendering of the HAA is shown in Figure 1.

Figure 1. Illustration of the HAA suggesting some of its surveillance and communication capabilities. (Figure courtesy of Lockheed-Martin.)

The HAA will be capable of lifting a 225-kg (2-ton) load to a nominal altitude of 20 km (~65,000 ft). At this altitude the HAA will be able to view a 1000-km diameter footprint of the ground. The thin atmosphere at this height allows for extended range operation of Electro-Optical/Infra-Red (EO/IR) equipment. These attributes make the HAA an ideal platform for conducting sensor and/or communication operations for a variety of military and civilian purposes at a fraction of the cost of satellite-based systems.

1.2. Station Keeping Control

At altitudes between 16 and 20 km, minimal wind conditions during a significant part of the year and lack of air traffic make this an optimum region for HAA operations. The HAA will be required to maintain station—otherwise known as "station keeping"—over a fixed point above the earth for a month at a time. [Advanced versions of the HAA may be required to maintain station for up to a year.] Station keeping accuracy is required to be <2 km 50% of the time, and <150 km 95% of the time. The requirement for long duration shifts drives the need for a renewable power source; weight considerations restrict the amount of power that can be provided by the power source. Engineering studies have shown that an HAA-sized airship may not meet station keeping performance requirements in certain months of the year due to power limitations (Schmidt et al. 2006)

The HAA station keeping problem can be partitioned into two operational regimes. These regimes are a consequence of the limited propulsion capability. The "sub thrust limit" (STL) regime corresponds to the range of wind speed (up to 15 ms^{-1}, or 30 kt) within which station keeping can be accomplished with the thrusters operating at or below maximum thrust. The "post thrust limit" (PTL) regime covers the higher range of wind speed (over 15 ms^{-1}, or 30 kt) where the thrust required for station keeping exceeds capacity. Operation of the HAA during PTL conditions requires an alternate station keeping strategy. One possible solution is to make flight level adjustments designed to exploit vertical variations in wind speed and direction, i.e., vertical wind shear. This technique—called shear direction control, or SDC—was proposed for the Global Air-ocean IN-situ System (GAINS; Girz et al. 1999) to maintain the balloon trajectory within a confined latitudinal range. A control law was developed to extend shear direction control to two degrees of freedom in the horizontal plane for HAA PTL station keeping. However,

Corresponding author address: George D. Modica, AER, Inc., 131 Hartwell Ave., Lexington, MA, 02421-3126; email: gmodica@aer.com

during an earlier phase of this project an analysis of several wind data sources showed that the vertical wind shear at HAA altitudes would not provide a reliable steering control mechanism during PTL station keeping (Modica et al. 2006). Alternative PTL station keeping strategies were then explored based on the assumption of horizontal shears of wind velocity. These concepts were developed using direct collocation optimization. One strategy was based on minimum time return to the nominal station even if the wind speed there exceeded the maximum airspeed of the HAA. A more promising strategy involved defining a "utility function" for the HAA that quantified the reduction in mission effectiveness as a function of radial distance from the nominal station. For communication and surveillance missions this was defined in terms of the decrease in data transmission rate (bits/sec) with increasing radial dispersion from the nominal station. It was found that an optimal control law based on directly maximizing the total data transmitted in a specified time interval provided better mission performance than minimizing the time to return to the nominal station. The improved understanding of the wind field in high wind events reported here indicates that the temporal variation of wind speed and direction are more important than the spatial variations. New optimal control strategies based on maximizing total data transmission in the presence of temporal wind variations are now being considered. These control laws would exploit available numerical weather prediction data.

Current operational NWP models appear to be an attractive off-the-shelf resource to provide the needed estimates of the temporal variation of wind speed and direction for optimal PTL control. NWP models can supply the predicted wind field at nearly any point in space and time occupied by the HAA. Furthermore, an onboard estimate of real time wind velocity at the vehicle can be obtained by differencing GPS-derived earth frame velocity and airspeed from the air data system. The next section provides an introduction to the HAA wind estimator

2. PROCEDURE

We acquired NCAR/NCEP Reanalysis data (Kalnay et al. 1996) to create a long-record (i.e., 01 January 1979 through 31 December 2003) of stratospheric winds. While the reanalysis extends as far back as 1948, the year 1979 has special significance since it marked the beginning of a new era in global observations that included satellite data. The reanalysis consists of global atmospheric fields produced from a data assimilation system that includes a global spectral model (about 209-km; 28 vertical levels), as implemented at NCEP in December 1994. The gridded fields are available on a 2.5° × 2.5° latitude/longitude grid. We selected 6-hourly data from stratospheric pressure levels at 100, 70, 50, and 30 hPa.

The reanalysis data were searched for high wind events at several CONUS locations. The data was presented in terms of time-series, PDFs, and power spectra plots. We used the Environmental Scenario Generator (ESG; Kihn et al. 2001) to extract data from the reanalysis. The ESG enables one to create a query using any combination of desired environmental parameters (e.g., the highest wind speeds) and receive a ranked list of events that best match the desired conditions in the historical archive. ESG also provided an easy way to generate long time series of the wind at the desired locations. Figure 2 shows the locations where data were extracted from the reanalysis.

Figure 2. Geographic locations corresponding to NCEP/NCAR Reanalysis data points (yellow pushpins) selected to examine horizontal wind speed spectra.

3. RESULTS

Figure 3 shows a wind speed time series for a point located at 50-hPa (~20 km) over the Colorado location shown in Figure 2 for the entire 1979-2003 period considered in this study. The series appears to show a regular pattern of wind peaks separated by a period of lower wind speed activity.

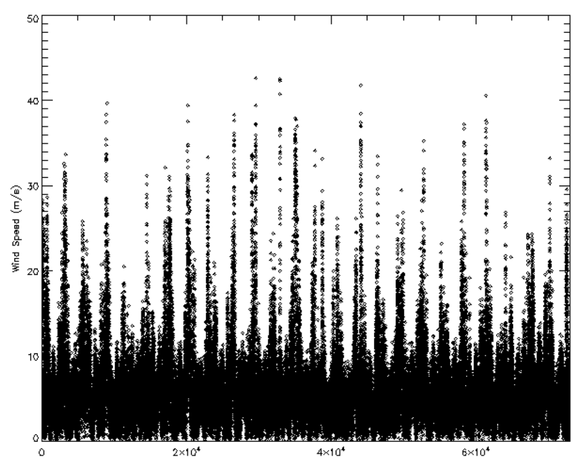

Figure 3. Time series of 50 hPa wind speed (ms^{-1}) for the period January 1979-December 2003 at the Colorado location (see Figure 2) from the 6-hourly NCEP/NCAR Reanalysis.

The data in Figure 3 was used to produce a power spectrum of the wind speed. Specifically, we computed the average power spectrum within regularly spaced bins [in $\log_{10}$] of frequency. Figure 4 shows the mean power in each of 200 bins for the data in Figure 3. The main peaks in the power spectrum were determined to correspond to periods of 3.17×10^{-8}, 1.27×10^{-7}, and 1.15×10^{-5} Hz (1 year, 90 days, and 1 day, respectively).

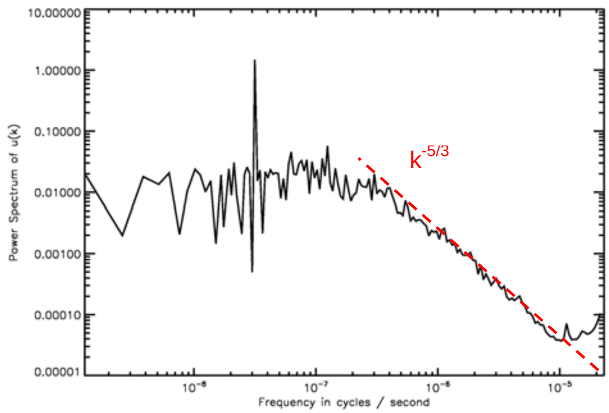

Figure 4. Power spectrum (m^2s^{-3}) of wind speed for mean power in each of 200 bins for data shown in Figure 3. A line with a slope of -5/3 is provided for reference (red dashed).

We compared the distribution of variance density across the frequency spectrum in Figure 4 to theoretical predictions based on physical models. One of the most well known physical models is the $k^{-5/3}$ wavenumber power law predicted by Kolmogorov (1941) for homogeneous isotropic turbulence. Figure 4 includes a line having a -5/3 slope, providing a reference for the spectrum in the inertial sub-range. This is not to argue that the atmosphere at 50 hPa is dominated by 3-D isotropic turbulence; as pointed out by Lilly and Peterson (1983), horizontal spectra of kinetic energy in the earth's atmosphere exhibit a $k^{-5/3}$ behavior at scales of tens and hundreds of kilometers, where thermal stratification prevents the vertical development of turbulent eddies anywhere close to those scales. Several recent explanations for the $k^{-5/3}$ behavior are rooted in ideas ranging from the presence of gravity waves to quasi 2-D turbulence (see Cho 1999 for a review). Our point here is that atmospheric power spectra often exhibit $k^{-5/3}$ behavior, and we are reassured by the fact that this is also the case in the reanalysis data.

Power spectra at the other CONUS locations indicated in Figure 2 were examined for the same 24-year period. The spectra for these other locations (not shown) share several common characteristics. The spectra at the lowest frequencies tend to have a generally flat profile, although there is quite a bit of superimposed noise. Near the annual period each spectrum displays a sharp, well-defined peak. From here, the spectra differ in the degree of sharpness of the intermediate peaks. For example, in the southwest and Gulf spectra, there are well-defined peaks at around 120 and 190 days. All of the spectra show evidence of the steady slope characteristic of the inertial sub-range, eventually leading to a diurnal peak. The diurnal peak is strongest in the lower-latitude spectra. The spectrum from the southeast CONUS location is shown in Figure 6.

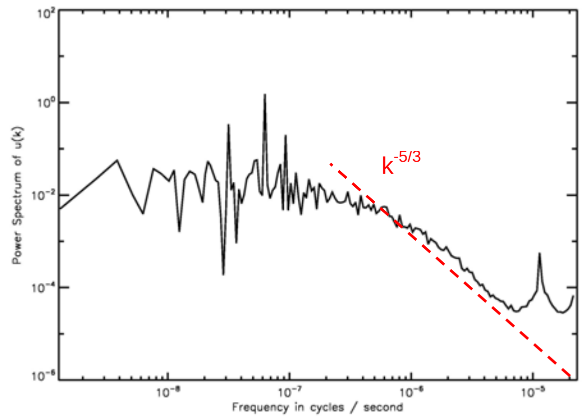

Figure 5. Same as Figure 4, but for the southeast CONUS location shown in Figure 2.

We examined in more detail several of the individual wind events shown in Figure 3. An example is presented in Figure 6, which shows a time series of 50-hPa wind speed from the reanalysis at the southeast CONUS location. The data ranges from 19 October 2002 to 18 April 2003. Beginning around the start of the new year the winds over the southeast location grew rapidly in force, reaching a peak of nearly 50 ms^{-1} around 19 January 2003. Over the next two weeks, the wind speed had receded to its typical range of about 10-20 ms^{-1}. This case is typical of many annual wind events, taking about 3 weeks to evolve from trough to peak to trough and reaching peak wind speeds of 40-50 ms^{-1}.

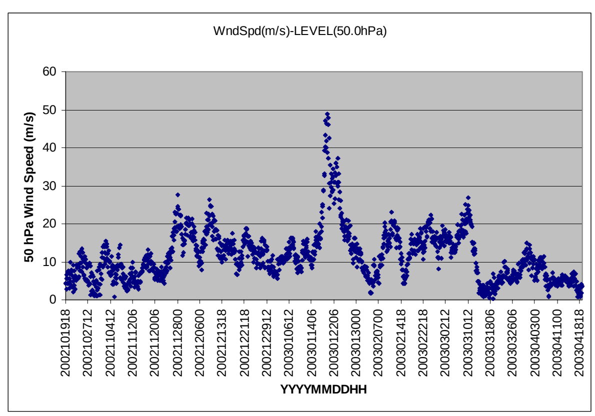

Figure 6. Time series of 50 hPa wind speed (ms^{-1}) from the reanalysis at the southeast CONUS location indicated in Figure 2.

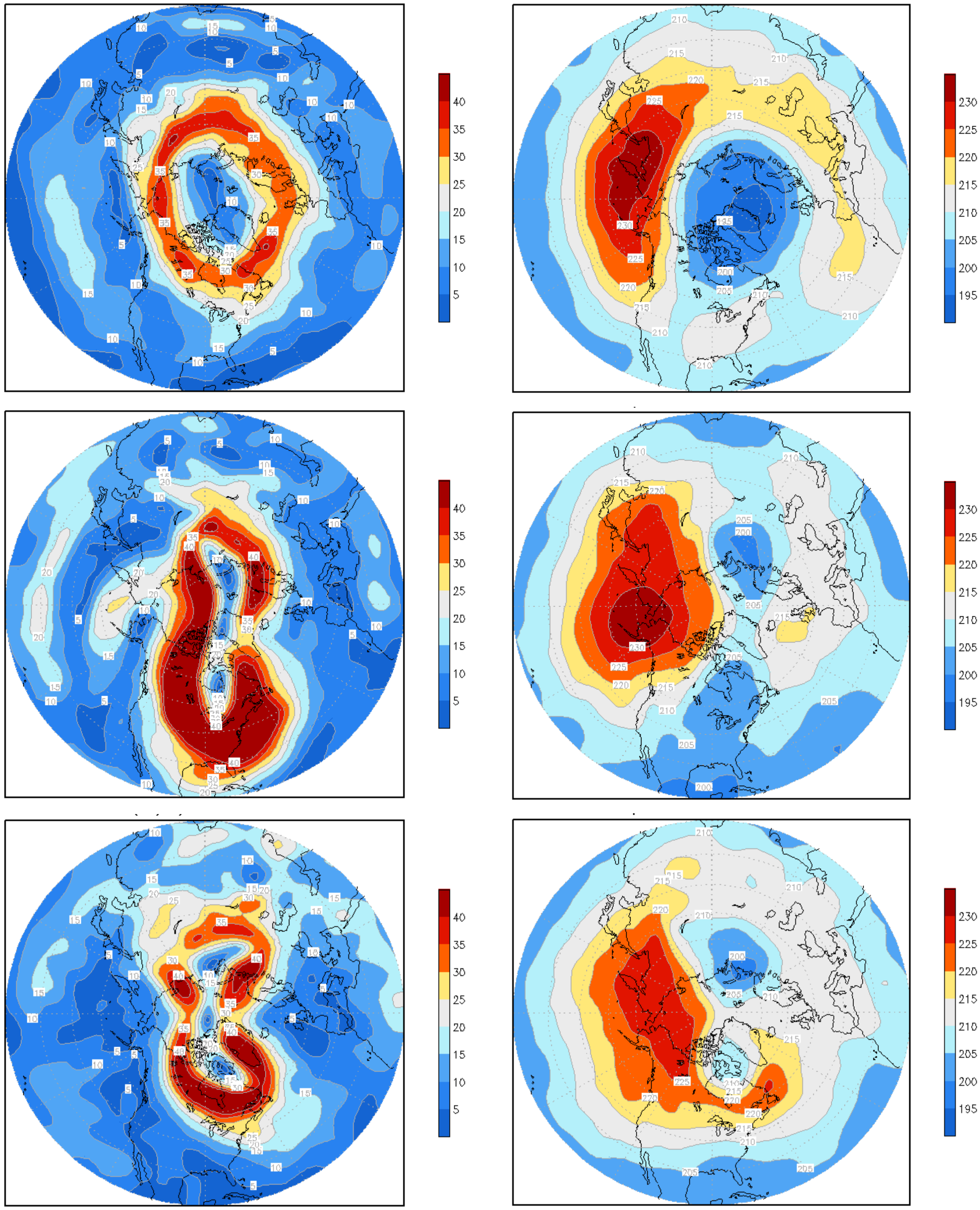

Figure 7. Sequence of wind speed (left, contours every 5 ms^{-1}) and temperature (right, contours every 5 K) from the NCEP/NCAR Reanalysis for the January 2003 wind event. Data are shown for 00 UTC 15 December 2002 (top), 12 UTC 19 January 2003 (center), and 18 UTC February 2003 (bottom). Reanalysis plots obtained from the NOAA Operational Model Archive Distribution System (Data acquired from NOMADS; http://nomad3.ncep.noaa.gov).

Figure 7 shows the 50 hPa wind speed and temperature at three times from the NCEP/NCAR Reanalysis: 00 UTC 15 December 2002, 12 UTC 19 January 2003, and 18 UTC 15 February 2003. These times correspond to the beginning, peak, and end of the event. Figure 7 shows that on 15 December 2002, the "ring" of maximum winds ($\geq$ 30 ms^{-1}) was confined mainly north of 60° N. The temperature exhibits a dipole pattern, with the coldest temperatures generally centered over the Arctic Circle. By 19 January 2003, the pattern of maximum winds had become elongated in a wavenumber-2 pattern, with winds $\geq$ 40 ms^{-1} dropping as far south as 30° N and resulting in the peak wind trace seen in Figure 6. This large-scale change is also reflected in the temperature field; note that the region over the Arctic Circle has been encroached upon by the large area of warmer temperatures—hence the term stratospheric sudden warming. Like the wind speed, the temperature field over the pole also exhibits a wavenumber-2 pattern. By 15 February 2003, the area of maximum winds had receded considerably, although it retained the wavenumber-2 pattern—as did the temperature field.

For a preliminary evaluation of these high-wind events by current-day operational NWP models, we compared real-time forecasts of stratospheric high wind events with the ensuing operational analysis. An example is shown in Figure 8 for a case this past December. At this time, the NCEP Global Forecast System was forecasting a breakdown in the polar vortex of 50-hPa winds during the next seven days. The verifying analysis confirms that change in the pattern. While not as extreme an example as the 2003 case discussed above, this does show there is reason to expect useful guidance from the operational models. This type of analysis can also be extended to 2-week forecasts.

4. SUMMARY AND CONCLUSIONS

We acquired gridded reanalysis data for the region of the atmosphere between about 16–23 km (~55,000–75,000 ft), a region generally known as the lower stratosphere and upper troposphere. This range brackets the operational altitude of the HAA (~65,000 ft). The data were used to construct long-duration (20+ years) time series of horizontal wind speed at several CONUS locations. Power spectra computed from the time series data revealed prominent spikes corresponding to periods of one year, 90 days, and 1 day, with the annual peak generally dominant. The high wind events usually occurred during the boreal winter months and typically evolved over a 3-4 week period. We examined a recent case of a high wind event characterized by background environmental winds of about 10 ms^{-1} that increased to over 40 ms^{-1} during 1-2 week period. This case exhibited many of the features of a Sudden Stratospheric Warming. The high winds associated with the breaking polar vortex extended as far south as 30° N. Furthermore, it appears that this wind event was well predicted by the NCEP GFS, which forecast a breakdown in the polar vortex 1 week in advance. The capability of the forecast system to produce reliable stratospheric wind speed guidance will be crucial for maintaining the integrity of the HAA by providing adequate lead time for evasive maneuvers.

Acknowledgements: This work was supported by the Missile Defense Agency under contract HQ0006-04-C-7094. The NCEP Reanalysis data were obtained from the NOAA-CIRES Climate Diagnostics Center, Boulder, CO from their web site at http://www.cdc.noaa.gov. The NCEP GFS data were obtained courtesy of the NOAA/National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC)/NOMADS development group. Approved for Public Release: 07-MDA-2989 (12 DEC 07).

REFERENCES

Cho, J.Y.N. and others, 1999: Horizontal wavenumber spectra of winds, temperature, and trace gases during the Pacific exploratory missions: 1. Climatology, *J. Geophys. Res.*, **104**, 5697-5716.

Girz, C., A. MacDonald, R. Anderson, T. Lachenmeier, F. Caracena, and R. Collander, 1999: Global Air-Ocean In-Situ System (GAINS), International Balloon Technology Conference, AIAA, 99-3870, Norfolk, VA.

Kalnay, E. and others, 1996: The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Amer. Met. Soc.*, **77**, 437-471.

Kihn, E.A., M. Zhizhin, S.J. Lowe, and R.A. Siquig, 2001: The Environmental Scenario Generator, *Preprints, 17th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Amer. Met. Soc., Albuquerque, NM.

Kolmogorov, A.N., 1941: The local structure of turbulence in incompressible viscous fluids for very high Reynolds numbers, *Dokl. Akad. Nauk SSSR*, **30**, 201-305.

Lilly, D.K., and E.L. Petersen, 1983: Aircraft measurements of atmospheric kinetic energy spectra, *Tellus*, **35**(A), 379-382.

Modica, G.D., T. Nehrkorn, and T. Meyers, 2006: The development of a vertical wind shear model for the lower stratosphere in support of the High Altitude Airship, *Preprints, 12th Conference on Aviation, Range, and Aerospace Meteorology*, Amer. Met. Soc., Atlanta, GA.

Schmidt, D.K., J. Stevens, and J. Roney, 2006: Near-space station-keeping performance of a large high-altitude notional airship, *Preprints, Atmospheric Flight Mechanics Conference and Exhibit,* Amer. Inst. Of Aeronautics and Astronautics, Keystone, CO.

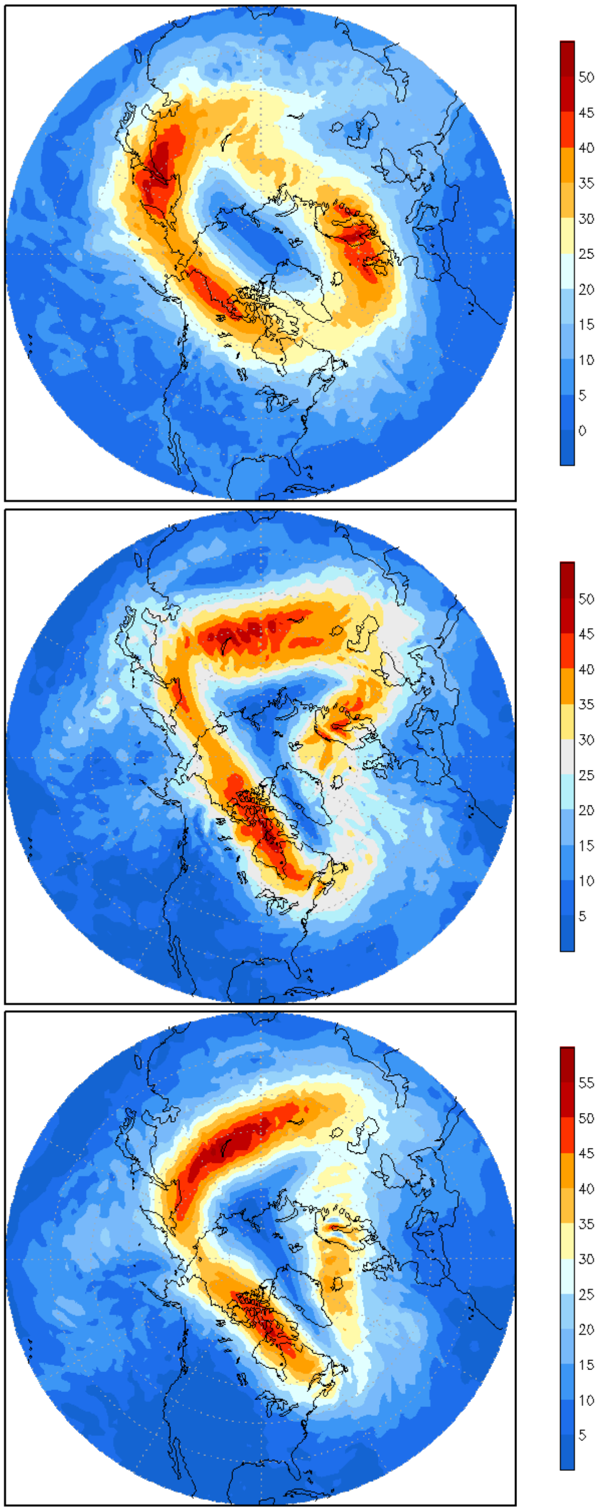

Figure 8. Northern hemisphere 50 hPa wind speed from the NCEP Global Forecast System: analysis at 00 UTC 15 December 2006 (top), 180-h forecast valid 12 UTC 22 December 2006 (center), and verifying analysis valid 12 UTC 22 December 2006 (bottom).