RECENT INNOVATIONS IN DERIVING TROPOSPHERIC WINDS FROM METEOROLOGICAL SATELLITES

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Innovative new research advances aimed at improving ways of deriving tropospheric winds from satellites have been a focus of WMO and CGMS cosponsored International Wind Workshops.

The evolving constellation of environmental/meteorological satellites and their associated sensor technology is rapidly advancing. This is providing opportunities for creatively improving satellite-derived products used in weather analysis and forecasting. The proper specification and analysis of tropospheric winds is an important prerequisite to accurate numerical model forecasts. The retrieval of atmospheric motion vectors (AMVs) from satellites has been expanding and evolving since the early 1970s (Menzel 2001). Most of the major meteorological geostationary satellite data centers around the globe are now producing cloud- and water vapor–tracked winds with automated algorithms using imagery from five operational geostationary satellites (Fig. 1). Contemporary AMV processing methods are continuously being updated and advanced through the exploitation of new sensor technologies and innovative new approaches. It is incumbent upon the research community working in AMV extraction techniques to ensure that the quality of the current operational products meets the needs of the user community. In particular, the advances in numerical weather prediction (NWP) in recent years have placed an increasing demand on data quality. With remotely sensed observations dominating the initialization of NWP models over regions of the globe that are traditionally data sparse, the motivation is clear: the importance of providing *high-quality* AMVs becomes crucial to their relevance and contribution toward realizing superior model predictability.

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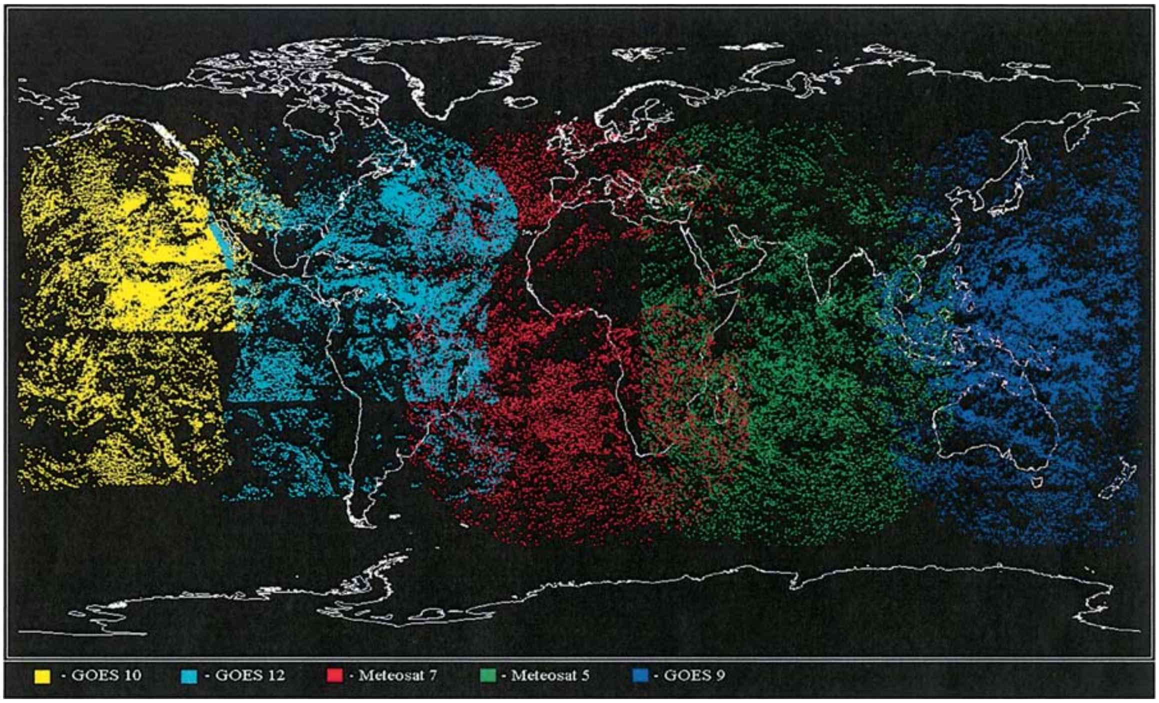

FIG. 1. Example of global atmospheric motion vectors being processed operationally on a daily basis from five geostationary meteorological satellites.

As an example, a recent observing system experiment (OSE) conducted by the European Centre for Medium-Range Weather Forecasts (ECMWF) shows the impact of various satellite observing systems on model forecasts (Kelly 2004). Figure 2a shows the importance of AMV in the Tropics on subsequent ECMWF model forecast performance. The OSE AMV impacts are not as dramatic in the midlatitudes (Fig. 2b) in great part due to the improved assimilation of satellite radiances, such as those from Advanced Microwave Sounding Unit (AMSU) on board the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. This was also borne out in a study by Su et al. (2003). The improved data assimilation methods now emerging from the NWP community are challenging the AMV researchers and providers to advance the quality of their products.

To achieve global consistency in the derivation of AMVs, the World Meteorological Organization (WMO) and Coordination Group for Meteorological Satellites (CGMS) cosponsor International Winds Workshops (IWWs) every 2 yr. The IWWs provide a fertile ground for the global AMV research community to interact and advance ideas. The IWW scientific committee consults with the CGMS, and, in particular, its working group on satellite products, including AMVs, on issues related to the derivation and utilization of tropospheric wind information from satellites. The IWWs bring together AMV researchers from around the world to present new, innovative ideas on AMV extraction techniques, interpretation, and applications. The NWP community is always well represented at these workshops and provides an important exchange of information on the latest in data assimilation issues.

This paper draws from recent IWWs, and describes several new innovations in satellite-produced wind technologies, derivation methodologies, and products. Because, as stated above, it is imperative that AMV observational quality remains a positive contributor to advancing data assimilation systems, this article also provides a glimpse into the pending opportunities that will be afforded with emerging/anticipated new sensor technologies.

RECENT INNOVATIONS. *Winds from rapid-scan satellite imagery.* In the United States, rapid-scan imagery from Geostationary Operational Environmental Satellite (GOES) has been used in operational forecasting since the 1980s. Forecasters can utilize the additional detail that can be captured from more frequent imaging in events associated with rapidly changing cloud structures. The value of more frequent imaging is evidenced by the recent inclusion of a 15-min update cycle over the continental U.S.

(CONUS) sector in the current GOES schedule, and by the multitude of special National Weather Service (NWS) operational requests for more frequent sampling at 7.5-min intervals [rapid-scan operations (RISOP)]. On occasion, special periods of super-rapid-scan operations (SRSO) have been requested by the research community. The SRSOs allow for limited-area coverage of 1-min- interval sampling over meteorological events of interest (e.g., severe weather and tropical cyclones).

The importance of image frequency in AMV tracking is well recognized. New strategies have been developed for operational wind processing to take advantage of the higher-frequency interval imagery offered by the current GOES scanning schedules. The capability to routinely use higher-frequency interval imagery in the operational derivation of infrared (IR) and visible (VIS) AMVs has been added to the wind production suite at NOAA/National Environmental Satellite Data and Information Service (NESDIS). The GOES 15-min CONUS and eastern Pacific and western U.S. (PACUS) image sectors are now used routinely for the generation of IR and VIS cloud-drift wind vectors for both operational GOES satellites. In addition, the more frequent 7.5-min rapid-scan images are automatically utilized when the GOES imager is placed in rapid-scan mode (RISOP). The Northern Hemispheric image sectors, which are scanned every 30 min, are used to generate wind products outside the CONUS, PACUS, and RISOP domains in order to achieve full Northern Hemispheric coverage. The Southern Hemispheric image sectors, which are also scanned every 30 min, are used to achieve coverage in the Southern Hemisphere. All of these image sectors are illustrated in Fig. 3.

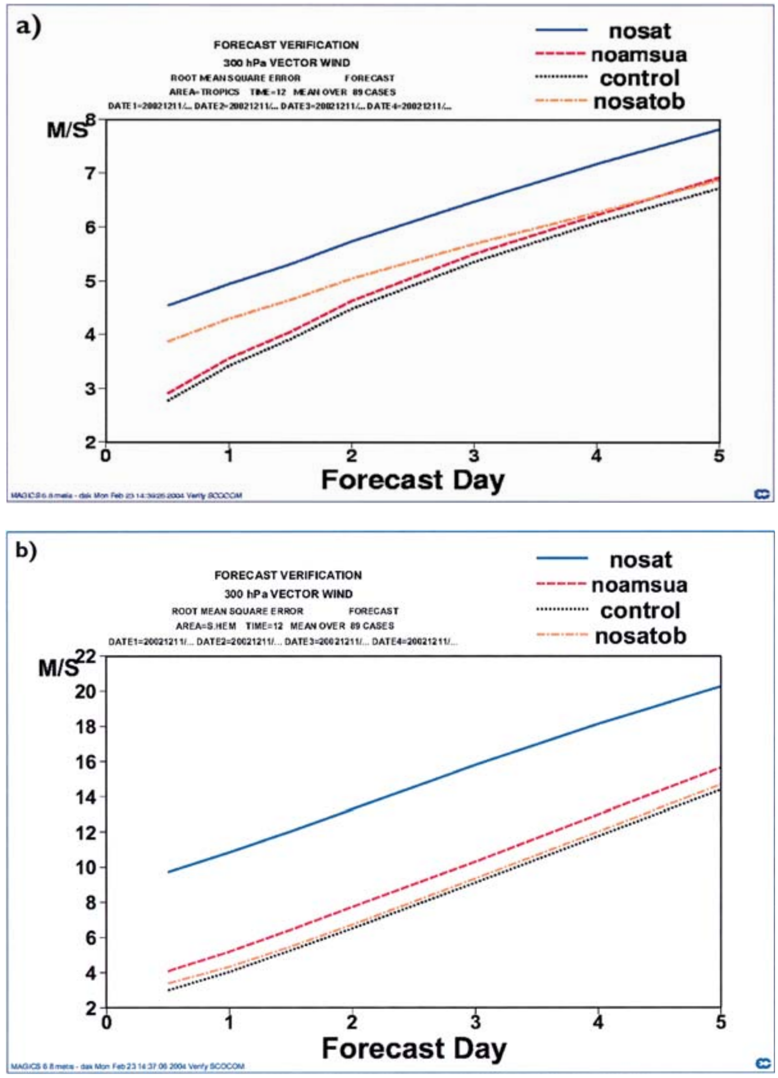

FIG. 2. OSE conducted by ECMWF, showing the impact of removing different satellite data on the forecasts of 300-hPa winds. (left axis) Forecast rmse (m s^{-1}) is indicated. Control: The current operational system at ECMWF that assimilates data from three AMSU and two HIRS instruments aboard the NOAA satellites, AMVs from five geostationary satellites and one polar orbiter (*Terra*), clear-sky water vapor radiances from three geostationary satellites, three SSM/I instruments from the DMSP platforms, a Seawinds instrument from Quikscat, as well as conventional observations (radiosonde temperatures and pilots, wind profilers, aireps, synops, drifting buoys, and paobs). Nosat: All satellite data removed. Nosatob: No AMVs. Noamsua: No AMSU-A radiances. The OSE included an 89-day period during 2002: (a) tropical region and (b) Southern Hemisphere region. (From: Kelly 2004.)

Figure 4 illustrates an example of the impact from using higher-frequency interval imagery on the operational *GOES-10* VIS wind product. This figure shows *GOES-10* low-level AMV around Hurricanes Dora and Eugene in 1999 using imagery from the 15-min PACUS and 30-min Northern Hemispheric sectors. Note the dramatic increase in vector coverage and the more uniform flow associated with the 15-min wind field.

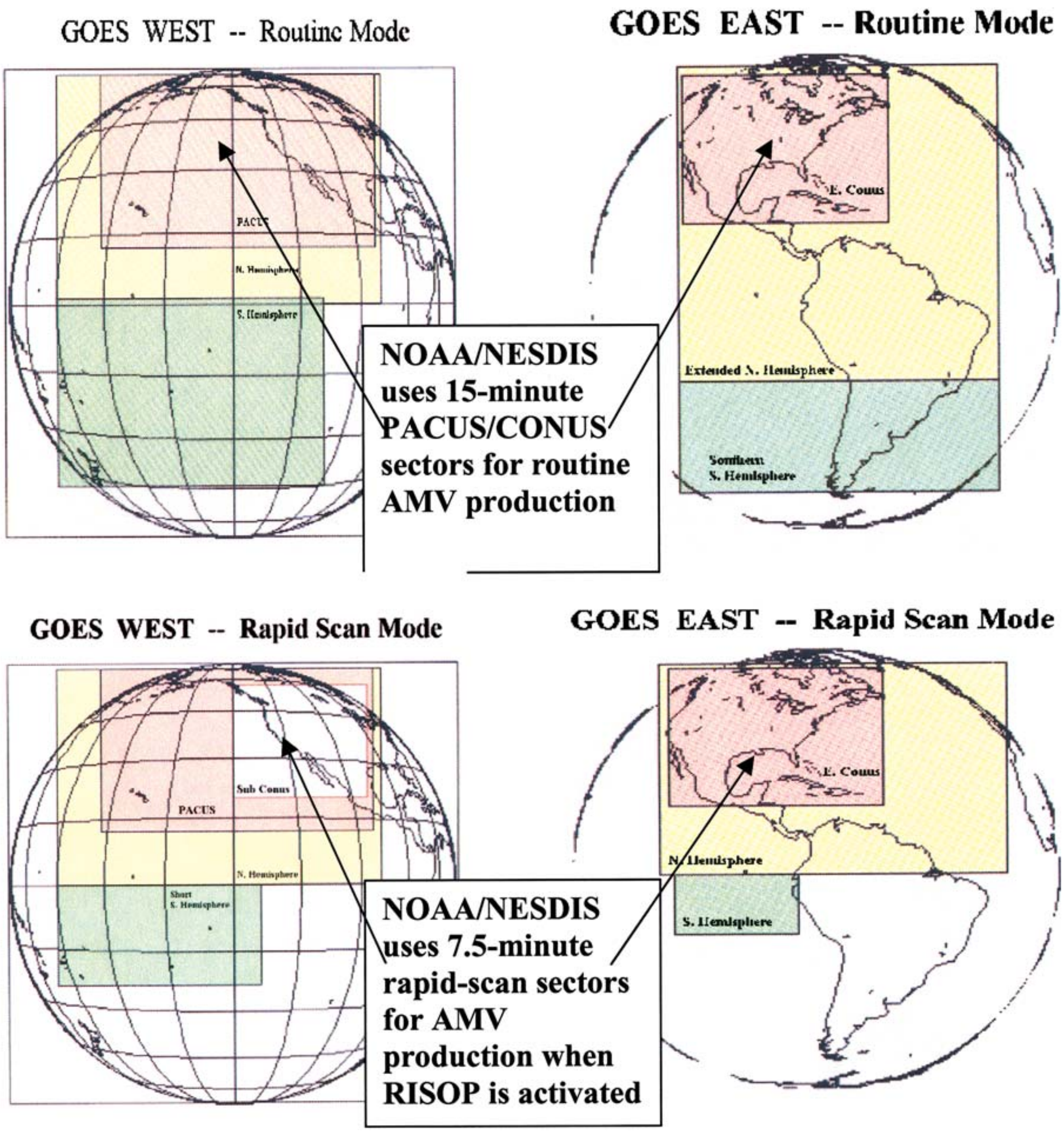

Fig. 3. GOES-East and GOES-West image sectors. Use of CONUS, PACUS, and RISOP sectors offer benefits to AMV processing.

Successful tracking of features such as cumulus clouds over land, which have lifetimes that can be considerably less than 30 min, demands the use of imagery with time intervals in the 5–15-min range. Velden et al. (2000) investigated the impact of using GOES RISOP and SRSO imagery on the coverage and quality of various derived wind products. Immediately after the launch of *GOES-10,* the satellite was put into a science test mode for a 4-week period (16 March–12 April 1998). During this time, continuous 5-min sampling over the CONUS domain was achieved in all the available spectral bands. Winds were derived over the central United States from *GOES-10* full-resolution water vapor (WV), IR, and VIS images using an automated tracking algorithm (Velden et al. 1997, 1998). Three successive images were employed in the AMV derivations. For the evaluation, tests were run using various image spacing intervals: 5, 10, 15, and 30 min.

Results from the Velden et al. (2000) study showed that the more frequent image sampling improved the VIS and IR vector field density and quality, and the optimal tracking time interval was dependent on the spectral band. For GOES, the optimum image intervals for processing winds were found to be 5 min for VIS, 10 min for IR, and 30 min for WV. The criteria used to define "optimum" included the number of satellite wind vectors produced and the vector root-mean-square error (rmse) and speed bias between the collocated satellite-based wind observations, rawinsonde observations, and background model first-guess fields that were used in the processing.

Special GOES SRSO periods have been collected during several Atlantic tropical cyclone (TC) events. The SRSO provides periods of continuous 1-min-interval image sampling. Because TC cloud structures are characteristically fast evolving, the advantages of super-rapid-scan imaging on AMV derivations can showcase a prime application. Examples are shown in Fig. 5 for Hurricane Luis (1995) and Fig. 6 for Hurricane Isabel (2003). The ability to retrieve mesoscale cloud motions is notably enhanced using 3–5-min image intervals. Regular use of the full 1-min frequency is not practical with the current operational capabilities, primarily due to intermittent navigation/registration inaccuracies introduced at this high temporal imaging frequency. However, sophisticated image preprocessing and tracking methodology and high-end computers can help to overcome these limitations (Hasler et al. 1998). Applications of these rapid-scan datasets extend to TC genesis studies and research on TC intensity change (Knaff and Velden 2000; Berger 2002).

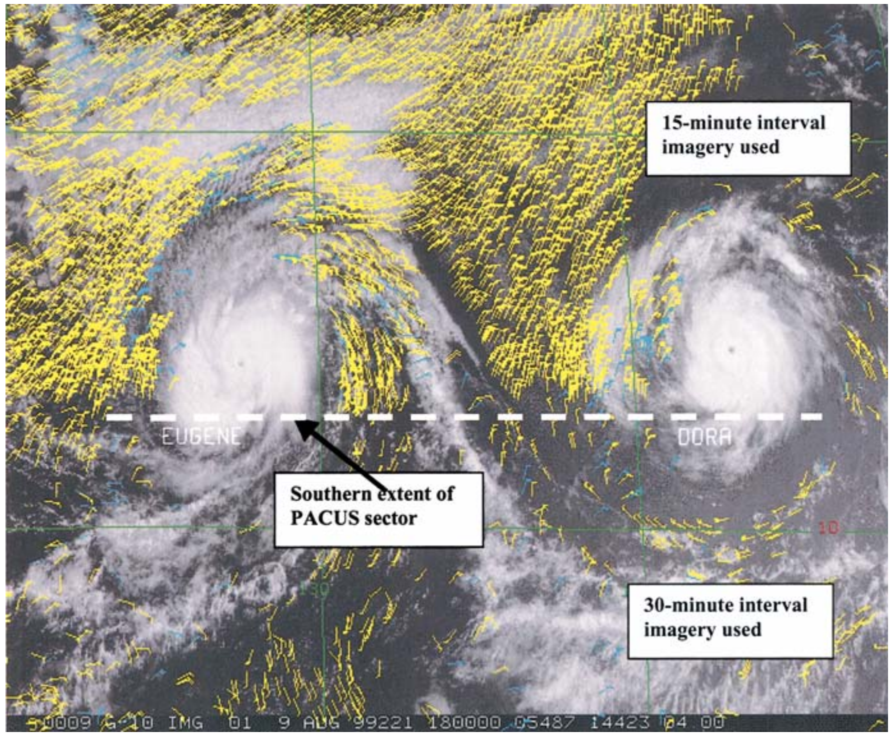

Fig. 4. *GOES-10* low-level cloud-drift winds (yellow: 800–950 hPa, cyan: 700–800 hPa) around Hurricanes Dora and Eugene using 15- and 30-min-interval visible imagery.

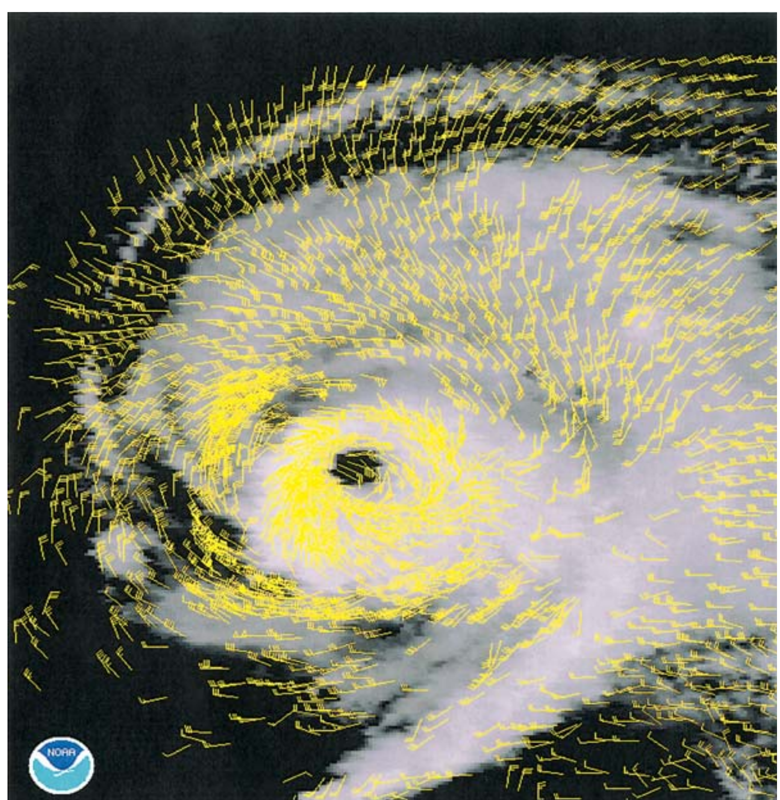

Fig. 5. High-density wind vectors determined by tracking upper-level cloud features in successive GOES 5-min rapid-scan imagery during Hurricane Luis in 1995.

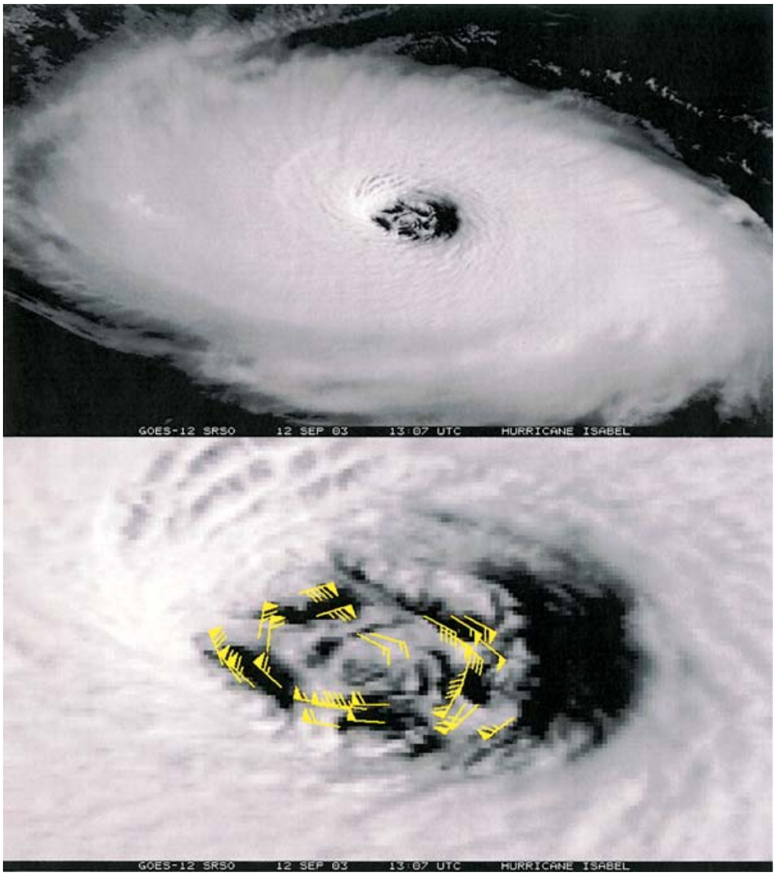

FIG. 6. (top) *GOES-12* VIS imagery of Hurricane Isabel on 12 Sep 2003. (bottom) Low-level (~850 hPa) AMVs in Isabel's eye derived from *GOES-12* super-rapid-scan (3-min image intervals) VIS imagery.

The utility of GOES rapid-scan winds has been further demonstrated in field experiments designed to maximize observational abilities in regions of high-impact weather events. As an example, the GOES Rapid-Scan Winds Experiment (GWINDEX) was carried out for 2-month periods in each of the years of 2001–2003 (Velden et al. 2001). The primary objective of GWINDEX was to demonstrate the improvement that could be gained in both quantity and quality of AMVs using *GOES-10* RISOP imagery over the data-sparse northeast Pacific Ocean. The rapid-scan winds were produced in real time and provided mission-planning and forecast support to the coincident Pacific Landfalling Jets Experiment (PACJET). An assessment of the GWINDEX datasets included a data impact study using the NWS Rapid Update Cycle (RUC) model. Assimilation of the GWINDEX winds showed a positive impact on RUC analyses and short-term forecasts for the western U.S. coastal area (Weygandt et al. 2001).

Other field programs are being designed to test "targeted" observations and adaptive sampling strategies. During the North Pacific Experiment (NORPEX) field program in 1998 (Langland et al. 1999), several *GOES-9* SRSO periods were examined during intensive observing periods (IOPs). The IOPs were conducted over the North Pacific Ocean, and offered the opportunity to assess the value of targeted satellite-derived data over marine environments. High-density, rapid-scan winds were derived from the SRSO imagery (5-min intervals) over limited "regions of interest," defined by objective numerical methods as areas of potential rapid analysis error growth. The resulting datasets were assessed in numerical impact studies and found to contribute significantly to the reduction in 2-day forecast errors over western North America. The concept of targeted observations is a focus of the newly formed The Observing System Research and Predictability Experiment (THORPEX)—a global atmospheric research program, which is being developed under the auspices of the WMO World Weather Research Program. THORPEX will promote field campaigns and provide opportunities for adaptive sampling that will include creative uses of observations from weather satellites.

The availability of rapid-scan winds is not restricted to the GOES platforms. Schmetz et al. (2000) demonstrated the use of rapid-scan winds from the European Meteosat platforms. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT's) Rapid Scanning Service started operations in September 2001, providing images every 10 min from *Meteosat-6*. Routine AMV generation became operational in April 2002 (De Smet 2002). The Japan Meteorological Agency (JMA) operated the Geostationary Meteorological Satellite (GMS) series in 15-min rapid-scan mode during selected typhoon events. The impact of AMVs derived from these rapid scans on numerical prediction of typhoon track and intensity was found to be positive (Nakamura et al. 2002).

In summary, the value added to geostationary satellite–derived AMVs from rapid-scan imaging is undeniable. It has been demonstrated that using 5–10-min image intervals in the VIS and IR channels notably improves the vector quantity and quality relative to the more commonly used 30-min image frequency. Fortunately, the global satellite providers and AMV producers are realizing the gains that are possible from rapid scans. So, the outlook is good for more frequent scanning cycles on near-term future geostationary satellite systems worldwide. As rapid-scan imaging becomes a routine part of observing system strategies, quantities such as operational AMVs will greatly benefit. This, in turn, will directly benefit NWP forecasts and the operational forecast community.

Winds from shortwave IR imagery. Contemporary AMV coverage is diurnally consistent in the mid- to upper levels (100–600 hPa) through the use of the 6.7-μm water vapor and 10.7-μm longwave infrared (LWIR) channels. However, in the low levels (600–950 hPa), AMVs are provided by a combination of the VIS and LWIR channels, depending on the time of day. During daylight imaging periods, the VIS usually provides superior low-level tracer detection to the LWIR channel due to its finer spatial resolution (some satellites) and decreased susceptibility to attenuation by low-level moisture. Therefore, nighttime low-level AMV coverage typically decreases sharply when the visible channel is no longer available. Operational NWP data assimilation systems can be significantly affected by this diurnal reduction in coverage, because the assimilation methods operate best with spatially and temporally consistent observations.

Current techniques for tracking low-level (600–950 hPa) AMV winds at night utilize the 10.7-μm LWIR window channel found on all operational geostationary satellites. A new alternative has emerged in the form of the 3.9-μm shortwave infrared (SWIR) channel now available on the GOES imagers. The usefulness of this channel for wind derivation is limited to nighttime applications because of its sensitivity to solar contamination. However, this is acceptable because tracking clouds using the visible channel is already very effective in daylight hours. The SWIR channel is a slightly cleaner window channel than the LWIR (less WV attenuation), making it more sensitive to warmer (lower tropospheric) temperatures. This allows for a higher detectability rate of low-level cloud tracers. The SWIR channel is also not as sensitive as the LWIR channel to cirrus clouds that may obscure low-level cloud tracers. These two characteristics make it a superior channel for producing low-level AMV at night.

Techniques have been developed to enhance the SWIR imagery, as well as improve automated tracking in order to better detect cloud tracers in these enhanced images (Dunion and Velden 2002a). Until very recently, satellite data processing software has been limited to 8 bits per pixel in the imagery. Because the SWIR channel is characterized by relatively small gradients in brightness temperatures in the warmer low levels, this limited the ability of tracking algorithms to detect viable cloud targets and resultant tracers over time. To overcome this limitation, a technique was developed to enhance the SWIR imagery by stretching the brightness temperature contrast in the warmer end of the spectrum (Dunion and Velden 2002a). This enhancement greatly improves the depiction of low-level targets at the cost of confining the mid- to upper-level gradients in the image. Therefore, tracer detection is strictly limited to clouds below 600 hPa (based on LWIR brightness temperature-determined height estimation). Recent AMV software improvements have made it possible to use 2-byte raw radiance data for targeting and tracking. With this application, gradients are not smoothed by converting the original 10-bit counts to 8-bit values prior to tracking, so this is an alternative to "contrast stretching."

Recent tests have shown that the new SWIR technique (compared to the traditional LWIR technique) results in a ~40% increase in the number of nighttime low-level AMVs. Figure 7 illustrates this increased coverage and shows low-level *GOES-8* AMVs provided by both IR channels on 3 October 2001. Features such as the well-defined ridge in the north-central Atlantic Ocean (~30°N, 48°W) and a possible tropical wave axis in the southwestern Caribbean Sea (~77°W) are well depicted by the SWIR AMVs (Fig. 7, top). However, these features are more difficult to discern looking at the LWIR AMVs (Fig. 7, bottom).

In summary, the SWIR AMVs from GOES provide significantly increased low-level wind information at night over that which is currently available with the routine operational LWIR techniques. The enhanced SWIR AMVs reduce the diurnal disparity in low-level AMV data coverage that currently exists using only the LWIR, and will likely improve the ability of models to assimilate these satellite data. The GOES SWIR AMVs are currently being transitioned into NESDIS operations (Daniels et al. 2002). The recently launched European geostationary satellite [Meteosat Second Generation (MSG); Schmetz et al. 2002] and the next Japanese geostationary satellite [Multi-functional Transport Satellite (MTSAT-1R)] have the 3.9-μm channel and the ability to produce low-level SWIR AMVs operationally, taking us closer toward the goal of global production in the near future.

AMVs over the polar regions from MODIS observations. Geostationary satellites do not generally provide use-

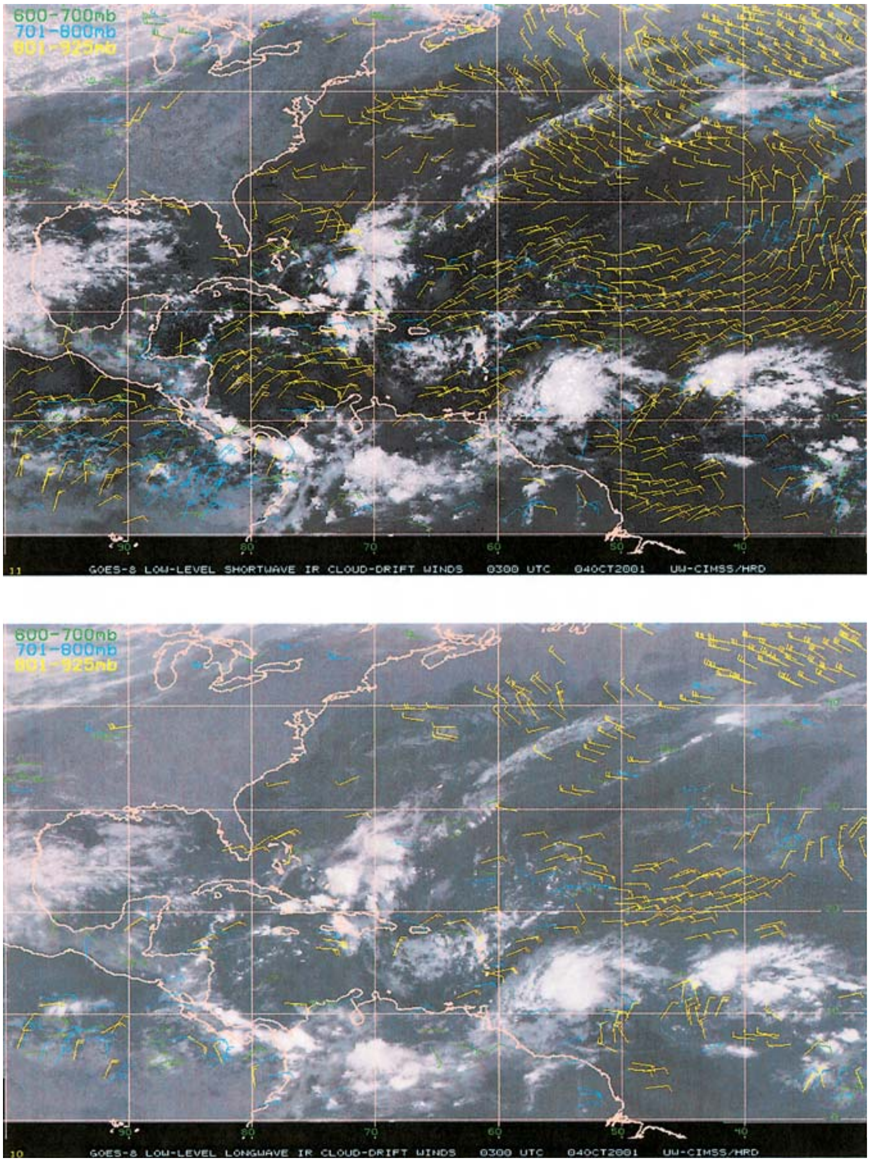

Fig. 7. Comparison of *GOES-8* nighttime (top) SWIR and (bottom) LWIR AMVs over the western Atlantic Ocean on 3 Oct 2001.

ful wind information poleward of about 65° latitude due to their equatorial orbit. In this section we describe an initiative for deriving AMVs at high latitudes from polar-orbiting satellites. Polar orbiters have orbital periods of approximately 100 min, and, therefore, provide consecutive scans over nearly the same polar region at these intervals. Imagers on polar orbiters have scanning swath widths of 2300 km or more, providing significant geographic overlap by consecutive orbits at high latitudes. These temporal and spatial characteristics provide the opportunity for deriving AMV from successive orbits (single or multiple satellites) over the polar regions. The AMV processing methodology employed is based on the automated tracking algorithms used with geostationary satellites, modified for use with the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the National Aeronautics and Space Administration's (NASA's) polar-orbiting *Terra* and *Aqua* satellites. Cloud and water vapor tracking with MODIS data is based on the established procedures used for GOES, which are essentially those described in Nieman et al. (1997) and Velden et al. (1997, 1998). With MODIS, cloud features are tracked in the IR window band at 11 μm and WV features are tracked using the 6.7-μm band. An example of typical MODIS AMV coverage is shown in Fig. 8. Additional details are given in Key et al. (2003). It is also possible to employ this approach with Advanced Very High Resolution Radiometer (AVHRR) imagery provided by the NOAA polar-orbiting satellite series. However, the lack of a WV channel on the AVHRR is a major limitation. As an initial demonstration of the concept, MODIS AMVs were derived at the University of Wisconsin (UW) Cooperative Institute for Meteorological Satellite Studies (CIMSS) over both polar regions during 5 March–3 April 2001. The 1-km-resolution image data were normalized and systematic detector-to-detector offsets were removed to reduce the effect of detector noise and variability. Approximately 25,000 quality controlled AMVs, on average, were produced per day over each pole for the 30-day study period. A statistical analysis of the AMVs versus collocated drawinsonde observations yielded rmse values similar to, but slightly larger than, those typically found for AMVs derived from geostationary satellites. This was expected given the much larger temporal sampling intervals inherent with the polar-orbiting satellites. The best results are obtained from the mid- to upper-tropospheric (400–600 hPa) WV AMVs. Given the sparse rawinsonde observation network in the polar regions and the relative importance of high-latitude wind observations in NWP forecasts noted by Francis (2002), the MODIS AMVs have the potential to improve forecasts in polar and subpolar areas. In order to test this hypothesis, model impact studies using the 30-day demonstration dataset were performed at the ECMWF and the NASA Global Modeling and Assimilation Office (GMAO). The primary goal was to determine if forecasts are improved when MODIS winds are assimilated.

The initial model impact study performed at the ECMWF with the 30-day case study dataset employed a 3D variational data assimilation (3DVAR) scheme with 6-hourly analyses that used the model's first guess (FG) at the appropriate observation time. Two experiments were conducted: the control experiment, with routine observational data used as in operations, and the MODIS experiment that included the routine observational data plus the assimilation of MODIS AMVs over the polar regions. Over polar land areas, only IR and WV winds above 400 hPa were used. Over the ocean, IR winds above 700 hPa and WV winds above 550 hPa were used. These restrictions were chosen after trial experiments indicated a somewhat poorer quality of lower-level AMVs, possibly due to height assignment problems over orography and ice, and the use of relatively coarse-resolution model data for the height assignment. As with operational AMVs from geostationary satellite data, the MODIS winds were thinned to a 140-km resolution, and quality control in the assimilation was based on an asymmetric check against the first guess (Rohn et al. 2001).

Statistics from a comparison of the MODIS IR and WV AMVs against the model first guess used in the assimilation showed that, as with the rawinsonde comparisons, for most levels and regions the values are similar to other AMVs currently assimilated by ECMWF. An exception was found at lower levels in the Antarctic region where the statistics revealed large rms vector errors and relatively strong, fast speed biases (reaching 1.3 m s^{-1}). These poorer statistics motivated the cautious use of the MODIS winds at lower levels.

There was a significant positive impact on model forecasts of the geopotential heights when MODIS AMVs were assimilated, particularly over the Northern Hemisphere. Figure 9 shows the improvement in forecasts of the 1000- and 500-hPa geopotential heights over the Arctic (north of 65° latitude). The correlations between the forecast height anomaly and the verifying analysis with the forecasts from MODIS and the control experiments each validated against their own verifying analyses are shown. The forecast improvements are significant at the 98% confidence level or better at most vertical levels for a forecast range of 2–5 days (Bormann et al. 2002; Santek et al. 2002).

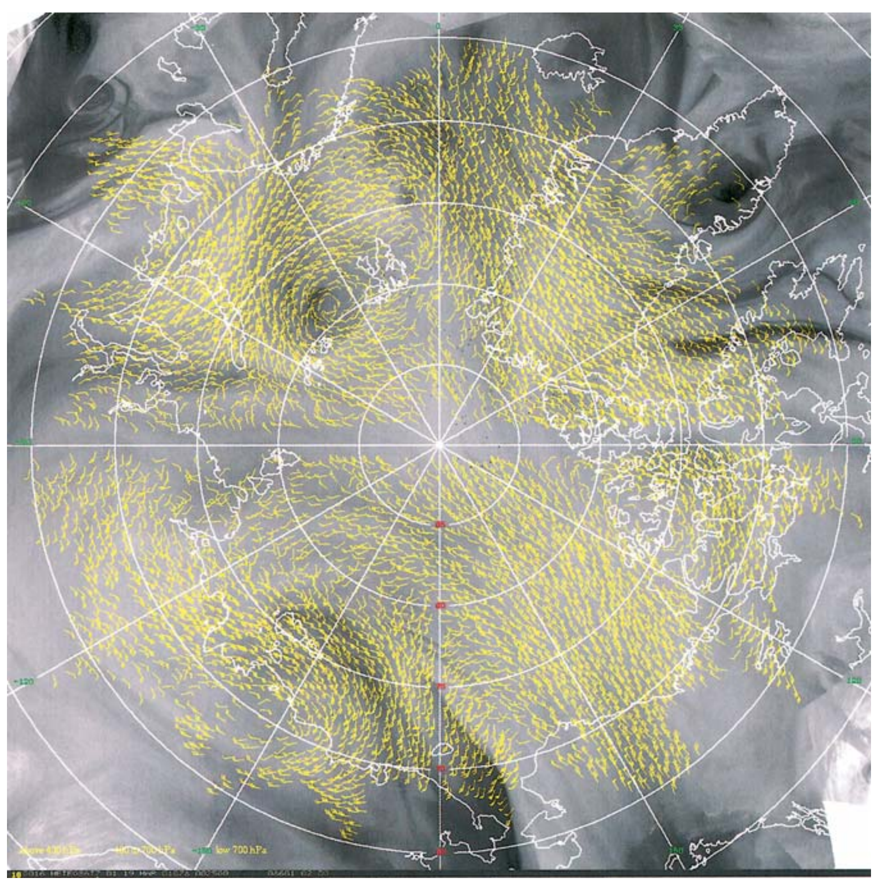

Fig. 8. Wind vectors derived by tracking clouds and water vapor features from successive MODIS passes over the Arctic on 19 Mar 2001. Shown is a 12-h sample of AMV coverage from the *Terra* satellite overlaid on a water vapor image composite.

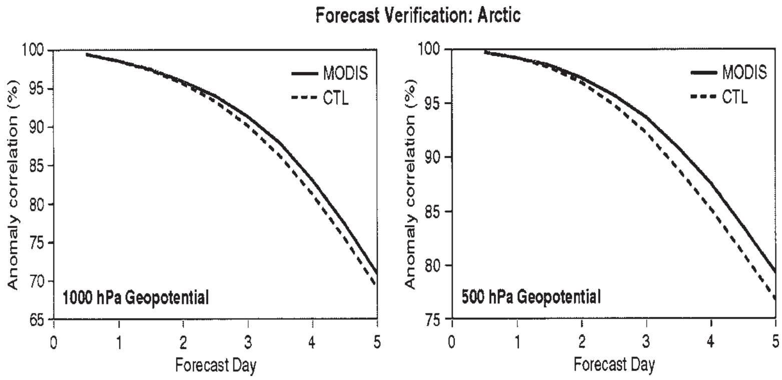

FIG. 9. Anomaly correlation as a function of forecast range for the (left) 1000- and (right) 500-hPa geopotential height forecast in the Arctic region (north of 65° latitude) from the ECMWF MODIS winds impact experiments. The MODIS experiment (solid) and the control experiment (dashed) have each been verified against their own analyses. The study period is 5–29 Mar 2001. (From: Key et al. 2003.)

The MODIS AMVs were also tested in the next-generation assimilation system of the NASA GMAO (Riishojgaard and Zhu 2002). At each analysis time and observation location the observation-minus-6-h forecast (OMF) residuals were calculated for a control run that did not include the MODIS winds. Next, an assimilation that included the MODIS winds was performed and the OMF residual was again calculated. The OMF residual for the assimilation that includes the MODIS winds was significantly smaller than in the control assimilation, especially at 500 hPa. This demonstrated that the observations are consistent with the dynamics of the model, and that the MODIS winds contain information that can be ingested and retained by the assimilation system. As a result, the short-range forecast becomes more consistent with the observations at subsequent analysis times. In the ECMWF study, both sets of forecasts were compared to their own verifying analyses. In the GMAO study, they were instead verified against operational ECMWF analyses. As with the ECMWF impact study, forecasts from the MODIS AMV assimilation scored significantly higher than the control experiment in the Arctic, and marginally higher in the Antarctic. Due to the lack of observations over Antarctica, the Southern Hemisphere result may, therefore, be less meaningful than the Northern Hemisphere result. For the extratropics of each hemisphere, the MODIS AMVs improved the forecast skill in the Northern Hemisphere while the Southern Hemisphere impact was nearly neutral.

The aforementioned two studies sparked an immediate interest in the MODIS polar AMVs as a potential operational product. Subsequent follow-on studies were conducted involving longer time periods and additional numerical weather prediction centers, including the Met Office, the Canadian Meteorological Centre (CMC), the JMA, and Deutscher Wetterdienst. The findings of these studies were as follows: 1) There is a consensus that MODIS AMVs are a promising new dataset for a region traditionally void of wind observations. 2) Timing issues associated with data reception, acquisition, processing, and dissemination are a concern to both forecasters and operational NWP centers. 3) Data processing is not yet optimized. In particular, the robustness of the AMV height assignments over cold terrain/ice is an area of concern. Issues under investigation include AMV height assignment, parallax corrections, and the use of additional spectral channels. 4) The overall impact of the MODIS winds on forecasts is positive. However, in some cases (times or regions) the MODIS AMVs yield a positive impact, and in other cases the impact is neutral or slightly negative. The data producers and NWP centers are working together to reconcile these results and problem areas. Nevertheless, the MODIS AMVs are now used in operational forecast systems at ECMWF (Bormann and Thépaut 2004), and JMA (Arctic only), and are being considered for operational use at other centers.

One important factor for operational data assimilation is the timeliness of the datasets. Due to the time required to download and process the raw data by NOAA personnel at the NASA Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC), UW CIMSS normally does not have access to the MODIS granules until 1–4 h after the satellite overpass time. As a result, the 2–5-h lag before MODIS AMVs become available to users is often too long for operational data assimilation systems. This delay may be partially alleviated if direct readout stations with X-band capabilities in the polar regions permit the AMV producers to have direct access to the MODIS data in real time. Direct broadcast sites that may be utilized include Fairbanks, Alaska; Kiruna, Sweden; Svaalbard, Norway; Tromso, Norway; and McMurdo Station, Antarctica. It should be noted that the National Polar-orbiting Operational Environmental Satellite System (NPOESS) era of satellites (~2008) plan to have no more than a 28-min data acquisition time delay.

In summary, the feasibility of deriving tropospheric wind information at high latitudes from polar-orbiting satellites has been demonstrated. The methodology is based on the algorithms currently used with geostationary satellites, modified for use with the polar-orbiting MODIS instrument. The scanning frequency, relatively low water vapor amounts, and complex surface features create some unique challenges for the retrieval of high-latitude AMV. Nevertheless, initial model impact studies with the MODIS polar AMVs conducted at NWP centers are very encouraging. For approximately the past 2 yr, CIMSS has been processing the MODIS AMVs from the *Terra* satellite in near–real time. The *Aqua* satellite AMVs were added in early 2003. Both wind sets are being made available via file transfer protocol (FTP) server to interested users. The dataset processing success rate has been very good (>95%), with datasets normally available 2–5 h after the satellite overpass time. In mid-2003, the NESDIS Office of Research and Applications began processing the MODIS AMVs locally in a demonstration mode, in anticipation of transitioning to fully operational processing at NESDIS in the near future.

New AMV processing methodologies. The automated derivation of AMVs involves an elaborate process of defining targets in the initial set of imagery, tracing the targets, determining the optimal displacement vectors, assigning altitudes to those tracers, and, finally, applying quality control to the final AMV product. While many advances have been made over the years in all of these areas (information available in IWW-published postprints), the height assignment and quality control issues have garnered the most attention.

Each AMV is assigned a specific altitude based on a number of estimation methods (Schmetz and Holmlund 1992; LeMarshall et al. 1993; Nieman et al. 1993; Campbell and Holmlund 2000). Properly assigning heights to tracers is absolutely critical for enhancing the quality and utility of the AMVs. These pressure-level height assignments are an approximation to the tropospheric layer of air in which the target (cloud or WV feature) is actually being tracked. This, in itself, introduces some vector "error" when comparing to rawinsonde winds. A recent study by Rao et al. (2002) confirmed this notion and went further in showing that AMVs represent layers that vary in depth depending on the ambient vertical moisture profile. This study not only sheds light on the AMV characteristics and representativeness, but also indicates how to interpret these data and make better use of them in data assimilation strategies. In another study, Daniels and Bresky (2001) further suggest that information on the peak of the local WV channel radiation contribution function (or weighting function) at the AMV target location can be used to better assign the vector height. They show that a significant reduction in height biases (versus collocated rawinsondes) can be achieved for GOES clear-air water vapor winds using this approach.

The final step in automated AMV processing involves quality assessment. Two objective methods are being used extensively in operational AMV production. The recursive filter (RF) analysis method (Velden et al. 1998) and the automatic quality control procedure (Holmlund 1998) are currently employed by several of the global AMV data producers. These two techniques yield quality indicators for individual AMVs that are appended to each data file that is passed on to users of these products. The quality indicators include information on each vector's "fit" with its neighbors, tracer consistency, and deviation from a background first-guess field (global model). Higher-quality AMVs determined by the above approaches are allowed to pass through the quality control step, and are given a weighted value depending on their quality assessment. A new scheme proposed by LeMarshall et al. (2004) builds on the aforementioned two approaches, but extends the quality indices to reflect an a priori estimate of the absolute and spatially correlated error associated with each vector. Better knowledge of the AMV observation error characteristics can lead to more effective ways of treating the data prior to data assimilation and NWP applications (Berger 2004). AMV quality indices are now being employed directly by operational data assimilation schemes to more effectively apply the AMVs in NWP (Holmlund et al. 2001). The IWWs have been instrumental in promoting an exchange of ideas on automated quality control of AMVs. One result of this forum is that the international AMV data producers now share common algorithms that provide information on AMV quality.

The traditional means of assessing the accuracy of AMVs is to collocate satellite-derived winds with rawinsondes and derive match statistics. For example, a time series prepared by NESDIS of daily verification statistics (sat – rawinsonde mean vector difference and wind speed bias) for upper-level (100–400 hPa) *GOES-8* IR cloud drift winds and WV winds are shown in Figs. 10 and 11. Each time series covers the period of 6 May 1998–18 March 2004. A steady reduction in the magnitudes of the AMV error statistics for both wind types is observed in these time series. These improvements are reflective of the implementation of numerous advances made to the operational AMV production suite, some of which are described above. These positive trends are generally reflective of other global AMV processing centers.

Large gains in AMV quality and quantities have been realized in other national AMV processing centers as well. Perhaps the most dramatic improvement in AMV performance metrics over the past several years comes from the India Meteorological Department (IMD). Recent upgrades to the Indian Geostationary Multi-function Satellite (INSAT) AMV processing, primarily from improved image navigation routines, height assignment techniques, and quality control procedures, have resulted in AMV quality comparable to METEOSAT-derived AMVs (Khanna et al. 2000; Bhatia et al. 2002). Higher-density AMVs are now being produced by the Meteorological Satellite Center (MSC) of the JMA. Tokuno (1998) and Kumabe et al. (2002) have shown that the upgrades to the MSC JMA AMV processing system have resulted in considerable improvements in AMV coverage and quality derived from the GMS satellite (now replaced with *GOES-9*). Even greater AMV capabilities are expected after the launch of the new Multi-functional Transport Satellite (MTSAT) series in the 2004–2005 time frame. The Bureau of Meteorology in Australia is now locally producing high-density multispectral AMVs that are being ingested into their regional models (LeMarshall et al. 2002). The impact of these AMVs has been very positive on NWP forecasts. AMV derivation has been attempted by the National Satellite Meteorological Center of the China Meteorological Agency (Xu et al. 2000), despite initial difficulties with the Feng Yun 2 (FY-2) satellite. Good results are expected after FY-2C is launched in late 2004. Finally, as a national backup to NESDIS, the U.S. Air Force Weather Agency (AFWA) is now producing global AMVs from multiple satellites based on automated tracking software using the latest advances provided by CIMSS.

Recent upgrades in satellite sensor capabilities are also providing new opportunities for improved AMV derivation. For example, changes made to the GOES imagers include the addition of the 13.3-μm channel that is allowing the use of the well-known CO_2 slicing algorithm (Menzel et al. 1983) to better assign heights to viable cloud tracers. The resultant CO_2 slicing algorithm height assignments supplement those provided by the water vapor intercept algorithm (Schmetz and

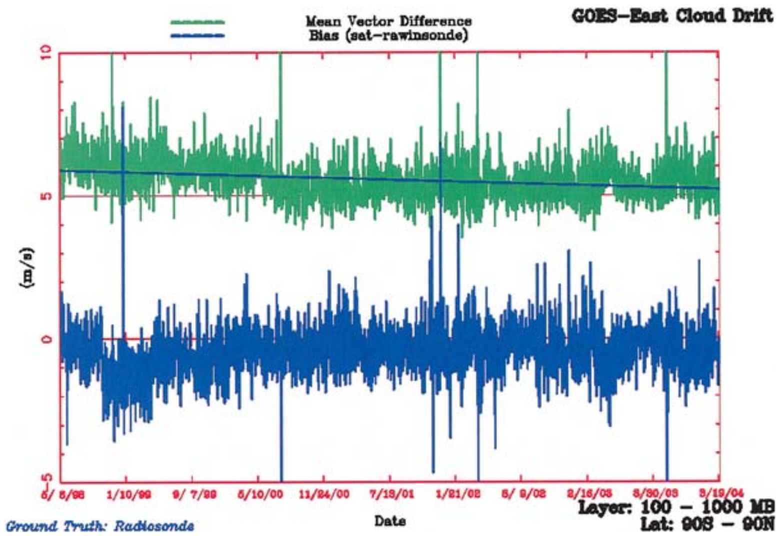

FIG. 10. Mean vector difference (green) and speed bias (blue, satellite – rawinsonde) for *GOES-8/-12* upper-level (100–400 hPa) IR cloud-drift winds for the period 6 May 1998–18 Mar 2004 (*GOES-12* statistics began in April 2003).

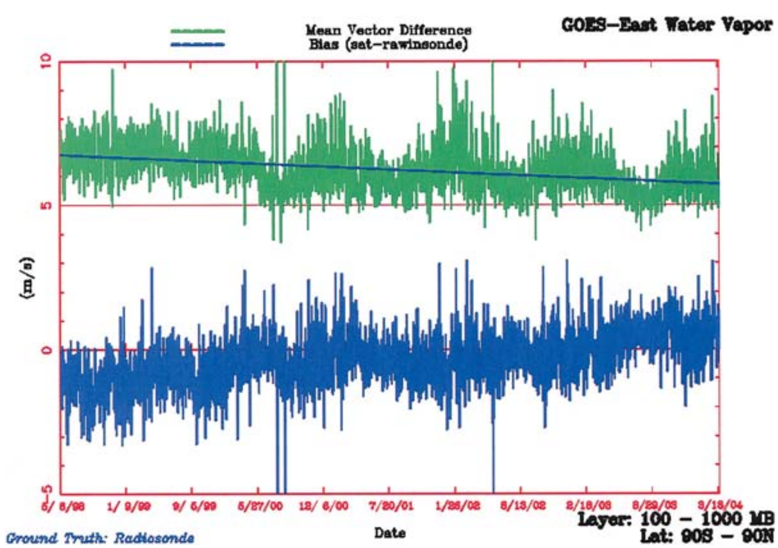

FIG. 11. Mean vector difference (green) and speed bias (blue, satellite – rawinsonde) for *GOES-8/-12* upper-level (100–400 hPa) water vapor winds for the period 6 May 1998–18 Mar 2004 (*GOES-12* statistics began in Apr 2003).

Holmlund 1992). Also, the finer resolution (4 km) in the current GOES WV channel (now similar to the Meteosat series) is contributing to an improved water vapor wind product.

Meteosat Second Generation (MSG) is the newest in a series of the European Space Agency's geosynchronous meteorological satellites (Schmetz et al. 2002). MSG is providing full-disk imagery every 15 min, and represents a major step forward in geostationary imaging capabilities. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) is an imaging radiometer, which is the main element of the MSG satellite. It scans the Earth using spectral bands that can provide daylight images and surface/tropospheric thermal information. SEVIRI observes the earth with improved performance over its Meteosat predecessors, and is particularly beneficial to meteorological "nowcasters." The design incorporates many new features, which is providing state-of-the-art pointing accuracy and simultaneous, precise multispectral radiometry. Its operating principle is based on collecting radiation from a scene and focusing it on detectors sensitive to 12 different bands of the electromagnetic spectrum. Figure 12 presents a segment of the electromagnetic spectrum as observed at the top of the atmosphere together with the infrared spectral band coverage provided by the MSG SEVIRI instrument. For comparison, the spectral bands of the *GOES-12* sounder and imager are presented as well.

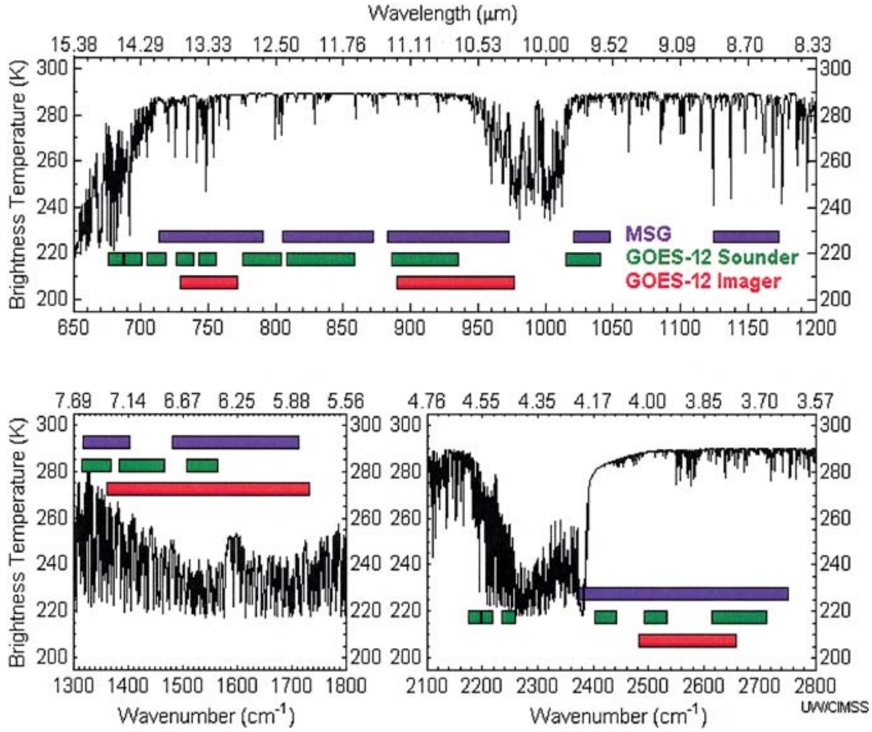

Fig. 12. A segment of the electromagnetic spectrum as observed at the top of the atmosphere together with the infrared spectral band coverage of the MSG SEVIRI instrument. For comparison, the spectral coverage of the *GOES-12* sounder/imager is also shown.

AMV extraction from MSG is benefiting from the extra spectral information provided by SEVIRI (Borde et al. 2004). The product suite includes all of the traditional elements of the contemporary Meteosat satellites, but also incorporates the additional SEVIRI WV channel centered at 7.3 μm. The AMV fields can be derived continuously (every 15 min), however, the current baseline is that a final product is extracted and disseminated once every hour. Of special interest is the high-resolution VIS (HRVIS) channel that is enabling the production of high-quality low-level wind fields. The HRVIS winds product is derived from the EUMETSAT's Satellite Applications Facility (SAF) in support of nowcasting (NWC)/MSG software package. With respect to the utilization of the new ozone channel centered at 9.7 μm, there is currently little experience in producing AMVs. However, this channel could potentially provide important information on lower-stratospheric flow patterns above the tropopause. The main problems associated with deriving AMVs from this channel are the difficulties in deducing total ozone information when cold clouds are present (hence, limiting its use to regions free of high cloud), and the assignment of reliable AMV heights. It is foreseen that ozone channel AMVs may become available when a complete validation and assessment of their quality has been performed.

Dissemination of the geostationary satellite AMV products to users is another key issue with regard to realizing user impacts from improvements in processing. In addition to transmitting the AMV products over the Global Telecommunications System, major AMV processing centers are now also encoding the AMV information into WMO-sanctioned Binary Universal Form for the Representation (BUFR) of meteorological data. This file format allows for additional data descriptors, which can be interrogated by AMV users to better integrate the information into analyses and data assimilation systems. MSG BUFR AMV bulletins are available on EUMETSAT's alternative dissemination service, EUMETCast. Finally, NESDIS is now disseminating the operational GOES AMVs to the NOAA/NWS Advanced Weather Interactive Processing System (AWIPS; Seguin 2002). This represents a significant milestone for NOAA, because this is the first time these products will be distributed via an operationally supported network to NWS field forecast offices. Once at the NWS field forecast offices, weather forecasters can use existing AWIPS graphics capabilities to easily integrate these products with other data sources (model output, rawinsondes, aircraft reports).

In addition to the traditional method of tracking features from successive geostationary satellite images, another method for estimating winds from satellites is to measure the temperature and moisture fields and then use dynamical constraints to determine the horizontal flow. This approach is only valid in flow regimes where the hydrostatic approximation can be applied in the vertical and a suitable balance exists between the pressure and wind in the horizontal. The hydrostatic approximation is fairly accurate for horizontal scales of motion larger than 10–20 km. Some examples of a balance between the pressure and wind are the geostrophic approximation, which is valid for synoptic-scale flow, and the gradient wind, which is valid for flows with a high degree of circular symmetry. The nonlinear balance equation can also be solved to determine the horizontal wind field from the pressure field and provides a more accurate estimate than the geostrophic equation. This method for wind estimation is being applied to the soundings from AMSU on the NOAA polar-orbiting satellite series to deduce wind fields in tropical cyclones. The technique provides a reasonable estimate of the outer wind profile and the upper-level anticyclone (Demuth et al. 2004). In another study, Zou and vanWoert (2002) apply a thermal wind approach to Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) retrievals to derive winds over the polar regions.

Satellite remote sensing of ocean surface wind vectors has evolved considerably over the past decade (Liu 2002). Wind speed–only retrievals were first derived from the *Earth Resources Satellite* (*ERS*)*-1*/*-2*, and are now available on a routine basis from the SSM/I aboard the Defense Meteorological Satellite Program (DMSP) series that was first launched in 1987. More recently, NASA launched the QuikSCAT mission in July 1999. The scatterometer aboard QuikSCAT provides 25-km-resolution wind vector retrievals over 90% of the ice-free ocean on a daily basis. Since March 2000, QuikSCAT has been producing near-real-time ocean vector wind retrievals that have been available to the operational forecasting and data assimilation communities. Utilization of this data has become routine worldwide, especially by forecasters with marine responsibilities. Satellite missions planned over the next several years promise continuity of ocean surface wind data. Looking further ahead, the U.S. military and civilian operational environmental polar orbiting satellites are being merged into NPOESS, and the first satellite is scheduled for availability in 2008. EUMETSAT plans to put a C-band scatterometer [Advanced Scatterometer (ASCAT)] on the Meteorological Operational (METOP) satellites in 2006 (Figa-Saldana et al. 2002). While there promises to be a variety of microwave sensors operating at different frequencies using different measurement methodologies over the next decade, most will ultimately provide ocean surface wind vectors as a product.

Some other recent applications of AMV. The abundance of recent studies regarding AMVs is too numerous to cover here. However, a few notable studies can be highlighted to illustrate the diverse applications of AMVs. Readers are advised to peruse the IWW proceedings (the reader will find information on these proceedings in the references) for a more complete sample.

While AMVs are prone to greater uncertainty than balloon wind measurements, they have recently been shown to improve numerical analyses and forecasts over ocean areas (Goerss et al. 1998; Langland et al. 1999; Soden et al. 2001; Xiao et al. 2002; Kelly 2004). These data impact studies show the utility of AMVs in helping to resolve meteorological events on scales ranging from large to subsynoptic. The greatest impact appears to occur over the Southern Hemisphere and Tropics (e.g., Fig. 2). This is not too surprising given that the Southern Hemisphere is dominated by ocean (less conventional type observations), and the Tropics are characterized by frequent mass/wind imbalance (divergent flow), so that satellite radiances alone are not sufficient. Global NWP center monitoring statistics show, however, that the AMV impact on large-scale analysis and forecasts are much less in the Northern Hemisphere, and particularly over landmasses with high-density rawinsonde coverage. However, a recent study by Zapotocny et al. (2005) shows surprisingly strong positive impact of GOES AMVs on the Eta regional model (Rogers et al. 1996) forecasts over a predominantly North American domain.

In order to explore the use of AMVs in mesoscale applications over land, an automated method for calculating frequent water vapor wind fields is being applied to GOES imagery (Rabin et al. 2004). A new set of winds is computed every 30 min. These wind fields are being made available on an experimental basis to the NOAA Storm Prediction Center. The quality control of the AMV process is tuned to allow more significant deviations from the model guess field than the operational production methods that generally assess larger scales. This allows the detection of perturbed flow aloft due to thunderstorms and other small-scale features that are not correctly captured by forecast models. It has been found that analyses derived from these AMVs are important in resolving upper-level divergence and vorticity fields with superior temporal and spatial resolution than is possible from most other observational sources. Upper-level divergence patterns can be useful in diagnosing areas of vertical air motion prior to possible convective development, especially when synoptic-scale forcing and surface fronts are lacking. In addition, the AMVs capture the divergence that develops as a consequence of storm updrafts and can be useful in diagnosing the areal extent and updraft intensity of storm clusters. Similar positive impact results were found by Cram et al. (2001), using a four-dimensional data assimilation system coupled with a mesoscale model. Their results of data sensitivity tests indicate a small, but consistent, positive impact on the short-term mesoscale forecasts when the GOES AMVs are assimilated.

CIMSS began demonstrating a new, specialized, real-time GOES low-level AMV product focused in the vicinity of tropical cyclones during the 1997 hurricane season. The AMVs are generated using a combination of the GOES visible and 3.9-μm shortwave infrared channels to provide continuous coverage of the tropical cyclone environment. The low-level winds are extrapolated to the surface using techniques described by Dunion and Velden (2002b) and provide valuable surface wind coverage in the periphery of tropical cyclones where conventional in situ observations [e.g. ships, buoys, and Coastal Marine Automated Network (CMAN) stations] are often widely spaced and low-level reconnaissance aircraft do not normally fly. These surface-adjusted AMVs are produced routinely in the western Atlantic and eastern Pacific tropical cyclone basins. Since 2000, the data have been included into the NOAA Hurricane Research Division (HRD) real-time tropical cyclone surface wind analyses (H*Wind; Powell et al. 1998). The H*Wind analyses are provided to tropical cyclone forecasters and other users. The inclusion of the surface-adjusted AMV in the H*Wind analyses has been shown to improve the estimation of the 34-kt (17.5 m s^{-1}) surface wind radii and can help define the 50-kt (26 m s^{-1}) wind radii in some hurricane cases (Dunion et al. 2002).

Pending advances. A series of observing system simulation experiments (OSSEs) have been conducted at the NASA GMAO in order to determine the potential impact of space-based lidar wind profiles in current data assimilation/numerical weather prediction systems and to evaluate trade-offs in lidar instrument design (Masutani et al. 2002; Atlas 2003). The lidar has the ability to sense vertical wind profiles, which is a marked advantage over currently available techniques (Baker et al. 1995; Marseille and Stoffelen 2003). The results of this evaluation show a very substantial improvement in forecast accuracy resulting from the assimilation of simulated space-based lidar winds. Based on promising results such as these, it is expected that demonstrational space-based wind lidars will be launched on polar-orbiting satellites in this decade. The Atmospheric Dynamics Mission (ADM) Aeolus of the European Space Agency (ESA) will be the first space-based lidar mission to sense the global wind field from space. It is based on an incoherent nonscanning Doppler lidar operating at 355 nm with a two-interferometer receiver for aerosol and molecular return. The launch is planned for October 2007 and the nominal operation time is 3 yr. An airborne instrument demonstrator is under development for ground and airborne campaigns envisaged in the years 2005 and 2006 (Reitebuch et al. 2001, 2003).

In preparation for the launch of hyperspectral imagers/sounders (thousands of spectral channels) in geosynchronous orbit over the next decade, research and development activities have begun using simulated datasets, and aircraft high-spectral-resolution datasets from the Scanning High Resolution Interferometer Sounder (S-HIS) and the NPOESS Airborne Sounder Testbed-Interferometer (NAST-I). The aircraft measurements along with radiative transfer calculations allow the construction of simulated datasets to support these activities. The hyperspectral data will foster in a new approach for retrieving winds from geosynchronous satellites. The current AMVs derived from water vapor channels only provide limited clear-sky information in the upper troposphere. The new measurement concept for "altitude resolved" AMV from hyperspectral measurements should provide the needed vertical resolution to provide vertical profiles of wind velocity.

Specifically, an algorithm to derive clear-sky, altitude-resolved AMV is being developed and evaluated using simulated hyperspectral data (Velden et al. 2004). The simulated datasets are based on the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument (Smith et al. 2000). The method utilizes the same basic automated tracking code developed at CIMSS, however, the input to the algorithm is in the form of constant-level moisture analyses derived from the hyperspectral sounding information. In clear-sky regions, vertical profiles of moisture can be derived from the simulated multiple GIFTS water vapor sensing channels [it has already been extensively demonstrated through GIFTS aircraft experiments how well these moisture features can be depicted (Smith et al. 2000)]. Data cubes are processed and merged into three-dimensional analyses of moisture variables. Sequences of retrieved water vapor fields (such as constant-pressure mixing ratio analyses) then become the "imagery" for tracking winds. Because the moisture fields will already be analyzed to constant pressure surfaces by the retrieval, the heights of the wind vectors will be predetermined. The height assignment error that contemporary AMVs suffer should be minimized, and improved WV-tracked winds should result. Furthermore, the hyperspectral information allows analyses of moisture at multiple vertical levels, which can then be used to attempt winds tracking to create vertical profiles of wind.

These new concepts have been demonstrated by first examining simulated hyperspectral datasets (Fig. 13), and also on one case of real data from airborne observations provided by the NAST-I instrument. The AMV coverage in Fig. 13 derived from the simulated GIFTS shows the density and vertical profiles that can be achieved. The results from the NAST-I case (not shown) indicate good agreement with a Doppler wind lidar that was also flown on the aircraft, and nearby rawinsondes (Velden et al. 2004). From these first attempts, the "proof of concept" has been successfully demonstrated. Furthermore, this concept will be tested using retrievals of moisture fields from successive passes of the AIRS instrument over polar regions. This new methodology to retrieve wind profiles from satellites in cloud-free areas could become a new standard in regions where geosynchronous satellite hyperspectral observations are available.

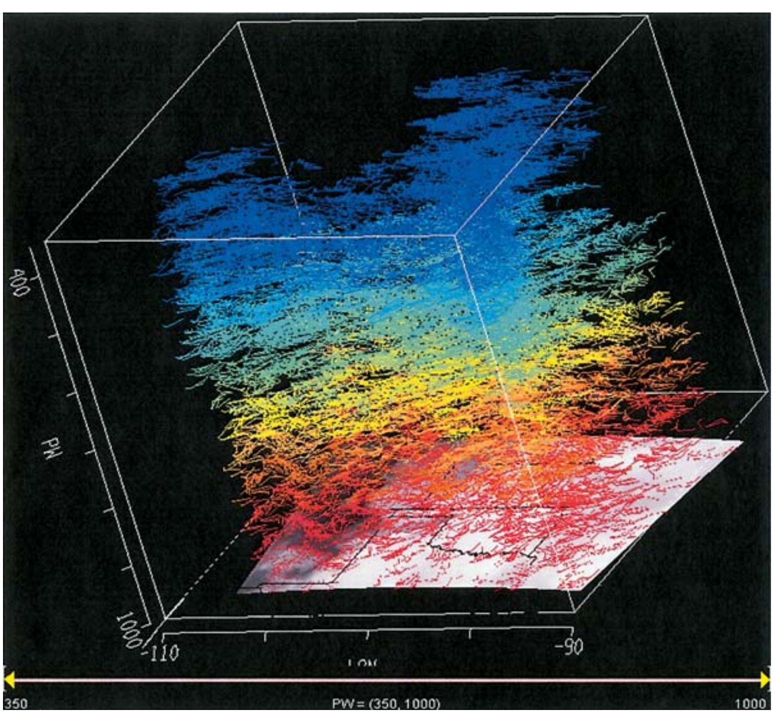

Fig. 13. VisAD display [latitude–longitude–altitude (hPa) cube] of simulated GIFTS winds illustrates the data density and vertical distribution that could be achievable from hyperspectral sounders of the future.

SUMMARY. The scientific community working on the retrieval of tropospheric winds from meteorological satellites recognizes the importance of steadily improving AMV observational quality so that the data make a positive contribution to advancing data assimilation and forecast systems. In order to keep pace with these demands, innovative research toward improving ways of deriving winds from satellites has been a focus of the World Meteorological Organization and Coordination Group for Meteorological Satellites cosponsored International Winds Workshops. These workshops are held every 2 yr, and bring together AMV researchers from around the world to present new, innovative ideas on AMV extraction techniques, interpretation, and applications. The NWP community is always well represented at these workshops and provides an important exchange of information on the latest in data assimilation issues.

The studies described here mostly draw from recent IWWs, and represent just a small sample of the new innovations in satellite-produced wind technologies, derivation methodologies, and products that have recently become available. The AMV data processing community is continuing to progress in all of these areas, and is looking forward to pending new opportunities with emerging advanced sensor technologies.

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