

WindSat polarimetric microwave observations improve southern hemisphere numerical weather prediction

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WindSat was launched in 2003 and is the first satellite-borne fully polarimetric microwave radiometer (Gaiser et al. 2004). This is an early report indicating the potential benefit of polarimetric microwave observations from this instrument. Initial studies examining the impact of WindSat polarimetric microwave observations when assimilated into a version of the National Centers for Environmental Prediction's (NCEP) Operational Global Data Assimilation System have been completed. The studies were designed to quantify the utility of these data for operational numerical weather prediction (NWP). The initial studies involved the use of WindSat Version-2 wind vectors generated at the Naval Research Laboratory (NRL). The utility of the vectors has been assessed in terms of the assimilation methodology, data thinning, quality control and their benefit to the operational forecast system. Their impact has also been compared to that of data from the QuikSCAT polar-orbiting satellite.

In these initial studies for the period 1 January to 15 February 2004, forecasts using the operational database (January 2004) plus WindSat wind vectors showed a modest positive impact compared to using only the operational database in forecasts out to five days. It should be noted however that the control in these studies used the full operational database including QuikSCAT data, which cover much of the area observed by WindSat for each analysis period. Over the southern hemisphere, for this study period, the impact of WindSat data in the operational database without QuikSCAT data was also recorded and shown to be of less benefit than that from the inclusion of QuikSCAT data in the operational database.

Introduction

Measurement of global ocean surface-wind vectors is important for short and medium-term weather fore-

casting, ocean forecasting, issuing of timely warnings, and the climate record. As a result, WindSat, a space-based multifrequency polarimetric microwave radiometer (Gaiser et al. 2004), was developed by the Naval Research Laboratory for the US Navy and the

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National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO). It was designed to demonstrate the capability of polarimetric microwave radiometry to measure ocean surface-wind vectors from space. Similar technology was planned for the NPOESS Conical Microwave Imager/Sounder instrument (CMIS). The Coriolis/WindSat satellite was launched on 6 January 2003 into a 98.7° inclined orbit at an altitude of 830 km. It was designed for a three-year lifetime.

The WindSat radiometer

The WindSat radiometer has polarimetric channels at 10.7, 18.7 and 37.0 GHz and dual-polarisation (vertical and horizontal) channels at 6.8 and 23.8 GHz. These provide information related to surface wind vectors as well as sea-surface temperature (SST), atmospheric water vapour, integrated cloud liquid-water and rain rate over the ocean. Measurements of the modified Stokes vector, which includes the vertical and horizontal polarisations and the third and fourth Stokes parameters, provides sufficient information to retrieve the ocean surface-wind vector (Bettenhausen et al. 2006). The 6.8 GHz dual-polarised channel is more sensitive to SST than to winds and is used to determine effects due to variations in SST. Similarly, the 23.8 GHz dual-polarised channel is highly sensitive to atmospheric water vapour. Consequently, measurements at 23.8 GHz help determine the effects of atmospheric attenuation on radiation from the ocean surface. The WindSat instrument characteristics are summarised in Table 1.

The Coriolis/WindSat satellite provides global coverage with a repeat cycle of eight days and a 1025 km swath width. The winds have a nominal horizontal resolution of 25 km. It is of note that the proposed CMIS had a swath width of 1700 km.

For comparison, QuikSCAT/Sea-Winds Scatterometer provides global coverage with a repeat cycle of 41 days and a 1800 km swath width. The QuikSCAT winds have a horizontal resolution of 25 km.

The ocean surface-wind vectors used in this study have been determined using a non-linear iterative optimal estimation method (Rogers 2000). The method also provides SST, total water vapour, and cloud liquid water. Details of the scheme, which uses a one-layer atmospheric model and a sea-surface emissivity model, may be found in Bettenhausen et al. (2006). The Environmental Data Records (EDRs) generated by this scheme have been put into Binary Universal Form for the Representation of meteorological data (BUFR) format at NCEP in preparation for operational use. The characteristics of the WindSat (and QuikSCAT) wind vectors are described in Lee et al. (2006).

Data selection and thinning

In relation to data selection, the wind vector ambiguity issue was addressed by selecting the WindSat wind vector closest to the NCEP model wind field that was used in the ambiguity selection routine when generating the EDRs. This ambiguity removal method was adopted for Version-2 of the NRL EDRs after some preliminary validation and discussion with the NRL data producers. This approach is expected to change with the next version of the wind-generation algorithm, which has more skill in selecting the correct ambiguities and less dependence on the model fields. Use of the model first-guess fields for data selection, however, is not unusual in meteorological analysis and is used, for example, in the generation and quality control of satellite Atmospheric Motion Vectors.

Data thinning was achieved using a similar technique to that used operationally for QuikSCAT wind vectors, namely using super-obs. Tests were run to determine whether 1.0° or 0.5° latitude by longitude averaging boxes were more effective and it was found that the 1.0° boxes gave the best forecast result. In terms of quality control an accurate land-sea mask was used to eliminate any data that could be contaminated due to land effects. In addition the 'retrieval

Table 1. WindSat characteristics.

<i>Frequency (GHz)</i>	<i>Polarisation</i>	<i>Bandwidth (MHz)</i>	<i>Incidence Angle (deg)</i>	<i>Spatial Resolution (km)</i>
6.8	V, H	125	53.5	40x60
10.7	V, H, ±45, L, R	300	49.9	25x38
18.7	V, H, ±45, L, R	750	55.3	16x27
23.8	V, H	500	53.0	12x20
37.0	V, H, ±45, L, R	2000	53.0	8x13

status' of the EDRs used had to be flagged 'OK', and the 'confidence status' of the record had to indicate there were no problems in the retrieval process, including those caused by rain, ice or land contamination. A gross-error check of 6 m s^{-1} against the background field was also employed in selecting the data to be used. Information from M. Bettenhausen, A. Gaiser and J. Goerss (personal communications) assisted in the establishment of quality control criteria. The gross-error check was based on an examination of O-B statistics and reduces the number of super-obs by around two per cent. For comparison purposes, data thinning and assimilation methods for QuikSCAT are recorded in Yu and Gemill (2004).

Data assimilation

The effect of adding WindSat Version-2 wind vectors to the NCEP operational forecast system was gauged using a T254, 64-level version of the Global Forecast System (GFS) (Version, November 2005). Comprehensive documentation of the GFS was completed by the NCEP Development Division in 1988 and can be found online at <http://www.emc.ncep.noaa.gov/gmb/wd23ja/doc/web2/tocold1.html>. Subsequent model developments after completion of the above documentation have been summarised by Kanamitsu (1989), Kalnay et al. (1990), and Kanamitsu et al. (1991). More recent updates to the radiation, surface layer, vertical diffusion, gravity wave drag, convective precipitation, shallow convection and non-convective precipitation can be found at <http://sgi62.wwb.noaa.gov:8080/research/SONGYU/doc/physmrf1.html>. The most recent information about the GFS atmospheric model (2003) is in *NCEP Office Note No. 442* or online at <http://emc.ncep.noaa.gov/officenotes/newernotes/OF442.pdf>. A summary of GFS changes and references up to and past the dates of this study are available in an 'updates' log of changes online at http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html.

The analysis scheme is a three-dimensional variational (3DVAR) scheme cast in spectral space and is

referred to as the Spectral Statistical Interpolation (SSI) algorithm (Derber et al. 1991; Parrish and Derber 1992). With this type of analysis system, the incorporation of radiances directly in an analysis and assimilation system is practical. The analysis becomes a 3D retrieval of mass, momentum and moisture fields derived from all available data including the radiances. In October 1995 the direct use of clear and cloud-free satellite radiances in the construction of mass, momentum and moisture fields was first introduced (Caplan et al. 1997). The methodology for using the radiance data (including the bias correction, ozone analysis, skin temperature and quality control) are described in Derber and Wu (1998) with the latest upgrades described in Derber et al. (2003). The Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) described by Kleespies et al. (2004) has been incorporated into the SSI to improve radiance assimilation.

The satellite data used operationally with the NCEP Global Forecast System in 2004 is shown in Table 2. As a result, the impacts recorded in this paper are in comparison to a control, which uses data from about thirty satellite instruments.

In the first two experiments a control database was established which contained all operational data without QuikSCAT data. The forecast performance using the Control database was compared to that of the same database with QuikSCAT data, in a series of experiments to gauge the impact of QuikSCAT data over the southern hemisphere. In a second experiment, forecasts from the control database were compared to those generated using the Control database plus WindSat data. In a final series of experiments, forecasts from the full operational database (which included QuikSCAT data) were compared to forecasts using the full operational database plus WindSat data.

The forecasts

In these experiments, the NCEP operational forecast system (Version, November 2005) was run from 1

Table 2. The satellite data used operationally within the NCEP GFS in 2004.

HIRS sounder radiances	TRMM precipitation rates
AMSU-A sounder radiances	ERS-2 ocean surface-wind vectors
AMSU-B sounder radiances	Quikscat ocean surface-wind vectors
GOES sounder radiances	AVHRR SST
GOES, Meteosat	AVHRR vegetation fraction
atmospheric motion vectors	AVHRR surface type
GOES precipitation rate	Multi-satellite snow cover
SSM/I ocean surface wind speeds	Multi-satellite sea ice
SSM/I precipitation rates	SBUV/2 ozone profile and total ozone

January to 15 February 2004. In the first series of experiments, forecasts from the control that contained the operational database without QuikSCAT data were compared with forecasts using the full operational database that contains QuikSCAT data. The results for this experiment are summarised in Fig. 1, where the 500 hPa geopotential height anomaly correlations for the control and the QuikSCAT runs are recorded. It can be seen, as in past studies (see, for example, Yu and Gemmill (2004)), QuikSCAT has had a positive influence on southern hemisphere forecasts for the NCEP system.

In a second series of experiments, (control) forecasts based on the operational database without QuikSCAT data were compared with forecasts from the operational system without QuikSCAT data, but with the addition of WindSat data (WindSat). It can be seen in these experiments (Fig. 2), the addition of WindSat data has had a positive overall impact on the forecast skill, but of lesser magnitude than that measured for QuikSCAT data.

In a final series of experiments, forecasts using the full operational database, which includes QuikSCAT data (Ops), were compared with those obtained from the operational database, including QuikSCAT data and with the addition of WindSat data (Ops+WindSat). It can be seen from the southern hemisphere 500 hPa geopotential height anomaly correlation curves shown in Fig. 3 that, for the period studied, WindSat has had a modest but positive impact on the forecast. The results for including WindSat data in the operational database for the northern hemisphere (Fig. 4) are similar to those for the southern hemisphere and are included here for completeness. The improvement in anomaly correlation of geopotential height at 1000 hPa for the southern hemisphere is quite small, and for the northern hemisphere, the results show small improvement.

The results from adding WindSat data to the operational database for the tropics (20° N to 20° S) are shown in Fig. 5, where an improvement in the 850 hPa anomaly correlation for the v -component of the wind can be seen. Improvements in anomaly correlation in the 850 hPa v -component of the wind field in the tropics from the use of scatterometer data have been recorded previously for QuikSCAT in Yu (2003).

Conclusions

This is an early report of the potential benefit of WindSat polarimetric data to operational numerical weather forecasting. For the period 1 January to 15 February 2004, the impact of WindSat surface wind vectors (NRL, Version-2 EDRs), obtained from

Fig. 1 The 500 hPa geopotential height anomaly correlations versus forecast period for GFS forecasts using the operational database without QuikSCAT data (control) and using the operational database including QuikSCAT data (QuikSCAT) over the southern hemisphere.

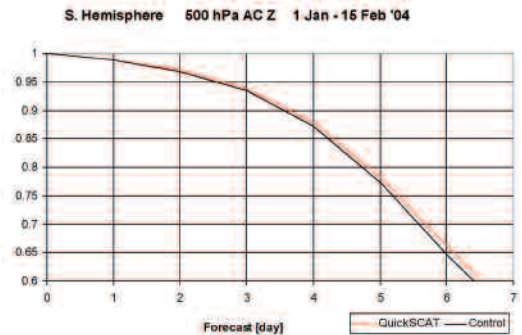
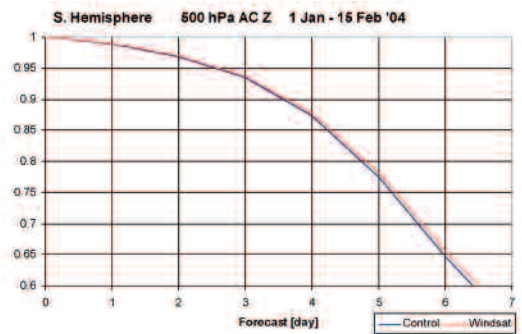


Fig. 2 The 500 hPa geopotential-height anomaly correlations versus forecast period for GFS forecasts using the operational database without QuikSCAT data (control) and using the operational database without QuikSCAT data but with WindSat data (WindSat) over the southern hemisphere.



polarimetric microwave radiometer observations, on the NCEP operational forecast system has been assessed. It was found, for the period studied, and over the southern hemisphere, that the WindSat data had a positive impact on the Global Forecast System when added to the full operational database without QuikSCAT data. It was also found, for the same period and domain, that the WindSat data had a modest positive impact when added to the full operational database that includes QuikSCAT data. The impact of

Fig. 3 The 500 hPa geopotential-height anomaly correlation versus forecast period for GFS forecasts using the operational database with QuikSCAT data (Ops) and for the operational database with QuikSCAT data and WindSat data (Ops + WindSat) over the southern hemisphere.

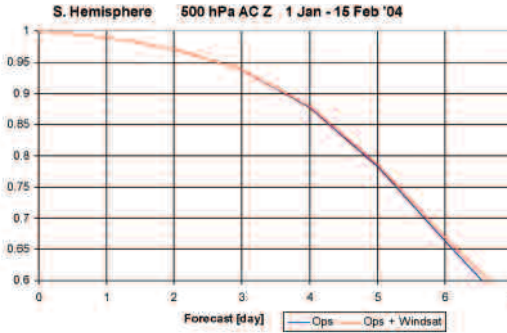
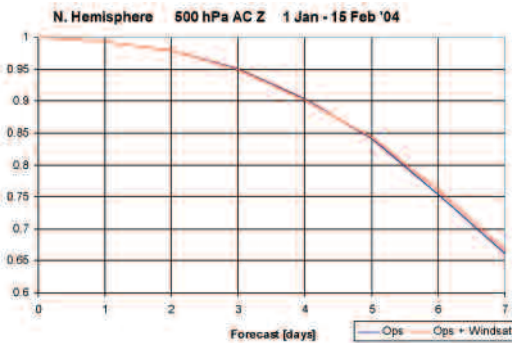


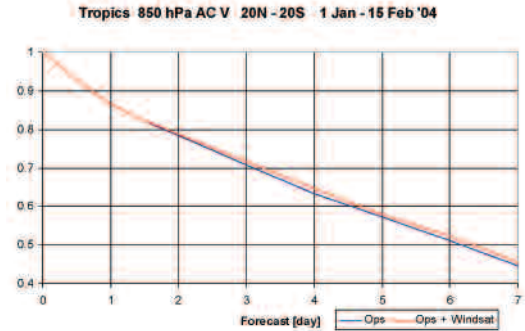
Fig. 4 The 500 hPa geopotential-height anomaly correlation versus forecast period for GFS forecasts using the operational database with QuikSCAT data (Ops) and for the operational database with QuikSCAT data and WindSat data (Ops + WindSat) over the northern hemisphere.



WindSat data was not as large as that of QuikSCAT; however, it was also found that WindSat and QuikSCAT together had larger impact than either by themselves. For completeness the small improvement to northern hemisphere GFS forecasts in this study from including WindSat data in the operational database was also shown.

In conclusion, the potential benefit of using polarimetric microwave observations to estimate surface-wind vectors for operational application in the south-

Fig. 5 The 850 hPa v-component of wind anomaly correlation versus forecasts using the operational database with QuikSCAT data (Ops) and for the operational database with QuikSCAT data and WindSat data (Ops + WindSat) over the tropics (20°N to 20°S).



ern hemisphere has been shown. These sea-surface vectors could be estimated through a space-based imaging and sounding payload with polarimetric capability such as the previously proposed Conical Microwave Imager/Sounder. This polarimetric information is not available through current microwave imagers and sounders (other than WindSat); however some current instruments do enable surface wind speed estimates (e.g., in the case of the Spectral Sensor Microwave/Imager (SSM/I)) for operational analysis and forecasting. In terms of future directions for these studies, a real-time experiment during the northern hemisphere autumn and winter is underway. Later this will use wind vectors generated with newer algorithms that are less dependent on the model first-guess fields. An experiment involving the direct assimilation of radiances is also planned. It is anticipated these studies will allow these data to be transitioned to operational use for the JCSDA Partners. In the short term, it is also worth noting that, while the WindSat data used in this study did not provide as large a skill improvement (or data coverage, given its smaller swath width) as QuikSCAT, and only provides marginal skill improvement when combined with QuikSCAT, the data would be valuable as a replacement if QuikSCAT fails.

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