An Evaluation of the Potential of Polarimetric Radiometry for Numerical Weather Prediction Using QuikSCAT

Stephen J. English, Brett Candy, Adrian Jupp, David Bebbington, Steve Smith, and Anthony Holt

***Abstract*—It has been proposed that wind vector information derived from passive microwave radiometry may provide an impact on numerical weather forecasts of similar magnitude to that achieved by scatterometers. Polarimetric radiometers have a lower sensitivity to wind direction than scatterometers at low wind speed but comparable sensitivity at high windspeed. In this paper, we describe an experiment which aimed to determine if an observing system only capable of providing wind direction information at wind speeds over 8 ms^{-1} can provide comparable impact to one providing wind vectors at wind speeds over 2 ms^{-1}. The QuikSCAT dataset used in the experiments has a wide swath and is used operationally by several forecast centers. The results confirm that assimilation of wind vectors from QuikSCAT only for wind speeds above 8 ms^{-1} gives similar analysis increments and forecast impacts to assimilating wind vectors at all wind speeds above 2 ms^{-1}. Measurements from the WindSat five frequency polarimetric radiometer are compared with calculations from Met Office global forecast fields, and this also confirms that WindSat measurement and radiative transfer model accuracy appears to be sufficiently good to provide useful information for numerical weather prediction.**

***Index Terms*—QuikSCAT assimilation, weather, WindSat.**

I. Introduction

NUMERICAL weather prediciton (NWP) requires an initial three-dimensional analysis of atmospheric temperature, humidity and wind. Satellite data from the Advanced Microwave Sounding Unit (AMSU) and Special Sensor Microwave Imager (SSM/I) have become a very important part of the global observing system for temperature and humidity. By contrast there is rather little satellite information on wind. In 2005, satellite information on wind can be obtained from three sources: surface winds (only) from active microwave (scatterometry), passive microwave (radiometry), and from atmospheric motion vectors (feature tracking), these corresponding to the altitude of the tracked feature. Ocean surface wind vectors derived from scatterometers have been used successfully for many years at NWP centers. Scatterometers have been available at C-band in near real time for data assimilation since the early 1990s, following the launch of the European Remote Sensing 1 (ERS-1) satellite. This record has been maintained by ERS-2. Since 1999 observations have also been available from the Ku-band Seawinds instrument on QuikSCAT. These spaceborne scatterometers, which measure radar backscatter from the ocean surface from at least two look directions, are used to produce high-quality ocean wind speed and direction retrievals. It has been demonstrated (Fig. 1) that the impact of ERS-2 wind vectors is comparable with SSM/I wind speeds even though ERS-2 has a much narrower swath than SSM/I. QuikSCAT also has a wide swath, comparable with that from radiometers such as SSM/I. Fig. 1 also shows that the impact is approximately additive between SSM/I wind speeds and scatterometer wind vectors (see [3] for details). Therefore, it is known that wind direction information does add skill to the forecast over and above that obtained from wind speed alone. The C-band scatterometers are almost insensitive to cloud and precipitation but Ku-band scatterometers do have a rain sensitivity.

Dual-polarized high incidence angle passive microwave data can provide surface wind speed (ocean-only) information. This utilizes the lack of sensitivity of vertically polarized measurements to surface wind speed between 10 and 100 GHz, in contrast to horizontally polarized brightness temperatures which increase rapidly as wind speed increases. Data from the single-look passive SSM/I microwave radiometer, which measures vertically and horizontally polarized brightness temperatures, is used operationally at many NWP centers to provide valuable ocean wind speed information over a relatively wide swath (1400 km), but cannot be used to derive instantaneous wind direction information. Comparison of SSM/I-derived wind speeds with buoy measurements has shown that a directional signal in measured brightness temperatures contributes to errors in wind speed retrievals [20]. Wentz went on to demonstrate that monthly averaged wind vectors could be derived from SSM/I data. It has been widely suggested [2], [4], [18], [20], [25] that a microwave radiometer similar to SSM/I but with the addition of polarimetric channels may be able to provide instantaneous wind vectors due to the additional information on the relative correlation of the vertically and horizontally polarized radiation from the wind-roughened ocean surface. However, the technology is still in its infancy, with the first experimental spaceborne instrument, the U.S. Navy's WindSat, launched in January 2003.

Manuscript received January 11, 2005; revised May 16, 2005. This work was supported in part by the European Space Agency under Grant CAO/CB/cb/02.1025.

S. J. English, B. Candy, and A. Jupp are with the U.K. Met Office, EX14 3HW Exeter, U.K. (e-mail: Stephen.English@metoffice.gov.uk).

D. Bebbington, S. Smith, and A. Holt are with the University of Essex, CO4 3SQ Colchester, U.K. (e-mail: david@essex.ac.uk).

Digital Object Identifier 10.1109/TGRS.2005.855998

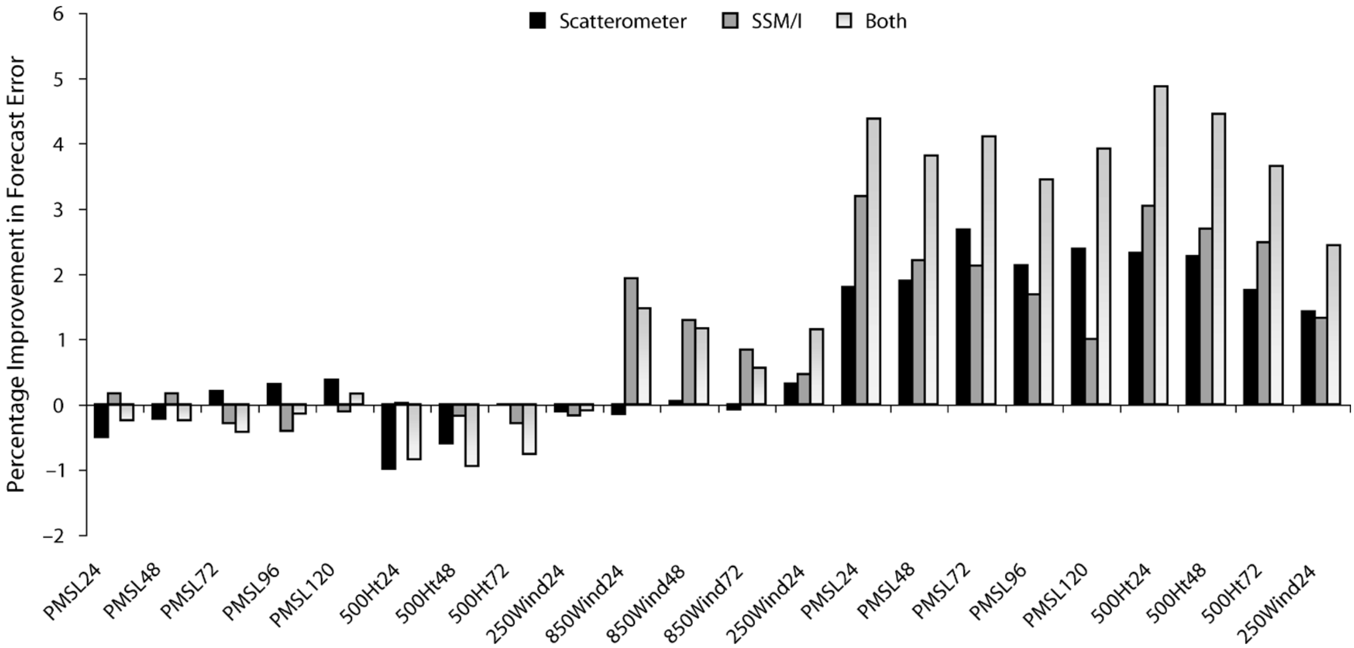

Fig. 1. Relative impact of SSM/I wind speed and ERS-2 scatterometer wind vector observations. Results are shown for the principal forecast parameters [PMSL (mean sea level pressure), 500-hPa height, and wind speeds at 250 850 hPa] at a range of forecast times out to five days.

II. Modeling the Sensitivity of Ocean Emissivity to Wind Speed and Direction

The microwave emission from an undisturbed ocean surface is highly polarized. The hydrodynamic processes associated with wind forcing alter the emissivity characteristics, tending to increase the emissivity while reducing the degree of polarization. The relationship between wind forcing and the emissivity has been long established using geometric optics (e.g., [21]). Using such models it is possible to analyze wind speed (e.g., [14]). To be able to obtain wind direction from ocean surface radiance measurements these models need to be extended to be fully polarimetric. This means the full Stokes vector must be measured. This comprises four real parameters, in the classical definition, I, Q, U, and V where I is the total intensity (or equivalently mean brightness temperature). $I = (T_h + T_v)/2$ expressed in terms of the brightness temperatures in the horizontal and vertical channels (or any orthogonal pair). The other three parameters can be measured as differences: $Q = (T_h - T_v)/2$, while U and V are differences between intensities resolved in $+45^\circ$ and -45° slant polarization, and left and right circular polarization, respectively. Unfortunately there is no single definition of V with some texts (e.g., Jackson's "Classical Electrodynamics" [8] defining V as the same sign as the helicity (projection of angular momentum along wave vector), and hence positive V+ is left handed; but another classic text, Born and Wolf "Principles of Optics" [1] assigns positive V to right hand. The WindSat convention is that positive V is left handed and that convention is used in this paper. U and V can be determined along with I and Q using a single dual-polarization (hv) feed if the complex correlation between the voltages can be measured. In the radiative transfer literature, modified Stokes parameters (e.g., [7]) are often defined, where T_h and T_v are used in place of I and Q. Coppo *et al.* [4] give a detailed account of the Stokes vector in the context of wind analysis from passive microwave radiometry.

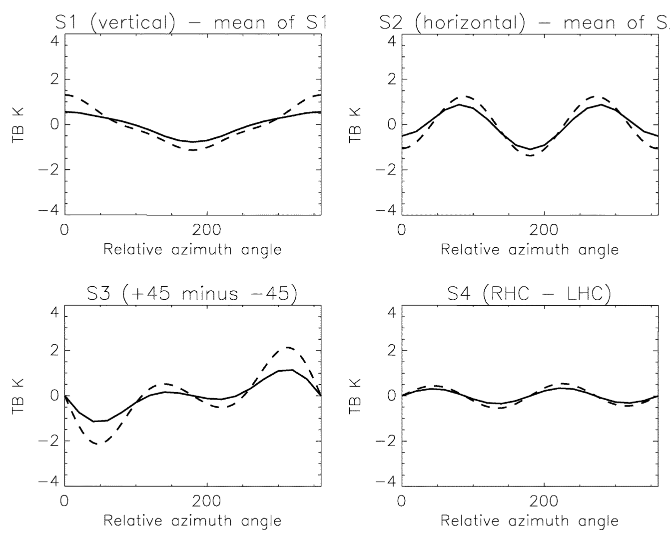

Fig. 2. Comparison of azimuthal brightness temperature dependence from (dashed line) the fast model of Liu and Weng and (continuous line) the model of Coppo. Frequency $=$ 37 GHz, wind speed $=$ 8.7 ms^{-1}, sea surface temperature $= 293$ K, view angle $= 55^\circ$. The four elements of the Stokes vector are labeled S1 (T_v), S2 (T_h), S3 (U), S4 (V), and in each case the mean across all relative azimuth angles is subtracted.

Coppo *et al.* [4] have also provided a physical two scale model solving the small scale scattering for anisotropic ocean surfaces based primarily on Yueh *et al.* [23] thus providing a sound physical model for comparison with faster models. Liu and Weng [11] have developed a fast model based on the model of St. Germain and Poe [16] which has been validated against aircraft data. Comparison of the Liu and Weng [11] and Coppo *et al.* [4] models is shown in Fig. 2 for the departure of the brightness temperature from the mean for a range of azimuth angles. There is a difference in the amplitude of the signal; it is already known that the size of this variation depends on sea surface temperature and wind speed. For the specific case of Fig. 2 the Liu model amplitude at 8.7 ms^{-1} is about 60% larger than that predicted by the Coppo model. This reflects current uncertainty in the size of the azimuthal response, an uncertainty which needs to be reduced to use polarimetric radiometer data effectively. Note that Yueh *et al.* [24] proved that the first two Stokes vectors are even and the third and fourth are odd functions of the azimuth angle so the only uncertainty between different models is the amplitude and the relationship of the amplitude to wind speed.

The individual modified Stokes parameters have different attenuation and emission characteristics. I is sensitive to both attenuation and emission, while Q, U, V are usually insensitive to atmospheric emission (an exception is in areas of precipitation) and $Q/I, U/I, V/I$ are insensitive to atmospheric attenuation (again in nonprecipitating areas). These considerations suggest that $Q, U,$ and V may provide more consistent and reliable ocean surface information in comparison to horizontal and vertical polarization measurements considered individually or added together.

Other geophysical parameters other than those directly associated with wind forcing may also affect the emissivity. These include sea surface temperature and salinity (through changes in the permittivity of sea water) and oil slicks. Although these parameters may affect absolute brightness temperatures, they are not expected to alter the polarization state of the radiation from the sea surface.

A considerable number of laboratory and aircraft studies have been performed in order to investigate the nature of the directional dependence of the Stokes parameters, together with any dependence on other geophysical parameters over a broad range of incidence angles. Some studies are briefly summarized to give an indication of the level of uncertainty in the radiative transfer models for polarimetric radiometers.

Aircraft experiments at incidence angles of 30°, 40°, and 50° measuring the first three Stokes parameters at 19.35 and 37 GHz performed off the coast of Oregon in 1993 and 1994 also confirmed the presence and predicted periodicities of wind direction signals in T_v, T_h, Q, and U, with off-nadir peak to peak magnitudes of several Kelvin [25]. However, experiments outlined in Van Woert *et al.* [19] showed that the directional dependence of T_V was altered at the same frequencies for an incidence angle of 65° in comparison to the response at 45° and 55°, showing a reduction in amplitude of the signal about the 0° (upwind) direction. The U directional signature also appears to shift from a $\sin 2\varphi$ toward a $\sin\varphi$ periodicity, indicating the increased importance of the first harmonics at larger incidence angles where the view of the ocean surface is more oblique. Furthermore, peak to peak amplitudes of the directional signals were also found to vary with incidence angle. T_V signals increased from 3 K amplitude at 45° to around 4 K at 65°. In contrast, U signal amplitudes decreased from 5 to 3.5 K.

Yueh *et al.* [25] found a correlation between transients observed in T_v and T_h data and the presence of clouds, whitecaps or foam. Because the emission from these sources is unpolarized, $T_v - T_h$ and U were found to be insensitive to the transient features since, for any increase in T_v, there will be a corresponding increase in T_h. This is an important illustration of the potential of polarimetric radiometers to reduce errors associated with rapid and anomalous changes in whitecap and foam coverage, together with that associated with cloud liquid water. Sensitivity to precipitation requires more thorough investigation.

Airborne experiments performed using the WINDRAD instrument in the 45° to 65° incidence angle range at 19 and 37 GHz have suggested that the wind direction signals present in T_V, T_h and U would exhibit only weak frequency dependence over this middle range of incidence angles [19] which are more relevant to a possible future spaceborne instrument. A number of studies comparing theoretical models have been carried out using both WINDRAD [22], [27], and the radiometer system flown by the Technical University of Denmark [9], [17]. In both cases models [25], [26] have shown good agreement with observations. [27] note some important discrepancies. Upwind downwind asymmetry is weaker in the observed data than the model. This was reconfirmed in the study by Meissner and Wentz [13]. The signal at 37 GHz is stronger than at 19 GHz. The azimuthal variations are negligible at low wind speeds, except for U at very high incidence angle, increasing for moderate wind speeds before leveling off and actually falling for very high wind speeds. Coefficients for an empirical model were presented by Yueh *et al.* [27], allowing an empirical alternative to the models of Coppo *et al.* [4] or Liu and Weng [10]. It has already been noted that other geophysical parameters may affect polarimetric wind retrievals. All airborne experiments performed thus far indicate that although absolute microwave brightness temperatures are dependent on sea surface temperature (SST), polarimetric wind direction signals are very similar in nature and amplitude for SSTs ranging from 6.5 °C to 26 °C.

In summary there remains uncertainty in the radiative transfer model simulations which will have a significant impact on the wind direction accuracy. Van Woert *et al.* [19] and Skou [18] suggest that in practical analysis combined observation and radiative transfer model errors of order 0.1 K are required to derive useful wind vectors.

III. Error Analysis for WindSat

By assuming a linear framework [5] it is possible to gain some insight into the wind direction analysis accuracy for different wind speeds within the data assimilation environment. To do this we need to make an assumption about observation error.

The analysis error [5] is given by

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \boldsymbol{H}^T.\mathbf{R}^{-1}.\boldsymbol{H}$$

where $\mathbf{B}$ is the background error covariance matrix for the state vector, $\mathbf{x}$ (i.e., it tells us what we already know about the state vector $\mathbf{x}$) and $\mathbf{R}$ is the error covariance matrix associated with the observations, $\mathbf{y_o}$ where $\mathbf{y} = \mathbf{H}(\mathbf{x})$. $\mathbf{R}$ contains errors both in the observations themselves and in the observation operator, $\mathbf{H}$, where simulated observations $\mathbf{y} = \mathbf{H}(\mathbf{x})$ and may therefore be significantly larger than the instrument noise equivalent delta temperature (the change in temperature that yields a signal-to-noise ratio of unity) and indeed larger than its calibration error. $\boldsymbol{H}$ is the gradient of the operator $\mathbf{H}$ evaluated at $\mathbf{x}$.

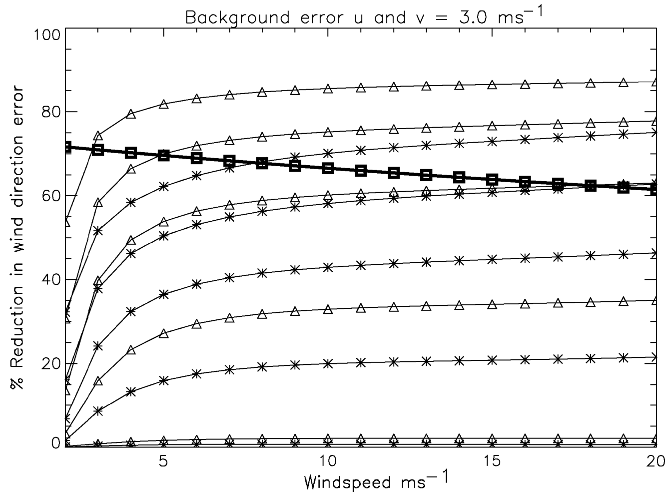

Fig. 3. Percentage reduction in wind direction error compared to background using linear error estimation theory. The arctic test profile of Saunders *et al.* [15] was used for cloud-free conditions. The triangles correspond to observation errors of 1.0, 0.5, 0.2, 0.1, and 0.05 K (in order lowest curve to highest curve) for a dual-look WindSat data analysis. The stars are the equivalent values for a single look. The thicker line is the currently assumed scatterometer impact, where it is assumed the scatterometer gives estimates of orthogonal components of wind direction with uncorrelated errors, and errors ranging from 0.7 ms^{-1} at 0 ms^{-1} to 2.0 ms^{-1} at 30 ms^{-1} in each orthogonal wind component.

T and -1 denote transpose and inverse matrix operations. $\mathbf{A}$ is the estimate of the analysis error for the linear problem.

An uncorrelated background error of 3 ms^{-1} for the two orthogonal wind vector components, 4 kg $\cdot$ m^{-2} for total column water vapor (here it is assumed we are only analyzing total column water vapor and not a profile), 0.3 kg $\cdot$ m^{-2} for cloud liquid water, and 2 K for surface temperature were assumed, and all error correlations were set to zero. No other quantities were included in the analysis. Observation errors of 2 K were assumed for the first two elements of the Stokes vector which is consistent with those used for the vertical and horizontal polarized channels in the assimilation of SSM/I at the Met Office. A range of possible observation errors were assumed for the third and fourth elements of the Stokes vector. For wind direction this is equivalent to doing an analysis primarily based on the third and fourth elements but weakly constrained by the first two elements. Most of the information in the first two elements of the Stokes vector will be used to improve the analysis of wind speed, total column water vapor and cloud liquid water. The gradient of the observation operator is computed using RTTOV-7 [15] with the addition of the gradient of the model of Liu and Weng [10] using coefficients derived from a set of runs of the model of Coppo *et al.* [4].

Linear error estimation theory was used to test the sensitivity of wind direction error to changes in observation error and number of views available. The improvement in wind direction information for various assumptions about WindSat and C-band scatterometer are shown in Fig. 3. The scatterometer and WindSat wind information content has been computed in exactly the same way. All observations errors are assumed uncorrelated. For the dual-view case, it was assumed that the scene was observed twice at two different relative azimuth angles, i.e., there were 32 spectral samples used in each one-dimensional analysis rather than 16.

For very low wind speeds (< 4 ms^{-1}) the wind direction information changes rapidly and very low errors in the third and fourth elements of the Stokes vector are required to match scatterometer performance. Between 4 and 8 ms^{-1} the linear analysis error changes less rapidly and at 8 ms^{-1} observation errors of $\sim$0.05 K (single view) and 0.1 K (dual view) would give comparable information to scatterometer. Above 8 ms^{-1}, the linear analysis error becomes less dependent on wind speed. The results in Fig. 3 are averaged across all relative azimuth angles and all WindSat scan positions and the information content does also depend on these quantities (i.e., some relative azimuth angles are more favored than others). It would be an interesting further study to examine in detail the variation of information content with scan position and relative azimuth angle under different assumptions of error (and correlated error), but such a detailed study is beyond the scope of this paper. As Fig. 3 is only valid for a linear error estimate it does not deal with any problems arising from the nonlinearity of the true observation operator. Fig. 3 does not identify a wind speed above which WindSat data is useful and below which it is useless. There is reduction in information with reduced wind speed which becomes rapid below about 4 ms^{-1}. To consider a threshold at which WindSat data are likely to be "useful" is therefore an unhelpful concept, but it is helpful to consider the relative value of high and low wind speed observations, as it is clear WindSat will be most effective at high wind speed and least effective at low windspeed.

The analysis does suggest that it is very likely that the sensitivity is good enough to give useful wind direction information above 10 ms^{-1} and equally likely it will not give useful information below 4 ms^{-1}. In the observation system experiments which follow QuikSCAT data above 8 ms^{-1} is used to give insight into the relative impact of wind vectors at high and low wind speed which can then tentatively be used to tell us about the potential of polarimetric radiometer data through the information in Fig. 3.

It should be noted that a rather high background error was assumed (3 ms^{-1} in both u and v wind components) and several components of error which are similar for QuikSCAT and WindSat are ignored (e.g., nonlinearity error, representivity error, ambiguity error, errors arising from correlated observation errors) and the theoretical error estimate also assumes an optimal system for a linear problem. Therefore, the absolute reduction in error is probably overestimated, but for the purpose of this paper it is the comparison of scatterometer and polarimetric radiometer which is important.

IV. WindSat

WindSat, the first experimental spaceborne polarimetric radiometer, was developed by the U.S. Naval Research Laboratory (NRL) [6]. It is a conical scanning, two look multichannel polarimetric radiometer, operating in a sun-synchronous orbit at 830 km altitude with an active swath of 1025 km. The instrument is fully polarimetric in the 10.7-, 18.7-, and 37.0-GHz channels, and dual polarimetric (vertical and horizontal polarizations) at 6.8 and 23.8 GHz. The fully polarimetric channels will be used primarily to investigate the potential of the technique for providing wind vector information, while the inclusion

TABLE I
OBSERVATION SYSTEM EXPERIMENTS FOR ASSESSING POTENTIAL OF POLARIMETRIC RADIOMETRY FOR NWP

Name of experiment	Description
AllWinds	Matches current operational use of QuikSCAT at the Met Office, using wind vectors in the range 2-25 ms^{-1}.
HighWinds	Uses wind vectors only for wind speeds above 8 ms^{-1}, simulating the information WindSat may provide.
LowWinds	Uses wind vectors only for wind speeds below 8 ms^{-1}.
NoWinds	Uses no QuikSCAT wind vectors

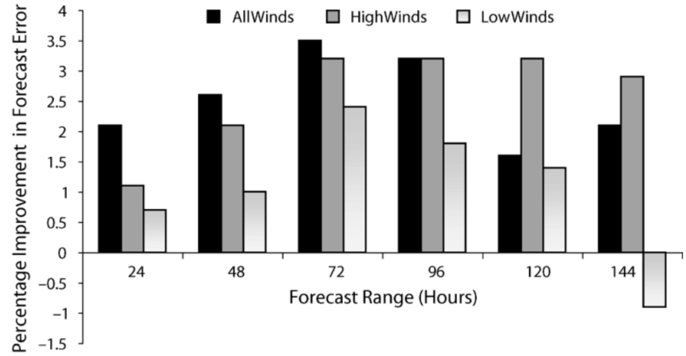

Fig. 4. Comparison of percentage reduction of mean sea level pressure forecast error against analysis for AllWinds, HighWinds, and LowWinds experiments against NoWinds control in the region 20° S to 90° S.

of a 23.8-GHz channel should provide information on the degree of water vapor contamination of a measurement. The 6.8-GHz channel will be used primarily for SST retrievals. The instrument was launched in January 2003.

The inclusion of fore and aft views for all channels is likely to be of use in calibrating the instrument, and will permit the comparison of wind retrievals obtained from single or two-look fully polarimetric measurements with those derived from two-look viewing geometry at dual polarization. This information could then inform the design of future operational passive microwave wind retrieval system.

Measurement of the full Stokes vector may be achieved by different approaches. Three separate feeds may be used to measure the vertical and horizontal, $\pm 45°$ slant linear, and right– and left-hand circular polarizations. This is the method employed by WindSat. This arrangement may mean that it is difficult to achieve the accuracy required for polarimetric wind retrievals, since a measurement error is associated with each feed, and combinations of measurements, each with their associated error will be required in order to calculate wind direction. However it had the advantage of using tried and tested technology and thus enabling a mission to be assembled and launched and operated successfully on a very rapid timescale.

V. IMPACT EXPERIMENTS

It has already been discussed that the greatest potential of polarimetric radiometry to provide information on wind direction is at high wind speeds. Scatterometers provide useful wind direction information at wind speeds as low as 2 ms^{-1}. For an instrument like WindSat, as has been discussed, this lower limit is likely to be between 4 and 8 ms^{-1}. To this end, a set of forecast impact experiments were run for four different choices of scatterometer wind assimilation, which are listed in Table I. QuikSCAT data are used for these experiments as it has an 1800-km swath (so gives good coverage). Scatterometer data have a proven positive impact on NWP [3]. Apart from the broader range of wind speeds for which valid wind vector retrievals are possible QuikSCAT has similar characteristics to polarimetric radiometer wind information (e.g., the ambiguity problem discussed in [3]). QuikSCAT level 2 wind vectors produced by NOAA/NESDIS were used in this study.

These experiments were run for the period May 12 to June 20, 2003 at a global model configuration of N144L38 (i.e., 38 levels, and a horizontal grid of 144 points east to west). The remainder of the system matched the Met Office operational global model configuration at the time [12] except that data from three ATOVS systems (NOAA15, 16, and 17) are used. Although the experiment was run at a lower resolution than normal operational forecasts this resolution is routinely used in the early stages of preoperational testing for the Met Office forecast system and is believed to give results which are consistent with those at full operational resolution. Note the system uses wind information from SSM/I (so has wind speed information globally in each cycle over the ocean). It also uses atmospheric motion wind vectors from geostationary satellites and conventional ship, buoy, sonde and aircraft winds. Forecasts up to six days ahead are produced once per day (at 12UTC).

Fig. 4 shows the reduction in forecast error of the three experiments (AllWinds, HighWinds, and LowWinds) compared to a control using no scatterometer winds (NoWinds). Fig. 4 shows that both the HighWinds and LowWinds experiments added skill compared to the NoWinds experiment at a stastically significant level, the error bar being about 1% for a day one forecast rising to 3% at 3 days and 7% for a day 6 forecast (for this trial, i.e., 40 days, 1 forecast per day). The results at days 1–4 are therefore statistically significant. They suggest polarimetric wind information is likely to be useful at day 2 and beyond (in the extra-tropics), assuming accuracy is sufficient to provide wind vectors of comparable quality to scatterometer at wind speeds above 8 ms^{-1}. Furthermore the impact of the HighWinds and AllWinds experiments was comparable except for the 24-hour forecast. This suggests a stronger statement can be made: that an instrument only capable of providing wind vectors at high wind speed is likely to have only marginally less value in the extra-tropics that an instrument providing wind vectors from 2–25 ms^{-1} except at short range (day 1 of the forecast). It can also be noted that in these experiments the assimilation of scatterometer winds below 8 ms^{-1} actually gave a small negative impact at $T + 144$ and indeed at both $T + 120$ and $T + 144$ the most skilful forecasts arise from those using scatterometer data only for wind speeds above 8 ms^{-1}. The reason for this is not known. This result may suggest that some aspect of the assimilation of low wind speed wind vectors from QuikSCAT is suboptimal in the Met Office system although the sample size (40 days) is small so the differences at $T + 120$ and $T + 144$ are not statistically significant.

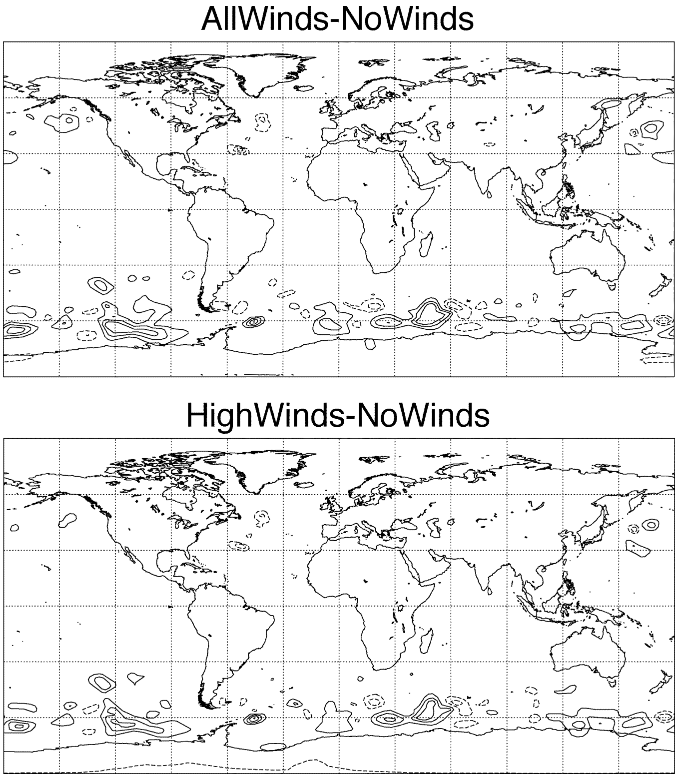

Fig. 5. Difference in mean sea level pressure analysis increments in the HighWinds and AllWinds experiments compared to those in the NoWinds control experiment. The contour interval is 0.2 hPa, and continuous contours denote positive increments and dashed contours negative increments.

In addition to studying the forecast impact it is also useful to compare the changes the assimilation makes to the analysis for the HighWinds and AllWinds experiments. These are shown in Fig. 5. The analysis increment patterns look remarkably similar in both experiments with only subtle differences in size of the increments. This gives further confidence that assimilation only of high wind speed wind vectors can modify the analysis in a similar manner to that which would occur if wind vectors were available for all wind speeds.

There are, however, some important differences in the tropics, where a tropical storm has analysis increments at 180° W 25° N in the AllWinds experiment. As the storm moved to the west small analysis increments continued to be applied throughout its life. By contrast the HighWinds experiment did not apply any increments until the storm had reached 160° W 30° N and the increments then applied were larger than those applied in the AllWinds experiment. Although this is only one storm (and hence had little impact on mean tropical verification scores for the whole period) it may suggest that the AllWinds observation system will perform better than HighWinds for tropical storms.

VI. Observations With Met Office Global Short-Range Forecasts

The two preceeding sections have demonstrated that if WindSat data observation errors (where observation errors are taken to include radiative transfer errors as well as instrument calibration errors, instrument noise and representivity error) are at or below 0.2 K for the third and fourth elements of the Stokes vector then WindSat has real potential to deliver similar extra-tropical impact to QuikSCAT. For a limited (120 000) sample the fit (in observation space) to the Met Office global model fields is shown in Table II.

TABLE II
Fit to WindSat Channels With and Without Modelling of Azimuthal Variation of Emissivity

	Root mean square difference of observed and modeled rightness temperature K					
	With azimuthal variation of emissivity modelled			With azimuthal variation of emissivity *not* modelled		
Channel	Wind $<$ 4 ms^{-1}	4 ms^{-1} $<$ Wind $<$ 8 ms^{-1}	Wind $>$ 8 ms^{-1}	Wind $<$ 4 ms^{-1}	4 ms^{-1} $<$ Wind $<$ 8 ms^{-1}	Wind $>$ 8 ms^{-1}
6.8 Tv	0.62	0.68	0.67	0.70	0.82	0.76
6.8 Th	1.28	1.64	1.76	1.27	1.60	1.84
10.7 Tv	0.68	0.93	0.88	0.91	0.93	0.86
10.7 Th	1.58	1.69	1.61	1.60	1.84	1.78
10.7 U	0.26	0.26	0.25	0.28	0.37	0.35
10.7 V	0.07	0.09	0.10	0.08	0.11	0.15
18.7 Tv	2.00	1.73	1.51	2.16	1.92	1.70
18.7 Th	4.11	3.92	3.31	4.45	4.25	3.63
18.7 U	0.25	0.26	0.25	0.32	0.35	0.31
18.7 V	0.09	0.10	0.10	0.12	0.15	0.16
23.8 Tv	3.25	3.00	2.74	3.50	3.22	2.87
23.8 Th	5.80	5.41	4.74	6.08	5.77	5.05
37 Tv	2.42	2.46	2.34	2.66	2.63	2.45
37 Th	5.41	5.44	5.17	5.72	5.66	5.43
37 U	0.17	0.20	0.20	0.19	0.30	0.23
37 V	0.07	0.10	0.13	0.06	0.06	0.07

The RMS measure of misfit of real WindSat observations and short range forecast shown in Table II contains the contribution from errors in the short range forecast as well as the observations, and these are assumed to be uncorrelated with each other. It therefore represents an upper bound on the total observation error. It can be seen that for all channels except the channel labeled "37 V" the fit is improved by modeling the azimuthal variation of emissivity more especially for higher windspeeds, as would be expected. This is even the case for the vertical and horizontal polarizations, which are primarily sensitive to water vapor, cloud liquid water, and windspeed.

This demonstrates that in a data assimilation context analysing the wind direction more accurately will enable more effective use of the radiances for water vapor, windspeed and cloud liquid water. The measurements made by the 37-GHz V channel of WindSat showed negligible variation with wind direction whereas the models do predict high sensitivity, so in this case fit is actually worse when the variation is modeled. If we assume that the measurements of fit in Table II represent the total observation error, which as stated is an upper bound and the true observation error is likely to be lower, we can compare information content for QuikSCAT and this "worse case scenario" for WindSat. This is shown in Fig. 6, which demonstrates that using WindSat in single-view mode may become comparable with QuikSCAT for windspeeds above 15 ms^{-1} but will remain at a slightly lower level of information than QuikSCAT, whereas the dual view, even for this pessimistic scenario, matches QuikSCAT for windspeeds above 6–8 ms^{-1}.

VII. Conclusion

This study demonstrates that the lack of sensitivity of a polarimetric radiometer to wind direction at wind speeds below 8 ms^{-1} may have little effect on its impact on numerical

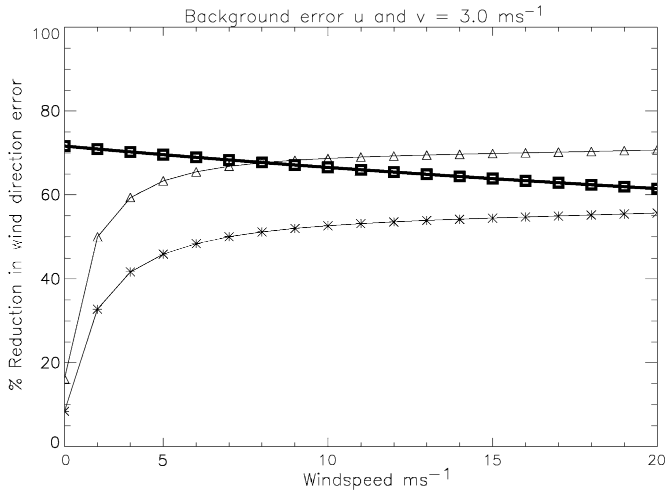

Fig. 6. Comparison of information content for (stars) WindSat single view, (triangles) WindSat dual view, and (continuous line) scatterometer.

weather prediction in the extra-tropics. Furthermore it has been shown that an instrument such as WindSat, if used in dual-view mode, should give comparable information content to scatterometer for all windspeeds above 6 ms^{-1}, and possibly even lower windspeeds, though information content falls very rapidly below 5 ms^{-1} for WindSat. Information content for a single view is significantly lower than for dual view, assuming that the observation errors in the two looks are not correlated. Whilst this is an encouraging analysis for polarimetric radiometer data it does not imply that scatterometer winds may not have advantages over polarimetric radiometer winds. In particular the ambiguity question is not addressed: ambiguities in wind direction (i.e., two or more wind directions are equally probable given a single observation) are an issue for scatterometers and may also be an issue for polarimetric radiometer data. A further caveat is necessary in the tropics where wind speeds are usually small but surface wind vector information is crucial for driving ocean models. This aspect has not been considered in this paper. However, it has been demonstrated that the lack of sensitivity to wind direction at low wind speed is not itself an obstacle to the successful use of polarimetric radiometer data for wind direction analysis in numerical weather prediction.

Acknowledgment

The authors would like to acknowledge the WindSat team at NRL for provision of data and advice on WindSat data processing, F. Weng (NOAA/NESDIS) for the use of the Liu and Weng model, P. Pampaloni (CNR, Italy) for use of the Coppo model, and the reviewers for their helpful comments.

References

[1] M. Born and E. Wolf, *Principles of Optics*. Cambridge, U.K.: Cambridge Univ. Press, 1999.

[2] A. J. Camps and S. C. Reising, "Wind direction azimuthal signature in the Stokes emission vector from the ocean surface at microwave frequencies," *Microw. Opt. Technol. Lett.*, vol. 29, no. 6, pp. 426–432, 2001.

[3] B. Candy, "The assimilation of ambiguous scatterometer winds using a variational technique: Method and forecast impact," The Met Office, Exeter, U.K., Forecasting Research Tech. Rep., vol. 349, 2001.

[4] P. Coppo, J. T. Johnson, L. Guerriero, J. A. Kong, G. Macelloni, F. Marzano, P. Pampaloni, N. Pierdicca, D. Solimini, C. Susini, G. Tofani, and Y. Zhang, "Polarimetry for passive remote sensing," Eur. Space Agency, Noordwijk, The Netherlands, ESA Contract Final Rep. 1146/95/NL/NB, 1996.

[5] J. R. Eyre, "The information content of data from satellite sounding systems: A simulation study," *Q. J. R. Meteorol. Soc.*, vol. 116, pp. 401–434, 1990.

[6] P. W. Gaiser, K. M. St Germain, E. M. Twarog, G. A. Poe, W. Purdy, D. Richardson, W. Grossman, W. L. Jones, D. Spencer, G. Golba, J. Cleveland, L. Choy, R. M. Bevilacqua, and P. S. Chang, "The WindSat spaceborne polarimetric microwave radiometer: Sensor description and early orbit performance," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 11, pp. 2347–2361, Nov. 2004.

[7] A. Ishimaru, *Wave Propagation and Scattering in Random Media*. Piscataway, NJ: IEEE Press, 1997.

[8] J. D. Jackson, *Classical Electrodynamics*. New York: Wiley, 1980.

[9] B. Laursen and N. Skou, "Wind direction over the ocean determined by an airborne, imaging, polarimetric radiometer system," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 7, pp. 1547–1555, Jul. 2001.

[10] Q. H. Liu and F. Z. Weng, "A microwave polarimetric two-stream radiative transfer model," *J. Atmos. Sci.*, vol. 59, no. 15, pp. 2396–2402, 2002.

[11] ——, "Retrieval of sea surface wind vector from simulated satellite microwave polarimetric measurements," *Radio Sci.*, vol. 38, no. 4, 2003. Art. No. 8078.

[12] A. C. Lorenc *et al.*, "The met office global three-dimensional variational data assimilation scheme," *Q. J. R. Meteorol. Soc.*, vol. 125, pp. 2991–3012, 2000.

[13] T. Meissner and F. Wentz, "An updated analysis of the ocean surface wind direction signal in passive microwave brightness temperatures," *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 6, pp. 1230–1240, Jun. 2002.

[14] L. Phalippou, "Variational retrieval of humidity profile, wind speed and cloud liquid-water path with the SSM/I: Potential for numerical weather prediction," *Q. J. R. Meteorol. Soc.*, vol. 122, no. 530, pp. 327–355, 1996.

[15] R. W. Saunders, M. Matricardi, and P. Brunel, "An improved radiative transfer model for assimilation of satellite radiances," *Q. J. R. Meteorol. Soc.*, vol. 125, pp. 1407–1426, 1999.

[16] K. St. Germain and G. Poe, "Polarimetric emission model of the sea at microwave frequencies, Part II: Comparison with measurements," Nav. Res. Lab., Washington, DC, NRL Rep., 1998.

[17] N. Skou, B. Laursen, and S. Sobjaerg, "Polarimetric radiometer configurations: Potential accuracy and sensitivity," *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 5, pp. 2165–2171, Sep. 1999.

[18] N. Skou, "Retrieval of wind direction over the ocean from polarimetric radiometer data," Met Office, Exeter, U.K., Cost712 Draft Rep., 2000.

[19] N. Van Woert *et al.*, "Ocean winds from Sspace...The Next Generation," Off. Nav. Res., Arlington, VA, Rep. 32296-13, 1996.

[20] F. J. Wentz, "Measurement of oceanic wind vector using satellite microwave radiometers," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. Sep., pp. 960–972, 1992.

[21] T. T. Wilheit, "A model for the microwave emissivity of the ocean's surface as a function of wind speed," *IEEE Trans. Geosci. Electron.*, vol. GE-17, no. 4, pp. 244–249, 1979.

[22] C. P. Yeang, S. H. Yueh, K. H. Ding, and J. A. Kong, "Atmospheric effect on microwave polarimetric passive remote sensing of ocean surfaces," *Radio Sci.*, vol. 34, no. 2, pp. 521–537, 1999.

[23] S. H. Yueh, J. A. Kong, R. Kwok, F. K. Li, S. V. Nghiem, and W. J. Wilson, "Polarimetric passive remote sensing of ocean wind vectors," *Radio Sci.*, vol. 29, no. 4, pp. 799–814, 1994.

[24] S. H. Yueh, R. Kwok, and S. V. Nghiem, "Polarimetric scattering and emission properties of targets with reflection symmetry," *Radio Sci.*, vol. 29, no. 6, pp. 1409–1420, 1994.

[25] S. H. Yueh, W. J. Wilson, F. K. Li, S. V. Nghiem, and W. B. Ricketts, "Polarimetric measurements of sea surface brightness temperatures using an aircraft K-band radiometer," *IEEE Trans. Geoscie. Remote Sens.*, vol. 33, no. 1, pp. 85–92, Jan. 1995.

[26] ——, "Polarimetric brightness temperatures of sea surfaces measured with aircraft K- and Ka-band radiometers," *IEEE Trans. Geosci. Remote Sens.*, vol. 35, no. 5, pp. 1177–1187, Sep. 1997.

[27] S. H. Yueh, W. J. Wilson, S. J. Dinardo, and F. K. Li, "Polarimetric microwave brightness signatures of ocean wind directions," *IEEE Trans. Geosci. Remote Sens.*, no. 2, pp. 949–959, Mar. 1999.

Stephen J. English received the B.Sc. degree in physics and meteorology from the University of Reading, Reading, U.K., in 1988, and the Dr.Phil. degree in atmospheric physics from the University of Oxford, Oxford, U.K., in 1991, where he specialized in microwave remote sensing.

He worked at the Remote Sensing Branch of the Met Office from 1991 to 1995 before moving to their headquarters (now in Exeter, U.K.) leading a group responsible for assimilation of satellite sounding and microwave imagery data in both global and regional data assimilation systems.

Brett Candy recieved the B.Sc. degree in physics from Imperial College, London, U.K., in 1993 and the M.Sc. degree in meteorology from the University of Reading, Reading, U.K., in 2002.

He joined the Met Office in 1996 and has worked on several applications of remote sensing data for both operational numerical weather prediction and climate research. Currently, his research concentrates on the improved use of microwave sounding data in regional numerical weather prediction models.

Adrian Jupp received the B.Sc. degree in mathematics and physics from the University of Warwick, Warwick, U.K., and the M.Sc. degree in earth observation science from Leicester University, Leicester, U.K., in 1998 and 1999, respectively.

He worked as a Research Associate from 1999–2000 at the Physics and Astronomy Department, Leicester University, investigating large-scale waves in the equatorial Pacific Ocean. He joined the Met Office, Exeter, U.K., in 2000, and has worked on assimilation of GNSS radio occultation and signal delay data into NWP models. He has also been involved in investigating the potential for NWP models to improve GNSS positioning accuracy.

David Bebbington received the B.A. degree in experimental and theoretical physics and the Ph.D. degree in radio astronomy from Cambridge University, Cambridge, U.K., in 1977 and 1986, respectively.

From 1981 to 1984, he worked on millimeterwave propagation research at the Rutherford Appleton Laboratory. Since 1984, he has been at the University of Essex, Essex, U.K., and currently holds the post of Senior Lecturer in the Department of Electronic Systems Engineering. His interests are weather radars, polarimetry, and applications of wave propagation in remote sensing.

Steve Smith is currently pursuing the Ph.D. degree at Essex University, Essex, U.K.

Anthony Holt received the B.A. and Dr.Phil. degrees from Oxford University, Oxford, U.K., in 1961 and 1965, respectively.

From 1967 to 2004, he was on the staff of the Mathematics Department, Essex University, Essex, U.K. He now holds the title of Emeritus Professor. His research field has been the theory and applications of scattering theory. Since 1975, this has been focussed on the scattering of microwaves by hydrometeors and its applications to microwave propagation and weather radar. He was the coordinator of two European Union Framework projects on weather radar. He is the author of nearly 100 journal articles.