Meteorology Research and Development

A Comparison of the Impact of QuikScat and WindSat Wind Vector Products on Met Office Analyses and Forecasts.

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Abstract

Several studies have demonstrated that retrievals of wind vectors from the WindSat polarimetric radiometer are of sufficient quality to be considered for assimilation in operational numerical weather prediction models. In this study WindSat data is used in a state of the art global meteorological analysis and forecasting system. Each wind vector contains a directional ambiguity and so is assimilated in a similar way to scatterometer data. The forecast impact of using analyses containing information from WindSat data was investigated for a period during August and September 2005, when a large number of tropical cyclones were present. Forecast errors were reduced in the surface pressure fields, and the average improvement across the forecast range was found to be 1.0 %. This is comparable to the improvement of 1.1 % found to the same fields when winds were assimilated from the QuikScat scatterometer. The impact on tropical cyclone tracks in the forecasts was also studied. The scatterometer improved (reduced) the track errors markedly by 25% in the analyses. When impacts across the forecast range out to five days were also included, the improvement was found to be 8%. In contrast, the assimilation of WindSat data improved the analysis track errors by 7%, although this figure was found to be 10% across the complete forecast range.

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INTRODUCTION

Space-borne observations of near-surface winds over the ocean form a significant part of the Global Observing System. Observations from scatterometer missions, such as QuikScat and ERS-2, are an important part of the global dataset used routinely to create Numerical Weather Prediction (NWP) analyses. These instruments make a series of backscatter measurements over the same region of ocean at differing azimuth angles. Various forward models have been developed that describe the backscatter signal as a function of surface wind speed and the relative direction of the surface wind to the radar beam, which can be used to retrieve surface vector information from each observation. Assimilation of wind vector products from these instruments has resulted in positive impacts on forecast accuracy at a number of centres, including the Met Office [1] and the European Centre for Medium-Range Weather Forecasts [2], [3].

The emission of microwave radiation from a smooth ocean surface is highly polarized and as the surface becomes roughened the emission becomes less polarized. This effect is exploited to determine the near surface wind speed from measurements made by microwave radiometers, such as SSM/I [4], which view the scene in two polarizations at each frequency. These observations have also been shown to deliver positive forecast benefit. Several studies using SSM/I data, e.g. [5] & [6], have shown that the polarization signal contains a small dependency on wind direction and so demonstrated the potential for wind vector retrieval from a passive radiometer. Airborne campaigns of fully polarimetric measurements (i.e. those which can measure the full Stokes' vector), [7] & [8], confirmed this result and also showed that the 3^{rd} and 4^{th} components of the Stokes' vector had wind direction sensitivity at moderate to high wind speeds. WindSat, the first space-borne polarimetric radiometer, was launched in 2003 [9]. The aim of this mission is to demonstrate that wind vector information can be derived from a space-borne passive instrument with near real time capabilities. This instrument is of considerable interest to the meteorological community as it acts as a complementary source of data to the existing scatterometer missions and as a baseline for future microwave imaging systems such as that being developed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

In this paper the impacts of wind vectors from QuikScat and WindSat are compared, in both NWP analyses and in the resulting forecasts. An earlier study at the Met Office [10] used QuikScat data to simulate the potential impact of WindSat in NWP. The simulations assumed WindSat wind vectors were only useable for wind speeds above 8 ms^{-1} since the sensitivity of the brightness temperatures to wind direction is small at lower wind speeds. The study demonstrated that it was likely that the WindSat data impact on NWP forecasts was comparable to the impact using all QuikScat data. It also suggested that the lack of low wind speed information may impact on the positioning of tropical cyclones. To attempt to examine this issue WindSat and QuikScat data are assimilated in this study during a period when there were over twenty tropical cyclones present.

This paper is structured as follows. In section II the QuikScat and WindSat wind vector products used in this study are briefly described and compared to estimates from short-range Met Office NWP forecasts. In section III assimilation aspects of the wind vector data are discussed. The analysis and forecast impact study is presented in section IV, including an investigation specific to tropical cyclone forecasting. Conclusions are presented in section V.

WIND VECTOR PRODUCTS

QuikScat

QuikScat measurements are processed at NOAA/NESDIS in near real time using a scheme which is fully described in [11]. Briefly, the backscatter measurements made by the rotating radar are geo-located into nodes of size 25 km resulting in 76 nodes across the outer swath. Winds are retrieved from several backscatter measurements using an empirically based forward model similar to that developed by Wentz & Smith [12], but adapted for QuikScat. The retrieval is performed for each node over the ocean, and between two and four directional ambiguities can be found per node. For a particular observation the ambiguities are ranked on the fit between the measurements and the forward model. Each ambiguity is disseminated to NWP centres along with additional information regarding the quality of the retrieval.

At the Met Office this wind vector product has been routinely assimilated in the operational global forecasting system since December 2002. The observations are quality controlled prior to assimilation [1] and data is rejected if the following is true:

- Attached quality flags denote rain in the field of view.
- Land or Sea-ice is present in the field of view (by comparing against Met Office sea surface temperature and sea-ice analyses).
- Nodes outside of the midswath region. The midswath region (~200 to 700 km on either side of the sub satellite point) has been shown to yield the best quality retrievals [11].
- Fit between the observations and the forward model exceeds a wind speed dependent threshold.

The latter test has been shown to be useful in detecting rain effects in the field of view for Ku-band scatterometers ([1], [13]).

WindSat

Retrieved wind vectors from WindSat are stored in a format referred to as Environmental Data Records (EDR) and are available from the Physical Oceanography Distributed Active Archive Center (PO.DAAC). Observations currently cover the period February 2003 to November 2005. Each EDR file contains observations from a particular orbit, with each record containing the retrieved products and associated quality flags. Full details on the EDR format can be found in [14]. The spatial resolution is approximately 50 km (defined by the lowest frequency channel) and data is over-sampled by a factor of 4.

The geophysical product retrieval has been developed by the Naval Research Laboratory [15] and uses a variational technique in which the atmospheric state vector is found that minimises the difference between the satellite radiance measurements and forward model equivalents. The forward model is a physically based radiative transfer model with some empirical tuning. In addition to the surface wind speed and direction, the retrieval vector contains sea surface temperature, integrated water vapour, and liquid water path. Up to four wind vector ambiguities are retrieved and each of these possible solutions is present in the EDR, along with a chi square (χ^2) value that indicates how large the difference is between the observations and the forward model, evaluated at the retrieved state. The ambiguities are ranked in order of χ^2, i.e. the Rank1 solution is the state that gives the best fit to the observations (lowest χ^2).

Prior to use in the assimilation system a series of quality control tests have been applied to the WindSat data. Data is rejected if the following is true:

- EDR quality flags indicate radio frequency interference in the field of view or poor confidence in the retrieval.
- If rain is indicated in the field of view, either through estimation from the radiances or if the retrieved liquid water path exceeds 0.1 mm.
- If the Rank1 χ^2 exceeds 20.0 (99% of the data should lie within this value).

Comparison with NWP Fields

It is normal practice at NWP centres to monitor incoming observations against the NWP model equivalent from short-range forecast fields. For instance the wind vector product from QuikScat is monitored by comparing the closest ambiguity in each retrieval to the model 10 m wind vector from the six hour forecast, valid at the time of the observation. Equivalent statistics for WindSat data are presented in Table 1 from twenty four hours worth of observations made during December 2006. Data has been included if it passed the quality control tests specified earlier in this section. QuikScat statistics for the same period are also shown. Note that WindSat data is plotted only above 5 ms^{-1} since a previous analysis of the data [16] suggests that the directional accuracy is poor below this wind speed, in line with sensitivity studies [10] which showed that there is little directional information in the low wind speed regime. Both the QuikScat and WindSat missions specify the required accuracy of the vector product to be 2 ms^{-1} in strength and 20° in direction ([9], [17]). It is encouraging to see that for most of the wind speed range WindSat data is well within these limits. Results are also very close to the QuikScat values and only at wind speeds below around 6 ms^{-1} is there an indication that the WindSat direction accuracy is worse than QuikScat. The wind speed bias between the observations and the NWP model has also been determined and is shown in Figure 1. Both QuikScat and WindSat data show a positive bias with respect to the Met Office 10 m winds and in both cases the bias increases with increasing wind speed. Since the wind retrieval scheme employed by each satellite system uses a forward model constructed from differing methodologies (in the case of QuikScat empirically and in the case of WindSat from a physically based model), it seems most likely that the high wind speed bias is due to a characteristic of the Met Office NWP model.

Figure 2 shows the fit of surface wind measurements from the complete range of instrumentation types used in operational Met Office analyses. WindSat wind vectors have a slightly better fit to the model forecasts than the Active Microwave Instrument (AMI) scatterometer on ERS-2. It should be noted that ERS-2 has been in space for over a decade. However a recent impact study [18] has demonstrated that the despite its age the AMI still yields positive forecast benefit, in agreement with earlier trials at several centres [2],[19]. This can be seen as a good indication that the assimilation of the WindSat wind vectors is likely to result in positive forecast impact. The two outliers are worthy of note. Firstly ship data gives the worst fit and this is because there are several significant sources of error associated with this data such as the anemometer being located downwind of superstructure on the deck leading to shielding effects. For these observations rigorous quality control is required. The best fit to the NWP forecasts is shown by Advanced Scatterometer data on the recently launched METOP-A satellite. This is especially encouraging as at the time of comparison the instrument was still undergoing in-flight calibration.

WIND VECTOR ASSIMILATION

Met Office global analyses are created using a four-dimensional variational assimilation scheme (4D-Var) which is fully described in [20]. The scheme combines information from a previous short-range NWP forecast (often termed the background) with recent observations from both surface and satellite instrumentation. It does this by finding the model atmospheric state which minimizes a cost function, J. J contains a term that measures the departure of the model atmospheric state to the background and also a term, J_o, that measures the departure of the observations from the model state. To include wind information containing a directional ambiguity an appropriate contribution to J_o is required and the following is based on operational QuikScat assimilation [1], which has also been applied here to WindSat. For a conventional observation, if a Gaussian error distribution is assumed with zero bias, then this leads to a quadratic term in J_o, but in the case of a QuikScat (or WindSat) observation there are N wind vectors with components u_i^o, v_i^o. If each ambiguity has a probability P^o of being the true wind solution this leads to a contribution to J_o of the form:

$$J_{scat} = -\ln\left(\sum_{i=1}^{N} P_i^o e^{-j_i}\right)$$

with

$$j_i = \frac{(u - u_i^o)^2}{2s^2} + \frac{(v - v_i^o)^2}{2s^2}$$

where *u,v* represent the orthogonal components of the 10 m wind from the model atmospheric state and *s* represents the observation error. *s* contains contributions arising from the measurement error and errors in the retrieval to wind vectors. It is set to a value of 2 ms^{-1} for both the scatterometer and WindSat. Estimates of P^o are also required for each ambiguity and these were determined for WindSat by evaluating the percentage of events in which each ranked wind vector solution was the closest to the background wind direction. A strong dependency on wind speed was found and so the probabilities were tabulated as a function of the retrieved wind speed (Table II). This empirical model could potentially be extended and will be explored in a future study. For instance it does not contain any dependency on azimuthal difference between the wind direction and the radiometer line of sight.

Since the observations are assumed to contain zero bias against the NWP model, prior to assimilation the data is corrected for the wind speed bias noted in Section II. The assimilation scheme currently takes no implicit account of correlated errors in the observations and so the data is spatially thinned to account for this. Operationally all scatterometer data is thinned to 1 observation in a 100km square [1] and this thinning level was also applied to WindSat in the impact experiments detailed below.

OBSERVATION IMPACT EXPERIMENTS

Experimental Setup

In order to test the impact of real WindSat observations in the Met Office analysis and forecast system a series of impact experiments were performed. The trial period chosen was from 20th August to 25th September 2005. For this period WindSat data is available in the PO.DAAC archive, whilst QuikScat data is available from the Met Office observation database. In addition to this, the period was chosen because the 2005 hurricane season was one of the most active on record [21]. The trial period contains 21 tropical cyclones and this is of interest because the study in [10] suggested that WindSat observations may yield different impacts to the scatterometer in the forecasting of tropical cyclones. These impacts will be examined in the third part of this section.

The configuration of the analysis and forecast system used in the impact experiments was based on Met Office operations from mid-2005. The forecast model computations were performed on a grid of 432 points (east-west) x 325 points (north-south), which is equivalent to a resolution of approximately 60 km at mid-latitudes. The model contained 38 levels in the vertical and the model top was at a height of 40 km. Analyses were produced at 0, 6, 12 and 18 UTC using the 4D-Var data assimilation scheme with a spatial resolution of half the forecast model. At 12 UTC forecasts ran out to six days [note that operational runs also produce a six day forecast at 0 UTC but this was not performed for the experiments detailed here to reduce computational cost]. Table III gives details of the observing systems used in the experiments and these matched operations from mid-2005 with the following exceptions. Firstly in the control run QuikScat and SSM/I wind data have been withdrawn to provide a baseline set of forecasts that do not contain surface wind information from satellites. In addition to this, synthetic observations used to initialize tropical cyclones in the analysis [22] have been removed from the control and subsequent experiments. This was carried out because these observations are given a very high weight in the assimilation process and are likely to mask any information from the satellite wind data, particularly at short forecast lead time. Two experiments were performed, one in which QuikScat data was assimilated in addition to the observations used in the control and one in which WindSat data was assimilated on top of the control (Table III).

Impact on Analyses and Forecasts

Figure 3 shows the WindSat observations that were assimilated in a typical six hour period. This is around 50% less than the amount used from QuikScat. WindSat data voids occur principally in low wind speed regions such as in the area east of Indonesia and due to high cloud liquid water in the field of view (e.g. off the coast of Argentina). It is useful to compare how each observation type changes the analyses. In Figure 4 we compare the difference in analysis increments between each experiment and the control. The increment patterns are very similar in the Southern Ocean, the region where previous trials have demonstrated that QuikScat data has most impact. One notable difference are the larger increments observed in the tropical West Pacific arising from the assimilation of QuikScat data.

Forecasts arising from each experiment and control run were compared to the same set of quality controlled conventional surface observations to determine forecast errors. The improvement (reduction) in the forecast error for each experiment compared to the control run is shown in Figure 5 for pressure at mean sea level (PMSL). The benefit of assimilating QuikScat is again confirmed and is similar in magnitude to previous experiments at the Met Office [1]. Despite the lack of low wind speed data the assimilation of WindSat observations also results in positive impact, albeit slightly smaller for four of the six forecast times. Averaged across all these times the improvement to PMSL errors is 1.1 % for QuikScat and 1.0 % for Windsat. A similar signal is seen when upper tropospheric wind fields from each experiment are validated against radiosonde wind measurements.

It is worth noting that the use of the wind vector product from WindSat in these experiments has ignored any potential forecast benefits arising from moisture (and low wind speed) information. Information from the instrument could be assimilated in principle by using the radiances directly through the addition of a radiative transfer model to the observation cost function. Studies using SSM/I radiances in this way, such as [23], have demonstrated benefit to both wind speed and humidity NWP fields. This could potentially be extended to WindSat radiances.

Impact on Tropical Cyclones

Previous studies have demonstrated that a C-band scatterometer, such as the AMI scatterometer on the ERS satellite series, can have a beneficial impact on the forecasting of the tracks of tropical cyclones [2, 24]. This instrument can provide wind information from fields of view in which significant precipitation is present. This is not the case for QuikScat or WindSat, leading to potential data voids at the centre of tropical cyclones. For instance in Figure 6 the wind vector retrievals from the three instruments are compared in the vicinity of Hurricane Katrina. Despite its smaller swath valid AMI retrievals are available closer to the core of the cyclone, when compared to QuikScat and WindSat. It might be expected that the lack of the observations at the core of a cyclone may reduce the usefulness of an instrument for hurricane track forecasting, but despite this a study at ECMWF [3] demonstrated improvements to track positions when data from the NSCAT scatterometer was assimilated for three case studies. NSCAT operates at a similar frequency to QuikScat and also requires data screening in the presence of rain. In the following analysis the improvements to tropical cyclone track forecasts are investigated for both the QuikScat and WindSat experiments compared to the control run.

The method used is based on the operational system at the Met Office to track and evaluate tropical cyclones in the NWP model [25]. It uses observations of cyclone locations which are received as advisory messages at the Met Office and originate from monitoring centres such as the National Hurricane Centre in Miami and the Joint Typhoon Warning Centre in Hawaii. The tracking works in the following way. For a cyclone of interest the centre location was extracted from an archive of the advisories and then searched for in the model analysis or forecast by examining the relative vorticity field, ζ, at 850 hPa in a search area about the advisory position. The search area had a radius of 5° for analyses and 7° for subsequent forecasts. If the value of ζ of any grid point in the search area exceeded a threshold then the cyclone was considered to be present in the model field and the positional error (the difference between the grid point location and the advisory location) was determined. The ζ threshold was set to the value used in the operational tracking ($0.8 \times 10^{-4} s^{-1}$). The tracking procedure was repeated for each cyclone that lasted for at least two days during the trial period. The cyclones tracked were distributed across the tropical Pacific and Atlantic regions as shown in Table IV.

An example of the tracking is shown in Figure 7, which compares the representation of tropical cyclone Jova for a single analysis in each experiment and the control. At this time Jova had developed into a hurricane with winds in excess of 70 knots. Whilst the control contains the cyclone it is a much weaker feature (in terms of vorticity) than is seen in either experiment. This increase in strength of a cyclone when the satellite wind data is assimilated is generally seen in all the cases. The assimilation of the wind data from either instrument has improved the positioning error and is most notable in the case of QuikScat. Figure 8 shows the forecast tracks arising from the analysis in each experiment, along with the true locations from the advisories. In reality the cyclone moves initially westwards and then northwards towards Hawaii after 24 hours. The control forecast only makes the turn to the north after 72 hours. The assimilation of WindSat data improves the track slightly, but again the northward turn is still made too late in the forecast. The best track arises from the QuikScat experiment which turns the cyclone northwards correctly after 24 hours, though the movement of the cyclone is slower than was observed in reality.

The accumulated results of the tracking over all the cyclones are summarized in Figure 9. The top panels compare the number of cyclones correctly detected in the experiments compared to the control run and it can be seen that out to a forecast range of 24 hours the control run does very well and detects more than 95% of the events. However at longer forecast ranges the control run does not retain the cyclones. At a lead time of five days, for example, the percentage detected has dropped to 72%. The impact of assimilating either WindSat or QuikScat data helps to retain the cyclones in the model beyond 24 hours as shown by a higher percentage of cyclones detected. In particular at a forecast range of five days the QuikScat experiment detected over 85% of the cyclones present. The lower panels in Figure 9 show the mean positional error of the cyclones in the experiments compared to the control, taking the true cyclone positions as those supplied in the advisory messages. An event was only used in the accumulated statistics if it was detected in both the experiments and the control. Again the assimilation of either QuikScat or Windsat observations generally improves the positioning errors, albeit in a slightly different manner. For QuikScat the analysed cyclone positions improve quite markedly by around 25%. This improvement reduces with forecast time, becoming neutral at three days and beyond. The impact of WindSat data on the analyses is smaller with positional errors improved by 7%. However this level of improvement is retained at longer forecast lead times out to five days. Taken across the forecast range (a total of 453 events) the improvement of the cyclone track errors due to each instrument was found to be comparable in magnitude; 8% in the case of QuikScat and 10% in the case of WindSat. The differences between the cyclone positional errors in the WindSat and QuikScat experiments were only statistically significant at analysis time and at a forecast range of five days.

CONCLUSIONS

Retrievals of wind vectors from the WindSat polarimetric radiometer mission have been evaluated using the Met Office NWP System. The retrievals were performed at the Naval Research Laboratory and contain a directional ambiguity. Above wind speeds of around 6 ms^{-1} the fits of the retrievals to the Met Office global NWP model are comparable to QuikScat data. At high wind speed a positive bias in the retrieved wind speeds with respect to the model was observed which was also seen in the QuikScat comparisons. Assimilating WindSat data with wind speeds above 6 m/s provides roughly 50% of the data from QuikScat. Despite the lack of low wind observations, the impact of this data on the forecast model was found to reduce PMSL forecast errors out to a lead time of six days. This improvement was found to be of similar magnitude to a companion experiment which measured the impact of QuikScat data. Synthetic observations used to initialize tropical cyclones were deliberately withdrawn from all the impact trials, in order that the performance of forecasting these systems in the NWP model could be investigated. Unlike C-band systems such as the AMI and ASCAT, both WindSat and QuikScat data require screening in the presence of rain, leading to data voids at the centre of tropical cyclones. Despite this it was found that the assimilation of both QuikScat and WindSat data improved the positional errors of these systems and helped to retain them through the forecast. Whilst the use of the scatterometer resulted in significant benefit to the positional errors in the analysis, taken across the entire forecast range the improvements were found to be 8 % in the case of QuikScat and 10 % for WindSat. This study has demonstrated that the wind vectors generated from polarimetric radiometer measurements have useful benefit in NWP and that the directional ambiguity can be dealt with in a similar manner to scatterometer data. Future work should attempt to exploit the additional low wind and humidity information available from the radiometer via direct radiance assimilation.

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TABLE I
THE STANDARD DEVIATION OF OBSERVED MINUS SHORT-RANGE FORECAST DIFFERENCE FOR WINDSAT AND QUIKSCAT WIND VECTOR PRODUCTS FOR 24 HOURS OF DATA DURING DECEMBER 2006.

Wind Speed Range (ms^{-1})	Wind Speed (ms^{-1})		Wind Direction (°)	
	WindSat	QuikScat	WindSat	QuikScat
5-6	1.26	1.29	21.0	17.2
6-7	1.20	1.26	16.8	14.2
7-8	1.19	1.24	13.9	12.1
9-10	1.34	1.33	10.5	9.8
10+	1.42	1.49	8.6	9.0

TABLE II
EMPIRICALLY DERIVED LOOK UP TABLE OF WINDSAT WIND VECTOR PROBABILITIES (FOR FOUR AMBIGUITIES)

Wind Speed Range (ms^{-1})	Rank Solution			
	1	2	3	4
5-6	0.53	0.28	0.15	0.04
6-7	0.63	0.24	0.10	0.03
7-8	0.72	0.20	0.05	0.03
8-9	0.75	0.19	0.04	0.02
9-10	0.77	0.18	0.04	0.01
10+	0.80	0.15	0.05	0.00

TABLE III
OBSERVATIONS USED IN THE IMPACT EXPERIMENTS

Experiment	Observation Type	Number Used*
Control	ATOVS Radiances from NOAA-15, 16 and 18 satellites AIRS radiances from the Aqua satellite Wind Profilers Radiosonde profiles of temperature, wind & humidity Cloud track winds from GOES, Meteosat, Aqua and Terra Aircraft reports of temperature & wind Land station reports of surface pressure Ship & buoy reports of surface pressure	17000 3000 1000 800 6000 12000 5000 4000
QuikScat Experiment	As Control + QuikScat ambiguous winds	8000
WindSat Experiment	As Control + WindSat ambiguous winds	3300

*Typical number used in a 6-hour assimilation window after quality control and spatial thinning

TABLE IV
TROPICAL CYCLONES DURING THE TRIAL PERIOD

Region	Tropical Cyclones	
	Total Number	Number reaching hurricane strength
North Atlantic	7	6
North West Pacific	7	6
North East Pacific	7	4
Indian Ocean & Australia	0	0
Total	21	16

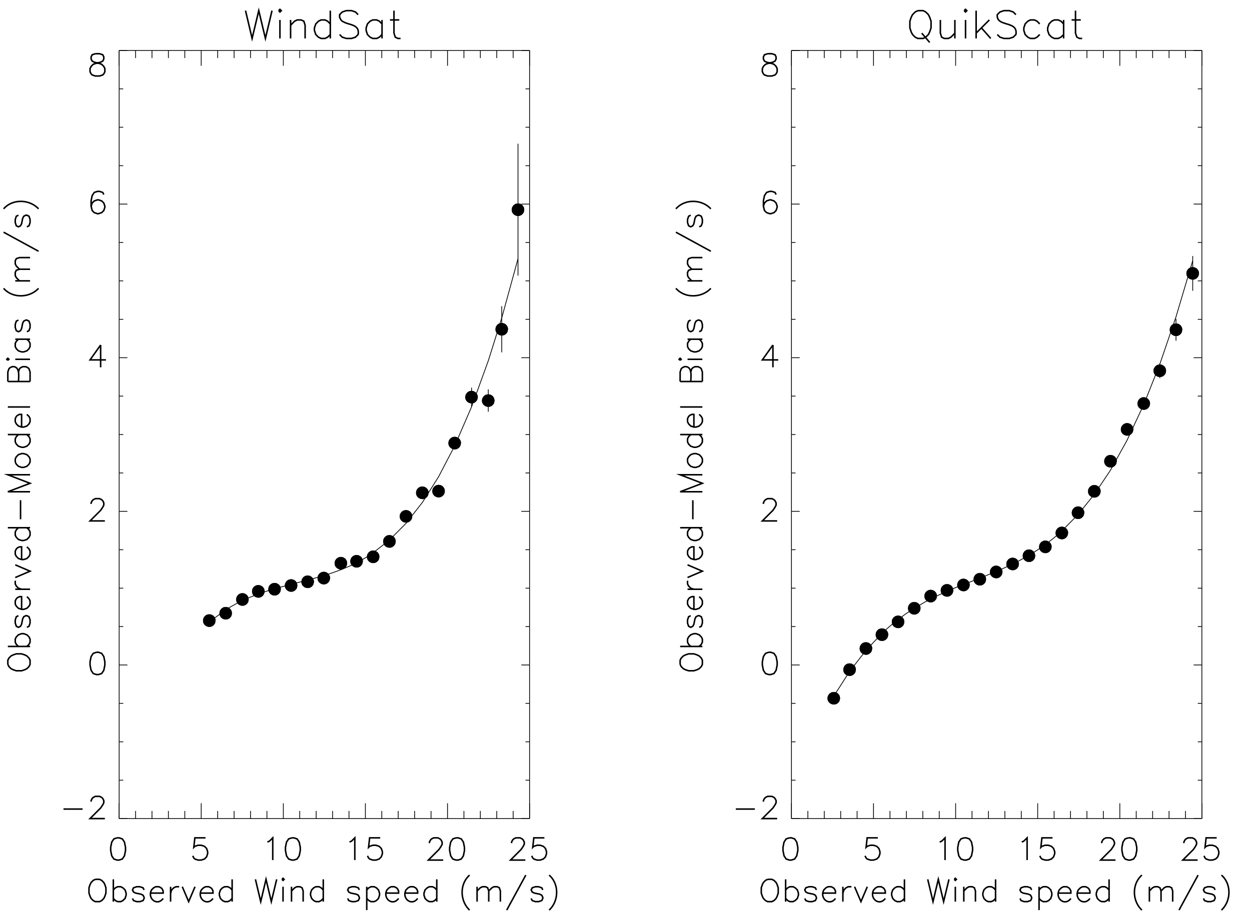

Figure 1. The observed wind speed bias with respect to the NWP model for different wind vector products. *Left panel*: WindSat data, *right panel*: QuikScat data.

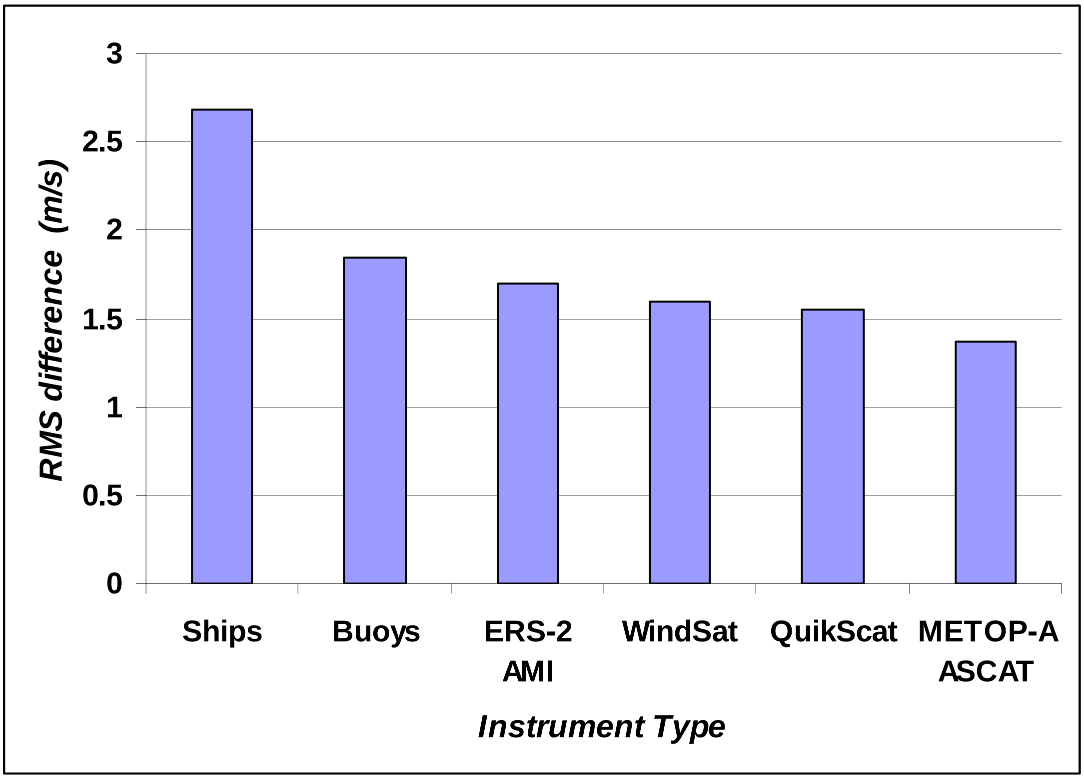

Figure 2. The fit of the u component of the 10m wind from various types of marine observation to the Met Office six hour forecast expressed as a root mean square difference. Statistics compiled using data from 30th April 2007.

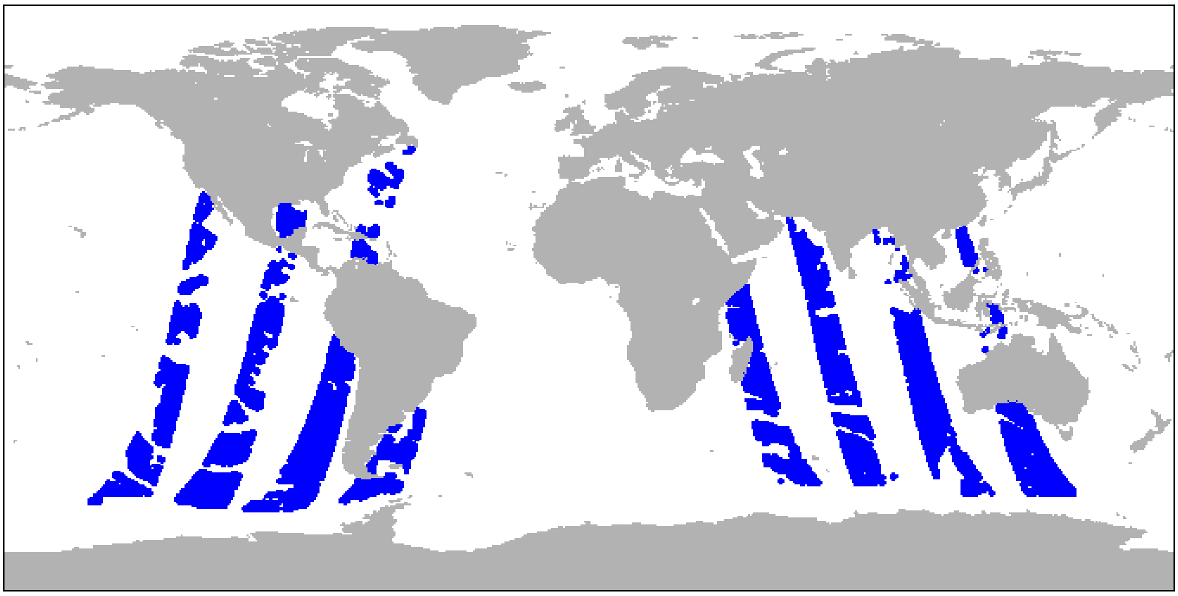

Figure 3. Typical coverage of WindSat observations over six hours after quality control.

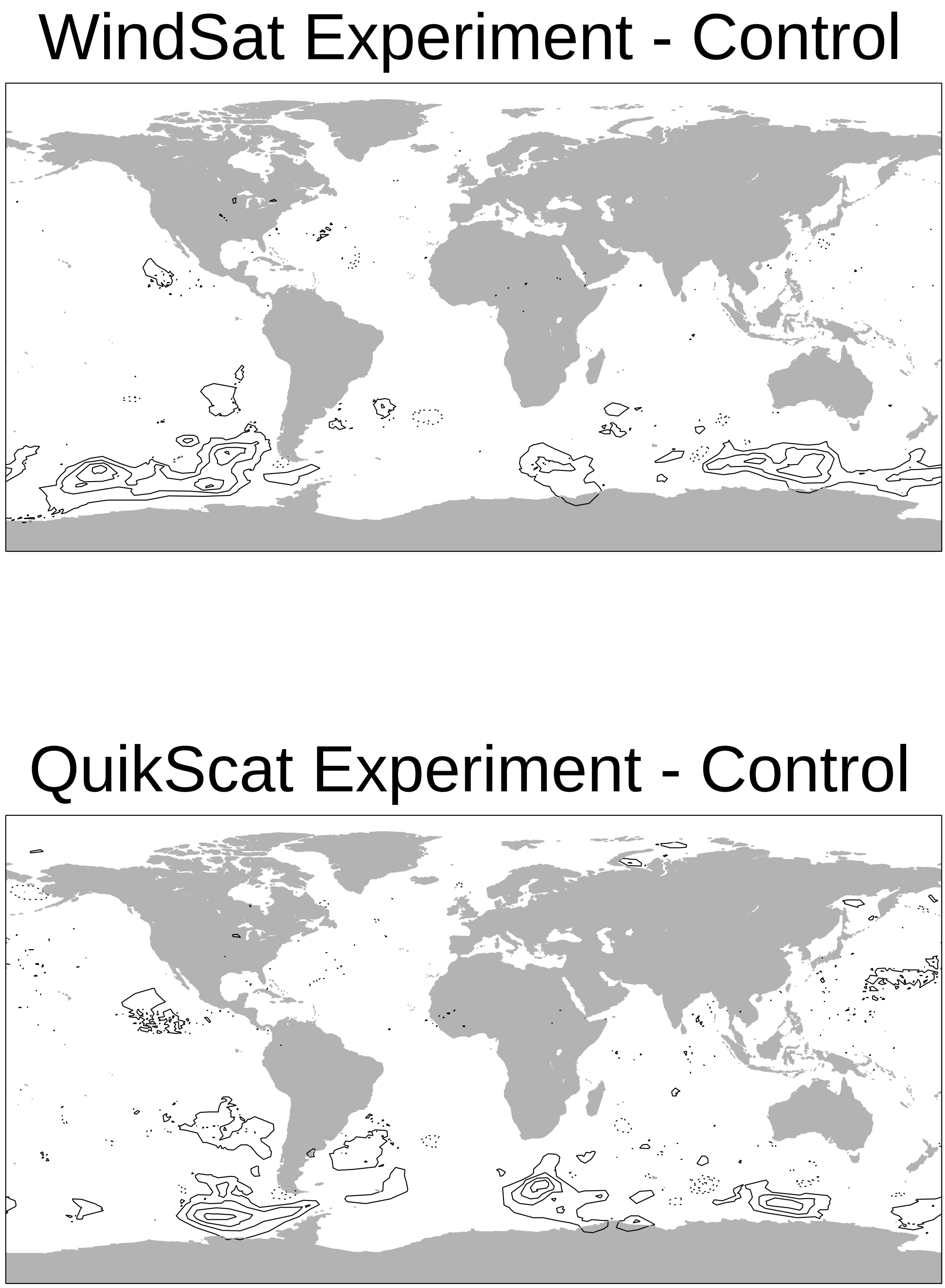

Figure 4. The difference in analysis increments between each experiment and control for pressure at mean sea level (PMSL). Top panel: QuikScat experiment, bottom panel: WindSat experiment. The contour intervals are 0.15 hPa and continuous contours denote positive increments, whilst dashed contours denote negative increments.

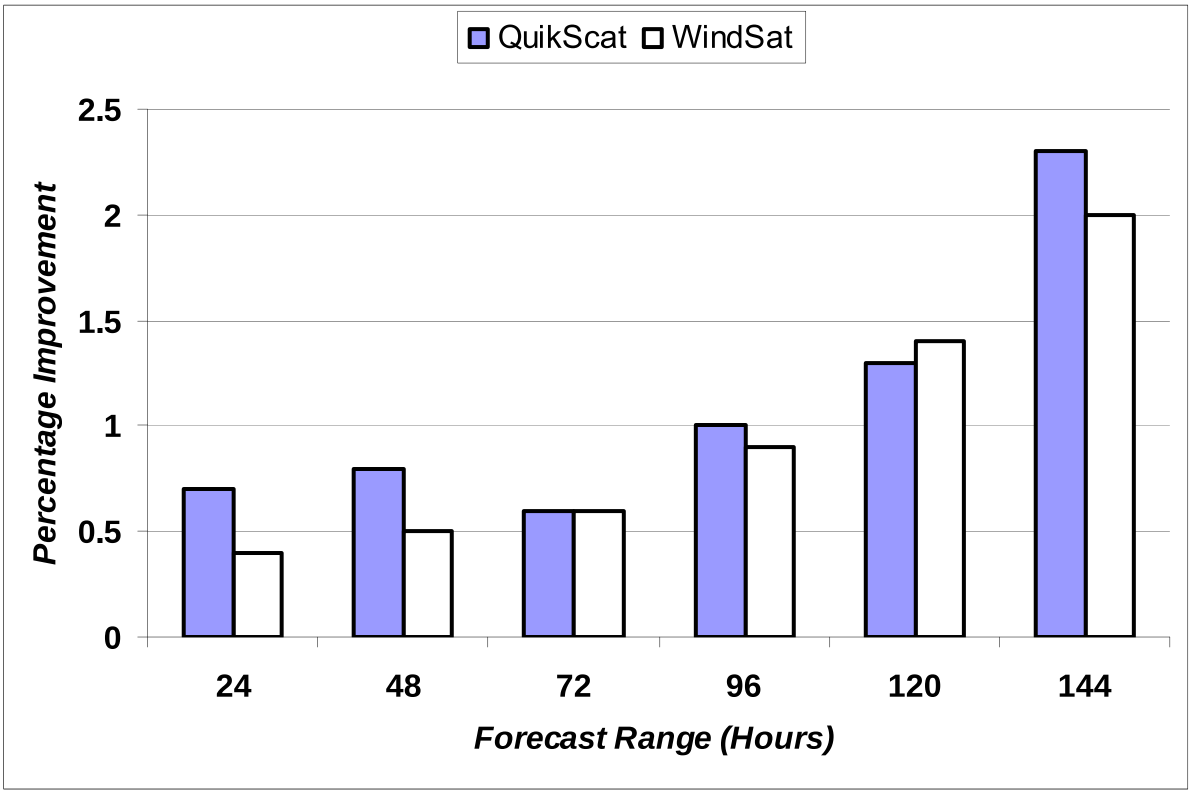

Figure 5. Comparison of the improvement in forecast error for pressure at mean sea level (PMSL) for the QuikScat experiment and the WindSat experiment. Forecasts were verified using PMSL reports from conventional surface observations.

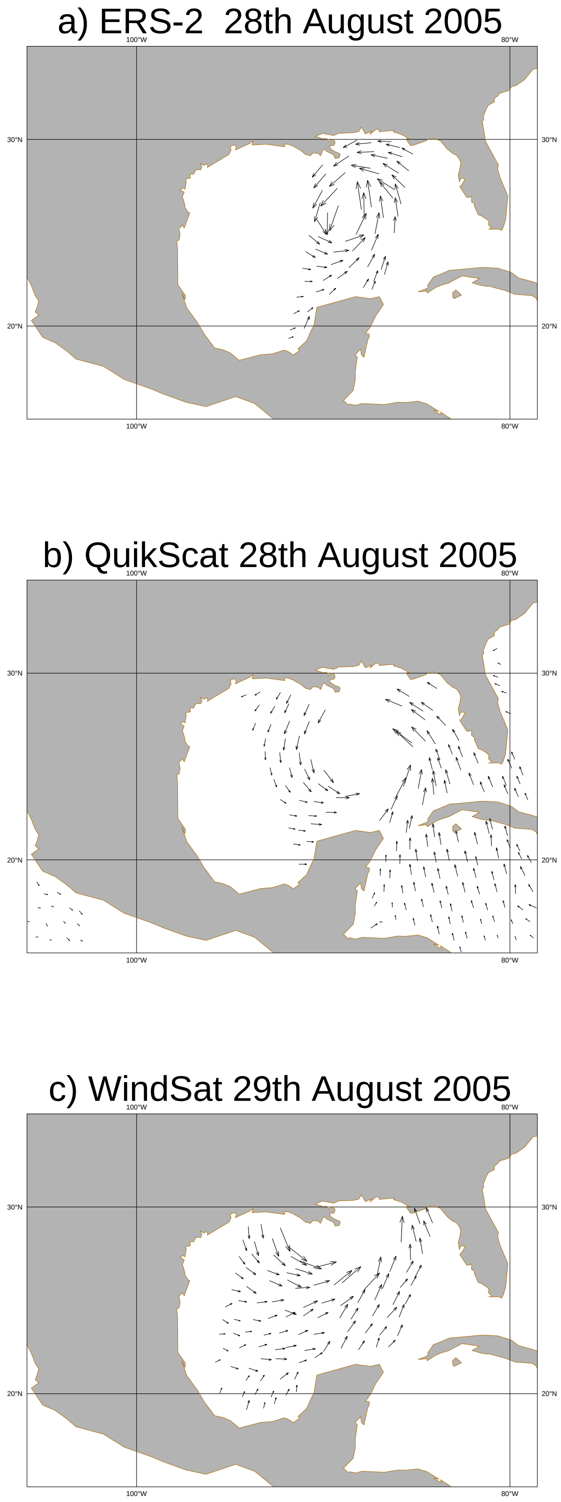

Figure 6. A comparison of the retrievals in the vicinity of tropical cyclone Katrina for a) AMI scatterometer on ERS-2, b) QuikScat and c) WindSat. In each case quality control has been applied and data thinned to 1 data point per 100 km box.

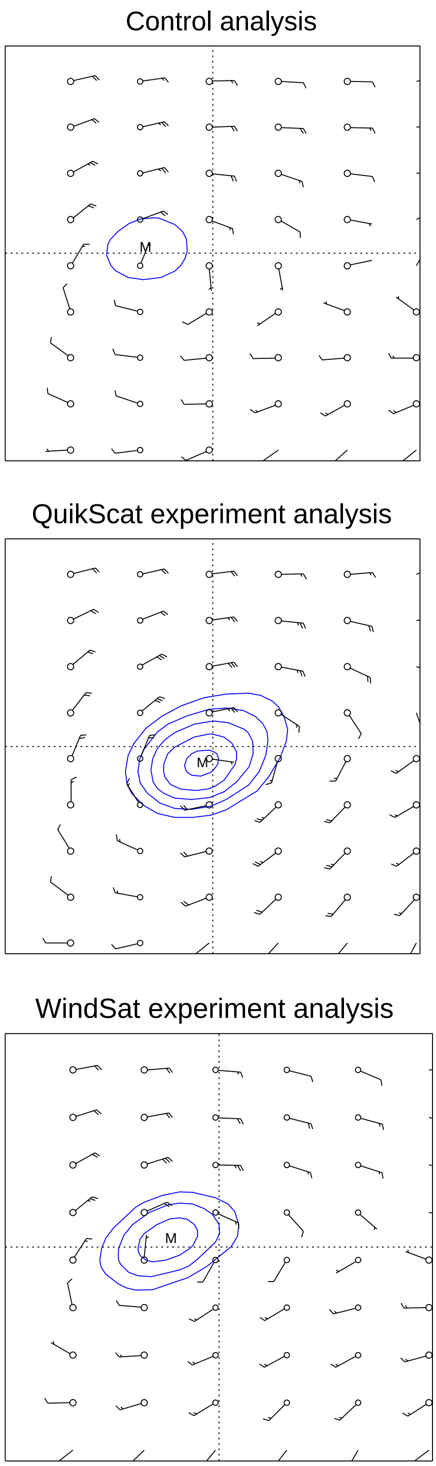

Figure 7. The representation of tropical cyclone Jova in NWP analyses for the 16th September 2005 at 12 UTC. Top panel: the analysis from the control run, middle panel: from the QuikScat experiment, bottom panel: from the WindSat experiment. In each case the centre of the plot locates the true position of the cyclone as determined from the advisory and ‘M’ locates the analysed position. Contours represent relative vorticity starting at $0.8 \times 10^{-4} s^{-1}$ in increments of $0.2 \times 10^{-4} s^{-1}$.

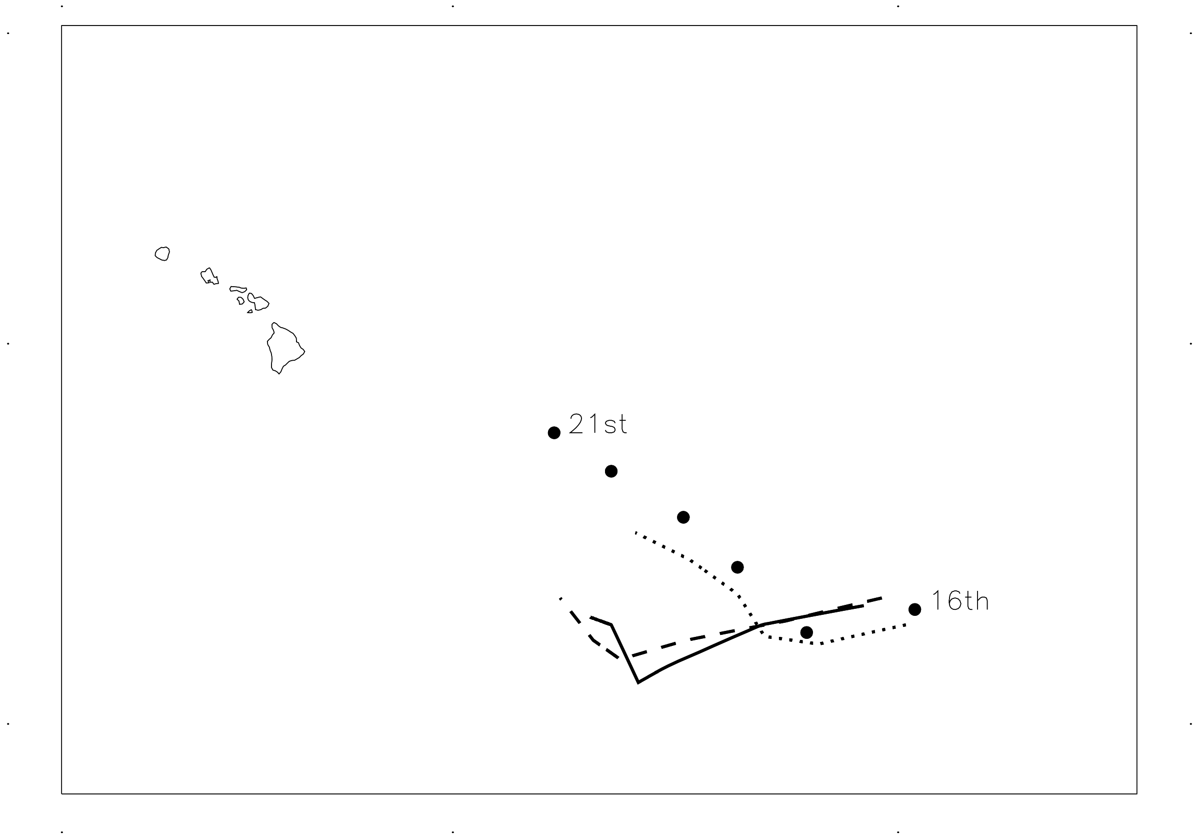

Figure 8. A chart depicting forecasts tracks of tropical cyclone Jova out to five days arising from the analyses in Figure 7 (16th September 2005). The solid line represents the track from the control, dashed line from the WindSat experiment and the dotted line from the QuikScat experiment. Filled circles represent the actual location of the cyclone from the 16th to the 21st September 2005. The islands of Hawaii are also present on the chart.

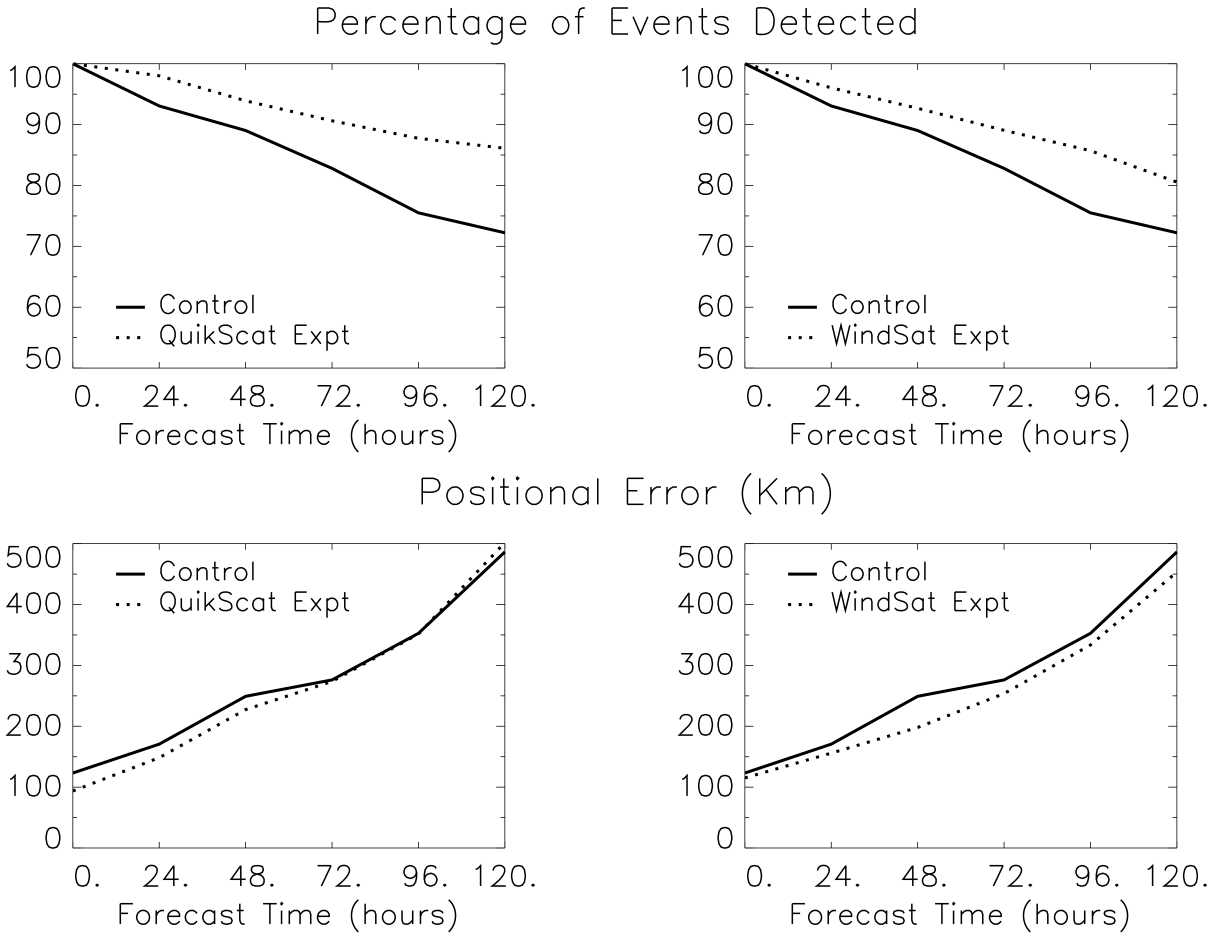

Figure 9. A Summary of tropical cyclone performance in each impact experiment compared to the control run. Top panels: the percentage of events correctly detected against forecast time. Bottom panels: the mean positional error against forecast time.