Active techniques for wind observations: scatterometer

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ABSTRACT

Ocean surface winds are an important parameter in NWP system since they affect the full range of ocean movements, from individual surface waves to complete current systems and modulate air-sea exchange of heat, momentum, gases and particulates having an impact on analysis and forecast on the atmosphere and ocean processes from short-range to seasonal to climate scales. The scatterometer is a unique spaceborne sensor capable of providing measurements of the ocean surface wind vector under clear and cloudy conditions, day and night. Scatterometer data are known to improve the quality of surface winds over the ocean, and therefore have an impact on the forecast skill of the atmospheric model and the ocean waves. For all these reasons, scatterometer wind observations have been assimilated in Numerical Weather Prediction systems for almost 20 years. At ECMWF the assimilation of scatterometer winds started in 1996 and since then many datasets from different sensors have been actively assimilated. In this paper, we shortly describe the scatterometer principles and give an overview of the impact of these observations on the ECMWF analysis and forecast.

1 Introduction

The scatterometer is a microwave radar that provides high precision radiometric measures of the normalized radar cross section (or backscatter) of the ocean surface. The backscatter depends on the surface roughness which is in turn related to the local wind. Since the microwave wavelengths used are independent of clouds and sun illumination, these data can be used in case of extreme events such as the case of Tropical Cyclone (TC).

Scatterometer was originally designed for wind retrieval over the ocean but now the measurements are also extensively used for soil moisture applications, which require high spatial resolution products and long term backscatter information. It is also used for ice cover retrieval.

It is almost 20 years since scatterometer wind observations have been used in Numerical Weather Prediction (NWP). The advantage of using such observations lies in the fact that these are the only synoptic surface wind observations available with a good acquisition frequency. This allows having surface wind observations also in areas where in-situ observations are lacking (i.e. in the Southern Hemisphere). In Figure 1 an example of 1 day coverage of ASCAT-A data is shown.

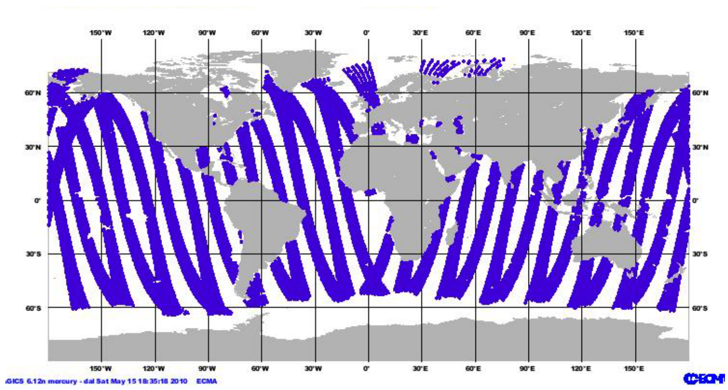

Figure 1: Example of 1 day of ASCAT-A data coverage.

Scatterometer data are currently used in most of NWP centers (ECMWF, Met Office, Météo-France, JMA and Environment Canada) and have been proven to have a positive impact on the analysis and forecast of several systems.

Horanyi et al. (2013) computed the impact of all the wind observations filtered for pressure levels. They showed (Figure 2) that among all the wind observations below 850 hPa, the impact of the scatterometer observations is the highest, well above 50% in terms of Forecast Error Contribution (FEC).

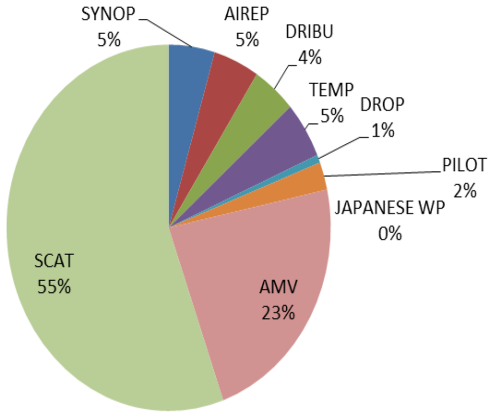

Figure 2: Wind observation FSO/FEC values relative quantities (in %) below 850 hPa. The different colours indicate the different observation types as denoted on the figure (Horaniy at al., 2013).

2 Scatterometer

The scatterometer is an active microwave instrument which is capable of measuring the normalized radar cross section (or backscatter σ_0) of the ocean surface with great radiometric accuracy and under multiple observation azimuth angles. On the ocean, the intensity of the backscatter depends mainly on the sea surface roughness. At the wavelength used, the instrument is sensitive to gravity and capillary waves (up to few centimetres) travelling in the direction of the emitted wave, which are generated by the local wind stress. This is due to a resonance phenomenon (Bragg resonance) that occurs between the radar waves and the ocean waves. The backscatter depends not only on the magnitude of the wind stress but also the wind direction relative to the direction of the radar beam (azimuth angle). The maximum backscatter value is obtained when the incoming wave is aligned with the surface wind direction, the minimum value when it is perpendicular. Hence multiple observations at different azimuth angles are needed to resolve the directional ambiguity. All the scatterometer are indeed based on this principle and provide at least 3 backscatter measurements.

C-band scatterometers on the European satellite series ERS and METOP have 3 beams (fore, mid, aft) which look at the same area on the Earth with three different azimuth angles (left-hand picture in Figure 3). Ku-band scatterometers typically on US, Indian, Chinese and Japanese missions (i.e. ADEOS, QuikSCAT, OCEANSAT, NSCAT) were characterized by fan-beam or pencil-beam antennas providing at least four observations (right-hand picture in Figure 3). However, because of uncertainties in the wind retrieval algorithm and noise in the backscatter measurements, a 180 degrees ambiguity still remains on the wind direction (Liu, 2002) which is typically resolved by comparing the two solutions to NWP wind fields. The backscatter also depends on other factors such as the frequency of the emitted pulse, the incidence angle, the polarization of the emitted and returned signal.

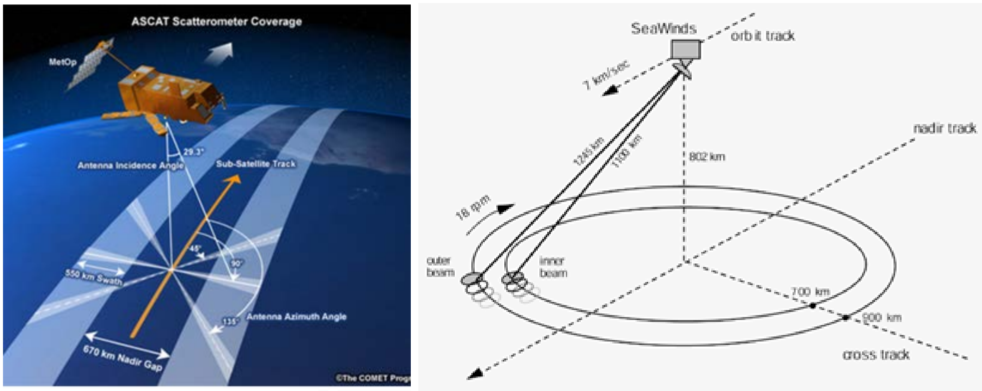

Figure 3: Radar geometry for the C-band ASCAT scatterometers (left-hand picture) and Ku-band OSCAT scatterometer (right-hand picture).

The relationship between the backscatter and the vector wind is theoretically know but its modelization would be rather complex. So in practice this relationship is determined empirically. Because the capillary waves, which determine backscatter, are governed by stress, the relationship should be obtained by collocating the backscatter to the surface stress observations. Very few in situ observations of this parameter are actually available; therefore historically the relationship is obtained by collocating the backscatter measurements to in-situ buoy and/or NWP model winds. The geophysical model function (GMF) describing the relationship among the backscatter and the mentioned parameters varies also on the frequency of the emitted pulse (typically C-band or Ku-band) and on the type of instrument. Examples are the CMOD models for the VV-polarized C-band scatterometers and the NSCAT and QSCAT models for Ku-band scatterometers.

In a 3-D observation space the CMOD model describes a "conical surface" which consists of two closely overlapping sheaths whose parameters are the wind speed and wind direction (in Figure 4 in blue the CMOD5 model). The direction along the cone is sensitive to the wind speed; the direction around the cone is sensitive to the wind direction (Hersbach, 2003). One sheath represents upwind conditions, whereas the other sheath corresponds to downwind conditions (Stoffelen, 1998). Physically, the extension of the cone in the 3D space is related to the amplitude of ocean capillary waves: the larger the amplitude, the greater the surface roughness, the larger backscatter measurements (which means larger wind speed).

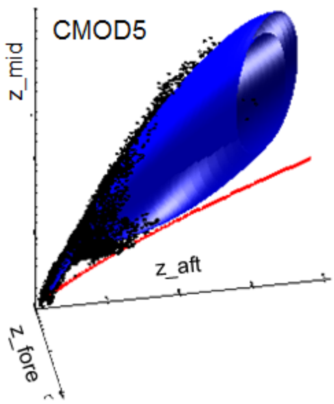

Figure 4: representation of the CMOD5 GMF (in blues) in a 3D observation space. In black the backscatter triplets.

The diameter of the cone is related to the differences between upwind and downwind measurements. In the same space the measured C-band backscatter triplets, for a given incidence angle, are distributed around the "conical surface" (black points in Figure 4). Due to noise in the observations and/or deficiency of the GMF, the triplets do not lie exactly on the cone. During the wind inversion process, the minimum distances between each triplet and all the solutions on the GMF are searched for. Because of the characteristics of the GMF, for each triplet at least two solutions, with a directional ambiguity of 180 degrees, are selected.

3 Operational use of scatterometer data at ECMWF

C-band scatterometers have been assimilated into the Integrated Forecasting System (IFS) since 1996, beginning with ERS-1 and ERS-2 Scatterometer data. Currently METOP-A ASCAT (ASCAT-A) and METOP-B ASCAT (ASCAT-B) wind products are used, whose assimilation started respectively in June 2007 (Hersbach, 2007) and July 2013 (De Chiara, 2013). ASCAT-A and ASCAT-B wind observations are assimilated using the same strategy (De Chiara et al., 2012) as defined for ASCAT-A in 2007.

At ECMWF, the METOP-A and METOP-B ASCAT products at 50 km horizontal resolution (oversampled on a 25 km grid) are used. These products contain observations from the two ASCAT swaths each gridded into 21 Wind Vector Cells (WVCs or nodes) resulting in 42 WVCs. The winds are obtained by applying an "in-house" wind inversion by means of a geophysical model function (GMF) that describes the relation between the backscatter measurements, triplets in case of ASCAT, and the U and V wind components. Since November 2010, scatterometer winds have been assimilated as neutral 10-m winds rather than 10-m winds, in order to take account for variations in stability. The CMOD5.N (Hersbach, 2010) GMF is used. For each backscatter triplets, two wind solutions are retrieved. A bias correction is applied to ASCAT measurements both in terms of backscatter before the inversion, and wind speed, after the inversion. This is important in order to compensate for any changes in the instrument calibration and to guarantee consistency between the retrieved and the model winds. Both corrections are WVC dependent. The wind speed correction is also dependent on the wind speed itself.

A quality control is applied before and after the wind inversion. The first check is done on the land fraction in the product which must be zero. A conservative sea-ice check is also applied: ASCAT data are rejected when the model sea-ice cover exceeds 1% or if the SST is below 273.15 K. Data are also discarded when the ASCAT and collocated model winds are stronger than 35 m/s. Not all the observations that pass QC are actively assimilated. A thinning is applied such that only one observation out of four is assimilated resulting in a horizontal resolution of about 100 km. In 4D-Var two ASCAT wind solutions are considered. The most appropriate is dynamically determined (de-aliasing) by comparison with the ECMWF model winds. For the selected solution, in 4D-Var, an observation error of 1.5 m/s is assigned to both U and V components through the cost function.

In Figure 5 the map of the wind speed biases between ASCAT-A and ECMWF First Guess (FG) is shown for the period December 2012 to February 2013. ASCAT-A winds are on a global average very close to the ECMWF FG winds. The performance of the data is quite stable in time with small differences ranging within the seasonal variability. The wind direction standard deviation is about 14 degrees, whereas the global wind speed bias is almost zero. In some areas, the difference can be a bit larger. For example, it is known that in the Gulf of Guinea the ECMWF model underestimates wind speed by 1 to 2 m/s. In the North West Atlantic and North West Pacific, area of strong surface currents (i.e. Gulf Stream and Kurushio Current) ASCAT-A winds are slightly stronger than ECMWF ones. In the sub-equatorial regions instead, ECMWF winds are slightly stronger that ASCAT ones.

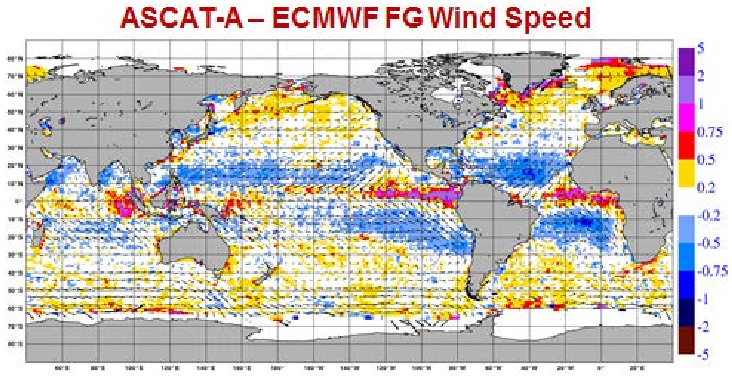

Figure 5: Mean wind speed bias (colours) and vector wind differences (arrows) between ASCAT-A and ECMWF FG wind from 17 December 2012 to 28 February 2013.

Ku-Band scatterometer data have also been assimilated at ECMWF. QuikSCAT data were assimilated from 2002 to November 2009. More recently, data from the scatterometer on board the OCEANSAT-2 Indian satellite were assimilated. OCEANSAT-2 was launched in September 2009 by ISRO (Indian Space Research Organisation). It carried on board a Ku-band Pencil Beam Scatterometer (OSCAT) providing backscatter measurements on a ground resolution cell of 50 km.

ECMWF received the OSI SAF OSCAT L2B products as generated in NRT by KNMI using the OSCAT Wind Data Processor (OWDP) to process L1B ISRO products. OWDP inverted the WVC backscatter data to ambiguous wind solutions using the NSCAT2 Geophysical Model Function (GMF). A first QC was based on the KNMI product flags related to the land/sea fraction, rain contamination, and data quality. On top of the KNMI QC, the land-sea fraction and sea-ice fraction (together with the SST check) are verified applying the same thresholds as used for ASCAT winds. Due to the lower grid spacing (50 km) no thinning is applied to OSCAT winds. However in order to have the same weight as ASCAT data, which are assimilated every 100 km, in 4D-Var a weight of 0.25 is applied to the 50 km OSCAT winds. A wind speed bias correction, WVC-dependent, was applied to have consistency between OSCAT and model winds. Since the wind speed bias would lead to unrealistically large corrections at high speed values, a wind speed threshold of 25 m/s is applied to the data so that winds above this value are discarded (De Chiara, 2012).

The comparison between bias corrected OSCAT winds and ECMWF FG winds is shown in Figure 6. The map shows a negative bias in the Southern Hemisphere mostly at latitude south of -50°. Several OSCAT users had reported negative biases of OSCAT winds with respect to NWP models in the southern hemisphere; this problem was believed to be due to an orbit issue and partially corrected in the OWDP by using a latitude dependent bias correction (Stoffelen et al., 2013), nevertheless some residual negative bias is still noticeable. A positive bias is distinguished in the subtropical South Pacific which might be correlated to the South Pacific Convergence Zone (SPCZ) and therefore possibly related to the precipitation contamination of the Ku-band signal.

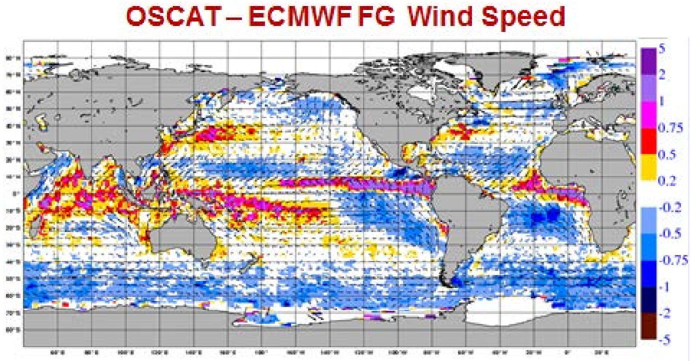

Figure 6: Mean wind speed bias (colours) and vector wind differences (arrows) between OSCAT and ECMWF FG wind from 17 December 2012 to 28 February 2013.

4 Impact of scatterometer winds on the IFS system

The impact of scatterometer winds on the IFS system is routinely evaluated. Recently, in the framework of a research project with EUMETSAT, an extensive impact study has been performed using different diagnostic methods.

The Forecast Error Sensitivity to Observations technique (FSO) which is an adjoint-based diagnostics to estimate the forecast sensitivity to individual observations (Cardinali, 2009) has been used, among other techniques, to assess the impact of scatterometer wind observation on the IFS. The tool computes the contribution of all observations to the reduction of the forecast error: a positive contribution is associated with forecast error increase and a negative contribution with forecast error decrease. The forecast range investigated is 24 hour. The forecast impact, called Forecast Error Contribution (FEC), depends on the forecast error, the assimilation system and the difference between the observations and the model. The FEC, computed as percentage over the whole set of observations, has been computed for each family of observations assimilated. In Figure 7, the global statistics are shown for the period December 2012-February 2013 for various experiments assimilating different combinations of available scatterometer datasets.

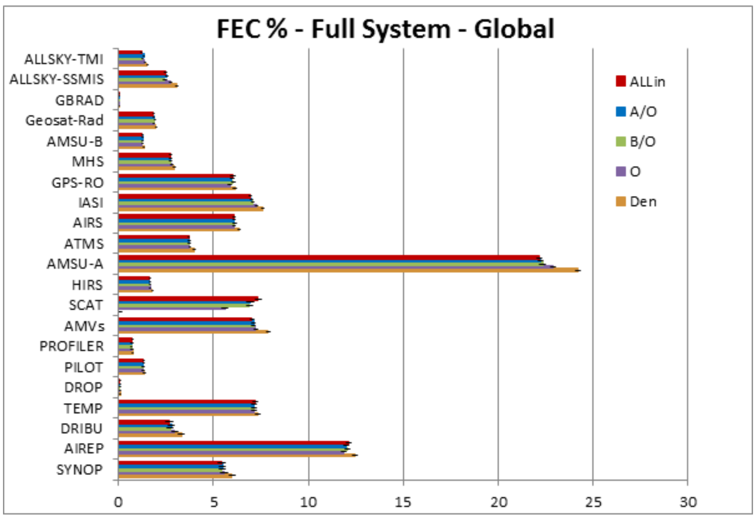

Figure 7: Global total forecast error contribution (in percentage) grouped by observation type for the Full System over the period 17 December 2012-28 February 2013. The error bars are computed using the standard deviation of the forecast error.

Results show that the FEC is about 7.5% when all the datasets available (ASCAT-A, ASCAT-B, OSCAT) are assimilated ("ALLin" experiment), around 7% when either ASCAT-A or ASCAT-B are assimilated with OSCAT ("A/O" and "B/O" experiments) and about 6% when only OSCAT ("O" experiment) is assimilated. The higher impact of OSCAT, compared to ASCAT, is due to the higher number of observations assimilated. As expected AMSU-A has the higher impact in the reduction of the forecast error with a FEC of about 22.5%. When no scatterometer observations are assimilated ("Denial" experiment), AMSU-A FEC reaches about 25%. The other observations that gain impact are IASI, AMVs and AIREP, all wind observations.

Statistics have also been computed for the Northern Hemisphere, Tropics and Southern Hemisphere (not shown here). Results show that the scatterometer impact is slightly lower in the Northern Hemisphere and Tropics with a FEC of about 6% when all the observations are assimilated ("ALL in" experiment), but is higher in the Southern Hemisphere with a FEC of about 10%.

4.1 Impact on Tropical Cyclones Forecast

One of the advantages of using scatterometer data is that their measurements are independent from the cloud cover. They can therefore provide wind information in TC areas characterized by big cloud structures near the eye wall. The impact of scatterometer data on the forecast of TC has been assessed by comparing the errors in Sea Level Pressure (SLP) and position of the TC centre for several experiments assimilating different scatterometer datasets. The errors have been computed using a tool developed at ECMWF (Vitart et al., 1997). This procedure detects tropical storms from ECMWF model fields. For each storm and forecast step, the minimum SLP at the centre of the storm have then been compared to the available observation values. The observed cyclone location and depth are received from the Regional Specialized Meteorological Centres (RSMC) recognized by WMO. These observations are also known as Best Track (BT). To have the same number of cases for each experiment, only the storms detected in all the experiments have been used for the statistics. In Figure 8 the Root Mean Square (RMS) forecast error (in hPa) between the observed minimum SLP and the ECMWF one is plotted for a number of experiments assimilating different scatterometer datasets.

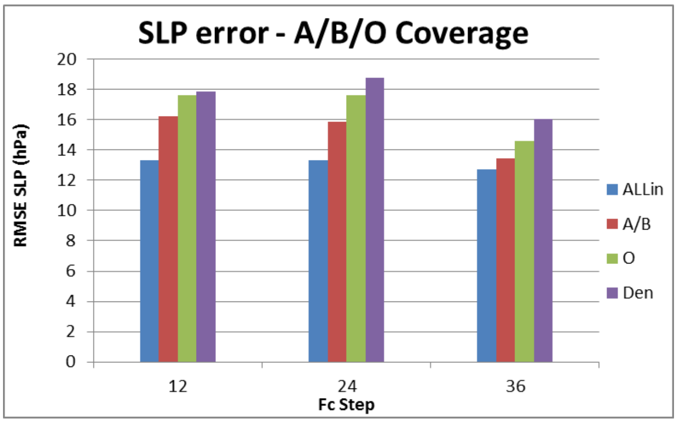

Figure 8: Root mean square forecast error of the Sea Level Pressure at the centre of the TC for 12, 24 and 36 hour forecast step (in blue the ALLin experiment assimilating ASCAT-A, ASCAT-B and OSCAT data; in red the A/B experiment assimilating ASCAT-A and ASCAT-B data; in green the O experiment assimilating only OSCAT data, in purple the Scatterometer Denial experiment). All experiments cover the period December 2012–February 2013.

Only storms for which ASCAT-A, ASCAT-B and OSCAT data were available have been selected. The statistics have been computed only for short range forecast because the number of available cases after step 36 hours was too small to be statistically significant. The experiment assimilating both ASCAT datasets and OSCAT ("ALLin" experiment in red) shows a lower RMS error of the SLP compared to the experiment assimilating only ASCAT-A and ASCAT-B ("A/B" experiment in red). Which is in turn lower than the one assimilating only OSCAT ("O" experiment in green) and the denial one ("Den" experiment in purple). This result shows that the more observations are used the better is the forecast. The same analysis has been performed for the error in the position of the TC. Results (not shown here) do not have a clear pattern, with all the experiments having an error that is within the model resolution.

4.2 Impact on Ocean parameters

At ECMWF preliminary analysis have been performed to verify the impact of scatterometer data on ocean parameters. In this context, a couple of experiments were run where the NEMO 1-degree ocean model is constrained by fluxes from the IFS atmospheric analysis and by the assimilation of temperature and salinity profiles. A standard run, assimilating scatterometer observations (CTRL) from September to November 2013 was conducted and compared to a similar run (NoSCAT) where none scatterometer data have been assimilated (ASCAT-A, ASCAT-B and OSCAT data have been blacklisted) (De Chiara et al., 2014). In Figure 9, the ocean temperature analysis differences for November 2013 between the CTRL and the NoSCAT experiments are plotted on an equatorial cross section. The differences in temperature are mostly located near the thermocline depth with maximum amplitude of about 1 degree. This means that the assimilation of scatterometer winds can have a significant impact in the ocean.

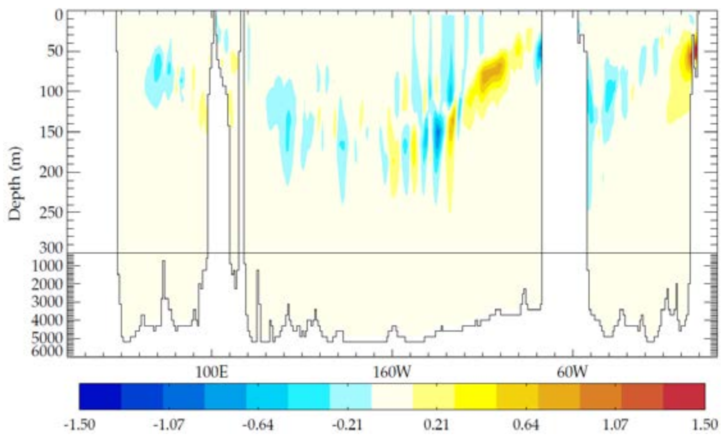

Figure 9: Equatorial cross section of the differences in mean ocean temperature analysis for November 2013 between CTRL experiment and NoSCAT experiment.

To evaluate whether the assimilation of scatterometer wind is beneficial for the ocean analysis, the RMS of the ocean analysis and background temperature departures have been computed with respect to conventional temperature observations. Figure 10 shows vertical profiles in three different tropical basins (Tropical Atlantic on the left, Tropical Indian in the middle, Tropical East Pacific on the right) of the background departure (solid lines) and analysis departure (dotted lines) RMSE for the CTRL experiment (in black) and the NoSCATT experiment (in red). In most regions, the CTRL experiment has a smaller RMSE in the background and analysis. This means that the assimilation of scatterometer winds improves the estimation of the ocean temperature in the thermocline.

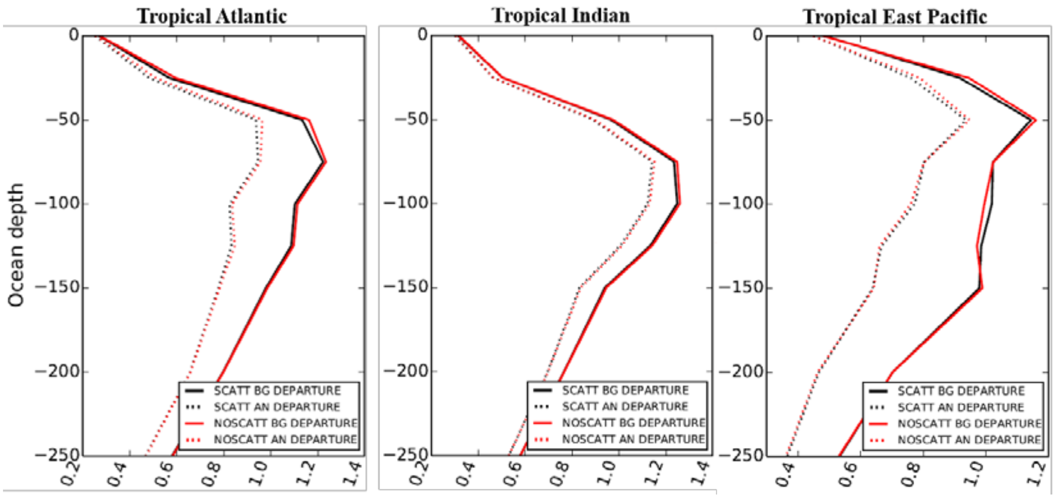

Figure 10: Vertical profile of the ocean analysis and background temperature RMSE with respect to conventional temperature observation for November 2013 in the Tropical Atlantic (left-hand panel), Tropical Indian Ocean (middle panel), Tropical East Pacific Ocean (right-hand panel) (CTL in black and NoSCAT in red).

5 Vertical propagation of the scatterometer information

It is known that near surface observations have hardly any impacts in the upper troposphere; this might be due more to a weakness in the data assimilation system rather than the observations themselves. Leidner et al. (2003) showed that in the early 2000, the scatterometer wind information was propagated up to about 200 hPa. This current reduced vertical impact is likely due to the higher number of observations used nowadays in the system. To verify the ability of 4D-var to propagate the scatterometer increments from the surface to higher model levels, some single observation experiments were run. In these experiments, only one single scatterometer wind observation is used; all the other observations, both conventional and from satellite, are not assimilated. For this analysis, the observation with the highest wind speed in the proximity of the centre of Typhoon Haiyan for the cycle on 12 December 2013, 12 UTC (with assimilation window from 9 am to 9 pm) has been selected. The scatterometer observation has been acquired around 1pm, 4 hours after the beginning of the assimilation window. Results show that the highest value of the wind U and V analysis increments are recorded after 9 hours since the beginning of the assimilation window. Analysis at different model levels showed that the largest analysis increments are around 850 hPa. A meridional cross-section along the maximum of the analysis increment is showed in Figure 11 for the U (left-hand panel) and the V (right-hand panel) components. The U-component analysis increments are quite visible up to model level 60 (around 100 hPa) with a maximum around model level 114 (about 850 hPa). The V-component analysis increments are weaker. The difference between the U and V components can be explained by the different background error. For the cycle analysed, the model background error was larger for the U-component which means that the analysis system gave more weight to this parameter in the assimilation resulting in larger increments.

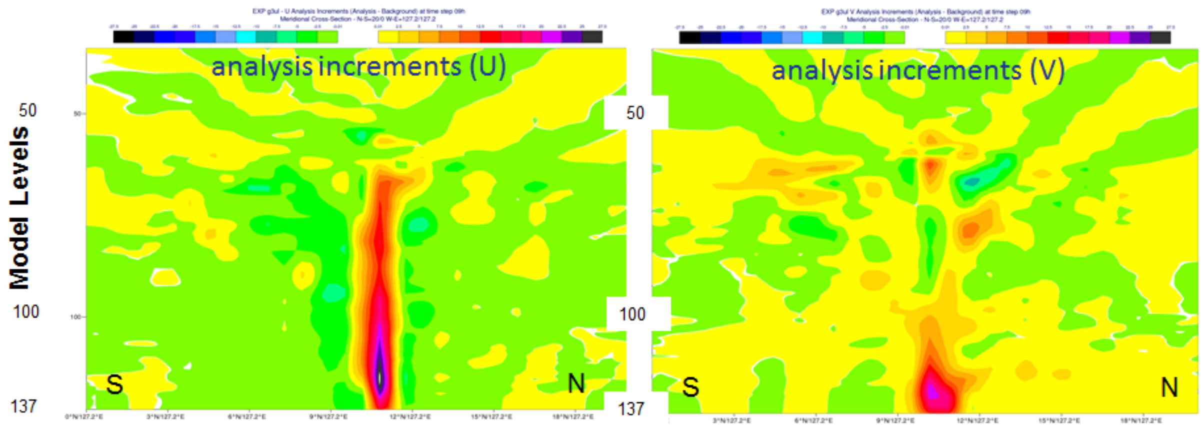

Figure 11: Meridional Cross section across of the U-component (left-hand panel) and the V-component (right-hand panel) analysis increments for the cycle 11 November 2013 12 UTC in the area of the Typhoon Haiyan.

6 Conclusions and final remarks

Scatterometer wind observations have been assimilated in NWP systems for many years, proving their valuable impact on analysis and forecasts. Over the last few years, the number of satellite and in-situ observations assimilated in NWP systems has been rapidly increasing, nevertheless the value of scatterometer winds has been shown in several impact studies. ECMWF has a long experience with scatterometry regarding monitoring, validation, GMF development and assimilation. At the moment of writing this paper, METOP-A ASCAT and METOP-B ASCAT winds are assimilated into the Integrated Forecasting System (IFS). Until the beginning of 2014 also observations from the OCEANSAT-2 scatterometer were actively assimilated. Scatterometer data are also used in the Reanalysis. ERS-1/2 and QuikSCAT data were assimilated in ERA-Interim. The new ASCAT-A reprocessed dataset will be assimilated in the next Reanalysis dataset (ERA-5).

An extensive study has been performed in order to assess the benefit of the assimilation of scatterometer winds in our system. Some results from this study have been presented in this paper. Forecast Error Contribution statistics show that overall the scatterometer observations contribute to about 7% to the reduction of the forecast error. Regional statistics show that the largest impact is from the Southern Hemisphere where usually surface in-situ observations are lacking.

We have also verified the benefit of these observations on extreme events like tropical cyclones, particularly for the analysis and forecast of the sea level pressure. Results showed that the more observations are assimilated, the better is the forecast. It is then clear that it is important to have as many good quality observations as possible. A higher number of available datasets to be used in the assimilation also helps to have a more resilient system. Moreover, datasets with different temporal coverage are important to capture differences due to the diurnal cycle. Currently several scatterometer missions are operational but for some of them not yet used at ECMWF. RapidSCAT was launched by NASA in September 2014 and is now operational on the International Space Station (ISS). Another scatterometer is currently operating on board the Chinese satellite HY-2A. These two datasets will be evaluated soon. Their values lie also in the fact that their temporal coverage is complementary to ASCAT ones.

A good quality of surface winds is essential not only for the atmospheric and wave models but it is essential also for any oceanographic application since they affect many ocean parameters such as fluxes, ocean circulation, mixing layer, etc. Recent preliminary investigations demonstrated the benefit of the scatterometer winds assimilation on the ocean temperature down to the thermocline.

Single observation experiments were also run to verify the vertical propagation of the scatterometer wind informations. Results show that the 4D-Var is able to propagate the information from scatterometer observations in time during the assimilation window and in space to the upper troposphere.

Scatterometer winds have been extensively assimilated in NWP centres and many research activities have been performed since the first products were available. Nevertheless there are still many areas in which the quality of the scatterometer data and their assimilation can be improved.

The way the scatterometer winds are used should also consider the dependency from other geophysical parameters. We know for example that scatterometer winds represent winds relative to the moving sea surface. Therefore the ocean current should be considered in the observation operator. However accurate ocean currents are needed as input for this. At ECMWF different thinning strategies, spatial resolution products and observation errors will be tested. Also a review of the QC procedures, mostly for extreme events, will be considered.

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