Comparative analysis between operational weather prediction models and QuikSCAT wind data near the Galician coast


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Abstract

Wind measurements from SeaWinds scatterometer on the NASA QuikSCAT satellite and wind forecasts from two different operational numerical models provided by MeteoGalicia were compared for a 4-year period (2002–2005) in Galician coast environment. Available wind data buoy measurements were also used to complement the analysis. A statistical analysis based on mean errors, root mean square errors and complex correlation was performed from spatial, temporal and directional points of view.

In the spatial comparison no significant differences between models and satellite were observed and the error magnitudes of the models are compatible with typical QuikSCAT errors. The suitability of satellite wind estimations for data assimilation in these models must be further investigated. Negative bias of models with respect to the satellite was also confirmed with buoy data, in such a way that models overestimation is smaller than the satellite one. Big errors in wind direction appear in southeasterly and southwesterly winds for both satellite and models, contributing to high RMSE values when compared to buoy data. These errors were mainly attributed to the effect of insufficient spatial resolution near shore.

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1. Introduction

The NW Iberian Upwelling System is the northernmost limit of the Eastern North Atlantic Upwelling System, which extends from 10° to about 44° N (Wooster et al., 1976). Although the intensity of this upwelling system is not comparable to the major upwelling regions of the world (the Canary Current System; the California Current System; the Benguela Current and the Peru-Humboldt Current), it has attracted the interest of oceanographers since the 1970s (Wooster et al., 1976; Fraga, 1981; Tenore et al., 1982; Blanton et al., 1984; Alvarez-Salgado et al., 1993; Pérez et al., 1995; Prego and Bao, 1997; Alvarez et al., 2005).

The Galician coast, which lies within the NW Iberian upwelling system, can be macroscopically divided in three regions. The western coast, stretching from the Northern part of Portugal to Cape Finisterre, with an approximate angle of 90° relative to the equator; the
middle coast, from Cape Finisterre to Cape Ortegal, with an approximate angle of 55°; and the northern coast, approximately parallel to the equator.

Upwelling in the western Galician coast is generally a spring–summer process characterized by favorable northerly winds along the coast (Blanton et al., 1984). These events have important biological implications due to the high input of nutrients (Prego et al., 1999) that greatly influences the distribution patterns of larvae (Fusté and Gili, 1991; Rivero et al., 2004) and reared mussel production (Blanton et al., 1987; Figueiras et al., 2002) and sustains large sardine fisheries (Guisande et al., 2004). However, some out of season upwelling events have been also observed in fall or winter under northerly winds blowing at shelf (Alvarez et al., 2003; deCastro et al., 2006). This fact may have negative impacts in the productivity of this area. Dickson et al. (1988) and Borges et al. (2003) showed that a decline in zooplankton and phytoplankton in the North Atlantic and subsequent declines in the sardine fishery off the Portuguese coast are associated with increased southward winds. In addition, Santos et al. (2001) statistically showed that the intensity and frequency of upwelling events during winter (the spawning season) have a negative impact on the recruitment of small pelagic Portuguese fisheries.

Cape Finisterre marks the abrupt change in Galician shore line being frequently the site of a stationary upwelling maximum and a recurrent upwelling filament (Blanton et al., 1984; Haynes et al., 1993; Castro et al., 1994; Rocha et al., 1999; Alvarez-Salgado et al., 2001; Huthnance et al., 2002; Torres et al., 2003). It is a well known fact that capes and bays may induce significant variations in wind stress (Enríquez and Friehke, 1995; Dorman et al., 2000; Edwards et al., 2001; Perlin et al., 2004).

Upwelling is also present north of Cape Finisterre, although it is not a common fact. Prego and Bao (1997) studied the meso-scale characteristics of upwelling off the Galician coast and they indicated that Galician upwelling to the north of Cape Finisterre is discontinuous and remains distant from the coast (near the edge of the continental shelf). In addition, Prego and Varela (1998) obtained a detailed description, on a local scale, of the upwelling at Cape Prior. Moreover, they studied the hydrographic pattern of the Artabro Gulf during summer and described the confluence of ENACW_{st} and ENACW_{sp} water masses (Fiuza, 1984).

The wind regime over the Galician coast is mainly characterized by two different situations depending on the position of the Azores High and the Iceland Low. In winter, the Azores High is located farther south off NW Africa and the low pressure centre in Iceland, which tends to induce southwesterly winds on the coast. However, in spring and summer the Azores High moves to the north provoking high pressures with northerly winds on the coast generating frequent upwelling events.

During the last years, wind fields in this region have been analyzed taking into account different periods of time at different coastal areas. McClain et al. (1986) considered the wind driven upwelling using a grid of stations covering the continental shelf from Cape Finisterre to Vigo during April 1982. Batten et al. (1992) considered a numerical study of wind stress curl effects on eddies and filaments off the northwest coast of the Iberian Peninsula for a 40-day model simulation period. Pérez et al. (1995) studied the correlation between inter-annual variations in wind stress and changes in ENACW by means of the combination of data obtained from the eastern North Atlantic region from 1974 to 1992 and data obtained near the Iberian coast (around 42° N, 10° W) in 1991 and 1993. Torres et al. (2003) studied spatial patterns of wind in the Galician upwelling region by means of the QuikSCAT wind data for the period 1999–2001. Herrera et al. (2005) analyzed the wind field on the western coast of Galicia from in situ measurements provided by six meteorological stations for a 1-year period (2001–2001). Gomez-Gesteira et al. (2006) studied the Ekman transport close to the Galician coast calculated from forecasted winds using nine control points around the coast during 4 years (2001–2004). From these studies it was observed that wind field in this area is far from homogeneous due to the particular coastal geometry. Summer and winter wind fields have a small number of dominant patterns which are not necessarily representative because summer patterns may dominate in winter and winter patterns may dominate in summer depending on the coastal area. Therefore, wind observations at a single point, coastal or offshore, will not necessarily be representative of the wind conditions along the coast. To characterize in detail the wind regime over the Galician coast it is necessary to have wind data on an extensive area, which can be provided by numerical models and by satellite scatterometry. The high temporal and spatial resolutions of these products make them a useful tool to carry out this kind of analysis.

During the very last years, some works have been published with comprehensive statistical analysis of QuikSCAT data compared to numerical weather predictions. Perlin et al. (2004) performed a comparison of QuikSCAT data with several atmospheric products as the operational 40 km resolution NCEP Eta model, and two high resolution regional models, COAMPS and ARPS, with 9 km and 12 km of horizontal resolution respectively, in the summer (June to September) periods of 2000 and 2001. Changes in accuracies in ECMWF
and NCEP operational global NWP models were assessed by Chelton and Freilich (2005) comparing them with QuikSCAT and NSCAT data considering almost 3 years of data distributed in three time periods: September 1996–June 1997, August 1999–July 2000 and February 2002–January 2003, and they also discussed the influence of the assimilation of QuikSCAT observations in those models. A regional study over the Mediterranean sea has been performed by Accadía et al. (2007) verifying 0.1° horizontal resolution QBOLAM regional model outputs with QuikSCAT data and comparing both datasets with buoy measurements during a two year period from January 2001 to December 2002.

The aim of this paper is to make a comparative analysis between high resolution wind data provided by the Galician Meteorological Service, MeteoGalicia, and wind data measured by the QuikSCAT satellite for a 4-year period (2002–2005) near the Galician coast. Wind data provided by MeteoGalicia were obtained from two operational numerical models, the Advanced Regional Prediction System (ARPS) and the Mesoscale Model 5 (MM5). Wind data supplied by three buoys of Deep Water Network from Puertos del Estado—Clima Marítimo (PE-CM) agency were used, as well, with further validation purposes.

2. Wind data

2.1. QuikSCAT satellite

The SeaWinds scatterometer was launched on the NASA QuikSCAT in June 1999. The Seawinds instrument on the QuikSCAT satellite is a microwave scatterometer that measures near-surface wind speed and direction over the global oceans. It uses a rotating dish antenna with two spot beams that sweep in a circular pattern. The antenna radiates microwave pulses at a frequency of 13.4 GHz across broad regions on the earth’s surface. Wind speed and direction are inferred from a measurement of microwave backscattered power from a given location on the sea surface. Wind stress over the ocean generates ripples and small waves, which roughen the sea surface. The scatterometer uses an indirect technique to measure wind velocity over the ocean transmitting microwave pulses to the ocean surface and measuring the backscattered power received at the instrument. The instrument can measure vector winds over a swath of 1800 km with a nominal spatial resolution of 25 km. Daily coverage is about 92% of the global ice-free oceans.

Wind data were obtained from the Jet Propulsion Laboratory website (http://podaac.jpl.nasa.gov/quikscat/qscat_data.html). The data set consists of globally gridded values (0.25° × 0.25°) of zonal and meridional wind velocity components at 10 m over the sea surface measured twice daily since 21 July 1999. Wind speed measurements over this period range from 3 to 20 m s⁻¹, with an accuracy of 2 m s⁻¹ and 20° in direction. The small coastal masking effect of around 25 km allows the data to be used for studying near shore wind patterns and processes. The data from the ascending pass (0600 LST equator crossing) and the descending pass (1800 LST equator crossing) were daily averaged. Gaps in the data were objectively interpolated.

2.2. Numerical models

Two different high resolution numerical weather prediction systems, ARPS and MM5, have been used during the last decades as operational and research numerical weather prediction models by several institutions all over the world, and during the last 5 years they have been used for both operational and research purposes in the Galician Meteorological Service MeteoGalicia. Data from operational outputs of both models have been studied in this work.

The Advanced Regional Prediction System (ARPS) was jointly developed at the University of Oklahoma and at the Center for Analysis and Prediction of Storms (CAPS) (Xue et al., 2000; Souto et al., 2003). It is a non-hydrostatic atmospheric model and it uses a generalized terrain following the coordinate system defined for a compressible atmosphere. ARPS solves prognostic equations for the x, y and z components of the Cartesian velocity, the potential temperature, pressure, and the six categories of water substance (water vapor, cloud water, rainwater, cloud ice, snow and hail). The continuous equations are numerically solved using finite difference methods on an Arakawa-C grid. The model runs in two grids covering southwest Europe in a one-way nesting. The coarser grid has a 50 km horizontal resolution and 59 × 51 × 30 grid points, and the finer one covers Galicia with 10 km of horizontal resolution and 43 × 43 × 30 grid points. An optimal interpolation equivalent data assimilation scheme named ADAS (ARPS Data Assimilation Scheme) was implemented in the ARPS model over a 6-hour assimilation cycle since February 2004.

The non-hydrostatic Penn State University/National Center of Atmospheric Research 5th generation Mesoscale Model (MM5) version 3 (Dudhia, 1993; Grell et al., 1995) was also used. MM5 is also a fully non-hydrostatic model resolving an equivalent set of equations in a ω-pressure terrain following vertical coordinate system. In this case, a coarse grid with 30 km of horizontal resolution with 100 × 80 × 23 grid points covering a similar area than...
ARPS’s coarser grid is resolved feeding, in a two-way nesting, the $43 \times 43 \times 23$ grid points finer grid which covers exactly the same area, and with the same 10 km resolution, than ARPS’s higher resolution inner grid. These models run operationally twice a day, starting at 0000UTC and 1200UTC, with forecast horizons of 96 and 84 h respectively. The 1200UTC run was operationally released in March 2003, thus 0000UTC run is the only one available through the whole time period, so only results from this run were considered in this study. Initial and boundary conditions each 3 h are routinely obtained from NCEP GFS at 1° of horizontal resolution. Simulations between 1st January 2001 and 31st December 2003 were initialized with the 12-h forecast from the previous GFS run, while non-delayed, i.e. analyzed, GFS initial conditions have been used from 1st January 2004.

2.3. Buoy network

In order to complement the study, field data were obtained from three buoys moored near the Galician shelf break at least 40 km away from the coast line (Estaca de Bares at 44° 3.6′ N, 7° 37.2′ W; Vilán-Sisargas at 43° 29.4′ N, 9° 12.6′ W; and Silleiro at 42° 7.2′ N, 9° 24′ W, points in Fig. 1). These buoys, supported by the Spanish Agency Puertos del Estado, measure atmospheric parameters at the 3 m level every 1 h.

3. Results and discussion

3.1. Description

The performance of ARPS and MM5 models in the high resolution Galician grid described before and QuikSCAT measurements will be presented by means of an extensive validation for the period 2002–2005. This analysis consists of two different parts: the first one is a spatial comparison between results of numerical models over the ocean and indirectly measured QuikSCAT winds, while the second part is a comparison between satellite local wind data and both numerical models with in situ buoy measurements. In these comparisons, values for the complete four year period have been obtained, despite both monthly and direction dependent statistical results have also been obtained.

It has been defined an $18 \times 14$ grid with $0.25° \times 0.25°$ resolution covering an area from 41° 7.5′ N to 44° 22.5′ N in latitude and from 10° 22.5′ W to 6° 7.5′ W in longitude where QuikSCAT data were available. An upscaling interpolation of the 10 km (about 0.12°) numerical
Fig. 2. Mean Error (bars) and Root Mean Square Error (lines) for all directions (“ad”) and as a function of the direction. Number of data used in each calculation is shown in brackets.
Fig. 3. Spatial behavior of ME (upper row) and RMSE (lower row) of wind speed for ARPS (left column) and MM5 (right column) compared with QuikSCAT.
Fig. 4. Spatial behavior of ME (upper row) and RMSE (lower row) of wind direction for ARPS (left column) and MM5 (right column) compared with QuikSCAT.
Fig. 5. Spatial behavior of module (upper row) and phase (lower row) of complex correlation for ARPS (left column) and MM5 (right column) compared with QuikSCAT.
models data has been done to allow this comprehensive spatial wind validation. Due to the coastal shadowing effect in the satellite data, only those values where every model grid point was a sea point have been used to interpolate to QuikSCAT grid. As shown in similar works (Accadia et al., 2007) such undersampling process usually assures the absence of changes in the statistical characteristics of the data set. Moreover, grid points with availability of data below 75% have been considered affected by land shadow in the QuikSCAT data, so they have been removed from the analysis. In such a way, from the original 18 × 14 grid, they only remain about a hundred of valid grid points.

Zonal and meridional components of wind have been chosen to interpolate, and afterwards wind speed and direction were calculated. Hourly data from 10-m wind model outputs and buoy data between 0500UTC and 0700UTC and between 1700UTC and 1900UTC were averaged to be respectively compared with the ascending and descending pass of satellite data. So, forecast lengths of about 6 and 18 h from the 0000UTC run have been used. Only wind data within the range of operation of the scatterometer (3–20 m s\(^{-1}\)) have been used.

Despite some other statistical indices that have been obtained, only mean error (ME), mean absolute error (MAE), root mean square error (RMSE) and complex correlation will be presented in this paper. Moreover, separate calculations for both ascending and descending satellite passes have been performed in order to study the role of the forecast lengths in this analysis, but unbiased differences between the descending pass (1800UTC) and the complete two passes datasets have been obtained with magnitudes around 5–10% of the RMSE. In this way, with these slight differences due to forecast length, only results from the complete dataset will be discussed later in order to include a more significant number of data and then a higher frequency 12-hour sampling instead of a daily basis.
3.2. Spatial comparison

The gridded QuikSCAT and both ARPS and MM5 data have been compared in detail in each grid point for the complete period of time on a monthly basis both for all directions (labelled as “ad”) and on a 45°-width sectors classification (labeled as “N”, “NE”, “E”, “SE”, “S”, “SW”, “W”, and “NW”). This directional classification has been done using QuikSCAT direction as the sector defining direction.

The main feature derived from the analysis for the entire grid and for the complete period is a performance of both models compatible with satellite accuracy. Values of MAE of 2.1 and 2.0 m s\(^{-1}\) in wind speed and 20.3° and 20.2° in direction, for ARPS and MM5 respectively, denote an average behavior of the models within the estimated values of satellite errors. ME (bars) and RMSE (lines) for both models are plotted in Fig. 2 showing values of RMSE slightly higher than MAE: 2.8 m s\(^{-1}\) in wind speed and 31.1° in direction for ARPS and 2.6 m s\(^{-1}\) and 31.1° for MM5, which assure that extreme errors seldom occur. Despite biases for zonal (u) and meridional (v) components have positive values: 0.2 m s\(^{-1}\) and 0.4 m s\(^{-1}\) for u and 0.9 m s\(^{-1}\) and 0.7 m s\(^{-1}\) for v, wind speed simulated by both models is slightly negative biased (−1.2 m s\(^{-1}\) for ARPS and −0.8 m s\(^{-1}\) for MM5). This fact can be due to bigger wind errors in the first quadrant, where both u and v are negative. In addition, these wind directions are also the most common in this area, increasing the relative weight of these errors in the average value. Then, as it can be observed in Fig. 2, modeled winds systematically show smaller speeds than satellite ones. Relative errors have been also studied for wind speed, throwing biases of −8.1% for ARPS and −3.7% for MM5 with RMSE values of 32.2% and 32.3% respectively. Moreover, almost no additional information was provided by relative errors in the directional study.

Direction biases show no significant differences between models and satellite for the averaged grid value, but a sign difference appears between ARPS and MM5 bias, with values of −0.8° and 4.4° respectively. As it will be confirmed with buoy statistics, this phase shift...
seems to be a characteristic of each one of the models. Despite the global value of ME is small, it seems that some problems arise in southeasterly winds, where both ME and RMSE show magnitudes higher than on the rest of the directions (Fig. 2). Southeasterly winds in this area are associated with very unstable situations with a weak synoptic forcing, giving place to very changeable winds. Thus, this kind of weather systems present usual difficulties in its forecasting, but they also present a very low frequency of occurrence, hardly affecting that global value.

The spatial behavior of the errors in wind speed (Fig. 3) and direction (Fig. 4) is analyzed by means of ME and RMSE values for both models. From this point of view, no representative spatial differences in ME and RMSE are present in wind speed, so a homogeneous spatial behavior of modeled wind speed is found with respect to the satellite estimated ones, while an increase on direction bias near the shoreline is shown. This increase is possibly due to the higher resolution of the models in comparison with the satellite one, which gives the numerical forecasts the ability to resolve wind features near shore that satellite is roughly able to estimate.

Similar results may be attained with the complex correlation (Kundu, 1976), which is a more suitable correlation index for vectorial quantities than classical Pearson correlation (Wilks, 1995). The complex correlation is calculated as a vector and it gives additional information of the correlation of two vectors regarding not only module correlation but also phase shifts. Gridded values of module and phase of complex correlation of both models compared with QuikSCAT are plotted in Fig. 5, while Fig. 6 shows the averaged grid values for each octant. Complex correlation modules shown in the upper row of Fig. 5 have a quite homogeneous spatial behavior, and a great degree of correlation between model and satellite data can be observed with values near 0.90 just suffering a slight decrease as we approach to the shoreline. The same effect is also shown in the lower row of the Fig. 5 with the complex correlation phase plots. Moreover, differences between direction biases of the two models are pointed out with global phase values of 1.26° for ARPS and −4.4° for MM5. It may be noted that different sign criterions for direction bias were considered, so positive ME values are defined clockwise, while complex correlation of each model data compared with QuikSCAT gives place to positive counter clockwise values. Once again, in Fig. 6 it can be observed that there are some problems in southeasterly winds, with an important change in complex correlation phase for both models and a significant decrease in complex correlation module.

Looking at the monthly evolution of bias and RMSE shown in Fig. 7, a seasonal behaviour appears in ME and RMSE of wind speed, with higher negative values of the errors in winter. By the other hand, as it would be expected, after successive changes and updates in model configuration some improvements appear in the model performance compared to satellite, which could be also additionally related to a better estimation of initial fields provided by GFS. Thus, a progressive removal of the bias between the models and the satellite data is shown since April 2003, and also a slight decrease in wind speed ME and RMSE. At that time, one of the main changes in the models configuration during the period 2002–2005 took place, with a new grid nesting scheme which hardly affects wind results in the ocean where lateral boundary conditions remain relevant, although other model variables as precipitation achieved a very much better performance. The other great update of the model systems was the inclusion in February 2004 of the ARPS Data Assimilation System (ADAS), and just a slight improvement on wind direction can be noted, but no other significant differences are shown in this area due to the lack of assimilation of oceanic meteorological data, only data from some surface stations and radiosonde from the Azores and Madeira Islands are ingested in that area. ARPS wind speed and direction errors tendency shows a light improvement slope during the last months after inclusion of ADAS.

One of the main relevant effects in the sea surface boundary is the momentum removal related to sea waves,
resulting in different effective roughness lengths. Wave drag have different effects depending on the characteristics of the waves (significant height, wave shape and stage of development, etc) in a bidirectional interaction in such a way that roughness lengths depend on both wave characteristics and wind module. This 2-way interaction exceed the scope of this paper, so the simple assumption of constant roughness over the ocean has been assumed in the models, but as it was stated by Janssen (2004) operational coupling of meteorological models with wave models have shown an ability to remove about a 10% of wind speed RMSE.

It should be also noted that for a more comprehensive comparison, additional effects, as atmospheric stability and surface ocean currents, should be taken into account. QuikSCAT estimates wind speed and velocity as if it were in a neutral stable atmosphere, while modeled winds are direct outputs resolved in the specific stability conditions. Anyway, Chelton and Freilich (2005) showed that stability effect does not have a very significant contribution and, on the other hand, in summer conditions where this effect can be non-negligible, atmospheric instability produced by elevated sea surface temperature may appear balanced by typical summer upwelling events in this area and their effects in the sea surface temperature. The presence of great surface currents could affect the comparison of modeled winds with indirect satellite measurements, so an absence of such significant currents in the area under study leads to a negligible influence of this issue in the showed results. Moreover, studies in the area in the framework of the Prestige disaster (Balseiro et al., 2003) had noted that even a simple wind drift model performed very well the oil spill evolution main features.

3.3. Buoys comparison

The second part of the analysis comprises the comparison of the numerical results and the satellite data with buoy measurements. In the 0.25° resolution grid, common to undersampled models and satellite data, the grid point
closer to each one of the buoys was chosen to the comparison. Buoy data have been considered the real data set to be compared with the rest of the wind data (QuikSCAT, ARPS and MM5). Thus, directional classification of the data at each buoy location has been done using the corresponding buoy data as the sector defining direction. In this second part, a smaller, even though significant, data set has been used due to a higher unavailability of buoy data with respect to satellite.

The first issue that can be observed is that QuikSCAT ME and RMSE show systematically higher values for wind speed than both numerical weather prediction models (Table 1).

Wind speed from numerical models had a negative bias when compared with QuikSCAT, so in statistical terms, QuikSCAT wind velocities are bigger than wind speed from numerical models and also bigger than buoy’s data. This confirms that forecasted wind speed was biased with respect to the satellite in the right direction. Moreover, differences in ME between models and satellite in these three singular points agree with values obtained in the previous study for the whole 0.25° grid, and because of the spatially homogeneous results obtained there, it can be assumed that a similar behavior occurs everywhere in the area under study. On the other hand, RMSE values also show an improvement of model results compared to the satellite. No important differences appeared between the statistical indices in the three buoys. Additionally, relative errors for wind speed confirm this behavior with similar results for ARPS and MM5 (biases of 9.5% and 13.2% and RMSE of 36.6% and 37.1%) while QuikSCAT shows a poorer performance with a bias of 22.4% and a RMSE of 44%.

Results for wind direction, also shown in Table 1, confirm some of the issues already studied in the previous comparison. In this way, values of ME are small and there are no big differences between models and satellite. Just a slight tendency to positive biases in MM5 and negative values in ARPS, and also in QuikSCAT, seems to appear systematically, and it could be possibly related to differences in the design of the models such as equations discretization and grid geometries. In addition, uncertainties in representing friction over sea surface could also have a significant role. Another important item of this comparison is the high value of the RMSE for both models and also satellite, here, the improvement in model RMSE with respect to satellite is not as significant as it was for wind speed. This high RMSE values, together with small values of ME, may suggest that some sort of randomness is present, nevertheless some other important elements arise in the directional study, as it will be discussed below.

Fig. 8 shows the results of the global comparison in the three buoys from a directional point of view, so both ME and RMSE for wind speed and direction are shown for the satellite data and numerical models.

QuikSCAT systematically gives an overestimation of wind speed for all directions, while numerical models also show an overestimation, even though it is systematically lower than satellite bias. Just some effect of subestimation appears in numerical models for winds coming from the northeast, and maybe a similar effect balances the bias in the easterly winds. Usually this winds are associated with anticyclonic circulation, the most frequent situation during the summer, giving place to moderate winds that may be accelerated in this approach to the continent specially around Cape Finisterre, and even the models seem to be able to also describe this effect with their small bias values, this particular wind configuration gives place to that light subestimation. As it was stated in the entire grid model-satellite comparison, no additional information is provided by relative errors from this directional point of view.

Important big errors in southwesterly and southeasterly winds appear (Fig. 8), specially in this last one, while for the rest of directions small values of bias and values of RMSE of about 20°–30° were obtained, which agrees with QuikSCAT known performance. That two particular results have a great contribution in the big RMSE values presented in Table 1, in the case of southwesterly winds encouraged by their relatively high occurrence as predominant autumn and winter winds, and in the case of southeasterly winds provoked by an extremely high RMSE value despite these are rare winds from the local climate point of view. Southeasterlies errors seem that it must be a problem of resolution, with wind direction neither adequately resolved by satellite measurements nor by the numerical forecasts, due to the high spatial variability of the winds under this weak synoptic configuration. On the other hand, an inadequate spatial resolution, common to both models and satellite data, compared to the typical size of frontal systems, may be responsible of the direction bias in southwesterlies, affected by these post-frontal changes in direction from southwest to northwest, that cannot be well resolved neither by models nor satellite, compared to in situ buoy measurements.

4. Conclusions

A comprehensive statistical comparison between QuikSCAT satellite wind measurements, high resolution numerical models from MeteoGalicia agency and buoy data from Puertos del Estado was carried out close to the Galician coast in the period 2002–2005.
High resolution local numerical models compared to satellite wind estimations show a behavior within the limits of confidence of the satellite scatterometer, so they could be used for similar purposes than the satellite, with the additional advantage of being forecasted data, available in advance. Bigger differences in this comparison appear in wind direction bias near the coast, where high resolution modeling presumably should offer better results. Moreover, ARPS and MM5 seem to present slight systematic differences in wind direction biases that could be due to differences in numerical design and model characteristics.

The two data sets show similar results when compared to buoy data, with better results for numerical forecasts in ME and RMSE for both wind speed and direction. Positive biases in wind speed were obtained, and just a slight subestimation appears in wind models under anticyclonic conditions. Anyway, as well as satellite measurements, high resolution models present significant high errors in wind direction in southeasterly and southwesterly winds. These may be caused by very high resolution local effects near shore not resolved neither by the models nor the satellite in the case of weak synoptic forcing with very changeable southeasterly winds, and in a similar way in the rapidly veering wind environment associated to frontal systems.

These results show that there is a high compatibility between models and satellite data sets, so further work in QuikSCAT data assimilation in the models must be done to investigate its impact on improving the forecast results. Even though a slightly better performance of the models has been shown in the near shore buoys locations, QuikSCAT satellite data have their strength in the high spatial frequency over the ocean where it could cover the usual lack of observations, contributing then to a better description of the surface wind field within the data assimilation process.

Further work should be also done to study the role of the roughness lengths over the ocean and the two-way coupling of ocean waves and meteorological models.

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References


