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Comparison of ALADIN and IFS model wind speeds over the Adriatic

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The wind output from atmospheric models is instrumental in forcing the oceanic models. Here we consider the wind output from the ALADIN and IFS models and compare it with the results of scatterometer and altimeter estimates of wind speed over the Adriatic Sea, as well as with the field data from 18 meteorological stations and a gas rig platform. A five-year period from 2008 to 2012 is considered in the comparison. Our principal conclusion is that, overall, both atmospheric models, when compared to the altimeter data, give very similar statistical results, with a scatter index of 0.33 and 0.35 for IFS and ALADIN respectively. More specifically, the ALADIN appears to be better in the Northern Adriatic whereas the IFS seems superior in the Southern Adriatic. A possible explanation of this difference could be that the higher spatial resolution of ALADIN is crucial in resolving the bora wind impact over the Northern Adriatic.

Key words: altimeters, scatterometers, wind fields, models

INTRODUCTION

The output of atmospheric models like wind fields, temperature, heat flux etc. is commonly used as a driving mechanism for ocean models. The complexity of ocean models can range from simple barotropic ones, i.e. storm surge models, needing only pressure and wind forcing fields to full baroclinic models requiring variables for bulk formulations of heat and water exchanges. Recently, atmospheric and ocean models have become tightly coupled (DUTOUR SIKIRIĆ *et al.*, 2013) in order to provide better physical representation of the ocean-atmosphere processes. In all these models and coupling variants the wind turns out to be the primary forcing variable, significantly affecting other variables. As a consequence, it is important to estimate the quality of the wind input of oceanic models. Another issue for discussion is the spatial extend of the models, i.e. the geographical region that is covered.

Nowadays, there are several Global Circulation Models (GCM) products available (GFS, IFS/ARPEGE, UM). These are operated by various agencies (NCEP, ECMWF, Météo France, Met Office) providing the necessary atmospheric fields. Such models usually use data assimilation in order to improve their forecasts but typically operate at a relatively coarse resolution. In contrast Limited Area Models (LAM) are commonly used by national institutes and have a higher horizontal resolution and use data from GCMs as a lateral boundary condition. Data assimilation is a key aspect of running operational atmospheric models. However, many meteorological institutes runs LAMs without data assimilation. When assimilation is run with LAMs it is more likely to be 3DVAR than a more complex ensemble or 4DVAR scheme. An essential factor for the quality of a LAM is the quality of the boundary forcing obtained from the GCM.

Here, we consider the special case of the Adriatic Sea and look for comparison between forecast wind speeds and station measurements and satellite estimates. SIGNELL *et al.* (2005) used output from four meteorological models to assess the quality of surface winds over the Adriatic Sea for March-April 2001. The authors found that "the high-resolution models provide not only more highly detailed structure, but significantly stronger and more accurate overall wind speeds". Nevertheless, they point out that even when tested LAM models provide significant improvements they cannot correct possible spatial and temporal inadequacies imposed by GCM data used at the open boundaries. When used directly the IFS fields were found to underestimate the wind magnitude and failed to reproduce some known spatial structures of strong wind events (like the bora).

In general, models tend to underestimate the wind field over the Adriatic (BERTOTTI & CAVALERI, 2009). For the bora wind, this is well known and explained by the complex orography of the Dinaric Alps (KUZMIĆ *et al.,* 2006). The orography also appears to have quite an important effect for sirocco wind (PASARIĆ *et al*., 2007). In SIGNELL *et al.* (2003) the wave response of the wind field was used as an indirect measure of the wind quality over the sea in comparison with the Acqua Alti station data. The underestimate of significant wave height by LAMI and COAMPS limited area models was considerably smaller than the underestimate by the global IFS model. Interestingly, it was found that that the correlation for observed wind data was better with IFS fields. This phenomenon is also discussed in HERRMANN *et al.* (2011) where it is concluded that the assimilation of QuikSCAT data in IFS was responsible for better correlation results.

A common approach to reducing errors is to rescale the wind speed by a factor that may be constant or spatially varying. This approach was pioneered by CAVALERI & BERTOTTI (1996) who reported significant improvements for the resulting WAM model forecasts of the wave height and wave period. The approach was extended to the whole Mediterranean in PETTENUZZO *et al.* (2010) for most of the prognostic fields provided by ERA-40. It was found that the underestimate can reach 50% for wind speed in some regions. For SST the bias was less than 0.1 K, for the heat flux, the bias is about -5W/m2 while for the freshwater flux the bias is -0.64m /year.

When it comes to wind field validation one has the choice of three data sources: anemometer, altimeter and scatterometer data. CHEN (2004) investigated systematic discrepancies among three kinds of wind estimates (the IFS model, TOPEX altimeter and NASA NSCAT scatterometer). Satellite-derived wind speeds (the altimeter and scatterometer) were found to have a larger overall bias but a much smaller overall rms discrepancy compared to IFS winds. Such a result suggests a systematic discrepancy between the model and satellite measurements, but an otherwise convergent outcome. The authors also noted "phase opposition" in latitude, season, and wind intensity between the TOPEX and NSCAT wind speed biases. The absolute value of the bias was smallest near the equator for both products, but increased towards the poles, positively for the altimeter, and negatively for the scatterometer. The biases also exhibited different non-monotonic dependence on the wind speed. The altimeter bias was low at low and high wind speed and high in the mid-range, whereas the scatterometer bias exhibited an inverse pattern (being high at both ends of the speed range, but low in the middle). In a similar intercomparison study, YANG *et al.* (2011) performed a comparison of the U.S. Navy NOGAPS model wind, wind speed measurements from the ENVISAT synthetic aperture radar (ASAR) and the MetOp-A scatterometer (ASCAT), and the U.S. National Data Buoy Center's moored buoy data. More specifically, the ASAR-derived winds were compared with collocated and coincident ASCAT scatterometer and NOGAPS model wind estimates. The authors found the ASAR-derived ocean surface wind speeds as accurate as the ASCAT and NOGAPS wind products. It is worth noting that their comparisons between ASCAT winds and synthetic aperture radar (SAR) winds averaged at different spatial resolutions show very little change. The COTTON (2009) report compares ocean surface wind speeds from QuikSCAT with wind data from the radar altimeter on board ERS-2 and several field data sources, using the Met Office model data as the background. ERS radar altimeter data were extracted daily from a database for a period of 32 days (some 21,500 useful wind speed observations each day from 1 February to 4 March 2009) and collocated with QuikSCAT observations over the same period. The radar altimeter wind speeds are not assimilated in the Met Office model, and therefore provide an independent source of observations. The radar altimeter winds agreed better with the uncorrected QuikSCAT wind speeds (the scatterometer exhibiting a small fast bias of +0.16 m/s) than the bias-corrected QuikSCAT winds (the scatterometer showing larger negative bias of -0.64 m/s).

The goal of this paper is to consider the question of whether or not LAMs should be preferred to GCMs in providing wind field estimates in the limited geographic setting of the Adriatic Sea. To this end the wind outputs from the ALADIN limited area model used by DHMZ and the global IFS model used by ECMWF are compared with altimeter 10 m wind speed estimates, scatterometer estimates of the wind vectors, and with field measurements. The paper is organized as follows. The models and data sources are briefly presented in the second section. The results of various inter-comparisons are presented and discussed in the third section. The conclusions obtained from the study are summarised in the final section.

Similar studies were conducted in ARDHUIN *et al.* (2007) using the ALADIN and COAMPS limited area models and the ARPEGE and IFS global models for two one-month periods for the Mediterranean Sea. The comparison shows that ALADIN has a systematically larger error in scatterometer and altimeter comparisons. For buoys, the comparison shows IFS to be better for the first period and worse for the second one. In BERTOTTI & CAVALERI (2009) the differences between modelling winds and waves in the Mediterranean Sea and in the Adriatic are discussed. It is concluded that while further resolution improvements are unlikely to help substantially improve forecasts in the Mediterranean, they are more likely to bring improvements for the Adriatic due to the more significant orographic effects. In addition, it is argued that the global model that is used is the most important aspect of a successful limited area model. In PASARIĆ *et al.* (2007), the ALADIN 8 km model and IFS are compared in 63 sirocco episodes in 2002-2003. It is concluded that the IFS wind does not correctly resolve the wind near the coast due to its much smoother orography but no measurements or satellite estimates are used. Another study by BERTOTTI *et al.* (2014) considers the March – April winds and waves in the western Mediterranean. The global models considered are GFS and IFS, and the limited area models are the WRF one (SKAMAROCK & KEMP, 2008) at 12 km and COSMO (BONAVITA *et al.*, 2010) at 7 km. The results show consistently better results from the IFS and GFS models with respect to WRF and COSMO when compared with the ASCAT scatterometer and ENVISAT altimeter. The use of WRF at 4 km did not yield improvements. In addition, IFS turns out to be better than GFS. The possible reasons for the worse performance of the LAMs were considered, one of them being an increased sensitivity to errors in their boundary conditions. In HORVATH *et al.* (2011) ALADIN results with or without dynamical adaptation were compared with ERA-40 re-analysis (UPPALA *et al.*, 2005) for three coastal stations at Novalja, Split-Marjan and Dubrovnik. It was found that dynamic adaptation systematically improves results. The ALADIN model was also better at the stations except at Dubrovnik where ERA-40 was better. It should be borne in mind that ERA-40 is based on the T159 version of IFS and that the version used operationally is T1279. In MARTIN *et al.* (2009), the output fields of the ALADIN model are used for forcing the NCOM model (MARTIN, 2000) in order to study the impact of the bora wind on the western Adiatic current. It was found that the wind is aligned with the direction of the current.

MODELS AND DATA USED

Altimeter data

Altimeters were originally designed for providing estimates of sea level. However, it is actually possible to estimate the surface wind speed by using the altimeter backscatter coefficient σ_0 .

The error estimated in WITTER & CHELTON (1991) is of about 2 m/s. However, the relations are empirical and σ_0 depends on wind speed, sea wave height and wave age. The data used was retrieved from the IFREMER ftp site; a detailed description of the used parameterisations can be found at ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/previous_versions/altimeter_wave_merge__9.0__annexe_II.pdf. Error estimates have been calculated in QUEFFEULOU (2003) for the satellites available at the time, and the errors are always less than 2 m/s. Model results were interpolated in time and space on the track of the altimeter. The interpolation method used is first order in time and space, which is more than adequate here. In Table 5 the specifications of the used altimeters are given.

Scatterometer data

Scatterometers also provide estimates of wind by emitting microwaves and measuring the radar cross section σ_0 . In addition to the altimeter, they also provide estimates of 10 m wind speed and direction over a larger geographical region. Estimates of QuickSCAT vs altimeters are computed at: http://cersat.ifremer.fr/data/products/cal-val/quikscat/quickscat-vs-altimeters. For ERS-2, they indicate a mean deviation of 0.13 m/s and a standard deviation of 1.61 m/s. Other estimates in TANG (2004) using coastal buoys, give a standard error of 1.83 m/s for wind speed. It should be pointed out that scatterometer estimates can also be used for the forcing oceanic model (BARNIER *et al.,* 1991). Sparsity is then compensated for by using extrapolation methods. The scatterometer results are gridded, and at every grid point there is an average of the signal at that point. Thus, our approach is to take the average of the model results contained in the region. In LIU & TANG (1996), it is argued that scatterometer results should be interpreted as equivalent neutral winds, while in VON AHN *et al.* (2006) such an approach is followed for the purpose of comparison. In DUTOUR SIKIRIĆ *et al.* (2012, 2013) we reported improvements by using neutral wind speeds as opposed to 10 m wind speeds. The neutral winds were obtained by using the bulk flux parameterisation of the ROMS model and other prognostic fields provided in the forcing files. The correction is most significant near the coast, and the effect is of around 0.1 m/s over the final statistics. Here, we directly compare the scatterometer wind fields with the model results, and assume neutrality. A comparison using neutral wind speeds would be more complex to do, since it would require an estimate of the stability functions which also depends on the thermodynamic parameters.

Anemometer wind measurements

Measurements of wind speed and direction at 18 meteorological stations and the Ivana A gas platform were also available (see Figure 1 for positions and Table 1 for other information). We obtained altitude information from DHMZ (http://prognoza.hr/karte_postaja.php?id=glavne) and from Google Maps (GM) and the Shuttle Radar Topography Mission (SRTM). For SRTM, error estimates for Eurasia are about 6.2 m (RODRIGUEZ *et al.,* 2005)

Table 1. Names, Longitudes, Latitudes, anemometer heights, altitude, number of data of stations and chosen extrapolation method to 10 m sensor height (none if the sensor is at 10 m, Charnock coefficient method near the sea or logarithmic profile with chosen roughness length)

Name	Lon (deg)	Lat (deg)	Sensor Height	Altitude	Nb meas.	Extrapol. Meth.
Palagruza	16 15	42 23	8 m	98 m	37077	profile z=0.03
Prevlaka	18 31	42 23	10 m	68 m	38210	none
Dubrovnik	18 05	42 38	10 m	52 m	36982	none
Lastovo	16 54	42 46	14 m	186 m	33297	profile z=0.03
Ploce	17 26	43 02	10 m	2 m	39832	none
Hum Vis	16 05	43 02	15 m	587 m	33748	profile z=0.03
Hvar	16 26	43 10	15 m	20 m	40074	profile z=0.03
Makarska - Pozari	17 01	43 17	15 m	52 m	38912	Charnock
Split - Marjan	16 25	43 30	12 m	122 m	40986	profile z=0.03
Sibenik	15 54	43 43	10 m	77 m	39091	none
Zadar	15 12	44 07	10 m	5 m	43565	none
Veli Rat	14 49	44 09	10 m	2 m	28383	none
Mali Lošinj	14 28	44 31	10 m	53 m	43176	none
Ivana A	13 17	44 44	10 m	0 m	39621	none
Rab	14 46	44 45	12 m	24 m	42522	profile z=0.03
Poreč	13 53	44 45	10 m	5 m	33370	none
Senj	14 54	44 59	10 m	26 m	42874	none
Sv. Ivan na Pucini	13 36	45 02	10 m	8 m	24217	none
Rijeka	14 26	45 20	10 m	120 m	43595	none

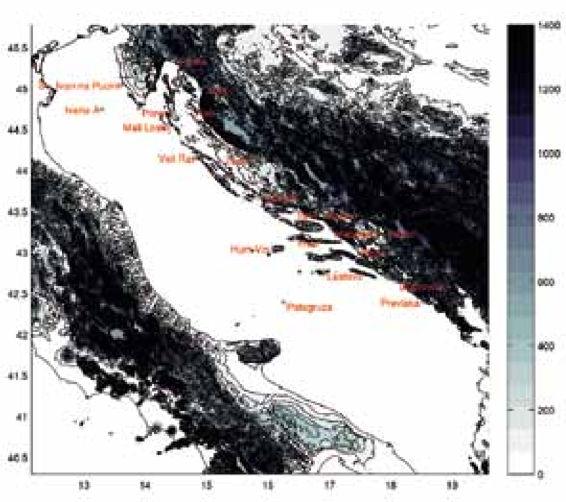

Fig. 1. Geography of the Adriatic sea and position of the meteorogical stations used

with negligible mean error. No error estimates were available for GM, but they were found to be within 6 m of SRTM for all data points. The altitudes reported on the DHMZ web-site were broadly similar with a maximum difference of 24 m for Lastovo, with SRTM reporting 161 m. Unfortunately, we do not have sensor height information for the gas station and simply assume it was 10 m based on photos. In principle model output is available at 10 m over the ground. For buoys, the methodology of BIDLOT *et al.* (2002) is to assume neutrality and a Charnock coefficient of 0.018; the wind at 10 m is then estimated by an iterative scheme. It seems reasonable to us to apply such a heuristic to stations such as Porer, Palagruža, Sv. Ivan na Pucini and Veli Rat, which are either lighthouses or very near to the sea and open on all sides. For land stations, the parameterization has to be different and the closure would depend on a parameterisation of the roughness: one possibility to use a simple power law rule with a coefficient of 1/7 (PANOFSKY & DUTTON, 1984), another one to use a logarithmic profile with an estimated value of roughness length. We choose to use logarithmic profile approach in that case since it is more physical. Table 1 gives for all stations the chosen extrapolation method.

The ALADIN model (http://www.cnrm.meteo.fr/aladin/ and TUDOR *et al.,* 2013) is a hydrostatic meteorological LAM model that uses spectral methods for its advection. The 8 km ALADIN grid in the implementation used by DHMZ covers the whole Adriatic domain from 4 to 24 degrees east in longitude and 36 to 52 degrees north in latitude. The lateral boundary conditions are obtained from the ARPEGE model (DEQUE *et al.,* 1994). The model is run every 12 hours. We chose, for the purpose of comparison, to use forecasts from T+12h to T+24h. The ALADIN model provides estimates of surface fields every 3 hours at a resolution of 8 km. A dynamic adaptation system (IVATEK-ŠAHDAN & TUDOR, 2004) was also used in order to provide 2 km estimates of wind speed on a grid from 10 to 21 degrees east in latitude and 39 to 47 degrees north in longitude. We had access to 2 km wind speeds from 1 January 2008 to 31 of December 2013. From 7 November 2011, ALADIN used 3DVAR assimilation for improved results and analysis so we provide a separate analysis for the period from 7 November 2011 to 31 December 2012. For 8 km fields, we only had access from 15 August 2007 to 15 December 2008. The ARPEGE model assimilates data, in particular scatterometer data, using a 4DVAR scheme.

The IFS model (http://www.ecmwf.int/research/ifsdocs/) is a hydrostatic meteorological GCM that is used by ECMWF. It uses semi-Lagrangian advection for its advection. In the implementation used by ECMWF, i.e. T1279, the spectral resolution of the model is 16 km. In order to deal with orographic effects, the model has a representation of sub-grid scale orographic drag. In addition, IFS is coupled with the WAM 3rd-generation wave model that provides Charnock coefficients for use in surface stress parameterisation. JANSSEN *et al.* (2001) has a detailed discussion of the coupling and its positive impact on significant wave height but also on other synoptic variables such as geopotential and wind speed. IFS uses assimilation from a variety of measurements with ensemble and/or 4DVAR schemes. The fields that are used are the analysed fields, i.e. they are not forecasts. Scatterometer estimates of wind speed and direction are used for the assimilation. However, altimeter estimates of wind speeds are not used in the assimilation but instead are used for validation purposes. Altimeter estimates of wave heights are assimilated in the WAM model used by IFS. It should be pointed out that the ECMWF operational system underwent 12 version updates in the period 2008-2012 (from 32r3 to 38r1), and therefore we cannot divide the analysis according to the model version.

RESULTS AND DISCUSSION

We will now compare the model results with the stations, altimeters and scatterometers. We will start first with the stations which we expect to be the most reliable measurements. Our general strategy is to linearly interpolate the model results to the time and space where the station measurements or satellite estimates were made. Below ME means mean error, i.e. the difference between the mean interpolated values from the model and the mean values that have been measured or estimated. RMSE means root mean square error, i.e. the square root of the mean of the square difference between the model and estimate. The scatter index SI is defined as the quotient of the root mean square error by the mean measured value. The scatter index is non-dimensional and so is a good tool for estimating the quality of a model. We should point out that the most interesting aspect for applications and the most challenging part of the comparison is the wind between the islands. However, neither scatterometers nor altimeters help in this comparison, since the satellite cannot provide reliable data for these regions.

Models and Station comparison

In Table 2 the MEs and RMSEs are given for the 19 stations under consideration and in Table 3. for the daily averaged statistics. The problem that we face is that the stations that we are considering are not buoys and so we have to discuss them one by one. We start first with the comparison for the Porer and Sv. Ivan stations, which are lighthouses and for which there are

Table 2. Mean error (ME) and Root Mean Square Error (RMSE) of ALADIN 2km and IFS modeled wind speed (m/s) compared with anemometer measurements at meteorological stations for the period 1 January 2008 to 31 December 2012. Total number of measurement is 719532

Name	ME ALADIN	ME IFS	RMSE ALADIN	RMSE IFS
Palagruza	-1.62	-0.59	3.19	2.94
Prevlaka	-1.77	-0.78	3.23	2.74
Dubrovnik	-0.66	0.34	2.64	2.26
Lastovo	-0.33	0.65	2.17	2.43
Ploce	0.69	1.7	2.15	2.81
Hum Vis	-0.7	0.34	2.4	2.55
Hvar	0.39	1.43	2.04	2.55
Makarska - Pozari	0.57	1.62	2.45	3.14
Split - Marjan	0.08	1.09	1.98	2.32
Sibenik	-0.01	0.99	2.35	2.69
Zadar	0.22	1.25	2.36	2.82
Veli Rat	-0.71	0.23	2.75	2.8
Mali Losinj	-0.01	1.01	2.14	2.68
Ivana A	-1.34	-0.28	3.25	3.12
Rab	1.34	2.35	2.35	3.28
Porer	-1.7	-0.76	3.47	3.13
Senj	-0.88	0.13	3.81	3.88
Sv. Ivan na Pucini	-0.95	-0.08	2.86	2.9
Rijeka	1.27	2.31	2.31	3.38
Total	-0.26	0.75	2.67	2.91

Table 3. Same as Table 2 for daily averaged files.

Nama	ME ALADIN	ME IFS	RMSE ALADIN	RMSE IFS
Palagruza	-1.62	-0.59	2.5	2.12
Prevlaka	-1.77	-0.78	2.5	1.89
Dubrovnik	-0.66	0.32	1.79	1.37
Lastovo	-0.33	0.65	1.47	1.81
Ploce	0.69	1.69	1.36	2.32
Hum Vis	-0.7	0.33	1.7	1.83
Hvar	0.4	1.43	1.43	2.09
Makarska - Pozari	0.57	1.62	1.73	2.56
Split - Marjan	0.09	1.1	1.31	1.77
Sibenik	0	1	1.61	2.07
Zadar	0.22	1.25	1.51	2.13
Veli Rat	-0.71	0.22	1.96	1.98
Mali Losinj	0	1.01	1.37	2.05
Ivana A	-1.37	-0.3	2.56	2.28
Rab	1.34	2.34	1.88	2.89
Porer	-1.7	-0.76	2.74	2.24
Senj	-0.9	0.11	3.21	3.21
Sv. Ivan na Pucini	-0.95	-0.08	2.08	2.01
Rijeka	1.27	2.3	1.85	3
Total	-0.26	0.74	1.99	2.26

Table 4. Same as Table 2 for the period 7 November 2011 to 31 December 2012

Name	ME ALADIN	ME IFS	RMSE ALADIN	RMSE IFS
Palagruza	-1.65	-0.67	3.24	2.98
Prevlaka	-1.8	-0.86	3.23	2.72
Dubrovnik	-0.63	0.32	2.64	2.27
Lastovo	-0.3	0.68	2.18	2.47
Ploce	0.71	1.67	2.16	2.78
Hum Vis	-0.7	0.29	2.41	2.55
Hvar	0.42	1.42	2.03	2.54
Makarska - Pozari	0.59	1.61	2.5	3.18
Split - Marjan	0.08	1.06	2.01	2.32
Sibenik	-0.02	0.94	2.4	2.69
Zadar	0.25	1.25	2.35	2.82
Veli Rat	-0.71	0.23	2.75	2.8
Mali Losinj	0.02	0.99	2.16	2.68
Ivana A	-1.39	-0.36	3.33	3.16
Rab	1.35	2.33	2.37	3.28
Porer	-1.7	-0.76	3.47	3.13
Senj	-1	-0.02	3.93	3.93
Sv. Ivan na Pucini	-0.95	-0.08	2.86	2.9
Rijeka	1.28	2.28	2.33	3.37
Total	-0.28	0.69	2.7	2.91

few non-resolved obstacles to the wind. The computation of statistics shows that for these stations the mean error is lower for IFS than for ALADIN. The mean error is also slightly smaller for IFS than for ALADIN.

Similar results are obtained for the Veli Rat and Prevlaka stations, which are very near to the shore and for which there are no obstacles to the wind. The Palagruža and Hum-Vis stations are problematic. Palagruža cannot be resolved in the model grids and Hum-Vis is very high. For these stations both models underestimate wind speeds significantly though IFS underestimates it less.

The Lastovo and Split-Marjan stations also have high altitude and the wind is not blocked by neighbouring obstacles. The Dubrovnik, Rab, Ploče, Mali Lošinj, Rjeka and Senj stations are all near building obstacles, which makes comparisons problematic with models that have at least 2 km of resolution. The Makarska—Požari and Zadar stations are similar in the sense that they are both blocked by obstacles in only one direction; for Makarska, this is by buildings to the north and for Zadar by ones to the east. In the end, when all the stations are accounted for, we find that ALADIN has a slightly lower error. The results of Table 4 for the period 7 November 2011 to 31 December 2012 for which ALADIN uses data assimilation, show no essential difference.

However, we see the comparison for the stations near the sea as more significant. The Ivana A station, which is offshore, is especially significant. We found 76 events where we had both ASCAT wind estimates and anemometer measurements. On average, ASCAT gives a 0.61 m/s higher estimate than the anemometer and the root mean square discrepancy is 1.34 m/s. Thus it seems very likely that the RMSE errors of more than 3 m/s for both ALADIN and IFS at Ivana A are significant. The comparison for daily fields shows that the removal of daily variability decreases the error significantly. However, the RMSEs that have been found are greater than 2 m/s for all stations and both models. We consider this to be a relatively bad result which shows that there is a large scope for improvement.

Models and Scatterometer comparison

Before comparing the results we should point out that the IFS model assimilates ASCAT data while the ALADIN model does not. However, the ARPEGE model, which provides the boundary condition for ALADIN does assimilate ASCAT. It is natural to expect a model that assimilates data to give better results, but we still find the comparison to be significant. We should point out that in the comparison of ARDHUIN *et al.* (2007) the ARPEGE model did not assimilate scatterometers for the periods considered. Nevertheless, since ASCAT estimates are expected to be good, we believe that comparing ASCAT estimates with the model output is useful in assessing the quality of the model output.

For the period 2009 to 2010, the ME of scatterometer estimates with model interpolated results is -0.58 for IFS versus -0.39 for ALA-

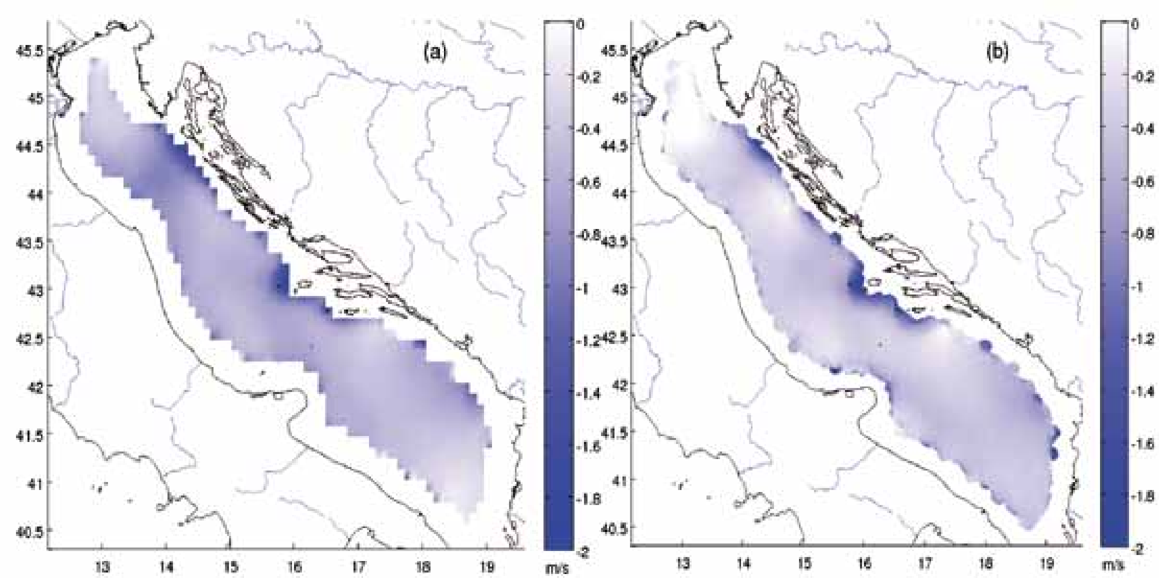

Fig. 2. Mean differences of wind speed for the ECMWF a) and ALADIN 2km b) forecasting system in comparison with ASCAT for the period 2008 to 2012

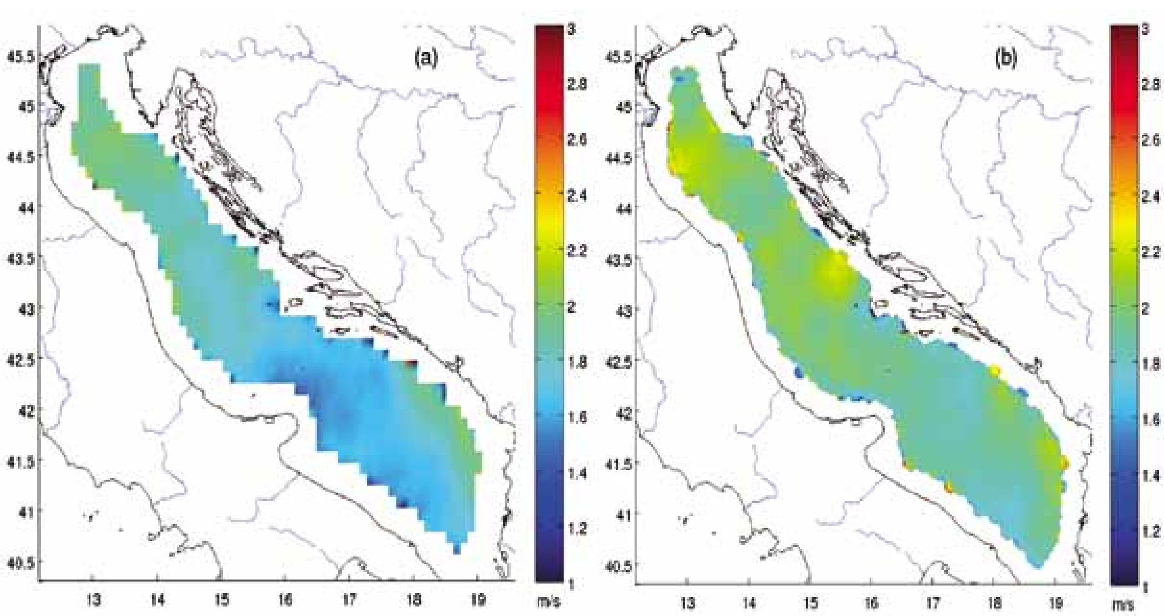

Fig. 3. Standard differences of wind speed for the ECMWF a) and ALADIN 2km b) forecasting systems in comparison with ASCAT for the period 2008 to 2012

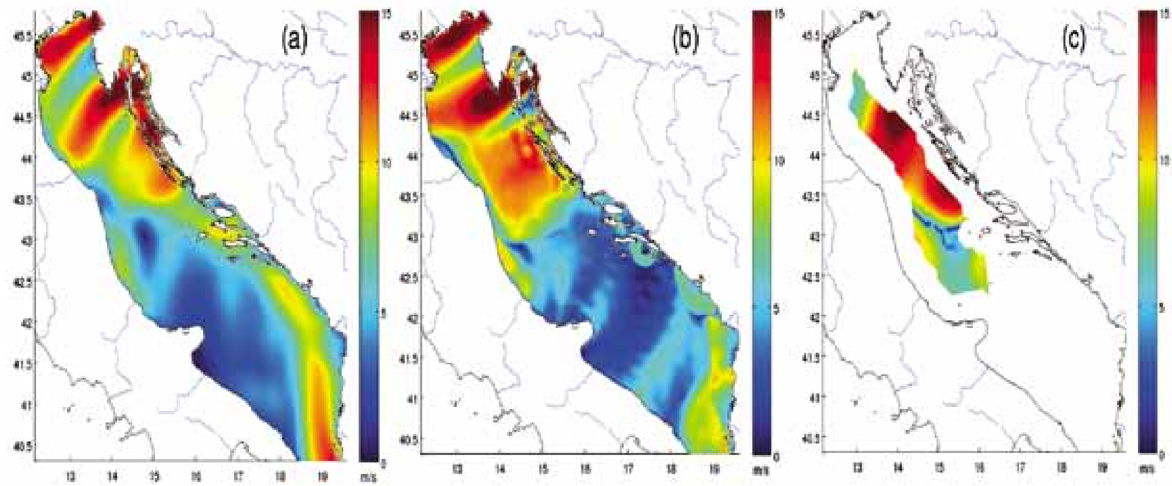

Fig. 4. Wind speed at 10 m for ECMWF (a) ALADIN 2km (b) and ASCAT (c) at 11 February 2012 at 20:36:00

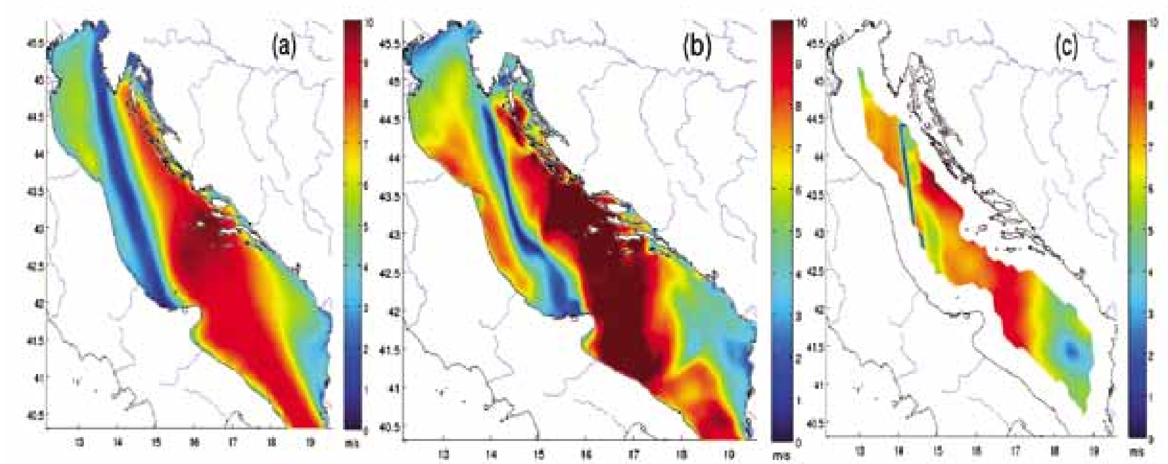

Fig. 5. Same as Figure 4 but at 18 November 2012 at 20:22:00

DIN 2km. Thus, ALADIN underestimates wind speed less than IFS which is what one would expect from a finer resolution model. Better results are especially apparent near Mali Lošinj with a smaller underestimate of wind speed. However, the overall absolute error is 1.40 m/s for IFS and 1.53 for ALADIN 2 km. Results are similar for the standard error, with 1.77 m/s for IFS and 1.96 m/s for ALADIN 2 km. A comparison for the year 2008 between ALADIN 8 km and ALADIN 2 km shows that ALADIN 2 km has a slightly smaller ME but that its RMSE is higher. However, in HORVATH *et al.* (2011), we should point out that the 2 km fields are qualitatively better than the 8 km ones, and the maximum wind speed is attained much nearer to the surface. In addition, 2 km fields are systematically better for the 4 stations considered in the paper than the ERA-40 winds.

Figures 2. and 3. show the ME and RMSE over the Adriatic. One can see that the global error is more or less constant but that IFS has a significantly smaller RMSE in the southern part of the Adriatic. It is also apparent that the ALADIN model better resolves the bora wind events in the northern Adriatic, with a near zero mean error and smaller RMSE than IFS. This is logical since ALADIN has a smaller horizontal resolution, which is key for resolving bora jets accurately.

Figure 4. illustrates the wind speeds forecast by IFS and ALADIN for a bora event and the estimate available from ASCAT. It is clear that the underestimate is higher for IFS but it is also

Table 5. Specification of the used Altimeters

Satellite	ERS 2	ENVISAT	JASON 1	JASON 2
Beginning time	2008-01-01	2008-01-01	2008-01-01	2008-07-06
Ending time	2011-07-04	2012-04-08	2012-12-30	2012-12-30
Nb Meas.	27172	20781	37937	40175

Table 6. MEs and RMSEs for comparison between IFS and ALADIN 2km wind speeds (m/s) and 4 altimeters for each year

		IFS		
	ERS 2	ENVISAT	JASON 1	JASON 2
2008	0.05 / 1.57	-0.67 / 1.88	-0.74 / 2.05	-0.72 / 2.23
2009	-0.38 / 1.87	-1.30 / 2.35	-0.89 / 2.21	-0.81 / 2.30
2010	-0.24 / 1.79	-1.07 / 2.27	-0.91 / 2.34	-0.88 / 2.36
2011	-0.30 / 1.70	-1.03 / 2.00	-0.67 / 2.08	-0.86 / 2.14
2012	N/A	-1.70 / 2.79	-0.91 / 2.02	-0.91 / 2.19
		ALADIN		
	ERS 2	ENVISAT	JASON 1	JASON 2
2008	0.19 / 1.78	-0.55 / 2.02	-0.72 / 2.38	-0.74 / 2.40
2009	-0.01 / 2.01	-1.02 / 2.40	-0.60 / 2.48	-0.55 / 2.66
2010	0.12 / 1.85	-0.56 / 2.11	-0.58 / 2.29	-0.70 / 2.39
2011	-0.04 / 1.81	-0.78 / 1.96	-0.63 / 2.12	-0.86 / 2.43
2012	N/A	-1.06 / 2.75	-0.62 / 2.27	-0.87 / 2.30

clear that neither model forecasts this bora event well. Figure 5 gives the same information for a sirocco event. Here, the model forecasts are reasonable and both models give similar results. However, the figures also show that the ALADIN models resolve more complex features than the IFS model.

Models and Altimeter comparison

For the period 2009 to 2012, data from the ENVISAT, ERS-2, JASON-1 and JASON-2 satellites was available. The GFO satellite provided only significant wave height for the period considered. In Table 6 we give the ME and RMSE for each satellite for each year.

For IFS, we found a mean error of -0.71 m/s and a root mean square error of 2.09 m/s. For ALADIN 2km we found a mean error of -0.50 m/s and a root mean square error of 2.23 m/s. The underestimate is smaller for ALADIN but the root mean square error is slightly larger. This means that the underestimate of wind speed is reduced by the higher resolution of ALADIN. However, the data assimilation scheme of IFS led to better overall results for the RMSE. This is in agreement with the scatterometer results, which is not suprising since both altimeters and scatterometers use the $\sigma 0$ return signal for estimating the wind speeds.

The scatter plot for both models and all satellites is shown in Figure 6. It appears that ALADIN predicts winds a little higher than IFS, which is to be expected. The slope m of best fit is 0.86 for IFS as opposed to 0.88 for ALADIN. We need to point out that for the two episodes considered in ARDHUIN *et al.* (2007) the scatter index for IFS in comparison to ERS-2 and JASON-1 varies between 0.22 and 0.28, with also better slopes of best fit. Considering that the resolution of IFS was 40 km for that period, in our view this confirms that the Adriatic is a harder region to model than the Mediterranean as far as wind is concerned. This is explained in detail in BERTOTTI & CAVALERI (2009) where it is argued that wind and wave forecasts beyond a limited time are harder in a semi enclosed sea than in the ocean.

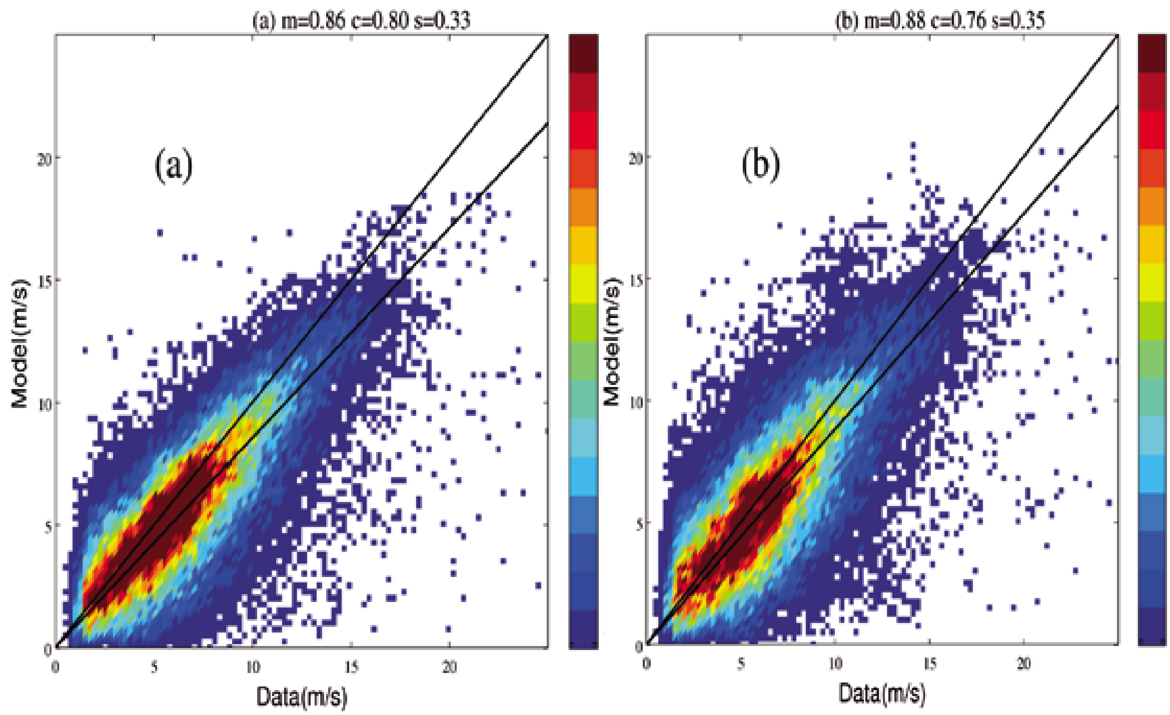

Fig. 6. Scatter plots of surface wind speed for ECMWF (a) and ALADIN 2km (b) when comparing altimeters and model results. M is the slope of best fit, c the correlation and s the scatter index

Overall results were very similar between the JASON 1 and JASON 2 satellites both for ME and RMSE for all years. For the ENVISAT satellite the ME and RMSE are also very similar but with a ME of -1 m/s in comparison with ALADIN 2 km for the years 2009 and 2012 versus -0.6 m/s for JASON 1 and 2. On the other hand, a comparison with the ERS 2 satellite shows both lower ME and lower RMSE than comparisons with the other 3 satellites. We do not know why this happens. Interestingly, in CAVALERI *et al.* (2012) where the COSMO model is applied to the Mediterranean Sea the ERS-2 satellite was excluded due to inconsistent results. Results for 2012 for which ALADIN uses data assimilation show no significant differences.

This comparison should be regarded as more significant than the one with the scatterometer for the reason that IFS does not use altimeter data in its assimilation scheme.

CONCLUSIONS

The comparison shows that ALADIN and IFS have relatively similar errors when compared with anemometers, scatterometers and altimeters. In the open sea the IFS model is superior to ALADIN in the southern Adriatic while the ALADIN model is better in the northern Adriatic, most likely because of its better spatial resolution, which is critical for bora wind simulations. In general, the ALADIN model shows a slightly smaller ME but larger RMSE than IFS.

For coastal winds, both models appear relatively unsatisfactory with anemometers reporting an RMSE above 2 m/s. They cannot resolve the station variability accurately. The problem concerns both time with the daily average showing a much smaller error, and also the spatial dimension with their insufficient resolution. The problem is best exemplified with the station at Palagruža with an altitude of 44 m on an island of less than one km in size. The island is resolved in neither IFS nor ALADIN and so the errors are large. However, we should point out that only a 10 m wind was available to us and that we could not compare the quality of station measurements with scatterometers or altimeters, which do not resolve the coasts.

It appears to us that there is much scope for improvement concerning coastal wind in the Adriatic Sea. One generally expects improvements from a higher resolution, but there is little evidence for gains when using LAMs in the Adriatic. This may be explained by the fact that we used analysed IFS winds versus ALADIN wind forecasts. On the other hand the study BERTOTTI & CAVALERI (2009) suggests that resolution improvements would yield more improvements to model results over the Adriatic Sea than over the Mediterranean Sea. Possibly, improvements could come by using non-hydrostatic models although BERTOTTI *et al.* (2014) do not report improvements with COSMO and WRF, which are both non-hydrostatic. Regarding our original question it seems to us that improvements in the use of LAM cannot come exclusively from resolution improvements. In order to progress further, LAMs need to develop similar strategies to GCMs, i.e. having coupling to the sea state similar to the one of WAM in IFS, and also robust assimilation strategies.

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REFERENCES

ARDHUIN, F., L. BERTOTTI, J. BIDLOT, L. CAVALERI, V. FILIPETTO, J.-M. LEFEVRE & P. WITTMANN. 2007. Comparison of wind and wave measurements and models in the western Mediterranean Sea. Ocean Eng., 34: 526—541.

BARNIER, B., M. BOUKTHIR & J. VERRON. 1991. Use of satellite scatterometer winds to force an ocean general circulation model. J. Geophys. Res., 96(C12): 22025—22042.

BIDLOT, J.R., D.J. HOLMES, P.A. WITTMANN, R. LALBEHARRY & H.S. CHEN. 2002. Intercomparison of the Performance of operational ocean wave forecasting systems with buoy data. Wea. Forecasting, 17(2): 287—310.

CAVALERI, L. & L. BERTOTTI. 1996. In search of the correct wind and wave fields in a minor basin. Mon. Weather Rev., 125: 1964-1975.

CAVALERI, L., A. ROLAND, M. DUTOUR SIKIRIĆ, L. BERTOTTI & L. TORRISI 2012. On the coupling of COSMO and WAM. Proceedings of ECMWF Workshop on Ocean Waves, 25-27 June 2012, edited by J. Bidlot.

BERTOTTI, L. & L. CAVALERI. 2009. Wind and wave prediction in the Adriatic. J. Mar. Syst., 78: S227—S234.

BERTOTTI, L. L. CAVALERI, A. SORET & R. TOLOSANA-DELGADO. 2014. Performance of global and regional nested meteorological models, Cont. Shelf Res., 87: 17—27.

BONAVITA, M., L. TORRISI & F. MARCUCCI. 2010. Ensemble data assimilation with the CNMCA regional forecasting system. Q. J. R. Meteorolog. Soc., 135(646): 132—145.

CHEN, G. 2004. An intercomparison of TOPEX, NSCAT, and ECMWF wind speeds: Illustrating and understanding systematic discrepancies. Mon. Weather Rev., 132: 780—792.

COTTON, J. 2009. A comparison of QuikSCAT with buoy, ship and radar altimeter wind speeds and evaluating the need for a new bias correction. Met Office Technical Report No. 538.

DEQUE, M., C. DREVETON, A. BRAUN & D. CARIOLLE. 1994. The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling. Clim. Dynam., 10: 249—266.

DUTOUR SIKIRIĆ, M., A. ROLAND, I. JANEKOVIĆ, I. TOMAŽIĆ & M. KUZMIĆ, 2013. Coupling of the regional ocean modelling system and wind wave model. Ocean Model, 72: 59—73.

DUTOUR SIKIRIĆ, M., A. ROLAND, I. JANEKOVIĆ & I. TOMAŽIĆ, 2012. Hindcasting the Adriatic Sea near-surface motions with a coupled wave-current model. J. Geophys. Res., 117: C00J36

ECMWF. 2012. IFS documentation, http://www.ecmwf.int/research/ifsdocs/CY38r1/

HERRMANN, M., S. SOMOT, S. CALMANTI, C. DUBOIS & F. SEVAULT. 2011. Representation of spatial and temporal variability of daily wind speed and of intense wind events over the Mediterranean Sea using dynamical downscaling: impact of the regional climate model configuration. Nat. Hazards Earth Syst. Sci., 11: 1983—2001.

HORVATH, K., A. BAJIĆ & S. IVATEK-ŠAHDAN. 2011. Dynamical downscaling of wind speed in complex terrain prone to bora-type flows. J. Appl. Meteorol. Clim., 50(8): 1676-1691.

IVATEK-ŠAHDAN, S. & M. TUDOR. 2004. Use of high-resolution dynamical adaptation in operational suite and research impact studies. Meteorol. Z., 13(2): 99-108.

JANSSEN, P.A.E.M., J.D. DOYLE, J. BIDLOT, B. HANSEN, L. ISAKSEN & P. VITERBO. 2001. Impact and feedback of ocean waves on the atmosphere. ECMWF Technical Memorandum 341.

KUZMIĆ, M., I. JANEKOVIĆ, J.W. BOOK, P.J. MARTIN & J.D. DOYLE. 2006. Modeling the northern Adriatic double-gyre response to intense bora wind: A revisit. J. Geophy. Res., 111: C03S13

LIU, W.T. & W. TANG. 1996. Equivalent neutral wind. JPL Publication 96-17.

MARTIN, P.J. 2000. A Description of the Navy Coastal Ocean Model Version 1.0. NRL Rep. NRL/FR/7322 – 00-9962, 42 pp., Nav. Res. Lab., Stennis Space Cent., Miss.

MARTIN, P.J., J.W. BOOK, D.M. BURRAGE, C.D. ROWLEY & M. TUDOR. 2009. Comparison of model-simulated and observed currents in the central Adriatic during DART. J. Geophys. Res. - Oceans. 114; C01S05-1-C01S05-18.

PANOFSKY, H.A. & J. A. DUTTON. 1984. Atmospheric turbulence, Wiley, 397 pp.

PASARIĆ, Z., D. BELUŠIĆ & Z. KLAIĆ. 2007. Orographic influences on the Adriatic sirocco wind. Ann. Geophys., 25: 1263—1267.

PETTENUZZO, D., W.G. LARGE & N. PINARDI. 2010. On the corrections of ERA-40 surface flux products consistent with the Mediterranean heat and water budgets and the connection between basin surface total heat flux and NAO. J. Geophys. Res., 115: C06022.

QUEFFEULOU, P. 2003. Long-term quality status of wave height and wind speed measurements from satellite altimeters. Proceedings of the Thirteenth International Offshore and Polar Engineering Conference Honolulu, Hawaii, USA.

RODRIGUEZ, E. C.S. MORRIS, J.E. BELZ, E.C. CHAPIN, J.M. MARTIN, W. DAFFER & S. HENSLEY. 2005. An assessment of the SRTM topographic products. Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 pp.

SIGNELL, R.P., S. CARNIAL, L. CAVALERI, J. CHIGGIATO, J.D. DOYLE, J. PULLEN & M. SCLAVO. 2003. Assessment of wind quality for oceanographic modelling in semi-enclosed basins. J. Marine Syst., 53: 217—233.

SKAMAROCK, W.C. & J.B. KEMP. 2008. A time-split non-hydrostatic atmospheric model for weather research and forecasting applications. J. Comput. Phys. 227: 3465—3485.

TANG, W., W.T. LIU, & B.W. STILES. 2004. Evaluation of high-resolution ocean surface vector winds measured by QuikSCAT scatterometer in coastal regions. IEEE T. Geosci. Remote, 42(8): 1762—1769.

TUDOR, M., S. IVATEK-ŠAHDAN, A. STANEŠIĆ, K. HORVAT & A. BAJIĆ. 2013. Forecasting weather in Croatia using ALADIN numerical weather prediction model. Climate Change and Regional/Local Responses, In: ZHANG, YUANZHI; RAY, PALLAV (Editors). Rijeka: InTech, 59—88.

UPPALA, S.M., P. W. KALLBERG, A. J. SIMMONS, U. ANDRAE, V. DA COSTA BECHTOLD, M. FIORINO, J. K. GIBSON, J. HASELER, A. HERNANDEZ, G. A. KELLY, X. LI, K. ONOGI, S. SAARINEN, N. SOKKA, R. P. ALLAN, E. ANDERSSON, K. ARPE, M. A. BALMASEDA, A. C. M. BELJAARS, L. VANDE BERG, J. BIDLOT, N. BORMANN, S. CAIRES, F. CHEVALLIER, A. DETHOF, M. DRAGOSAVAC, M. FISHER, M. FUENTES, S. HAGEMANN, E. HOLM, B. J. HOSKINS, L. ISAKSEN, P. A. E. M. JANSSEN, R. JENNE, A. P.MCNALLY, J.-F. MAHFOUF, J.-J. MORCRETTE, N. A. RAYNER, R. W. SAUNDERS, P. SIMON, A. STERL, K. E. TRENBERTH, A. UNTCH, D. VASILJEVIĆ, P. VITERBO & J. WOOLLEN. 2005. The ERA-40 re-analysis.

Q. J. R. Meteorol. Soc. 131: 2961—3012.

VON AHN, J.M., J.M. SIENKIEWICZ & P.S. CHANG. 2006. Operational impact of QuikSCAT winds at the NOAA ocean prediction center. Weather Forecast., 21: 523-539.

WITTER, D.L. & D.B. CHELTON. 1991. A geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development. J. Geophys. Res. 96(C5): 8853—8860.

YANG, X.F., X.F. LI, W.G. PICHEL & Z.W. LI. 2011. Comparison of ocean surface winds from ENVISAT ASAR, MetOp ASCAT scatterometer, buoy measurements, and NOGAPS Model. IEEE T. Geosci. Remote, 49: 4743—4750.

Usporedba ALADIN i IFS Modela brzine vjetra preko Jadrana

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SADRŽAJ

Vjetar dobiven atmosferskim modelima je instrumentalan u prisiljavanju oceanskog modela. U ovom radu razmotrit će se vjetra dobiven Aladin i IFS modelima te će se usporediti s rezultatima skaterometrijske i altimetrijske procjene brzine vjetra iznad Jadranskog mora, kao i s 18 meteoroloških postaja i plinske platforme u razdoblju 2008-2012. Glavni zaključak je da oba atmosferska modela, u usporedbi s podacima altimetrije, daju vrlo slične statističke rezultate, s indeksom raspršenja 0,33 za IFS i 0,35 za ALADIN. Čini se da ALADIN daje bolje rezultate za sjeverni Jadran, a IFS za južni Jadran. Moguće objašnjenje te razlike može biti veća prostorna rezolucija ALADIN-a koja je presudna u rješavanju utjecaja bure na sjevernom Jadranu.

Ključne riječi: altimetrija, skaterometrija, polja vjetra, modeli