

Surface winds in the Euro-Mediterranean area: the real resolution of numerical grids

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Abstract. Surface wind is a variable of great importance in forcing marine waves and circulations, modulating surface fluxes, etc. Surface wind defined on numerical grids is currently used in forecast-analysis, as well as in climatology. Gridded fields, however, suffer for systematic errors associated with the numerical procedures adopted in computing them. In this paper the climatology of surface wind produced by three different numerical models in the European-Mediterranean area is analyzed. The systematic loss of power at the smallest grid-scales appears in the power spectrum of all the different models. Some prototype numerical integrations show that this systematic over-smoothing is due to numerical stabilization operators that represent the main source of the diagnosed error; the error progression in space and time is also analyzed.

Key words. Meteorology and atmospheric dynamics (Mesoscale meteorology; Ocean-atmosphere interaction; Climatology)

1 Introduction

In forecasting weather, conventional observations of surface wind often do not play a particularly relevant role because over land they are, as other surface variables, very noisy (direct surface wind observations do not follow ordinary analysis schemes which form the basis for forecast-initialization) and over the ocean are, when reliable, very sparse. Also, in the non-tropical Northern Hemisphere, the contribution of remote sensing observations of surface wind to predictive skill seems to be overall modest (Atlas et al., 2001). On the other hand, surface wind stress is a key forcing agent for sea waves and circulations, and plays a fundamental role in modulating heat and water exchanges at the air-sea and air-soil interfaces. Moreover, experience suggests that the small (sub-synoptic) scale structure of wind can be very important in both forecasting sea-state and determining climatological

balances. Last, but not least, surface wind over the ocean observed from space begins to play an important role in the analysis of some relevant atmospheric features (Sharp et al., 2002). In conclusion, surface wind is presently the object of increasing interest for both scientific and applied purposes.

The European-Mediterranean area, which is the focus of our attention, fits the above general description. Traditionally, surface wind was not the object of particular studies, but over the past few years it has been given more attention for several reasons. For example, numerical wave forecast on the Mediterranean Sea shows a systematic underestimation (about 30%) in the forecast of significant height (Cavaleri and Bertotti, 1997; Cavaleri et al., 1997), possibly due to a lack of definition of surface wind. Also, for purposes of climatic application, it is well-known that small-scale modulations of local winds (Mistral, Bora, etc.) play a very relevant role in air-sea surface fluxes. Furthermore, reliable balances in the Mediterranean region cannot be computed on the basis of smoothed, average fields without taking into account the above small time-space scale modulations.

In view of the different application to service operations (in particular, by means of remote sensing from space), we analyzed the structure of surface wind in numerical grids covering the European-Mediterranean area. Specifically, the present study is an attempt to characterize the spatial variability of surface wind at the smallest scales of numerical grids. Studies concerning other areas of the world (Wilke et al., 1999; Tournadre, 1999) suggest that forecast-analysis fields may be affected by relevant errors at the smallest grid scales. Evidence of such errors begins to emerge also in the Mediterranean area (Zecchetto et al., 2002). Our specific approach is to analyze grids associated with different models with the purpose of identifying error features that appear, to some extent, in all models. In fact, comparative analysis of the power spectra of surface wind reveals that deficits of energy appear systematically at the highest wave numbers of all the different numerical grids. Such deficits are attributed to the over-smoothing produced by diffusion operators artificially introduced in the equations of motion in order to achieve numerical stability.

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It is well-known that the numerical diffusion plays a primary role in controlling the small-scale noise that can arise from numerical dispersion, nonlinear instability, etc. On the other hand, the impact of numerical diffusion on meteorological fields is also well-known, but often not quantified. The impact of dissipative schemes is to remove $2\Delta x$ and $3\Delta x$ waves. So the smallest resolvable wave is at least $4\Delta x$. In this paper we want to study this impact on the smaller (anyhow larger than $4\Delta x$) scales and to show that the real numerical resolution (where information is not too damped) is actually smaller than that which is usually assumed. The identification of such a general source of underestimation immediately suggests possible correction techniques for different applications.

The paper is organized as follows: in the following Sect. 2 we describe the data used in our analysis and in Sect. 3 the analysis method; in Sect. 4 we discuss the power spectra of surface wind and describe the over-smoothing errors at the smallest grid scales; such errors are numerically analyzed and physically interpreted in the following Sect. 5; finally, in Sect. 6 we present our conclusions and discussion.

The months of January and July are taken as representative winter and summer, respectively, based upon the typical weather conditions in the Mediterranean region. Specifically, we have in the Mediterranean area in January the highest wind speed and variability and in July high pressure and weak surface wind speed. In this way, differences in wind speed are emphasised.

2 The data

We considered a region covering 25° N– 65° N in latitude and 10° W– 40° E in longitude, corresponding roughly to Europe and the Mediterranean area. The lowest resolution data set considered is the NCEP-NCAR global reanalysis 10-m wind product, with a grid spacing of 2.5 deg, from which we extracted the monthly means for January and July 2001. As an intermediate resolution data set we used the 10-m wind produced by the general circulation model of the CNRS-Laboratoire de Meteorologie Dynamique zoomed (LMDZ) over the Mediterranean area: the grid spacing is approximately 50 km near the center of the zoom. We extracted the first and seventh months (January and July) of a 10-year climatological run (Li and Conil, 2003). Finally, we considered the 10-m wind produced by the Limited Area Model BOLAM¹ (Buzzi et al., 2003) at a spatial resolution of 0.1 deg over the same area and for the same time-period as the NCEP reanalysis. This data enabled us to explore spectra from several thousand kilometers to, respectively, about 900 km (NCEP), 250 km (LMDZ), 40 km (BOLAM): the smallest

¹The parallelized version QBOLAM, running on a QUADRICS supercomputer, is operated in conjunction with a sea-state forecast model (WAM) for the entire Mediterranean area and a sea-level prediction model (POEM) for the Adriatic sea in SIMM (Sistema Idro-Meteo-Mare) of the Servizio Idrografico e Mareografico Nazionale of Italy.

resolved horizontal scales correspond to approximately four times the spatial sampling of each data set in order to avoid aliasing problems. Note that we do not discuss the issue of the dissipation on smallest scales ($2\Delta x$, $3\Delta x$), since we consider only scales larger than $4\Delta x$.

3 Analysis method

The wave number spectra are estimated, independently for each data set, on the monthly means. Under the assumption of non-divergent and isotropic flow, the two-dimensional kinetic energy spectra are proportional to the one-dimensional components of the kinetic energy (Freilich et al., 1986). Accordingly, we compute the one-dimensional spectra for the meridional and zonal components of kinetic energy associated to surface wind. Note, however, that the physical conclusions we reached do not depend on the type of transform we adopted: some other kind of Fourier transform, structure function, exponent analysis, etc., could have been used, as well.

For each horizontal component u_l ($l=1, 2$) of the wind, we derived an individual estimation of the variance of the wind component sampled in the meridional (zonal) direction at longitude i (latitude j). This is derived from the spatial Fourier-transform $\Phi_u(k_y)$ ($\Phi_u(k_x)$) of the autocorrelation function $R_u(y)$ ($R_u(x)$) of the series composed of values along the meridian i (parallel j). This is the wave number in the x , zonal, (y , meridional) direction. The number of elements of the individual series in the zonal and meridional sampling direction is reported in Table 1, with an estimation of the sampling interval, as well as the maximum wave number that can be reached. For the uneven sampling inherent in the stretched LMDZ grid, we consider the spacing at the center of the domain as representative of the whole domain. The Fourier transform is computed as:

$$\Phi_u(K_x) = \int_{-\infty}^{+\infty} R_u(x) e^{-ikx} dx. \quad (1)$$

The individual one-dimensional kinetic energy spectrum is then derived from the one-dimensional component spectra by:

$$E^j(K_x) = |\Phi_u(k_x)|^2 + |\Phi_u(k_y)|^2. \quad (2)$$

The spectral estimates are then obtained by averaging individual spectra.

4 Power spectra and numerical over-smoothing errors

The spectra for the meridional and zonal components of the kinetic energy produced by applying the procedure described in Sect. 3 to the three data sets described in Sect. 2 are displayed in Figs. 1 and 2 for the winter (January) and the summer (July) months, respectively.

There are, however, very little seasonal variations for all three data sets. Also shown are the slopes for the k^{-3} and

Table 1. Sampling characteristics of the three numerical grids adopted in the paper.

| Sampling direction Model | Number of elements | | Sampling grid size(km) | λ_{\min} (km) | λ_{\max} (km) | |
|-----------------------------|--------------------|------------|------------------------|-----------------------|-----------------------|------|
| | Zonal | Meridional | | Zonal | Meridional | |
| NCEP | 21 | 17 | 210 | 800 | 8700 | 8100 |
| LMDZ | 57 | 51 | 65 ÷ 100 | 250 ÷ 400 | 5600 | 3200 |
| BOLAM | 429 | 171 | 10 | 40 | 7500 | 3700 |

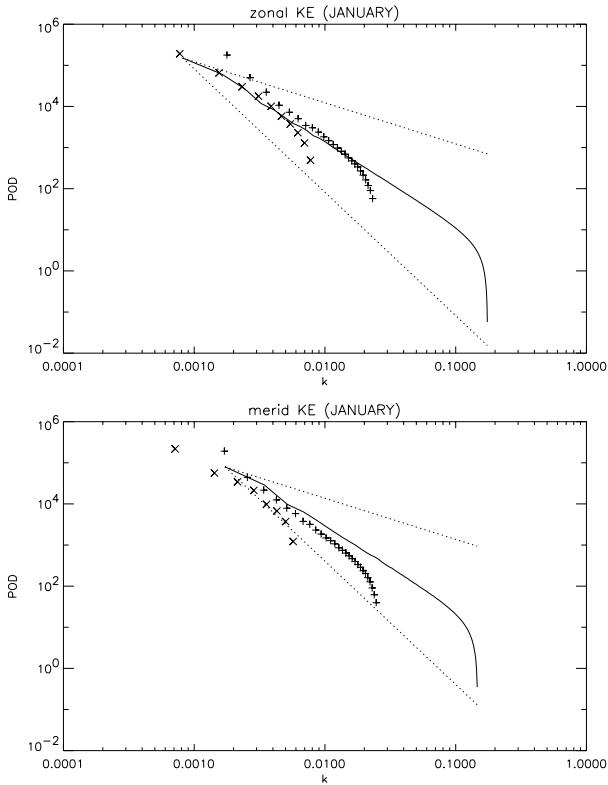


Fig. 1. Kinetic energy (KE) power spectra for winter (January). The power density (POD) is represented as a function of zonal and meridional wave number: the maximum resolved scale is about 40 km (see Fig. 3). For comparison, the theoretical slopes k^{-3} and $k^{-5/3}$ are represented by dashed lines. Starting from the top left the symbols represents the values derived, respectively: from NCEP reanalysis (x) from LMDZ (+) and from BOLAM (solid line).

$k^{-5/3}$ laws, corresponding to well-known theoretical scenarios. We are not interested here in discussing the scale-invariance properties of the surface wind field. The feature we want to highlight is that all spectra show power-law dependence quite uniform throughout the wave number range, except for a drop at the highest wave numbers. This drop represents a net loss of small-scale structure (both in deterministic and statistical terms) of the wind field. According to these results, the energy in the smallest scales of motion explicitly represented in the models considered here is clearly underestimated. As already stated, this same behavior is ob-

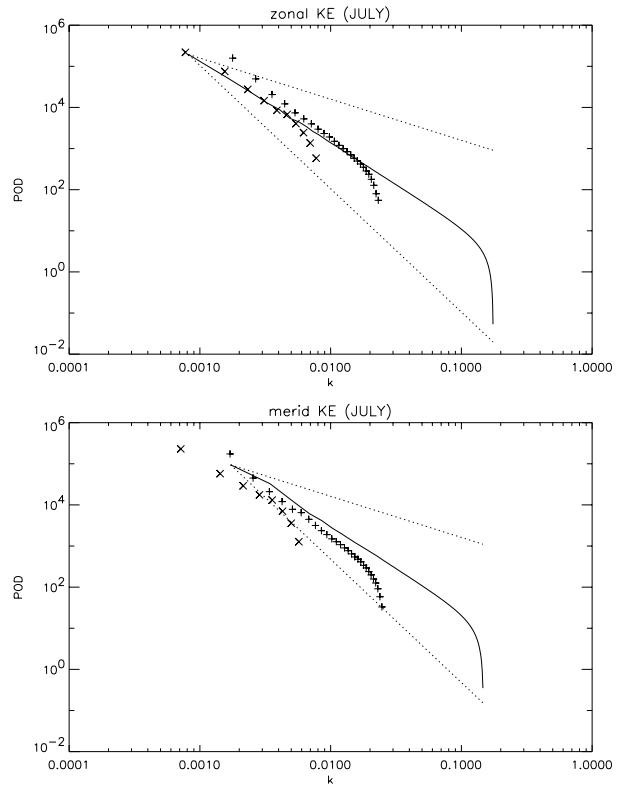


Fig. 2. As Fig. 1, but for summer (July).

served in other studies of the surface wind in different areas of the world; comparison with spectra of observed surface wind shows quite systematically that the power drop is a model artifact. Harris et al. (2001) found a similar result but for precipitation. The main source of this error is the over-smoothing of the wind field due to the super-dissipations that are inserted in the equations for purposes of numerical stabilization. For what concerns specifically the LMDZ and the BOLAM simulations, the spectral decay of energy is likely due to the Laplacian type dissipation operator used to stabilize the evolution equations. In particular in the LMDZ model the horizontal dissipation is performed with an operator based on an n time laplacian Δ^n . This operator is applied separately to the divergence ($n=1$ and vorticity $n=2$) of the flow. A filter may be activated near the poles for stabilising the state. BOLAM uses a fourth order operator on the zonal and meridional components of the wind.

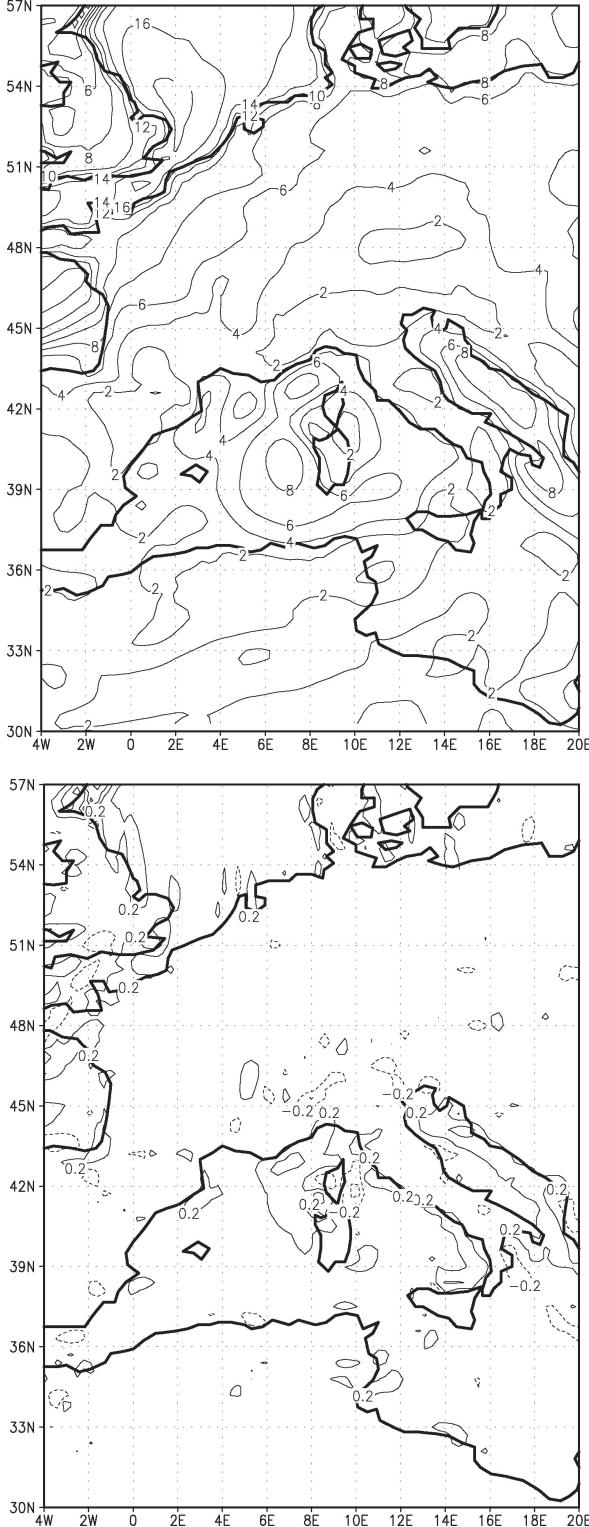


Fig. 3. **a)** 10-m wind speed for the control experiment, contour interval is 2 m/s **b)** differences between fields of wind speed (no diffusion minus control) at lowest sigma level after three hours of simulation. Dashed lines indicate negative values. Grid spacing is 0.3° , contour interval is 0.4 m/s. The projection conserves the aspect ratio; hence the latitudinal size is larger.

5 Numerical integration and physical interpretation

In order to clarify the way in which the diffusion terms operate on surface wind in generating the above described over-smoothing errors, we show comparative runs of the BOLAM code with and without diffusion. BOLAM is a primitive equations, finite differences, limited area model. The domain of integration is rotated over the equator in order to have an almost constant longitudinal step. The model is used in several European services, and has been used for the forecasting during the Special Observing Period of the Mesoscale Alpine Program (Buzzi et al., 2003). The horizontal grid points are disposed on an Arakawa C grid and the vertical coordinates are sigma-coordinates. The time integration of the prognostic advection equation is performed by the forward-backward advection scheme or FBAS (Malguzzi and Tartaglione, 1999), a scheme formally equivalent to the leapfrog scheme, but computationally more efficient, coupled with a forward-backward scheme for resolving gravity waves. Numerical integrations presented here are performed using a 90×105 grid, having a 0.3° grid spacing and with a 240-s time step. The sigma-levels are 40. This experiment was run on a grid different from that of the analysis shown above since, in this case, we want to focus the attention on differences in the 10-m wind in a single forecast. The analysis of 5 November 1999 at 12:00 UTC is used as initial conditions. We ran two experiments, one, as the control, with horizontal diffusion and another without horizontal diffusion. The experiment without diffusion was run for about four hours (60 time steps): the wind speed begins to diverge from the control wind speed after about 50 time steps. We considered the experiment for the first three hours (45 time steps), i.e. before nonlinear instability became dominant (at about 60 time steps). Figure 3a shows the wind speed field at the lowest sigma level after 3 h of simulation in the control experiment. Two areas with a strong wind speed (more than 8 m/s) and strong wind gradient are well visible over the Mediterranean Sea (near Sardinia and over the Adriatic sea). Other areas with these characteristics are visible north of England and near the oceanic coast of France. The wind difference field (no diffusion experiment minus control experiment) of the wind speed at the lowest sigma level is shown in Fig. 3b. The action of the diffusion is particularly pronounced where field curvature and gradient are strong, i.e. in coastal regions, as well as in the frontal or cyclonic regions. The latter are not well visible in the figure because the frontal region between Great Britain and Northern France and the cyclonic region over Sardinia and Corsica overlap coastal areas. The proposed picture is a snapshot: the differences have positive and negative values, depending on local ∇^4 (curvature and gradient) of the field; the diffusion makes the field smoother, adding or subtracting values locally, but globally the process is an explicit damping. BOLAM is written in sigma coordinates that can lead to spurious results near the surface when the distance between two vertical grid points is smaller than the elevation difference between two horizontally adjacent (in the sigma coordinate system) points (Mahrer, 1984).

This problem remains confined only to areas where the above condition holds. As a consequence, over the sea differences between the control experiment and the no diffusion experiments are not connected to the above source of error. As an illustration of the damping action of the diffusion scheme on the domain, Fig. 4 shows the lowest sigma level wind speed averaged on the domain for both experiments. It is clear that the kinetic energy of the control experiment is less than that of the experiment without diffusion. In a model without numerical diffusion the small-scale energy is aliased to large scale, with an accumulation of energy leading to nonlinear instability. We showed here numerical experiments without diffusion before nonlinear instability makes them meaningless.

6 Conclusions

We have shown that surface wind at smallest grid scales of numerical models is affected by systematic power deficits associated with the smoothing action of super-dissipation operators introduced in the numerical codes for numerical stabilization purposes. In fact, the power spectra of surface wind computed on different numerical grids systematically show a marked drop (with respect to typical power-law behavior) in spectral power at the smallest scales of the grid. We have illustrated the typical spatial distribution and time progression of the over-smoothing errors in a primitive numerical grid equation: in the case of a Laplacian type dissipation (as in the numerical models we adopted) the field is subject to particular smoothing in large flow curvature regions. The identification and interpretation of such a source of error can bear immediate consequences on practical applications. Different correction approaches can be devised, depending upon the specific application of the computed surface wind. Our primary concern is sea-state (wind waves and tides) forecast operations in the Mediterranean area. In this area, local, intermittent, strong winds (Mistral, Libeccio, etc.) play a central role in determining storms and floods that are the main concern of civil protection agencies, but also marine forecast (Pinardi et al., 2003) is of potential interest. The deterministic sub-synoptic scale structure of surface winds is known to influence considerably wind wave forecast, while only collective statistical effects of small-scales on the (long) tidal waves are important in sea-level forecast: the required corrections reflect this difference. In the first case, correction schemes based on the reconstruction of the local field (for example, from the value of diffusion operators at preceding times) can be applied. In the second case, recovery (for example, with spectral extrapolation) of the average (both in space and time) power lost is often sufficient. On the other hand, for future applications to marine forecast, given the very small Rossby deformation radius of Mediterranean seas, these may require levels of space-definition comparable with those of wind waves forecast. In the context of climate problems, the influence of systematic errors on the reconstruction of hydrological cycle on numerical grids is certainly upset by

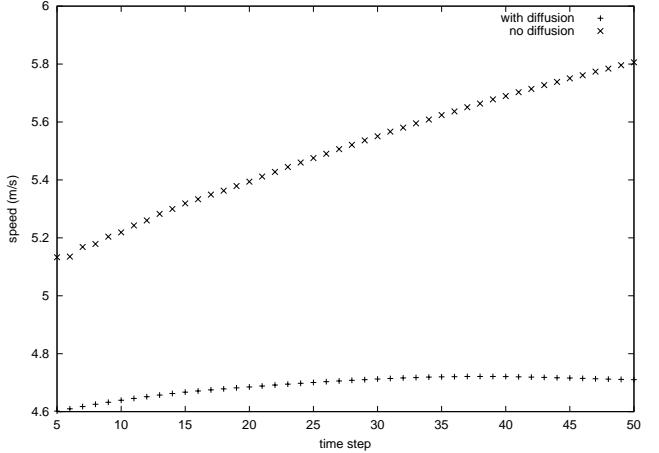


Fig. 4. The BOLAM wind speed, at lowest sigma level, averaged on the domain for the experiments with and without diffusion, in the former three hours of simulation.

systematic errors like those discussed in this paper, in particular when intense local winds have a strong climatological weight. This is certainly the case in the Mediterranean area, where a few impulses of local wind (say, Mistral) usually determine the seasonal average. Observations from space already provide valuable, direct information concerning both the deterministic and the statistical structure of the surface wind field over the ocean. Last, but not least, the analysis of the statistical properties of the wind field on numerical grids can be an important objective for remote sensing. In fact, this study was particularly stimulated by the possibility of having, within a few years, a system of radar observing from space with the strong potential for scatterometric use.

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