# Oscillations in an offshore blowing wind(*)

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(ricevuto il 15 Maggio 2000; revisionato il 27 Luglio 2001; approvato il 15 Novembre 2001)

**Summary.** — We suggest that, in situations where the wind is blowing from land to sea, the wind experiences some sort of inertial oscillations. This is shown by using a simplified version of the equations in the atmospheric boundary layer. In order to confirm that this effect can be present in a typical climate and weather prediction model, we have used the one-column version of the ECMWF global model. The model was used in a "Lagrangian" framework, being advected at constant speed from land to sea. Inertial oscillations, in the wind at 10 metres above the surface, are produced by this simulation. This confirms the initial conjecture. Considering the mean wind speed, the time required by the surface boundary layer to adapt to the new (from land to sea) situation is of the order of a few hours.

PACS 92.60.Gn – Winds and their effects.
PACS 92.10.Kp – Sea-air energy exchange processes.
PACS 92.10.Sx – Coastal and estuarine oceanography.

## 1. – Introduction

The WAM wave model [1] is operational at the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK) both at the global and European scale, the latter one providing a detailed description of the wave fields in the various local sub-basins. The quality of the results shows a marked variability. While the results are pretty good in the oceans, and in general in the large open spaces [2*a*], in the more enclosed basins we find a permanent underestimation of the wave conditions (wave heights and periods). In particular in the Mediterranean Sea the model wave heights are lower than the ones derived from satellite altimetry by about 30% [2*b*]. Looking more in detail to the distribution, the error seems to decrease with fetch. Given the physical

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connection between wind and waves, this suggests the possibility that the model speed of an offshore blowing wind is underestimated soon off the coast, the error decreasing while air propagates over the sea. It was suggested that this could be due to the time required by the model boundary layer to adapt to the new situation after the transition from land to sea. We have explored this hypothesis using the one-column version of ECMWF. Apart from providing a reply to the original question, this has allowed a detailed analysis of the transient situation. In particular we found, first from an analysis of the equations, then from the numerical experiments, some results not reported in the literature at our disposal, and that we suggest as a possibility to be verified.

In what follows sect. **2** is devoted to a compact description of the aspects of the model relevant for our purposes. In sect. **3** we describe the organisation of the tests, while in sect. **4** we report our main findings. Sections **4** and **5** include a discussion of the results.

## 2. – The one-column model

The one-column version of the ECMWF meteorological model, henceforth referred to as 1C ([3]; see also [4], for an overall description of the global model), has proved to be a very useful tool for testing and experimenting with the physical parametrization and with new developments in the vertical discretisation of the equations. Examples of successful applications in boundary layers studies are given by Duynkerke *et al.* [5] and Teixeira [6], in Lagrangian simulations by Bretherton *et al.* [7].

**2**˙1. *The model equations.* – The 1C model integrates the following set of equations for a column of the atmosphere:

$$\frac{\partial u}{\partial t} + \dot{\eta}\frac{\partial u}{\partial \eta} = f(v - V_g) + P_u + F_u\,, \tag{1}$$

$$\frac{\partial v}{\partial t} + \dot{\eta}\frac{\partial v}{\partial \eta} = -f(u - U_g) + P_v + F_v\,, \tag{2}$$

$$\frac{\partial T}{\partial t} + \dot{\eta}\frac{\partial T}{\partial \eta} = \frac{R}{C_p}T\frac{\omega}{p} + P_T + F_T\,, \tag{3}$$

$$\frac{\partial q}{\partial t} + \dot{\eta}\frac{\partial q}{\partial \eta} = P_q + F_q\,, \tag{4}$$

where $\eta$ is the hybrid vertical coordinate (see [8]), $u$ and $v$ are the zonal and meridional components of wind, $T$ is the temperature, $q$ is the specific humidity, $\omega$ is the vertical velocity in pressure coordinates, $p$ is the pressure, $R$ is the gas constant (taking into account the effect of moisture, liquid water and ice), $U_g$ and $V_g$ are the zonal and meridional components of geostrophic wind, $P_i$ is the tendency due to physics, $F_i$ is is the additional forcing term, in this case the horizontal advection of the mean variables. $f$ is the Coriolis term defined as $f = 2\Omega\sin(\Phi)$, where $\Omega$ is the Earth'rotation rate and $\Phi$ is the latitude. The geostrophic wind is defined as

$$U_g = -\frac{1}{\rho f}\frac{\partial p}{\partial y}\,, \tag{5}$$

(6) $$V_g = \frac{1}{\rho f}\frac{\partial p}{\partial x}$$

and in practice represents the pressure gradient term. The one-column model has the following set of physical parametrizations: the radiation parametrization is based on a band emissivity scheme for the long-wave parametrization and a delta Eddington scheme for the short-wave parametrization [9]; the cloud scheme is the one described in detail in Tiedkte [10]. The moist convection is parametrized by using a mass-flux scheme and is described in Tiedkte [11]; the vertical diffusion parametrization is based on a $K$-diffusion approach [12, 13] and on a Monin-Obukhov–type closure for the surface layer [14]; the sub-grid scale orographic scheme is described in Lott and Miller [15] and the soil/surface scheme is described in detail in Viterbo and Beljaars [16] and Viterbo *et al.* [17].

**2**˙2. *Some general considerations*. – Before proceeding to the numerical integration of the above set of equations, it is convenient to analyse their structure for a qualitative anticipation of the results.

Inertial oscillations are common in situations where the dominant terms in the momentum equations are the tendency, the Coriolis term and the pressure gradient term. Consider the following simplified version of the previous momentum equations:

(7) $$\frac{\mathrm{d}u}{\mathrm{d}t} = fv\,,$$

(8) $$\frac{\mathrm{d}v}{\mathrm{d}t} = f(U_g - u)\,,$$

where we have assumed $V_g = 0$ without loss of generality. From (7) and (8) the $u$-component can be written as

(9) $$\frac{\mathrm{d}^2u}{\mathrm{d}t^2} = -f^2(u - U_g)\,.$$

The solution to this equation is

(10) $$u - U_g = A\sin(ft) + B\cos(ft)\,,$$

where the parameters $A$ and $B$ can be determined from the initial conditions. It can be seen from (10) that the solution for the wind oscillates about the geostrophic value. The period of oscillations is $2\pi/f$, which gives for midlatitudes a value of about 17 hours.

This type of oscillations commonly occurs in stable atmospheric boundary layer during the night. During the day the winds in the boundary layer are below the geostrophic value because of strong turbulence and drag at the surface. When night comes the turbulence decreases considerably and the pressure gradient accelerates the wind. However, as seen in equations from (7) to (10), the Coriolis term induces an oscillation.

In the flow from land to sea a similar situation must occur. Therefore we should expect the following behaviour in the surface boundary layer: apart from a daily variation on land associated to the radiation cycle, entering the sea the surface wind speed will show an obvious increase due to lower drag on the sea with respect to land. However, at the same time we expect also the appearance of long oscillations superimposed to the average trend, whose frequency depends on the latitude, and the amplitude depends on

TABLE I. – *Parameters used for the simulation on land and on the sea. The momentum roughness length on the sea is wind dependent.*

| Parameter | Land | Sea |
|---|---|---|
| Vegetation cover | 0.867 | 0.0 |
| Momentum roughness length | 0.485 | 0.001 |
| Heat roughness length (log.) | −4.072 | −9.210 |
| Background albedo | 0.168 | 0.05 |
| Background LW emissivity | 0.996 | 0.996 |

the air-sea stability conditions, For more details on inertial oscillations in geophysical flows see, *e.g.*, Dutton [18].

## 3. – The organisation of the tests

For the basic test the model was set up for middle latitudes (41 degrees north) and the month of June, therefore for summer conditions and a marked daily cycle. The geostrophic wind was set up at $U_g = -1.7$ m/s, $V_g = -10.0$ m/s, with 31 levels in the vertical.

Two situations were modelled, on land and on the sea. The respective parameters are given in table I. Note that the momentum roughness length on the sea is given by the Charnock relationship $z_0 = \alpha \cdot u_*^2/g$. The corresponding figure in the table represents only the value of the first step.

Starting from the initial conditions, the system was left to evolve, *i.e.* to be advected, on land following the daily cycle. The time step was 15 minutes. The transition (advection) to the sea was simulated shifting to the use of sea parameters, starting from the latest conditions reached on land.

## 4. – Main results

The basic result is shown in fig. 1, showing the evolution in time of the two components and the absolute value of the 10 metre wind $U_{10}$. The time scale is given as integration steps, 15 minutes each, hence every small tick corresponds to three hours, while the larger (numbered) ones are one day each. The left part of the figure shows the evolution on land (4 days, beginning and ending at midnight). After 384 integration steps we shift to sea conditions. Note that, because the column of air is advected by the general motion, its evolution in time represents also its evolution in space.

The oscillations on land represent the daily cycle, with an intensification of the longitudinal $v$-component during the day, due to sun radiation, and the appearance of unstable surface conditions.

The situation changes dramatically at the transition to the sea. There is an expected sudden increase of both the wind components, that is associated with the drastic decrease of the surface friction. This appears as an overshoot of about 0.5 m/s, followed by a sequence of regular oscillations, whose period corresponds to the inertial one, about 17 hours. After the initial marked overshoot, there is a mild tendency for a decreasing amplitude of the oscillations with time passing.

Expectably, locating the tests at different latitudes changes the characteristics of the oscillations. Their frequency decreases moving the test area towards the equator, in

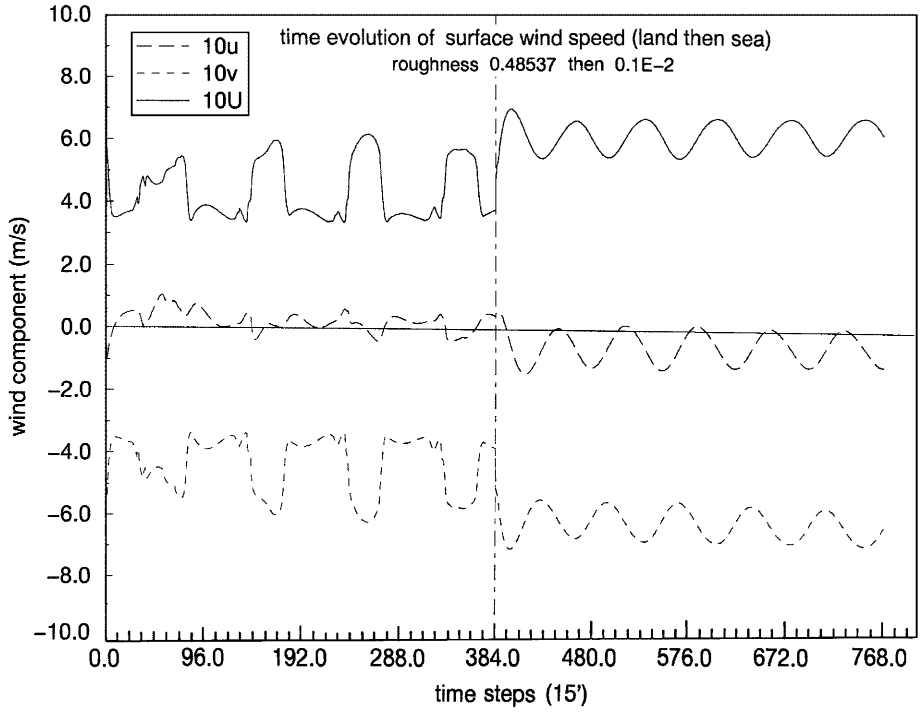
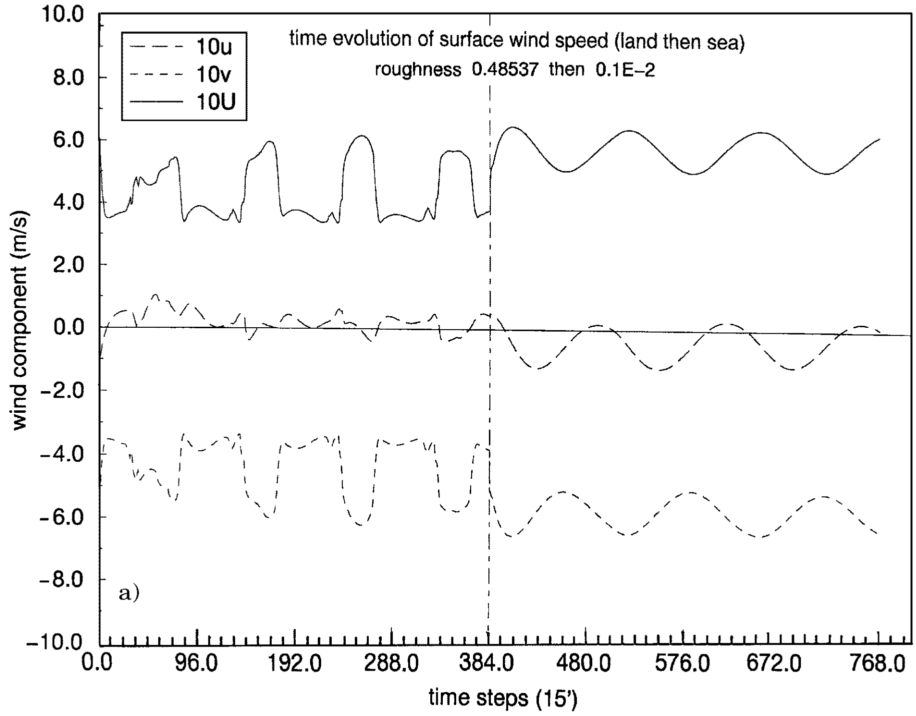



Fig. 1. – Time evolution of the surface wind speed $U_{10}$ on land, followed by a transition to sea (at the vertical line). Continuous line = modulus, broken lines = wind components. Horizontal units are integration time steps, 15 minutes each. The location is 41 degree north, during June.

correspondence to the lower value of the Coriolis term, and increases for the opposite reason towards the pole. The corresponding results for latitudes 21 and 71 degrees north are shown respectively in fig. 2a and b. Changing the latitude leaves the amplitude of the oscillations almost unaffected. There is an expected decrease (increase) of the mean value of $U_{10}$ and the peak of the overshoot moving towards the equator (the pole), due to the decrease (increase) of $f$, which leads to values of $u$ and $v$ smaller and further from (larger and closer to) the geostrophic wind values.

The tests can be, and have been, changed, varying all the basic characteristics of the run, but for the present purposes we show here only one extreme case, that illustrates the dynamics of the system. Figure 3 shows the output of the test at the equator. Note the different time scale, now 2+2 days. The lack of any inertial forcing leads to the complete absence of overshoot and oscillations, with a simple tendency to a lower equilibrium value for $U_{10}$ than in the other cases, reached in about 12 hours, with a value similar to that present on land during the day.

The initial overshoot at the transition to sea is part of the transient during which the wind adapts gradually to the new surface boundary conditions. As regards the question that stimulated the tests, *i.e.* if the transient could justify the underestimation of the model results in the Mediterranean Sea, and in general in the enclosed basins (see, *e.g.*, [19, 2*b*]), we feel the reply is negative. Even if the following oscillations impede an accurate evaluation of the duration of the transient, as seen in fig. 2 and fig. 3, this seems too short to justify the extended underestimation by the model.



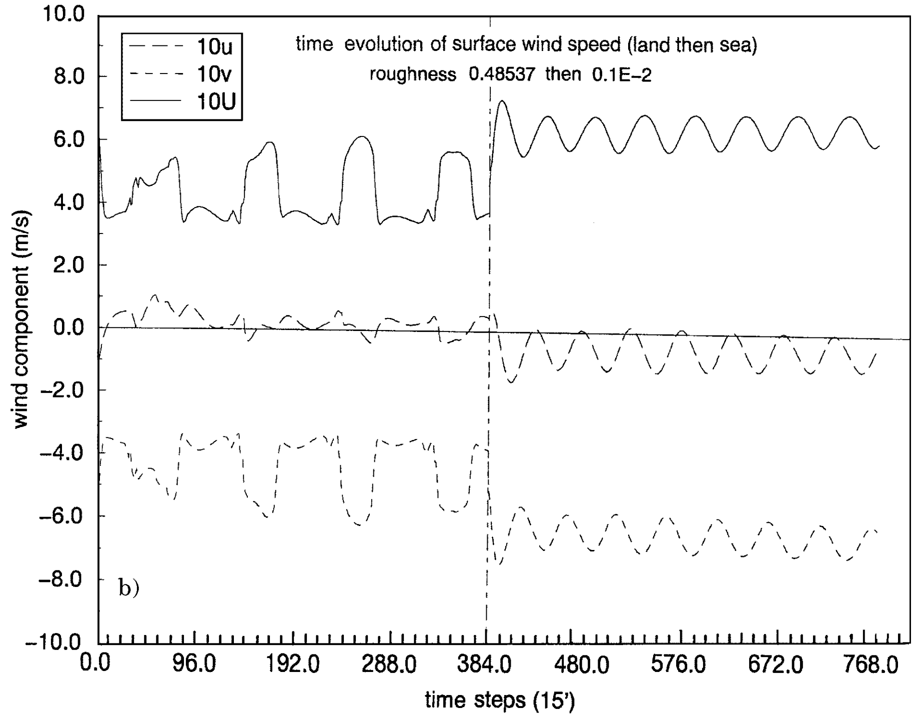




Fig. 2. – a) As fig. 1, but at 21 degrees north; b) as fig. 1, but at 71 degrees north.

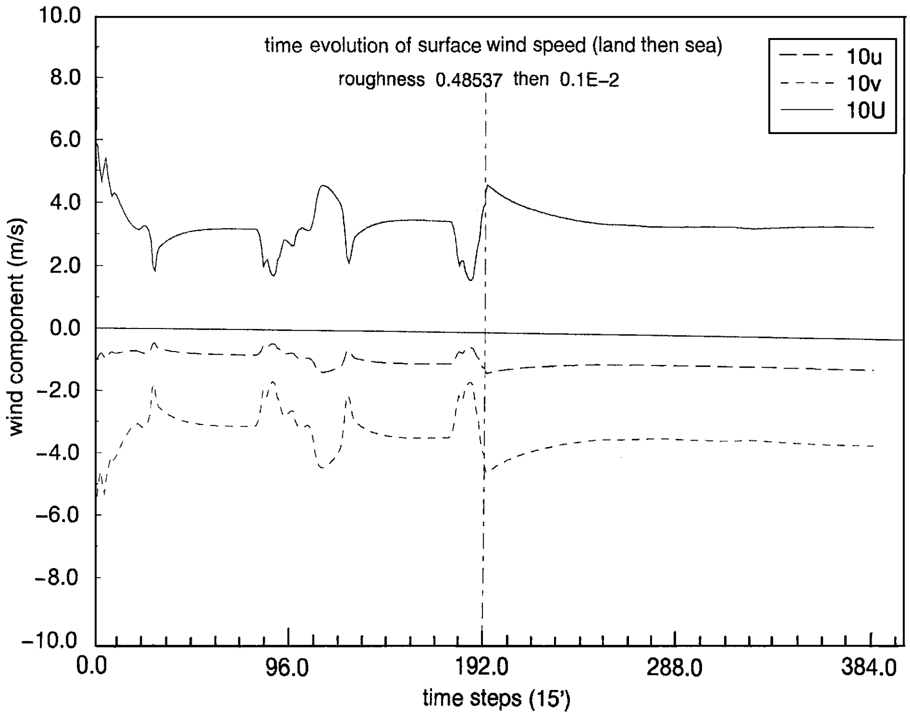



Fig. 3. – As fig. 1, but at the equator. Note also the different time scale, now 2+2 days.

## 5. – Discussion

Our results, based on the numerical integration of the 1C model, indicate that, when passing from land to sea, the wind fields experience some oscillations with an amplitude of the order of ±10% of the mean $U_{10}$ value. The oscillations, still depending on the initial conditions, are strictly related to the inertial forcing of the system. Therefore their frequency depends on the latitude. At intermediate latitudes the sudden decrease of surface roughness from land to sea leads to an increase of the 10 metre wind speed, with a marked initial overshoot.

When the test is performed at 0 degree latitude (the period is June), passing to the sea the wind shows a simple asymptotic approach to a much lower value than at intermediate latitudes.

As regards the original question on the response time of the surface boundary layer when passing from land to sea, according to our results this is of the order of a few hours. Also because of the presence of an overshoot, the transient boundary layer does not seem to be the complete explanation for the underestimation of the wind speed, hence of the wave height, in the case of an offshore blowing wind.

The question arises if the above results depend on the specific choice done when organising the tests. The values used for the geostrophic wind and the land roughness length were obtained from the 3D ECMWF weather forecast model, for the particular situation we were interested in, the transition from land to sea in the midlatitudes. We used different values for the geostrophic wind and the roughness length, in order to test the sensitivity of the one-column model experiments to these parameters. These different values for the roughness length and geostrophic wind had no impact on the overall conclusions of the study, as expected from the theoretical analysis from subsect. **2**˙2.

It is also quite clear that the oscillations reported in this paper are not of numerical nature. On the one hand, we have performed the same one-column model experiments with different time-steps (7.5 and 30 minutes), and no substantial difference was noticeable on the results. On the other hand, the period of the oscillations and its latitudinal distribution coincide with what is theoretical expected (see subsect. **2**˙2).

We have searched the literature for evidence, in favour of or against, our findings, but we could not find any experiment or related results dealing with the prescribed problem. Therefore we offer it as a hypothesis to be verified or rejected by suitable experimental data. On the other hand, pure inertial oscillations like the ones described in this paper are probably also very difficult to find in nature. This is because other forces, like friction, with different dominant space and time scales, are also controlling the evolution of momentum, and therefore interacting with, and masking, the inertial oscillations.

In this respect it is worthwhile to point out at least one approximation in the way we framed the experiment. We have assumed that the roughness of the sea surface is directly related to the wind speed via the Charnock relationship. There are indications (see, *e.g.*, [1], p. 248) that in the early stages of development of the sea, like the ones existing off the coast with an offshore blowing wind, the roughness increases substantially with respect to the value it approaches at a more mature stage. If this is the case, a larger initial roughness would decrease the value of the surface wind speed just off the coast, and possibly smooth the overshoot. A proper treatment of this aspect would have required a coupling between the 1C and a wave model, an effort that, given the approximations involved, was beyond our present purposes.

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The numerical experiments have been performed during a staying of one of the authors (LC) at ECMWF. The experiments have been suggested by Anthony Hollingsworth.

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