Impact of Wind Gustiness and Air Density on Modelling of Wave Generation: Implementation at ECMWF

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Abstract

The role of wind gustiness and air density in the evolution of wave fields is reviewed briefly. The implementation of both of them in the ECMWF forecasting system is introduced. Finally, some preliminary modelling results are given.

1. Introduction

Wind-wave modelling has reached a rather satisfactory level for practical applications with the development of the third generation wave models (e.g., Komen et al., 1994). At the same time the progressive improvement in meteorological modelling, and in particular in the description of the surface wind fields, has led to the gradual decrease of errors experienced in the last decade (see, e.g., Jacob et al., 2000, and Bidlot et al., 2000). Although the current level of accuracy in wave modelling is quite satisfactory for a wide range of practical applications, it still needs some enhancement. Part of this can be achieved by including the impact of various phenomena not modelled explicitly. Wind gustiness and actual air density are two important examples.

The reduction of the bias in the analysis, when compared to the measurements, is not reflected in a comparable reduction of the root mean square error. The reason for this is associated with the intrinsic variability of the atmosphere, also at the smaller scales, not sufficiently represented in the present meteorological models (see Simmons, 1991, and Cavaleri et al., 1997). The variability of the atmosphere is present basically at all the scales, from micro-turbulence, passing through the synoptic level, duly represented in the meteorological models, and above. The basic question of how to estimate the implications of the sub-synoptic oscillations, which we will refer to as gustiness, for the evaluation of wind waves in the oceans was addressed by a number of researchers (e.g. Janssen, 1986, Cavaleri and Burgers, 1992; Komen et al., 1994; Bauer and Weisse, 2000; and Abdalla and Cavaleri, 2002).

Wave models usually assume a constant air density ($\rho_a \approx$ 1.225 kg/m3) throughout. Actual air density varies in space and time. Variations in air density can reach up to ± 20% compared to the traditional value usually used in wave modelling. This implies the need for a more realistic representation of the air density in wave models.

2. Wind Input Source Term

From the wave modelling point of view, both wind gustiness and air density affect wave generation through the wind input source term that can be written generically as (e.g., Komen et al., 1994):

$$\frac{\partial F}{\partial t} = \gamma \ F \quad \text{with} \quad \gamma = \gamma \left({\rho_{air}}/{\rho_{water}} \ , \ U \right)$$

where, F is the energy density of a wave component, t is the time, $\rho_{air} / \rho_{water}$ is the air-water density ratio (which is usually assumed constant in wave models), and U is the wind (or the friction) velocity component along wave propagation direction. Usually mean wind (friction) velocity is used. This implies an ignorance of the impact of sub-grid, and even larger-scale, wind variability on wave generation.

3. Wind Gustiness

There is a fair amount of information on the variability of the atmosphere at the different scales. A general description of the characteristics of surface winds on the oceans can be found, e.g., in Freilich and Chelton (1986) and Tournadre and Blanquet (1994). Several dedicated experiments were conducted to study the small-scale characteristics, e.g. HEXOS (Smith et al., 1990). Notwithstanding this wealth of information, most of it has not yet found its way to wave modelling due to several reasons. Mainly, the level of gustiness present in the atmosphere is partially filtered in the available meteorological models as a result of the artificial numerical diffusion introduced in those models ensure their numerical stability (see Simmons, 1991).

There is ample evidence (e.g. Munn, 1966, and Smith et al., 1990) that the fluctuations of wind speed and direction around an average value are well represented by a Gaussian distribution. One can easily verify that the wind direction variability has only minor practical impact on wave modelling (see Abdalla and Cavaleri, 2002). There are two main approaches to include the wind speed variability in wave modelling. The first approach is the use of the Monte-Carlo simulation technique by superimposing random variability over the model (mean) wind speeds as was done by Cavaleri and Burgers (1992) and Abdalla and Cavaleri (2001). This approach provides instantaneous impact that may not represent the actual one. For the mean impact, one needs to carry out (at least) several 10's of realisations and average their impact. This is not a practical solution for the operational systems like the one operated at ECMWF.

The other alternative is to replace the traditional input source term in the model by an enhanced form that includes the mean impact of gustiness as was done by Janssen (1986), see Komen et al. (1994), and by Miles and Ierley (1998). Although it only gives the mean impact of the gustiness, this approach is rather convenient for operational applications.

The current set-up of the coupled ECMWF operational system passes the wind fields from the atmospheric model to the wave model at each time step (15 minutes). With this set-up, one can assume that the wind speed variations with scales much larger than both the spatial resolution and the time step are already resolved (apart from the impact of the added numerical diffusion). Therefore, we need to include the impact of the variability at scales comparable to and lower than the model resolution. To achieve this, an enhanced input source term with the mean impact of gustiness can be estimated as:

$$\bar{\gamma}(u_*) = \int_{u_*=-\infty}^{\infty} \frac{1}{\sigma_* \sqrt{2\pi}} \exp\left(-\frac{\left(u_* - \bar{u}_*\right)^2}{2\,\sigma_*^{\,2}} \right) \gamma(u_*)\, du_*$$

$$\cong\ 0.5\left[\gamma\left(\bar{u}_* - \sigma_*\right) + \gamma\left(\bar{u}_* + \sigma_*\right) \right]$$

where u_* represents the instantaneous (unresolved) wind friction velocity, σ_* is the standard deviation of the friction velocity and the over-barred quantity represents the mean value of the quantity over the whole grid-box/time-step. Note that $\bar{u}_*$ is the (gust-free) value obtained from the atmospheric model. The second equation follows from the Gauss-Hermite quadrature (proposed by P. Janssen, personal communication).

The magnitude of variability can be represented by the standard deviation of the wind speed. To estimate the standard deviation value, one can use the empirical expression proposed by Panofsky et al. (1977) which can be written as:

$$\frac{\sigma_{10}}{\overline{u_*}} = \left[12 + 0.5 \left(\frac{z_i}{-L} \right) \right]^{1/3}$$

where σ_{10} is the standard deviation of the 10-m wind speed, z_i is the height of the lowest inversion and L is the Monin-Obukhov length. The quantity (z_i / $-L$), which is a measure for the atmospheric stability, is computed by the atmospheric model. The constant value of 12 on the right hand side of the above equation represents the background gustiness that exists all the times irrespective of the stability conditions. The impact of this sustained level of gustiness is/should be already included implicitly in the parameterisations of the atmospheric model as well as in the wave model. Therefore, this constant value is dropped and the term related to the stability is only retained in the computations. Specifically, the right hand side of the equation, as been implemented, reduces to: $[0.5\ (z_i / -L)]^{1/3}$.

The WAM model is formulated in terms of the wind friction velocity, u_*, rather than the surface wind velocity, U_{10}. On the other hand, the empirical evidences support the Gaussian distribution of U_{10}. The relation between U_{10} and u_* is non-linear and depends on the sea-state. Therefore, the relation between σ_{10} and σ_* is not readily available. P. Janssen (personal communication) suggested the use of a parameterisation based on the wind drag coefficient and calibrated by numerical experimentation for this purpose.

4. Air Density

The air density depends on the air temperature, pressure and humidity. Therefore, the air density field is neither steady nor homogeneous. Abdalla and Cavaleri (2002) show that the overall mean impact of considering the actual air density (as estimated from the atmospheric conditions) on wave modelling results is almost negligible. However, for specific events the impact can be rather significant.

Based on basic thermodynamic concepts, it is possible to compute the air density using the following formula:

$$\rho_{air} = \frac{P}{R\ T_v}$$

where P is the atmospheric pressure, R is a constant ($R = R_* / m_a$, with R_* is the universal gas constant and m_a is the molecular weight of the dry air) and T_v is the virtual temperature. The virtual temperature can be related to the actual air temperature, T, and the specific humidity, q, by: $T_v = (1 + 0.6078\ q)\ T$. The pressure (mean sea-level pressure, MSL, is used), temperature (skin temperature is used) and specific humidity (humidity at 2-m height is used) are all standard products of the meteorological model.

5. Preliminary Results of the Implementation

Before the current implementation of wind gustiness and air density, the two-way coupling between the atmospheric model and the wave model implies the transfer of the wind fields, U10 and V10, in the atmosphere-wave direction and the Charnock parameter field, α, in the wave-atmosphere direction. The current implementation implies more data traffic in the atmosphere-wave direction with four extra fields; namely: P, q, T and z_i/L as shown schematically in Figure 1.

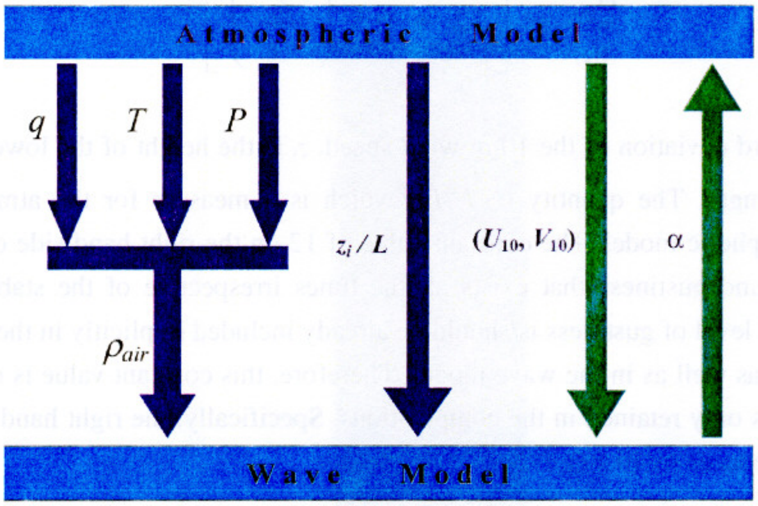

Figure 1: Data traffic across the meteorological/wave model interface after the current implementation.

Several experiments were carried out to test this implementation using low-resolution model (T159). The positive impact encouraged the application with the current ECMWF model resolution of T511/L60. The spatial resolution of the atmospheric model is about 40 km while that of the wave model is 55 km. The integration time step is 15 minutes. The two-way coupling between the atmospheric and the wave models is done at each time step. This set-up was run for the period 22 November – 14 December 2000. The wave scores (anomaly correlation and standard deviation of error) of the significant wave height compared to those of the control run are shown in Figure 2 for the 23 cases. Although the Northern Hemisphere (NH) scores are rather neutral for the first 7 forecast days, remarkable positive impact can be seen for the Southern Hemisphere (SH). The impact was further verified by computing the difference statistics between the model forecast significant wave heights and the ERS-2 radar altimeter significant wave height measurements as shown in Figure 3. The current implementation causes minor reduction in the root mean square differences (RMSE) and enhances the correlation between the forecast and the altimeter measurements. On the other hand, the negative bias was remarkably reduced in the NH. This is a direct result of the fact that under active areas (winter in the NH) the gustiness increases the wave heights.

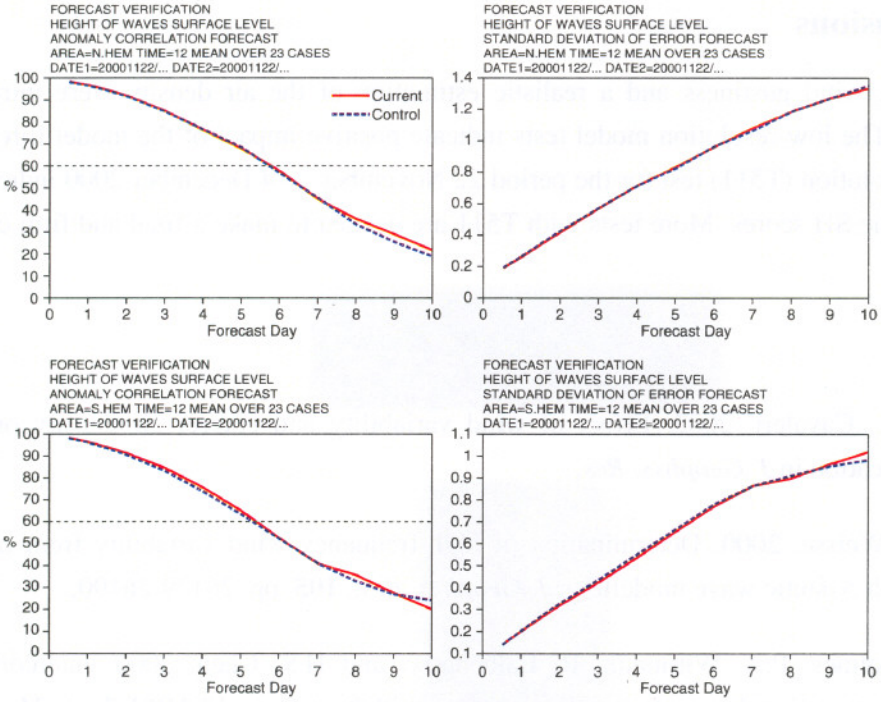

Figure 2: Significant wave height scores (anomaly correlation and standard deviation of error) for 23 cases (22 November – 14 December 2000) for NH (upper two panels) and SH (lower panels).

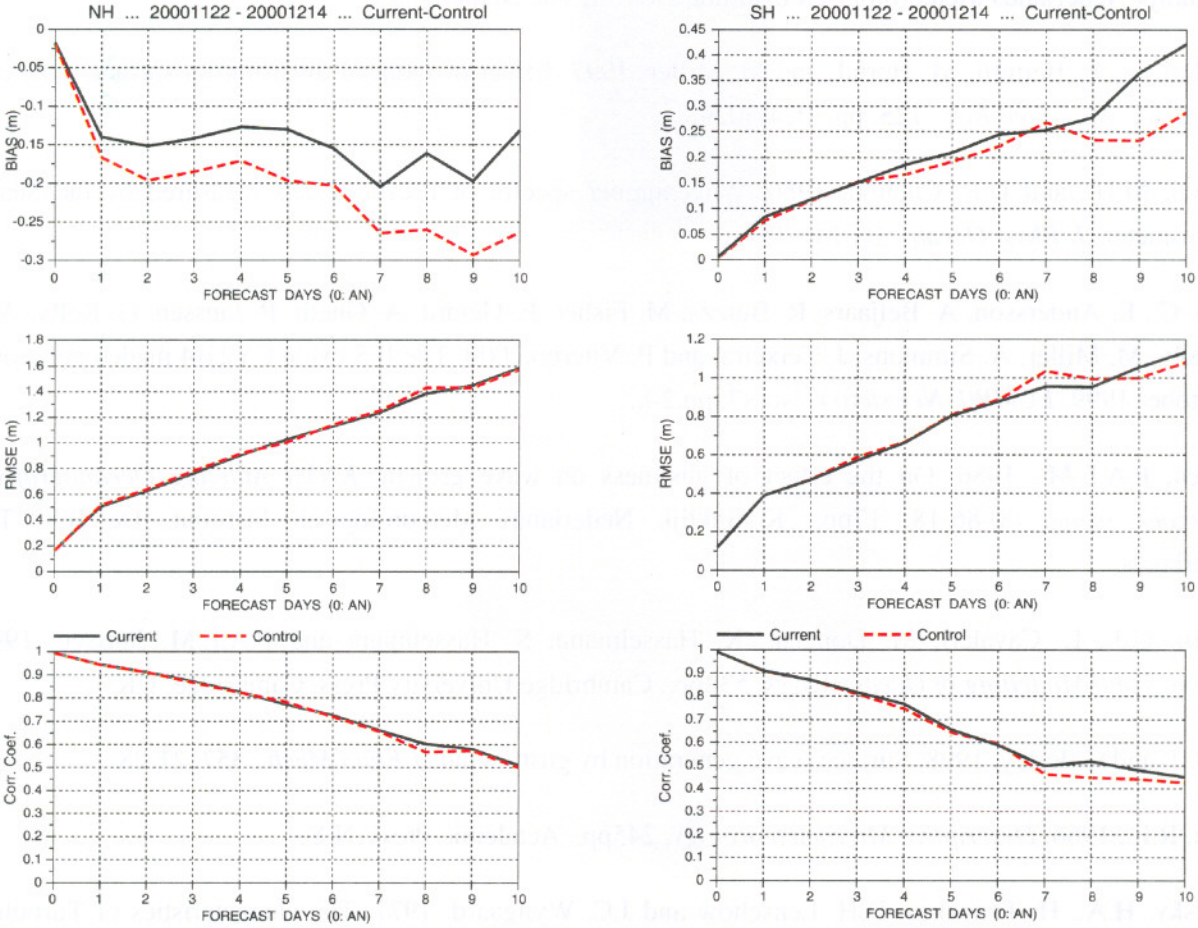

Figure 3: Comparison between model forecast and ERS-2 radar altimeter significant wave heights during 22 November - 14 December 2000 for (left) NH and (right) SH.

6. Conclusions

The impact of the wind gustiness and a realistic estimation of the air density were introduced into the ECMWF system. The low-resolution model tests indicate positive impact of the model forecasts. The more realistic higher resolution (T511) test for the period 22 November – 14 December 2000 indicated remarkable enhancements in the SH scores. More tests with T511 are needed to make a final and firm conclusion about the impact.

References:

Abdalla, S. and L. Cavaleri, 2002. Effect of wind variability and correct air density on wave growth, Accepted for publication in *J. Geophys. Res.*

Bauer, E., and R.Weisse, 2000. Determination of high-frequency wind variability from observations and application to North Atlantic wave modelling, *J. Geophys. Res.*, **105**, pp. 26179-26190.

Bidlot, J., D.J. Holmes, P.A. Wittmann, R. Lalbeharry, and H.S. Chen, 2000. Intercomparison of the performance of the operational wave forecasting systems with buoy data, *ECMWF Tech. Memo.* 315, 46pp.

Cavaleri, L. and G. Burgers, 1992. Wind gustiness and wave growth, *KNMI-Preprints*, 92-18, 38pp., Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Netherlands.

Cavaleri, L., L. Bertotti, M. Hortal, and M. Miller, 1997. Effect of reduced diffusion on surface wind and wave fields, *Mon.Wea.Rev.*, **125**, pp.3024-3029.

Freilich, M.H., and D.B. Chelton, 1986. Wavenumber spectra of Pacific winds measured by the Seasat scatterometer, *J. Phys. Ocean.*, 16, 741-757.

Jacob, C., E. Andersson, A. Beljaars, R. Buizza, M. Fisher, E. Gerard, A. Ghelli, P. Janssen, G. Kelly, A.P. McNally, M. Miller, A. Simmons, J. Teixeira, and P. Viterbo,2000. The IFS cycle CY21r4 made operational in October 1999, *ECMWF Newsletter*, No.87, pp.2-8.

Janssen, P.A.E.M., 1986. On the effect of gustiness on wave growth, *KNMI Afdeling Oceanografisch Onderzoek memo* 00-86-18, 17pp., Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Netherlands.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, 1994. *Dynamics and Modelling of Ocean Waves*, 532pp., Cambridge University Press, Cambridge, UK.

Miles, J. and G. Ierley, 1998. Surface-wave generation by gusty wind, *J.Fluid Mech.*, **357**, 21-28.

Munn, R.E., 1966. *Descriptive Micrometeorology*, 245pp., Academic Press, N.Y.

Panofsky, H.A., H. Tennekes, D.H. Lenschow and J.C. Wyngaard, 1977. The characteristics of Turbulent velocity components in the surface layer under convective conditions, *Boundary-Layer Meteor.*, **11**, 355-361.

Simmons, A., 1991. Development of the operational 31-level T213 version of the ECMWF forecast model, *ECMWF Newsletter*, No.56, 3-13.

Smith, S.D., K.B. Katzaros, W.A. Oost and P.G. Mestager, 1990. Two major experiments in the humidity exchange over the sea (HEXOS) program, *Bull. Amer. Meteor. Soc.*, 71, pp.161-172.

Tournadre, J., and S. Blanquet, 1994. Wind speed and wave mesoscale variability from in situ and altimeter data, *The Global Atmosphere and Ocean System*, **2**, 221-245.