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## Progress with wind-wave interaction

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In a previous Newsletter article (Janssen,1994) we discussed some of the direct practical benefits of ocean wave forecasting and the benefits ocean wave information may have for atmospheric modelling and data assimilation. One of the benefits of ocean waves for the atmosphere may come from a more accurate treatment of the momentum exchange between atmosphere and the ocean surface, since the efficiency of the momentum exchange depends on the steepness of the ocean waves. Waves that are just generated by wind (we call this 'young' wind sea) are steeper than mature wind seas. Steeper waves provide a rougher surface and therefore give rise to a larger momentum transfer. We discussed a synoptic example which showed that the sea-state dependent momentum transfer may have consequences for the evolution of a depression, whilst there was also systematic impact on the climate of the atmosphere and the ocean waves. In the present article we shall describe some recent results we have obtained with Cy18R6 of the IFS which includes the effects of wind-wave interaction. In addition, since ocean waves are now an integral part of the IFS, ensemble prediction of waves is now part of the EPS. A first example is discussed, which suggests that the EPS for waves contains useful information on swell prediction in the medium range.

### Model setup

Ocean waves affect the air-sea momentum transfer, and also the heat and moisture transfer over the oceans. In the previous versions of the atmospheric model the air-sea momentum transfer was modelled by means of the Charnock relation for the roughness length. The Charnock relation only models the average effect of ocean waves on the momentum transfer and therefore this momentum transfer depends only on wind speed. However, nowadays it is known that the Charnock parameter used in the parametrization of the momentum transfer is not a constant but may vary by a factor of 10 (typically from 0.01 to 0.1) depending on the stage of development of the ocean waves. In order to accommodate for this the theory of wind-wave interaction was extended by including the feedback of ocean waves on the mean airflow, resulting in a sea-state dependent Charnock parameter (Komen et al,1994). This interaction is currently known as two-way interaction and it requires the tight coupling of the atmospheric model and the wave model. In this two-way interaction mode the atmospheric model determines the surface winds needed to generate the ocean waves, while the wave model determines the amount of momentum that has been received from the atmosphere, and uses that information to determine the Charnock parameter which is returned to the atmospheric model. The effect is relevant in rapidly varying circumstances such as may occur near a low and near fronts. Additional benefits of this tight coupling are that the wind fields that drive the waves may be updated more frequently (previously this was done every 6 hours while presently winds are updated every hour) and that information such as the air-sea temperature difference and the air-sea density ratio may be passed to the wave model.

The atmospheric model has been modified to allow for this two-way interaction. Also, the analysis suite was changed. In 3D-Var, the first guess is modified in a manner consistent with the coupled physics, while also Altimeter wave height data are assimilated. In 4D-Var, both first-guess and trajectory calculations are performed in coupled mode, while the minimisation is done with a constant Charnock parameter. Altimeter data are assimilated in the final trajectory.

### Results

Early results on weather forecasting with the present setup, but with earlier cycles of the IFS and T213 resolution, have been reported during the air-sea interaction symposium last year (Janssen et al,1997). Although considerable synoptic differences were found in both forecast surface pressure and wave height field, in general the differences were found to be of small scale therefore resulting in only a modest positive impact on scores for atmospheric parameters. However, impact on scores for wave height and surface wind speed was somewhat larger.

In order to illustrate the relatively small scale of the impact of the sea state dependent roughness we discuss the case of a rapidly moving low from FASTEX. This event started on the 17th of February just south of New Foundland and arrived two days later west of Scotland. The day 2 forecast of this case is shown in Figure 1 and the surface pressure in the run with two-way interaction (coupled for short) is lower by 7 hPa, in good agreement with the coupled analyzed pressure of that low. Such differences in surface pressure result in considerable differences in the strength of the surface wind and therefore in wave height. In this case the wave height increased from 9 to 13 m (not shown). Because of the small scale of the differences there is hardly any change in anomaly correlation over the North Atlantic area; in fact, at day 2 of the forecast both coupled and control experiment have anomaly correlations close to 100%.

The next example concerns the day 2 forecast of the 24th of December 1997 for the North Pacific and is discussed here because it is an (exceptional) example of large scale impact of two-way interaction on the atmospheric circulation. Figure 2 shows the comparison of the coupled day 2 forecast with the control forecast. Substantial, large scale differences

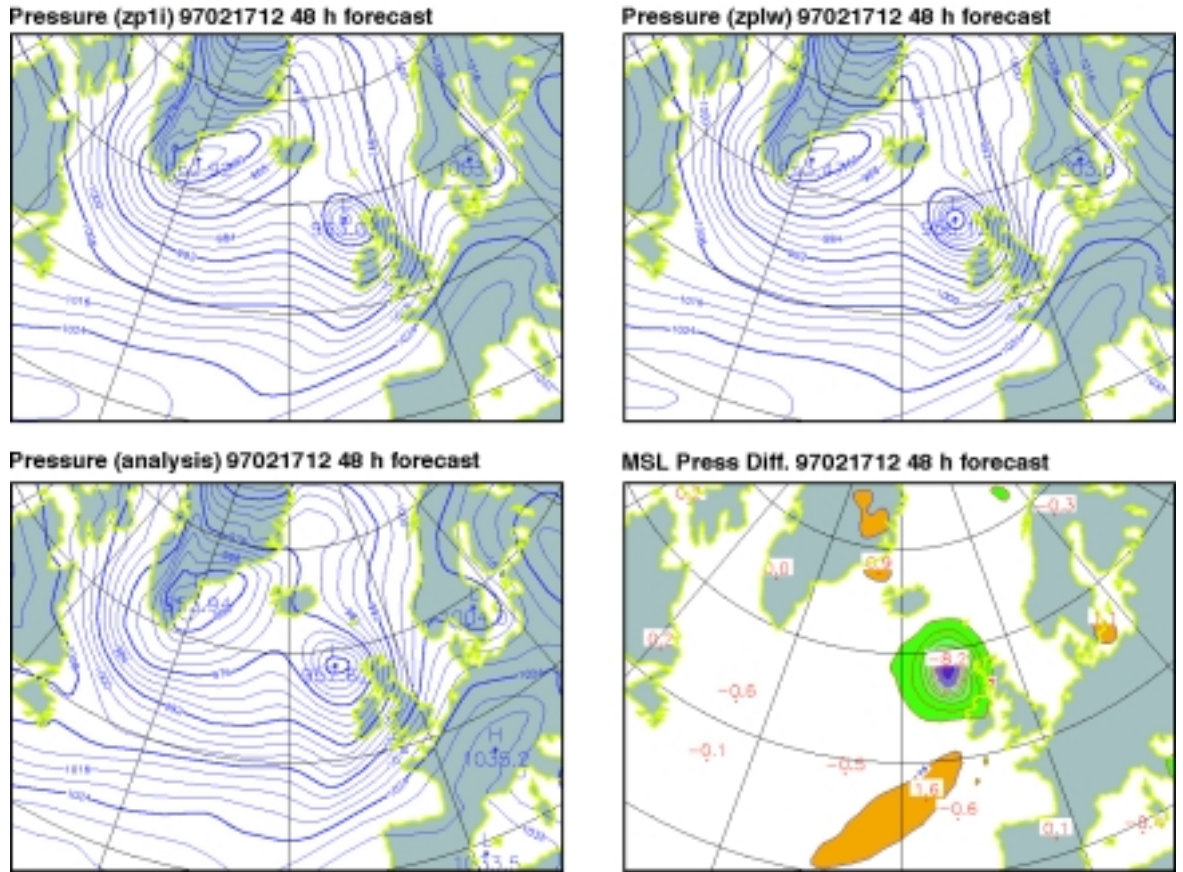


Fig. 1 Comparison of 2 day forecasted surface pressure of the FASTEX IOP-17 event from control(top left panel) and coupled(top right panel) experiment. Differences between coupled and control are shown in the bottom right panel while the verifying analysis is from the coupled experiment. Date is the 17th of February 1997.

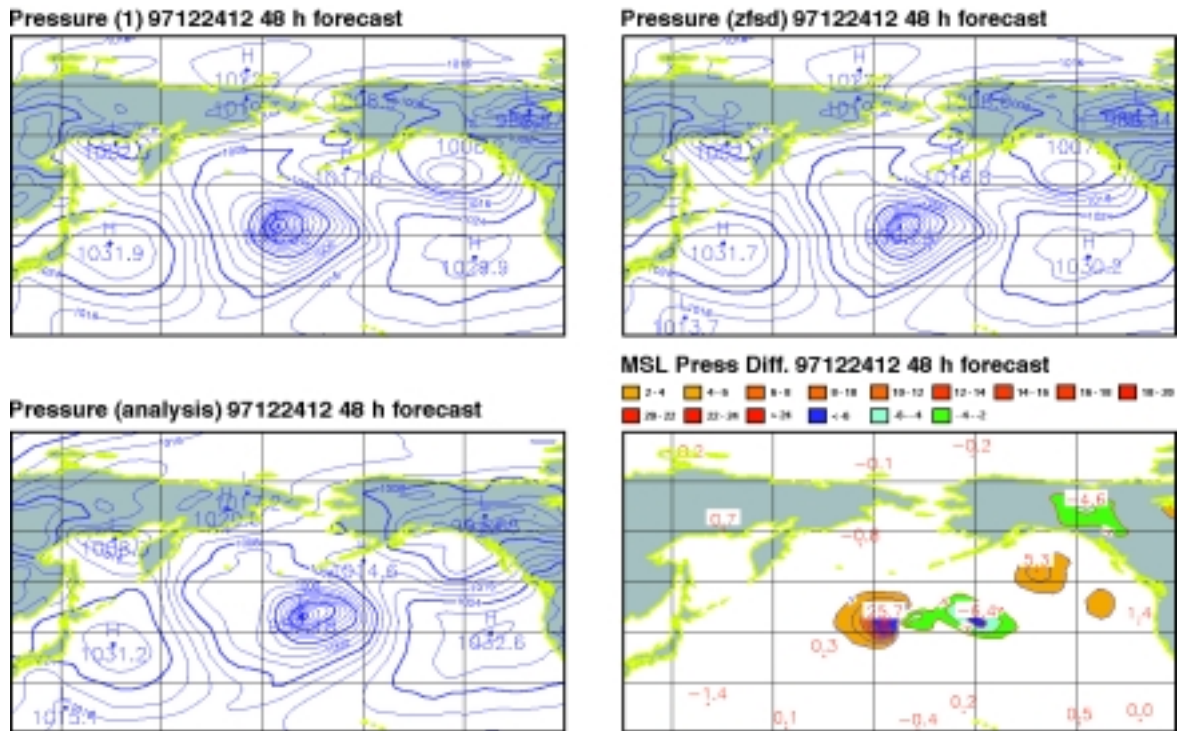


Fig. 2 Day 2 forecast of surface pressure for the 24th of December 1997. Area is North Pacific.

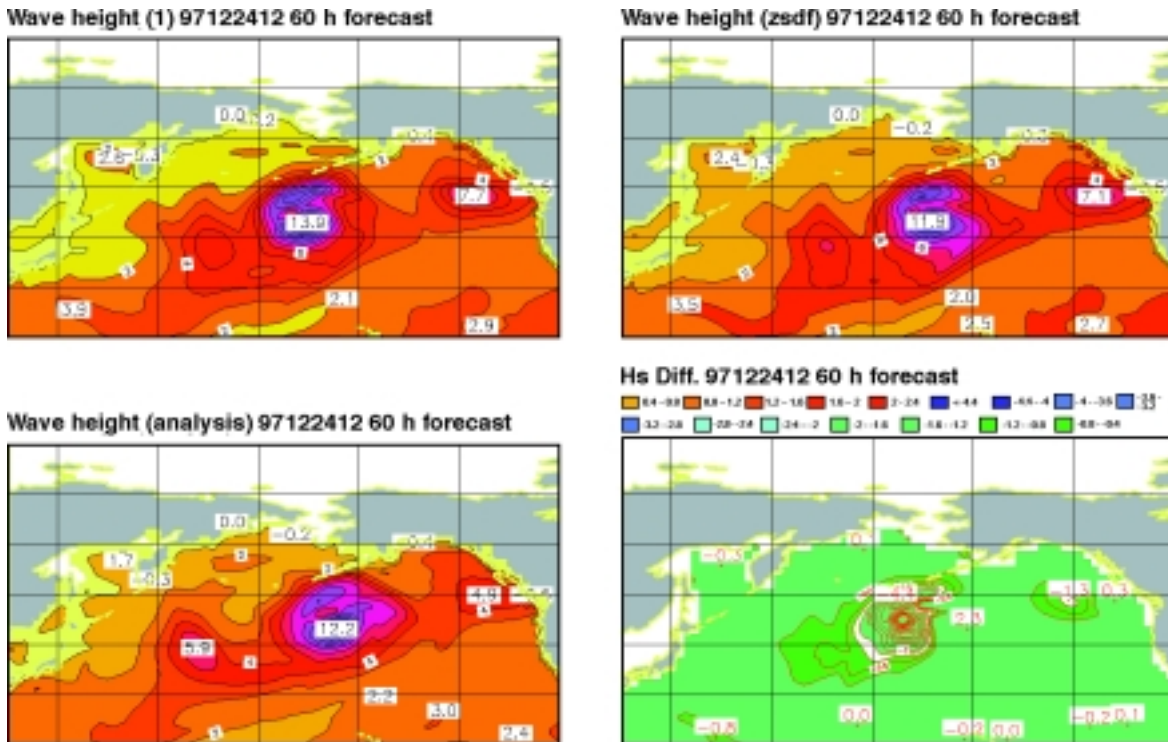


Fig. 3 Day 21/2 forecast of wave height for the 24th of December 1997. The control (uncoupled) forecast is shown in the top left panel, the coupled forecast in the top right panel and the verifying analysis in the bottom left panel. The difference between the coupled and uncoupled forecasts is shown in the bottom right panel.

in the surface pressure can be seen, and a better agreement between the coupled forecast and analysis is noted. As a result considerable improvements in the scores for surface pressure were obtained for the whole 10 day period. The different pressure distributions result in differences in surface wind field and wave height field. Figure 3 shows the comparison between coupled and control wave height forecast and verifying analysis on midnight of the 27th of December 1997. Differences between coupled and control wave height reach 4 m and the coupled forecast is in better agreement with the verifying analysis, while the control forecast is too high. This finding agrees with the property that the control forecasting system systematically has too high waves in particular in the later stages of the forecast range.

Recent experimentation with the T<sub>L</sub>319 version of the IFS system has given the impression that the impact of the waves on the atmosphere has increased somewhat. This is illustrated in Figure 4 where we show scores from the Southern Hemisphere, an area where previously we have not seen any systematic impact. The Figure compares T<sub>L</sub>319 results with the coupled version of Cy18R6 with the uncoupled one for an 18 day period in December 1997. There is positive impact for the 1000, 500 and even 200 hPa geopotential height field. Note that the impact of two way interaction on the upper layers of the atmosphere was also noted in the climate runs of Janssen and Viterbo (1996). It is probably caused by the fact that changes in surface friction have an impact of barotropic nature on the atmosphere, thus modifying the whole atmospheric column. A similar impact, albeit of smaller amplitude, was noted on the Southern Hemisphere scores during the e-suite which was run over 74 cases between 16th of April 1998 and 28th of June 1998. (The e-suite result should however be interpreted with care regarding the impact of waves on the atmosphere because Cy18R6 was compared with Cy18R5 and Cy18R6 contains in addition to two-way interaction of wind and waves numerous changes in the data assimilation, such as a new treatment of radio sonde data, assimilation of SSM/I total Column Water Vapour and the use of TOVS radiances over land). Nevertheless, as shown in Figure 5 the reductions in systematic error and standard deviation of error in wave height and surface wind speed are of a similar size as found from previous experimentation. We remark that in particular the reduction of the systematic wave height error during the forecast is quite considerable and suggests that we have removed a problem which was present in our forecasting system during the past few years.

### EPS waves

We have also made the necessary preparations for the EPS system to include the two-way interaction of wind and waves. As a consequence, ensemble products for waves are also being produced. At the time of writing the quality of these products is being assessed, prior to their dissemination to the Member States.

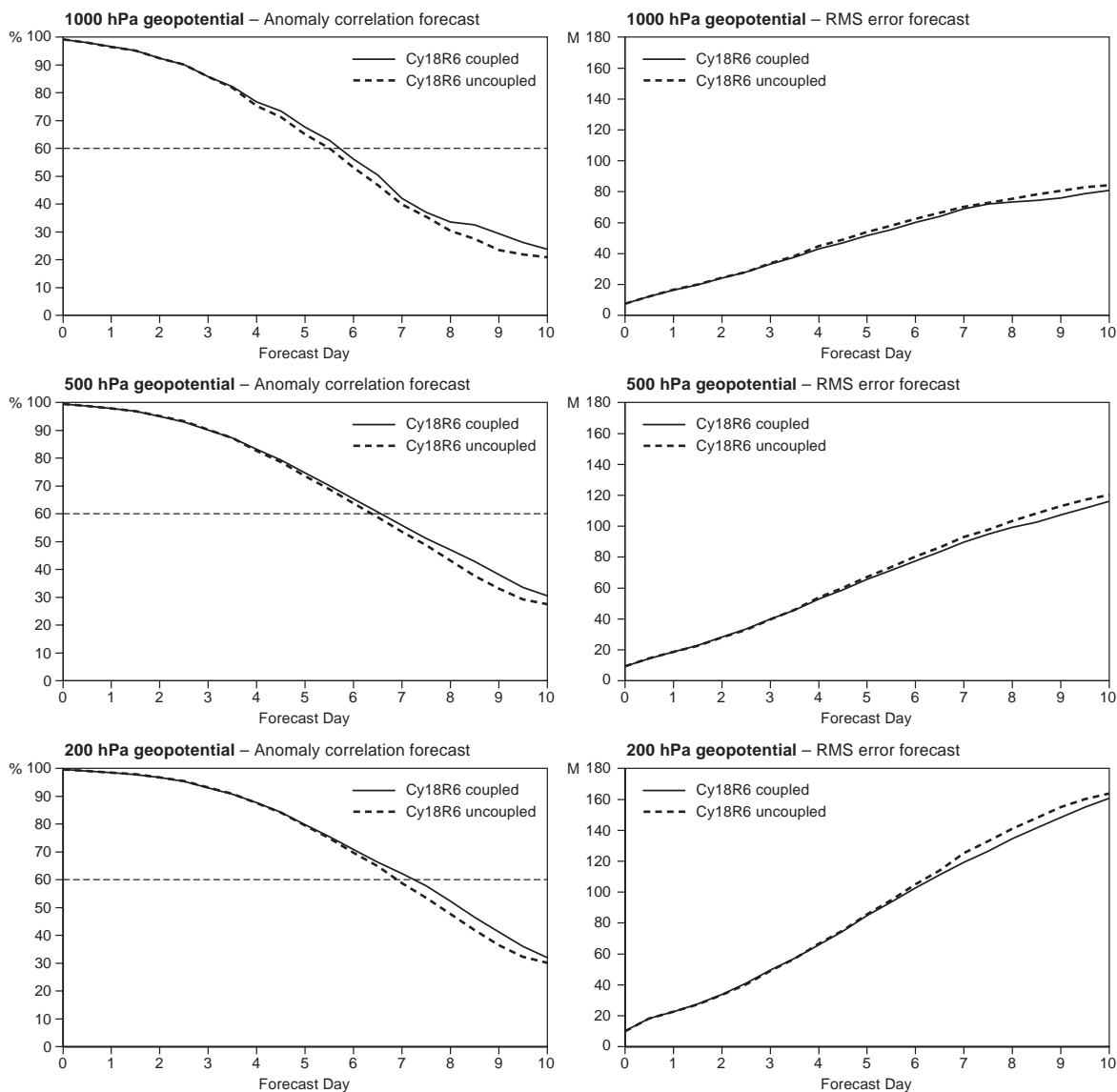


Fig. 4 Scores for 1000, 500 and 200 Geopotential height for Southern Hemisphere for a 18 day period in December 1997. Comparison of Coupled version of Cy18R6 with uncoupled one.

One of the most important applications of wave forecasting is the prediction of the timely arrival of low-frequency swells. An example of such a case is given in Figure 6 where we show plume diagrams of wind speed, peak period and significant wave height for buoy 51001 near Hawaii. Concentrating on the plume diagram for the peak period, it is seen that according to the deterministic forecast one would expect low-frequency swells to arrive after 5 days in the forecast, while according to the control forecast low-frequency swells only arrive after seven and a half days. The majority of the members of the ensemble indicate however that no low-frequency swell arrives in the 10 day forecast period, which is confirmed by the EPS forecast of the next day and the verifying analysis.

This suggests that the ensemble product of waves might contain useful information, and we will study this in a more systematic fashion by determining optimal ship routes for every member of the ensemble. In order to obtain sufficient data to do reliable statistics this study will cover a number of months over the coming Autumn and Winter season, since we shall take crossings from Europe to the USA over the North Atlantic.

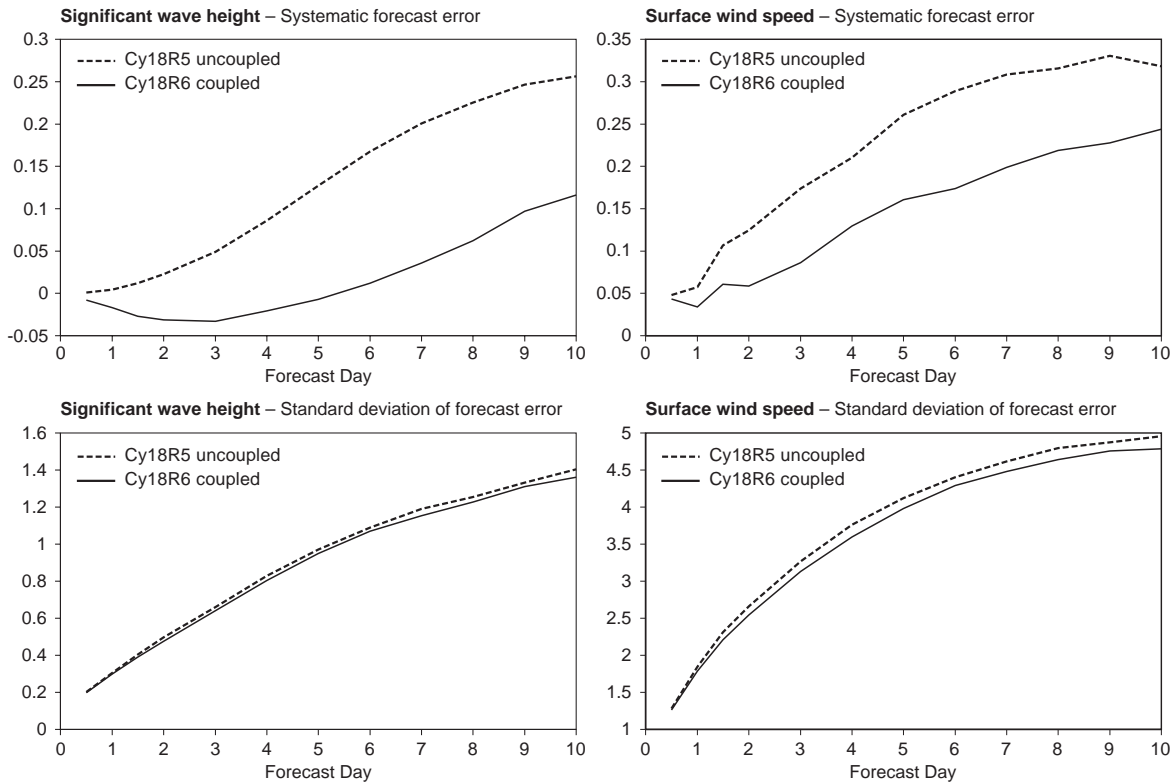


Fig. 5 Comparison of systematic forecast error and standard deviation of forecast error for significant wave height and surface wind speed. Period is 16th of April until 28th of June 1998. Area is Southern Hemisphere.

## Conclusion

We have seen that there are advantages for atmosphere and ocean waves when the two models are coupled. In the near future we hope to be able to further exploit the benefits of two-way interaction. On the one hand this may be achieved by means of a more accurate representation of the wave generation process by wind. For example, it is known that the growth of waves by wind depends on the air-sea density ratio and the stability of the air column. Presently, we take a constant value for the density ratio, while in practice this ratio may vary by 10%, in particular during cold-air outbreaks. Also, at the moment we assume for wave generation a neutrally stable airflow whereas in practice there may be strong deviations from neutrality, again during cold-air outbreaks. In the context of a coupled wind-wave system it will be relatively straightforward to pass the relevant information from the atmospheric part of the IFS to the wave part. In addition, since in a coupled system the sea state is known, this may help in providing a more accurate determination of the ocean surface albedo, while sea state information may also be of help in the interpretation of satellite observing systems such as the scatterometer, SSM/I and AMSU (Advanced Micro wave Sounding unit, just recently launched).

On the other hand, observed wave data (cf. Janssen,1994) may give beneficial information on the atmospheric state over the oceans and a coupled wind wave system seems to be the ideal framework to make optimal use of wave observations to specify the initial weather state over the oceans.

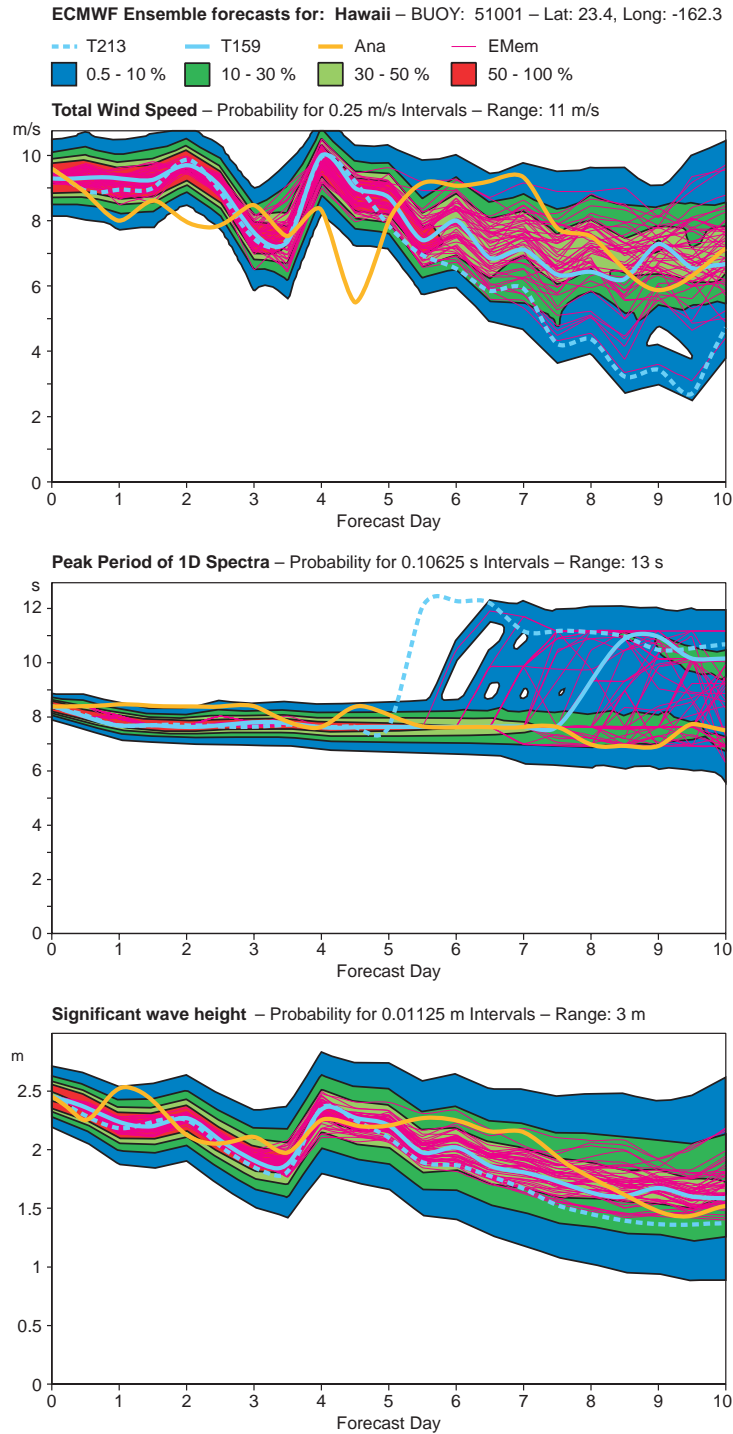


Fig. 6 Plume diagram of surface wind speed, peak period and significant wave height for buoy 51001 located North West of Hawaii. Forecast date is 23rd of June 1998.

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