DIAGNOSIS OF OCEAN-WAVE FORECASTING SYSTEMS

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Abstract

Errors in the analysed and forecast wind are so overwhelming that it almost prohibits an analysis of wave model errors. Evidence for the close relation between wave height error and wind speed error will be presented. As a consequence, at ECMWF wave model results have been used as a diagnostic tool for detecting errors and problems in the atmospheric model. A number of examples, such as the inconsistency between surface stress and wind and the apparent overactivity of the atmospheric forecast will be discussed.

1. INTRODUCTION

The past forty years has seen a rapid development of ocean-wave prediction models. This development was triggered by the work of *Gelci et al* (1957) who found that the basic evolution equation for ocean waves is given by the energy balance equation for the two-dimensional wave spectrum. In the context of the energy balance equation processes such as the generation of waves by wind, dissipation due to white capping and nonlinear four-wave interactions may be studied in isolation which resulted in a considerable simplification of the problem at hand (*Hasselmann*, 1960).

Nevertheless the early wave models from the 1960s (called first generation models) did not attempt to compute the wave spectrum from first principles alone. The main reasons were that the important role of the nonlinear interactions was not realized, while in addition a numerical implementation of the nonlinear transfer would have been computationally far too expensive. This changed by the 1970's when extensive experiments (*Mitsuyasu*, 1968, 1969) and field campaigns (*Hasselmann et al*, 1973) revealed the important role of the nonlinear interactions in controlling the shape of the wave spectrum and in shifting the peak of the spectrum towards lower frequencies. Therefore, second generation models emerged which, because of lack of computing power, used a simple parametrisation of the nonlinear transfer. This parametrisation worked satisfactorily for locally-generated wind sea but it was known to have defects in mixed wind sea-swell situations. The weakness of the approach was most pronounced in the case of hurricanes because these have strong and rapidly-varying winds.

As a result, a large international group of scientists (the so-called WAM = Wave Modelling Group) decided to develop a new wave model based on first principles, without relying on the somewhat artificial distinction between wind sea and swell. Stimulated by the introduction of efficient vector machines and the prospect of the availability of satellite wave observations on a global scale, there was rapid progress in the development of a third generation wave model, called the WAM model. At ECMWF, the global version of the WAM model started running in quasi-operational mode in March 1987, while the model became operational in June 1992. Nowadays, the WAM model has been installed at over 100 institutes.

The different generations of wave models have an important feature in common, namely, that an important error source in forecast or hindcast wave height may be attributed to the wind speed error. This follows from the validation of modelled wave height and wind speed against buoy data. Using operationally available winds from the 1980's *Cardone* (1987), *Zambresky* (1987), and *Clancy et al* (1986) found scatter indices (defined as the ratio of standard deviation of error to the mean observed wave height) for the analysed wave height ranging from 25% to 40%, while the scatter index for analysed surface wind was of the order of 30% or more. On the other hand, when using high quality, manually analysed winds (which have much lower rms errors), wave results improved dramatically. Examples of this may be found in an intercomparison study of shallow water wave models (SWIM group, 1985) or more recently in the SWADE experiment (*Cardone et al*, 1995). On average the scatter index was around 20% or even lower, suggesting that the quality of wave products is to a considerable extent determined by the accuracy of the driving wind fields.

Finally, at weather centres, such as ECMWF, there is a continuous effort to improve analysis and forecast. For example, *Janssen et al* (1997a) compared verification scores of wind and waves from the 1995 version of the ECMWF analysis and forecasting system with those of 1988 as reported by *Zambresky* (1989). The scatter index for wind speed was found to decrease on average by 16% which was accompanied by a reduction in the scatter index for significant wave height by 21%.

Similar results were obtained for limited area models in shallow water (see, e.g. *Janssen et al*, 1984). These authors even attempted to relate wave height error to wind speed error for one buoy station at different forecast ranges. While no relation between mean error in wave height and wind speed was obtained, a definite relation between scatter indices for wave height and wind speed was found.

The programme of this paper is as follows. In Section 2 a brief description of the present status of wave modelling at ECMWF is given, including some methods to validate the wind and wave analysis and forecast. Next, we reinvestigate the issue of the relation between wave height error and wind speed error. We do this, on the one hand, by studying results from a comparison of analysed and forecast wave height and wind speed with 30 Northern Hemisphere buoys over a 6 month period. From the different characteristics of the error growth curves (with forecast time) for wave height and wind speed, the respective contributions from wave model error and wind speed error to the total wave height error may be estimated. The resulting model of wave height error growth suggests that the wind speed error is overwhelming. On the other hand, the validity of the model of wave height error growth is confirmed by a comparison of forecast wave height and wind speed with the verifying analysis over the forecast range of 10 days. We considered monthly mean errors only over a period of about three years.

Having established that indeed the wave height error is dominated by the wind speed error, we turn things around and we use wave model results as a diagnostic tool for the detection of errors in the atmospheric model. Two examples are considered in some detail in this paper. The first one is the inconsistency between surface stress and surface winds, which is discussed in Section 3, while in Section 4 a discussion is given of how we detected problems with the overactivity of the atmospheric forecast.

In Section 5 we discuss the present quality of the analysed surface winds by presenting a verification against independent Altimeter surface winds. This verification shows that over the past 5 years we have seen a considerable improvement in the quality of the surface wind field, in particular in the Tropics and in the Southern Hemisphere Extra-Tropics. These improvements were facilitated by the increased awareness of the sensitive dependence of the sea state on the quality of the driving wind fields. They were caused by important changes in ECMWF's data assimilation system such as the introduction of 3DVAR and 4DVAR, by the use of new surface data, such as from the Scatterometer, and by the introduction of the coupling between wind and waves. We conclude by giving an outlook on future developments.

2. WAVE MODELLING

Modern wave prediction systems are based on a spectral description of the sea state. The two-dimensional wave spectrum $F(f, \theta)$, where f is the frequency and θ the direction of the waves, follows from the energy balance equation

$$\frac{\partial F}{\partial t} + \vec{v}_g \cdot \nabla F = S = S_{in} + S_{nl} + S_{ds} \qquad (1)$$

proposed by *Gelci et al* (1957) and further developed by *Hasselmann* 1960). Here, v_g is the group velocity of the waves, the source functions S describe the different physical processes that are relevant for deep-water surface gravity waves: S_{in} represents the direct atmospheric input by the surface wind, S_{nl} represents resonant four wave interactions and S_{ds} is the dissipation term. The advantage of this formulation of the evolution of ocean waves is that the relevant processes for wave evolution may be studied in isolation in laboratory experiments, field campaigns and theoretical work. As an example we mention the developments regarding the wind input source function S_{in}.

Miles (1957) was the first to suggest a rational explanation for the problem of the generation of wind waves by wind through a shear flow instability mechanism. Later, a field campaign in the bight of Abaco by *Snyder et al* (1981) measured the energy transfer from wind to waves by correlating the wave-induced pressure fluctuations with the rate of change in time of the surface elevation. The resulting growth rates of ocean waves by wind were in fair agreement with the results by *Miles* (1957) and they have provided wave modellers an important constraint for developing their ocean wave models. In addition, wind-generated ocean waves extract a considerable amount of momentum from the air flow, in particular when they are steep, resulting in a slowing down of the air flow. As a consequence, the momentum transfer from air to ocean becomes dependent on the sea state. Experimental evidence for this was first provided by *Donelan* (1982) and was confirmed by the HEXOS field campaign (*Smith et al*, 1992). From the theoretical point of view *Janssen* (1982) extended Miles theory to include the feedback of the ocean waves on the air flow with the consequence that the air-sea momentum transfer becomes sea state dependent (*Janssen*, 1989, 1991).

Regarding the nonlinear wave-wave interactions there has been a similar interplay between experiment and theory. On theoretical grounds *Phillips* (1960) showed the possibility of resonant energy transfer between four gravity waves while *Hasselmann* (1962) determined the four-wave nonlinear transfer for a continuous wave spectrum. Experimental evidence of the existence of the nonlinear transfer between four waves came from the careful laboratory measurements of *McGoldrick et al* (1966) while evidence for its existence in the field was provided by JONSWAP (*Hasselmann et al*, 1973).

Theoretically, the least well-known source function is the dissipation term. Assuming that dissipation is largely caused by white-capping (which is a highly nonlinear, local process) *Hasselmann* (1974) proposed a general functional form for the dissipation source function, which still contained a number of unknown parameters. More specific information on white-cap dissipation was obtained by *Komen et al* (1984) who solved the energy balance in the steady state using the *Snyder et al* (1981) parametrisation for wind input and the exact nonlinear transfer of Hasselmann(1962). By insisting that the steady state wave spectrum should agree with the empirical *Pierson-Moskowitz* (1964) spectrum, estimates for the unknown parameters in Hasselmann's dissipation function were obtained.

The first wave model that attempted to give an explicit solution of the energy balance equation was developed by the WAM group. It is called the WAve Model (WAM) and an extensive account of its development is given in *Komen et al* (1994). The WAM model has been extensively validated in realistic circumstances against for example buoy data (*Zambresky*, 1989, *Janssen et al*, 1997a) and Altimeter wave height data from Seasat and Geosat (cf. for example *Komen et al*, 1994) and ERS-1/2 (cf. for example *Janssen et al*, 1997). Although the overall performance of the WAM model was regarded satisfactory, underestimation of wave height during extreme events was noted. There may be several reasons for the underestimation of wave height. One reason could be related to problems with the physics of the WAM model, but the major cause of the underestimation of wave height turned out to be the quality of the driving wind field. This was illustrated by the work of *Cardone et al* (1995) who performed simulations with the WAM model during the SWADE experiment using two different wind fields. The first simulation used operational wind products from ECMWF, while the second simulation used manually analysed winds produced by Ocean Weather and the Atmospheric Environment Service (OW/AES). The latter winds are the result of a man-machine mix procedure that takes maximum advantage of all available products from numerical modelling, the know-how of the experienced meteorologist and all available observations made during the SWADE campaign. Considerable differences between ECMWF and OW/AES winds were found that resulted in considerable differences in simulated wave height. Compared to buoy data modelled wave heights based on the ECMWF winds were seriously underestimated while wave heights simulated with the OW/AES winds were in good agreement with the observations.

The SWADE campaign took place from October 1990 until March 1991, but even in 1995 the quality of operational ECMWF wind fields during extreme events was not always optimal. We have illustrated this in Fig.1 which shows the 36 hour surface pressure and wave height forecast for hurricane Luis in its extra-tropical phase. The two left hand side panels show the operational forecast of that time (the right hand side panels will be discussed later) and compared to observed surface pressure (965 mb) and observed wave height(17m) it is clear that the model simulations perform poorly.

At ECMWF there are two applications in the area of wave forecasting, namely a limited area model and a global model. We concentrate on global model results. The atmospheric model and the wave model are fully integrated so that the feed back of the ocean waves on the driving wind field is accounted for. Presently, the energy balance equation for the wave spectrum (which consists of 25 frequencies and 12 directions) is solved on an irregular spherical grid with a spatial resolution of 55 km. The wave analysis is obtained with an Optimum Interpolation technique using Altimeter wave height data from ERS-2. There is a continuous effort to verify forecast wave height against buoy data and against analysis.

2.1 Verification against buoy data

Systematic verification of the wave height forecast against buoy data began in 1995 and more details of this validation effort are given in *Janssen et al* (1997a). As an example we have taken results from the second half of the year 1995. The evolution of root mean square (rms) error of significant wave height and surface wind speed with forecast time is shown in Fig.2. It is seen that while the rms wind speed error grows linear with time up to day 4, error growth in significant wave height is slower, at least for the first two days of the forecast, but beyond day 2 of the forecast also wave height error grows linear with time. This different behaviour of error growth in wave height and wind speed requires an explanation.

An attempt to explain the relation between wave height and wind speed error starts from the following fundamental relation for the wave height H_s of equilibrium wind waves,

$$H_s = \beta U_{10}^2/g, \quad \beta = 0.22 \tag{2}$$

where U_{10} is the surface wind speed at 10m height and g is the acceleration of gravity. First, let us assume that wave height errors are just caused by local wind speed errors. The simplicity of this assumption should be emphasized, because there may be other causes for wave height error such as wave model errors and errors in the swell. Nevertheless, making this simple assumption and using Eq.(2), the rms wave height error σ_{ws} follows at once,

$$\sigma_{ws} = \sqrt{\langle \delta H_s^2 \rangle} \cong 2\beta U_{10}/g\sqrt{\langle \delta U_{10}^2 \rangle} \tag{3}$$

Then, using as wind speed the average wind speed over the period in question and the rms errors in wind speed, the rms error in wave height may be obtained and is plotted in Fig.3. By comparing with the actual rms errors in wave height it is seen that the simple model of Eq.(3) explains a considerable part of the error in wave height except for the analysis and the day 1 forecast.

The reason for this discrepancy may be that (1) there are also nonlocal errors (e.g. swell is an important component of the sea state, certainly in the open ocean) and (2) there are also wave model errors. Let us denote this second error by σ_{sw}, then the total wave height rms error becomes

$$\sigma_{hs} = \sqrt{\sigma_{ws}^2 + \sigma_{sw}^2} \tag{4}$$

and with $\sigma_{sw} = 20$ cm we have plotted the total wave height error in Fig.3 as well. Compared to the actual wave height error growth curve a good agreement is obtained. Since at day 0 (the analysis) $\sigma_{hs} = 45$ cm while $\sigma_{sw} = 20$ cm the wind speed errors are seen to dominate. This just supports the common belief in the ocean wave model community that a considerable part of errors in wave height is caused by errors in the wind field.

2.2 Verification against analysis

A problem with verification of model products against buoy data is the limited coverage over the globe. Typically, most buoys are located in the Northern Hemisphere storm tracks near the coasts so that from the forecast verification against buoys no information is available on the quality of the wave forecast in the Tropics and in the Southern Hemisphere, and even on the open oceans of the Northern Hemisphere. A way out of the problem posed by the limited coverage of the buoy observations is to validate the wave forecast against the analysis. However, this is only meaningful when the wave analysis is of sufficient quality.

As already mentioned, the wave height analysis is obtained through the method of Optimum Interpolation, in which we have given equal weight to the first-guess model wave height and the wave height observations from the ERS-1/ERS-2 Altimeters. Thus, (systematic) errors in the Altimeter wave height will induce an analysed wave height error but with a weight of 50%. The quality of the Altimeter wave heights from ERS-1 and ERS-2 has been studied extensively. *Janssen et al* (1997b) compared ERS-1 and ERS-2 Altimeter wave heights to buoy data over the period of June 1995 to May 1996. The verification was restricted to cases with wave heights larger than 1.5 m, because of known Altimeter problems at low wave height. The standard deviation of error (the random error for short) was 35 and 30 cm for respectively ERS-1 and ERS-2 while there was a systematic underestimation of wave height by respectively 15% and 8% (*Janssen et al,* 1997b). Later, we extended the ERS-2 Altimeter wave height verification to a period of four years and we found an even lower systematic error of only 5%. Therefore, the quality of the wave analysis is expected to be good, even in the Tropical and Southern Oceans. However, up to May 1996 (before that time we used ERS-1 data in our wave analysis) it seems plausible that the analysis underestimates wave height by about 8% (which implies with an average global wave height of 2.5m a systematic error of about 20 cm), while after May 1996, when we switched from ERS-1 data to ERS-2 data, the underestimation of wave height is about 4%.

In Fig.4 and 5 we show for Northern Hemisphere, Tropics and Southern Hemisphere the monthly mean of the random error of significant wave height H_s and surface wind speed U_{10} for different forecast times. The period is August 1994 until July 1999. Over this 5 year period considerable improvements in the skill of the ECMWF wave forecasting system may be noted. For example, in the Northern Hemisphere the day 1 wave height random error is reduced by 21%, while the day 1 wind speed error is reduced by 17%. Similar reductions in random error are also noted in the Southern Hemisphere. This improvement in the short term forecast scores for Northern and Southern Hemisphere seems to be related to a reduction of the seasonal cycle in the random error, suggesting that most of the improvements have been achieved in Northern and Southern winter time. The most prominent change in skill scores occurred, however, in the Tropics when in May 1997 a new formulation of the background cost function J_b was introduced in the analysis system (*Derber and Bouttier*, 1999).

Thus, the time series of random error in wave height and surface wind are a useful tool to diagnose changes in the ECMWF wave forecasting system. However, the interesting question of what has caused the improved skill requires additional information. In this context, it should be noted that at ECMWF there is a continuous program for improvement. Three to four times per year changes are introduced in the operational ECMWF system after extensive experimentation and a parallel suite which may last from several weeks to a few months. During the parallel runs a comparison between wave and wind scores of the old and new forecasting system is made and therefore the impact of the changes on forecast skill are in principle known. Over the past five years we have made several major changes to the ocean wave forecasting model. We increased spatial resolution twice, namely in July 1994 (from 3 deg. to 1.5 deg) and in December 1996 (from 1.5 to 0.5 deg.), we modified the advection scheme in May 1997 in order to alleviate problems with shadow effects behind islands. In addition, we switched from ERS-1 Altimeter data to ERS-2 Altimeter data in May 1996. None of these changes in the wave model and wave analysis resulted in significant reductions in the random wave height error, except the modification of the advection scheme. The latter change gave, however only a small reduction of about 1-2%, although considerable differences were noted in the individual forecast fields. Also, the switch from ERS-1 to ERS-2 data in the wave analysis resulted in a reduction of systematic error growth. Nevertheless, it should be emphasized that the overall impact of changes in the wave model is too small to account for the improvements found in the operational scores of Figs. 4 and 5. Thus, the improvements in wave scores can only come from changes in the atmospheric model which have led to an improved specification of the surface wind fields. This is indeed found upon inspection of the skill scores from a number of atmospheric parallel suites, notably testing

1) cycle 13R4, introduced in April 1995(which included a number of physics changes such as the reintroduction of mean orography),
2) 3DVAR(including the use of Scatterometer data) introduced in January 1996,
3) the formulation of the new Jb introduced in May 1997,
4) 4DVAR introduced in December 1997 and
5) the coupling between wind and waves introduced in June 1998.

All these changes combined have led to the considerable reduction of the day 1 random wave height error of about 20%. This once more supports the contention that the main contribution to the wave height error comes from errors in the driving wind fields.

Using the scores given in Figs.4 and 5 we have tested the validity of the model for H_s error growth given in Eq.(4). The result is presented in Fig.6 where on the y-axis we have plotted the random wave height error according to Eq.(4) using the monthly mean wind and random wind error from the 12 hour forecast until day 10 of the forecast, while on the x-axis we have plotted the corresponding random wave height error from the verification of the wave forecast against the analysis. We have chosen two areas namely the North Atlantic and the North Pacific. It is evident that there is a close relation between random wave height and wind speed error.

A more detailed discussion of the relation between wave height and wind speed error is given by *Janssen* (1998). Because according to the WAM model the waves are driven by the friction velocity rather than the wind speed, this study starts, in stead of Eq.(2), from a growth relation for wave height based on friction velocity scaling. Since in the later stages of the forecast the relative wave height errors become large (as is also evident from Fig.6), even higher moments of the wind speed error distribution should be taken into account. Nevertheless, as seen from Fig.6, a simple relation such as given in Eq.(4) seems to work in practice relatively well.

This concludes the standard diagnosis of a wave forecasting system. As we have established that the wave height error is dominated by the wind speed error, we turn things around and in the remainder of this paper we use wave model results as a diagnostic tool for the detection of possible errors or problems in the atmospheric model.

3. INCONSISTENCY BETWEEN SURFACE STRESS AND WIND

During the development of the WAM model in the mid 1980's a considerable part of the extensive validation work took place at ECMWF. Theory (*Miles*, 1957; *Charnock*, 1955) and semi-empirical scaling (*Janssen et al*, 1987) suggested that waves are generated by the surface stress rather than the surface wind, and therefore the wind input source function in the WAM model was formulated in terms of the friction velocity rather than the surface wind speed. At that time two option were available to determine the surface stress or friction velocity. The first option, which is still used today, is based on the assumption that the atmospheric surface layer is close to neutral stability and therefore the surface stress may be obtained from the surface wind and the neutral Drag coefficient. Here, the neutral drag coefficient follows from the assumption of a logarithmic wind profile and the Charnock relation for the roughness. The second option uses the surface stresses from an atmospheric model. Since in practice the surface layer over the oceans is indeed close to a neutrally stable state, one would expect that the two options give very similar results (provided, of course, that the two options have the same drag coefficient). Surprisingly, *Zambresky* (1986) discovered that this was not the case. Running the WAM model with ECMWF surface winds gave substantially larger wave heights than forcing the waves with ECMWF atmospheric stresses, while also the spatial structure of the extreme events differed. The reasons for this serious discrepancy between surface stress and surface wind were not clear at that time.

It turned out that several reasons caused a discrepancy between surface stress and surface wind speed, but the main cause was related to the manner physical and dynamical tendencies are treated by the numerical integration scheme (*Janssen et al*, 1992). The numerical integration scheme at that time was based on the split method which obtains the total tendency of, for example, the wind by adding the tendencies due to dynamics(e.g., pressure and coriolis force) and due to physics(e.g., turbulent transport of momentum). The problem is, however, that the dynamics and physics tendencies are obtained by different numerical schemes, namely Eulerian versus implicit, and then are just added to give the total tendency, disregarding any possible interaction between the two. In order to avoid numerical instabilities, physical processes, such as turbulent diffusion in the surface layer, are usually treated by means of an implicit scheme because the typical relaxation time of the diffusion may be shorter than the integration time step of the dynamical processes in the atmospheric model. As a consequence, the physics tendencies depend in a nonlinear way on the integration time step, while the dynamics tendencies, which follow from an Eulerian step, are linear in the time step. In equilibrium the two tendencies balance each other but the consequence is that the equilibrium wind speed U_{10} depends on the time step, in such a way that the larger the time step the larger the surface wind. Hence, for a given surface stress, the surface wind speed would be overestimated for large integration time step, which explains why a wave model running with surface winds gives higher wave height. A non-split method, where physical and dynamical processes are treated on the same footing was shown to resolve the problem of the time step dependence of surface wind speed and drag coefficient.

When the semi-Lagrangian advection scheme (rather than a Eulerian scheme) is used longer time steps are allowed and the use of the time-split method would have further enhanced the inconsistency between surface wind and surface stress. The non-split integration scheme (applied to velocity, temperature and moisture) was therefore introduced with the semi-Lagrangian T213 version of the ECMWF model (*Ritchie et al*, 1995) in September 1991. The introduction of the non-split, semi-implicit integration scheme had serious consequences for wave prediction of extreme events. This is illustrated in Fig.7 which compares winds and wave heights as determined from the split scheme with those obtained from the implicit scheme for the case of 1 March 1991 when a severe storm occurred in the North Atlantic area. Results were obtained with the T106/l19 ECMWF atmospheric model (cy44). It is seen from Fig. 7a that the implicit scheme gives a reduction in wind speed which may be as large as 5 m/s. As a consequence, a reduction in extreme wave heights of about 5 m from 17m to 12m is found, as shown in Fig.7b. At the same time this example illustrates once more the sensitivity of wave height to the quality of the wind field.

As a final remark it is noted that several atmospheric models have suffered from similar inconsistencies between surface winds and surface stress because these models used a split integration scheme, in particular in the 1980's. As examples we mention the FNMOC model (*Jim Doyle*, private communication 1997) and the NMC model (*John Derber*, private communication 1997). Although the relatively low resolution atmospheric models were rather successful in giving the 'right' winds in extreme events, it nowadays appears to be a coincidence since these winds were too large because of the use of the split scheme and a large time step. In fact, most likely the corresponding surface stress (and hence pressure gradient) was too weak in these low resolution models.

4. OVERACTIVITY OF THE ATMOSPHERIC FORECAST

In Section 2 we have established a relation between the random wave height error and the local random wind speed error. However, there is no simple theoretical understanding of the relation between the systematic wave height error and the local systematic and random wind speed error. A reason for this is that the bias in wave height is to a large extent determined by non-local wind speed errors from earlier times, in other words regarding the wave height bias there is a considerable memory. This would require the development of a non-local model for the systematic wave height error, which presumably would require the solution of a linearized version of the energy balance equation (1). This would certainly not result in a simple model for systematic wave height error growth. In fact, we made an attempt to find a relation between the bias in wave height and the local, instantaneous wind speed error but were unable to find a relation. A similar result may be found in *Janssen et al* (1984).

Nevertheless, it is of interest to study time series of the systematic wave height error for Northern Hemisphere, Tropics and the Southern Hemisphere, which are obtained by comparing wave height forecast maps with the verifying analysis. Therefore we show in Fig.8 the monthly mean of the systematic error in forecast waveheight over the five year period from January 1994 until July 1999. It is clear from this Figure that also regarding the bias in wave height considerable improvements in the skill of the ECMWF wave forecasting system may be noted. In recent years there is considerably less rapid growth in systematic error, suggesting that the forecasting system is more balanced. As the main part of the wave height error comes from wind speed errors this suggests that the ECMWF atmospheric model is more balanced in the sense that the intensity and the number of forecast storm systems and of analysed storm systems is of similar magnitude.

It is emphasized, however, that in particular in 1994 considerable systematic errors were found during the medium-range of the forecast in the Tropics and the Southern Hemisphere (as already reported by *Janssen et al*, 1997a). The tropical problem is probably caused by a too active atmospheric model in the Southern Hemisphere. In order to make this plausible we show in Fig.9 a comparison of the monthly mean of the day 1 and the day 7 forecast for May 1994. Substantial higher wave heights are seen in the Southern Oceans (e.g. southwest and south of Australia) while a considerably larger amount of swell is radiated towards the Tropics, in particular in the south Pacific and the Indian ocean.

Newer versions of the atmospheric model have been developed since 1994 with a reduction of atmospheric activity in mind (as reflected by too high levels of kinetic energy during the forecast). As a consequence, we now have a much reduced systematic error growth in all regions. The detailed reasons for this reduction have already been listed in Section 2.2. Regarding the systematic forecast error we add to this list that also the switch from ERS-1 to ERS-2 wave height data in the wave analysis, which occurred in May 1996, has resulted in a favourable reduction as is evident from the Tropical time series of Fig.8.

5. CONCLUSIONS AND OUTLOOK

In summary, we have provided evidence that the wave forecast error is to a large extent determined by errors in the forcing wind field. A wave model is therefore an excellent tool to diagnose problems in the atmospheric forecast. In addition, we have seen in the past 5 years a considerable effort to reduce systematic and random errors of the wind and wave forecast. The main reason for this seems to be the improvements in the forecast surface wind, once more illustrating the sensitive dependence of the wave forecast on the quality of the driving winds.

However, so far we have left unanswered the question whether there are any improvements in the quality of the wind and wave analysis. To this end an independent data set is required which is not used in the assimilation process. For winds, such a data set is available because ECMWF does not assimilate Altimeter winds. The quality of Altimeter winds is high as is evident from a comparison of Altimeter wind speed against buoy data, shown in Fig.10. The comparison was performed over the winter seasons of 1997/1998 and 1998/1999, and the buoy wind speeds were corrected for height if information on the observation height was available. During the winter season the Altimeter winds have a small negative bias of about 23 cm/s, but during the Northern Hemisphere summer the negative bias may be as much as 1 m/s. Hence, there is a seasonal cycle in the bias of Altimeter winds which mainly occurs in the Northern Hemisphere. A detailed discussion of the reasons for this is given in *Janssen* (2000).

The validation of analysed surface winds against ERS-2 Altimeter wind speed data is shown over the period of August 1995 to April 1999 in Fig.11. The dots indicate a monthly mean standard deviation of error, while in order to guide the eye a 6 monthly running average is plotted as well. Over the whole globe we see a reduction of analysis error by about 15% or more, which is largely due to large improvements in the Southern Oceans (about 17% reduction) and in the Tropics (about 25% reduction). Improvements in the Northern Hemisphere are less pronounced. A similar difference in improvement in Northern and Southern Hemisphere is also evident from the forecast scores displayed in the Figs. 4 and 5. In fact, nowadays Southern Hemisphere forecast skill (as measured by the anomaly correlation, not shown) is at least as good or perhaps even better than the Northern Hemisphere forecast skill. This is in marked contrast with the performance of the ECMWF atmospheric model 5 years ago (Janssen et al,1997). It is emphasized that this feature is confirmed by the error in the wind analysis shown in Fig.11., because wind speed errors in the Southern Oceans are nowadays about 1.5 m/s or less, while in the Northern Hemisphere the wind speed error has the slightly larger value of 1.6 m/s.

The reason for the lesser improvement in the Northern Hemisphere is not clear. Nevertheless, it should be remarked that over the past 5 years different types of satellite observations (for example, scatterometer winds) have been introduced in the atmospheric analysis which have resulted in considerable changes in the data sparse areas of the Tropics and the Southern Hemisphere. However, the Northern Hemisphere oceans, in particular the North Atlantic, have a relative abundance of conventional observations and the addition of new observations is therefore expected to have a reduced impact. Also, the possibility of a conflict between conventional and satellite observations cannot be excluded.

Finally, we speculate on future developments. In the short term further improvements in the quality of surface winds are expected. For example, the introduction of SSMI surface winds will give rise to a reduction in the random wind speed error of about 5-8%, while the random wave height error will enjoy a similar reduction. In the longer term we expect improvements from assimilation of SAR data in quantities such as the period of the ocean waves. Furthermore, atmospheric model developments such as a further increase of horizontal resolution are expected to be beneficial for a more realistic simulation of extreme storm events. This is illustrated by the 36 hour forecast of hurricane Luis, shown in Fig.1. The left-hand side panels show results for surface pressure and significant wave height from the operational T213 model, while the right hand side panels show the results with the T639 version. The increase in horizontal resolution nearly doubles the peak wave height from 9.8 to 16.7 m and is in good agreement with the observed wave height of about 17 m. A systematic study regarding the benefits of increased horizontal resolution is presently under way.

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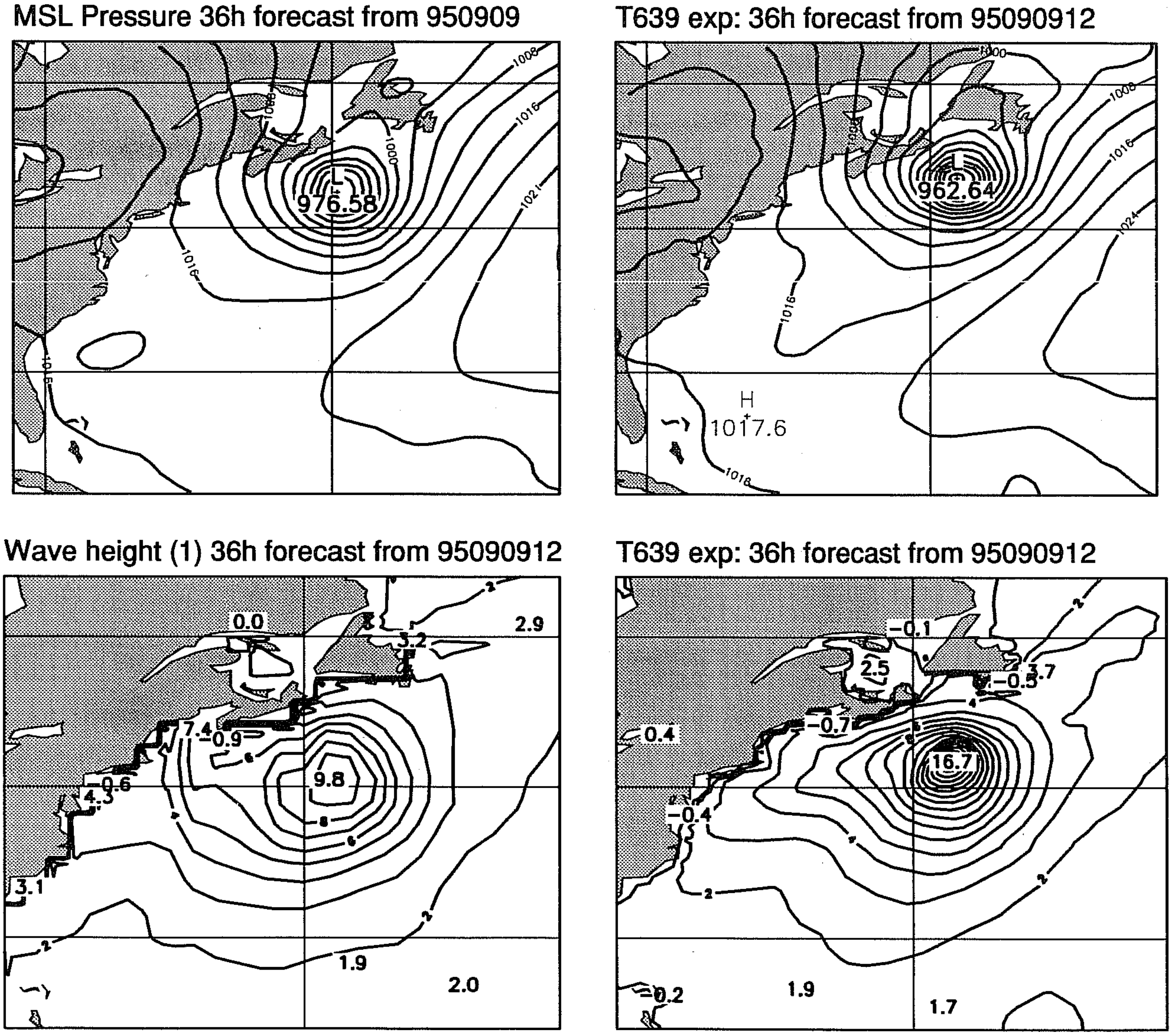


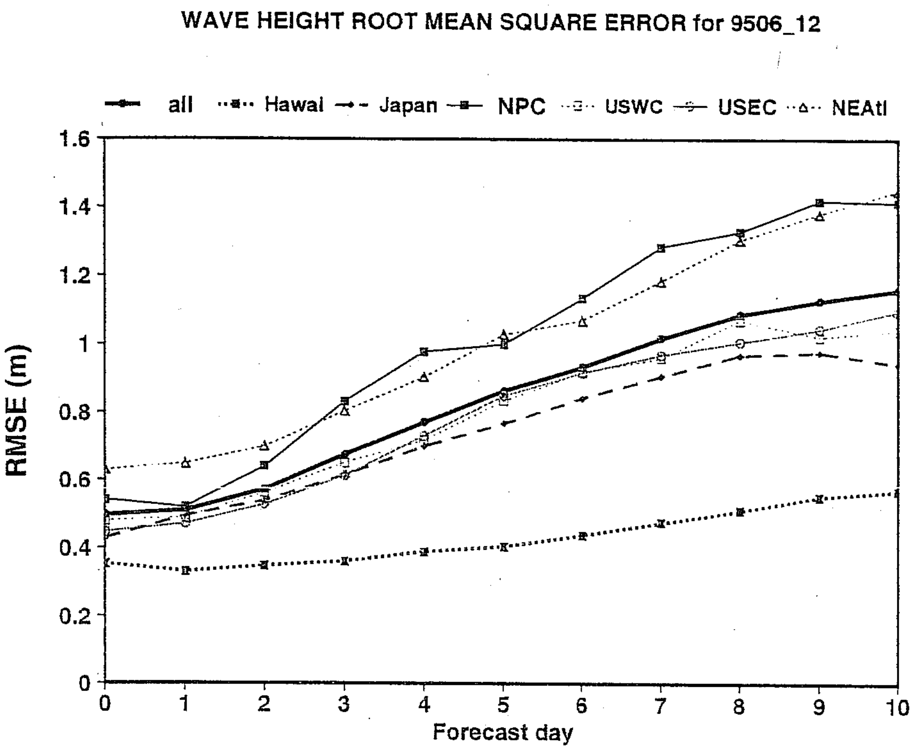
MSL Pressure 36h forecast from 950909

T639 exp: 36h forecast from 95090912

Wave height (1) 36h forecast from 95090912

T639 exp: 36h forecast from 95090912

Figure 1: Progress in extreme sea state forecasting as illustrated by the 36 hour forecast of Hurricane Luis. The top left panel shows the operational forecast mean sea level pressure of 1995090912 UT with T213 resolution while the top right panel shows the 36 hr forecast with T639 resolution. The bottom panels show the 36hr wave height forecast forced by low(left) and high(right) resolution winds.



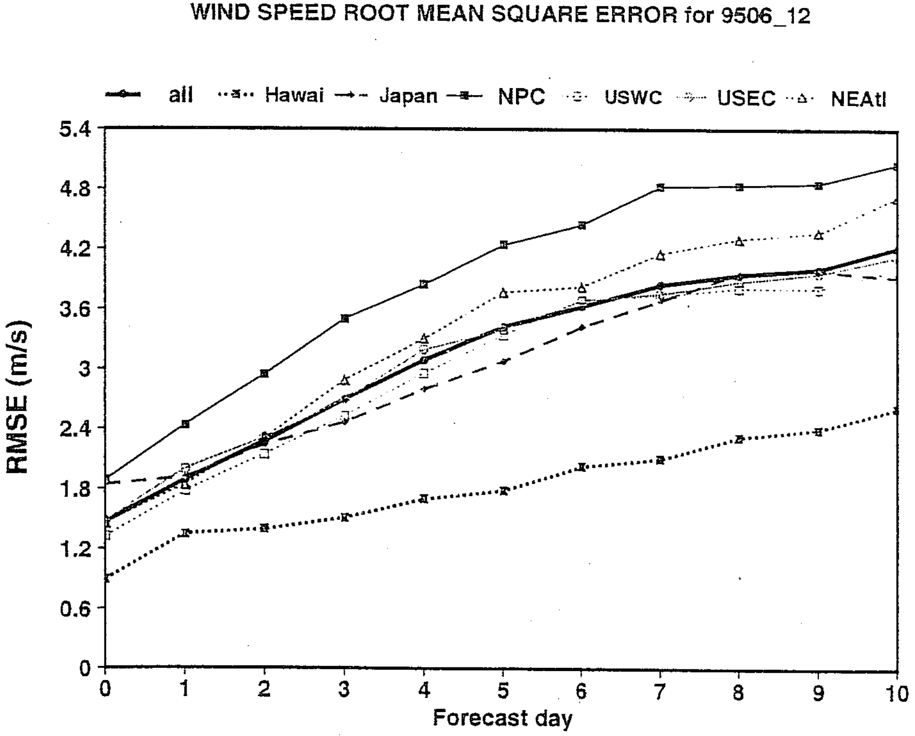


Figure 2: Evolution of rms error for wave height and wind speed as a function of forecast day at buoy locations. Symbols refer to different areas as displayed in the legend.

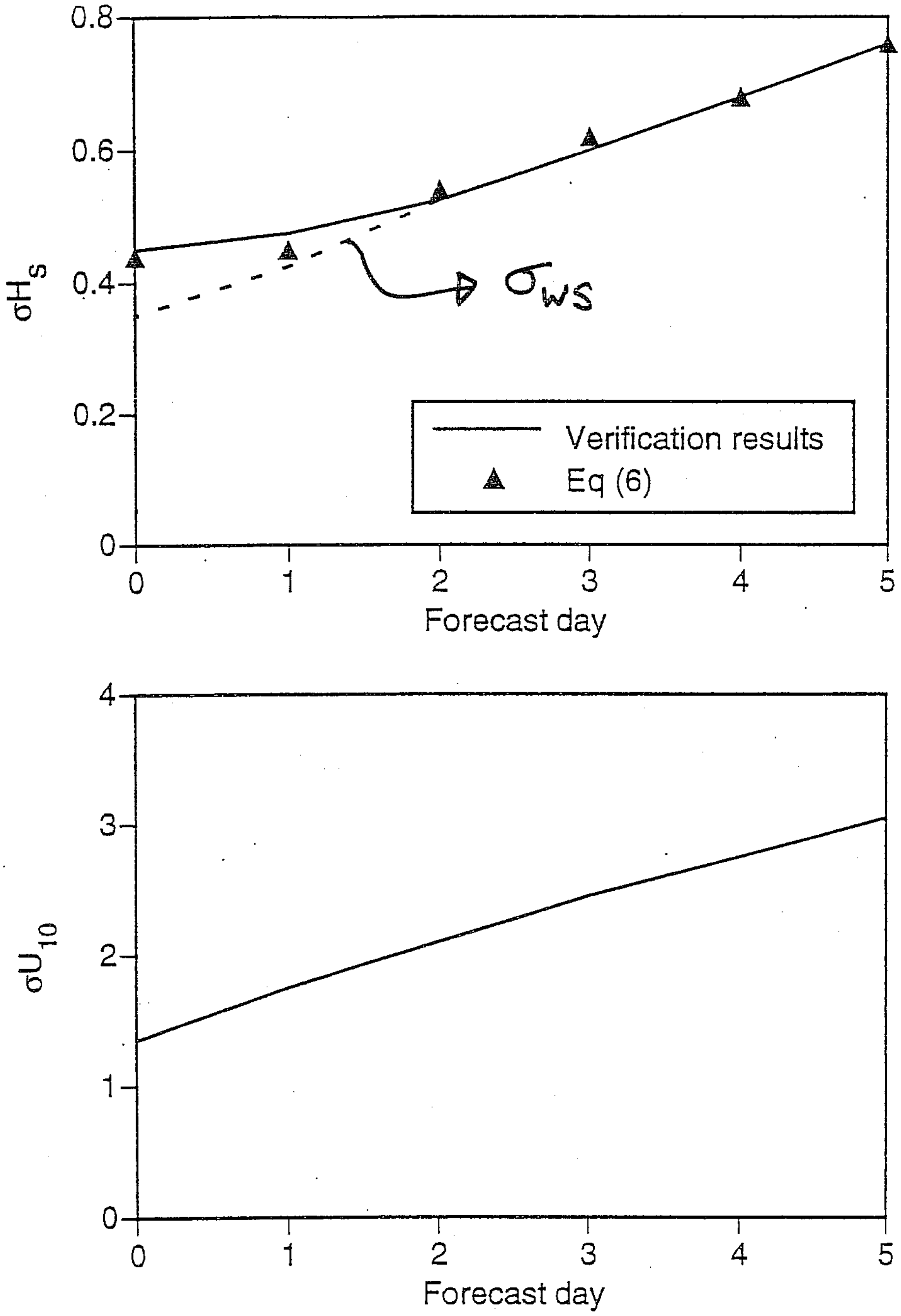


Figure 3: Rms error growth in wave and wind forecast during the period June-September 1995.

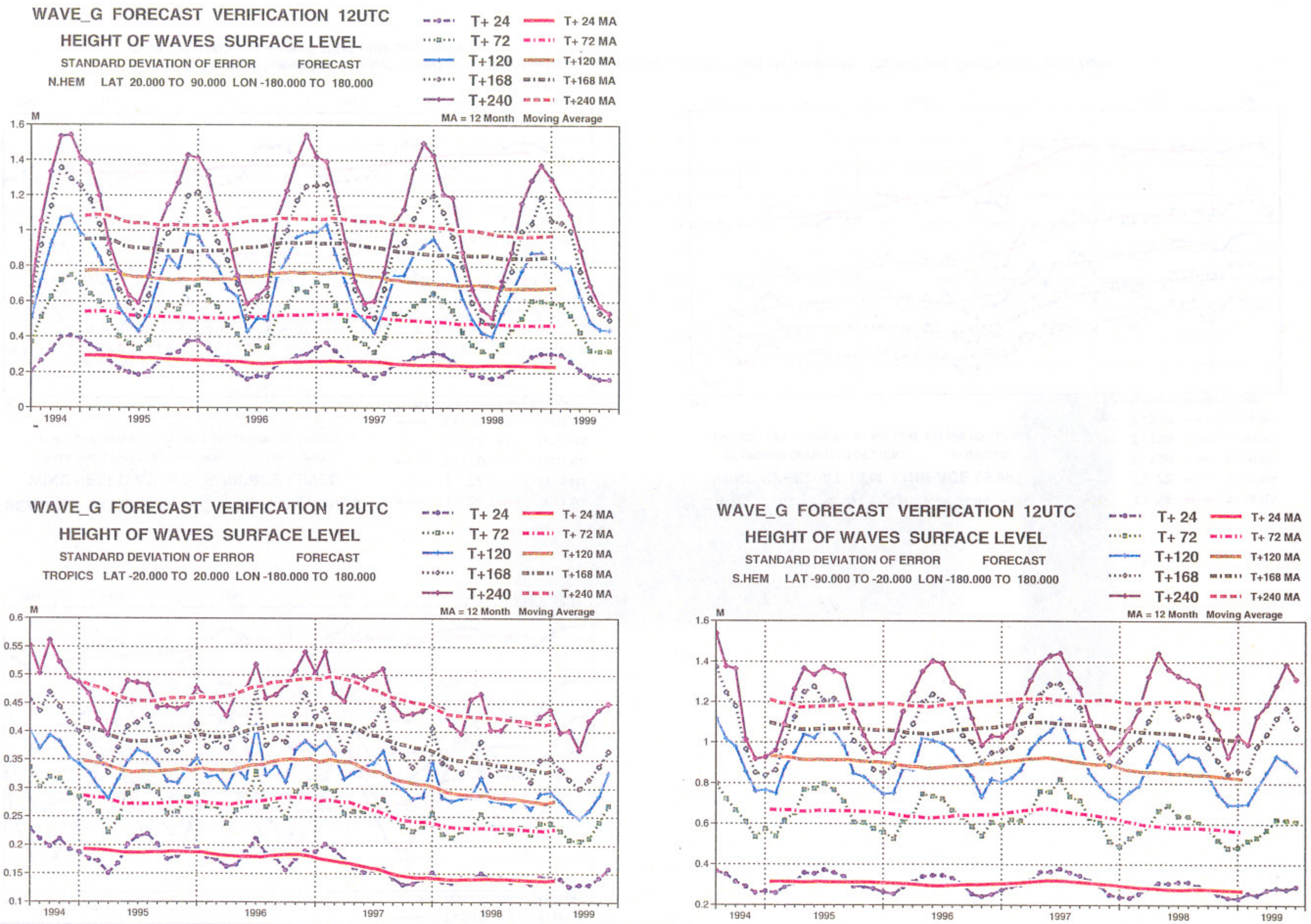


Figure 4: Standard deviation of wave height error (forecast versus analysis) for Northern Hemisphere, Tropics and Southern Hemisphere over the period of August 1994 until July 1999.

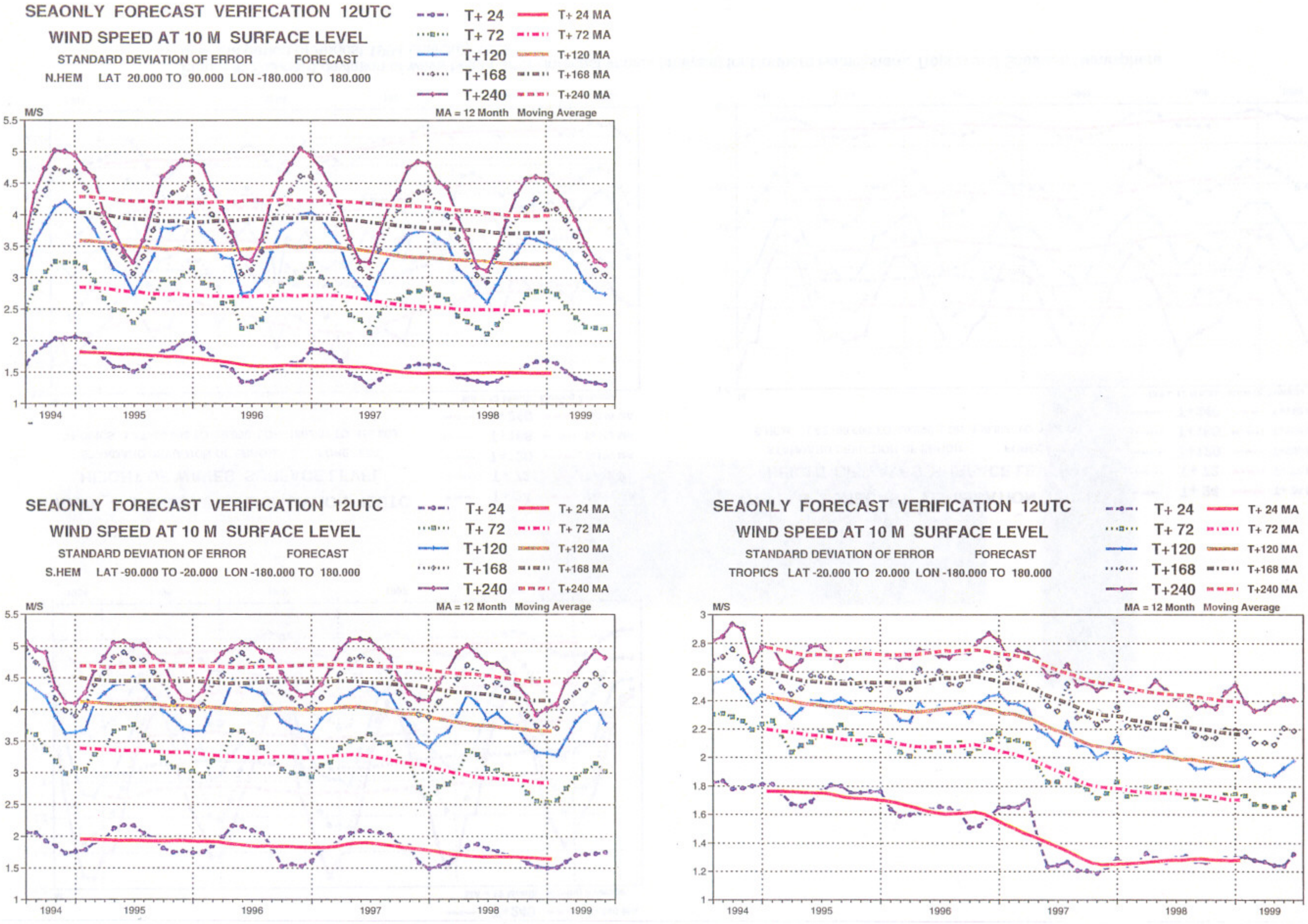


Figure 5: Standard deviation of wind speed error (forecast versus analysis) for Northern Hemisphere, Tropics and Southern Hemisphere over the period of August 1994 until July 1999.

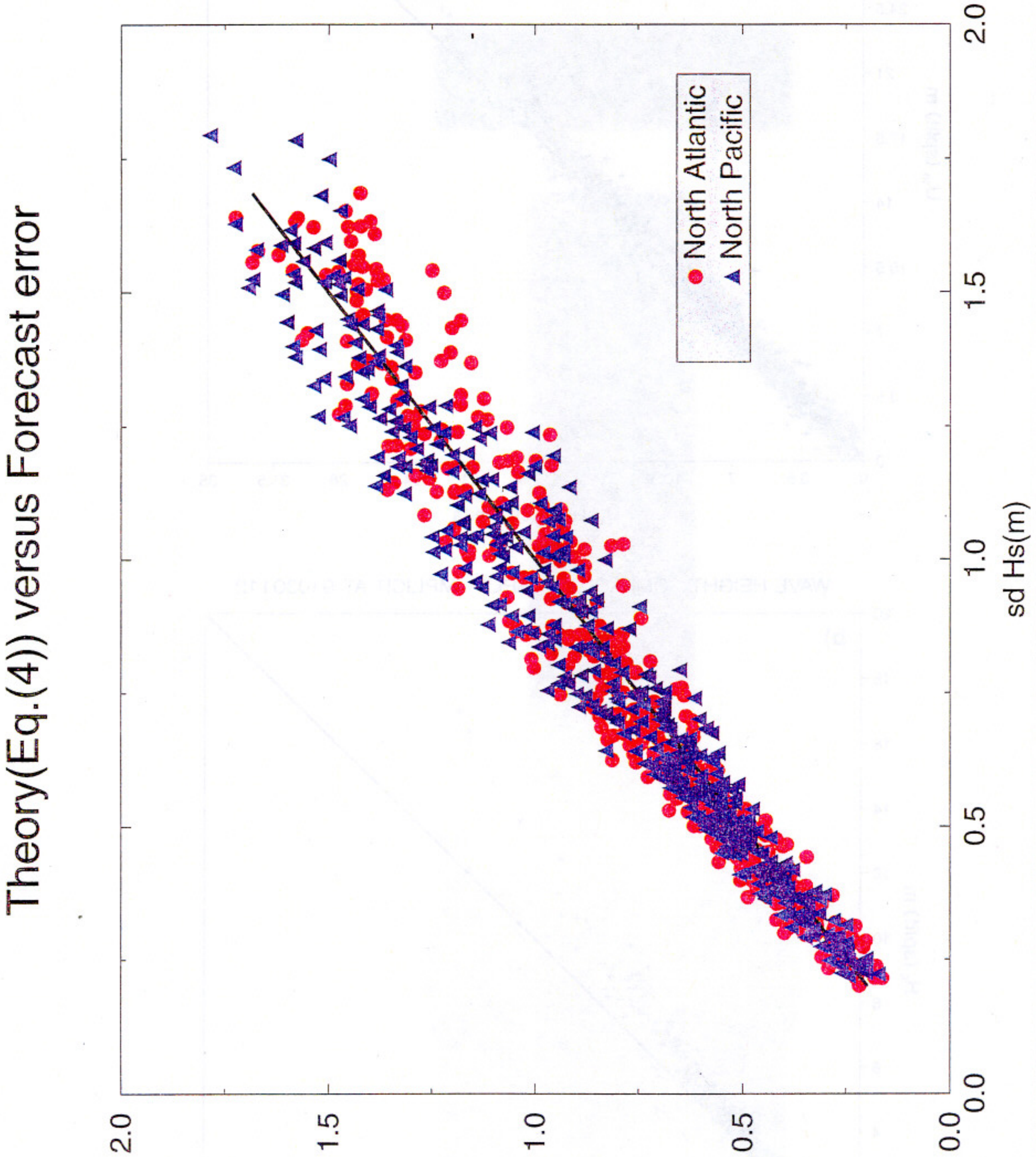


Figure 6: Comparison of random wave height error obtained from the theory(Eq.(4)) with the actual forecast error from the ECMWF archives for the North Atlantic and the North Pacific.

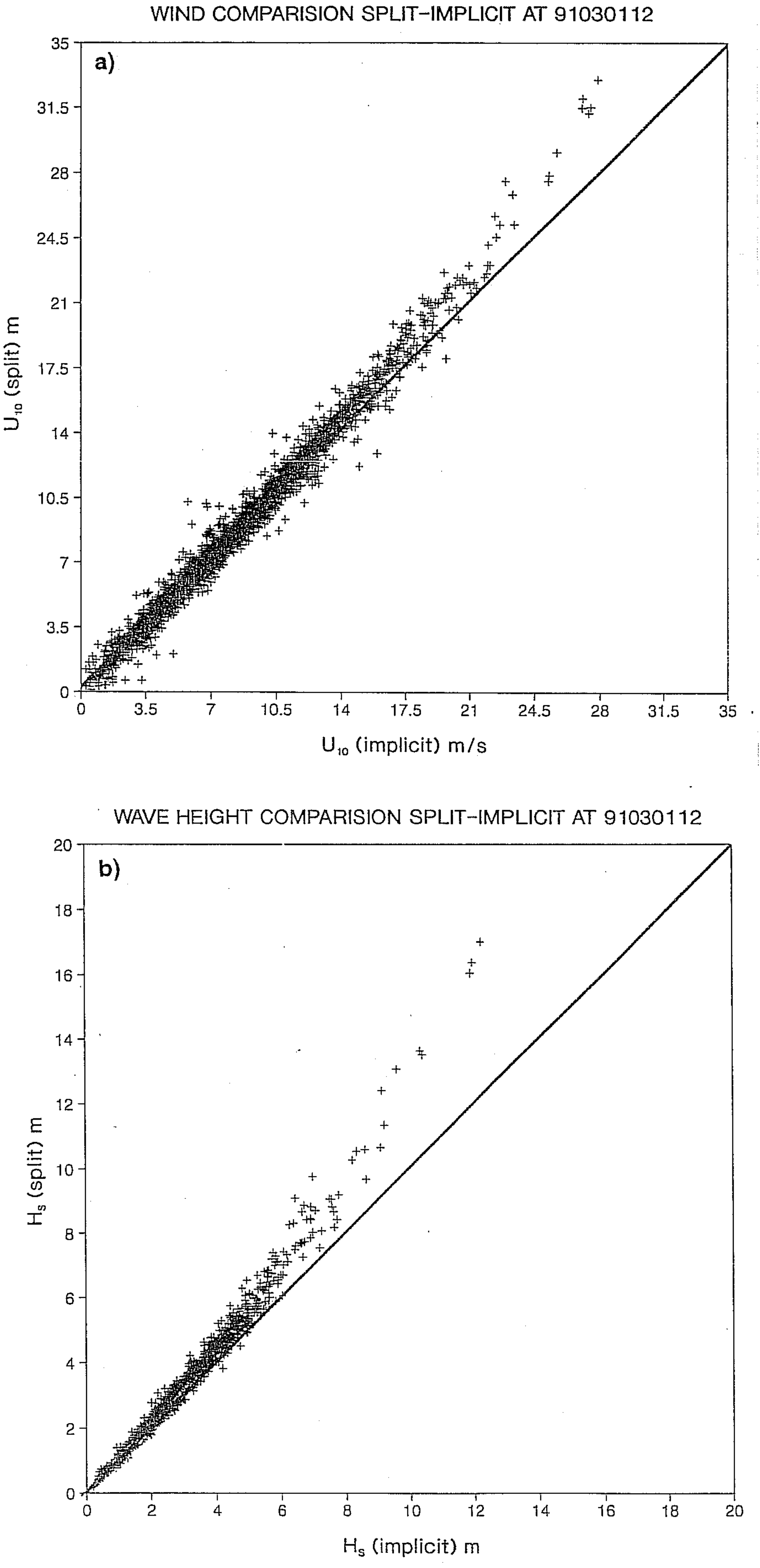
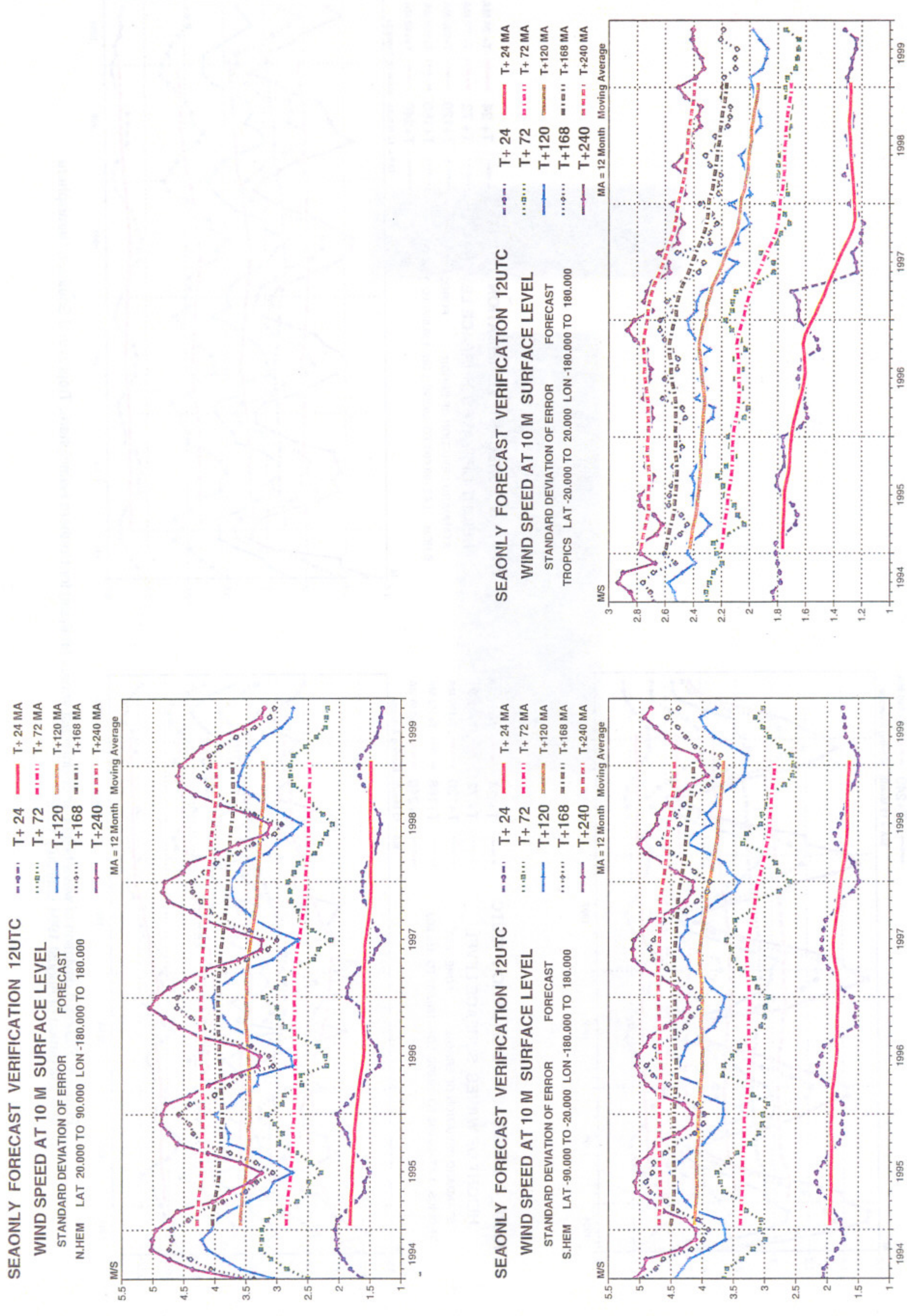


Figure 7: Comparison of surface winds (panel a) obtained from the split scheme and implicit scheme. The consequences for significant wave height are shown in panel b).

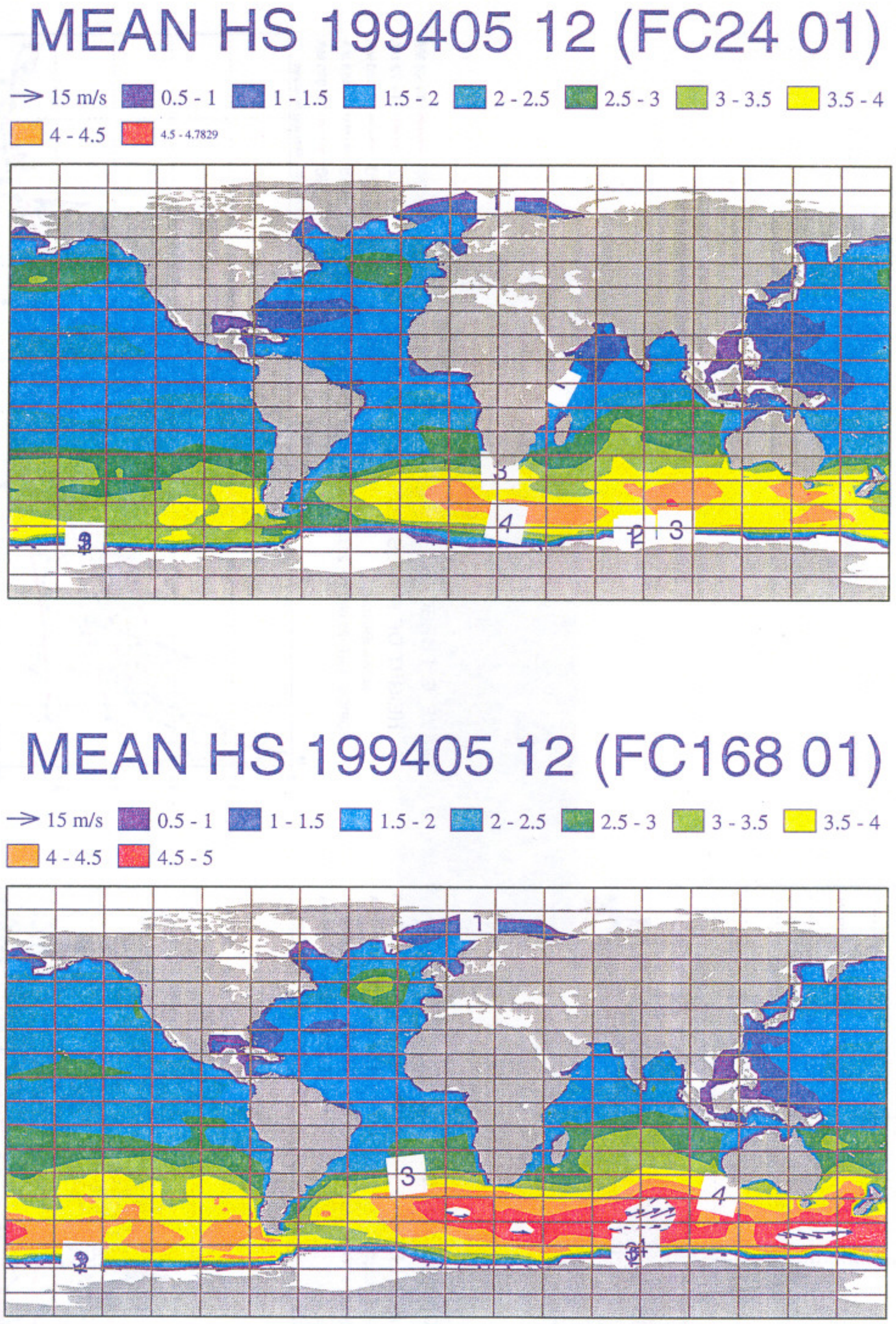


SEAONLY FORECAST VERIFICATION 12UTC
WIND SPEED AT 10 M SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
N.HEM LAT 20.000 TO 90.000 LON -180.000 TO 180.000

SEAONLY FORECAST VERIFICATION 12UTC
WIND SPEED AT 10 M SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
S.HEM LAT -90.000 TO -20.000 LON -180.000 TO 180.000

SEAONLY FORECAST VERIFICATION 12UTC
WIND SPEED AT 10 M SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
TROPICS LAT -20.000 TO 20.000 LON -180.000 TO 180.000

Figure 5: Standard deviation of wind speed error (forecast versus analysis) for Northern Hemisphere, Tropics and Southern Hemisphere over the period of August 1994 until July 1999.

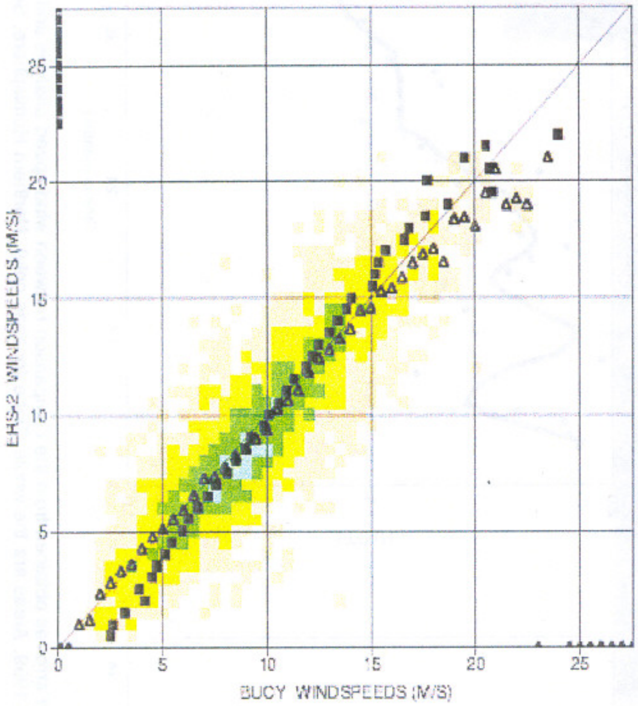


MEAN HS 199405 12 (FC24 01)

MEAN HS 199405 12 (FC168 01)

Figure 9: Comparison of monthly mean forecast wave height at day 7 with day 1 for May 1994.

BUOY / ERS-2 Comparison
Altimeter windspeeds
N HEM. EXTRA TROPICS OCT 1997
(radius=200km; local variability = 20%)
Winter Months (October-March)1997/1998 and 1998/1999



STATISTICS

ENTRIES	4499
MEAN BUOY	9.6080
MEAN ERS-2	9.3762
BIAS (ERS-2 - BUOY)	-0.2319
STANDARD DEVIATION	1.8456
SCATTER INDEX	0.1921
CORRELATION	0.8832
SYMETRIC SLOPE	0.9882 (0.0075)
REGR. COEFFICIENT	0.9449 (0.075)
REGR.CONSTANT	0.2977 (0.0769)

Figure 10: Validation of ERS-2 Altimeter wind speeds against buoy data for the winter seasons 1997/1998 and 1998/1999.

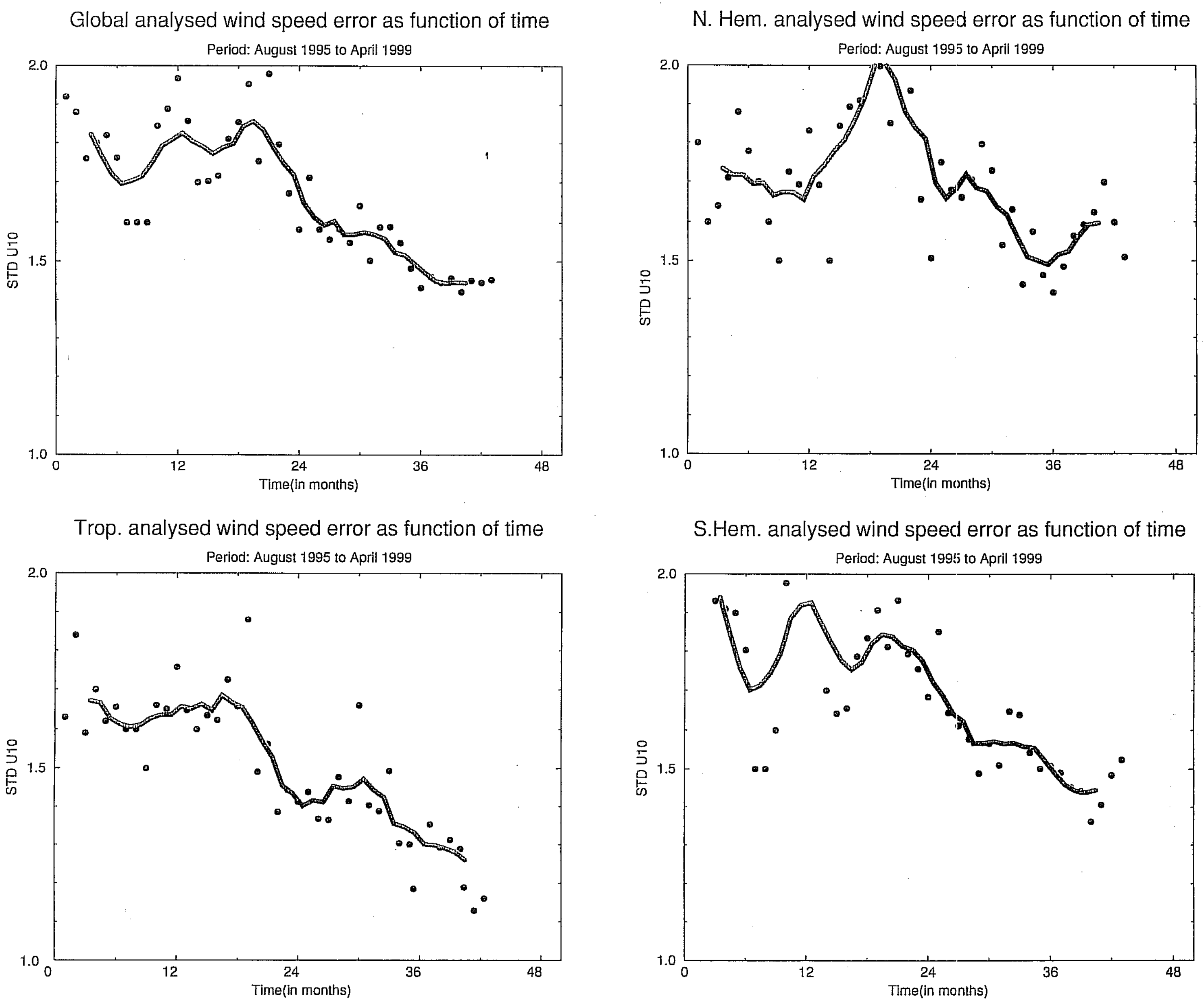


Figure 11: Standard deviation of analysed wind speed error as obtained from the comparison between wind speed analysis and ERS-2 Altimeter winds over the period August 1995 to April 1999. Areas are the whole Globe (oceans only), Northern Hemisphere, Southern Hemisphere and Tropics.