Verification of the ECMWF Wave Forecasting System against Buoy and Altimeter Data

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(Manuscript received 28 June 1996, in final form 22 May 1997)

ABSTRACT

The present status of ocean wave modeling at the European Centre for Medium-Range Weather Forecasts (ECMWF) is reviewed. Ocean waves are forecasted globally up to 10 days by means of the Wave Model (WAM), which is driven by 10-m winds from the ECMWF atmospheric model. Initial conditions are provided by assimilation of *ERS-1* data into the first-guess wave field.

The analyzed wave height and peak period field are verified against buoy data and show a considerable improvement compared to verification results of a decade ago. This is confirmed by a comparison of first-guess wave height against *ERS-1* altimeter data. The main reasons for this improvement are (i) the higher quality of ECMWF winds compared to a decade ago, (ii) the improved physics of the WAM model, and (iii) the assimilation of *ERS-1* data.

The forecast skill of the ECMWF wave forecasting system is also studied by comparing forecasts with buoy data and verifying analysis. Error growth in forecast wave height is less rapid than in forecast wind speed. However, considerable positive mean errors in forecast wave height are found, suggesting a too active atmospheric model in later stages of the forecast. Nevertheless, judging from anomaly correlation scores, the wave forecast seems to be useful up to day 5 in the forecast in the Northern Hemisphere. Since the wave forecast depends in a sensitive manner on the wind forecast, this confirms the high quality of ECMWF forecasts near the surface.

Finally, promising ways of improving the wave forecast are also discussed, and, as an example, the positive impact three-dimensional variational assimilation in the atmospheric model has on the wave product is also mentioned.

1. Introduction

In the past decade we have seen considerable progress in the field of ocean wave modeling. In the middle of the 1980s a group of mainly European wave modellers, who called themselves the Wave Model (WAM) Group, realized that it should be feasible to develop a wave model on first principles, that is, a model that solves the energy balance equation for surface gravity waves including nonlinear wave–wave interactions. First of all, there was a clear need for improving existing wave models at that time. Although these so-called first- and second-generation models performed reasonably well in many cases, it turned out that, in rapidly varying circumstances, they could not provide a proper description of the sea state. This was demonstrated in a comparison exercise where about 10 different models were run with the same hurricane wind field, resulting in widely varying maximum wave heights (ranging from 8 to 25 m). The reasons for the shortcomings of the first-and second-generation models have been discussed extensively in SWAMP (1985) and Komen et al. (1994). Recognizing the positive benefits of WAM over previous models, wave forecasting centers have therefore implemented WAM or are in the process of doing so (Khandekar and Lalbeharry 1996; Luo 1995).

Second, the solution of the energy balance equation (including a parametrized version of the nonlinear transfer) requires considerable computing power, which has only become available in recent years. Third, the mathematical and computational developments coincided with the development of remote sensing techniques for measurements of the ocean surface by means of microwave instruments [altimeter, scatterometer, and synthetic aperture radar (SAR)]. In this context it should be noted that there is a rather close relationship between wave model development and satellite remote sensing. Satellite observations can be used to validate the wave model and the model also gives a first check on the accuracy of the observations. Furthermore, a detailed description of the dynamics of the ocean surface is important for a correct interpretation of the radar signals.

At present, WAM is widely used as a research tool and it is used operationally in global and regional implementations to make forecasts of the sea state that are useful for many applications such as ship routing and

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offshore activities, and for the validation and interpretation of satellite observations. The capabilities of WAM have been assessed in detail (WAMDI Group 1988; Komen et al. 1994), giving confidence in its performance. Nevertheless, no systematic verification study of WAM results has been performed so far, except by Zambresky (1989), using conventional buoy data, and Romeiser (1993), using Geosat altimeter data. Both authors concluded that, in general, the modeled wave heights [obtained by forcing WAM with European Centre for Medium-Range Weather Forecasts (ECMWF) winds] showed good agreement with the data. However, considerable differences were found as well. Zambresky (1989) noted that WAM rather often has a tendency to underpredict extreme sea states. Romeiser (1993) found considerable regional and seasonal differences between modeled wave height and Geosat altimeter data. During the Southern Hemisphere winter WAM may underestimate wave height by about 20% in large parts of the Southern Hemisphere and the tropical regions, while for the rest of the time agreement with data is fairly good.

Both those verification studies were using modeled wave heights for 1988 obtained from cycle 2 of WAM, while the forcing wind fields were provided by the T106/19L version of the ECMWF atmospheric model. Since 1988 a number of important changes have been introduced in the wind–wave forecasting system at ECMWF. First of all, in September 1991 the resolution of ECMWF's atmospheric model was doubled in the horizontal and nearly doubled in the vertical. Because of the increased horizontal resolution, one would expect a better representation of the surface winds, which could be beneficial for analyzing and predicting ocean waves in the storm tracks, in particular of the southern oceans. Second, since November 1991 a new version of WAM, called cycle 4, was introduced operationally at ECMWF. This new version of WAM has been described in detail in Komen et al. (1994) and, compared to previous cycles of WAM, has different physics regarding wind input and dissipation of wave energy. Third, assimilation of *ERS-1* altimeter wave height data started in August 1993, and lastly, in July 1994, the horizontal resolution of the wave model was increased by a factor of 2 from 3° to 1.5°. This increase in horizontal resolution could, as already pointed out by Zambresky (1989), have a beneficial impact on the prediction of extreme sea states because more details of the generating wind field are taken into account.

Because of these important changes in the wind–wave forecasting system, it was thought of interest to investigate to what extent we have achieved improvements in wave analysis and wave forecasting at ECMWF. Possible improvements in performance will be judged by comparing analyzed wave height with observations from buoys and radar altimeters on board *ERS-1*. In addition, since the main goal of ECMWF is in forecasting, special attention is given to the quality of forecast wave height fields. In particular, forecast wave heights are compared with buoy observations and with the verifying analysis. This gives us the opportunity to apply some new verification tools in ocean wave forecasting that have already been in use in weather forecasting for quite some time. For example, the anomaly correlations provide information on how much more skill a wave forecast has over wave climatology. It turns out that the anomaly correlation is a sensitive indicator of the quality of the wave forecast, and also of the quality of forecast surface winds.

The program of this paper is therefore as follows. In section 2 we briefly describe the cycle 4 physics of WAM and we discuss the advantages of this formulation over previous cycles. The verification of analyzed wave height against buoy data over the 1-yr period of January 1995 to December 1995 is given in section 3, while in section 4 we compare wave heights with the altimeter wave heights from *ERS-1*. Section 5 is devoted to the verification of forecast wave height against buoy data and against verifying analysis, and the forecast skill is judged against persistence and wave climatology. Finally, section 6 gives a summary of conclusions and prospects for the future.

2. WAM at ECMWF

Since November 1991 cycle 4 of WAM has been running (quasi-) operationally at ECMWF. WAM is the first model that explicitly solves the energy balance equation for the two-dimensional surface wave spectrum $F(f, \theta)$ where f is the frequency and θ the wave direction. In deep water, the energy balance equation reads

$$\frac{\partial}{\partial t}F + \mathbf{v}_g \cdot \frac{\partial}{\partial \mathbf{x}}F = S_{\mathrm{in}} + S_{\mathrm{nonl}} + S_{\mathrm{diss}}, \qquad (1)$$

where $\mathbf{v}_g = \partial\omega/\partial\mathbf{k}$ is the group velocity, and the source functions on the right-hand side represent the physics of the generation of waves by wind, dissipation of energy due to white capping, and the energy transfer due to four-wave interaction (Hasselmann 1962). A complete discussion of the physics of wave evolution and wave generation and the actual details of the numerical implementation of the energy balance may be found in Komen et al. (1994), where a discussion of the performance of WAM is also given.

At ECMWF WAM has been implemented on the globe (with resolution of 1.5°) and on the Mediterranean and Baltic Seas (with a 0.25° resolution). However, only global results will be discussed in this paper. The wave spectrum has 25 frequencies and 12 directions at each grid point. The source term integration time step and the advection time step are 20 min. The model allows for the possibility of a variable ice edge, which is of particular importance in the Southern Ocean. The decision on whether a grid point is ice or water is based on the analyzed sea surface temperature. The ice edge is kept fixed during the 10-day forecast.

Before August 1993 the wave analysis was obtained by forcing the wave model with analyzed ECMWF wind fields. Since this date *ERS-1* altimeter wave height data have been assimilated using an optimum interpolation scheme from Lionello et al. (1992). The inclusion of altimeter data has a beneficial impact on the wave forecast that may last up to 5 days (Komen et al. 1994).

Significant wave height, mean period, and mean wave direction (for total sea, windsea, and swell) are disseminated once a day to the ECMWF member states. All integrated parameters for analysis and forecast are archived every 6 h, while the analyzed two-dimensional wave spectrum is stored once a day. In addition, monthly means of wave height, mean period, wave direction, surface wind speed, and direction are also archived. In collaboration with the Portuguese Meteorological Office we have extended the wave climate archive with 3° global results starting from 1 January 1987. This enabled us to generate a wave climatology based on 9 yr of wave model data, and therefore we are now able to determine the anomaly correlation of significant wave height (cf. section 5).

The cycle 4 version of WAM, which is operational at ECMWF, has a certain number of advantages over earlier cycles of WAM (Janssen et al. 1996). First of all, the latest cycle allows the surface stress to be determined, including the dependence on the sea state through the wave-induced stress (Janssen 1989, 1991). Second, the high-frequency part of the wave spectrum shows more realistic levels when compared to observations (Janssen 1991; Komen et al. 1994). Third, cycle 4 of WAM shows reduced dissipation of swell (Komen et al. 1994).

In order to investigate the impact of the changes introduced in cycle 4 of WAM, we hindcasted July 1990, using the analyzed ECMWF winds that forced cycle 2 of WAM. The monthly means of July 1990 of cycle 2 and cycle 4 of WAM are shown in Fig. 1 and some substantial differences are seen. The mean wave height in the Southern Ocean storm track is increased slightly while there is a substantial increase of wave height in the tropical and subtropical Indian ocean, the tropical central Pacific, and in the Southern Ocean east of New Zealand. Relative increases in wave height vary between 20% and 50% in those areas where Romeiser (1993) found discrepancies between Geosat altimeter data and WAM cycle 2 wave height data, suggesting that cycle 4 of WAM has given considerable improvements over earlier cycles of WAM.

Before we begin to study the quality of the present wave analysis and forecasting system at ECMWF, it should be remarked that the recent increase in resolution from 3° to 1.5° in the horizontal had a beneficial impact on the modeling of extreme wave events. This follows for example from a 15-yr hindcast of both versions of the model (A. Sterl et al. 1997, unpublished manuscript). The main reason for the improved performance of the high-resolution wave model comes from a better representation of the driving wind field (Cavaleri 1994).

3. Verification of wave analysis against buoy data

There have been extensive efforts to evaluate the quality of analyzed wave results by comparison with buoy observations, particularly in the 1970s and 1980s when the usefulness of wave prediction first became apparent for applications such as ship routing, coastal defense construction work, and offshore operations. The typical performance of early global wave models has been summarized by Cardone (1987), Zambresky (1987), and Clancy et al. (1986). Using operationally available winds, these authors found that the scatter index for the analyzed wave height (the ratio of the standard deviation of error to the mean of observed wave height) ranged from 25% to 40%, while the scatter index for analyzed surface wind speed was of the order of 30% or more. Similar results were obtained for limited area models in shallow water (see, e.g., Janssen et al. 1984). More recent evaluations of the performance of WAM in operational mode are described in Khandekar and Lalbeharry (1996) and Wittman et al. (1995).

On the other hand, when using high quality, manually analyzed winds (with much lower rms errors), wave results improved dramatically. Examples of this may be found in an intercomparison study (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.

Let us now discuss how the present ECMWF wave analysis system is performing. Wave analyzed fields are operationally evaluated using all available buoy data obtained through the Global Telecommunication System (GTS). On purpose, wave buoy data are not used in the wave analysis, so that the comparison of analysis and buoy data provides an independent test of the quality of the analyzed wave height. The modeled result was obtained by linear interpolation in space and was compared with the adequate observed value valid at one of the synoptic times (0000, 0600, 1200, 1800 UTC). It should be emphasized that buoy observations and the model represent different scales. Buoys exhibit high-frequency variability on a timescale of 1 h, which is absent in the model because the model value does represent a mean value over a grid box of size 1.5° × 1.5°. In other words, since waves propagate across the area where the instrumental sensors are located, one should not consider a single observation at any given time (representing an actual average over a short acquisition time) to be equivalent to the actual statistical wave height computed at each model grid box. Averaging of the observed wave height is therefore preferable where the averaging period should match the scales still represented by the model. With a mean group velocity of about 10 m s^{-1} an averaging time of 6 h thus seems appropriate to represent a 1.5° × 1.5° box averaged observation.

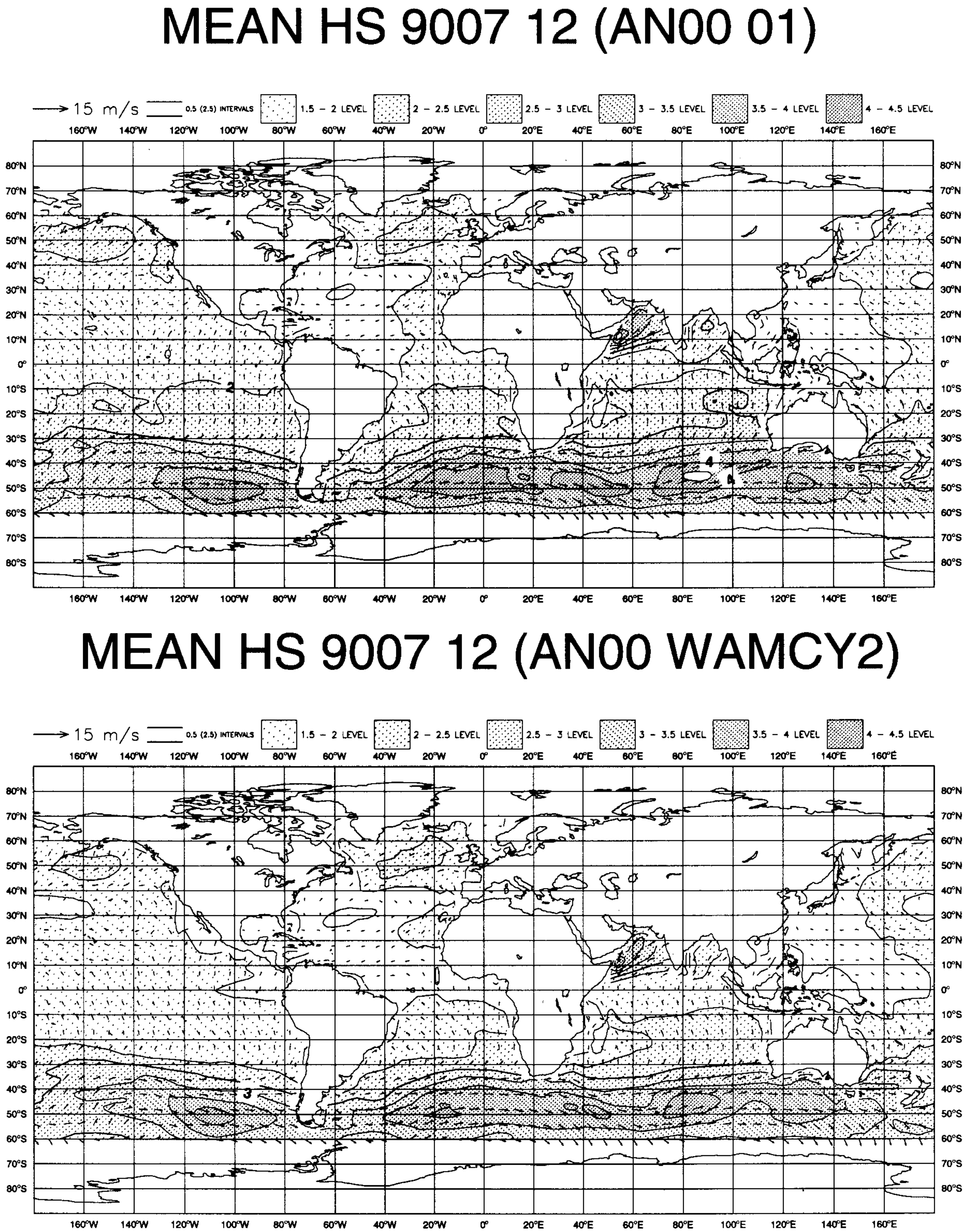


FIG. 1. Comparison of monthly mean wave height for July 1990. (top) Cycle 4 of WAM; (bottom) cycle 2 of WAM.

BUOY LOCATIONS

1	21004	South-East of Japan	16	46036	Canada West Coast, South Nomad
2	22001	East China Sea shelf break	17	46059	US West Coast, California
3	41001	US East Coast, E Hatteras	18	46184	Canada West Coast, North Nomad
4	41002	US South-East Coast, S Hatteras	19	51001	Hawaii North West
5	41006	US East Florida Coast, Daytona	20	51002	Hawaii South West
6	41018	Caribbean Sea	21	51003	Hawaii West
7	42001	Mid Gulf of Mexico	22	51004	Hawaii South East
8	44008	US North-East Coast, Nantucket	23	62029	UK Celtic Sea shelf break
9	44011	US North-East Coast, Georges Bank	24	62081	UK East Atlantic
10	46001	Gulf of Alaska	25	62105	UK East Atlantic
11	46002	US West Coast,Oregon	26	62106	UK North-East Atlantic
12	46003	Aleutian Peninsula	27	62108	UK East Atlantic
13	46005	US North-West Coast, Washington	28	62163	UK Celtic Sea shelf break
14	46006	US West Coast, SE Papa	29	63111	North Sea shelf break
15	46035	Bering Sea	30	64045	UK North-East Atlantic

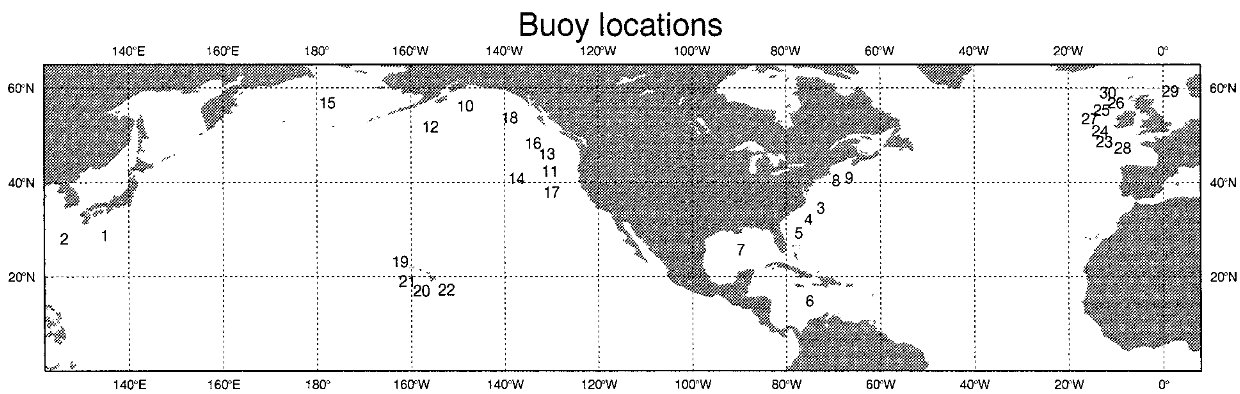


FIG. 2. Location of buoys used in the verification study of analyzed wave height, wave period, and wind speed. When looking at statistics, the buoys are grouped per geographical area: Hawaii (51001, 51002, 51003, 51004), Japan (21004, 22001), North Pacific (46001, 46003, 46035, 46184), U.S. west coast (46002, 46005, 46006, 46036, 46059), U.S. east coast (41001, 41002, 41006, 42001, 44008, 44011), and the northeast Atlantic (62029, 62081, 62105, 62106, 62108, 62163, 64045).

Most buoy data are reported every hour via the GTS and are archived in the ECMWF database, provided they arrive on time. It is a simple matter to use the monthly time series to perform a basic quality check on the data. This quality check will only keep values that are within an acceptable physical range. It will try to detect faulty instruments by removing all constant records of over 1 day long, and it will remove outliers by looking at the deviation from the mean of each monthly data record and from the deviation from one hourly value to the next.

Here we present the verification of analyzed wave height and wind speed over the period January 1995–December 1995 using 30 buoys (their location is given in Fig. 2), which produce fairly continuous data records (a prerequisite if filtering is used to produce a consistent data record). The buoys are located in deep water.

The comparison of analyzed wave height to the averaged buoy data shows a good agreement. This is illustrated by the verification plots for August 1995 and December 1995, given in Figs. 3 and 4, respectively. In order to quantify the comparison, we have computed the usual statistical parameters, which are displayed in Figs. 3–4 as well. Although there is a slight underestimation of wave height (of the order to 20 cm), the rms error is small (about 50 cm) while the scatter index is about 16% for the Northern Hemisphere winter and about 20% for the summer period. The monthly variation of bias, rms error, and scatter index is displayed in Fig. 5. It shows the good performance of the wave forecasting system during the chosen 1-yr period. If one takes the usual measure for quality, namely the scatter index, then Fig. 5 illustrates that the quality of the wave analyses is better during the winter than during the summer. It should be pointed out, however, that there are considerable regional variations. In order to see this, we have plotted in Fig. 5 the relevant statistical parameters for the regions Hawaii, North Pacific, U.S. west coast, U.S. east coast, and northeast Atlantic as well. A very good wave analysis is then found near Hawaii, the northeast Atlantic, and the west coast of the United States where scatter indices are of the order of 15%. In the North Pacific the wave analysis is found to be of a reasonable quality with scatter indices of the order of

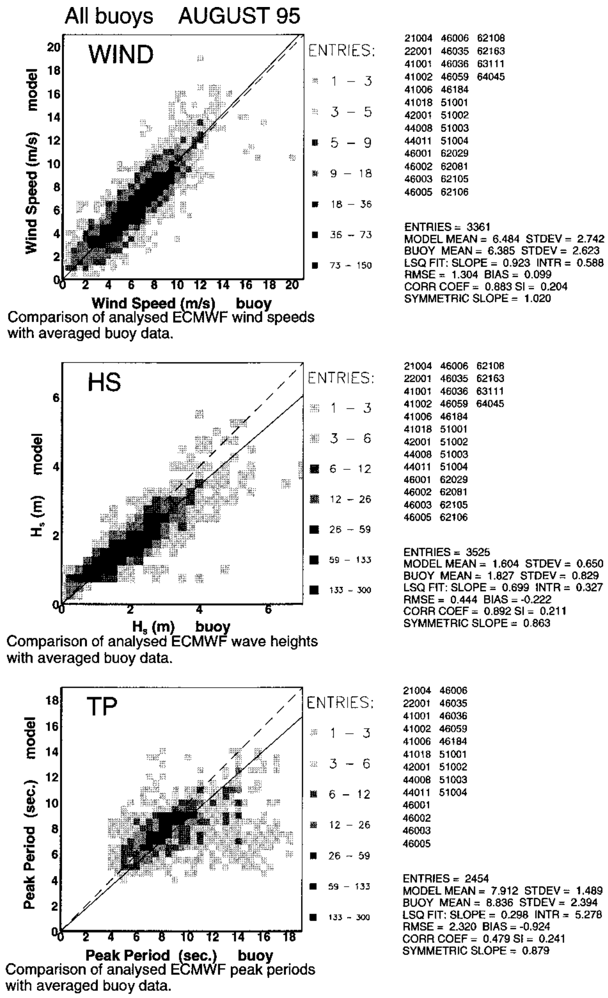


FIG. 3. Comparison of analyzed wind speed, wave height, and wave peak period with buoy measurements for August 1995.

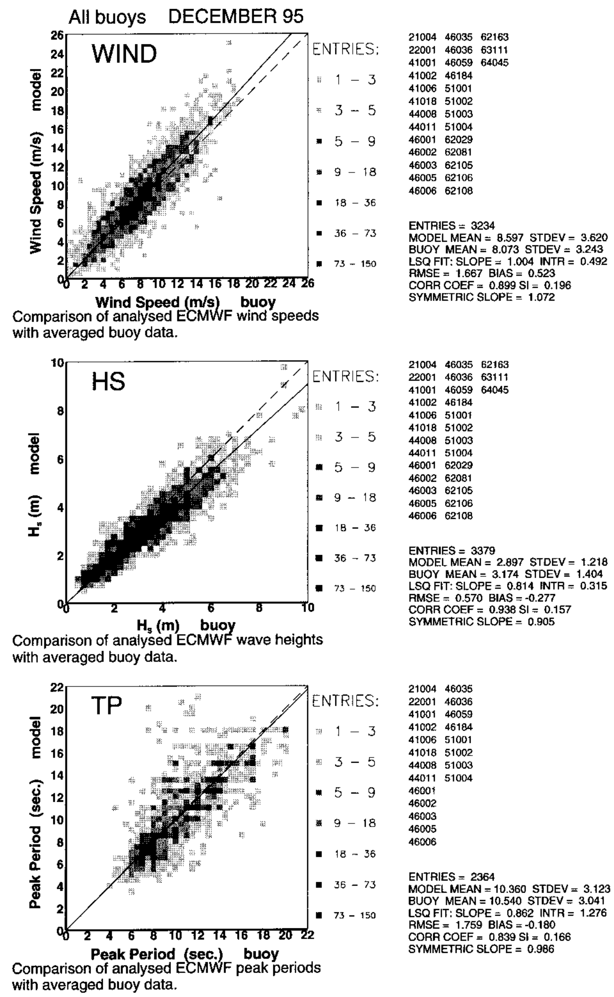


FIG. 4. Same as Fig. 3 but now for December 1995.

20%, while the wave analysis is relatively poor on the east coast of the United States where, in particular during the summer, the scatter index is around 25%. Since the quality of the wave model analysis depends critically on the quality of the surface wind, we also present statistics of the 10-m wind in Figs. 3, 4 and 6. Using the same technique to eliminate possible spurious buoy observations, a consistent wind dataset was obtained. However, no attempt was made to correct model winds for the actual buoy observation height, which is usually on the order of 4 m. This implies that when there is no bias between modeled and observed wind, there is in fact, because of this height difference, a model bias of about 10% of the mean wind speed. In addition, it should be remarked that modeled and observed winds are not independent because information from these observations has been used in the atmospheric analysis. Nevertheless, the comparisons shown in Figs. 3 and 4 for August 1995 and December 1995, and the time series for statistical parameters in Fig. 6, reveal the quality of the analyzed wind speed. The scatter index for wind speed is typically about 20% but shows large regional variations. In the North Atlantic we find on average a scatter index of 17%, while the east coast of the United States shows a relatively poor performance with scatter indices in the summer reaching about 25%. The bias in wind speed is generally quite low. Restricting our attention to regions with active wave generation (this excludes Hawaii) and bearing in mind the above-mentioned difference between buoy observation height and model height, it is seen that, except in the North Pacific area, modeled winds are too low by as much as 0.5 m s^{-1} (taking a mean wind speed of 8 m s^{-1}). Although this is quite a small bias in wind speed, it still may give a considerable bias in significant wave height. This may be seen as follows. Starting from the well-known relation between equilibrium wave height H_s and wind speed U_{10},

$$H_s = \beta U_{10}^2/g, \qquad (2)$$

where g is acceleration of gravity and β a constant (we

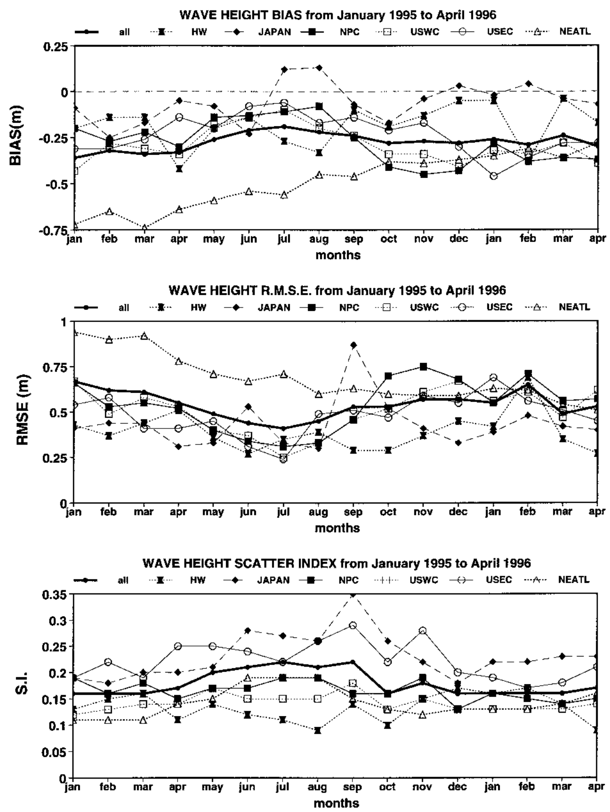


FIG. 5. Monthly variation of bias, rms error, and scatter index for analyzed wave height from January 1995 to April 1996. Symbols refer to different areas (see Fig. 2).

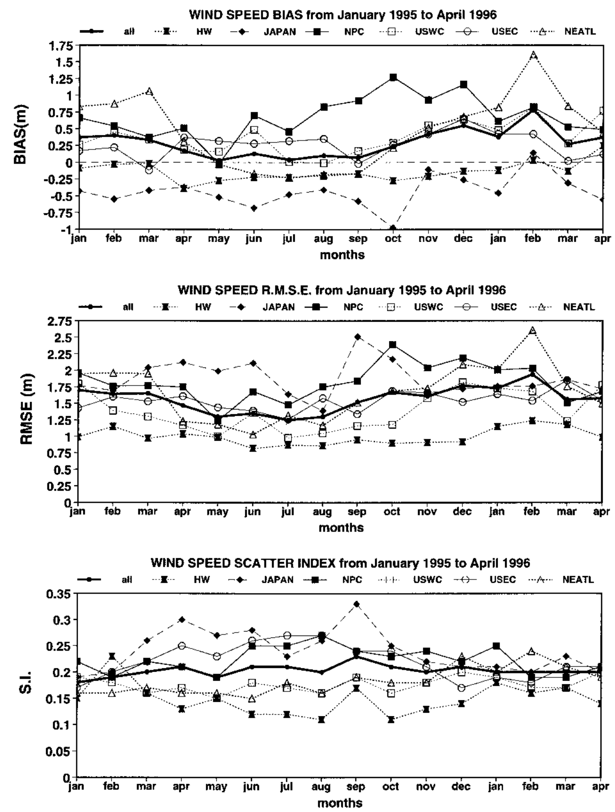


FIG. 6. Same as Fig. 5 but now for wind speed.

take $\beta = 0.22$), the wave height bias caused by a wind speed error is found to be

$$\delta H_s = 2\beta U_{10}\delta U_{10}/g. \quad (3)$$

Then, with a mean wind speed U_{10} of 8 m s^{-1} and a negative wind speed bias of -0.5 m s^{-1}, we find a wave height bias of about -0.20 m.

From Fig. 5 and Table 1b, it is clear that the comparison with the northeast Atlantic wave observations is an outlier. Following the monthly comparison with ECMWF data, it was found that in the course of 1994–95 the wave measurements from the northeast Atlantic network were deficient (Bidlot et al. 1997). This problem was reported to the data provider (U.K. Meteorological Office), which by the end of the summer 1995

TABLE 1. Statistics obtained by the WAM model driven by ECMWF winds for wave height H_s (m), peak period T_p (s), and wind speed U_{10} (m s^{-1}) for different areas. Bias is with respect to observations; SI is scatter index. In parentheses are the number of observations (Nobs) used for the statistics. The northeast Atlantic buoys do not report peak period.

	H_s		t_p		U_{10}	
Area (Nobs)	Bias	SI	Bias	SI	Bias	SI
(a) Period is December 1987–November 1988 (from Zambresky 1989): WAM (cycle 2: 3° × 3°)						
All (13827)	−0.32	0.23	−0.47	0.18	−0.09	0.25
North Pacific (4657)	−0.22	0.21	−0.70	0.17	0.49	0.25
Hawaii (2061)	−0.28	0.17	−0.01	0.21	−0.38	0.17
U.S. east coast (4284)	−0.38	0.30	−0.71	0.16	0.07	0.30
Northeast Atlantic (2825)	−0.40	0.25	—	—	−0.54	0.28
(b) Period is January 1995–December 1995: WAM (cycle 4: 1.5° × 1.5°)						
All (39288)	−0.27	0.18	−0.47	0.19	0.24	0.21
North Pacific (5473)	−0.25	0.18	−0.44	0.19	0.77	0.23
Hawaii (5324)	−0.19	0.14	−0.05	0.19	−0.19	0.14
U.S. east coast (7482)	−0.19	0.24	−0.57	0.18	0.30	0.23
Northeast Atlantic (8812)	−0.53	0.14	—	—	0.29	0.19
U.S. west coast (7234)	−0.27	0.15	−0.68	0.17	0.30	0.18

took the necessary steps to improve the quality of their products. Since then, the montly comparison have resulted in statistics that are comparable to those obtained for the U.S. west coast, an area with similar swell and windsea importance.

Finally, we would like to compare our verification results with the results of Zambresky (1989). In that study, results from WAM cycle 2 driven by winds from the T106/19L version of ECMWF's atmospheric model were compared with buoy observations during the period December 1987–November 1988. A summary of her verification results for four areas is shown in Table 1a. In order to avoid problems with subgrid-scale effects, Zambresky averaged the observations over a 3-h period, while spurious observations were rejected manually (if needed). Comparing the scatter indices of the present version of the wave analysis system with the earlier one, a considerable improvement is seen in the quality of wind speed and significant wave height in all areas, with the exception of an increased bias in wave height in the northeast Atlantic. The peak period statistics, although having a somewhat reduced bias, have however a similar scatter index. This may be related to the fact that in the present wave analysis system the peak period has similar variability around the mean as observed, while the earlier system showed much reduced variability.

4. Verification of first-guess wave height against *ERS-1* altimeter data

The validation of wave model results against satellite data started relatively recently, at least compared to the verification against buoy data. The first validation studies used altimeter wave height data obtained during the Seasat mission in 1978 (Janssen et al. 1989; Bauer et al. 1992; Francis and Stratton 1990). The scatter index for wave height was typically between 30% and 40%, while the wave height bias was +0.15 m for WAM driven with 1000-mb ECMWF winds. The poor performance during the Seasat period may be attributed, to a large extend, to the poor quality of the driving wind fields. This follows from the study by Romeiser (1993) who compared WAM-modeled wave height with Geosat data during the year 1988. The seasonal variability of the scatter index parameter as used by Romeiser (defined as the rms wave height error normalized by the square root of the product of mean observed and mean modeled wave height) is depicted in Fig. 7 (the lower half of the plot will be discussed later). Although there is considerable seasonal variability, it appears that the mean scatter index for 1988 was found to be around 0.25, a number that is consistent with the findings of Zambresky (1989) who verified the modeled WAM wave height against buoy data (cf. Table 1).

Let us now compare modeled wave height and wind speed of the present ECMWF wave model system with *ERS-1* altimeter data. *ERS-1* was launched in July 1991

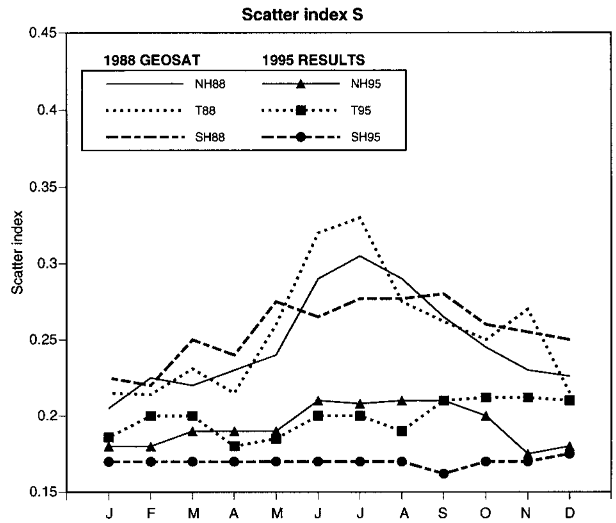


FIG. 7. Monthly variation of Romeiser's scatter index obtained from comparison of analyzed wave height with Geosat altimeter (year 1988) data for Northern Hemisphere, Tropics, and Southern Hemisphere. For comparison, scatter indices for 1995 are also shown, which were obtained from the comparison of first-guess wave height and *ERS-1* altimeter.

and reliable altimeter observations were disseminated routinely from the end of 1991. During the commissioning phase between July and the end of 1991, altimeter wave height and wind speed were routinely compared with WAM-modeled wave height and ECMWF wind speed to assure the quality of the altimeter products. As a result of this comparison, it was found that the wave height retrieval algorithm gave satisfactory results when compared with modeled wave height (although it should be emphasized that, compared to buoys, *ERS-1* altimeter wave heights are too low by about 10% for high sea states). Similarly, regarding the wind speed retrieval, *ERS-1* uses the same algorithm as Geosat. However, tuning of the radar altimeter backscatter observations is required since the overall gain of the satellite is unknown beforehand and the wind speed determination depends on the absolute determination of the backscatter. Applying a bias correction to the observed backscatter and inserting the corrected backscatter into the retrieval algorithm gave virtually no bias when the resulting wind speed was compared with the ECMWF winds. Thus, the quality of the altimeter winds depends to a certain extent on the quality of the ECMWF winds from 1991. In particular, when comparing the two products as will be done in a moment, it should be realized that the information obtained from the bias between the two should be regarded with caution, while the standard deviation of error contains valuable information.

Since August 1993 altimeter wave height data has been used to give a better specification of the initial conditions for the wave forecast. It is therefore clear that a validation of the analyzed wave height against

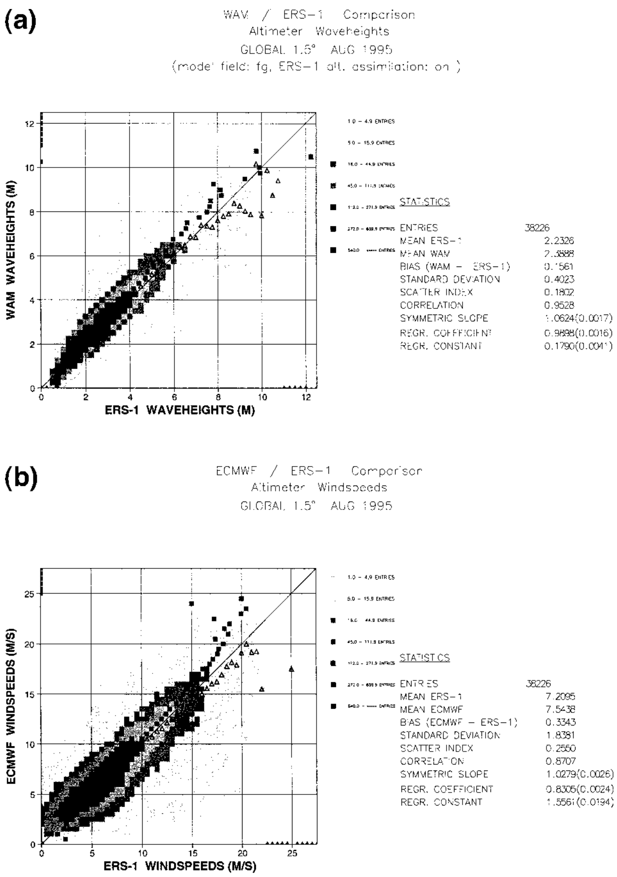


FIG. 8. Comparison of first-guess wave height and analyzed wind speed with altimeter data for the whole globe for August 1995. Triangles denote mean altimeter as a function of modeled parameter, while squares denote mean modeled parameter as a function of altimeter.

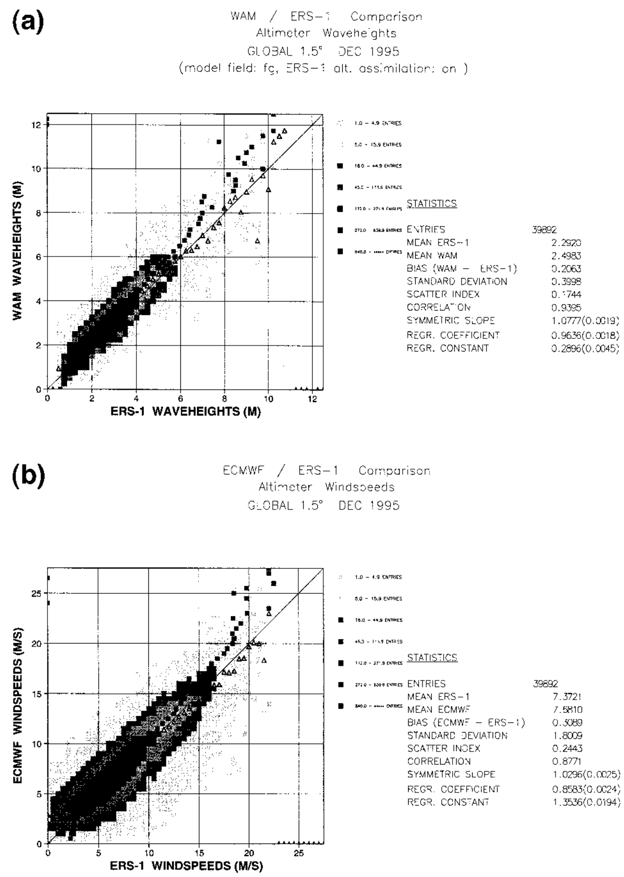


FIG. 9. Same as Fig. 8 but now for December 1995.

altimeter wave height data is not very meaningful; thus, it was decided to compare first-guess wave height fields with altimeter wave height data. In that manner, since the first guess for the waves is actually a 6-h forecast, we will be looking at the quality of this short-term forecast obtained from the best estimate of the sea state at the start of the forecast. At the end of the 6-h forecast first guess and observed wave height may be regarded as independent because the altimeter data have not been used in previous wave analyses. In addition, the locations where the first-guess wave field is compared with the altimeter data are different from the locations where altimeter data were used in the last analysis. Nevertheless, it may be argued that the quality of the 6-h forecast should have benefited from the use of altimeter wave height data in previous analysis cycles. In particular, swell systems that may have quite a long memory should benefit from the observed information. To a certain extent, this was indeed found in the study reported in Komen et al. (1994), where results of 30 forecasts starting from wave analysis with and without altimeter wave data were compared. The two sets of forecasts were verified against altimeter data, and the forecasts based on analyses with altimeter data showed a considerable reduction in the bias that could last up to 5 days in the forecast. Differences between standard deviation of errors of the two sets of forecasts were less dramatic and were small from day 1 in the forecast. This suggests that the standard deviation of error of the first-guess wave field (when compared to altimeter data) shows hardly any dependence on whether altimeter data have been used in the previous analyses or not.

The *ERS-1* altimeter data are received in real time from the European Space Agency through the GTS. The along-track resolution is 7 km, corresponding to approximately one measurement per second. In order to obtain observations that represent similar spatial and temporal scales to the wave model, the altimeter time series are smoothed to a resolution of 200 km. Unrealistic, rapid changes in the signal were filtered out by applying quality control in a similar manner to that of Janssen et al. (1989) and Bauer et al. (1992).

ERS-1 data and model data are routinely compared in this fashion, and examples of this comparison are shown in Figs. 8 and 9 for August 1995 and December 1995, while Table 2 shows the seasonal variation of statistical parameters such as modeled mean, bias, and

TABLE 2a. Monthly statistics obtained when comparing WAM first-guess heights with the *ERS-1* altimeter wave heights. Bias is with respect to observations. The statistics are presented for the globe (global), the Northern Hemisphere (NH), the Tropics (±20°), and the Southern Hemisphere (SH). Wave height comparison: WAM–*ERS-1,* 1995.

Wave height (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Global mean	2.6	2.4	2.6	2.5	2.4	2.4	2.3	2.4	2.5	2.4	2.4	2.5
NH mean	3.3	2.9	2.8	2.3	1.8	1.6	1.4	1.5	1.8	2.3	2.5	3.1
Tropics mean	1.9	1.7	1.8	1.7	1.7	1.9	1.9	1.9	1.8	1.7	1.8	1.8
SH mean	2.6	2.5	2.9	3.0	3.3	3.3	3.2	3.4	3.4	2.9	2.8	2.6
Global STD	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
NH STD	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5
Tropics STD	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.3	0.3
SH STD	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
Global bias	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
NH bias	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Tropics bias	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SH bias	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2

standard deviation of error for three areas (Northern Hemisphere, Tropics, and Southern Hemisphere) and the globe. The comparisons for both significant wave height and wind speed are shown.

Several interesting features of this comparison should be noted. First of all, the mean difference between modeled and observed wave height is typically about 20 cm. This positive bias, which has been present since the introduction of the high-resolution (1.5° × 1.5°) version of the WAM model at ECMWF, cannot be regarded as a negative aspect in view of the known underestimation of wave height by the altimeter for high sea states (Carter et al. 1992). The standard deviation of first-guess error is fairly low (being typically 50 cm or less in the extratropics while 30 cm or less in the Tropics), considering that the expected observed wave height error is the maximum of 10% in the wave height or 50 cm. Similarly, modeled analyzed wind speed may be regarded of high quality because of the low bias and a standard deviation of error, which is 2 m s^{-1} or less. Scatter indices obtained from the wave height comparison range from 15% to 20% and are consistent with the results we have found in our verification study with buoy data (cf. Table 1). A similar conclusion is reached regarding the wind speed comparison.

In order to conclude our discussion on the validation of first-guess wave height by means of altimeter data, we compare results for the year 1995 with those obtained by Romeiser (1993) who, as already mentioned, studied the quality of WAM model results over the year 1988. We determined the symmetrical scatter index as defined by Romeiser for the Northern Hemisphere, the Tropics, and the Southern Hemisphere and plotted the resulting scores in Fig 7. The considerable improvement of the ECMWF wave analysis system over the past 7 yr is evident from this figure. Before we discuss possible reasons for this progress we first discuss some pertinent details of the seasonal variations of the symmetrical scatter index for wave height. First of all, there is a pronounced increase in scatter index for 1988 during the Northern Hemisphere summer, which is absent during the 1994–95 season. Realizing that Romeiser's scatter index is based on the root mean square error and not on the standard deviation of error, it may be noted that this increase during the summer is probably related to an increase in bias of modeled wave height. In the Northern Hemisphere

TABLE 2b. Monthly statistics obtained by comparing ECMWF analyzed 10-m wind speeds with *ERS-1* altimeter wind speed observations. Bias is with respect to observations. The statistics are presented for the globe (global), the Northern Hemisphere (NH), the Tropics (±20°), and the Southern Hemisphere (SH). Wind speed comparison: model analysis–*ERS-1,* 1995.

Wind speed (m s^{-1})	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Global mean	7.7	7.4	7.6	7.6	7.4	7.4	7.4	7.5	7.6	7.5	7.6	7.7
NH mean	9.4	8.7	8.6	7.7	6.7	6.2	6.1	6.2	6.8	7.7	8.2	9.2
Tropics mean	6.0	5.6	5.6	5.5	5.6	6.1	6.4	6.6	6.1	5.9	5.9	5.8
SH mean	7.8	7.8	8.4	8.8	9.1	9.0	9.0	9.2	9.3	8.6	8.5	8.1
Global STD	1.8	1.8	2.0	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8
NH STD	1.9	1.9	1.9	1.7	1.6	1.6	1.5	1.6	1.6	1.7	1.8	1.9
Tropics STD	1.7	1.7	1.8	1.7	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.7
SH STD	1.9	1.9	2.1	2.0	2.2	2.2	2.1	2.1	2.0	1.9	1.9	1.8
Global bias	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.3	0.3	0.2	0.3
NH bias	0.1	0.2	0.3	0.4	0.6	0.8	0.9	0.7	0.5	0.3	0.1	0.2
Tropics bias	0.1	0.4	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.3	0.3	0.4
SH bias	0.3	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.4

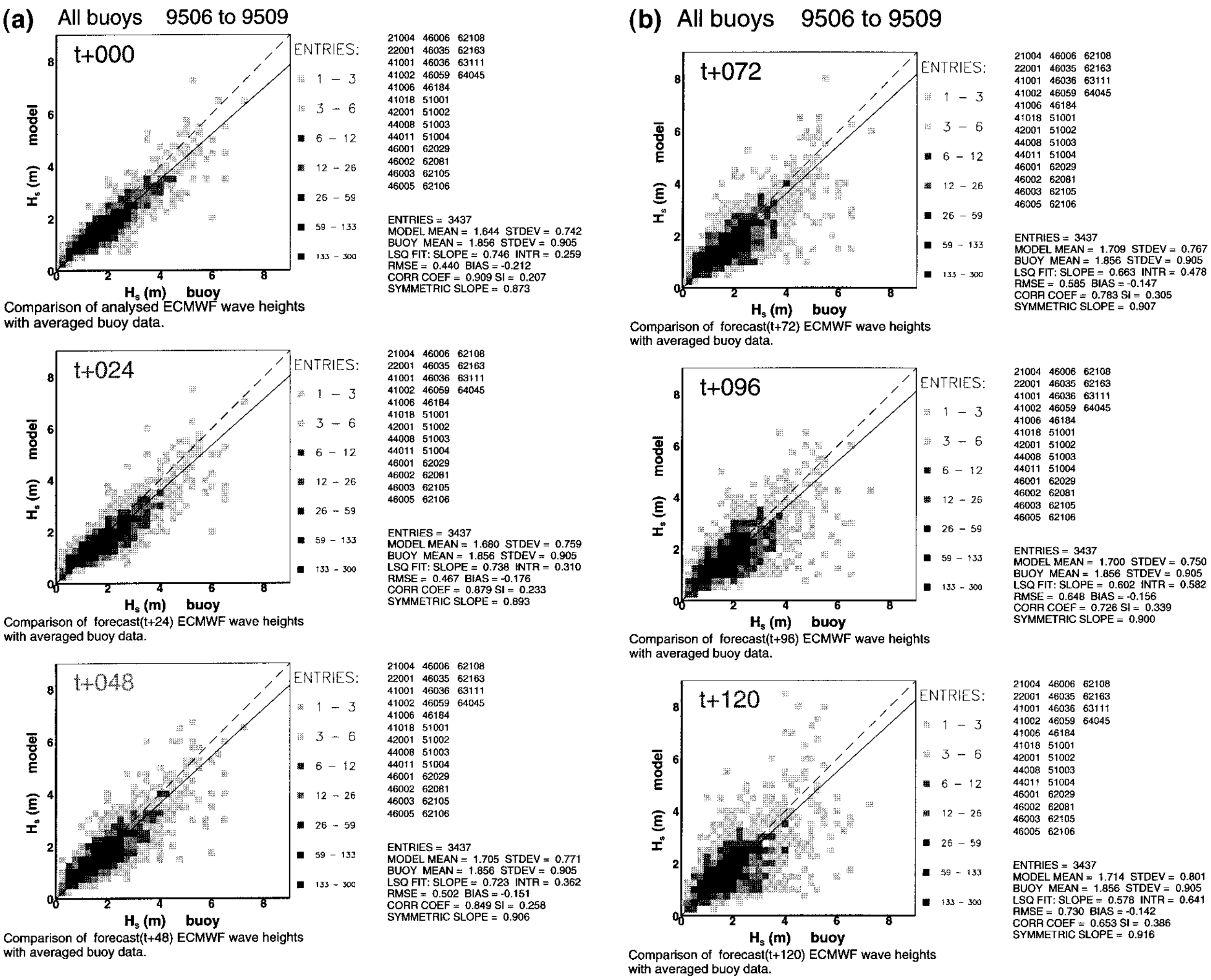


FIG. 10. Verification of analyzed and forecast wave height against buoy data for the period of June–September 1995.

and the Tropics the bias is caused by the afore-mentioned underrepresentation of swell in earlier cycles of WAM, while in the Southern Hemisphere winter the underestimation of modeled wave height was probably caused by too weak winds. It is emphasized that in the present wave analysis system these problems no longer occur, as is evident from Table 2.

We conclude this section by means of a brief discussion of the possible reasons for the improved performance of the ECMWF wave analysis system over the past decade. First of all, it is thought that the quality of the driving wind fields has improved considerably. This is evident from the comparison with buoy data summarized in Table 1, which shows a considerable reduction in the scatter index for wind when comparing results from 1988 with those of 1994–95. Unfortunately, Romeiser did not compare ECMWF winds with altimeter winds for the year 1988, but the present day results for modeled winds as compared to altimeter winds are impressive (e.g., in the Northern Hemisphere the scatter index for altimeter wind speed ranges between 20% and 25% which is somewhat higher than seen from the buoy comparison).

Second, a number of changes have been introduced in WAM giving, for example, an improved representation of the swell component of the wave field. In addition, the increase of resolution from 3° × 3° to 1.5° × 1.5° has resulted in better performance during extreme events.

Finally, it is thought that the assimilation of altimeter data in WAM has also contributed to some extent to an accurate first-guess wave field. Although data assimilation impact studies only showed improvements in the bias of the wave forecast (and not in the standard deviation of error), it seems likely that the swell component of the wave field (which may have a longer memory of the assimilated data) has benefited from the assimilation of altimeter data in the wave analysis. This claim is supported by results of an experiment where the wave forecasting system was run for the month of December 1995 without data assimilation. Verifying the analyzed waves against *ERS-1* altimeter data showed

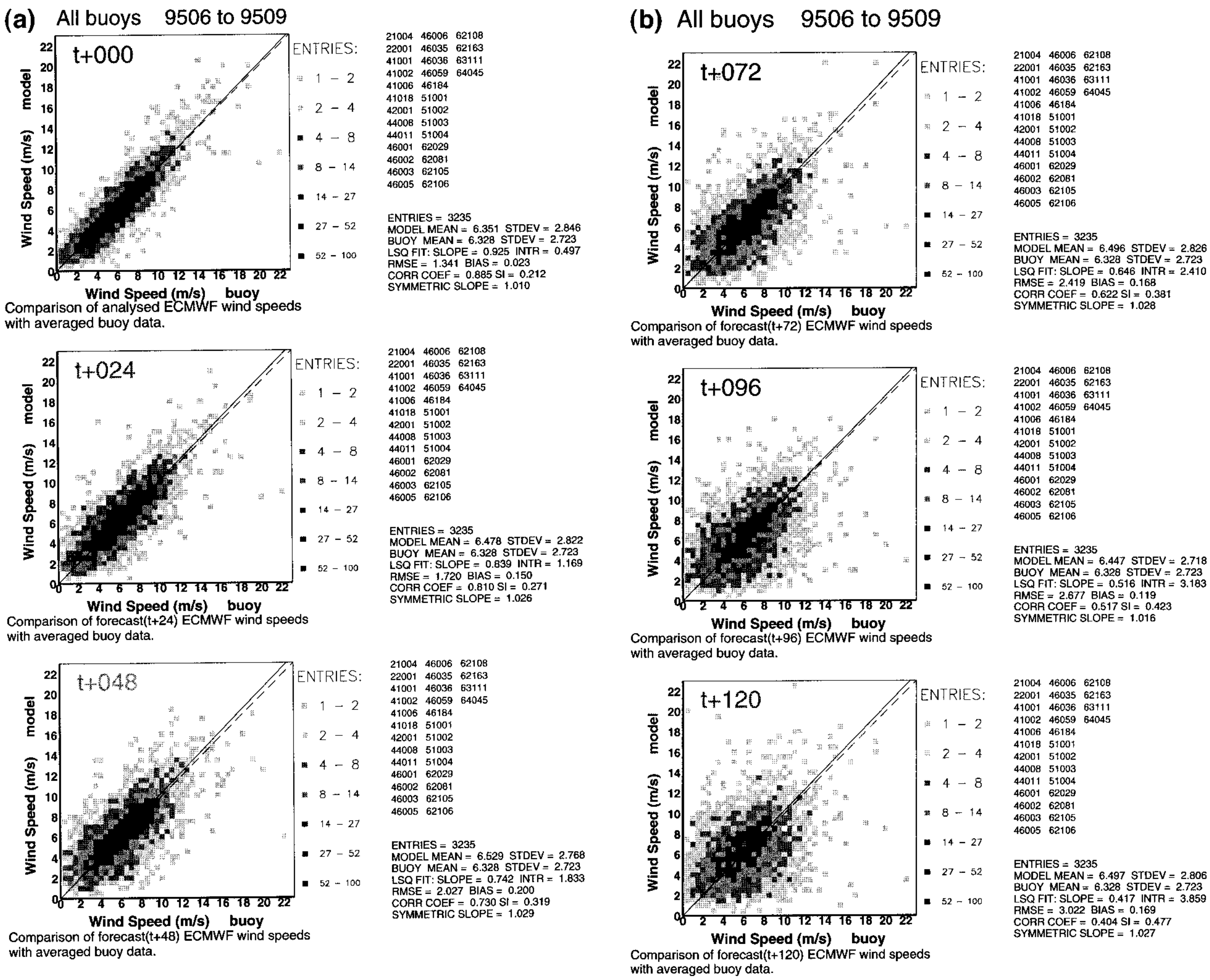


FIG. 11. Same as Fig. 10 but now for wind speed.

that, compared to the operational results with data assimilation, the standard deviation of error hardly changed but the bias changed by about 20–25 cm, which is considerable, in particular in the tropical areas.

5. Quality of wave forecast

In the previous sections we have seen that nowadays the ECMWF wave analysis system is producing reasonably accurate analyzed wave height fields. Although the wave model community has only paid little attention to verifying wave forecasts [an exception is perhaps Cavaleri et al. (1994)], it should be clear that at ECMWF, with its main emphasis on forecasting, there is a keen interest in the quality of the wave forecast.

The quality of the forecast is usually judged by a comparison with the verifying analysis. Using the experience gained from the atmospheric community, this enabled us to introduce some new verification tools in ocean wave forecasting in a relatively easy manner. We mention skill scores based on persistence and the anomaly correlation. It will be seen that, in particular, the anomaly correlation is a sensitive indicator for the quality of the wave forecast.

We have recently introduced an additional quality control of the wave forecast based on verification against buoy data. Results of the forecast verification against buoy data will be analyzed first, after which we present results from the comparison of wave forecast with the verifying analysis.

a. Verification of wave forecast against buoy data

At ECMWF a 10-day global wave forecast is issued once a day and uses the 1200 UTC wave analysis as an initial condition. Because the wave forecast is done only once a day, there are fewer possibilities to collocate modeled wave height with buoy data than in the case of wave analysis, which is produced four times a day. For this reason the wave forecast is compared with buoy observations over a 4-month period. Figure 10 shows the comparison of analyzed and forecast wave height

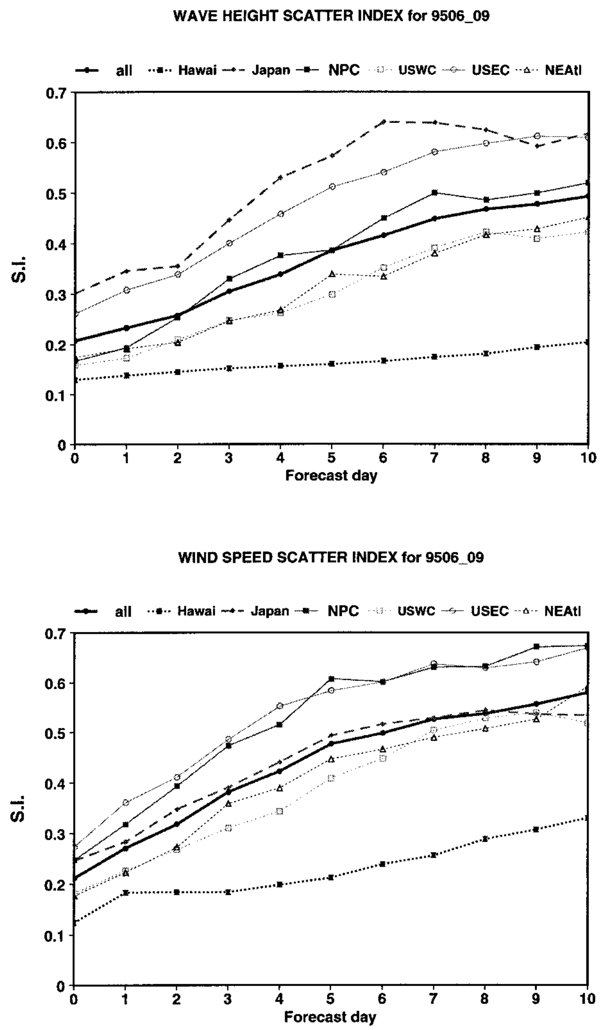


FIG. 12. Evolution of scatter index for wave height and wind speed as a function of forecast day at buoy locations. Symbols refer to different areas as displayed in legend.

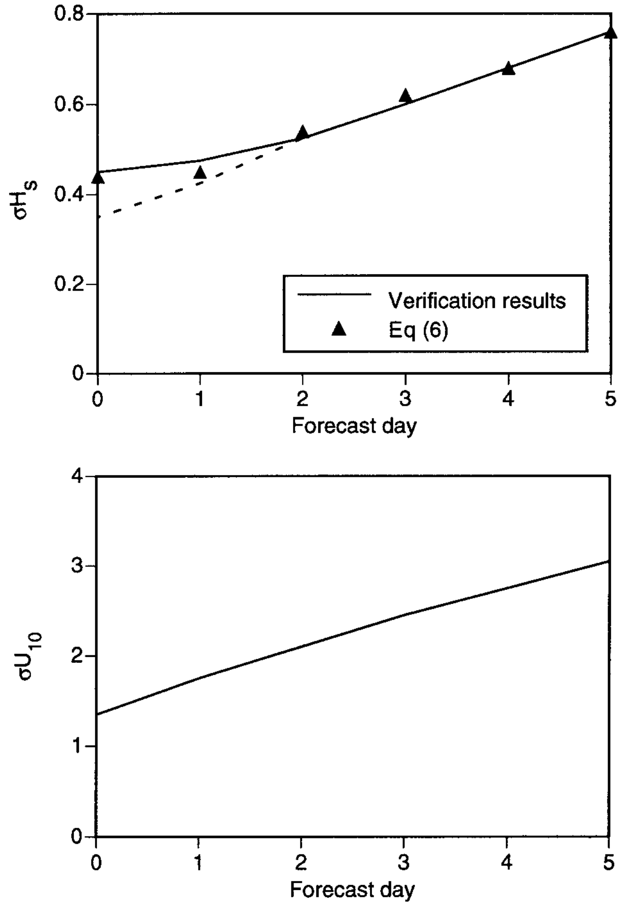


FIG. 13. Rms error growth in wave and wind forecast for all buoys during the period June–September 1995.

with buoy data for the period of June to September 1995, while Fig. 11 shows a similar comparison for wind speed. Only forecasts up to day 5 are presented. The comparison of wave height illustrates the slow deterioration of the modeled wave height with time, although forecasts up to 2 days still agree relatively well with the buoy observations. Also, the wind speed comparison shows the deterioration of the quality of the wind forecast, although at a somewhat more rapid pace. The slower degradation of the wave height forecast may be attributed to the fact that a considerable part of the wave height field consists of swell generated by winds earlier in the forecast, which are therefore of higher quality. All this is also evident from Fig 12. where the scatter index of wave height and wind speed for all buoys is plotted as a function of forecast day up to day 10. Over the 5-day period the wind speed scatter index increases by a factor of 2.2 while the wave height scatter index only increases by a factor of 1.7. In the same figure we have also shown the error growth for different regions. Clearly, results differ considerably from region to region. Regions that have mainly swell, such as Hawaii, show only a very small error growth while the windsea-dominated area of the North Pacific gives the most rapid error growth. The east coast of the United States appears to be the worst case mainly because it has by far the largest analysis error.

It is of considerable interest to try to understand the causes of error growth in wave height. To this end, in Fig. 13 we have plotted the rms error for wave height and wind speed as a function of forecast day. It is a common belief in atmospheric modeling that the error growth of atmospheric quantities, such as wind speed, is linear with time (A. Hollingsworth 1995, personal communication; only a perfect model would show exponential error growth). This indeed follows from the wind speed plot in Fig. 13. However, the error growth curve for wave height differs as, initially, the error growth is much flatter and only later in the forecast is there a linear growth with time. It is important to understand the different behavior of error growth in wave

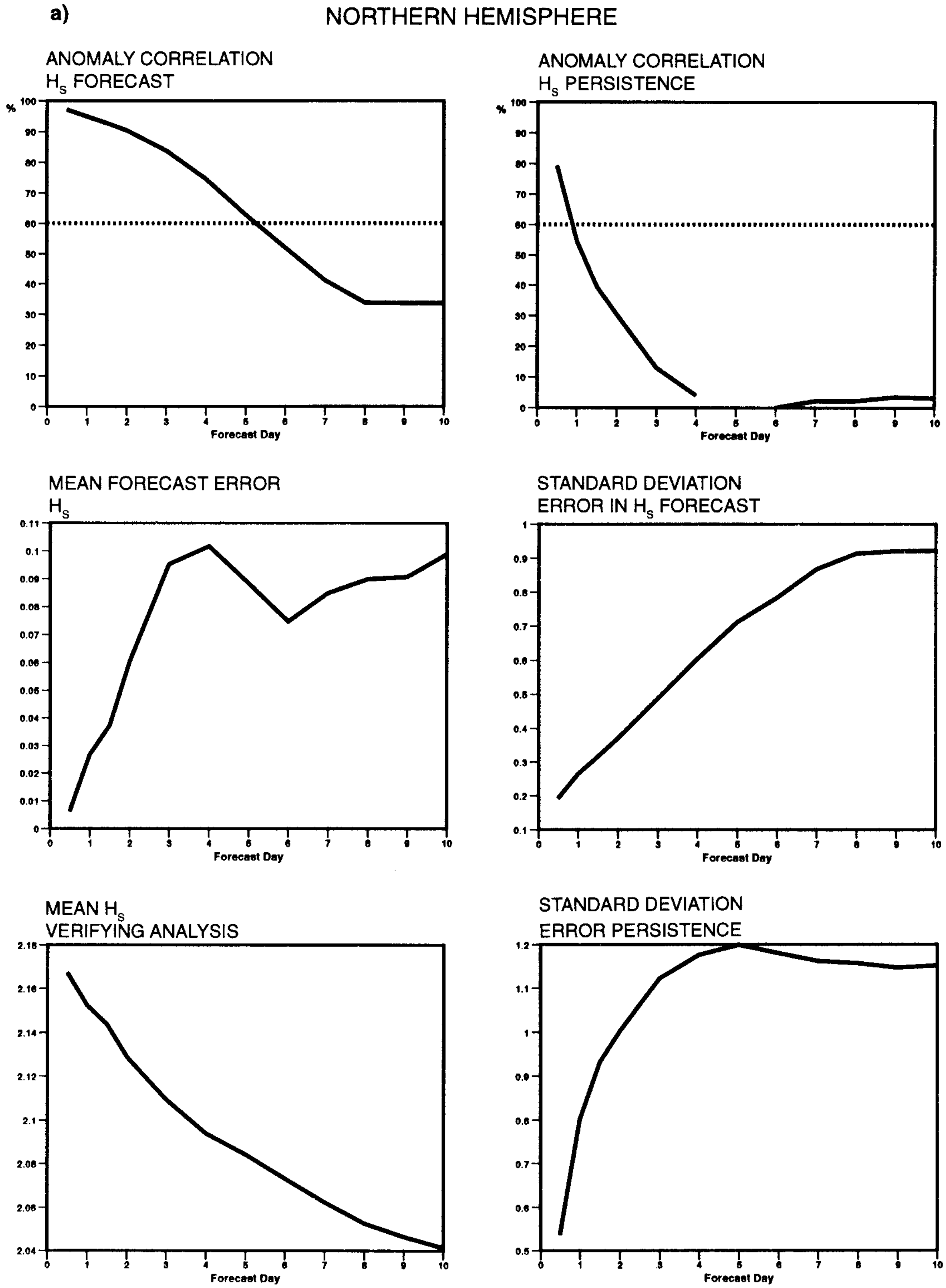


FIG. 14. Wave forecast verification scores for April 1995.

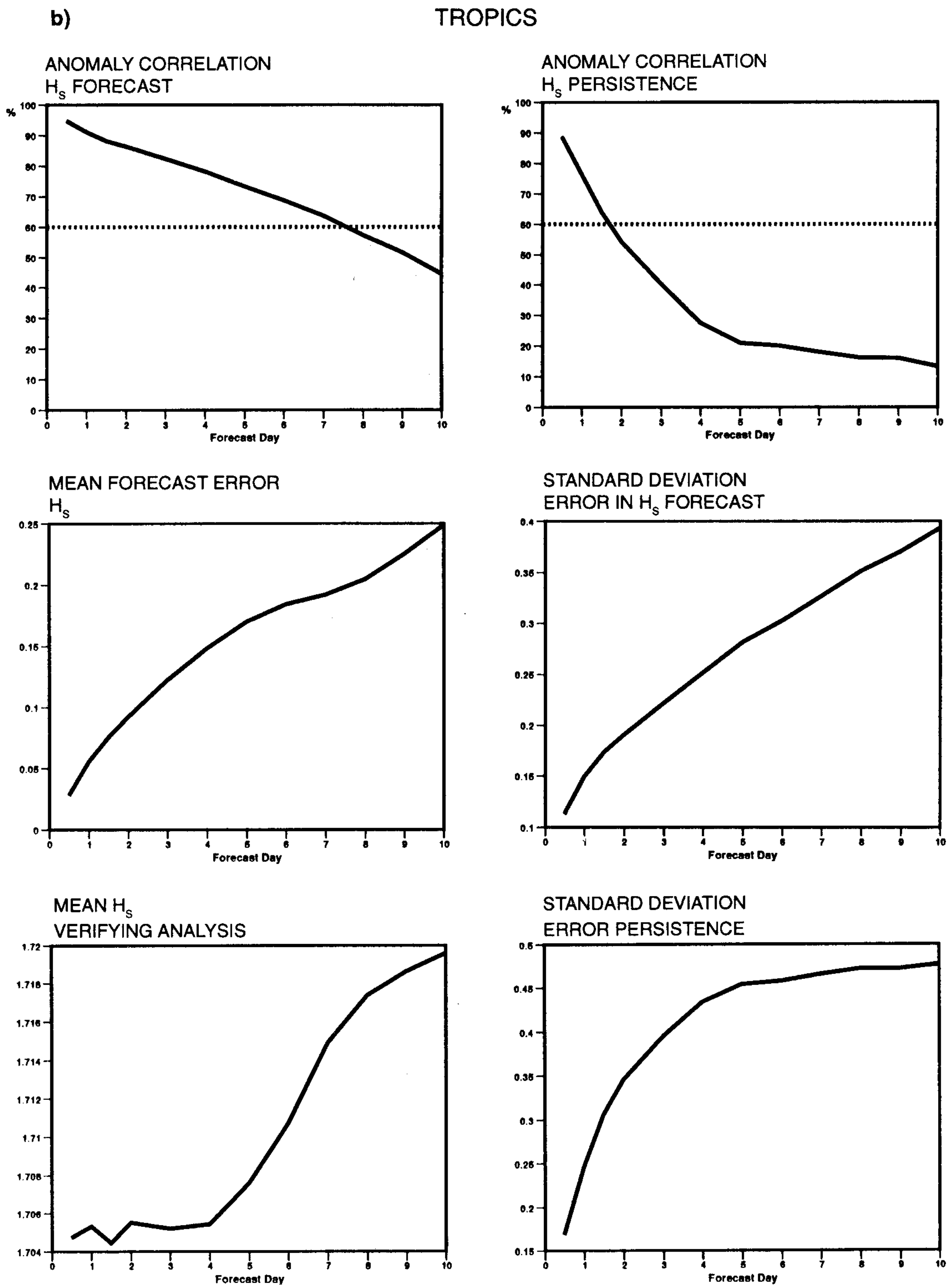


FIG. 14. (*Continued*)

height. In order to do that, it seems obvious from the previous discussions to distinguish between windsea and swell components of the wave field. Regarding error growth in swell, it seems reasonable to assume that this is virtually independent of forecast time. This assumption is supported by the error growth curves of Fig. 12, which show this to be case for the Hawaii error. Denoting the error in swell wave height by σ_{sw}, we then pose that, based on the verifications of model wave height against buoy data and altimeter data, σ_{sw} is 12%

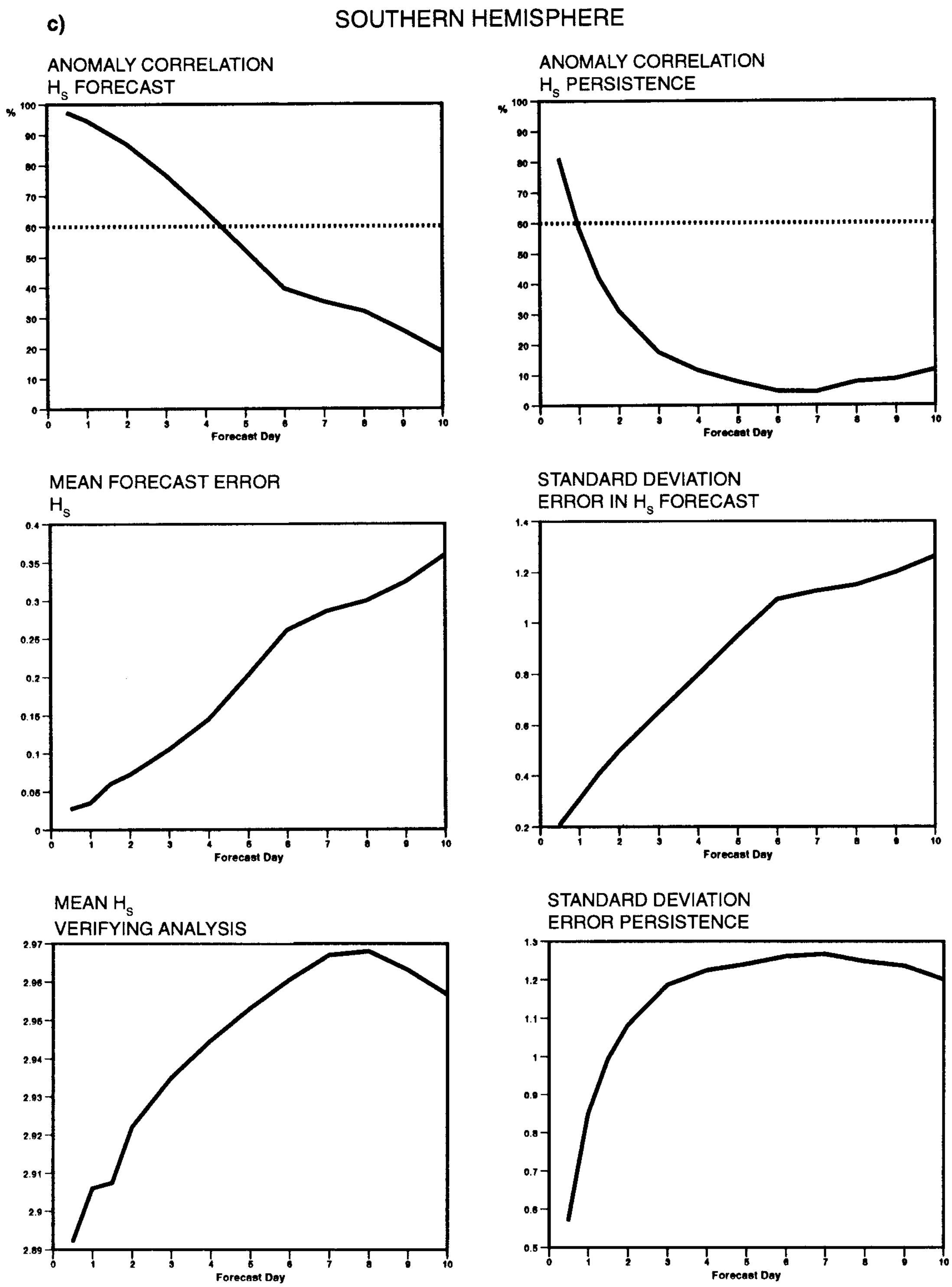


FIG. 14. (*Continued*)

of the average wave height. Thus, with an average wave height of 1.6 m, we have

$$\sigma_{sw} = 0.20 \text{ (m)}. \tag{4}$$

Next, it is assumed that the error in the windsea component of the wave field is mainly determined by the error in the wind field. Since for the period of interest the mean wind speed is about 6–7 m s^{-1}, it seems fair to assume that, on average, we are dealing with equilibrium wind waves so that Eq. (3) applies. Denoting

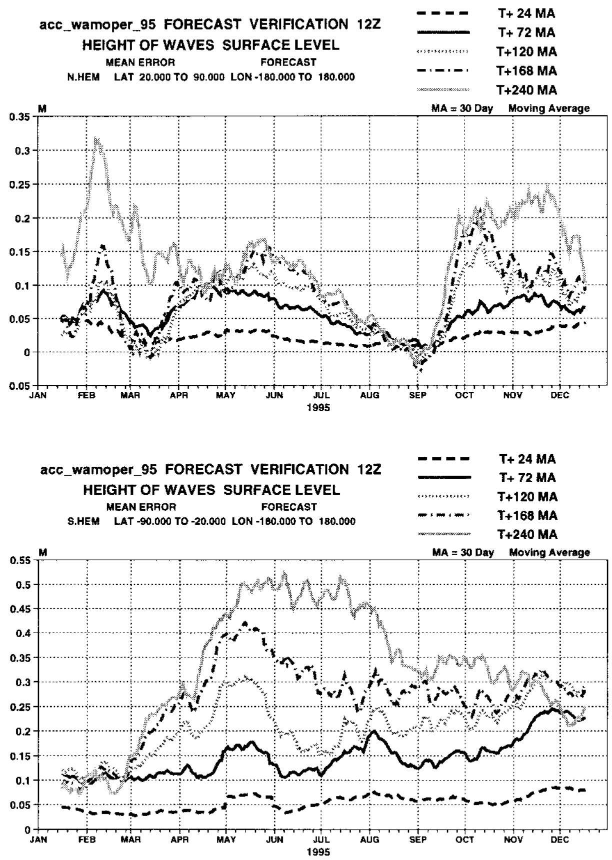


FIG. 15. Mean forecast error in wave height for Northern and Southern Hemispheres for the year 1995.

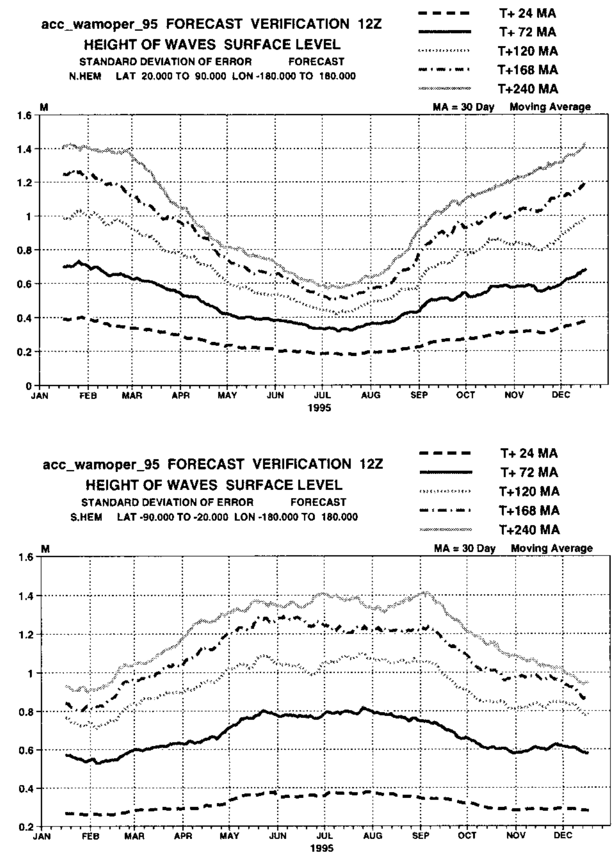


FIG. 16. Standard deviation of wave height error for Northern and Southern Hemispheres over the year 1995.

the error in windsea wave height by σ_{ws}, we therefore have

$$\sigma_{ws} = \frac{2\beta U_{10}}{g}\langle \delta U_{10}^2 \rangle^{1/2}, \tag{5}$$

where $\langle \delta U_{10}^2 \rangle$ is the rms error in wind speed, which is known from the wind speed forecast statistics. Assuming that for the case of all buoys the windsea and swell components of the wave field have equal weight, the following error σ_H in wave field is found:

$$\sigma_H = \sqrt{\sigma_{ws}^2 + \sigma_{sw}^2}. \tag{6}$$

Using the modeled mean wind speed and the wind speed error in the wave height error plot of Fig. 13, we have plotted the results of Eq. (6) as well, which look reasonable. Equation (6) therefore provides an explanation for the initial flat error growth in wave height, because the error in the swell part of the wave field also plays a role. On the other hand, since the swell error is only 0.2 m, it is evident that the error in wind speed, resulting in the windsea error (5), is dominant. This just supports the common belief in the wave model community that a considerable part of errors in wave height is caused by errors in the wind field. Thus, Fig. 13 may be regarded as a nice illustration of this belief.

We should finally point out that a somewhat different interpretation of the results in Fig. 13 is also possible. What is needed to explain the initial slow growth of wave height error is, in addition to the windsea error, an additional constant (in time) error. In the above, this error was assumed to be related to errors in swell (-propagation) but other errors may contribute as well. For example, buoy data are not perfect, as they have a relative error of 5%–10%. There are, no doubt, also wave model errors but the magnitude of these errors is not known. An upper estimate of the model error may now be given by assuming that the constant background error is only caused by the model; thus we obtain a model wave height error on the order of 12% of mean wave height. This model error is, however, small compared to errors caused by the wind field. In fact, with a mean wind speed of 7 m s^{-1}, an extremely small rms error in analyzed wind speed of 70 cm s^{-1} is needed to obtain errors in the modeled windsea wave height that are of comparable magnitude to the above estimate of the model error. Thus, with present-day rms errors in wind speed of about 1.5 m s^{-1} (cf. Fig. 13), which are considerably smaller than errors found a decade

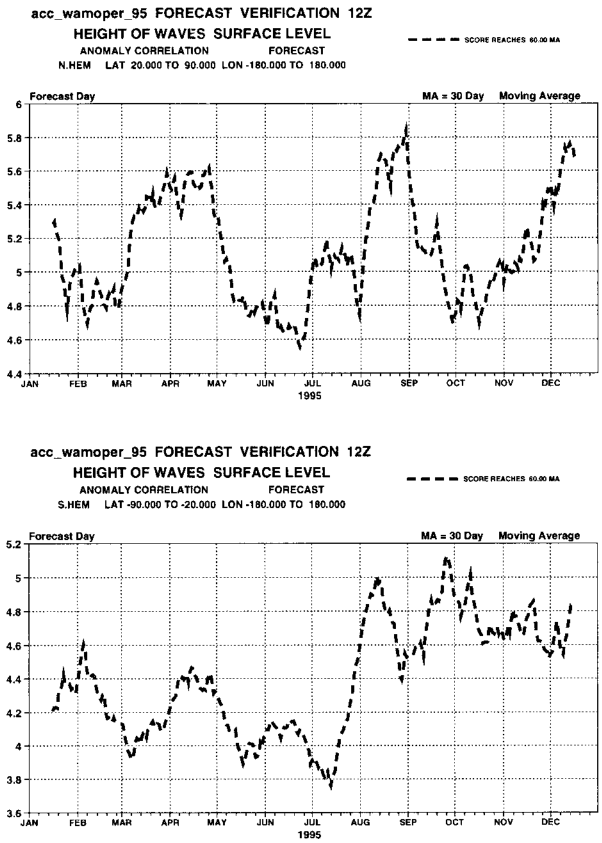


FIG. 17. Forecast skill in wave height for Northern and Southern Hemispheres over the year 1995 (anomaly correlation reaching 60%).

ago, it is concluded that wind speed errors still dominate the wave forecast error.

b. Verification of wave forecast against analysis

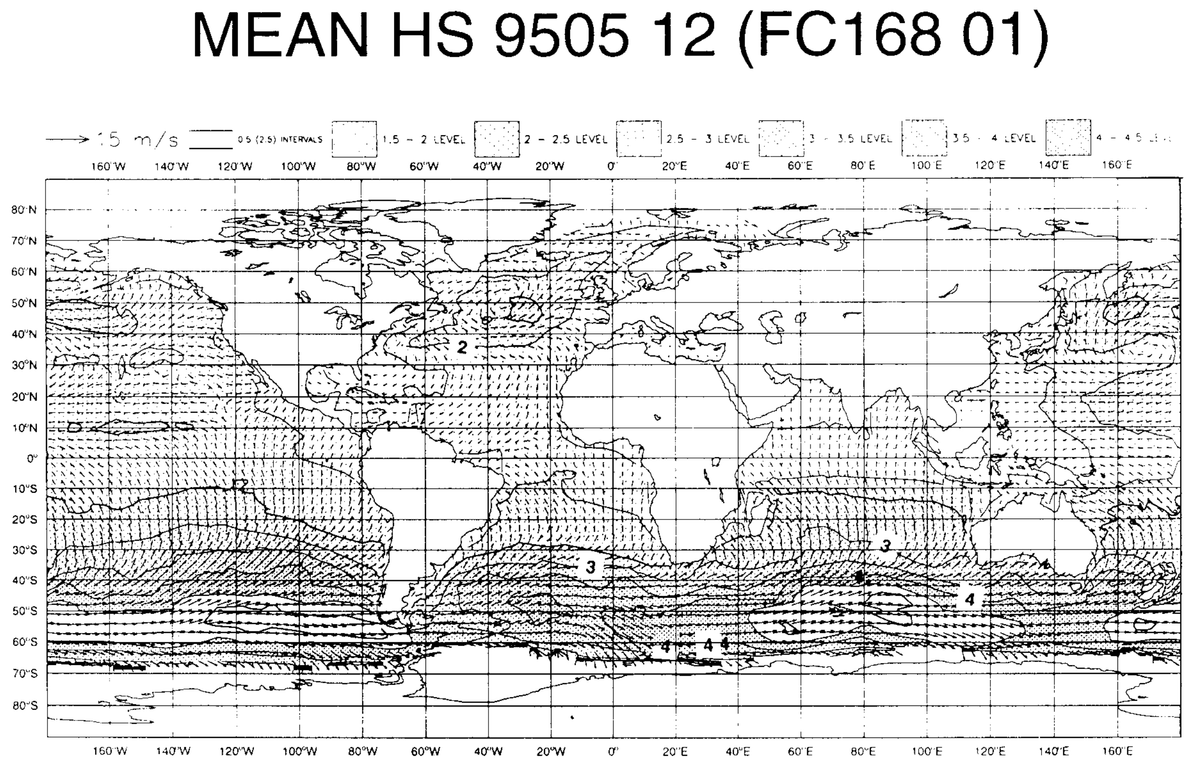
Having obtained sufficient confidence in the quality of the wave height analysis, it seems a good idea to judge the reliability of the wave forecast by means of a comparison with the verifying analysis.

A number of verification scores have a certain historical background, and it seems appropriate to explain their meaning in this context. Scores are intended to express, to a certain extent, the usefulness of a forecast and, as a benchmark (''yardstick''), one uses information that is already available. For example, one may ask to what extent the wave forecast has more skill than a persistence analysis (in which during the whole forecast the state is given by the initial condition). In practice, a 10-day wave forecast always beats the persistence analysis, as follows from a comparison of the rms error of wave forecast with persistence analysis. A more useful (but also more ''impressive'') yardstick to judge the quality of the wave forecast is the wave climatology. (Incidentally, the ECMWF wave climatology was produced from a 9-yr hindcast using analyzed ECMWF winds.) Thus, the anomaly correlation for wave height, defined as the normalized correlation of forecast anomaly and verifying analysis anomaly (both anomalies with respect to climatology), measures how much more skill the wave forecast has over climatology. However, in the case of positive correlation, when the forecast beats the climatology one does not necessarily have a forecast that is regarded as useful by the forecaster. The relation between usefulness of the forecast and anomaly correlation is not straightforward and can only be established by means of the subjective step that forecasters assess by inspection of weather maps whether, for a given anomaly correlation, a forecast is useful or not. In this way weather forecasts were found to be useful when the anomaly correlation exceeded 60%. However, such a relationship has not been established yet for ocean wave forecasting. Despite this shortcoming, it will be seen that the anomaly correlation is a sensitive tool for measuring the skill of a wave forecast.

Several verification scores for wave height are nowadays determined routinely. An example for April 1995 for several regions is shown in Fig. 14. The panels show the anomaly correlation of wave forecast, the anomaly correlation of persistence, the mean error of the forecast, the standard deviation of error of the forecast, the mean of the verifying analysis, and the standard deviation of error of persistence as a function of the forecast day. It is seen from the wave forecast anomaly correlation plot that in the Northern Hemisphere the forecast is useful up to day 5 and in the Southern Hemisphere the forecast is useful up to day 4, while in the Tropics, which has much lower variability, the forecast is useful up to day 7. On the other hand, the persistence analysis in the extratropics already loses its value after day 1 in the forecast. The mean error of forecast wave height is quite small in the Northern Hemisphere, being only 5% of the mean wave height, while in the Tropics and the Southern Hemisphere the mean error is somewhat larger. Finally, in the Northern Hemisphere the standard deviation of forecast error is up to day 3 in the forecast below the one from the comparison between first-guess and altimeter data, and reaches about 1 m at day 10 of the wave forecast. In contrast to this the quality of the forecast in the Southern Hemisphere seems to deteriorate somewhat faster.

Thus, the scores over April 1995 confirm the experience of atmospheric forecasting that the quality of the forecast is better in the Northern than the Southern Hemisphere. The mean error and standard deviation of forecast error are at an acceptable level. It should be pointed out, however, that there may be considerable seasonal variations in the wave forecast scores. This is shown in Figs. 15–17 where, over the year 1995, we present the evolution of mean forecast error, standard deviation of error, and forecast skill for the Northern and Southern Hemispheres. Here, the forecast skill is defined as the forecast period in which the anomaly correlation is larger than 60%.

Regarding the time series for the Northern Hemi-



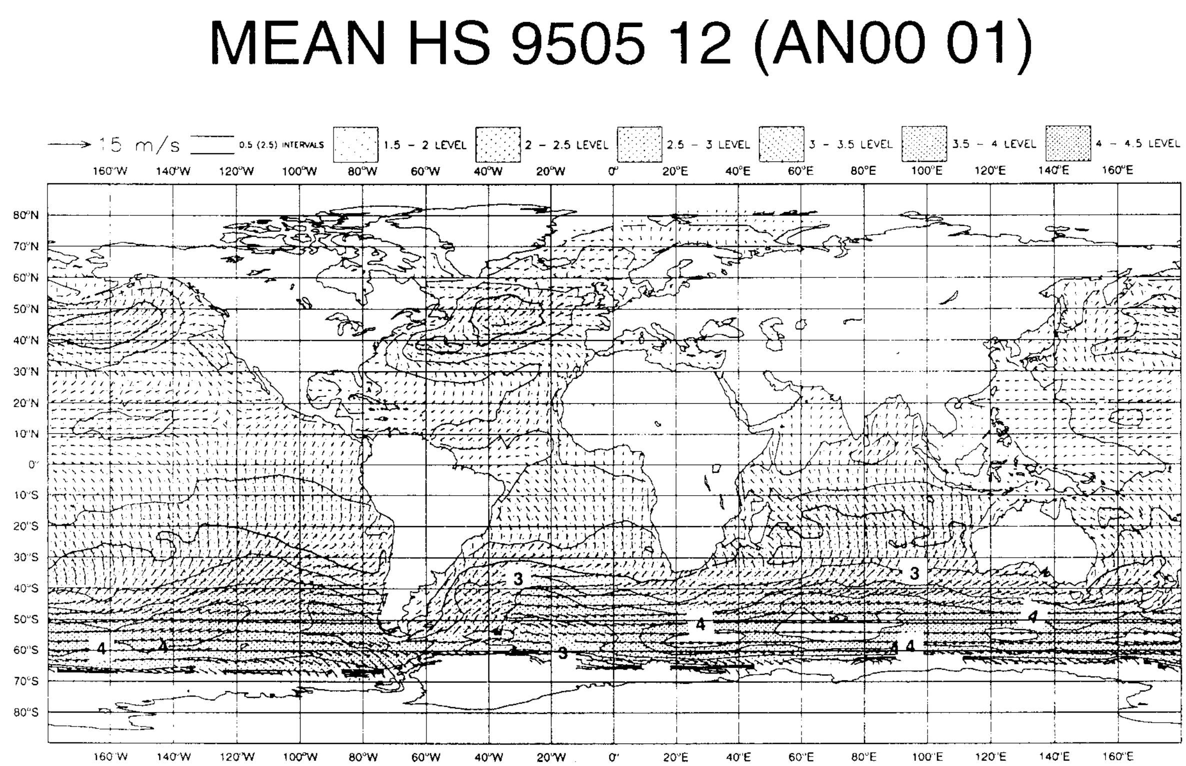


FIG. 18. Comparison of monthly mean forecast wave height (day 7) with analyzed wave height for May 1995.

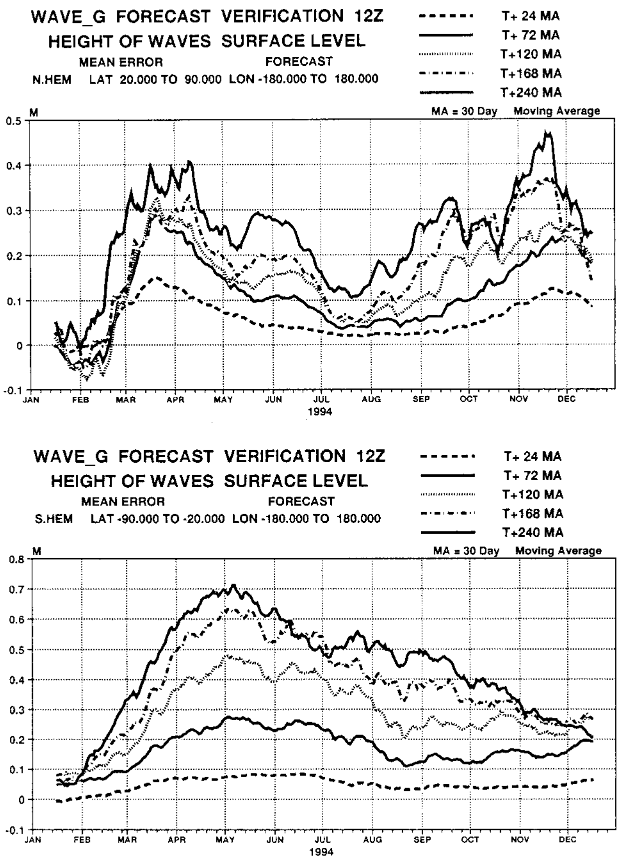


FIG. 19. Mean forecast error in wave height for Northern and Southern Hemispheres over the year 1994.

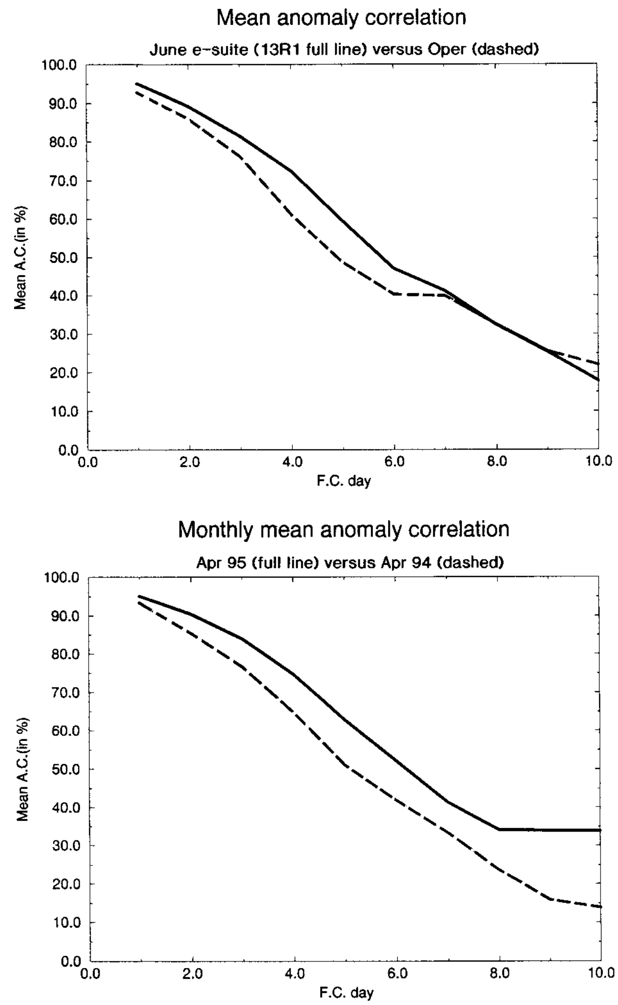


FIG. 20. Monthly mean anomaly correlation for June *e* suite and operations (top). (bottom) Anomaly correlation for April 1994 and April 1995. Area is Northern Hemisphere.

sphere scores, we note a small mean forecast error since April 1995, while before that date mean forecast errors are quite considerable, in particular during the last 3 days of the forecast. The time series for the standard deviation of forecast error follows a seasonal cycle where, as expected during the stormy seasons, the standard deviation is the largest. The time series for the forecast skill shows variations of the order of ½ day around a mean value that appears to be slightly larger than 5 days. (It is noteworthy that, even for the relatively small limited area of the North Atlantic, the mean forecast skill is 5 days.) The Southern Hemisphere scores during the Southern Hemisphere winter show considerable biases in the latter part of the wave forecast and there is a less clear seasonal cycle in the standard deviation of forecast error. The forecast skill in this part of the world appears to be about 4.4 days.

The growth of the mean forecast error with forecast error is, unfortunately, a rather serious problem. In order to see this we have compared the mean of the day 7 forecast for May 1995 with the verifying analysis in Fig. 18. Although the average forecast error is only 0.4 m (see Fig. 14), there are regional differences of about 1–1.5 m (e.g., southwest of Australia) while a considerably larger amount of swell is also radiated towards the Tropics. However, problems seem to be less severe over the year 1995 than 1994. This is illustrated in Fig. 19. Now comparing the results of 1994 and 1995 (see Fig. 14) it is seen that from April 1995 the Northern Hemisphere mean error has reduced by a factor of 2. There is also a reduction of Southern Hemisphere mean error but to a lesser extent.

The reason for the reduction of mean forecast error is probably related to a reduction of overactivity of the atmospheric model during the later stages of the forecast. In April 1995 a new version of the ECMWF atmospheric model was introduced. Previous versions of the ECMWF model showed too high levels of kinetic energy during the forecast. This new version of the model has a fully interpolating semi-Lagrangian scheme and a new gravity wave drag scheme with mean orography. The above changes led to a favorable error reduction. These changes also gave rise to a considerable reduction of mean forecast error in wave height as followed from

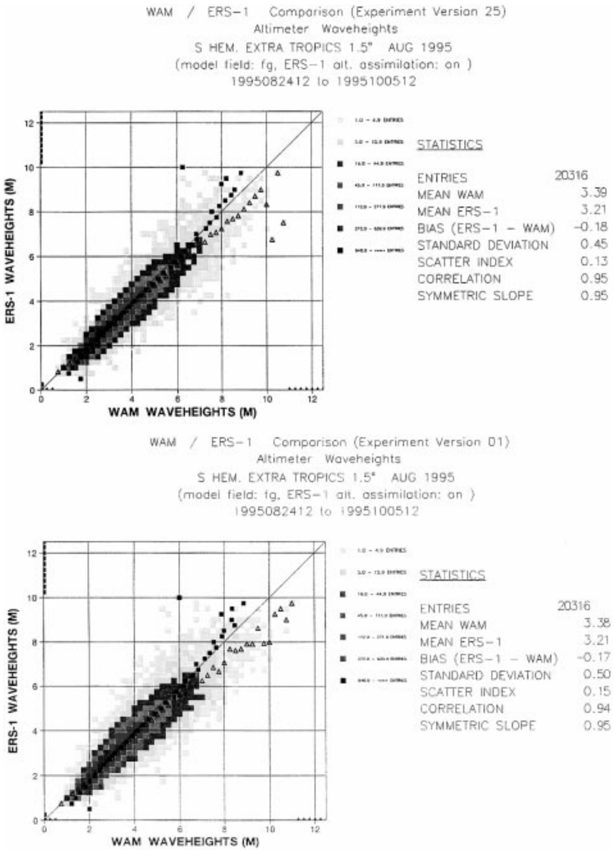


FIG. 21. First-guess wave height comparison with altimeter wave height data for 3D-Var atmospheric *e* suite. (top) WAM model as driven by 3D-Var winds. (bottom) WAM model driven by operational winds. Length of *e* suite is 43 days and area is Southern Hemisphere.

the comparison of wave results from the operational forecast with results from a parallel run (*e* suite) over the period 1–19 June 1994. The parallel run also showed a considerable improvement in Northern Hemisphere anomaly correlations, as shown in Fig. 20. By comparing monthly mean anomaly correlations for April 1994 with April 1995, significant improvements with the new version of the ECMWF model are to be noted, suggesting that the new version of the ECMWF model is robust. The forecast skill has improved by about 1.5 days. Finally, we note that the atmospheric forecast skill has also improved (about ½ to ¾ day) but to a lesser extent. This, once more, illustrates that wave results are sensitive to the quality of the atmospheric winds.

6. Conclusions

We have reviewed the present status of wave modeling at ECMWF. Ocean waves, driven by ECMWF 10-m winds, are forecasted by WAM (cycle 4), which solves the energy balance equation for the wave spectrum. Initial conditions are provided by assimilation of *ERS-1* altimeter data into the first-guess wave field.

Comparison of analyzed wave data with independent buoy observations reveals the high quality of the wave analysis. Furthermore, the first-guess wave field also seems to be of good quality as follows from the verifications against altimeter wave height data. It appears that considerable progress has been made in comparison with wave model results a decade ago. Plausible reasons for this progress are (a) the continued improvement of the atmospheric analyses, (b) improvements in wave modeling with respect to wind input and dissipation, and (c) the inclusion of altimeter data in the wave analysis.

Regarding wave forecasting, it is not so easy to compare with results in the past. This is partly caused by the fact that in the past there was more interest in wave analysis than wave forecasting. On the other hand, we have introduced tools, such as anomaly correlation, that have not been used before in wave modeling.

Nevertheless, the comparison of forecast wave height with buoy observation has shown the slow deterioration of the quality of the wave forecast with time. It is suggested that the error growth is determined on the one hand by a constant error (which we termed the error in swell) and on the other hand an error caused by uncertainties in wind speed. Verification of wave forecast against verifying analyses suggests that in the Northern Hemisphere we have a reasonable forecast up to day 5 while the forecast skill in the Southern Hemisphere is somewhat less.

In spite of the overall good quality of wave forecast and analysis, it should be emphasised that there are also areas where wave modeling is less accurate. An example is the east coast of the United States. On the other hand, the relatively poor quality of the wave analysis in the northeast Atlantic is probably caused by the unreliable behavior of the wave buoys in that area, because verifications against altimeter data show good agreement. In the summer of 1995 we asked the U.K. Meteorological Office (which is in charge of the northeast Atlantic buoys) whether there were perhaps problems with these buoys. A program to replace the communications systems on these buoys was already in hand, and by December 1995 the systems on all the buoys had been upgraded, resulting in a more accurate report of wave conditions (M. Holt 1995, personal communication). In fact, we have seen during the autumn of 1995 a gradually improved agreement between model and observations (cf. Fig. 5). It is therefore concluded that wave model results are now sufficiently reliable to also be used for quality control of wave height observations. Examples of the quality control of observations by the ECMWF atmospheric model are given in Hollingsworth et al. (1986).

At ECMWF there is a continuous effort to improve analysis and forecast. The relatively poor results on the east coast of the United States could perhaps be alleviated by the introduction of the effects of the Gulf Stream. Prediction of extreme events could be improved by including effects of gustiness (Cavaleri et al. 1994).

Finally, wave modeling could also benefit from improvements in weather forecasting. We have already discussed the recent improvements in the ECMWF atmospheric model that resulted in benefits for wave modeling. However, an improved atmospheric analysis achieved by new data assimilation techniques and new types of data may also give rise to improved wave analysis and forecasting. Recently, ECMWF has completed the considerable task of upgrading the data assimilation in its atmospheric model to a three-dimensional variational approach (3D-Var). The new scheme is able to handle the wealth of data from the scatterometer that provides information on the surface wind field. Results from a 42-day parallel run suggest an improved wind speed analysis over the Southern Hemisphere as followed from a comparison with altimeter wind speed. Also, a reduction of 10% in standard deviation of wave height error is found, as is shown in Fig 21. Finally, the forecast skill has improved by half a day. Since variational assimilation is only beginning, further progress in weather and wave forecasting is expected to occur in the near future.

Acknowledgments. We thank Liana Zambresky, Heinz Günther, Piero Lionello, and Anne Guillaume who provided an important contribution in the development of the ECMWF wave forecasting system. Useful discussions with Anthony Hollingsworth, Martin Miller, and Adrian Simmons are gratefully acknowledged. We thank Brian Norris for his support in developing the wave forecast scores, while Georgios Konstandinidis's support for producing the wave climatology is gratefully acknowledged. Björn Hansen's contribution was supported by ESA(RFQ/3-8488/95/NL/CN).

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