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Preliminary assessment and use of ERS-1 altimeter wave data

by

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ABSTRACT

ERS-1, launched in July 1991, carries a radar altimeter which provides co-located measurements of wave height and wind speed over the oceans. During the calibration period, data from wave models at several operational centres were used to assess the accuracy of the observations. This provided a rapid check on data quality and assisted in validating the instrument. Comparison of altimeter data with fields from the UK Met Office wave model showed the model to be lacking in swell. The verification figures were similar to those comparing the model against moored buoy data.

Once the quality of altimeter data was established, an assimilation trial was run. From the start of November 1991 to the end of January 1992 the altimeter data in real time were assimilated into the UK Met Office wave model, in parallel with the operational run. The major impact of assimilating the data was to go some way to removing the lack of swell. For waves up to 6m height the mean bias in the model was reduced by 30cm. The largest impact was noticeable in the Central Pacific. There was little impact for waves higher than 6m, which were mostly forced by local wind conditions.

1.0 Introduction

Numerical models of sea surface gravity waves are run operationally at several weather forecast centres around the world. These provide forecasts of wave height and wave period which help to improve the safety and efficiency of maritime operations. Surface waves evolve in response to the wind blowing over the sea surface and to the currents within the ocean. Unlike the processes governing the evolution of winds and currents, surface gravity waves have no internal instabilities and are thus predictable, at least in a statistical sense. Forecasts and analyses (often called "hindcasts") are possible without observations being assimilated into the system.

Conventional observations of surface waves are largely subjective, obtained by visual estimates. These are made routinely by ships and issued with their weather reports. Other sources of wave information are oil platforms and wave buoys. Instruments provide measurements of significant wave height and one dimensional spectra (the energy of a range of frequency components). Full two dimensional spectra (energy classified by both the frequency and the direction of the waves) are rarely reported in real time. Uncertainty over the accuracy of ship wave reports (Laing, 1985), and the restricted geographical distribution of instrumented buoys and platforms, have inhibited production of wave analysis schemes except for semi-enclosed seas (eg NEDWAM, V Makin, personal communication).

SEASAT in 1979 gave a glimpse of the potential of satellite observations of waves. This satellite carried three instruments of direct relevance to wave modellers. The wind scatterometer was able to provide data from which surface wind speeds and directions could be estimated (Peteherych *et al.*, 1984). Synthetic Aperture Radar (SAR) was able to provide images from which the wave spectra could be determined, albeit with some difficulty (Hasselmann *et al.*, 1988). Significant wave height and wind speed could be estimated from the spread and strength of the signals received by the radar altimeter (Fedor and Brown, 1982). GEOSAT, for which data were available from November 1986 to January 1990, carried a radar altimeter from which long term climatologies of the wave height field could be derived (eg Carter *et al* , 1992).

ERS-1 was launched in July 1991 and carried a synthetic aperture radar (SAR), a scatterometer, a radar altimeter and other instruments. Despite the decade since SEASAT, there was still lively debate about how best to interpret SAR wave data at the time of the launch of ERS-1 (eg Hasselmann and Hasselmann, 1988). The best use of scatterometer data for wave modelling appeared to be to assimilate the scatterometer data into the weather forecast models used to provide the forecast winds which drive the wave models. Schemes to assimilate the wind and wave data from the radar altimeter into wave models had been developed (eg Francis and Stratton, 1990).

Assessment of the data from earlier satellites had suggested that the satellite altimeter wave data were accurate, and were able to improve the short term forecasts of the wave models (Esteva, 1988; Francis and Stratton, 1990). Plans to assess the altimeter data from ERS-1 were made at several weather forecast centres (including the UK Met. Office (UKMO), the European Centre for Medium-range Weather Forecasts (ECMWF), and the Norwegian Meteorological Institute (DNMI)).

By the time provisional ERS-1 data were available in real time (August 1991), these centres were able to compare the ERS-1 wave heights and wind speeds with those of their wave models. Weekly reports on the accuracy of the ERS-1 altimeter data were sent to the European Space Agency (ESA). A number of changes to the post-processing software were made by ESA before the in situ calibration campaign started. The real time use of wave models in assessing the accuracy of the altimeter data was a novel feature of the ERS-1 validation phase, and provided a rapid check on the quality of the data.

Once the modelling centres had accepted the quality of the data, they started to assimilate them into the wave models. At the UKMO an assimilation trial started in November 1991 and ran until the end of January 1992. This trial was designed to give a preliminary insight into the impact of ERS-1 data on the UKMO wave model. The initial work is described in this paper; it is planned to publish a more rigorous assessment of the assimilation later.

This paper falls into five sections of which the first is this introduction. The second section describes the UKMO wave model used in the assimilation trial. In the third section the quality of the ERS-1 wave data is discussed. Details and results of the preliminary data assimilation experiment are given in the fourth section. A summary and discussion of the results is given in section five.

2.0 Model Description

The UKMO wave model (based on that described by Golding, 1983) is a 'second generation' wave model: the exchange of wave energy between different wave components by nonlinear wave-wave interactions is parametrised. A parametrisation of directional relaxation in turning winds is also included, and the advection of swell energy on a latitude-longitude grid allows for the curvature of the earth, to ensure propagation of swell energy along a great circle. The wave model uses 16 direction components, giving a directional resolution of 22.5°, and 13 frequency components between 0.04Hz and 0.324Hz with a logarithmic increment. The waves represented in the model have periods between 25 seconds (975m wavelength) and 3 seconds (15m wavelength). A timestep of one hour is used for the source terms representing input of wind energy, dissipation and nonlinear exchange of energy. The advection timesteps are frequency dependent, allowing a longer timestep for the slower waves, but for all frequencies the advection timestep is a divisor of the source timestep, and is such that the scheme is numerically stable.

The wave model is run operationally on a global grid with resolution 0.833° latitude by 1.5° longitude, the same resolution as the atmosphere model. Wave model data points lie under the 'wind' points of the atmosphere grid. Hourly values for the winds are taken from lowest level of the atmosphere model. The formulation of the atmosphere numerical weather prediction model is described by Cullen (1991).

Statistics from the operational wave model for January 1992 are shown in Figure 1. Figure 2 shows the location of the buoys used to compile the verification statistics. Light windspeeds were slightly overestimated by the NWP model (Figure 1a), and strong winds were underestimated at the buoy sites. Model wave heights were biassed low (Figure 1b), the bias ranges from 0.4m lower than observed for waves up to 3m height, to 1.3m lower than observed for wave heights in the range 6-9m. For the 4 extreme cases with observed waveheight >9m the model mean wave heights were 2.2m lower than observed. For these higher waves the model depends very much on the accuracy of the winds used, and the negative mean bias of wave height is consistent with the lower model windspeeds for extreme cases. At many of the buoy locations there was also swell present, generated in regions distant from the point of observation. If the winds used in the model are lower than observed in the areas where swell is generated, then in the model less swell reaches the buoy sites. The UKMO wave model had shortcomings in the way it handled swell (Gunther and Holt, 1992). This contributed to the overall mean bias of 0.7m lower than observed.

2.1 Assimilation technique

The assimilation scheme developed at the UKMO from the work of Thomas (1988) had been calibrated with data from Geosat and Seasat. The present scheme was developed from that described by Francis and

Stratton (1990), extended to use an iterative procedure. The conversion from wave height to wave energy spectrum takes place after the analysis of wave height data. The method is described further by Stratton *et al* (1991).

At each iteration of the assimilation scheme, model values for wind speed and wave height are interpolated to the observation position, the difference between observed and modelled values are then interpolated back to model gridpoints. These are used to find analysed values of wave height and windspeed on the model grid. The model value of wind direction and windspeed is used to split the model wave spectrum into windsea and swell components. The windsea energy is then re-scaled according to the altimeter windspeed, and the swell energy re-scaled so that in the final spectrum the total significant wave height matches the analysed value. The scheme applies 3 iterations at each timestep, with the area of influence of observations reduced at each iteration, to a final value of 300km for waves and 175km for winds.

3.0 Comparison of ERS-1 observations with other data

During its lifetime ERS-1 will operate in three different repeat cycles; a 3 day, a 35 day and a 176 day repeat orbit cycle. The density of observations available for assimilation into the wave model will be significantly different for each of these three cycles. During the assimilation trial period ERS-1 operated in a 3 day repeat orbit. Data coverage for a typical 12 hour period is shown at Figure 3a. After the trial was complete ERS-1 moved into a 35 day cycle. Twelve hours of data coverage for this is shown at

Figure 3b. The 176 day repeat orbit is due towards the end of the ERS-1 mission. The quality of ERS-1 altimeter wave height and windspeed observations was assessed on a weekly basis. Hindcast fields of wave height and wind speed from the operational wave model, without any assimilation, were interpolated to buoy and ERS-1 observations locations. Model wind speeds, nominally at 19.5m, were converted to 10m wind speeds in order to compare against ERS-1 10m wind speed observations.

ERS-1 observations were subject to various quality control checks before comparison with model values. These checks were independent of the quality control in the assimilation scheme. The positions of ERS-1 observations were compared against a 1/3 degree land sea mask and observations not over sea were removed. An ERS-1 observation includes a satellite instrument mode value. Only observations with an instrument mode of 128 ("track on sea") were used. Some high valued observations were made as a result of the altimeter being in "track on sea" mode during the transition from sea to land. Also there was a time delay for the altimeter to adjust to observing wave height after having moved from land to sea, which resulted in unrealistically high observed values. Upper limits on wave height and wind speed observations were enforced in order to exclude these high values from the statistics. During the calibration period these limits were adjusted. They were set at 55m/s and 25m for the period 30 August 1991 to 4 October 1991, at 45m/s and 25m for the period 4 to 25 October 1991 and at 45m/s and 16m from 25 October 1991 onwards and throughout the assimilation trial (5 November 1991 to 31 January 1992). Model wave heights of 0m were also rejected and windspeed observations were not used if the wave height observation was rejected for that time and position.

Buoys from the operational global wave model verification list were used. Any buoy in shallow water or at a model coast point was not used, along with any which were known to be unreliable. The buoy positions are shown at Figure 2.

Statistics were calculated from 30 August 1991 onwards on a weekly basis. A typical week's verification is shown at Figure 4. Out of around 280,000 ERS-1 observations received each week approximately 200,000 passed the quality control checks and were then used in the statistical calculations. In general ERS-1 observations did not coincide with the buoy observations in time or space, and covered a much larger area of the globe. Comparing both ERS-1 and buoy observations with the model allows the two sets of observations to be compared, assuming the model has no geographical biases. Statistics calculated were the global means of wind speed and wave height and the mean bias of observation-model for different value ranges of height and speed and different latitudes. Observations were assigned to these ranges according to latitude and observed value. Over the whole trial period the ERS-1 value for the global mean wind speed was 6.67m/s and that for the global mean wave height was 2.67m.

Buoy windspeed observations verified well against model values for speeds less than 20m/s. The lower band, 0-5m/s, had a negative bias for the whole period, model values being greater than buoy observations. The middle three bands fluctuated between positive and negative biases of less than 1m/s. The few observations in the higher band, >20m/s, were usually greater than model values.

ERS-1 biases varied more with time than did the buoy biases, as a result of re-calibration of the instrument by ESA. Observations falling into the low windspeed band, 0-5m/s, were consistently lower than model values, the size of the low bias decreasing slowly from around 2.5m/s in August to around 1.2m/s towards the end of the trial. From the start of the assessment period ERS-1 observations were less than model values for windspeeds between 5m/s and 15m/s by around 2m/s. ERS-1 observations then increased until during the trial period (November 1991 - January 1992) they were consistently higher than model values by up to 2m/s for winds between 10m/s and 15m/s. For windspeeds between 15m/s and 20m/s model values were always lower than observations.

Observations greater than 20m/s were contaminated by the presence of high values associated with instrument land-sea transition which were not picked up by the quality control. The adjustment of the upper limits set in the quality control reduced this bias.

For significant wave height, ERS-1 and buoy biases show a similar pattern. Observed heights were greater than model values throughout both the pre-trial and trial periods with the exception of the ERS-1 bias for the 4 weeks preceeding the trial for the 3-6m range, for which the model was 0.43m higher than observed. For wave heights less than 6m ERS-1 observations were greater than model values during the trial by around 0.7m. The few buoy observations which fell into the >9m band gave biases of around 3m, well below those of the ERS-1 observations, which were again contaminated by high values associated with instrument land-sea transition.

Both buoy and ERS-1 data show similar patterns when compared with model values, confirming that the model wave heights are lower than observed, not only at the buoy sites but also in mid ocean.

4.0 The assimilation trial

By the end of October 1991 much of the calibration of the ERS-1 altimeter wave heights and windspeeds had been completed, and weekly comparison with wave model data showed a similar pattern to the model comparison with conventional buoy data. There was enough confidence in the altimeter data for the assimilation trial to begin. However it was still necessary to apply a rigorous quality control to the data.

For use in the wave model, the altimeter data were grouped into averages over a 20 second time interval. Data bins were opened on passing from land to sea, and closed on passing from sea to land, as determined by the model land sea mask. Further, any wave height over 16.5m was rejected, to exclude observations over land or ice points not resolved in the model land sea mask. A "buddy check" was carried out on each bin, and observations further than 2 standard deviations from the mean bin value were rejected. The mean bin value was then recalculated. If the wave height was rejected, the corresponding wind speed was not used. The resulting quality controlled and averaged data values were thus at intervals of some 140km, slightly coarser than the model resolution. The source timestep in the wave model was one hour, and the altimeter data values were assigned to the hour nearest to the time of observation.

The assimilation trial was run each day following the operational runs from the data times of midnight and midday, using the wind fields from the operational "hindcast" steps. Each run consisted of two 6 hour wave model assimilations. The trial was started by copying the operational start fields, but thereafter the wave fields for the assimilation run evolved separately from the operational fields. The trial started on 5th November 1991, and ended on 31st January 1992.

The most obvious impact of the assimilation was to raise the background swell heights in mid ocean. Charts of swell height and direction from the operational and assimilation runs are shown at Figure 5 (Arrows of swell direction are plotted for swell heights > 1m). Swell heights were raised to over 1m almost everywhere in the assimilation run, whereas charts of windsea height showed little difference between operational and assimilation runs. This may be expected because of the high quality of the model wind fields, and because of the short timescale for local adjustment of the waves to equilibrium with windspeed. A similar sensitivity to the assimilation of SEASAT data has been demonstrated by Bauer *et al* (1992).

Verification figures against all buoy observations for both the operational wave model and the assimilation trial are shown at Figure 6, categorised by the observed value. This shows most impact to be for waves up to 3m height, consistent with the raising of background swell heights in the model. It must be remembered however that the area covered by buoy observations is very small, and the buoys are sited on the edges of the main oceans. The buoy locations have different wave climatologies. Buoys on the east coast of the USA are predominantly exposed to fetch and duration limited windsea, whereas buoys in the Gulf of Alaska in the NE Pacific experience both windsea and swell under the North Pacific storm track. Also the local transition from windsea to swell as the depressions pass through is important here. In the central Pacific there is swell arriving from both northern and southern hemispheres, in addition to the locally generated Trade Wind seas. Thus both the wave model performance and the impact of assimilating altimeter data may be expected to vary between these regions. The verification figures grouped by buoy location are shown at Figure 7, again showing the increase in wave height particularly in the central Pacific. By contrast there is little impact on the windsea dominated regions such as the NE Atlantic or the North Sea.

Timeseries at a buoy in each of the areas discussed above are shown at Figure 8. In regions dominated by locally generated windsea (Fig 8a) the timeseries confirm that the impact of assimilation was small and short lived. For the central Pacific (Fig 8b) the timeseries shows both the overall background increase of wave heights, and also the instantaneous impact of the arrival of wave energy assimilated from a nearby pass of the satellite.

That the model retains only assimilated swell is confirmed by the timeseries in the mixed windsea and swell regime of the NW Pacific (Fig 8c).

5 Discussion

A novel feature of the ERS-1 calibration campaign was the planned use of numerical models to assess the satellite observations. At least three centres monitored in real time the wave and wind observations made by the radar altimeter and compared the observed values with forecast ones. Because the models used were global, and because analyses were available at frequent intervals, it was possible to derive a large statistical database on colocated model and ERS-1 values. To build up an equivalent data base using wave buoy data would have taken many years. Further, because the wave models (and ERS-1) sampled the whole ocean surface, it was possible to assess the satellite data for a greater range of wave conditions than would be feasible for in situ validation/calibration cruises. The wave models themselves contain errors, but by using the existing long time series of comparison of the wave model results with observations from buoys, it is possible to allow for these in assessing the satellite data. In essence, the technique used the wave models to interpolate from the ERS-1 observation points to the buoy positions.

Three specific instances of the benefit of rapid feedback from wave models on the calibration of the ERS-1 radar altimeter are: an error in the post processing software for observations was identified before the start of the in situ calibration/validation campaign; systematic low biasses of ERS-1 wind speeds were addressed; and a pre-flight calibration of wave heights was found to be in error (Günther, personal communication). Because several independent wave models were used in the assessment it was possible to be confident that the common errors were due to the satellite data and not the models.

Assimilation of the ERS-1 observations of wave height and wind speed into the Met. Office wave model was found to reduce the systematic lack of swell in the wave model. Benefits to the simulation of wind sea were less obvious, in common with the findings of other authors (Bauer *et al*, 1992).

As a result of the data assimilation trial and a comparison of the simulations of the Met. Office wave model with those of the WAM wave model (Günther and Holt, 1992), the Met. Office wave model formulation has been revised to improve its treatment of swell. A further, more rigorous, assessment of the assimilation of ERS-1 wave data into the revised wave model will be reported in the future.

The value of using wave models to assess new instruments has been demonstrated. Models provide a cost effective way to assess the observations, and offer the possibility of long term continued monitoring of their quality throughout the life of the satellite.

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FIGURES

Figure 1

Wave model verification 1-31 January 1992

a) windspeed b) waveheight.

Values are of model minus observation. There are only 4 cases with wave height > 9m.

Figure 2

Positions of wave observations used to validate the Met Office wave model.

Figure 3

Sample data coverage from the ERS-1 radar altimeter. Points are plotted at 1 minute intervals.

a) 3 day repeat orbit (00z to 12z 10th January 1992).

b) 35 day repeat orbit (00z to 12z 9th May 1992).

Figure 4

Bias of ERS-1 and buoy wave and wind observations relative to the Met Office forecast models during the period 10th-17th January 1992. Only 4 cases were found with windspeed greater than 20m/s, and the model did not produce any waves over 9m at the buoy sites.

Figure 5

Swell height (m) as diagnosed by the wave model.

Arrows show the direction of swell over 1m.

a) Standard hindcast for 00z 19th January 1992.

b) Assimilation hindcast for the same time. Contour interval 1m.

Figure 6

Operational and assimilation trial verification, January 1992. Wave heights categorised by observed value. Values shown are model minus observation. There were only four cases of wave height greater than 9m.

Figure 7

Operational and trial verification for January 1992 grouped by buoy position.

a)windspeed b) wave heights.

Values shown are the bias, model minus observation.

Figure 8

Timeseries of observed, operational and assimilation trial values of wave height (m).

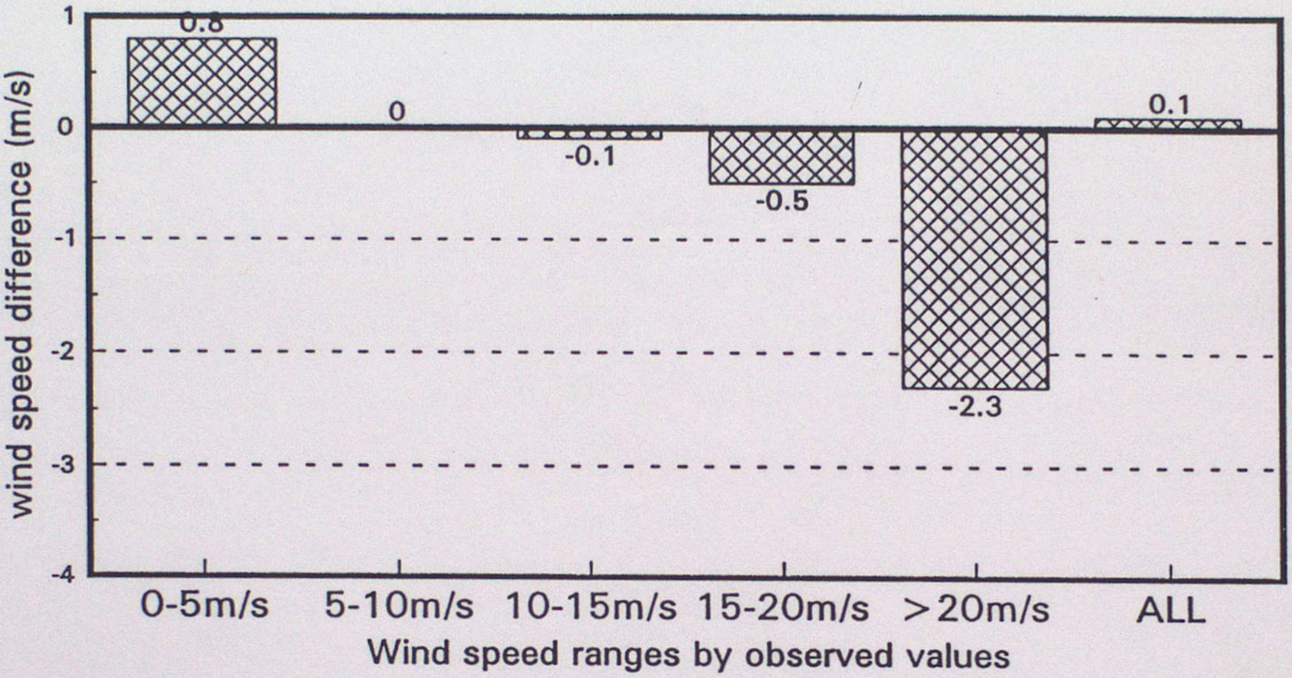
a) Buoy 44011 (Eastern Atlantic, 41.1N 66.6W)

b) Buoy 51004 (Hawaii, 17.5N 152.6W)

c) Buoy 46003 (NW Pacific, 51.9N 155.9W)

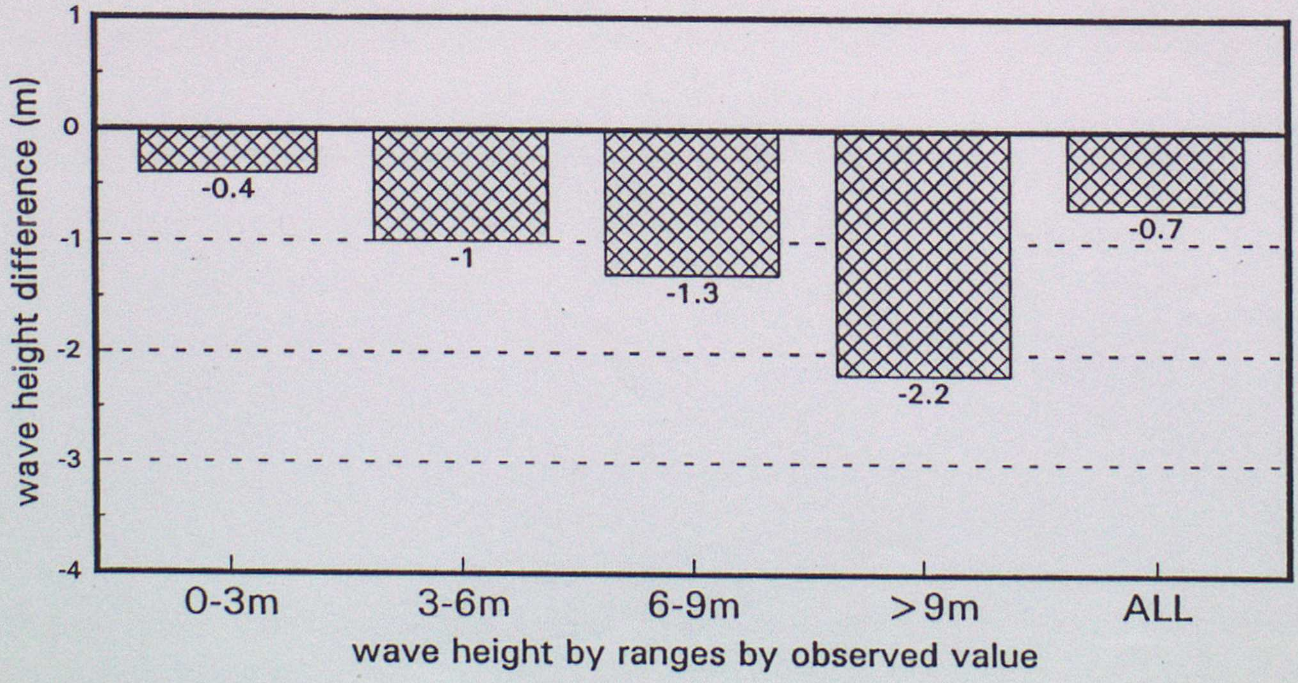
Figure 1

a)



1
0
-1
-2
-3
-4
wind speed difference (m/s)
0.8
0
-0.1
-0.5
-2.3
0.1
0-5m/s
5-10m/s
10-15m/s
15-20m/s
>20m/s
ALL
Wind speed ranges by observed values

b)



1
0
-1
-2
-3
-4
wave height difference (m)
-0.4
-1
-1.3
-2.2
-0.7
0-3m
3-6m
6-9m
>9m
ALL
wave height by ranges by observed value

Figure 2

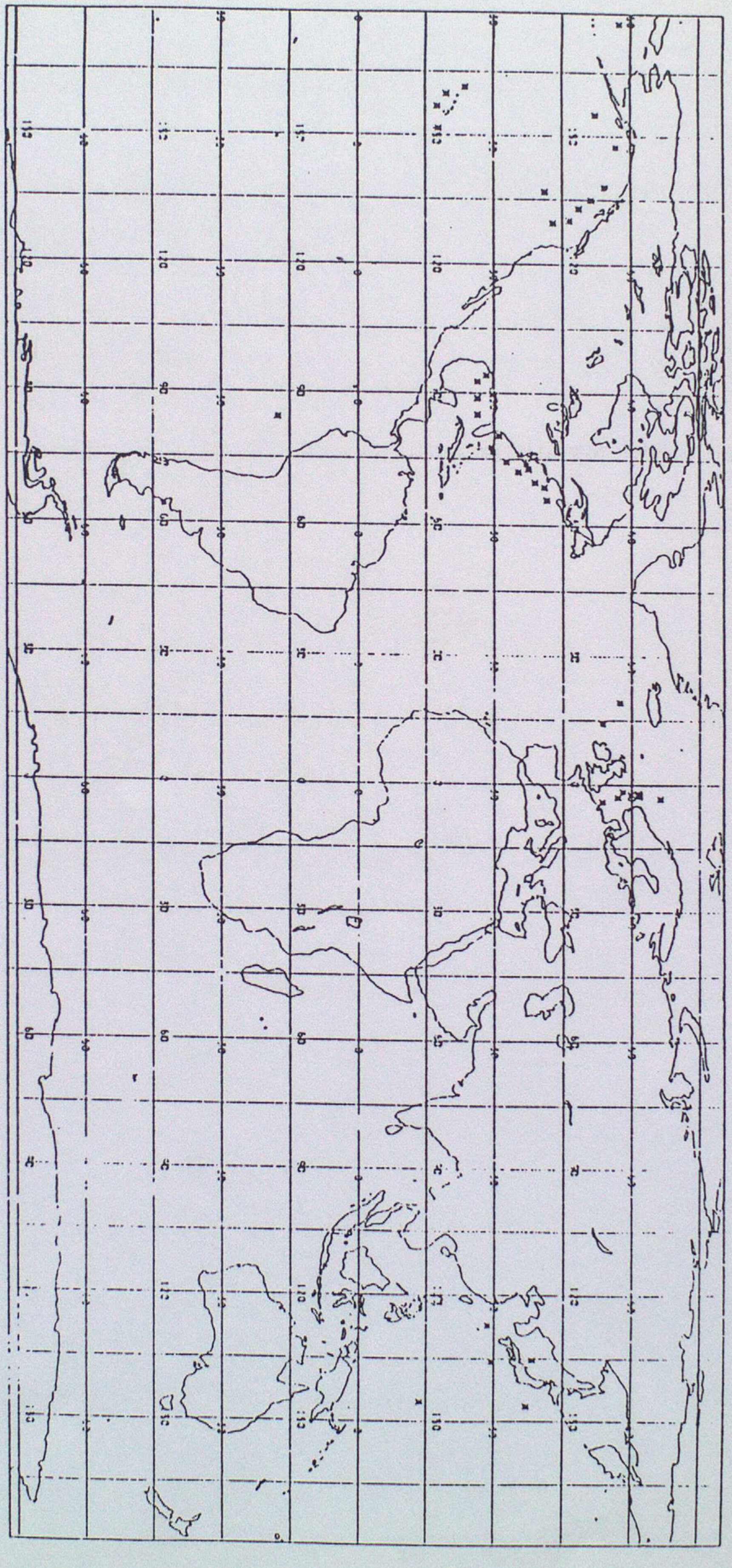


Figure 3a

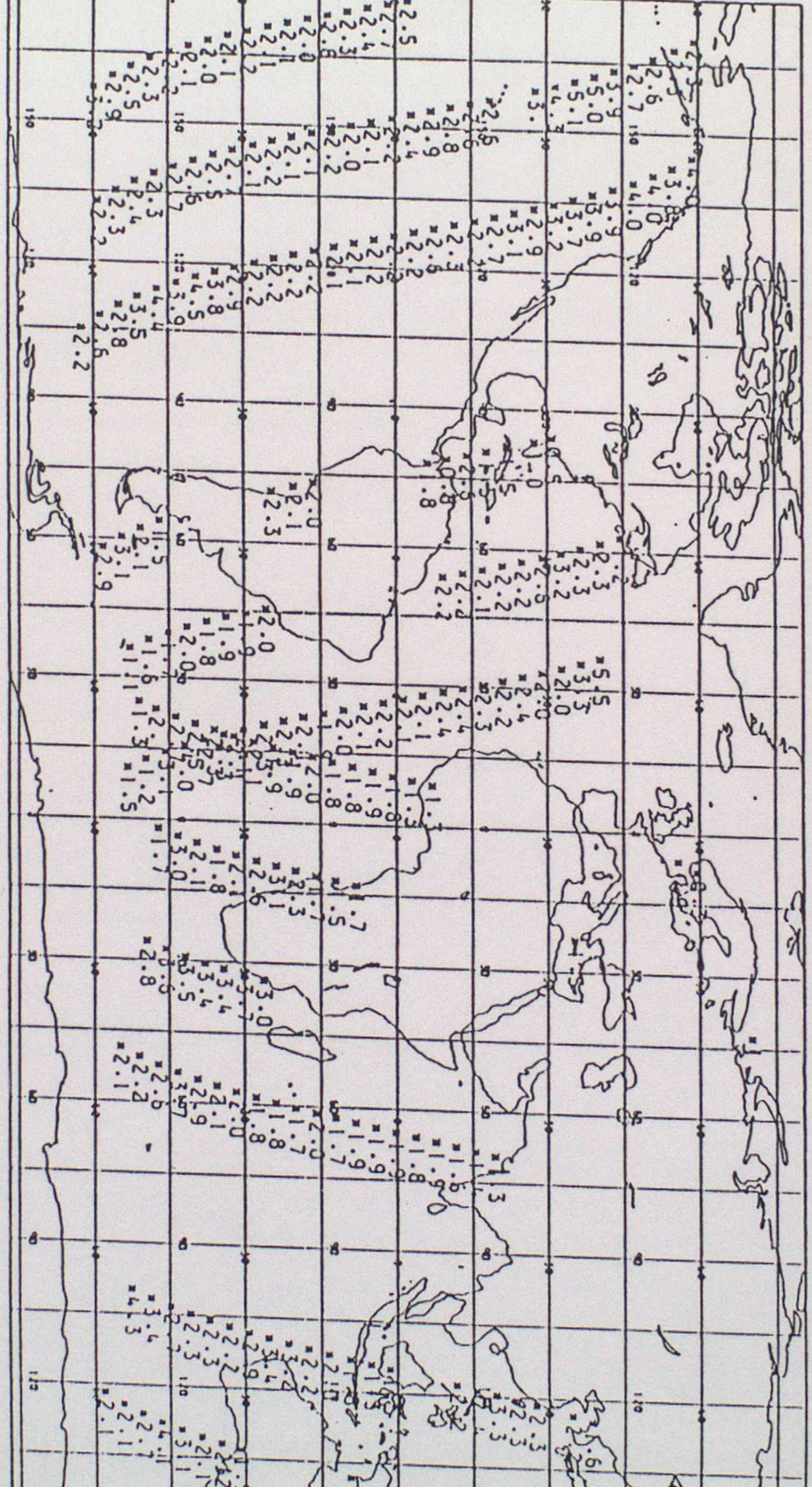


Figure 3b

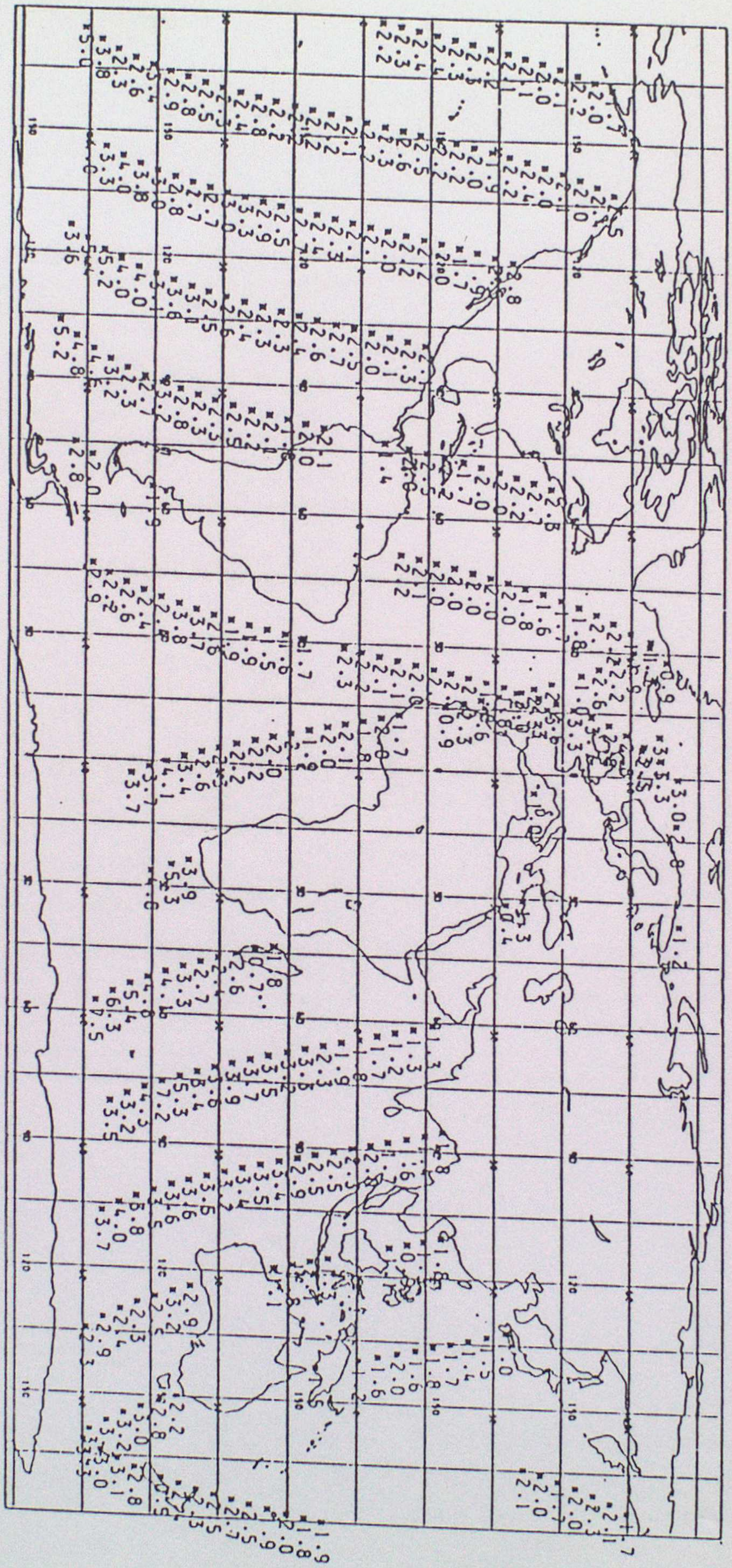
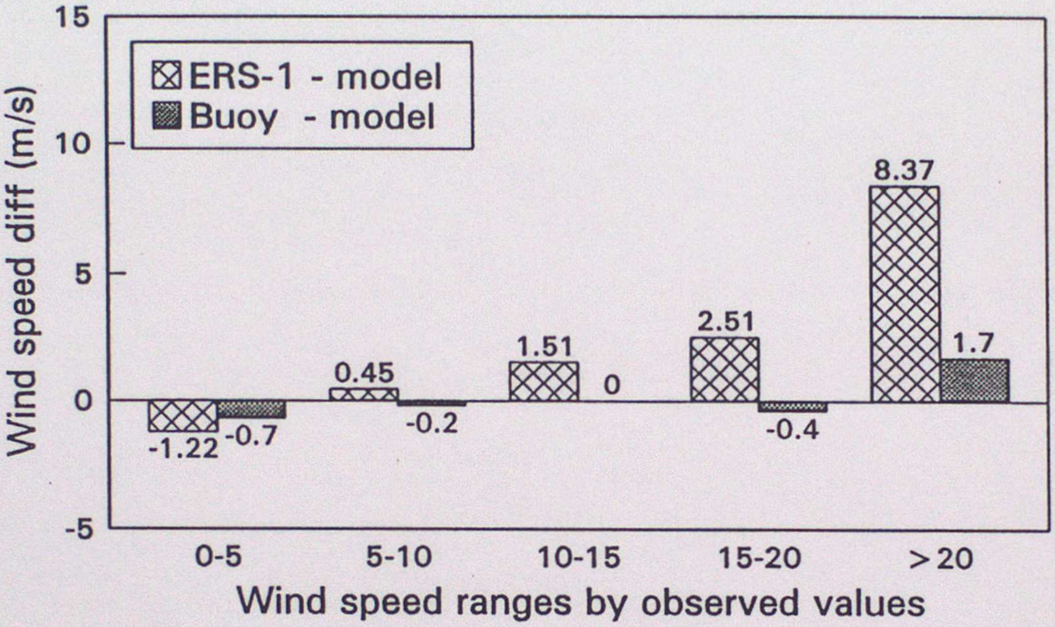


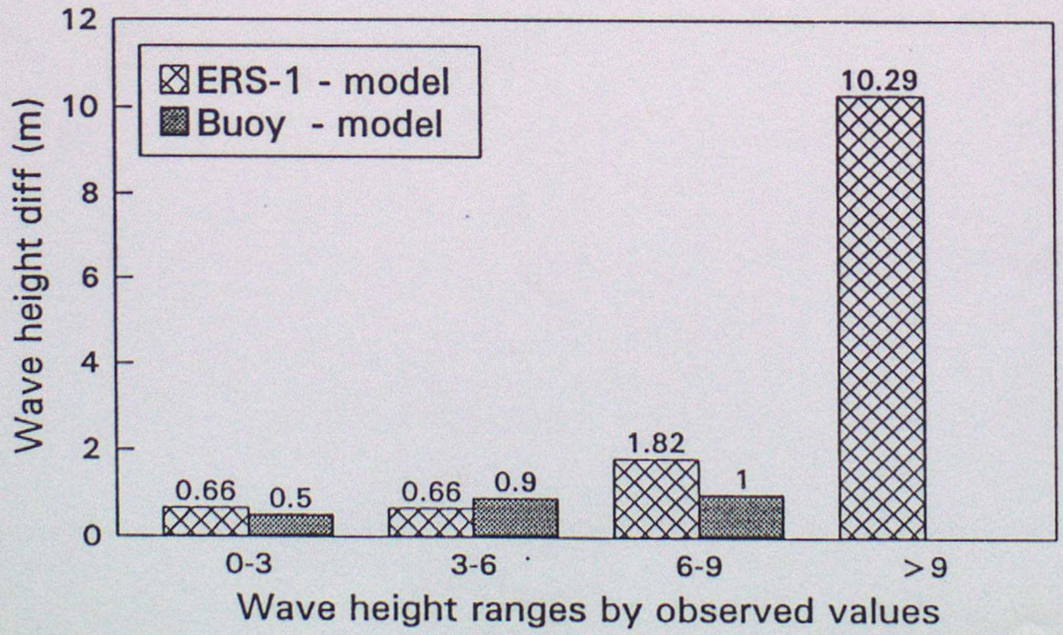
Figure 4

a)



ERS-1 - model
Buoy - model
Wind speed diff (m/s)
15
10
5
0
-5
8.37
1.7
2.51
-0.4
1.51
0
0.45
-0.2
-1.22
-0.7
0-5
5-10
10-15
15-20
>20
Wind speed ranges by observed values

b)



ERS-1 - model
Buoy - model
Wave height diff (m)
12
10
8
6
4
2
0
10.29
1.82
1
0.66
0.5
0.66
0.9
0-3
3-6
6-9
>9
Wave height ranges by observed values

Figure 5a

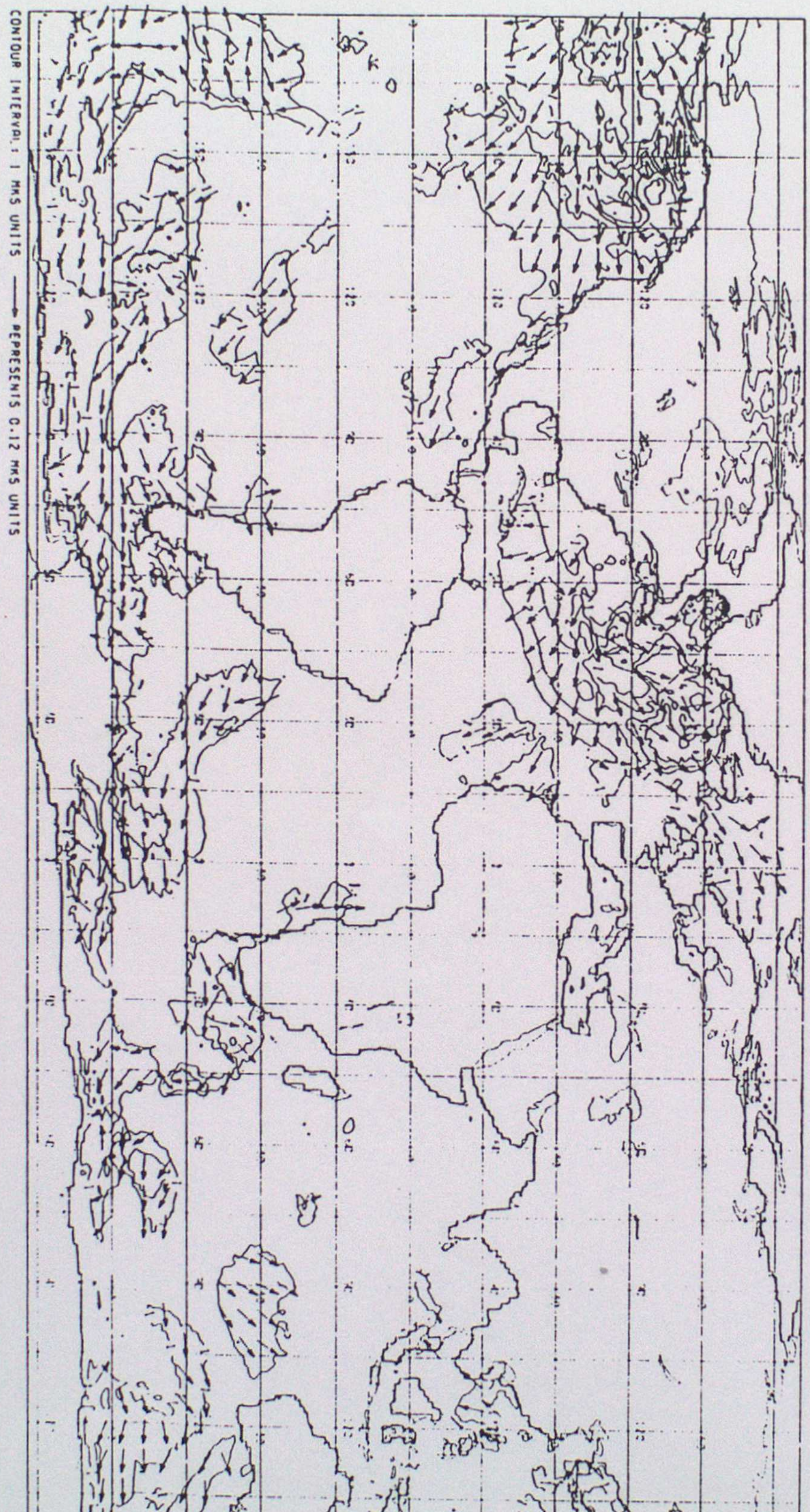


Figure 5b

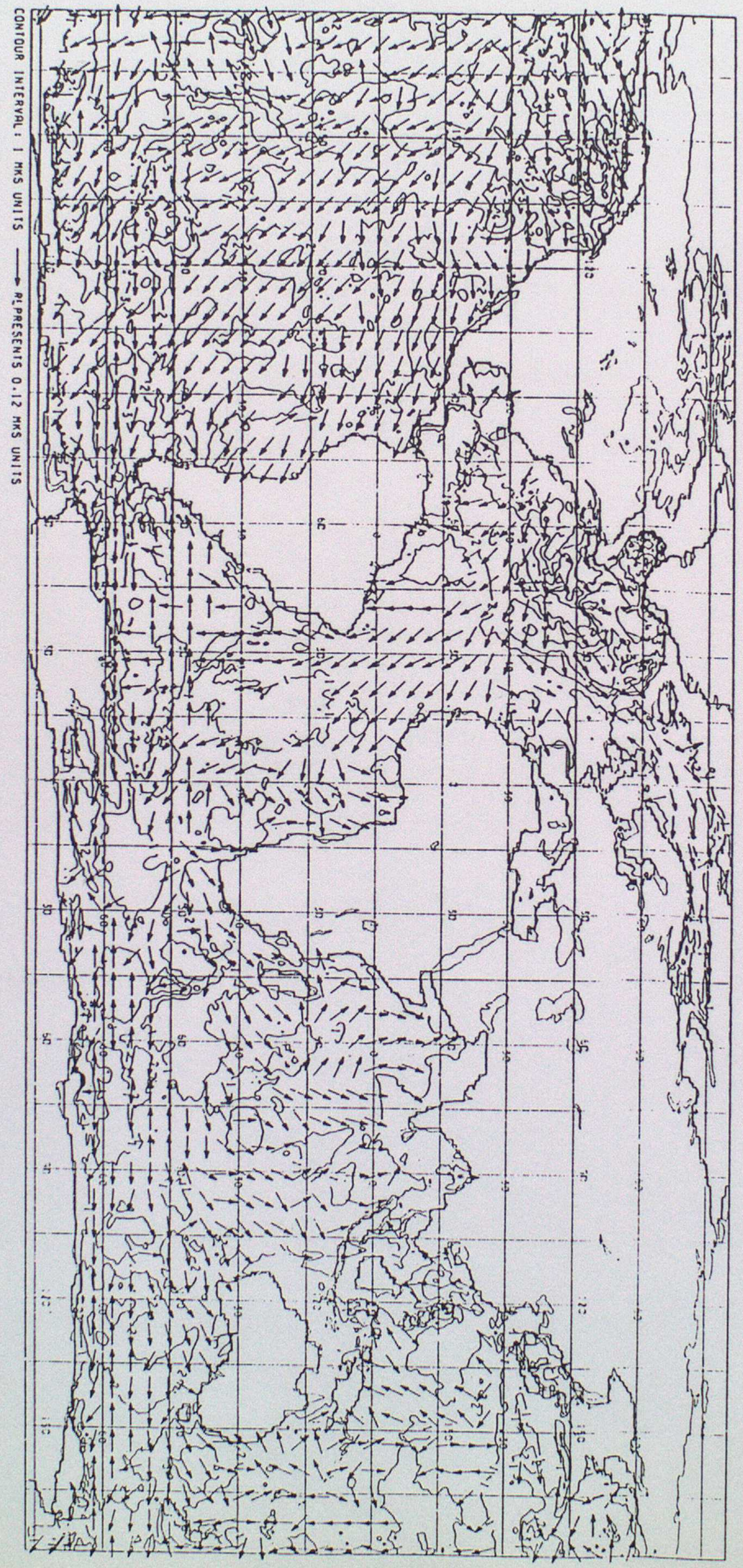
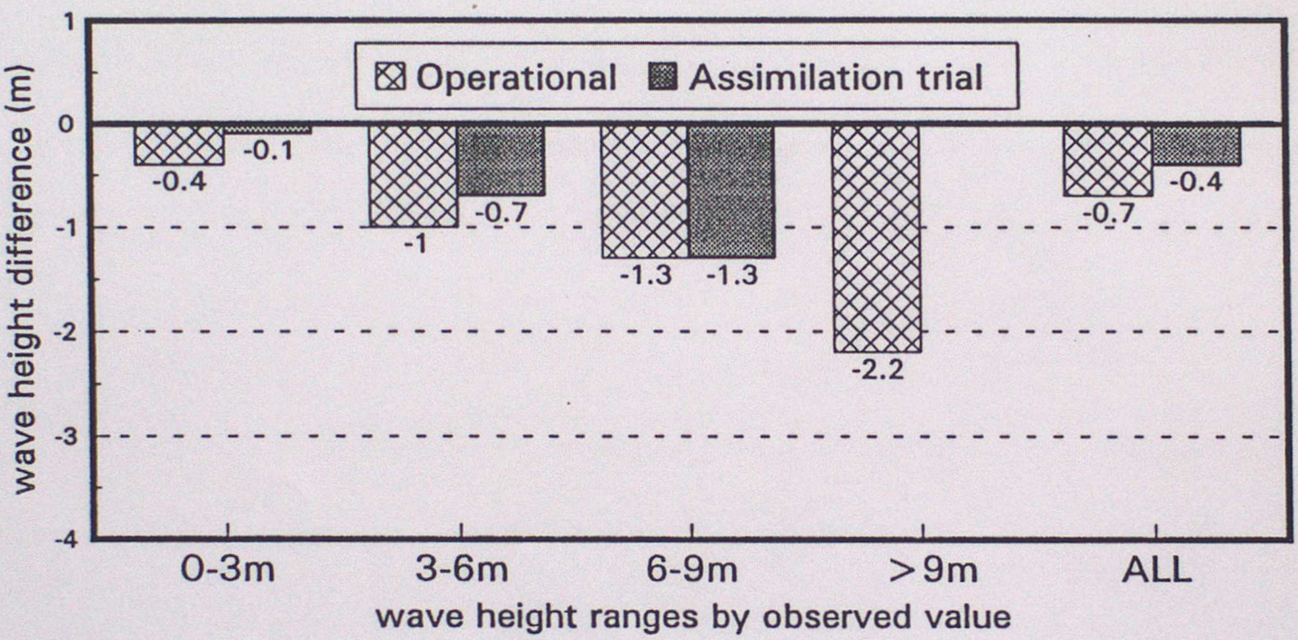


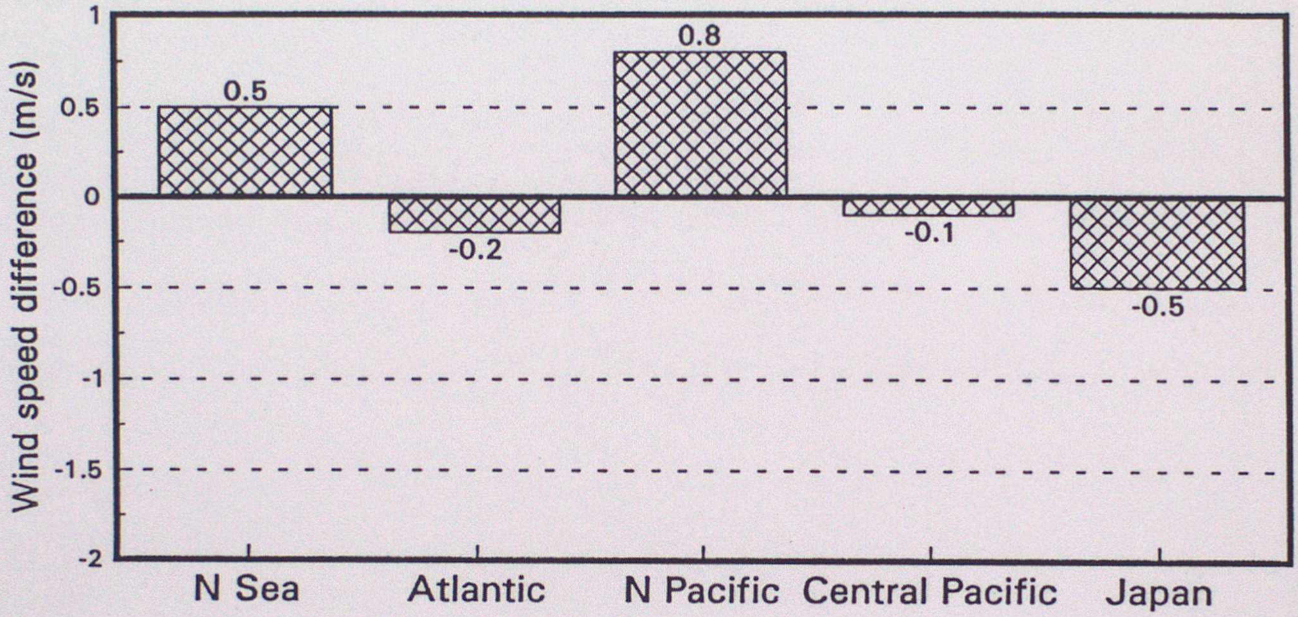
Figure 6



Operational
Assimilation trial
wave height difference (m)
1
0
-1
-2
-3
-4
-0.4
-0.1
-1
-0.7
-1.3
-1.3
-2.2
-0.7
-0.4
0-3m
3-6m
6-9m
>9m
ALL
wave height ranges by observed value

Figure 7

a)


1
0.5
0
-0.5
-1
-1.5
-2
Wind speed difference (m/s)
0.5
-0.2
0.8
-0.1
-0.5
N Sea
Atlantic
N Pacific
Central Pacific
Japan

b)

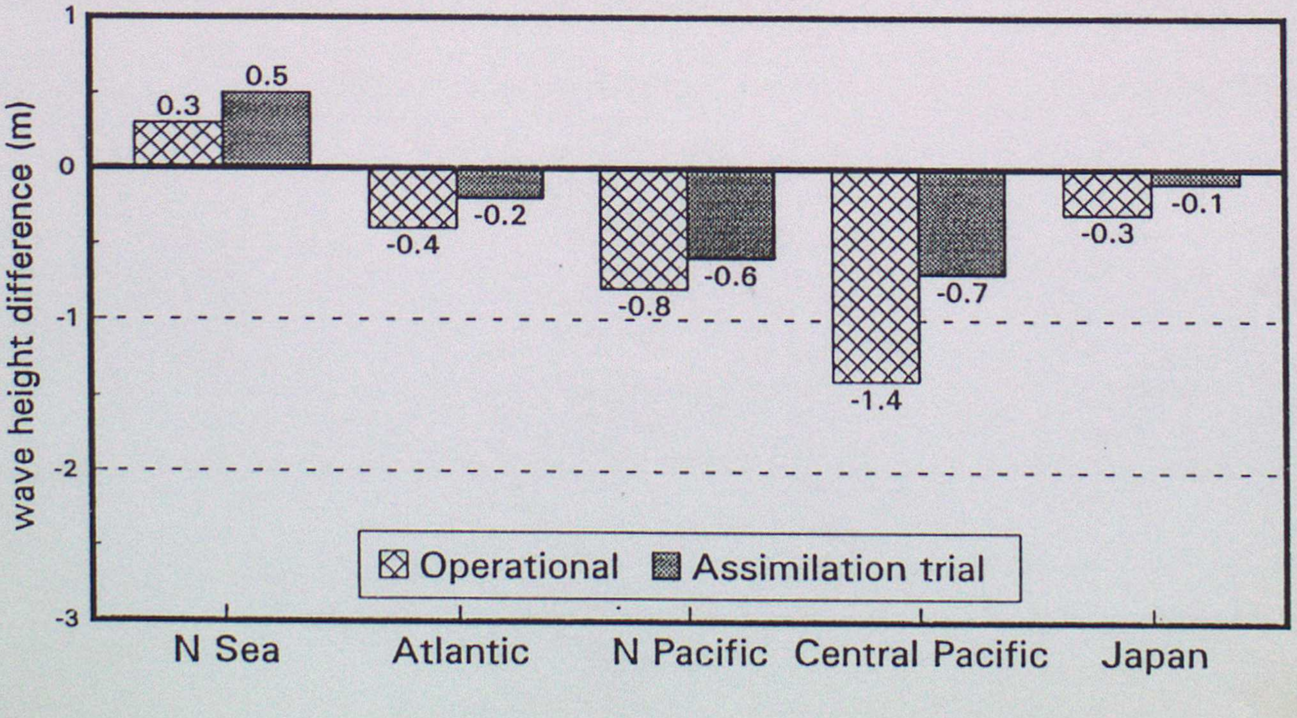
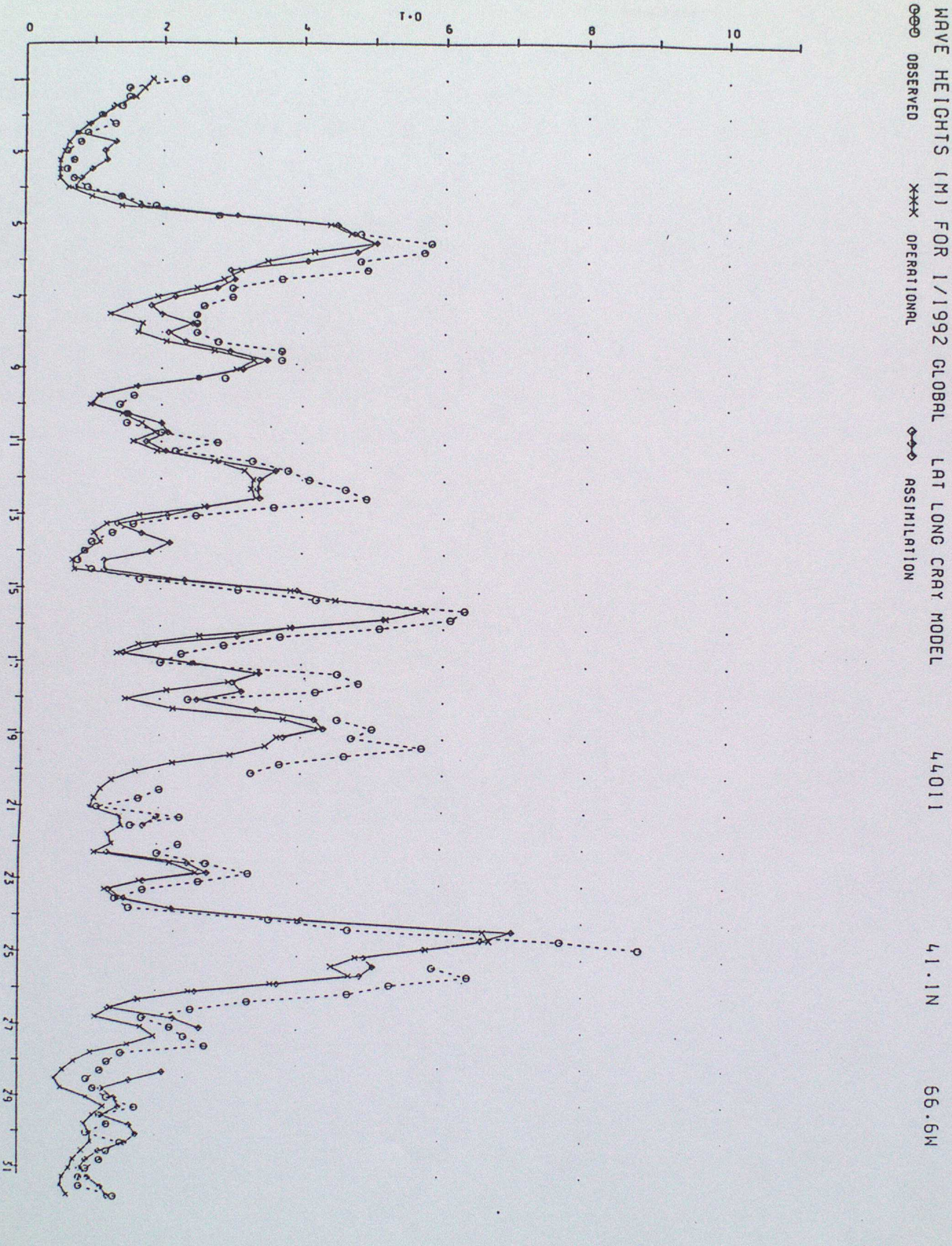

1
0
-1
-2
-3
wave height difference (m)
0.3
0.5
-0.4
-0.2
-0.8
-0.6
-1.4
-0.7
-0.3
-0.1
Operational
Assimilation trial
N Sea
Atlantic
N Pacific
Central Pacific
Japan

Figure 8a


WAVE HEIGHTS (M) FOR 1/1992 GLOBAL LAT LONG CRAY MODEL 44011 41.1N 66.6W
OBSERVED
OPERATIONAL
ASSIMILATION
0
2
4
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8
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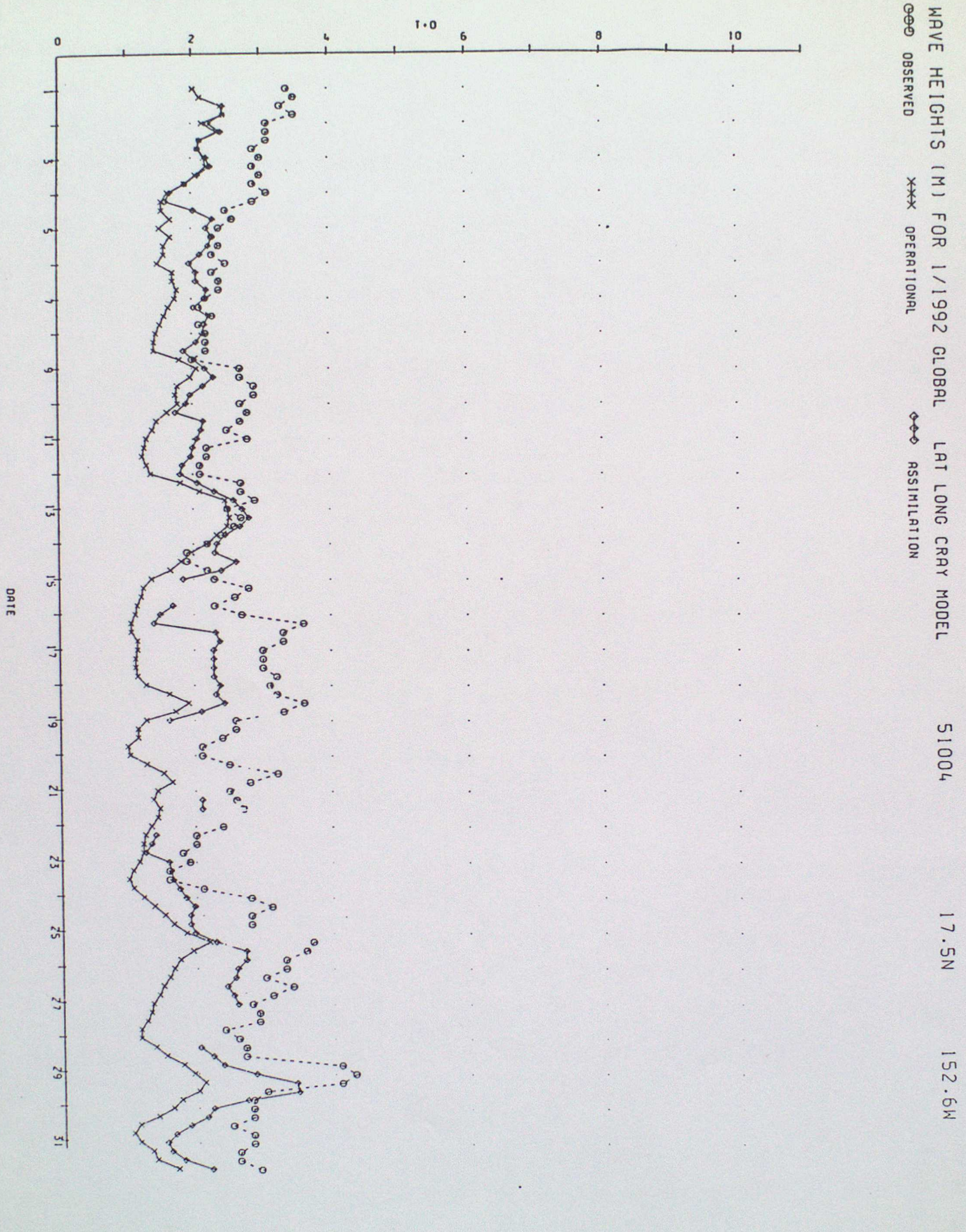
27
29
31

Figure 8b



WAVE HEIGHTS (M) FOR 1/1992 GLOBAL LAT LONG CRAY MODEL 51004 17.5N 152.6W
OBSERVED
OPERATIONAL
ASSIMILATION
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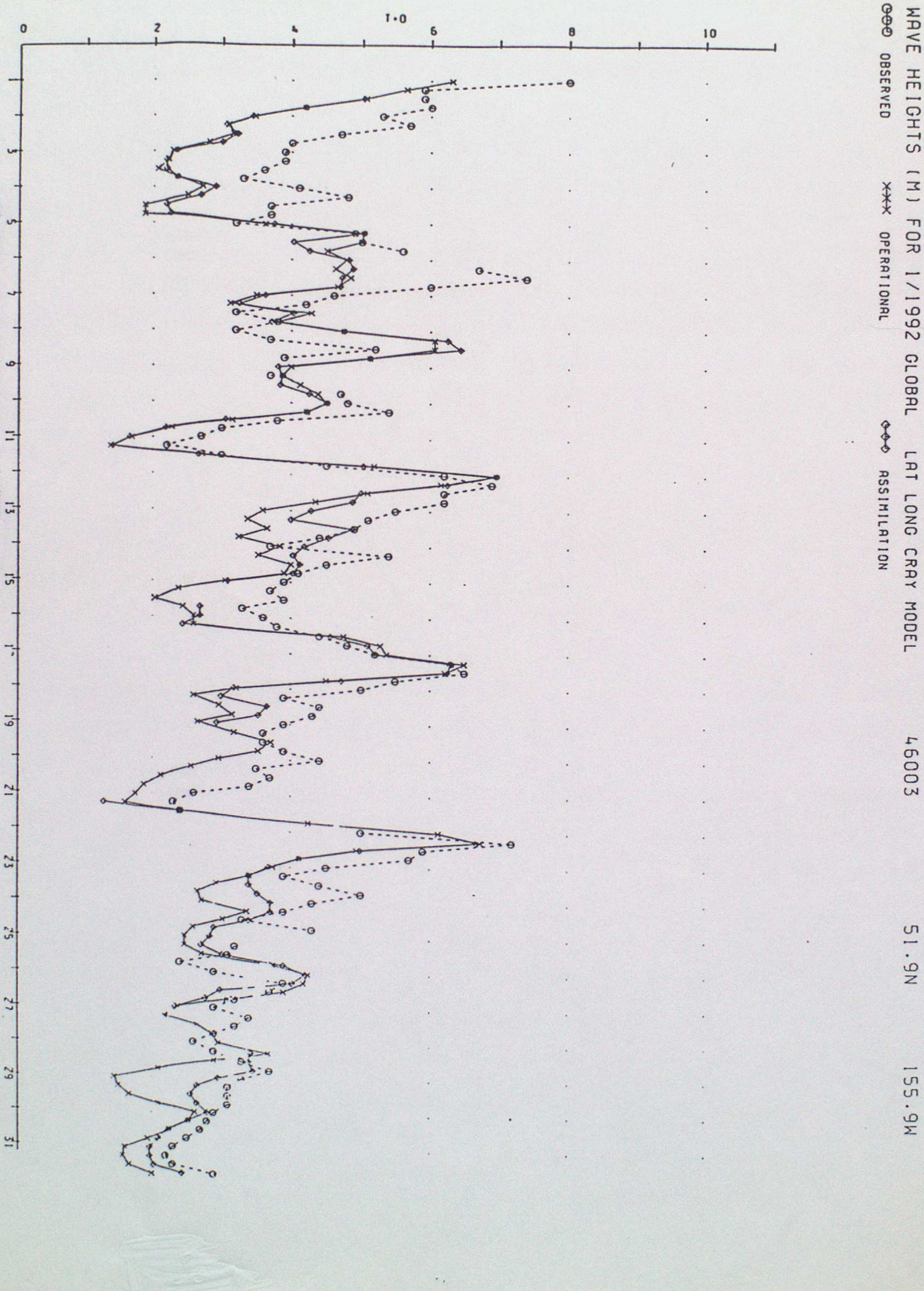
Figure 8c


WAVE HEIGHTS (M) FOR 1/1992 GLOBAL LAT LONG CRAY MODEL 46003 51.9N 155.9W
OBSERVED
OPERATIONAL
ASSIMILATION
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