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A FEASIBILITY STUDY ON OPERATIONAL USE OF GEOSAT WIND AND WAVE DATA AT THE NATIONAL METEOROLOGICAL CENTER

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TECHNICAL NOTE

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Abstract

The feasibility of the use of Geosat altimeter-derived wind speed and significant wave height data for operational applications is investigated. Geosat wind and wave data are compared with buoy observations for a 17 month period to determine the error characteristics as a function of various data acceptance time windows and spatial separation distances between the colocated data points. The results show that Geosat wind speed errors are sensitive to the time acceptance windows and less so to spatial separation distances, whereas Geosat wave height errors are not so sensitive to spatial and temporal separations.

Three days of Geosat wind speeds and two periods of near real time Geosat significant wave height data are assimilated into the NMC's operational weather and wave forecast models. The results show that inclusion of Geosat wind speed data leads to a small impact in the southern Hemisphere, and virtually no impact in the northern Hemisphere. The Geosat significant wave height data, on the other hand, are found to have a positive impact and are extremely beneficial in short range wave forecasts over the global oceans.

1. Introduction

Wind and wave data derived from the Geosat's radar altimeter measurements have been validated in a recent study by Dobson et al (1987), who compared 1166 collocated wind and wave data between Geosat and buoy reports during a seven month period. Geosat wind and wave measurements derived from several algorithms were compared with buoy reports for two temporal (15 minutes and 30 minutes) and three spatial (50 km, 100 km, and 150 km) separations between the collocated data points. Based on the statistics calculated for the time separation of 30 minutes and space separation of 150 km between the Geosat and buoy measurements, they found an overall RMS (Root Mean Squared) difference of about 3 m/s for wind speed, and of less than 1 m for significant wave height from Geosat altimeter measurements, and Dobson et al (1987) conclude that their error statistics are within the measurement goals.

The present study investigates the error characteristics of near real time Geosat wind and wave data, and their feasibility for use in an operational environment. When we consider polar orbiting satellite data for meteorological and oceanographic applications at an operational center such as NMC, the question of data acceptance window is particularly important. This window is referred to the time interval within which all the asynoptic observations are accepted as though they were reported at the synoptic hours. If the acceptance window from a synoptic analysis time is short, one may expect the data to be more representative of the synoptic hour, however at the expense of fewer data points. On the other hand, if the acceptance window is too large, a larger number of data points may be expected at the expense of the data not being representative. Typically, a data acceptance window of ± 3 hours from each synoptic hour is used in the National Meteorological Center (NMC) for all the polar orbiting meteorological satellite data.

The error characteristics of the Geosat wind and wave data pertaining to various time acceptance windows and spatial separations for operational applications at NMC are addressed in Section 2. Approximately 17 months of Geosat and buoy report pairs for the period January 2, 1988 to May 31, 1989 are compared, thereby covering a complete seasonal cycle with a large data base. These wind error statistics are taken into account later in the analyses using the Geosat wind data in the assimilation experiments. Results of these assimilation experiments designed to demonstrate preliminary applications of the Geosat wind data to the NMC's numerical weather prediction systems are discussed in Section 3. Recently Esteva (1988) has reported results of impact of assimilating Seasat significant wave heights into the specification of the initial wave field for the NMC's global spectral wave model. Esteva shows that use of the satellite data can lead to a substantial reduction in the mean absolute errors of the forecast significant wave heights. In section 4, results of assimilating the Geosat significant wave height data in near real time into the initial wave fields of the same wave model are discussed.

2. Error Characteristics of the Geosat Data

Statistics are computed between Geosat and buoy measurements over a 17 month period to determine the error characteristics of the Geosat altimeter-derived wind and wave data. The Geosat altimeter estimates of wind speed and significant wave height are provided at the rate of one per second along the satellite track. To eliminate questionable data values, these wind and wave data were first subjected to a gross error check, and then to an averaging procedure to make the data free from unresolvable smaller scale features as described in Esteva (1987). On the average, there are about 40 data points used for the calculation of mean wind speeds or wave heights in a 2.5 by 2.5 degrees longitude and latitude grid box.

Because the satellite swath rarely coincides with either the buoys' reporting times or the locations, there always exist temporal and spatial separations between Geosat and buoy observations. The approach taken by Dobson et al (1987) limits the time separation to a maximum of 30 minutes and the spatial separation to a maximum of 150 km between the two collocated observations. In our study, several intervals of extended time and distance separations between the pairs of observations are considered. Statistics between Geosat and buoy observations are presented for distance separations of 0.5, 1.0 and 1.5 degrees longitude and latitude, and time windows of less than ± 1 hour, ± 2 hours, and ± 3 hours. Of particular interest is the time window of ± 3 hours, for this is the typical maximum acceptance time interval for asynoptic data (such as those obtained from the polar orbiting satellites) at an operational center.

a. Wind Speeds

Statistics comparing the collocated the Geosat winds and NDBC buoy observations are presented for the following three categories: (a) NDBC buoy network statistics for offshore buoys, nearshore buoys, and combined offshore and nearshore buoys. The offshore buoys are more than 40 km from the shore of the east and west coasts of the United States, while the nearshore buoys are located within 40 km from the shore; (b) Regional statistics covering five regions, each region including several buoys (see Table 1); (c) Seasonal statistics for spring (April to June), summer (July to September), fall (October to December) and winter (January to March). Furthermore, statistics are presented for three wind speed categories corresponding to speeds of < 5 m/s, 5 to 15 m/s, and > 15 m/s.

Table 2 shows the statistics calculated between Geosat winds and buoy winds for the three different time window. For the one hour window, the overall (from all buoys and over all wind speeds) bias is 1.3 m/sec and the root mean squared difference (RMSD) is 3.3 m/s. Geosat wind speeds tend to be biased high when compared to the buoy observations. It should be mentioned that Dobson et al (1987) reported a bias of 0.1 to 1.5 m/s and a RMSD value of 2.5 to 3.0 m/s between Geosat and buoy wind speeds for a 30 minute separation time window. This range of RMSD values reported in their study is based on statistics stratified as a function of several different antenna pointing attitudes and ranges, and of four different wind speed algorithms. Thus, the overall statistics found in the present study are comparable to those of Dobson et al (1987), with a slightly larger RMSD value reported in this study. Both values of bias and RMSD increase to about 1.7 m/s and 3.7 m/s respectively for the 2 hour acceptance window. Note that the number of data points increases substantially when the time window increases. Note also that when the time window further increases to 3 hours, both the bias and RMSD values appear to remain the same as those for the 2 hours window.

The wind speed errors are different in different wind speed subcategories (see Table 2). For example, the bias is about 3.7 m/s and the RMSD is about 4.8 m/s for the lower wind speeds under 5 m/s, while both of them are much smaller for the medium wind speed range of 5 to 15 m/s. In fact, over the medium wind speed range in which the largest number of collocated data points exist, the bias is very small (less than 1 m/s), and RMSD value is about 2.3 m/s for the 1 hour time window. The RMSD value increases to about 3.1 m/s as the time window increases to 3 hours for the wind speed range of 5 to 15 m/s. As the wind speed range becomes larger than 15 m/s, the Geosat winds tend to be biased low by 2 - 3 m/s with a larger RMSD value of about 5 m/s when compared to buoy wind speeds.

The overall statistics for the offshore and nearshore buoy stations show characteristics very similar to those for the all buoys. However, detailed inspection of the statistics for the different wind speed categories shows that the values of bias and RMSD are smaller when the time window is 1 hour, but are larger when the time window is 2 hours or greater for the offshore buoys than for near shore buoys. The most striking feature is the very large bias and RMSD values for the wind speed range of 0 to 5 m/s. These error characteristics strongly suggest that Geosat wind data are unreliable for wind speeds under 5 m/s.

The very large bias associated with the Geosat wind data in the low wind speed range is prevalent in all regions and seasons. For this reason only statistics for the medium range wind speed will be discussed for the regional and seasonal cases. Table 2 shows that there are regional and seasonal variabilities. Hawaii region has the smallest bias and RMSD values and the East Pacific has the largest RMSD values for all the time windows. For the 1 hour time window, both winter and spring seasons clearly have the largest RMSD values due to stronger wind regimes, and the summer has the lowest RMSD values due to weaker wind regimes in all regions. However, as the time window increases to 3 hours, except for a relatively large bias evident in the summer season, there is hardly any evidence of seasonal variability in the wind speed RMSD values.

The statistics for various separation distances between the buoy and Geosat wind observation locations are shown in Table 3. These statistics are calculated from three separation distances of 0.5, 1.0, and 1.5 degrees longitude and latitude between the Geosat and buoy reports. All the statistics shown in Table 3 are for the time window of 3 hours, but the conclusions are equally valid for the shorter time windows. It can be seen from Table 3 that the statistics are not very sensitive to the separation distance. The bias and RMSD values do not increase as the separation distance increases from 0.5 degrees to 1.5 degrees.

b. Significant Wave Heights

The statistics for significant wave heights are presented for similar subsets of the collocated data set as those discussed in Section 2a. However, significant wave heights are stratified at 2 meter intervals resulting in a larger number of subsets. Table 4 shows the bias and RMSD between the Geosat and buoy significant wave heights for 1, 2, and 3 hour time windows. For all the buoys, the bias for a 1 hour time window is 0.03 m, while for a 3 hour window it is 0.04 m. Likewise, the RMSD changes from 0.87 m for the 1 hour window, to 0.91 m for the 3 hour. Thus, it appears that increasing the time window to up to 3 hours has little effect on the resulting statistics. Table 5 shows that when all the buoys are considered, the statistics are unchanged for the wider spatial separations. It is thus suggested that significant wave height statistics remain relatively invariant over areas of up to 1.5 by 1.5 degrees in latitude and longitude, and for three hour time intervals.

The overall statistics for offshore and near shore locations indicate that there is a slight deterioration of altimeter estimates of the significant wave heights for the nearshore locations (see Table 4). This is likely due to greater departures at nearshore locations of the observed significant heights from a Guassian distribution which the altimeter algorithm assumes (Fedor, et al, 1979). Similar to the total buoys statistics discussed earlier, these errors for the offshore and nearshore buoys do not seem to increase appreciably as the time window increases from 1 hour to 3 hours or as the spatial separation distance increases from 0.5 degrees to 1.5 degrees of longitude and latitude (see Tables 4 and 5).

From the stratification by significant wave height intervals it is seen that best agreement between the buoy and altimeter estimates are for the 2 to 4 meter interval, with a RMSD value of about 0.6 m. This is much smaller than the value of about 0.9 m for the overall statistics. The worst agreement between the Geosat and buoy reports occur when the wave heights are greater than 6 meters. For this case, both the bias and RMSD are considerably larger than the overall statistics discussed earlier. There are no appreciable changes for the longer time windows or for the wider areal windows. Thus, the spatial and time resolution (1.5 by 1.5 degrees and three hours respectively) chosen for most operational wave models is justified. However, since the wind speed statistics are worse for the two and three hour time window, and since wave models depend so heavily on the wind input, a one hour time step would be desirable for running wave models. The stratification by significant wave height intervals also shows that the altimeter tends to overestimate significant wave heights under 2 meters and underestimate those above 4 meters.

Regional and seasonal statistics presented in Sections b and c of Tables 4 and 5 are for the 2 to 4 meter height interval only. There are slight regional differences, with the East Pacific and Hawaii having the smallest bias, and the Gulf of Mexico and North Atlantic the largest. The RMSD is largest for the East Pacific and Gulf of Mexico regions and smallest in the North Atlantic. The reasons for this small regional dependency seen in Tables 4 and 5 are not known. Perhaps significant wave heights estimated by the radar altimeter are affected by atmospheric constituents such as water vapor contents (see e.g., Zimbelman and Busalacchi, 1990). Because these atmospheric conditions may have regional dependence, the significant wave heights measured by the radar altimeter could give small regional differences as shown in Tables 4 and 5. No significant seasonal variation is evident for this height interval.

3. Geosat Wind Data Assimilation Experiments

The NMC's global data assimilation system (Knamitsu, 1989) consists of three components: a spectral atmospheric forecast model, a multivariate three dimensional optimum interpolation scheme, and a nonlinear normal mode diabatic initialization. For four cycles daily, the forecast model makes a six hour forecast. This forecast then serves as a first guess which is updated with the observations. The update procedure is accomplished by the optimum interpolation scheme (DiMego, 1987) in which all the conventional observations together with satellite measurements of temperatures and winds, such as Geosat wind speed data, can be used. Two experiments were conducted, one including the Geosat wind speed data, the other excluding the data. The Geosat wind speed data were assigned the directions according to the 1000 mb wind directions from the 6 hourly forecast. The data acceptance window for the Geosat winds is ± 3 hours. Further, based on the wind error characteristics in Section 2, Geosat wind speed data less than 5 m/s are excluded in the assimilation experiments. Outside this wind speed range, the error statistics in Section 2 show the Geosat wind speed data to be of reasonably good quality, with a RMSD value of less than 4 m/s, which is comparable to the accuracy of ship winds (Gemmill, et al, 1987). Therefore, in the assimilation experiments, Geosat winds were treated as if they were ship winds, starting at 0000 UTC, August 28, 1987 and ending at 0000 UTC, August 30, 1987. On the average, the number of Geosat wind speed data after applying the editing and averaging procedure (Esteva, 1987) is about 1000 for each six hour cycle. However, the actual number of Geosat winds, excluding those with speeds less than 5 m/s is about 600.

After three days of data assimilation, it is found that including the Geosat wind speed data has virtually no impact in the northern Hemisphere (Fig.1). This finding is similar to that from the results of the earlier impact studies using scatterometer vector winds from Seasat (Yu and McPherson, 1984, Atlas et al, 1984, Baker et al, 1984, Anderson et al, 1987). This lack of impact has been attributed to the improved first guess fields (i.e., typically from the model forecasts) together with more abundance of conventional observations in the northern Hemisphere, which as a result, reasonably good three dimensional structures of the atmosphere may be defined without the use of such satellite surface wind data as Seasat scatterometer winds or Geosat altimeter winds.

In the southern Hemisphere, inclusion of Geosat wind speed data leads to differences in the analyses. Fig. 2 shows an area over the southern Indian ocean with differences of about 40 meters in the height analysis at 1000 mb and accompanying wind difference of about 5 m/s. Smaller differences in height and wind analyses also occur over other areas of the southern Hemispheric oceans (not shown). These differences in height and wind analyses from the Geosat wind speed assimilation experiments reported in this paper are much smaller than those of the earlier studies using the scatterometer vector wind data. For example, Yu and McPherson (1984), after two days of data assimilation, found a difference of over 200 meters in the 1000 mb wind analysis with accompanying wind differences of more than 15 m/s over the southern Hemispheric oceans. There are two main reasons for the much smaller impact shown in the Geosat wind data. First, the data coverage for the scatterometer winds is much larger than that for the Geosat winds. Consequently, there are at least five times many more data points from the scatterometer winds than from the Geosat winds. Further, the Geosat altimeter winds cover only a narrow region along the nadir direction of satellite, whereas the Seasat scatterometer winds span a much wider swath. Second, and perhaps more importantly, Geosat wind data contain only wind speeds without directions. In this sense, Geosat wind data cannot provide independently useful information as ship and buoy winds or the satellite scatterometer winds.

4. Geosat Wave Data Assimilation Experiments

Unlike operational numerical weather prediction models, ocean wave forecast models are not initialized with observed data. The common practice is to apply a hindcast procedure in which the model wave fields from 12 (or 24) hours ago are brought forward to the current time through the use of analyzed wind fields. The wave field so determined prescribes the initial state for the wave model. Wave forecasts are then generated using the wind forecast from an operational numerical weather prediction model.

In the wave data assimilation study, the Geosat averaged wave heights were assimilated into the wave forecast model during the hindcast stage. This determined the initial wave fields before a forecast was issued. Wave forecasts were then made using the same forecast winds provided to the NMC operational wave model run. These forecasts are referred to as the " assimilation " runs (see Esteva (1988) for details). The NMC operational ocean wave forecast model is a deep water, second generation spectral model (Greenwood et al, 1985). The model forecasts waves for 24 directional spectrum and 15 frequency bands on a 2.5 by 2.5 degree latitude and longitude grid. The Geosat significant wave height data were assimilated into the hindcast directional spectrum by scaling the model forecasted spectral components with the ratio (H_o / H_f) , where H_o and H_f are the observed and forecasted significant wave heights. Thus the total energy under the modified spectrum will correspond to the observed significant wave heights, while the shape of the distribution of energy in frequency and direction remains unchanged.

Statistics on bias and RMSD for the forecasts were computed for the operational and assimilation runs. The observations used for computing the forecast errors are the wave heights measured by Geosat altimeter, and the statistics are computed separately for the northern and southern hemispheres. Figures 3 and 4 show the bias and RMSD values of significant wave heights for the 24 hour forecast over the southern (top) and northern hemispheres (bottom) during two periods. Both bias and RMS errors are smaller for the assimilation runs than for the operational run. Further, the error reduction is greater in the southern Hemisphere than in the northern Hemisphere. This is probably due to the fact that the winds used to drive the ocean surface waves are less accurate in the southern Hemisphere than in the northern Hemisphere on the one hand, and because there are more Geosat wave estimates in the southern Hemisphere than in the northern Hemisphere, on the other. The forecast improvements in January are greater than those in December for both hemispheres. This indicates that as the assimilation of wave data continues, the representation of the initial wave field improves. These results demonstrate that near real time wave data from the radar altimeter can be extremely useful in wave forecasting.

5. Summary

This study shows that Geosat wind speed errors are quite sensitive to the time acceptance windows and less so to the separation distance. For the ± 1 hour time window, the wind statistics are quite comparable to (although slightly worse than) those reported in Dobson et al (1987). However, for the ± 3 hour time window, which is typical of the data acceptance time employed in an operational center for measurements from asynoptic sources, Geosat wind speed errors increase. The RMS differences between Geosat winds and buoy winds vary from 3.2 m/s for a 1 hour time window to 3.7 m/s for a 3 hour time window. This indicates that the Geosat wind speed data are of about the same quality as the ship reports for the 3 hour time window. It further suggests that for asynoptic satellite wind data in general, and the Geosat altimeter wind data in particular, the time acceptance window should not be too large. The current ± 3 hour data acceptance window employed in operational centers should be regarded as a maximum limit. Further, the Geosat altimeter wind speed measurements tend to have a large bias in the 0-5 m/s wind speed range. For meteorological applications, Geosat wind speed data less than 5 m/s are unreliable and are not useable.

Assimilation experiments using three days of Geosat wind speed data show a small impact on the analyses of heights and winds in the southern Hemisphere and virtually no impact in the northern Hemisphere. There are two reasons for the small impact of the data. First, the Geosat wind data cover only a narrow swath with relatively fewer data points compared to scatterometer wind data. The second, and perhaps more importantly, is the fact that the Geosat wind data contain only wind speeds without directions. Although the method of assigning the 1000 mb wind directions from a six hour forecast to the Geosat wind speed data, which was used in the assimilation experiments, is practical for operational applications, it is not the best way, however. Other techniques for assigning wind directions to the Geosat winds (and winds from other satellite sensors such as SSM/I which contain only wind speeds) should be explored.

Unlike the wind statistics, the wave statistics are not very sensitive to either the time of data acceptance window or to the separation distance between Geosat wave measurements and buoy reports. This insensitivity suggests that the ocean wave properties are less critical to the asynoptic nature of the satellite borne altimeter measurements and therefore potentially more useful for assimilation than the Geosat wind speed data. This study further indicates that altimeter and buoys agree well for significant wave heights in the 2-4 m range. The RMSD values between the two data sets increase with wave heights.

Real time global assimilation experiments of inserting significant wave height data into the NMC operational wave forecast model were successfully performed for two periods of several consecutive days in December 1987 and January 1988. These experiments have demonstrated the potential improvements that data from satellite borne altimeters can have on wave forecasts.

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Table 1. Locations of Buoys at Various Regions

Regions	Buoy Identification	Latitude/longitude
Hawaii	51001	23.4N/162.3W
	51002	17.2N/157.8W
	51003	19.2N/160.8W
	51004	17.5N/152.6W
East Pacific	46002	42.5N/130.4W
	46003	51.9N/155.9W
	46004	50.9N/135.9W
	46005	46.1N/131.0W
	46006	40.8N/137.6W
	46035	57.0N/177.7W
Gulf of Mexico	42001	25.9N/ 89.7W
	42002	26.0N/ 93.5W
	42003	26.0N/ 85.9W
South Atlantic	41001	34.9N/ 72.9W
	41002	32.2N/ 75.3W
	41006	29.3N/ 77.4W
North Atlantic	44008	40.5N/ 69.5W

Table 2. Bias and Root Mean Squared Difference (RMSD) in wind speeds (m/sec) betweenGeosat wind speeds and buoy winds at various time window (T) of the colocation for the period January 2, 1988 to May 31, 1989. The separation distance of the collocation is 1.5 degrees of longitude and latitude.

Categories	T = 1 hr			T = 2 hrs			T = 3 hrs		
	N	Bias	RMSD	N	Bias	RMSD	N	Bias	RMSD
a. NDBC Buoys									
Total Buoys	1038	1.34	3.30	2787	1.67	3.74	4351	1.69	3.71
0 - 5 m/s	325	3.72	4.78	903	3.60	4.68	1316	3.65	4.73
5 -15 m/s	713	0.26	2.33	1849	0.81	3.16	2981	0.90	3.13
> 15 m/s	0	--	--	35	-2.94	4.96	54	-1.77	5.10
Off Shore Buoys	488	2.02	3.28	1222	2.36	3.97	1972	2.33	4.03
0 - 5 m/s	205	3.23	4.41	429	3.46	4.52	626	3.71	4.83
5 -15 m/s	283	1.13	2.10	793	1.76	3.64	1346	1.69	3.60
> 15 m/s	0	--	--	0	--	---	0	--	--
Near Shore Buoys	550	0.74	3.32	1565	1.13	3.56	2379	1.17	3.42
0 - 5 m/s	120	4.54	5.36	474	3.73	4.82	690	3.59	4.63
5 -15 m/s	430	-0.32	2.47	1056	0.09	2.74	1635	0.24	2.67
> 15 m/s	0	--	--	35	-2.94	4.96	54	-1.77	5.10
b. Regional									
Hawaii	100	-0.13	1.78	232	0.14	1.71	382	0.45	2.25
East Pacific	171	0.33	3.27	443	1.27	3.99	739	1.56	4.12
Gulf of Mexico	35	1.52	2.55	89	2.43	3.83	155	1.38	3.27
South Atlantic	12	2.43	2.46	69	2.34	3.78	100	1.98	3.22
North Atlantic	29	1.66	2.27	70	1.13	2.07	91	1.37	2.15
C. Seasonal									
Spring	142	0.18	3.47	332	0.74	3.28	491	1.02	3.31
Summer	4	1.47	1.59	4	1.47	1.59	47	2.09	3.19
Fall	132	0.57	1.95	334	1.03	3.54	505	1.27	3.92
Winter	69	0.99	2.34	224	1.92	3.30	424	1.46	3.06

Table 3. Bias and Root Mean Squared Difference (RMSD) in wind speeds (m/sec) between Geosat wind speeds and buoy winds at various separation distance (D in units of degrees of longitude and latitude) of the collocation for the period January 2, 1988 to May 31, 1989. The time window of the collocation is 3 hours.

Categories	D = 0.5			D = 1.0			D = 1.5		
	N	Bias	RMSD	N	Bias	RMSD	N	Bias	RMSD
a. NBDC Buoys									
Total Buoys	614	1.78	3.74	2201	1.73	3.70	4351	1.69	3.71
0 - 5 m/s	188	3.28	4.44	664	3.44	4.56	1316	3.65	4.73
5 -15 m/s	419	1.14	3.35	1506	1.03	3.21	2981	0.90	3.13
> 15 m/s	7	-0.28	4.87	31	-0.93	5.18	54	-1.77	5.10
Offshore Buoys	431	2.44	4.20	1043	2.39	4.10	1972	2.33	4.03
0 - 5 m/s	110	3.11	4.36	337	3.44	4.60	626	3.71	4.83
5 -15 m/s	208	2.08	4.10	706	1.89	3.85	1346	1.69	3.60
> 15 m/s	0	--	--	0	--	--	0	--	--
Nearshore Buoys	296	1.07	3.17	1158	1.14	3.29	2379	1.17	3.42
0 - 5 m/s	78	3.52	4.56	327	3.44	4.52	690	3.59	4.63
5 -15 m/s	211	0.20	2.38	800	0.27	2.51	1635	0.24	2.67
> 15 m/s	7	-0.28	4.87	31	-0.93	5.18	54	-1.77	5.10
b. Regional									
Hawaii	44	0.56	2.06	185	0.75	2.30	382	0.45	2.25
East Pacific	141	2.31	4.64	514	1.89	4.04	739	1.56	4.12
Gulf of Mexico	26	1.06	2.51	110	1.40	3.18	155	1.38	3.27
South Atlantic	17	3.03	4.74	46	2.16	3.45	100	1.98	3.22
North Atlantic	9	1.91	2.32	34	1.80	2.24	91	1.37	2.15
C. Seasonal									
Spring	74	1.82	3.78	287	1.64	3.27	491	1.02	3.31
Summer	13	2.95	3.94	37	3.09	3.61	47	2.09	3.19
Fall	94	1.83	4.78	330	1.36	4.05	505	1.27	3.92
Winter	56	1.82	2.73	235	1.66	3.08	424	1.46	3.06

Table 4. Bias and Root Mean Squared Difference (RMSD) in significant wave height (m) between Geosat and buoy estimates at various time windows (T) of the collocation for the period January 2, 1988 to May 31, 1989. The separation distance of the collocation is 1.5 degrees of longitude and latitude.

Categories	T = 1 hr			T = 2 hrs			T = 3 hrs		
	N	Bias	RMSD	N	Bias	RMSD	N	Bias	RMSD
a. NDBC Buoys									
Total Buoys	2899	0.03	0.87	4911	0.01	0.86	6984	0.04	0.91
0 - 2 m	1294	0.32	0.85	2223	0.26	0.79	3208	0.28	0.92
2 - 4 m	1406	-0.09	0.66	2291	-0.09	0.68	3229	-0.07	0.68
4 - 6 m	179	-0.94	1.63	344	-0.64	1.66	477	-0.62	1.61
6 - 8 m	11	-1.34	1.78	38	-1.34	2.05	51	-1.12	1.88
> 8 m	9	-2.49	3.83	15	-1.57	2.98	19	-1.72	2.84
Offshore	1741	0.06	0.84	2974	0.02	0.84	4242	0.04	0.80
0 - 2 m	765	0.37	0.92	1291	0.27	0.83	1841	0.26	0.81
2 - 4 m	849	-0.10	0.61	1445	-0.08	0.65	2090	-0.05	0.63
4 - 6 m	117	-0.70	1.46	206	-0.72	1.64	266	-0.58	1.56
6 - 8 m	10	-1.09	1.34	26	-0.99	1.46	39	-0.82	1.38
> 8 m	0	-	-	6	-0.18	0.42	6	-0.18	0.42
Nearshore	1158	-0.03	0.91	1937	0.01	0.90	2742	0.03	1.05
0 - 2 m	529	0.25	0.74	932	0.25	0.73	1367	0.29	1.04
2 - 4 m	557	-0.09	0.73	846	-0.11	0.72	1139	-0.10	0.77
4 - 6 m	62	-1.38	1.92	138	-0.53	1.69	211	-0.67	1.68
6 - 8 m	1	-4.14	4.14	12	-2.09	2.95	12	-2.09	2.95
> 8 m	9	-2.49	3.83	9	-2.49	3.83	13	-2.42	3.43
b. Regional									
Hawaii	281	-0.14	0.56	519	-0.10	0.58	712	-0.05	0.55
East Pacific	480	0.02	0.61	798	0.02	0.69	1168	0.02	0.68
Gulf of Mexico	84	-0.21	0.65	103	-0.21	0.68	109	-0.22	0.67
South Atlantic	26	0.11	0.33	57	-0.20	0.69	93	-0.16	0.56
North Atlantic	42	-0.32	0.40	69	-0.28	0.46	108	-0.22	0.48
c. Seasonal									
Spring	387	-0.13	0.57	689	-0.10	0.60	877	-0.17	0.57
Summer	45	-0.23	0.65	65	-0.20	0.62	113	-0.11	0.51
Fall	264	0.02	0.64	412	0.05	0.61	559	0.00	0.64
Winter	207	0.01	0.53	380	-0.06	0.75	641	0.00	0.69

Table 5 Bias and Root Mean Squared Difference (RMSD) in significant wave height (m) between Geosat and buoy estimates at various separation distance (D in unit degrees of longitude and latitude) of the collocation for the period January 2, 1988 to May 31, 1989. The time window of the collocation is 3 hours.

Categories	D = 0.5			D = 1.0			D = 1.5		
	N	Bias	RMSD	N	Bias	RMSD	N	Bias	RMSD
a. NDBC Buoys									
Total Buoys	847	-0.02	0.80	3244	0.05	0.95	6984	0.04	0.91
0 - 2 m	458	0.17	0.66	1568	0.26	1.00	3208	0.28	0.92
2 - 4 m	329	-0.15	0.73	1432	-0.06	0.70	3229	-0.07	0.68
4 - 6 m	58	-0.70	1.59	222	-0.55	1.55	477	-0.62	1.61
6 - 8 m	1	-4.79	4.79	15	-1.06	2.29	51	-1.12	1.88
> 8 m	1	-0.98	0.98	7	-1.50	2.54	19	-1.72	2.84
Offshore	482	0.06	0.67	1858	0.07	0.75	4242	0.04	0.80
0 - 2 m	222	0.20	0.68	825	0.25	0.78	1841	0.26	0.81
2 - 4 m	227	-0.04	0.61	916	-0.03	0.62	2090	-0.05	0.63
4 - 6 m	33	-0.25	0.95	107	-0.47	1.35	266	-0.58	1.56
6 - 8 m	0	-	-	8	0.15	1.30	39	-0.82	1.38
> 8 m	0	-	-	2	0.20	0.20	6	-0.18	0.42
Nearshore	365	-0.12	0.95	1386	0.02	1.16	2742	0.03	1.05
0 - 2 m	236	0.14	0.64	743	0.26	1.20	1367	0.29	1.04
2 - 4 m	102	-0.40	0.94	516	-0.13	0.82	1139	-0.10	0.77
4 - 6 m	25	-1.30	2.16	115	-0.62	1.72	211	-0.67	1.68
6 - 8 m	1	-4.79	4.79	7	-2.09	3.06	12	-2.09	2.95
> 8 m	1	-0.98	0.98	5	-2.17	3.00	13	-2.42	3.43
b. Regional									
Hawaii	51	-0.13	0.59	288	-0.04	0.54	712	-0.05	0.55
East Pacific	156	0.04	0.67	609	0.04	0.70	1168	0.02	0.68
Gulf of Mexico	9	0.13	0.49	48	-0.08	0.65	109	-0.22	0.67
South Atlantic	14	-0.16	0.36	43	-0.17	0.44	93	-0.16	0.56
North Atlantic	7	0.23	0.54	34	-0.15	0.51	108	-0.22	0.48
c. Seasonal									
Spring	84	0.00	0.48	383	0.02	0.55	877	-0.17	0.57
Summer	18	0.01	0.35	62	-0.02	0.43	113	-0.11	0.51
Fall	72	-0.02	0.83	282	0.01	0.76	559	0.00	0.64
Winter	63	0.03	0.60	295	-0.05	0.67	641	0.00	0.69

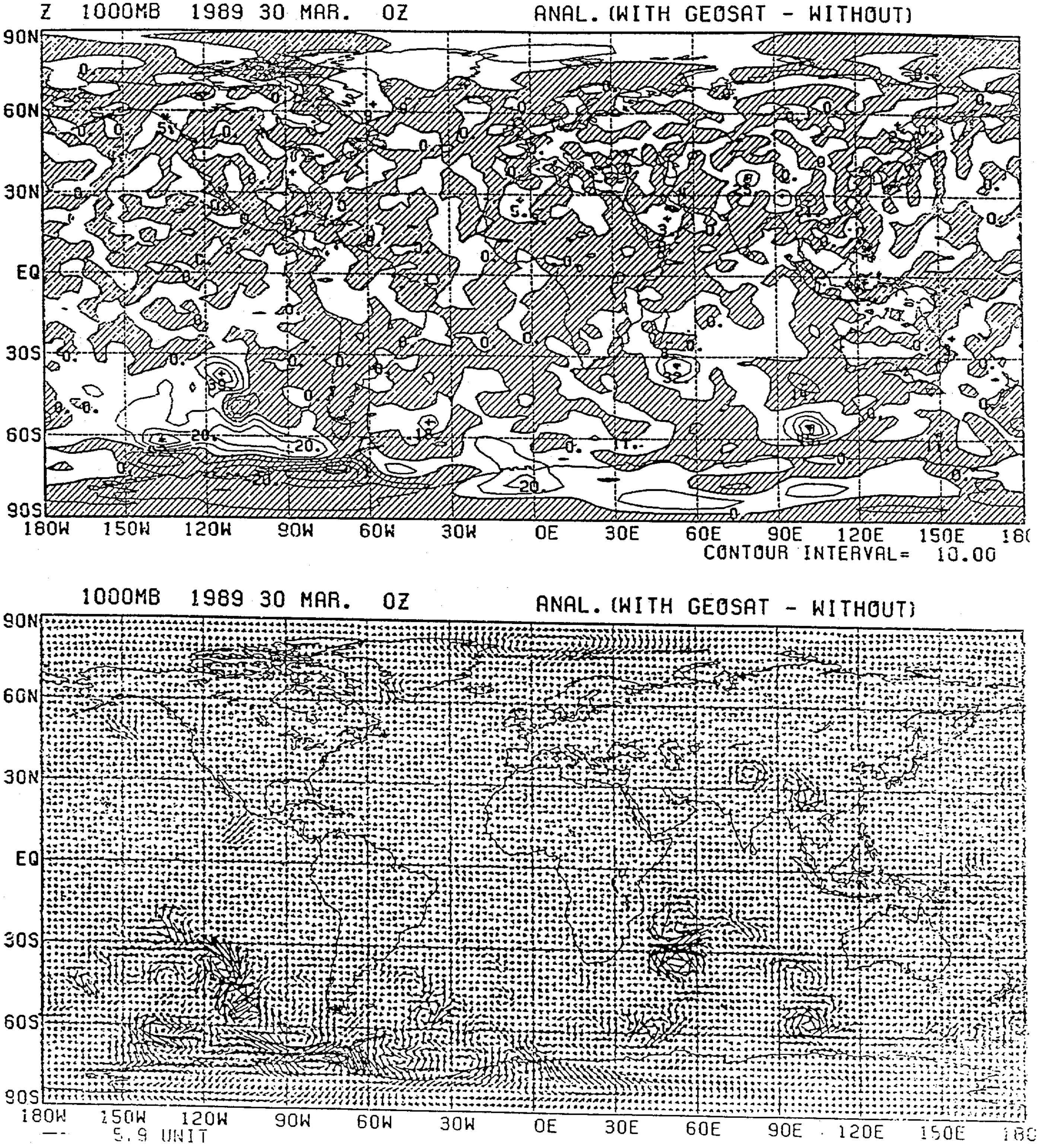

Figure 1: Differences of 1000 mb height (top) and vector wind (bottom) analyses valid at 0000 UTC March 30, 1989 between the assimilation experiments including Geosat wind speed data and those without the wind data

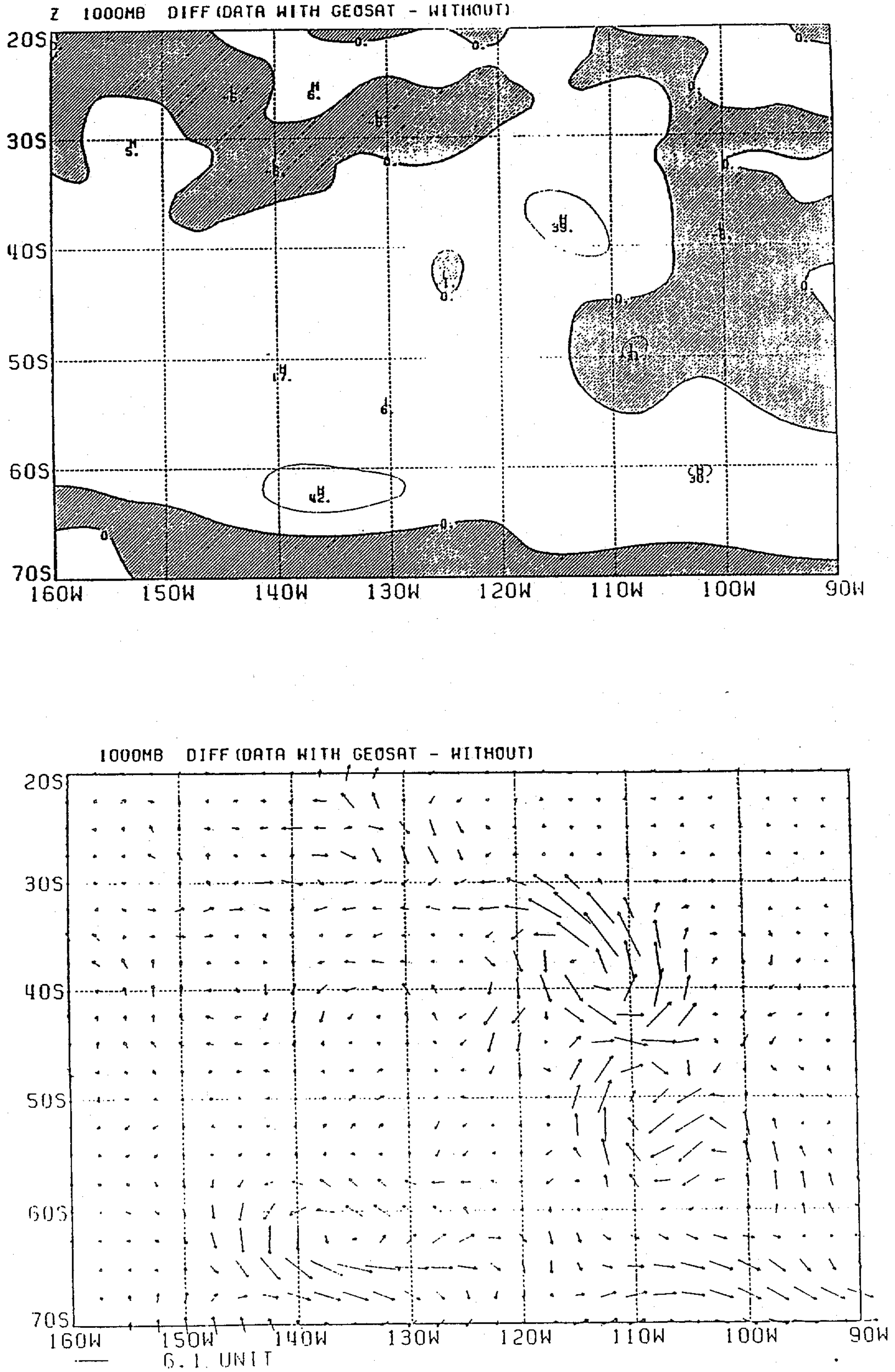

Figure 2: Same as Figure 1 except for the limited region enclosed between 90 W to 160 W longitude and 20 S to 70 S latitudes

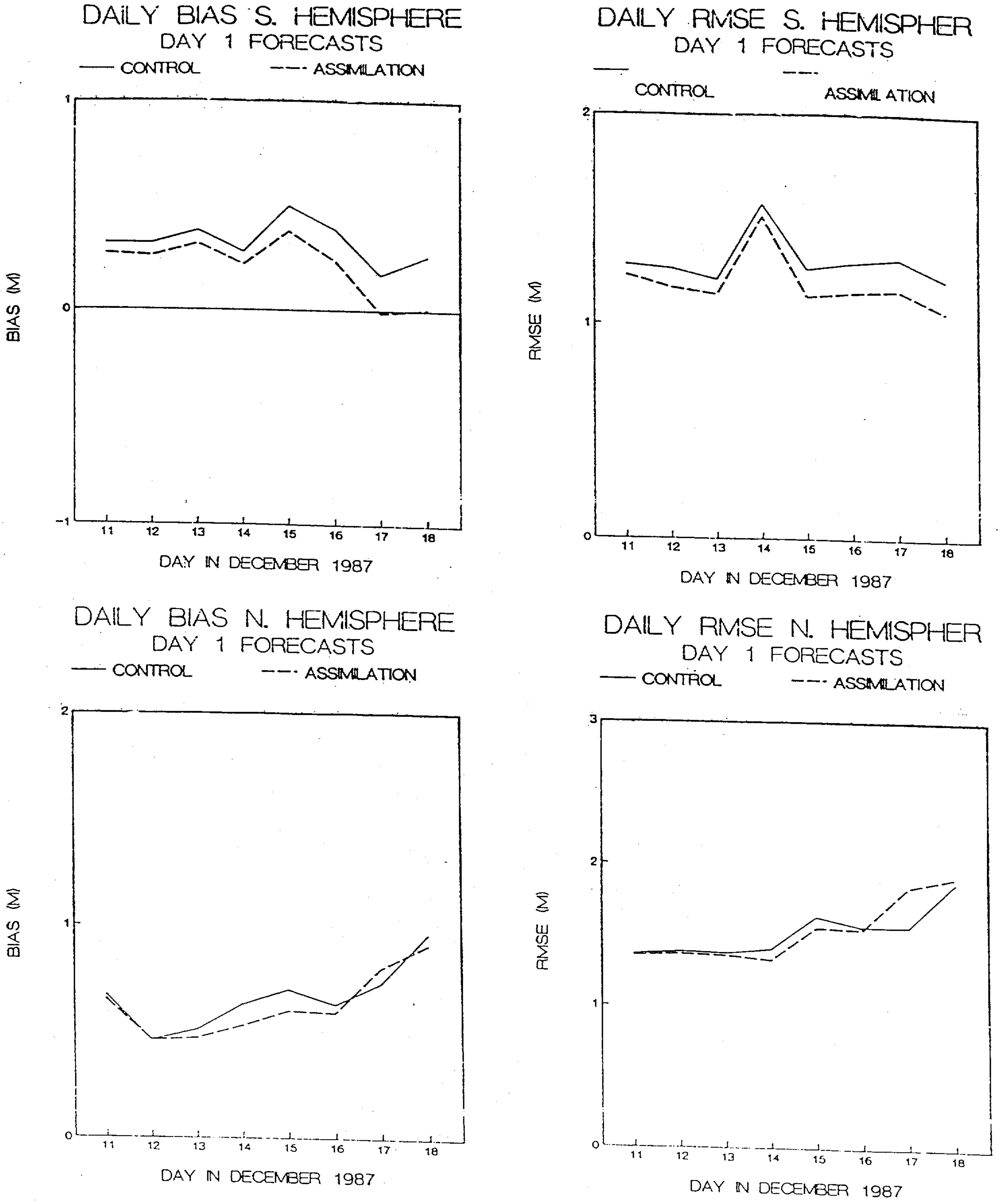

Figure 3: Bias and Root Mean Squared Errors (RMSE) of the 24 hours significant wave height forecast for the control and assimilated experiments in the Southern Hemisphere (top) and Northern Hemisphere (bottom) during the period of December 1987

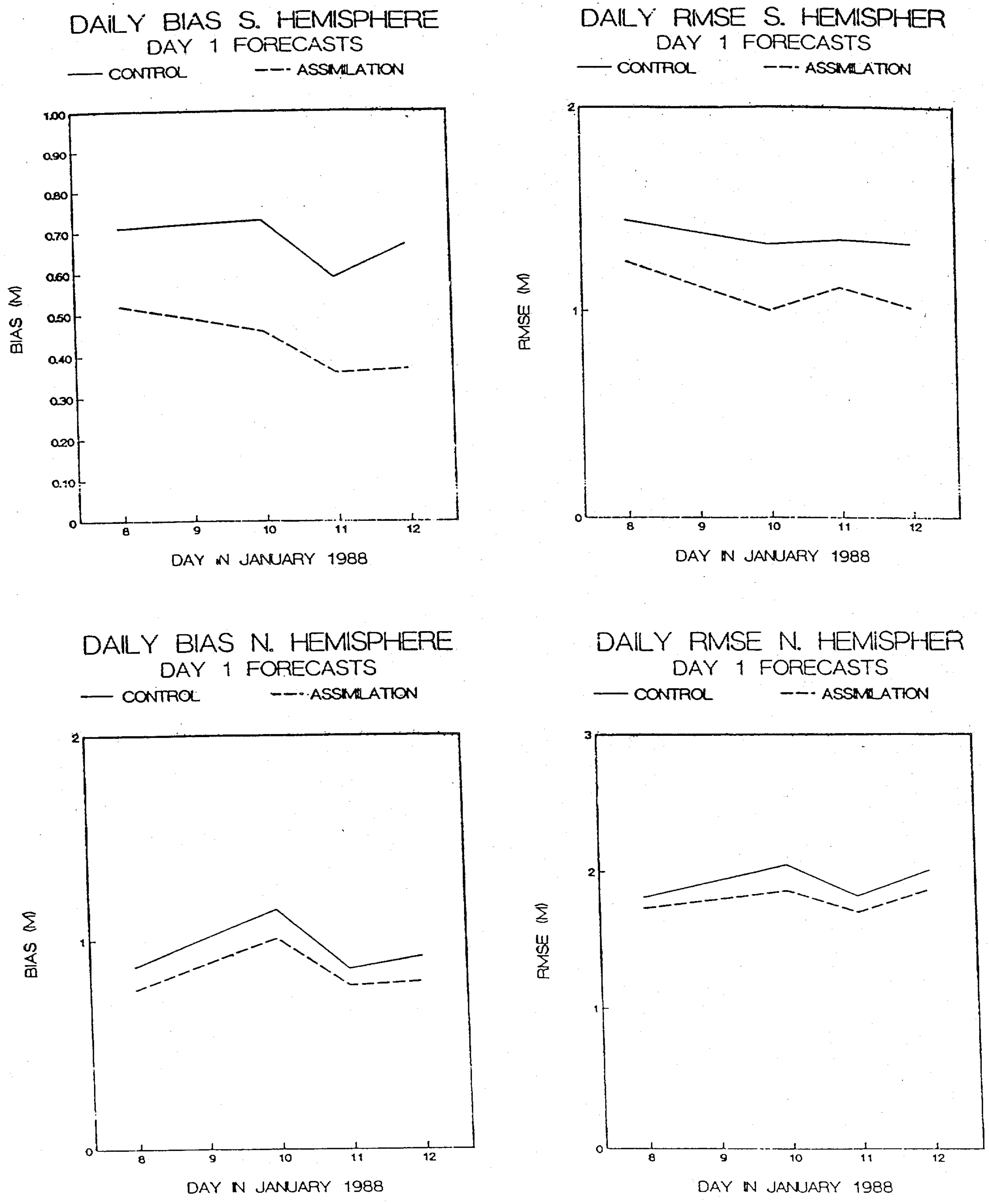

Figure 4: Same as Figure 3 except for the period of January 1988

26.	Infinite Elements for Water Wave Radiation and Scattering.	H.S. CHEN	INTER. JOURNAL FOR NUM. METHODS IN FLUIDS (in press)	1/91
27.	A Statistical Comparison of Methods for Determining Ocean Surface Winds.	W.H. GEMMILL T.W. YU D.M. FEIT	WEATHER AND FORECASTING VOL. 3 #2	6/88
28.	A Review of the Program of the Ocean Products Center.	D.B. RAO	WEATHER AND FORECASTING VOL. 4 #3	9/89
29.	Infintie Elements for Combined Diffraction and Refraction.	H.S. CHEN	PREPRINT, 7TH INTER. CONF. OF FINITE ELEMENT METHODS FLOW PROBLEMS	4/89
30.	An Operational Spectral Wave Forecasting Model for the Gulf of Mexico.	Y.Y. CHAO	PREPRINT, 2ND INTER. WORK. ON WAVE FORE. & HINDCASTING	4/89
31.	Improving Global Wave Forecasts Incorporating Altimeter Data.	D.C. ESTEVA	PREPRINT, 2ND INTER. WORK. ON WAVE FORE. & HINDCASTING	4/89
32.	Computer-Worded Marine Forecasts.	W.S. RICHARDSON J.M. NAULT D.M. FEIT	PREPRINT, 6TH SYMP. ON COASTAL OCEAN MANAGEMENT COASTAL ZONE 89	7/89
33.	A Columbia River Entrance Wave Forecasting Program Developed at the Ocean Products Center.	Y.Y. CHAO T.L. BERTUCCI	NMC OFFICE NOTE #361/ TECHNICAL NOTE	10/89
34.	Forecasting Open Ocean Fog and Visibility.	L.D. BURROUGHS	PREPRINT, 11TH CONF. ON PROBABILITY & STATISTICS/ AMS MONTEREY, CA	10/89
35.	Local and Regional Scale Wave Models.	D.B. RAO	PROCEEDING (CMM/WMO TECHNICAL CONF. ON WAVES	5/90
36.	Forecast Guidance for Santa Ana Conditions.	L.D. BURROUGHS	TECHNICAL PROCEDURES BULLETIN #391	4/91
37.	Ocean Products Center Products Review Summary for 1988.	L.D. BURROUGHS	NMC OFFICE NOTE #359 TECHNICAL NOTE	8/89
38.	Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center (revision 1).	D.M. FEIT	NOAA TECHNICAL MEMORANDUM NWS NMC 68	6/89
39.	Directional Wave Spectra for the Labrador Extreme Wave Experimental (Lewex).	D.C. ESTEVA Y.Y. CHAO	APL. TECHNICAL REPORT (in press)	1/91
40.	An Analysis of Monthly Sea Surface Temperature Anomalies in Waters off the U. S. East and West Coasts.	L.C. BREAKER W.B. CAMPBELL	FISHERIES BULLETIN (to be submitted)	
41.	A Difinition for Vector Correlation and Its Application to Marine Surface Winds.	D.S. CROSBY L.C. BREAKER W.H. GEMMILL	NMC OFFICE NOTE #365/ TECHNICAL NOTE	6/90
42.	Expert System for Quality Control and Marine Forecasting Guidance.	D.M. FEIT W.S. RICHARDSON	PREPRINT, 3RD WORK. OPER. & METEOR CMOS	5/90
43.	OPC Unified Marine Database Verification System.	V.M. GERALD	NMC OFFICE NOTE #368/ TECHNICAL NOTE	8/90
44.	Sea Ice Edge Forecast Verification Program for the Bering Sea.	G.M. WOHL	NWA Digest (submitted)	5/90
45.	An Operational Marine Fog Prediction Model.	D.M. FEIT J.A. ALPERT	NMC OFFICE NOTE #371	6/90
46.	The Circulation of Monterey Bay and Related Processes.	L.C. BREAKER W.W. BROENKOW	SPRINGER-VERLAG (submitted)	8/89
47.	On the Specification of Wind Speed Near the Sea Surface.	Y.Y. CHAO	MARINE FORECASTER TRAINING MANUAL (submitted)	8/90
48.				
49.	The Gulf of Mexico Spectral Wave Forecast Model & Products.	Y.Y. CHAO	TECHNICAL PROCEDURES BULLETIN # 381	10/90
50.	Wave Calculation Using WAM Model & NMC Wind.	H.S. CHEN	8TH ASCE ENGIN. MECH. CONF. (preprint)	12/90
51.	On the Transformation of Wave Spctra by Current and Bathymetry.	Y.Y. CHAO	8TH ASCE ENGIN. MECH. CONF. (preprint)	12/90
52.	A Vector Correlation Coefficient in Geophysical: Theoretical Background and Application.	L.C. BREAKER W.H. GEMMILL D.S. CROSBY	JOURNAL OF ATMOS. & OCEANIC TECH. (to be submitted)	12/90