WESTERN REGION TECHNICAL ATTACHMENT
NO. 03-05
May 14, 2003

High Wind and Wave Events Along the Northern California Coast During Summer

Jeff Lorens
WFO Eureka, California

1. Introduction.

a. Background. During the summer months, swell from distant storms normally decays to a few feet or less by the time it reaches the west coast of North America, and is often only a slight contributor to the total significant wave height (with a few significant exceptions, as will be noted later). Instead, wave generation along the northern California coast is largely driven by regional and local wind patterns. Beardsley, et. al. (1987) describes the predominantly low level flow along the California coast in summer. Mass, et. al. (1987) describes particular flow regimes in this same region which result in occasional shifts in the low level flow along the coast to a southerly direction. Additionally, Burke and Thompson (1996) describe a phenomena known as the northerly low level jet. Each of these flow situations are largely driven by synoptic and mesoscale features, including coastal topography, but they will not be further discussed here.

Regardless of the particular flow regime, however, the most direct and persistent influence on surface winds in this region comes from sea level pressure patterns. Pressure patterns here are typically characterized by the presence of a thermally-induced trough along or near the California coast, and the persistent eastern north pacific high pressure cell. As a result of these features, moderate to strong pressure gradients often develop over the northern California coastal waters. The resultant winds (also influenced by the other factors mentioned previously), depending on their strength, duration, and fetch length and orientation, can generate large and/or steep waves in a short period of time. These rapidly-developing wind and wave conditions pose a significant hazard to mariners, especially smaller vessels, and are the primary focus of this study.

Because the thermal trough and eastern north Pacific high are such persistent features in this region, long-term averages of winds and waves are potentially very useful in daily forecasting applications. In the following study, a detailed climatology of summer (June through September) wind and wave information is presented, based on approximately 20 years of data from NOAA environmental data buoys located along the northern California coast (see paragraph 2b, below). Based on this data, long-term average values of wind speed and direction, wave height, and dominant period are presented. Historical extremes (from the period of study) are also included for wind speed and wave height data. Additionally, information on duration of these summer wind and wave events will be presented.

Finally, a series of short case studies will be presented. These case studies will highlight wind and wave characteristics typical of summer wind and wave events along the northern California coast. Examples will focus primarily on two types of events: (1) "periodic" events (dominated by moderate to strong diurnal variations in wind speed and wave height), and (2) "rapid-rise" events (characterized by longer duration build-ups of wind speed and wave height).

b. Data. Quality-controlled wind, pressure, and wave data for the months of June through September, 1981-2001 was obtained from NOAA's National Data Buoy Center (NDBC) archive files (on-line and CD-ROM). The four buoy locations selected were: #46027 (8 nautical miles west of Crescent

City), #46022 (17 nautical miles west-southwest of Eureka), #46030 (8 nautical miles west of Cape Mendocino),[1] and #46014 (19 nautical miles northwest of Point Arena). See also Figure 1 for buoy locations. Data elements included for analysis in this study include the following variables:

(1) Wind Speed and Direction (averaged over 8-minute periods),
(2) Wind Gust (peak wind speed over 8-minute periods),
(3) Significant Wave Height (average of the highest one-third of wave heights observed in a 20-minute sampling period), and
(4) Dominant Period (wave period with maximum energy)
(5) Atmospheric Pressure (Mean Sea Level)

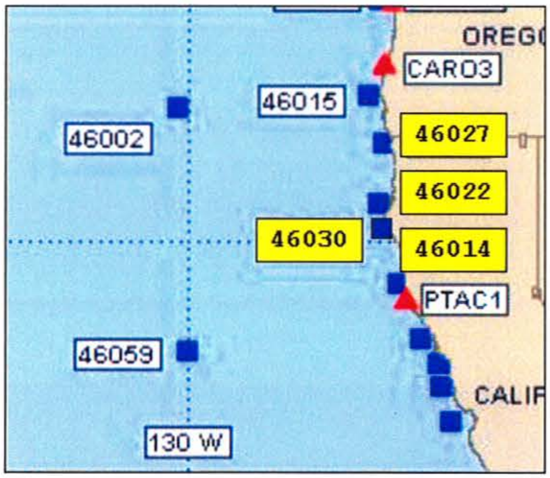


Figure 1. Buoy locations (buoys used for this study shown in yellow). (Note: Buoy #46030 is no longer located at position shown; this buoy was relocated off the southern Oregon coast and re-designated as #46015.)

There were occasional periods of missing data throughout the entire period evaluated. Most commonly, one or a few elements were missing for relatively short periods (one to several hours). In a few cases, however, *all* data from particular buoys was missing for extended periods (up to several months), due to several possible reasons, including sensor or data transmission problems. On rare occasions, buoys have broken their moorings in strong storms and gone adrift. In such cases, data transmission is normally suspended until the buoy can be returned to service. Appendix 1 summarizes the data availability for each of the buoys for this study period.

2. Wind and Wave Averages.

a. Wind speed and direction. Table 1 shows the overall maximum sustained wind speeds and significant wave heights, along with the number of observations each was based on. Figure 2 shows wind speed frequencies (based on all available data for all directions) at each buoy, in terms of increasing speed thresholds. Wind speeds for all locations were 10 knots or greater more than 35 percent of the time (up to 62 percent of the time for buoy #46030). At higher wind speed thresholds (>= 20 knots), buoys #46027 and #46014 tended to dominate.

Table 1. Maximum observed wind speeds (sustained) and significant wave heights for buoy locations for entire period of study (see Appendix 1 for specific periods of data availability).

[1] Buoy #46030 went adrift off Cape Mendocino in September 2001. It was subsequently moved to a new location west of Cape Blanco, Oregon, and redesignated as #46015.

Buoy	Max. Wind Speed (kt)	*# observations*	Max. Significant Wave Height (ft)	*# observations*
#46027	44.6	36,051	16.1	36,108
#46022	31.6	49,859	22.3	48,672
#46030	38.8	34,635	18.1	31,695
#46014	34.7	57,032	20.7	56,724

Figure 3 shows the frequency distribution of wind direction. Directions from 031° through 130° (clockwise) were not included in the analysis, primarily because speeds in this range of directions tended to be relatively light. Additionally, winds from these directions have an offshore component, so fetch lengths are typically shorter. Therefore, the associated wind-waves tend to be lower than those associated with other directions (131° clockwise through 030°). Figures 4 and 5 show the overall average and maximum wind speed and gust (by direction) for each location. Figures 6 through 9 show wind speed and direction frequencies for individual buoy locations.

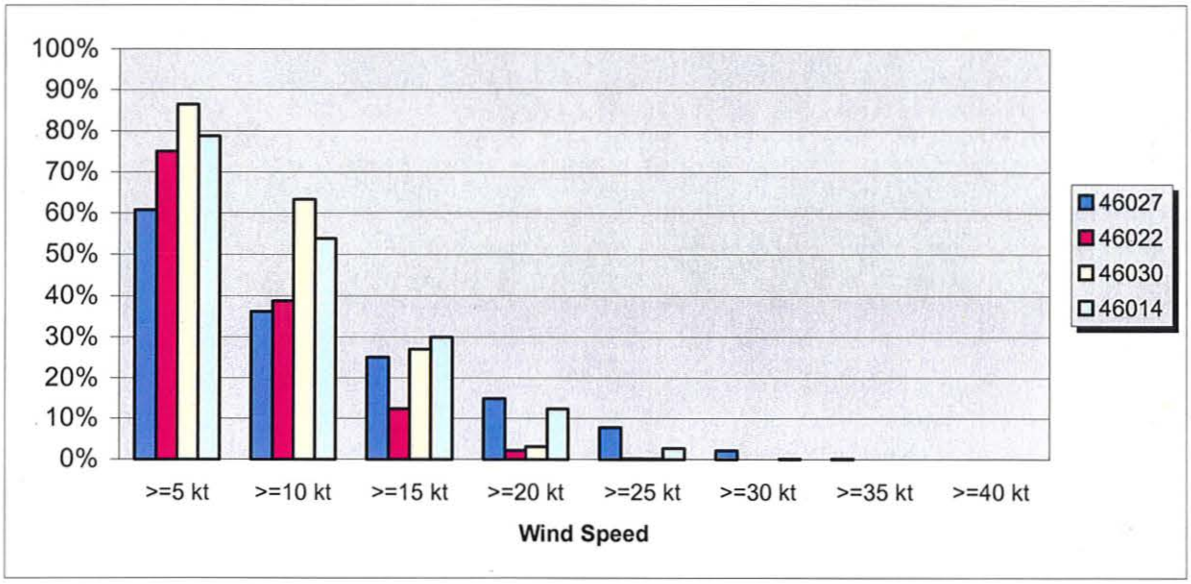


Figure 2. Wind speed frequency (cumulative) for specified thresholds.

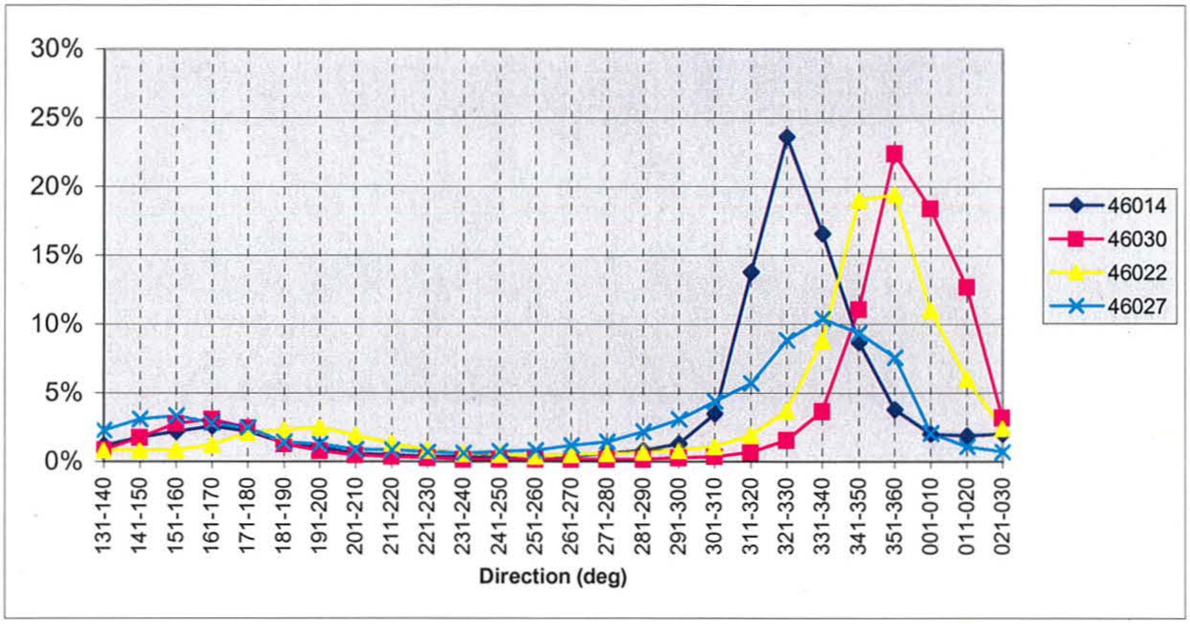


Figure 3. Wind direction frequency (131° through 030°).

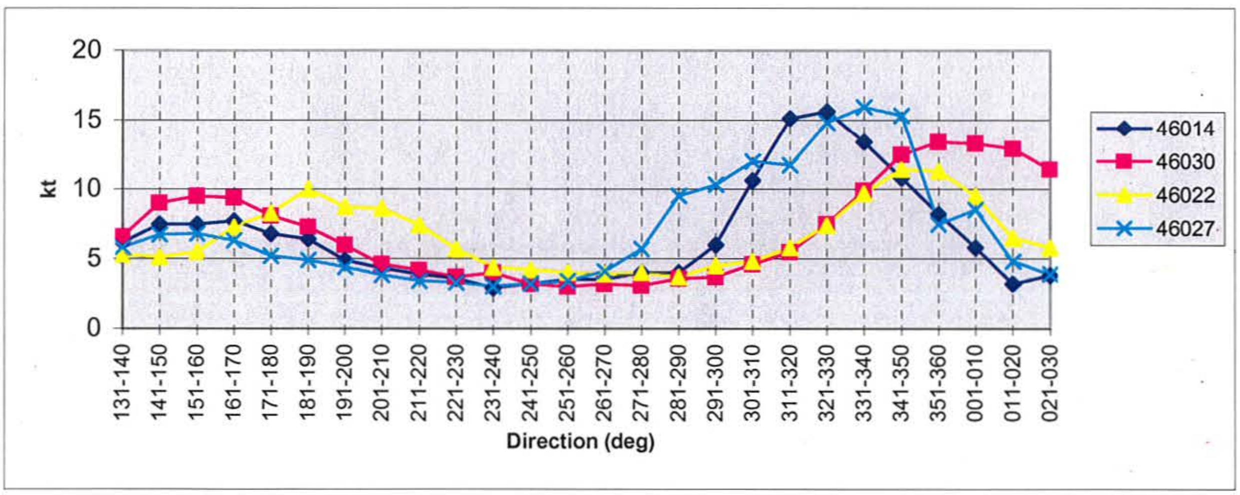


Figure 4. Average wind speed by direction.

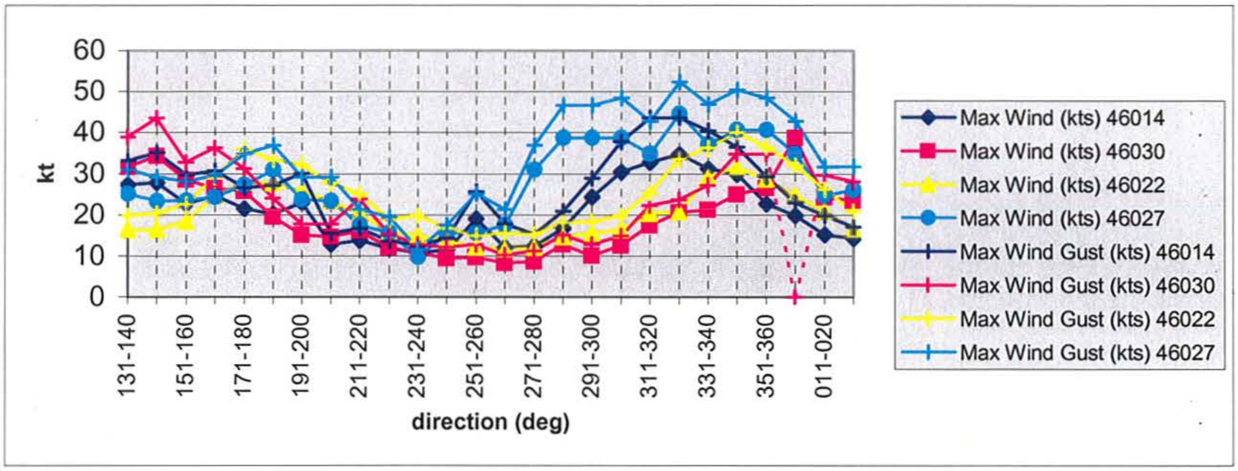


Figure 5. Maximum wind speed and gust by direction (dashed line denotes missing data).

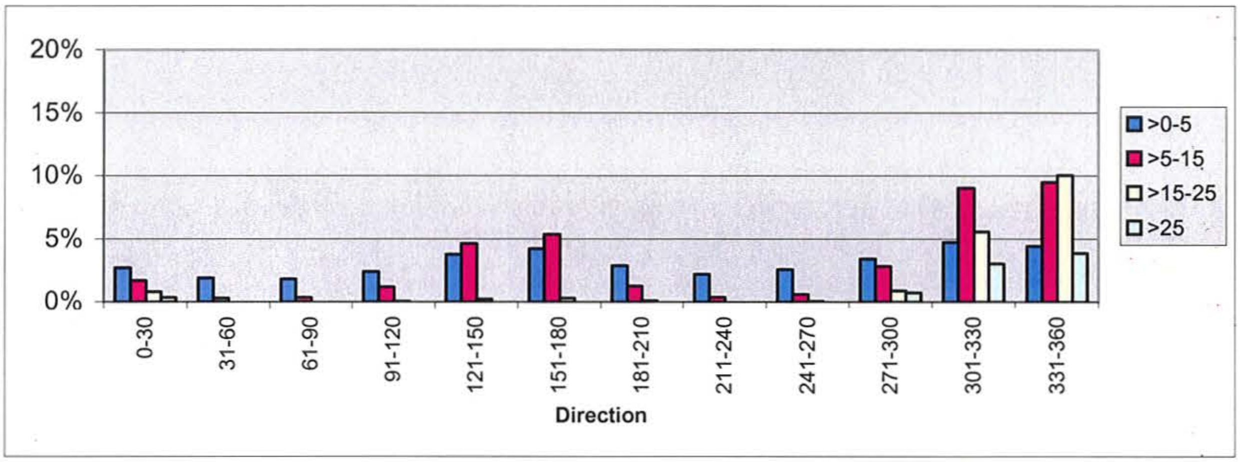


Figure 6. Frequency of wind speed (knots) classified by direction (buoy # 46027).

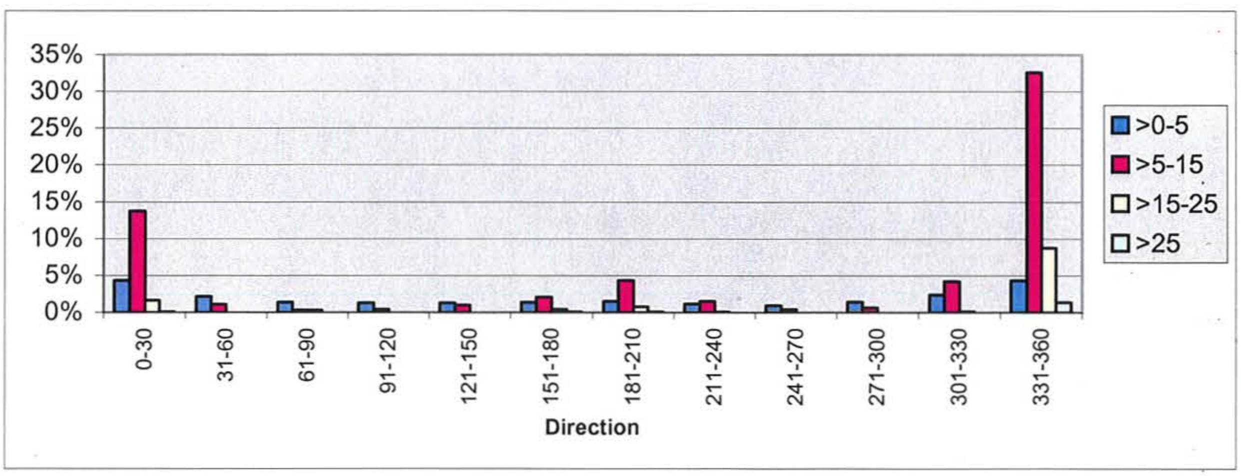


Figure 7. Frequency of wind speed (knots) classified by direction (buoy # 46022).

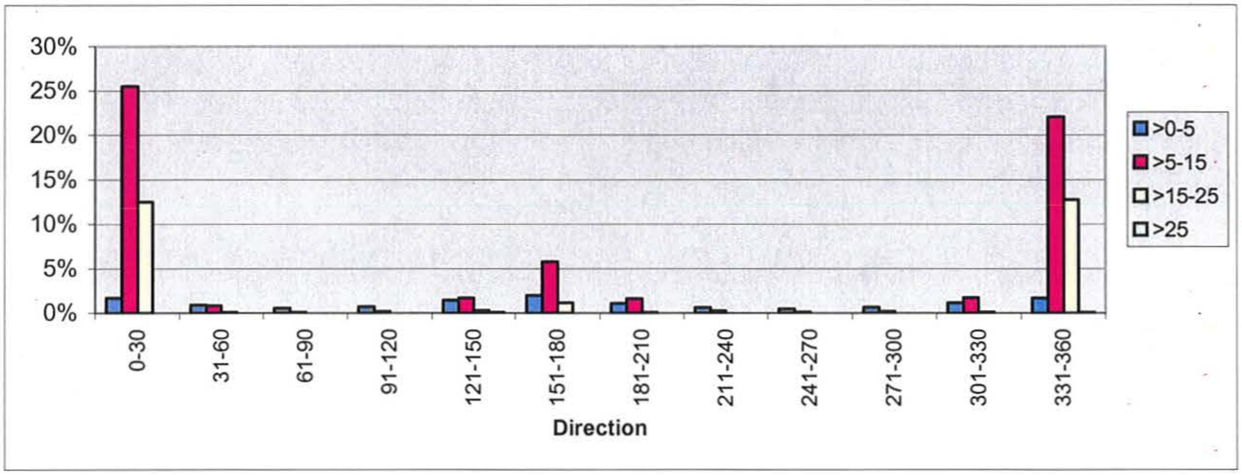


Figure 8. Frequency of wind speed (knots) classified by direction (buoy # 46030).

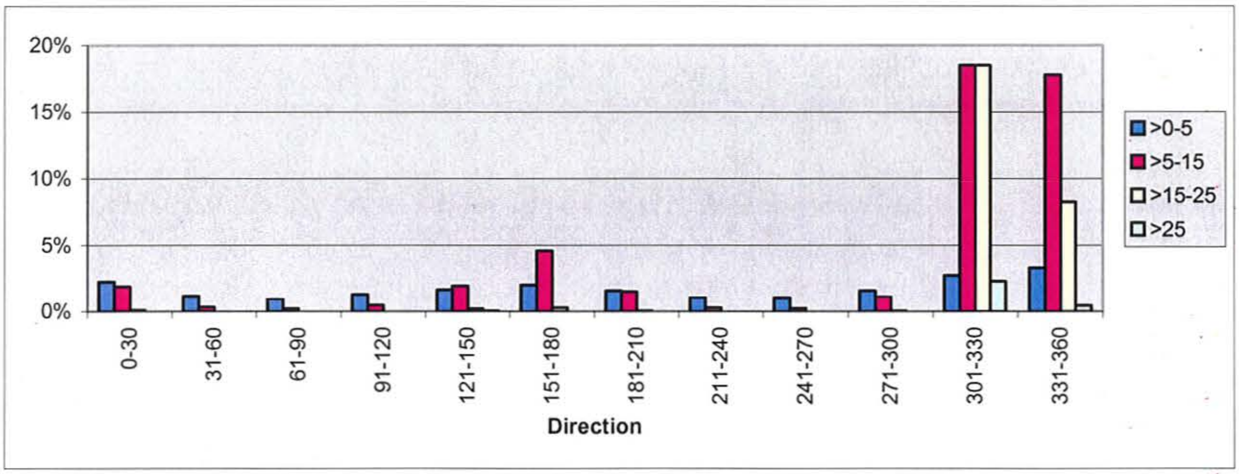


Figure 9. Frequency of wind speed (knots) classified by direction (buoy # 46014).

b. Significant wave heights. Long-term averages of significant wave heights along the Northern California coast during the summer vary, depending on location and wind direction. This is due, in part, to the resultant effects of direction on fetch lengths. Wind directions from the north, south and west (along-shore and on-shore) have longer (potential) fetch lengths than directions from the east (offshore). Figure 10 shows the frequency of significant wave heights at each buoy, classified according to wind direction. Data for wind directions with a significant offshore component are not included because of the shorter fetch lengths involved. As noted above, north to northwest winds, and (to a lesser extent) south to southwest winds are also associated with higher average wind speeds. The combination of higher wind speeds, longer fetch lengths, and (likely) greater persistence all contribute to higher significant wave heights (i.e. locally and regionally wind-generated waves). As noted previously, wind speeds associated with westerly directions average lower (only about 3-4 knots) and are less frequent than those from the north to northwest or south to southwest. Therefore, despite essentially unlimited fetch lengths, waves associated with westerly directions are lower on average. Additionally, although a directional analysis of wind persistence was not conducted here, longer wind speed persistence values are probable, due to higher frequencies of occurrence (paragraph 2d for a non-directional discussion of wind event durations).

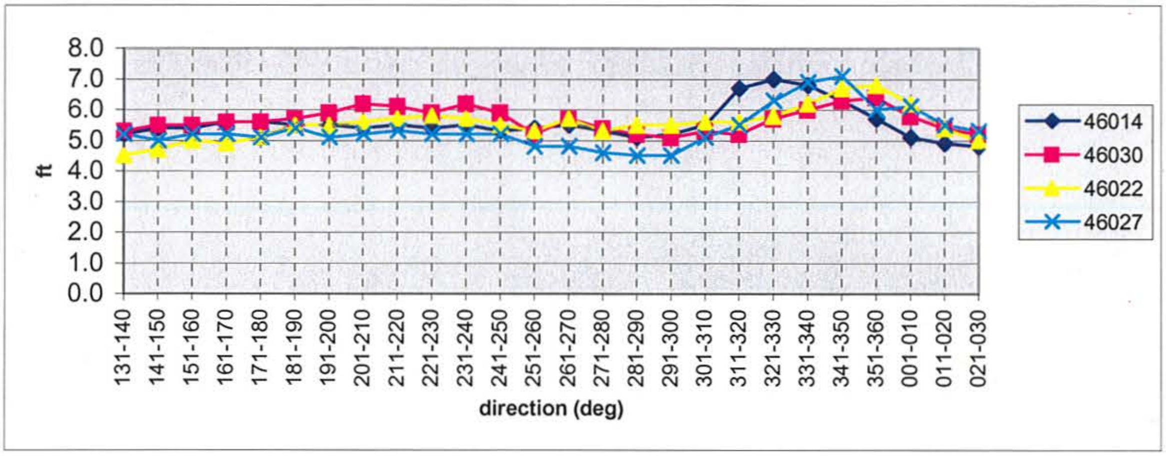


Figure 10. Significant wave heights (by wind direction).

c. Dominant wave periods. Figure 11 shows the frequency of occurrence of dominant wave periods. Figure 12 displays the same information, but in a cumulative fashion. As with wave height, wave period is a function of fetch (length and orientation), wind speed, and wind duration.

The "dominant" wave period is that period associated with the maximum wave energy, and is also one of the two period values reported by the buoys (the other is "average period" -- not used here). Other period values, associated with "wind wave" and "swell," are derived via a Fourier transform technique from the buoy spectral wave data (Tucker, 1991), and are not included here.

As noted previously, and as will be discussed further in the case studies section later, wind speeds and durations vary widely during the summer months in this region. Fetch length, however, is typically limited to distances on the order of a few hundred miles and, given the predominance of north to northwest and (secondarily) south to southwest winds, this commonly results in a fetch orientation parallel to the coast (or nearly so).

Wind-generated waves are typically characterized by short periods, typically less than about 6 to 8 seconds. As waves propagate out from the generation (fetch) area, wind waves gradually transition to swell; periods tend to become longer and wave heights subside, due to dispersion of energy. As will be further discussed in the case studies, one of the most common fetch areas in this area in summer is associated with tighter pressure gradients along the far northern California and southern Oregon coasts, as a result of interaction between the thermal trough and the northeast Pacific high. Given that the most common wind directions here are from the north to northwest, along with the highest average speeds, this typically results in shorter fetch lengths at the north end of this area (near buoy #46027), and conversely, longer fetch lengths at the southern end (near buoy #46014). Figure 13 shows the variation of dominant periods categorized by wind direction. This figure shows the tendency for shorter dominant periods (especially at buoy #46014) with the north to northwest winds so characteristic of this region in summer.

Based primarily on the variation in fetch length, shorter wave periods should typically be expected to the north and longer periods to the south, and the long-term averages in dominant period tend to reflect this. Looking at Figure 11, shorter dominant periods (especially from about 7 to 8 seconds) are more frequent at buoy #46027 than at buoys to the south. At longer periods (from about 8 through 11 seconds), there is a slightly higher frequency of occurrence at the buoys to the south of #46027. At the long end of the range, e.g. periods around 16 seconds, the two southern-most buoys in this area (#46030 and #46014) show a slightly higher frequency of occurrence than at the two northern buoys (#46027 and #46022). Using simple wave decay assumptions, the dominant period would not typically increase by more than a few seconds in propagating southward over the distances involved here (maximum distance approximately 200 miles, from buoy #46027 to #46014). It may be that conditions south of Cape Mendocino allow for a broader spectrum of wave energy to be observed, i.e. the influence of long-period wave energy (due to swell from distant storm systems) becomes greater. Because the difference is so slight at these longer periods, though, it is not certain that the difference is significant.

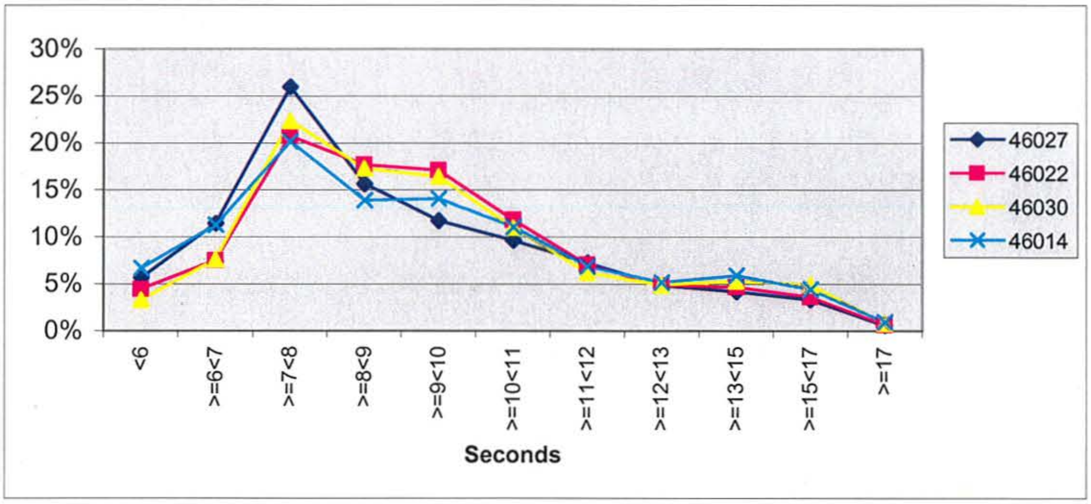


Figure 11. Frequency of dominant wave periods.

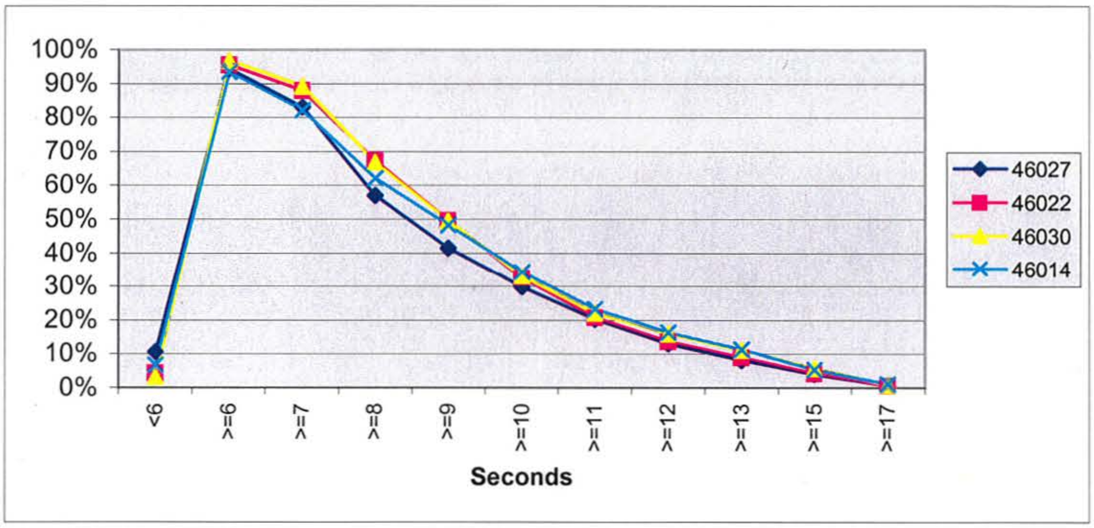


Figure 12. Cumulative frequency of dominant wave periods.

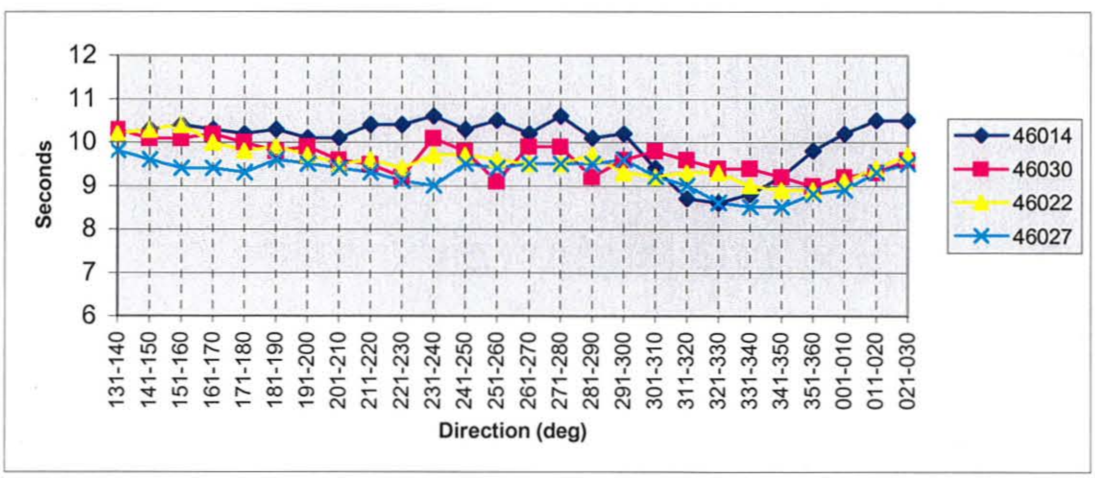


Figure 13. Average of dominant wave period categorized by wind direction.

d. Duration of wind events. Fetch length and orientation tend to be the most persistent factors in wave development in this region. So, wind speed and duration become critical factors in determining wave growth and decay along the coast. Wind data at each buoy were evaluated to determine how long wind speeds in this coastal region persist, based on certain conditions. "High wind events," are defined here using sustained wind speed thresholds of 20, 25, and 30 knots, and durations of at least 12 hours (consecutive). Although directions are not explicitly included, general observation of the data showed the vast majority of events to be of relatively constant direction (i.e. wind directions did not typically vary by more than about 30 degrees when winds were at these levels. Table 2 lists the number of events for each buoy, along with maximum sustained wind speed and significant wave height for each event. Figures 14-17 graphically show the results for each buoy. Clearly, buoys #46027 and #46014, at the north and south ends of this area, had the greatest number of "high wind" events, and also the greatest number of long-duration events (including a few exceeding 72 hours) were much more frequent). It is important to note here that this data may not include the longest durations, highest wind speeds, or highest waves, due to occasional long periods of missing data (refer to Appendix X for summary of missing data). Additionally, as will be seen in the some of the information presented in the following case studies, longer dominant periods (up to 17 seconds) at times indicated that swell from distant sources was a significant contributing factor to the high waves observed.

Table 2. Wind duration summary for specified wind speed thresholds (for events >=12 consecutive hours), with maximum wind speed (sustained) and wave height.

	#46027			#46022			#46030			#46014		
	Wind Speed (kt)											
	≥20	**≥25**	**≥30**	**≥20**	**≥25**	**≥30**	**≥20**	**≥25**	**≥30**	**≥20**	**≥25**	**≥30**
# Events	139	60	8	13	4	0	10	1	0	180	19	1
Max. Duration (hrs)	101	45	20	37	17	N/A	49	1	N/A	83	42	12
Max. Speed (kt)	44.6	44.6	44.6	31.6	31.2	N/A	34.3	31.6	N/A	34.7	34.7	34.7
Max. Sig. Wave Ht. (ft)	18.8	16.1	*	18.4	18.4	N/A	15.3	11.0	N/A	17.7	15.0	14.1

*Data missing.

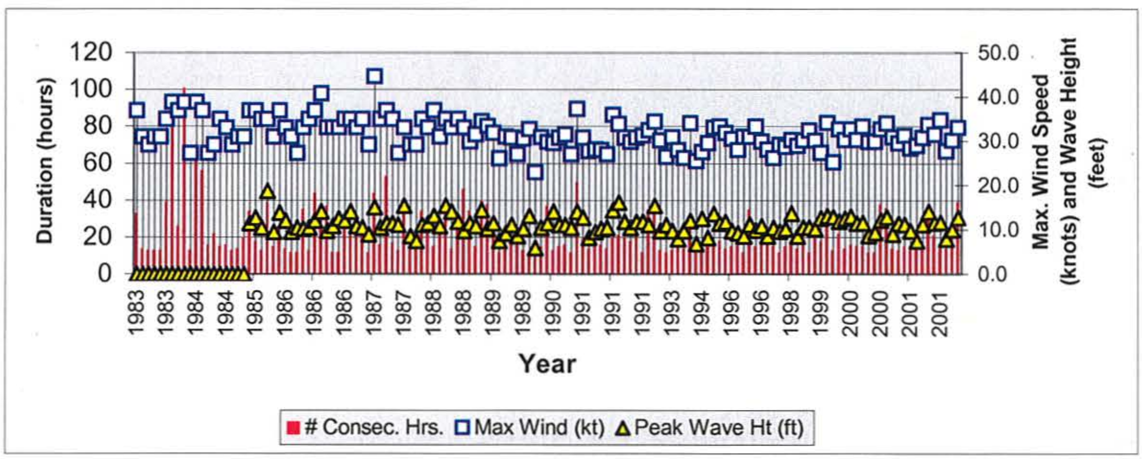


Figure 14. Duration of wind events (buoy # 46027) >= 20 knots and >= 12 hours, with associated maximum wind speeds and wave heights (zero-values denote missing data).

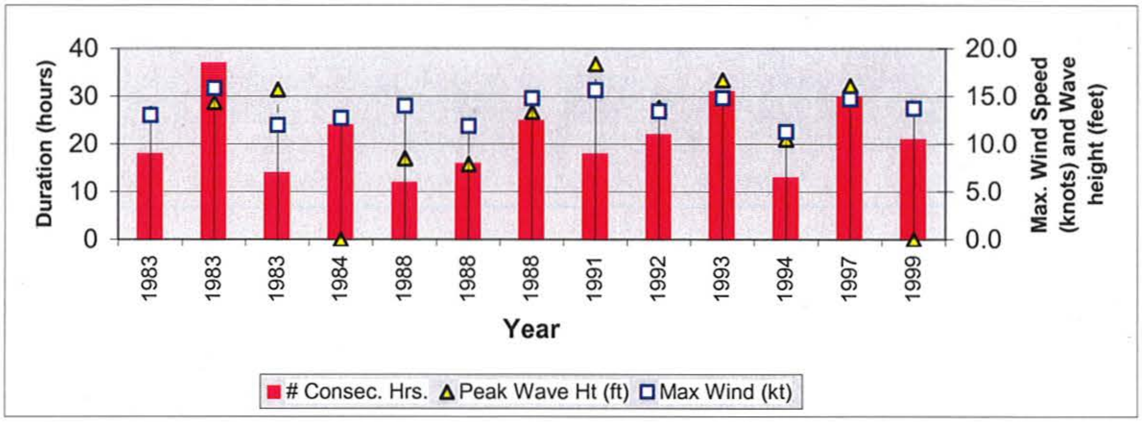


Figure 15. Duration of wind events (buoy # 46022) >= 20 knots and >= 12 hours, with associated maximum wind speeds and wave heights.

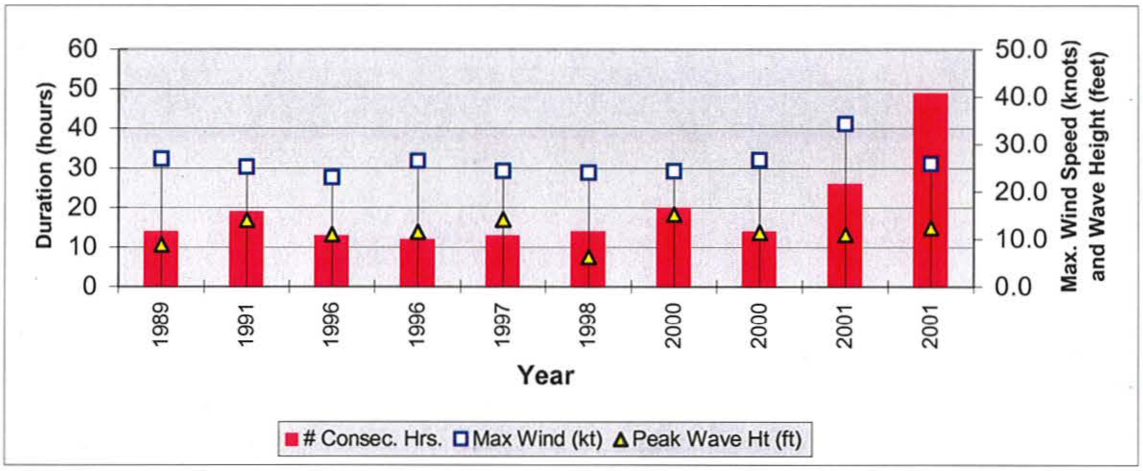


Figure 16. Duration of wind events (buoy # 46030) >= 20 knots and >= 12 hours, with associated maximum wind speeds and wave heights.

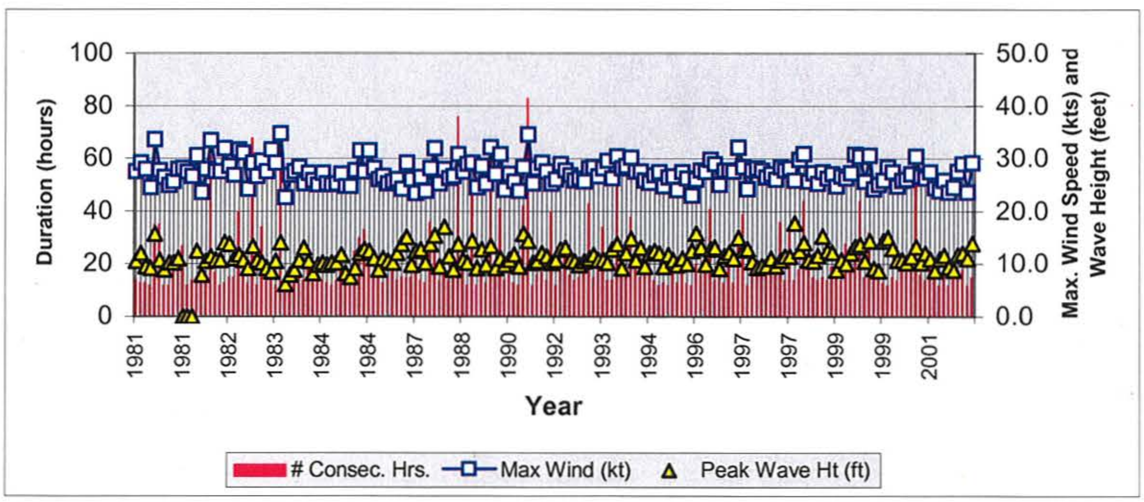


Figure 17. Duration of wind events (buoy # 46014) >= 20 knots and >= 12 hours, with associated maximum wind speeds and wave heights (zero-values denote missing data).

e. Long-term correlation between pressure gradients (between buoys) and wind speeds (at the buoys). Correlation coefficients were calculated using all buoy data available for the summer months (June-September) through 2001, in order to evaluate relative strength and weakness of the long-term gradient-wind speed relationships. Consideration was given only to the absolute difference of pressure gradients and their relation to wind speed. Wind direction and orientation of the pressure gradients were not evaluated. Correlation coefficients between wind speeds and pressure gradients at the same times were calculated. Additionally, correlation coefficients for specified "lag times" (time of observed pressure gradient – time of observed wind speed) up to 24 hours were calculated to assess possible predictive value. Although buoy #46030 wind and pressure data was available for the period of study, it was not used. As noted previously, buoy #46030 is no longer located off Cape Mendocino, and therefore the results of the analysis at this particular location are of only limited use for future predictive purposes. The correlation coefficient results for the other three buoy locations are given in Figures 18-20.

Overall, correlation was strongest ($r = 0.68$) between wind speeds at buoy #46014 and the buoy #46022-46014 pressure gradients with a lag time = 0 hours (pressure gradient and wind speed at the same time). Thereafter, correlation coefficients steadily decreased, to 0.40 with a lag time = 24 hours. In some cases, however, correlation coefficients actually increased as lag time increased. At buoy #46027, correlation coefficients (using #46027-46014 pressure gradients) increased from 0.25 at lag time = 0 hours to 0.41 at lag time = 14 hours. Also at bouy #46027, while correlation coefficients initially dropped from 0.50 (at lag time = 0 hours) to 0.11 (at lag time = 10 to12 hours), they then rose back to 0.30 at lag time =24 hours, possibly due (at least in part) to repetitive, and at times strongly diurnal wind patterns at this location. Other correlation coefficients (as shown below) also showed some increasing tendencies as lag time increased, indicating possible predictive value. Pressure gradient and wind speed relationships are evaluated in more detail in some of the case studies to follow.

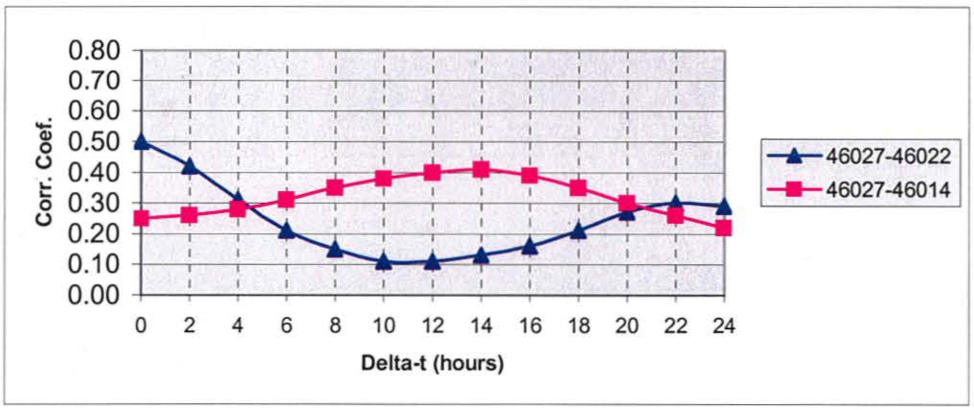


Figure 18. Wind speed (buoy #46027) and pressure gradient (absolute value) correlation coefficients for specified "lag times," i.e. pressure gradient at time=t and wind speed at time= t + delta-t).

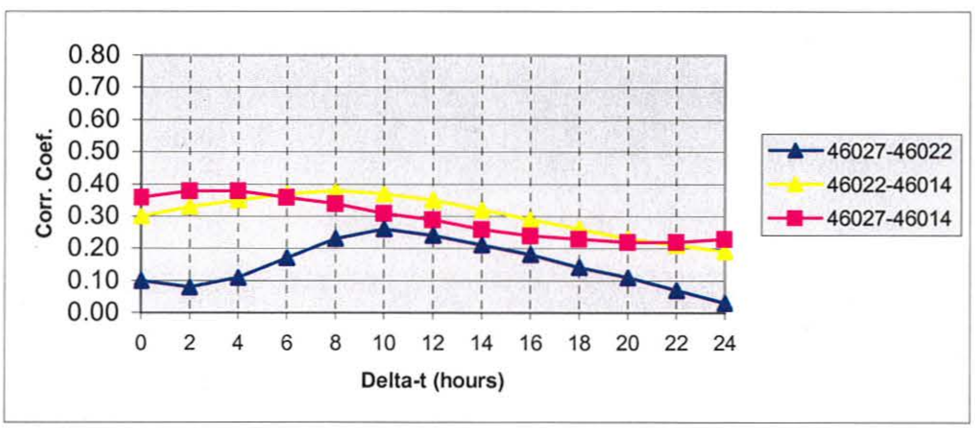


Figure 19. Wind speed (buoy #46022) and pressure gradient (absolute value) correlation coefficients for specified "lag times," i.e. pressure gradient at time=t and wind speed at time= t + delta-t).

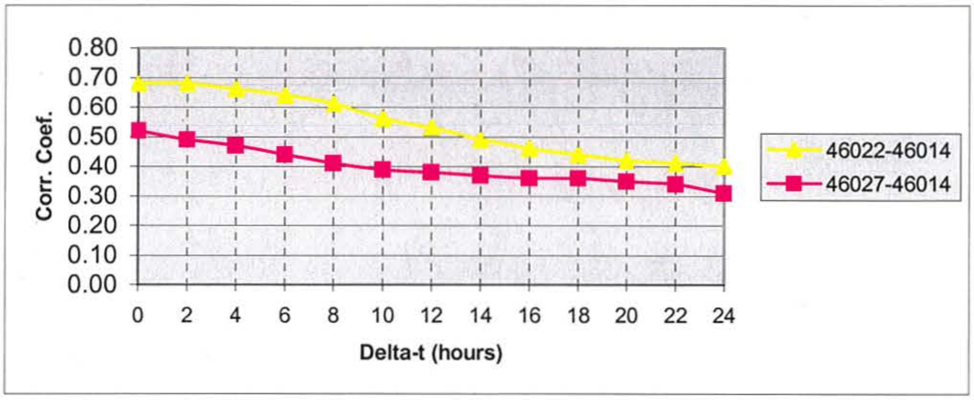


Figure 20. Wind speed (buoy #46014) and pressure gradient (absolute value) correlation coefficients for specified "lag times," i.e. pressure gradient at time=t and wind speed at time= t + delta-t).

Appendix 1. Data Inventory.

("X" denotes available data; blanks denote periods of missing data)

Buoy #46014 (19 NM northwest of Pt. Arena)

Operational Period (month/year)	*Mean Sea Level Pressure*	*Wind (Speed/Direction)*	*Wave (height and period)*
4/81-2/83	X	X	X
3/83-5/83	X	X	
5/83-4/84	X	X	X
5/84-6/84	X		X
7/84-4/86	X	X	X
5/86	X	X	
6/86-3/88	X	X	X
4/88	X		X
5/88-9/88	X	X	X
1/89	X	X	X
2/89-3/89	X	X	X
4/89-5/89	X	X	X
6/89-11/89	X	X	X
12/89-1/90	X	X	X
2/90-7/90	X	X	X
8/90	X	X	X
9/90	X	X	X
10/90-1/91	X	X	X
2/91	X	X	X
3/91-4/91	X	X	X
5/91	X	X	X
6/91-8/91	X	X	X
9/91-10/91	X	X	X
12/91	X	X	X
6/92-2/93	X	X	X
5/93-5/95	X	X	X
6/95	X		X
7/95	X	X	X
8/95-7/98	X	X	X
8/98-11/98	X	X	X
12/98-09/99	X	X	X
10/99-12/01	X	X	X

Buoy #46022 (17 NM West-Southwest of Eureka)

Operational Period (month/year)	*Mean Sea Level Pressure*	*Wind (Speed/Direction)*	*Wave (height and period)*
2/83-12/83	X	X	X
1/84	X		X
2/84-9/84	X	X	X
9/84-1/85	X	X	
1/85-11/86	X	X	X
3/87-9/88	X	X	X
10/88-11/88	X	X	
12/88-1/89	X	X	X
2/89-5/89	X	X	X

6/89-5/90	X	X	X
6/90-7/90	X	X	X
9/90-11/90	X	X	X
12/90	X	X	X
2/91-9/92	X	X	X
10/92-11/92	X	X	X
12/92-3/93	X	X	X
5/93-12/93	X	X	X
1/94-2/94			
3/94-5/96	X	X	X
1/97-3/98	X	X	X
7/98-01/00	X	X	X
06/00-12/01	X	X	X

Buoy #46027 (8 NM West of Crescent City)

Operational Period (month/year)	*Mean Sea Level Pressure*	*Wind (Speed/Direction)*	*Wave (height and period)*
9/83-3/84	X	X	
6/84-10/84	X	X	
4/85-8/85	X	X	X
10/85-8/86	X	X	X
11/86-12/86	X	X	X
1/87-9/88	X	X	X
10/88	X	X	
11/88-12/88		X	
3/89-8/89	X	X	X
9/89-11/89		X	X
12/89-6/90	X	X	X
7/90-8/90	X		X
9/90-10/91	X	X	X
12/91-3/92	X	X	X
4/92-5/93	X		X
9/93-6/95	X	X	X
9/95-12/96	X	X	X
9/97-10/98	X	X	X
01/99-04/99	X	X	X
05/99-10/00	X	X	X
10/00-12/01	X	X	X

Buoy #46030 (Formerly Near Cape Mendocino)

Operational Period (month/year)	*Mean Sea Level Pressure*	*Wind (Speed/Direction)*	*Wave (height and period)*
10/84-1/85	X	X	
2/85	X	X	
3/85-3/86	X	X	
4/86-5/86	X		
8/86-11/86	X	X	
3/88-2/90	X	X	X
3/90	X		X
4/90-10/90	X	X	X
11/90-12/90	X	X	X

2/91-10/91	X	X	X
12/91	X	X	X
10/92-7/93	X	X	X
8/93	X		X
9/93-2/94	X	X	X
3/94-4/94	X	X	X
5/94-7/94			
8/94-3/95	X	X	X
4/95-5/95	X		X
6/95-10/97	X	X	X
07/98-01/99	X	X	X
02/99-06/99	X	X	
07/99-08/99			
09/99-11/00	X	X	X
12/00-03/01	X	X	X
04/01-09/01	X	X	X

References.

Beardsley, R.C., C. E. Dorman, C.A. Friehe, L.K., and C.D. Winant, 1987: Local Atmospheric Forcing During the Coastal Ocean Dynamcis Experiment, 1. A Description of the Marine Boundary Layer and Atmospheric Conditions Over a Northern California Upwelling Region. Journal of Geophysical Research, 92, 1467-1488.

Burke, S.D. and W.T. Thompson, 1996: The Summertime Low-Level Jet and Marine Boundary Layer Structure along the California Coast. Monthly Weather Review, 124(4), 668-686.

Gilhousen, D.B., 1987: A field evaluation of NDBC moored buoy winds. Journal of Atmospheric and Oceanic Technology, 4, 94-104.

Mass, C. F. and M. D. Albright, 1987: Coastal Souterlies and Alongshore Surges of the West Coast of North America: Evidence of Mesoscale Topographically Trapped Response to Synoptic Forcing. Monthly Weather Review, 115, 1707-1738.

Neiburger, M., D.S. Johnson, and Chen Wu Chien, 1961: Studies of the structure of the atmosphere over the eastern Pacific Ocean in summer, Pt. 1: The inversion over the eastern north Pacific Ocean. Publications in Meteorology, Univ. of California, 1(1), 1-94.

Tucker, M.J., 1991: Waves in Ocean Engineering: Measurement, Analysis, and Interpretation. Ellis Horwood, LTD., 431 pp.

Steele, K.E. and T.R. Mettlach, 1993: NDBC wave data - current and planned. Ocean Wave Measurement and Analysis - Proceedings of the Second International Symposium. ASCE, 198-207.

3. Case studies.

a. Case #1. Periodic Event: Buoys #46027, #46022, #46030, and #46014 (12-23 June 2001).

(1) Event description: Figures 3a(1) through 3a(4) show the wind speed and wave height trends for buoys 46027, 46022, 46030, and 46014, respectively, and Figures 3a(5) through 3a(8) show the corresponding wind direction and wind speed trends. This event was characterized by strong diurnal variations in both wind speed and wave height over an extended period (12 consecutive days).

Winds were typically moderate to strong from the north to northwest at favored times of day, depending on each buoy. Diurnal tendencies were most pronounced during this period at buoy 46027, where wind speeds typically varied from near calm in the early morning, to moderate or strong in the early evening. Wind speed increases occurred rapidly on most days, especially at buoys 46027 and 46014, where hourly increases up to 14 knots occurred. For the 12 days as a whole, winds were strongest at buoy 46027, with 9 of the 12 days peaking at or above 25 knots (maximum 31 knots with gusts to 39 knots). Conversely, winds were weakest overall at buoy 46022, where daily wind peaks were typically only about 12-15 knots. Diurnal trends were more difficult to assess at buoy 46022 due to frequent missing data.

Wave heights also tended to follow diurnal patterns, generally following the wind trends. Wave heights were highest overall at buoy 46014, which is not surprising, since its location was near the downwind end of the fetch for most of this period.

(2) General Weather Situation: Figures 3a(9) through 3a(20) show the surface and upper air analyses for this event. A strong surface pressure gradient prevailed along the northern California and southern Oregon coasts, due to interaction between the thermal trough and high pressure off the coast. The upper air pattern was characterized by a series of weak upper level lows moving through the Pacific Northwest, with a generally zonal flow over northern California. This pattern persisted until a stronger upper trough moved southeast from the Gulf of Alaska near the end of the event. The surface pressure gradients then weakened, as a pair of weak cold fronts moved into northwest California in association with the upper trough.

(3) Harmonic Analysis of wind speed and wave height. Harmonic analysis was conducted on wind speeds and wave heights, with a fundamental period of 24 hours to assess the diurnal trends in a more detailed fashion. Analysis was not conducted for buoy 46022 due to frequent missing data. Table 3a and Figures 3a(21) through 3a(24) summarize the results of the analysis for buoys 46027 and 46014, where diurnal trends were strongest. Overall, buoy 46027 showed 47 percent of the total variance to be explained by the first harmonic (period = 24 hours), with each day individually exceeding 60 percent, and seven days exceeding 80 percent. Concerning wave heights for this case, buoy 46027 also displayed the highest percent-variance (23.6%) explained by the first harmonic.

(4) Pressure Gradients. Figures 3a(25) through 3a(27) show wind speeds for buoys #46027, 46030, and 46014, along with absolute values of the pressure gradients (46027-46022, 46022-46014, and 46027-46014) for this event. The actual numerical pressure values appeared to be somewhat suspect, based on comparison with the surface pressure analyses in Figures 3a(9)-(20), especially for buoys #46027 and/or #46022. In most cases, the 46027-46014 pressure difference should have been larger than the 46022-46014 difference (given the observed pressure patterns and larger distance between buoys), but for this period the *opposite* was generally true. It is possible that there could have been a pressure sensor calibration problem at one or both of the buoys. However, the actual pressure values are much less important than the *trends*, which do appear to be reasonable. Wind speed data for 46022 was not included here, due to frequent periods of missing data.

Harmonic analysis was also conducted on wind speeds and pressure gradients for this event (Figures 3a(28) thorugh 3a(30)), to better illustrate the timing differences of each cycle, as well as the overall strength of relationships. Similar to the wind speeds, each set of pressure gradients displayed definite diurnal tendencies for the duration of the event, with the first harmonic of the 46027-46022 pressure gradients explaining 63.5 percent of the observed variance over the 12 days of the event (highest of the three sets of pressure gradients for this event).

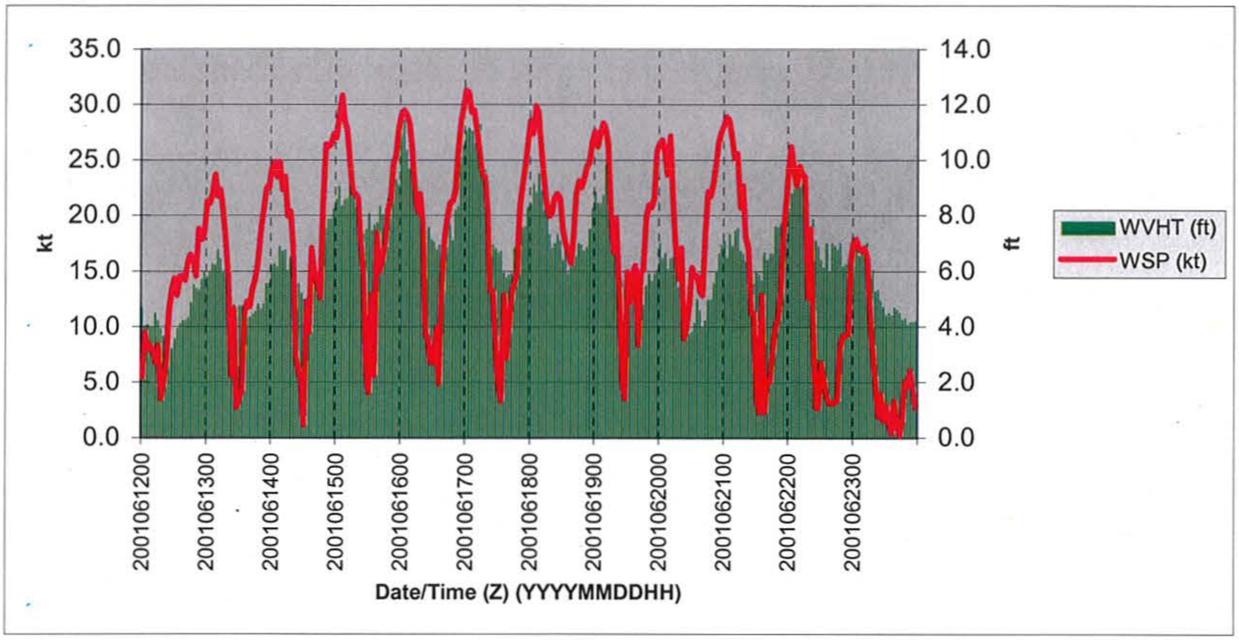


Figure 3a(1). Wind speed and wave height, buoy #46027 (12-23 June 2001).

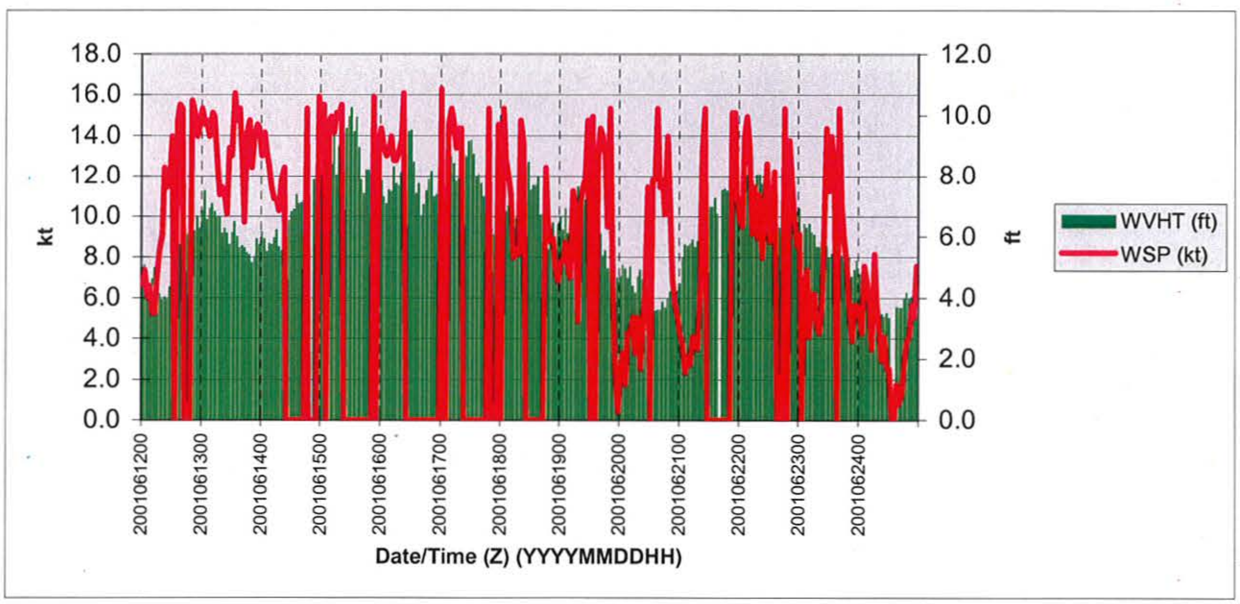


Figure 3a(2). Same as Figure 3a(1), but for buoy #46022. Zero-values denote missing data.

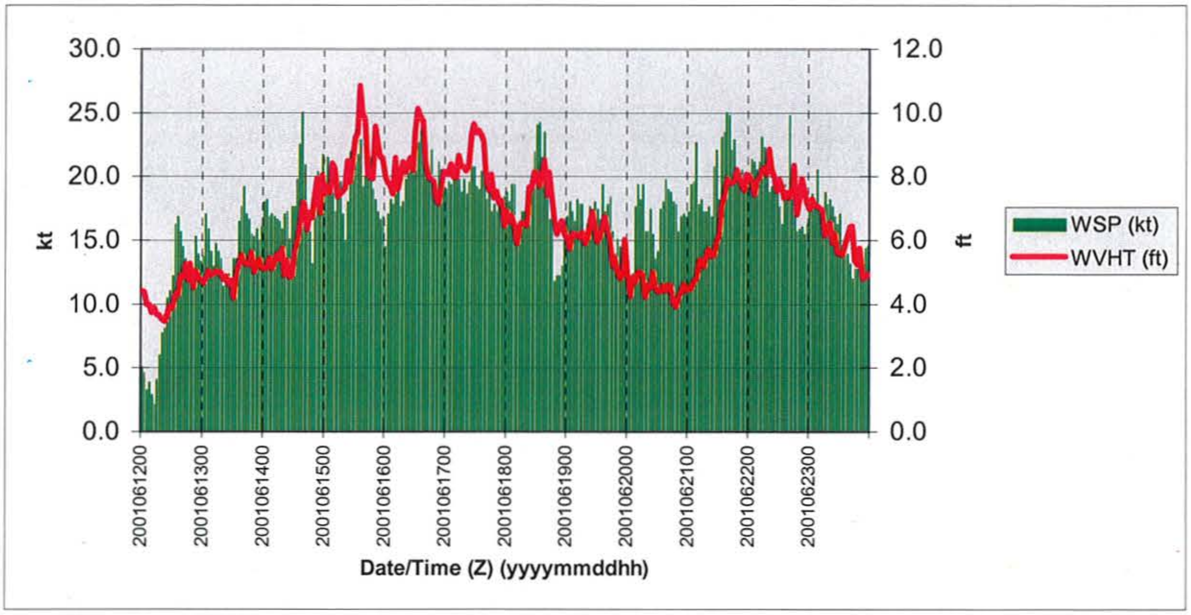


Figure 3a(3). Same as Figure 3a(1), but for buoy #46030.

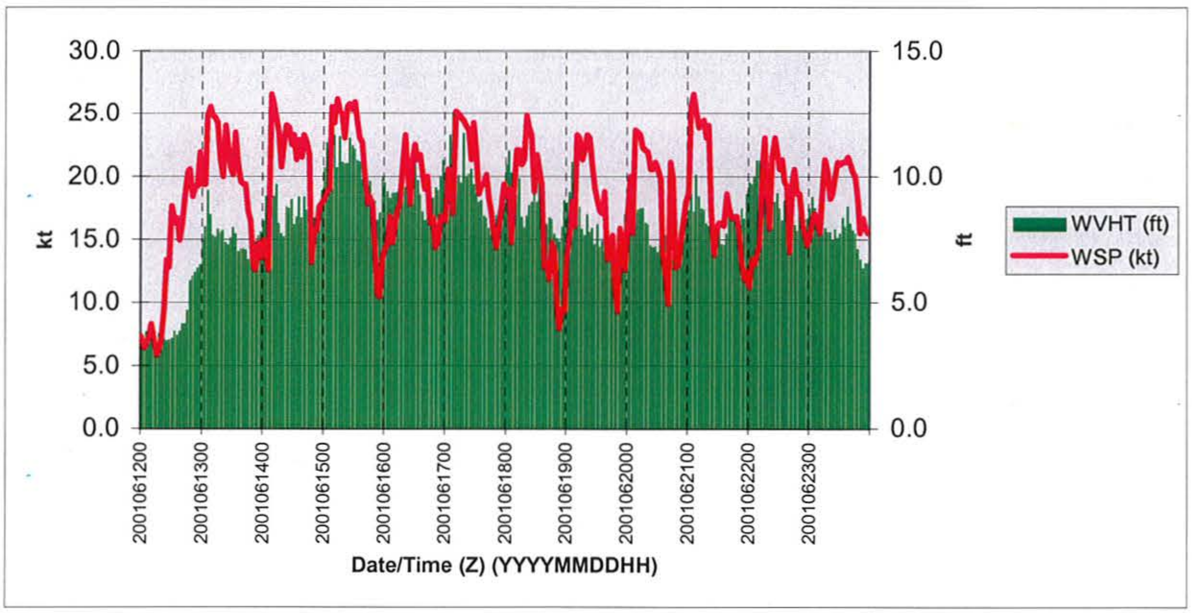


Figure 3a(4). Same as Figure 3a(1), but for buoy #46014.

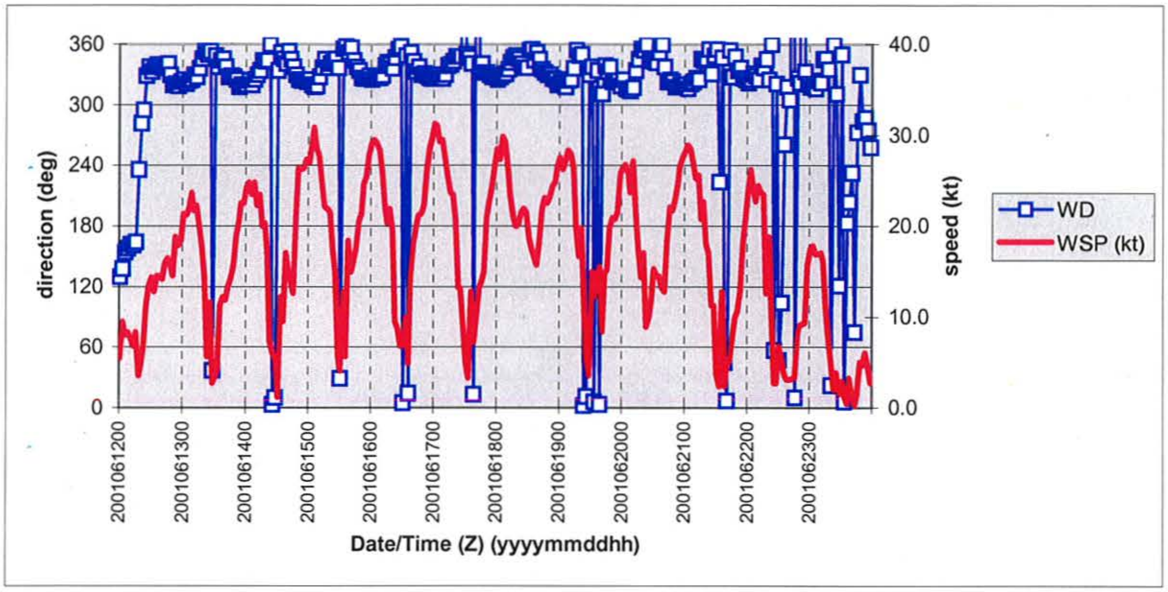


Figure 3a(5). Wind speed and direction, buoy #46027 (June 12-23, 2001).

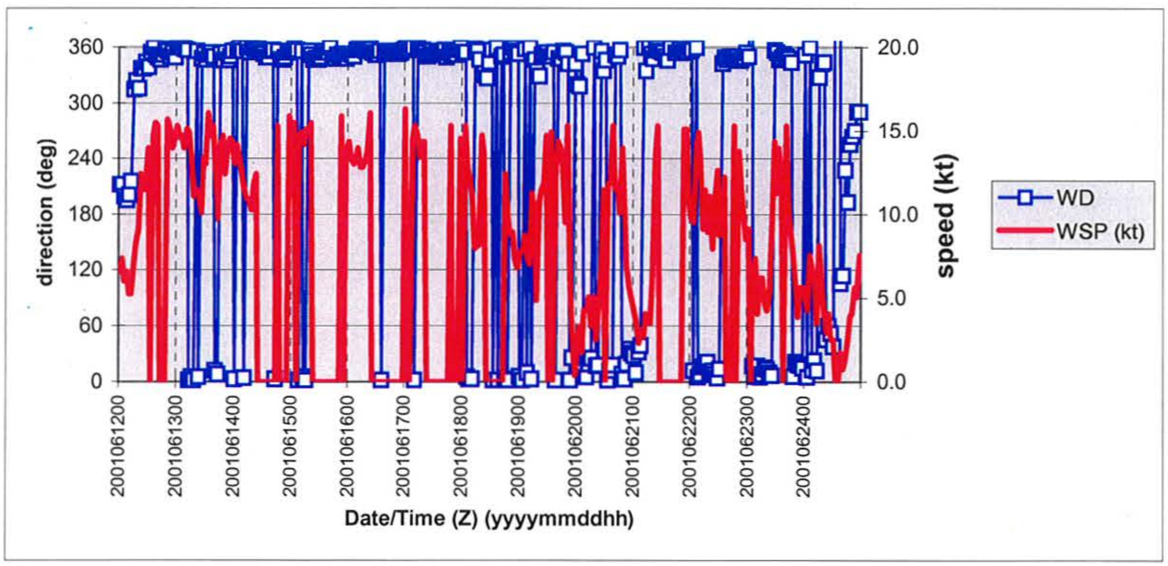


Figure 3a(6). Same as Figure 3a(5), but for buoy #46022. Zero-values (speed) denote missing data.

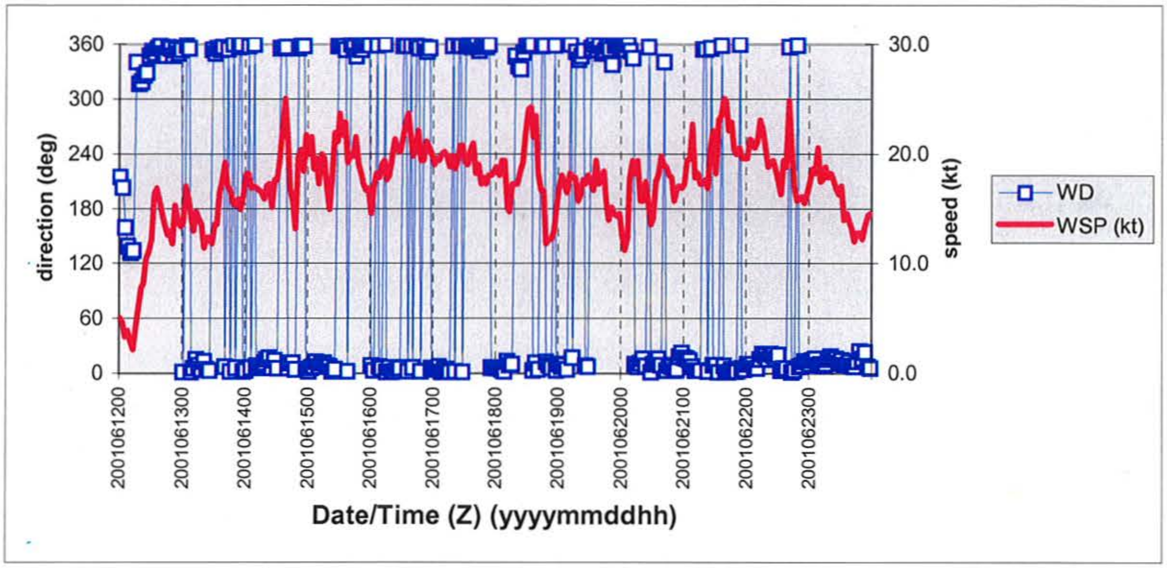


Figure 3a(7). Same as Figure 3a(5), but for buoy #46030.

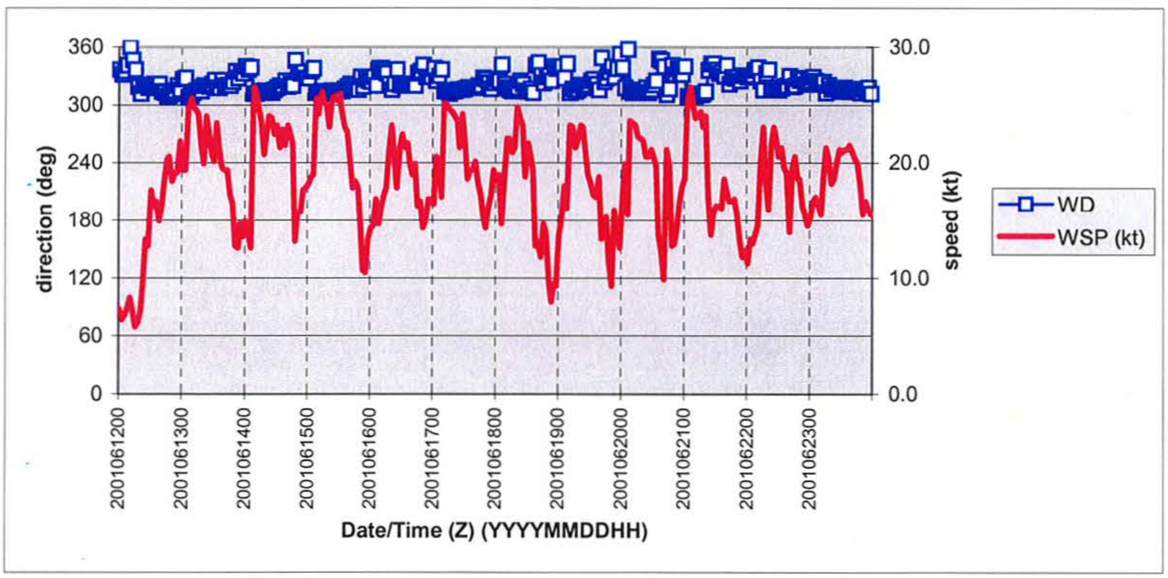


Figure 3a(8). Same as Figure 3a(5), but for buoy #46014.

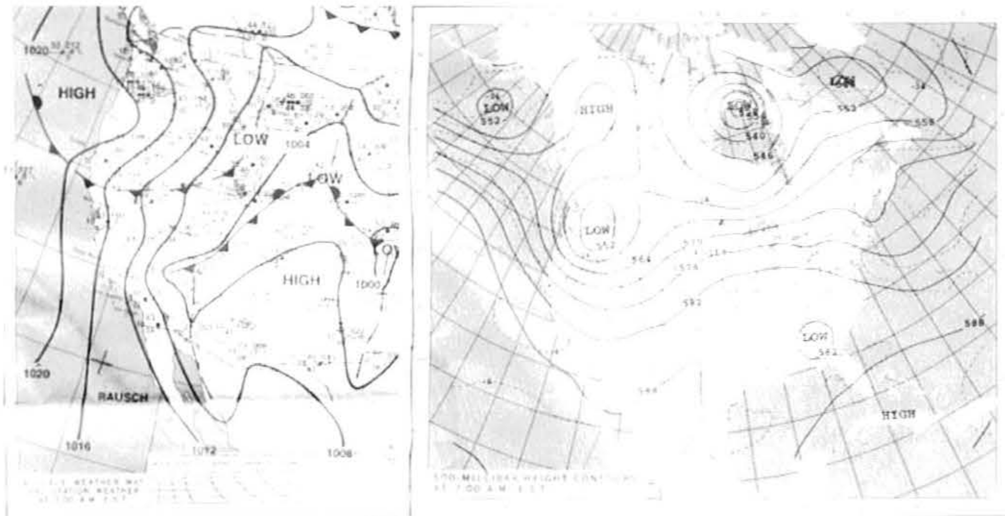
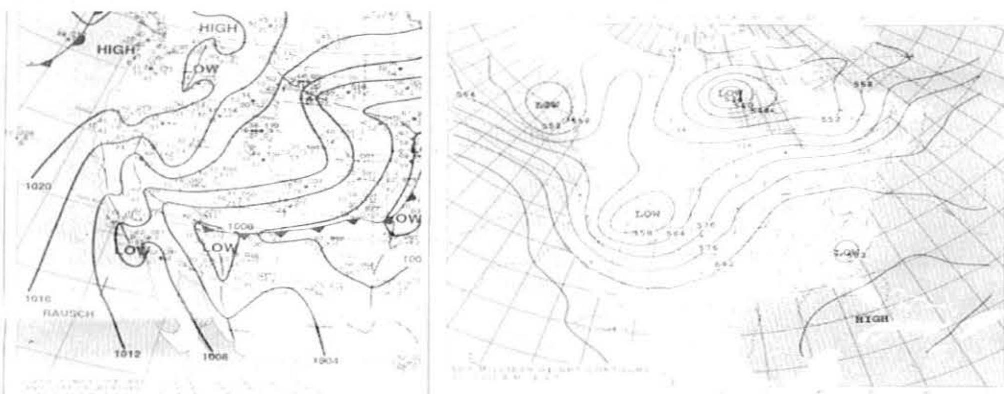
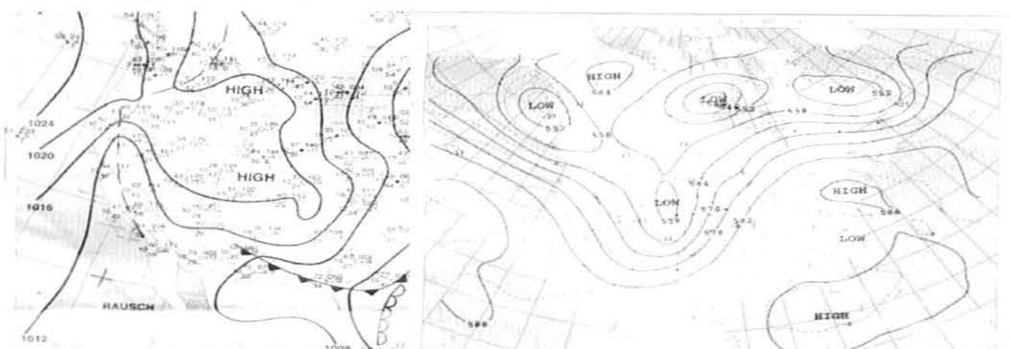


Figure 3a(9). Surface analysis (left) and 500 mb analysis (right) : 1200Z, 12 June 2001.



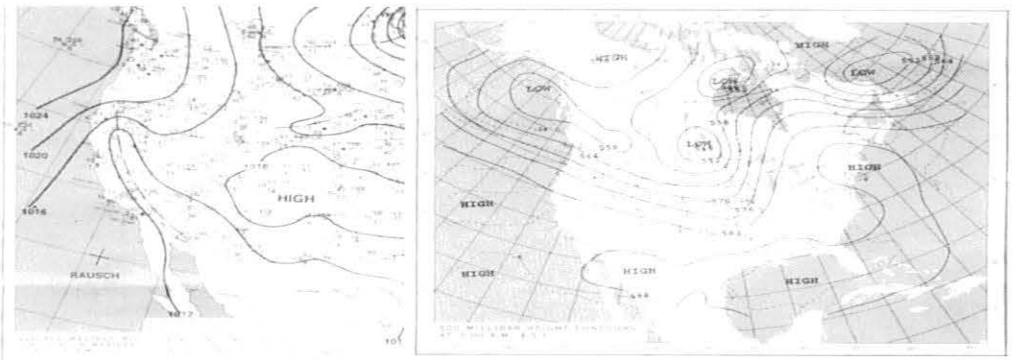
June 13, 2001

Figure 3a(10). Same as Figure 3a(9), but for 13 June 2001.



June 14, 2001

Figure 3a(11). Same as Figure 3a(9), but for 14 June 2001.



June 15, 2001

Figure 3a(12). Same as Figure 3a(9), but for 15 June 2001.

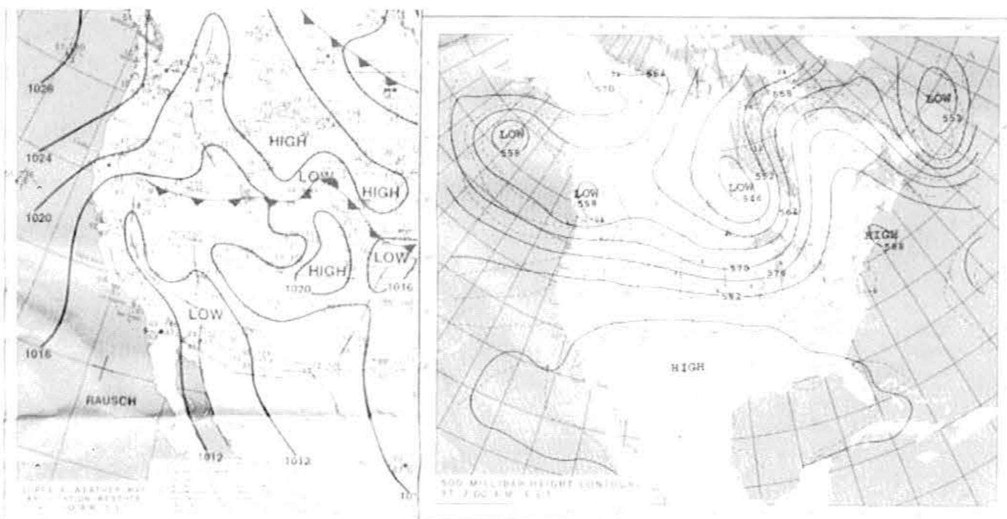
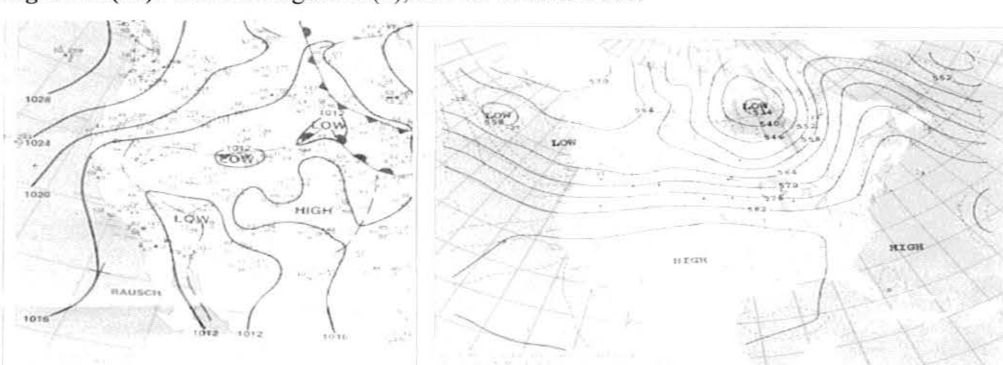
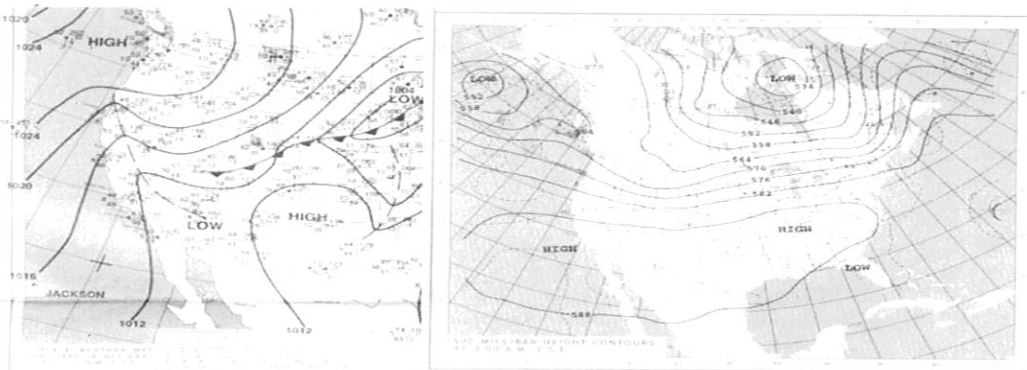


Figure 3a(13). Same as Figure 3a(9), but for 16 June 2001.



June 17, 2001

Figure 3a(14). Same as Figure 3a(9), but for 17 June 2001.



June 18, 2001

Figure 3a(15). Same as Figure 3a(9), but for 18 June 2001.

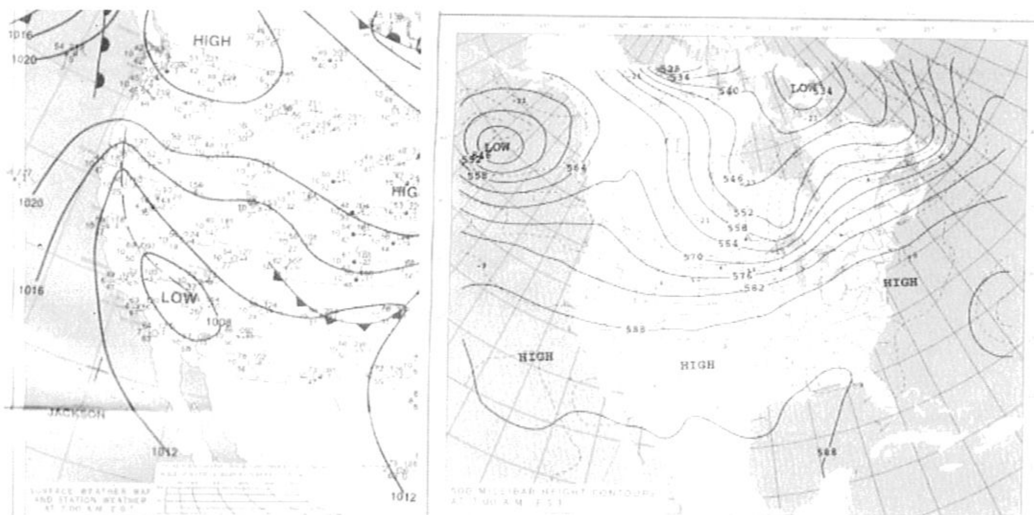


Figure 3a(16). Same as Figure 3a(9), but for 19 June 2001.

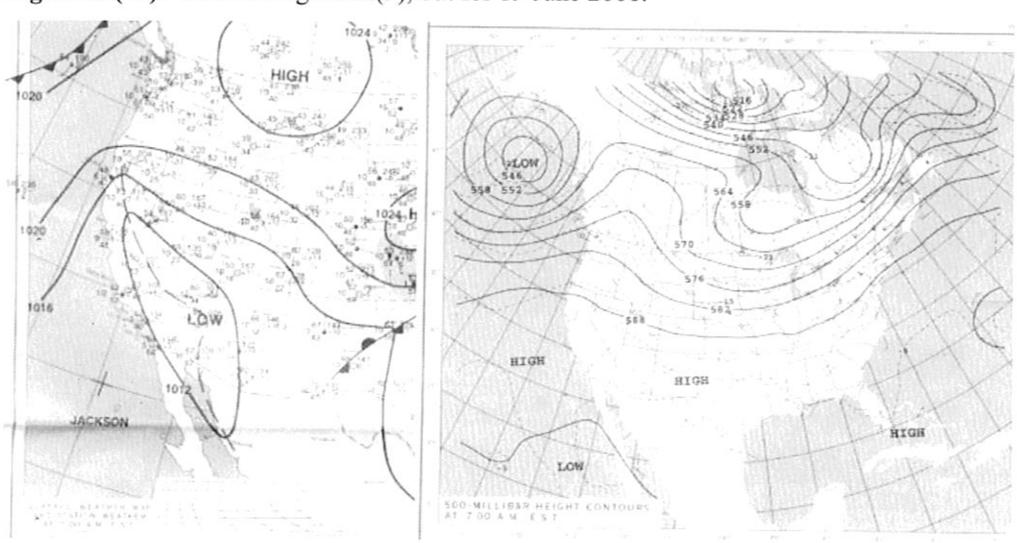


Figure 3a(17). Same as Figure 3a(9), but for 20 June 2001.

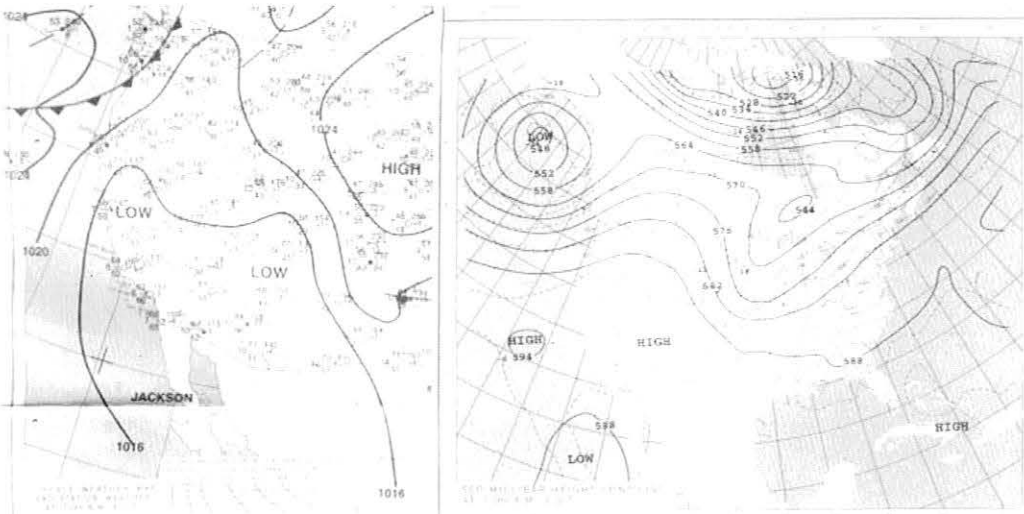


Figure 3a(18). Same as Figure 3a(9), but for 21 June 2001.

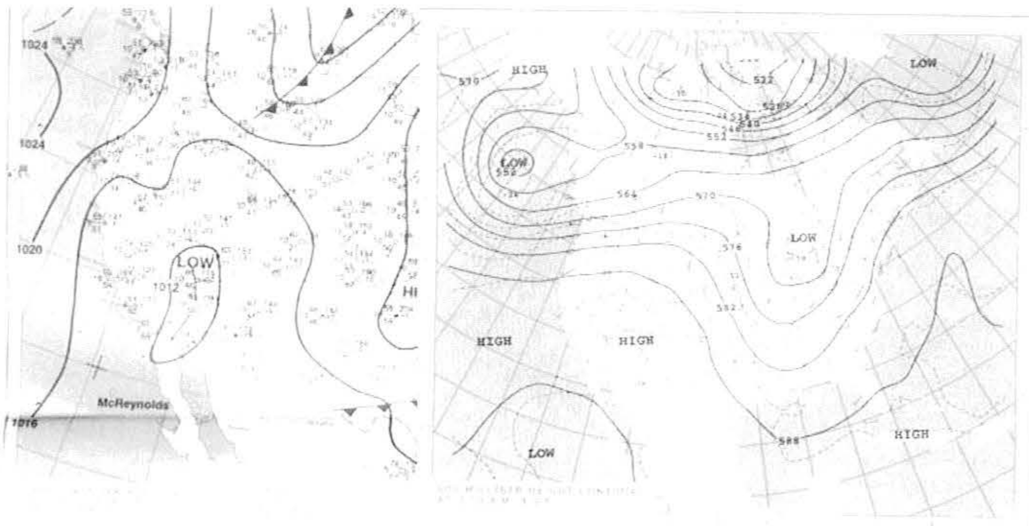


Figure 3a(19). Same as Figure 3a(9), but for 22 June 2001.

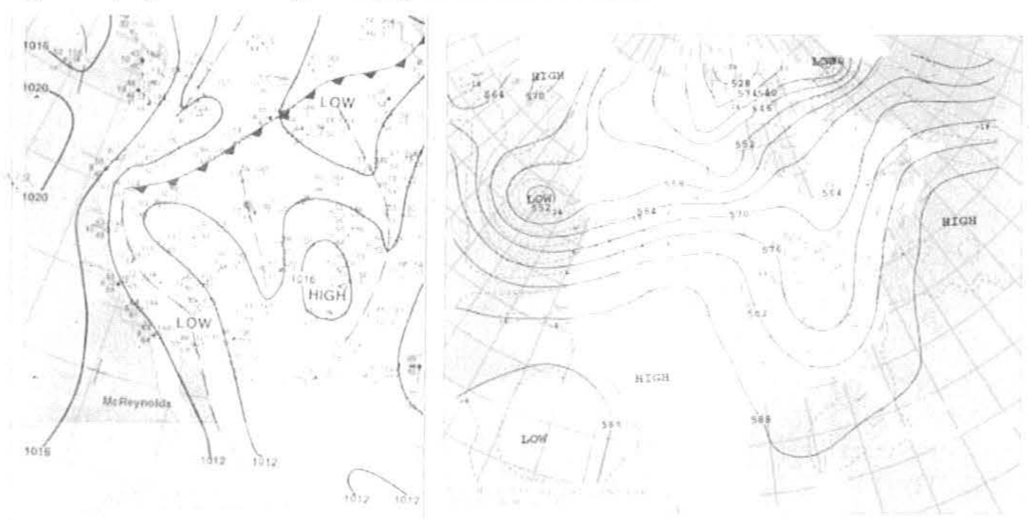


Figure 3a(20). Same as Figure 3a(9), but for 23 June 2001.

Table 3a. Time of peak amplitude and percent-variance explained by the first harmonics of wind speed and wave height (period = 24 hours) at buoys #46027 and #46014 (12-23 June 2001).

	#46027				#46014			
	Wind		*Wave*		*Wind*		*Wave*	
Day	**Time (Z)**	**Percent Variance Explained**	**Time (Z)**	**Percent Variance Explained**	**Time (Z)**	**Percent Variance Explained**	**Time (Z)**	**Percent Variance Explained**
1	0500	67.7%	0142	69.6	1830	72.7%	2142	56.7
2	0142	80.4%	0436	88.7	0830	58.2%	0454	43.8
3	0100	77.4%	0118	58.2	1048	44.9%	0000	9.4
4	0206	81.3%	0142	61.5	1000	77.4%	0748	55.1
5	0112	86.8%	0236	84.1	1224	71.3%	0730	19.6
6	0242	90.5%	0418	87.1	0842	72.1%	0600	73.0
7	0200	77.0%	0342	74.6	0906	76.8%	0530	21.3
8	0200	74.7%	0436	75.7	0848	76.3%	0436	61.2
9	0042	84.3%	0200	84.2	0718	51.6%	0430	60.4
10	0354	87.4%	0024	67.5	0548	47.1%	0200	46.1
11	0400	83.2%	0506	65.9	1254	50.9%	0606	75.5
12	0342	71.9%	0512	67.7	1318	72.1%	0745	14.7
ALL	***0206***	***47.2%***	***0312***	***23.6***	***1042***	***22.0%***	***0530***	***6.8***

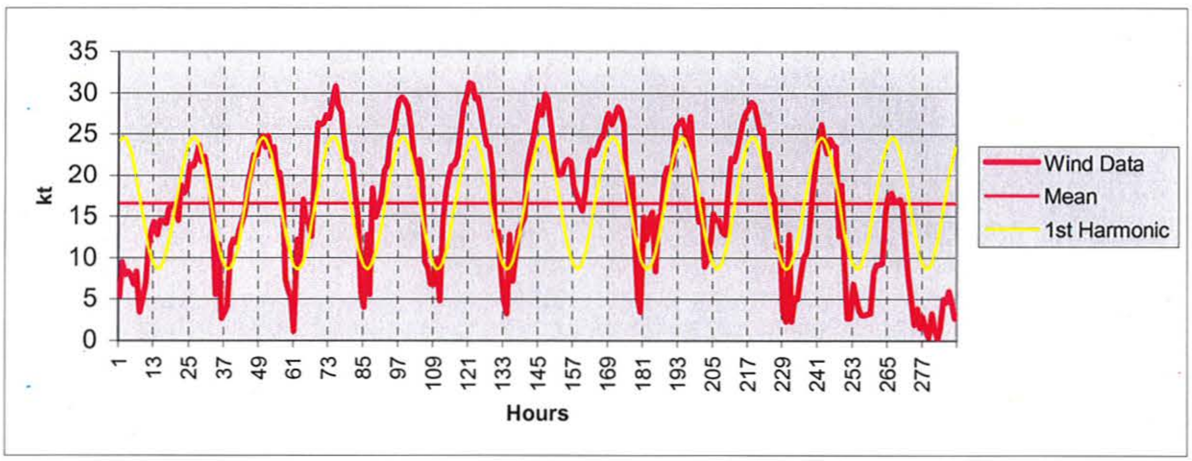


Figure 3a(21). Harmonic analysis of wind speed data, Buoy #46027, 12-23 June 2001.

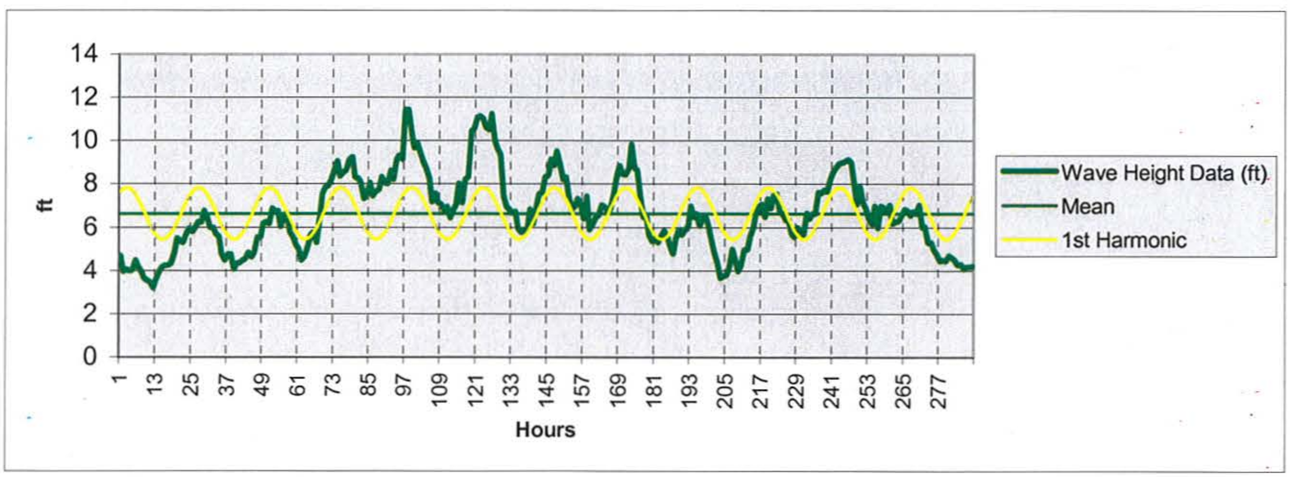


Figure 3a(22). Harmonic analysis of wave height data, buoy #46027, 12-23 June 2001.

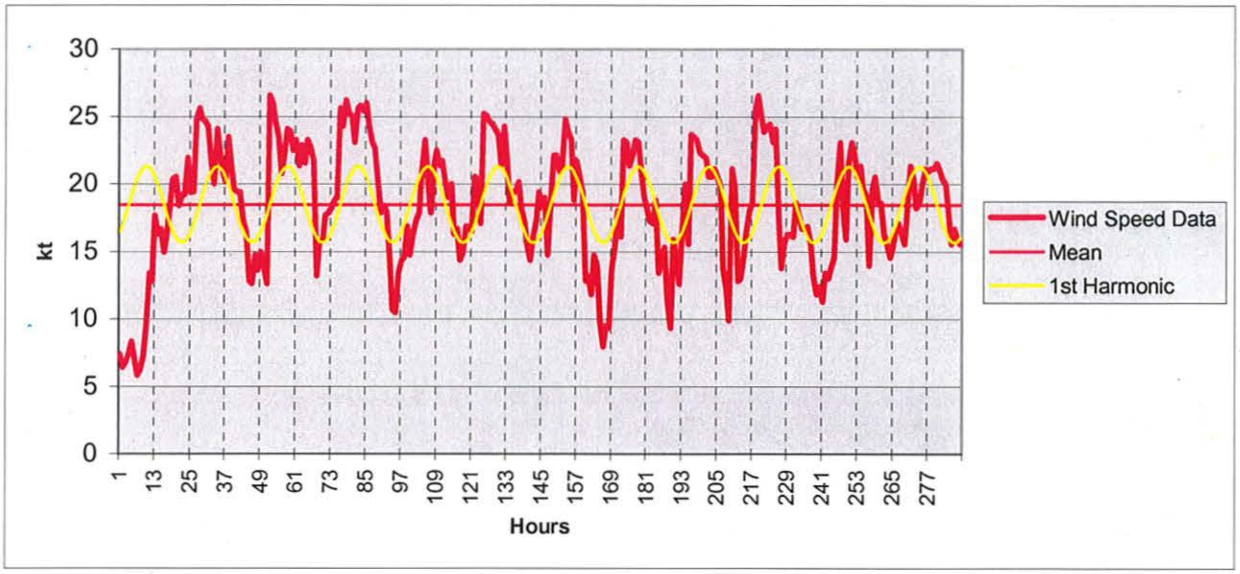


Figure 3a(23). Harmonic analysis of wind speed data, buoy #46014, 12-23 June 2001.

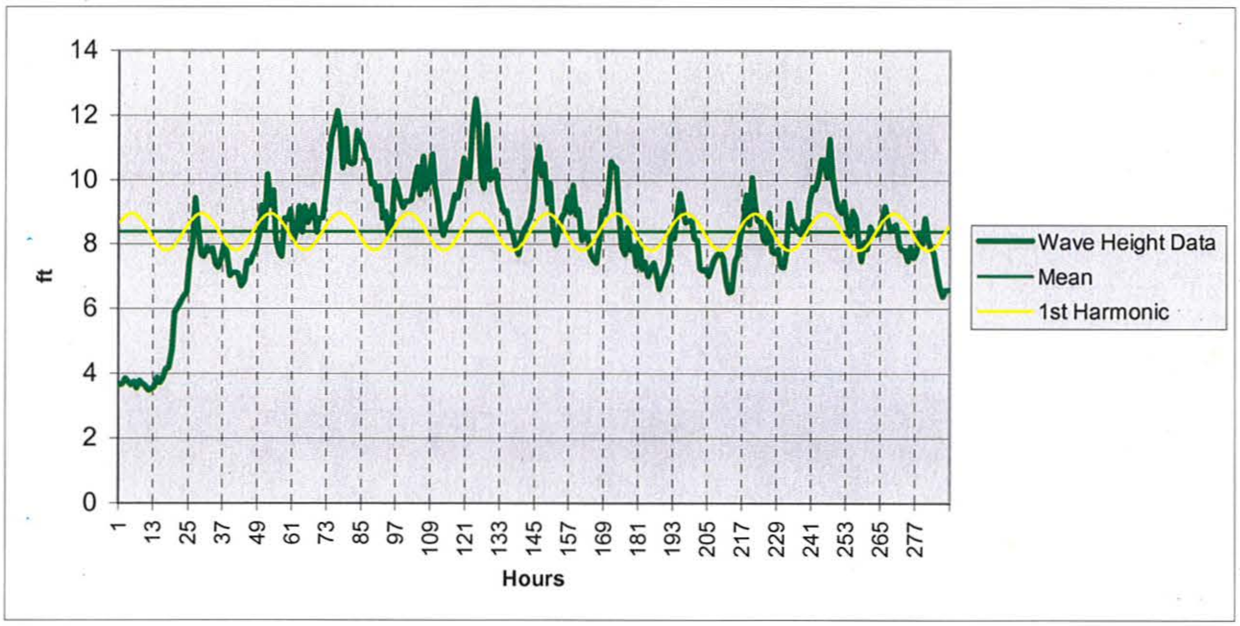


Figure 3a(24). Harmonic analysis of wave height data, buoy #46014, 12-23 June 2001.

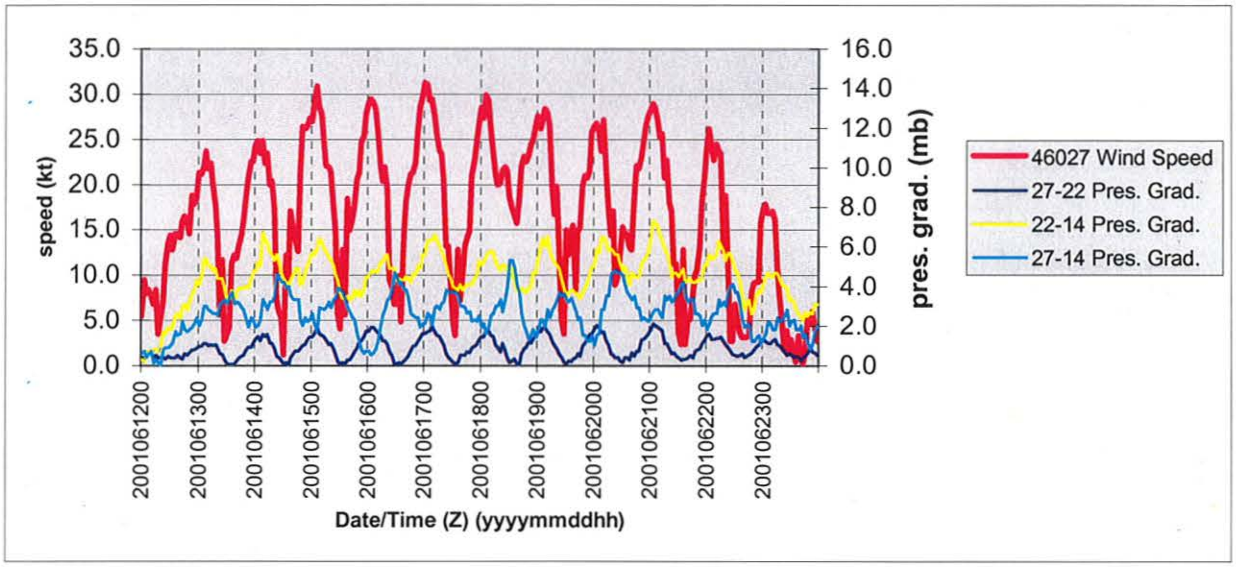


Figure 3a(25). Wind speed (#46027) and pressure gradients (between buoys) , 12-23 June 2001.

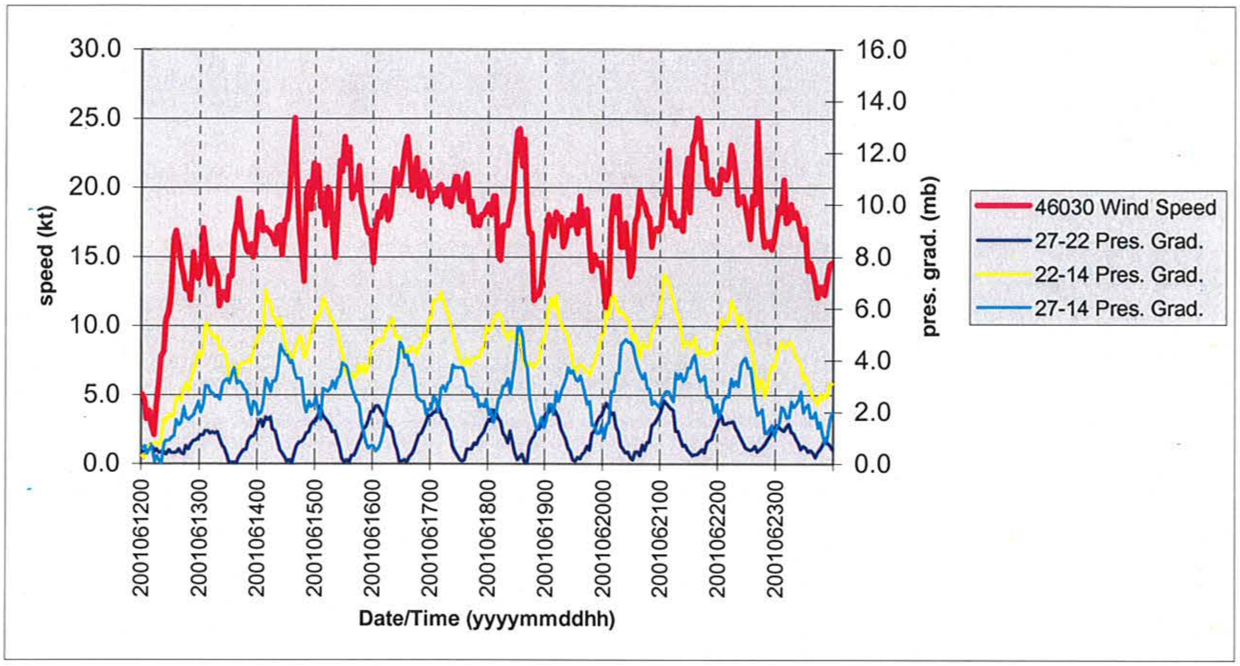


Figure 3a(26). Wind speed (#46030) and pressure gradients (between buoys) , 12-23 June 2001.

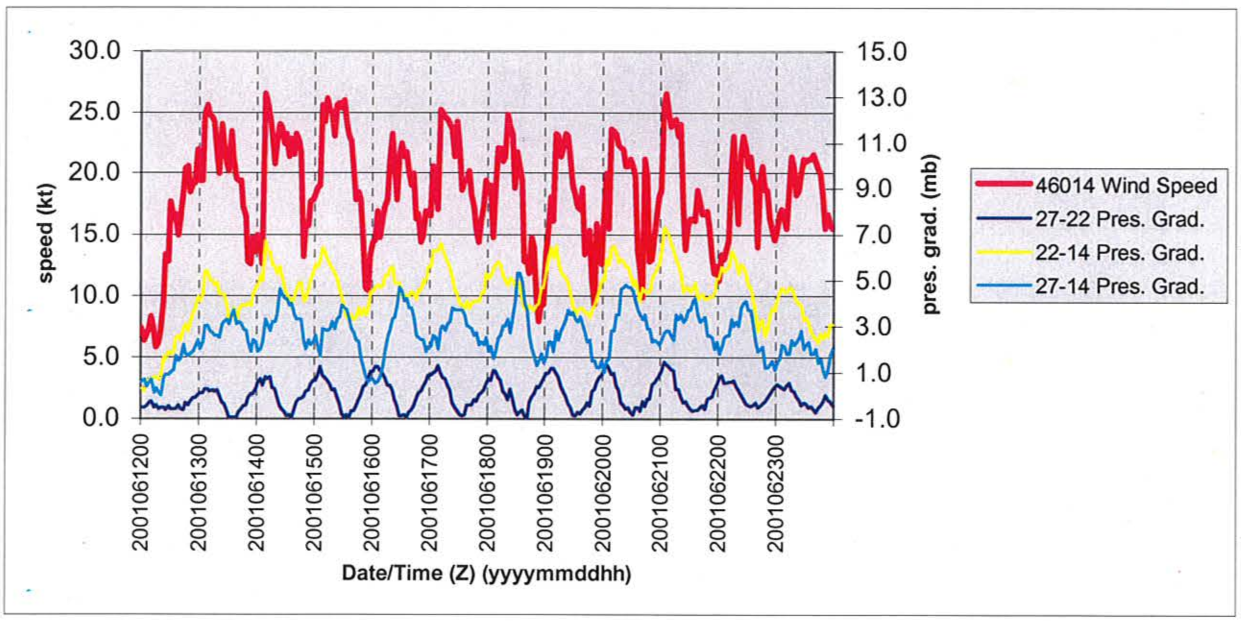


Figure 3a(27). Wind speed (#46014) and pressure gradients (between buoys) , 12-23 June 2001.

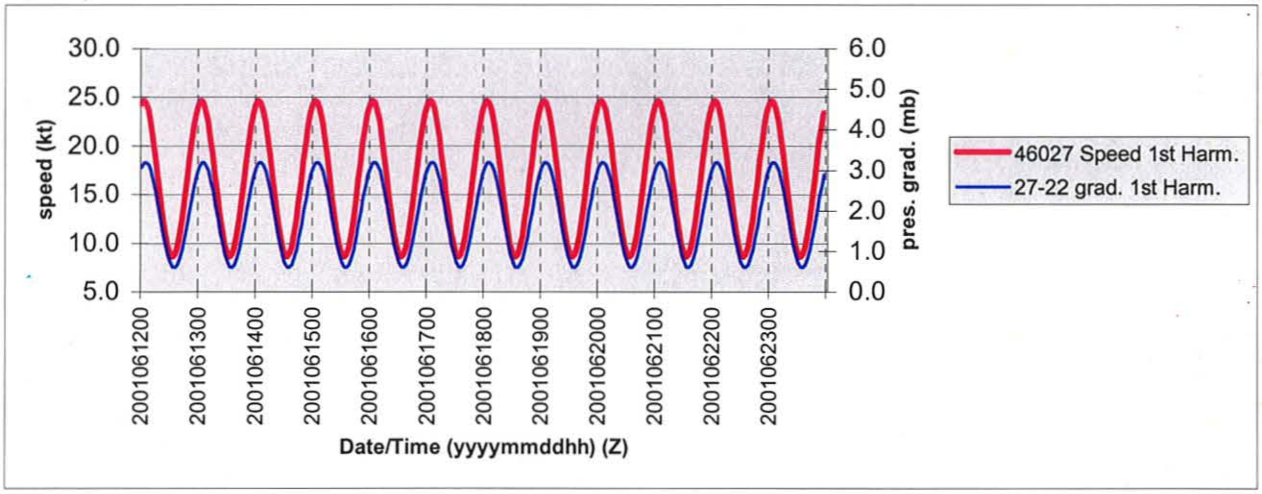


Figure 3a(28). First harmonics of wind speed (#46027) and pressure gradient magnitudes (#46027-46022), 12-23 June 2001.

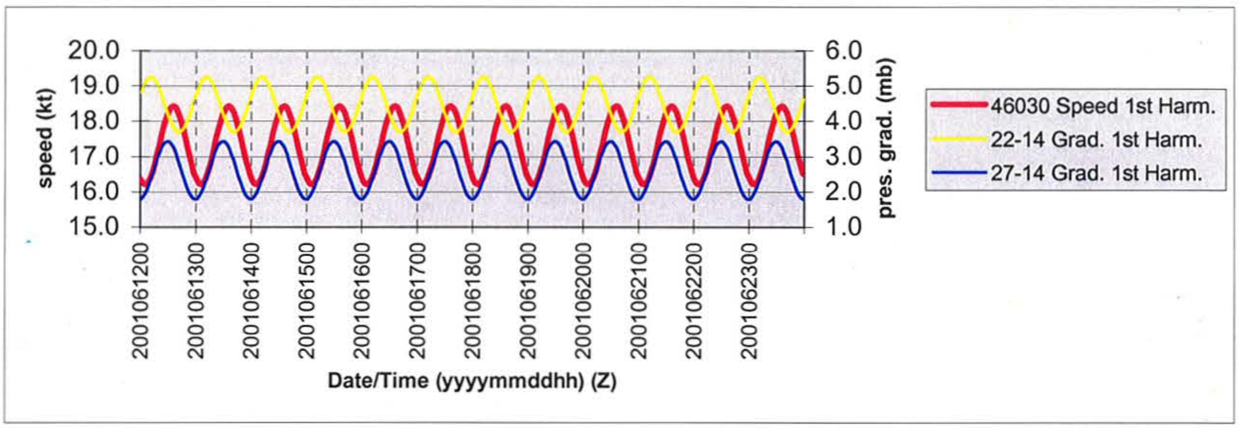


Figure 3a(29). First harmonics of wind speed (#46030) and pressure gradient magnitudes (#46027-46014 and #46022-46014), 12-23 June 2001.

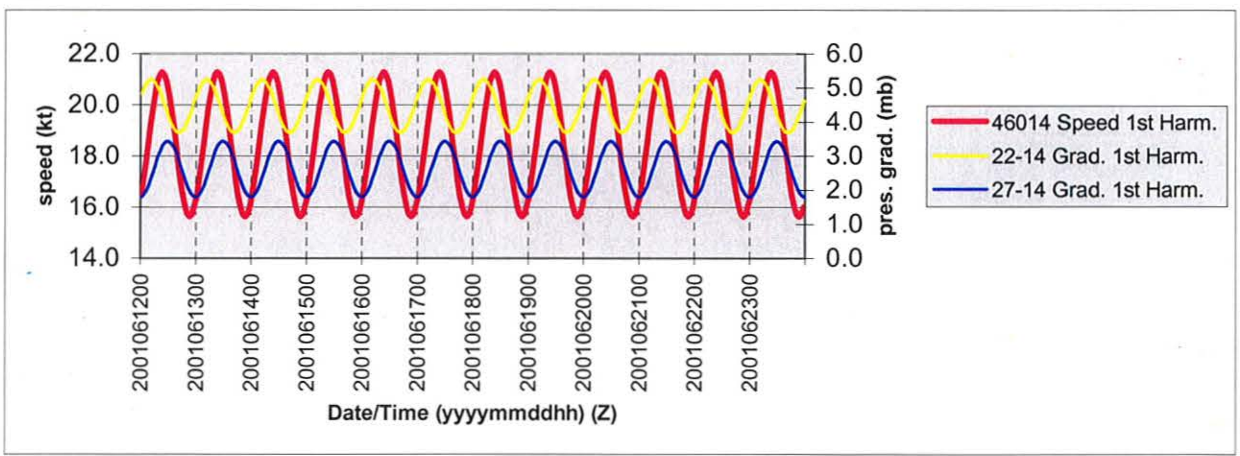


Figure 3a(30). First harmonics of wind speed (#46014) and pressure gradient magnitudes (#46022-46014 and #46027-46014), 12-23 June 2001.

b. Case #2. Rapid Rise in Wave Height: Buoy #46022 (13-16 July 1982).

(1) Event description: Figure 3b(1) shows wind speed and wave height trends for this case, while Figure 3b(2) shows wind speed and direction trends. In contrast to the previous case, this four-day event showed weaker overall diurnal characteristics, lower wind speeds (maximum sustained speeds near 21 knots), and the slowest rates of increase in wind speed among the cases analyzed in this study (4.7 knots/1 hour, 5 knots/3 hours, and 8.5 knots/6 hours). The primary significance of this event was in the sustained build up of wave heights, initially from about 3 feet late on day 1 to near 13 feet early on day 3. Even more significant, wave heights built rapidly at times, with maximum increases of 4.3 feet/3 hours, among the most rapid of rates observed in the cases evaluated in this study. This event also had the largest 1-hour increase, 3.3 feet on day 4, culminating in the overall peak wave height for this case (15.4 feet). The wave height increases observed were likely due to a combination of local wind wave generation and contribution from waves propagating down the coast from the north.[1]

Winds speeds increased late on day 1 (afternoon hours) as pressure gradients intensified (see **General Weather Description**, below), up to 12 knots by early evening of day 2, then increased further, to 18 knots in the early morning hours on day 3. Wind directions were consistently from the north or north-northwest, except early in the morning on day 1, when light northeast to east-northeast winds observed. As noted above, wave heights steadily built beginning on the evening hours on day 2, lagging behind the initial wind increase by several hours. After the initial increase in both wind speed and wave height through day 3, diurnal characteristics became more evident, with the highest wind speeds and wave heights for this event observed during the late night and early morning hours on days 4 and 4.

(2) General Weather Situation: Figures 3b(3) through 3b(6) show the surface and upper air analyses for this event. As indicated by the sequence of mean sea level pressure analyses for this event, pressure gradients intensified along the northern California coast on days 1-2, due to an intensification of the east Pacific high (west of Washington state) and a simultaneous intensification of the thermal trough over interior California. During the same time frame, an upper low over the northeast Pacific shifted east over Vancouver Island, and an upper ridge amplified behind it along 145° west longitude. Surface pressure gradients further intensified on day 3 as the thermal trough shifted near the central California coast and the east Pacific high shifted east toward Vancouver Island. An upper level trough, trailing south from the upper low along the Pacific northwest coast on days 1-2, continued to lag behind over northwest California and southwest Oregon on days 3-4, even as the parent upper low continued to move east along the Canadian border. Surface pressure gradients began to weaken on day 4, as the east Pacific high moved west and the thermal trough shifted further inland (east).

(3) Harmonic Analysis of wind speed and wave height: Table 3b and Figures 3b(7) and 3b(8) show the harmonic analyses for wind speed and wave height for this event. As mentioned above, this event showed generally weaker diurnal tendencies than in the previous case (June 2001), with an overall percent-variance explained by the first harmonic (period = 24 hours) of only 5.3 percent for wind speeds, and only 1.3 percent for wave heights. Similar to other events, though, the overall rising trends in wind speed and wave height obscured the diurnal cycle. On individual days, 66 to 86.5 percent of the variance was explained by the wind speed first harmonic, with the highest value on day 4. Concerning wave heights, the percent-variance explained by the first harmonics ranged from 43.5 to 67.2 percent, again with the highest value on day 4. The overall percent-variance explained by the first harmonics for both wind speed and wave height were probably low because of the large daily variation in times of peak amplitude, but the analysis nevertheless *generally* indicates a diurnal cycle with an early morning maximum in both wind speed and wave height, superimposed on the overall rising trends.

[1] Assessment based primarily on surface pressure analyses, since data from buoy 46027 (80 miles north of buoy 46022) was not available for this period.

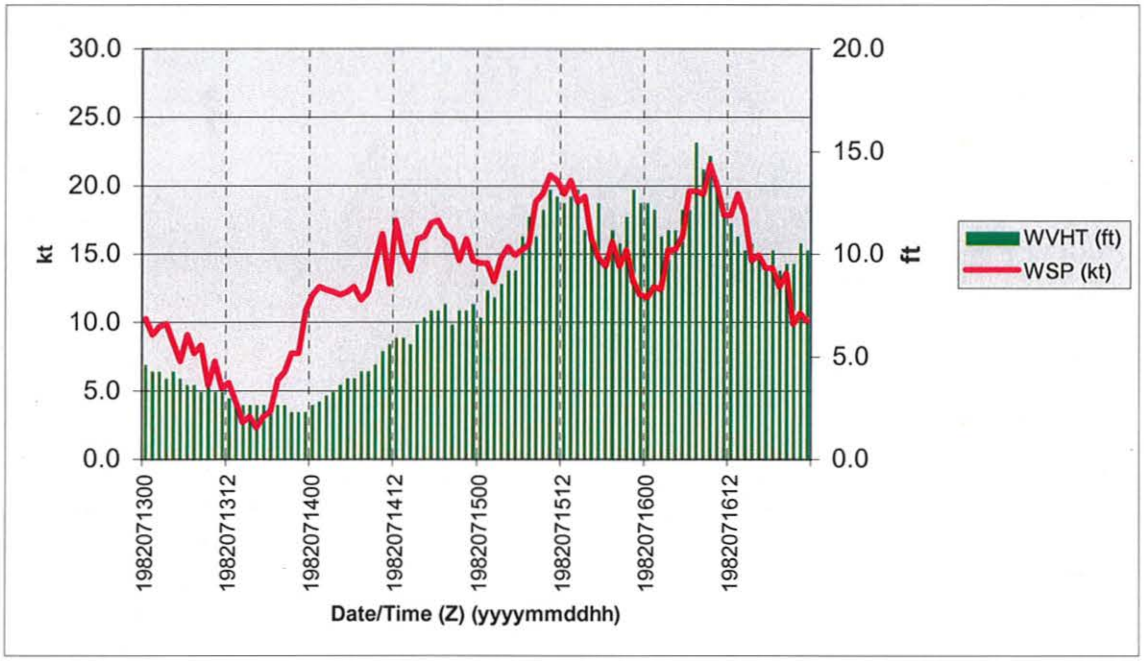


Figure 3b(1). Wind speed and wave height, buoy #46022 (13-16 July 1982).

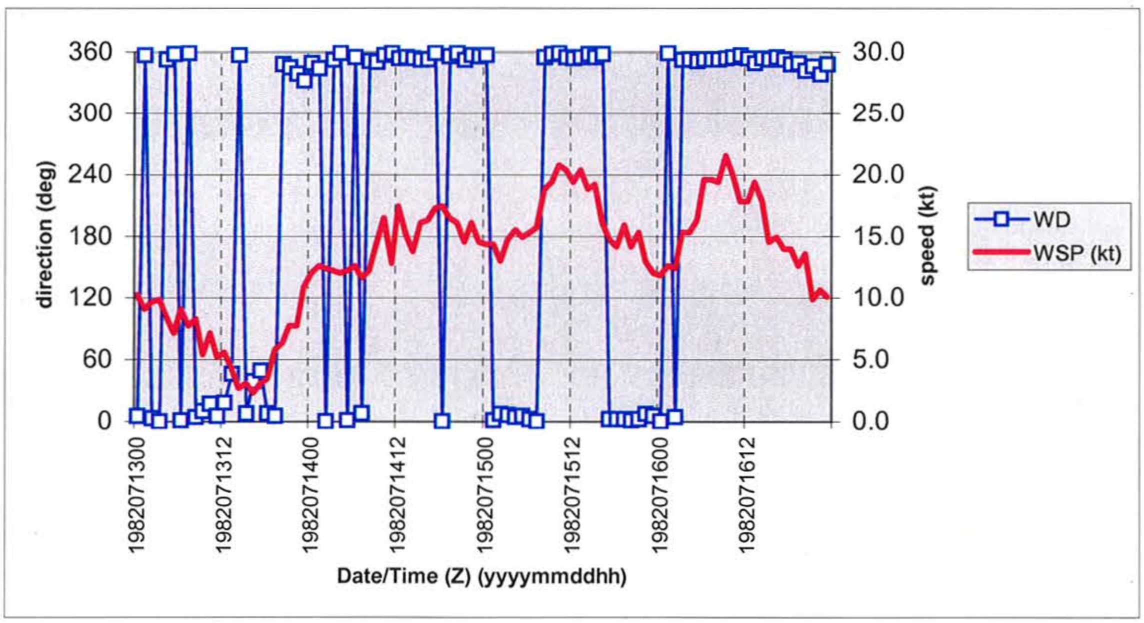


Figure 3b(2). Wind direction and speed, buoy #46022 (13-16 July 1982).

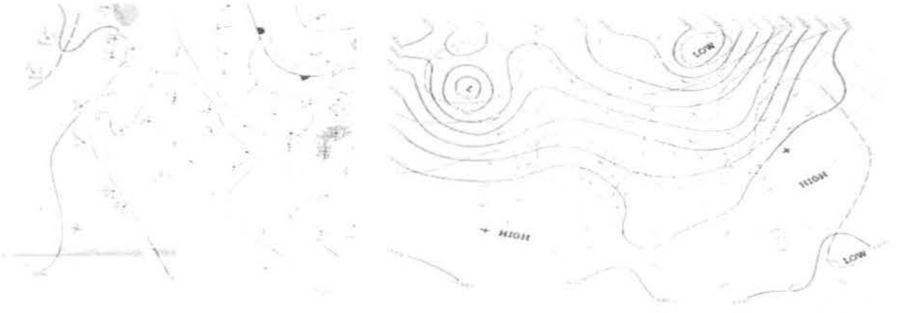


Figure 3b(3). Surface analysis (left) and 500 mb analysis (right): 1200Z, 13 July 1982.

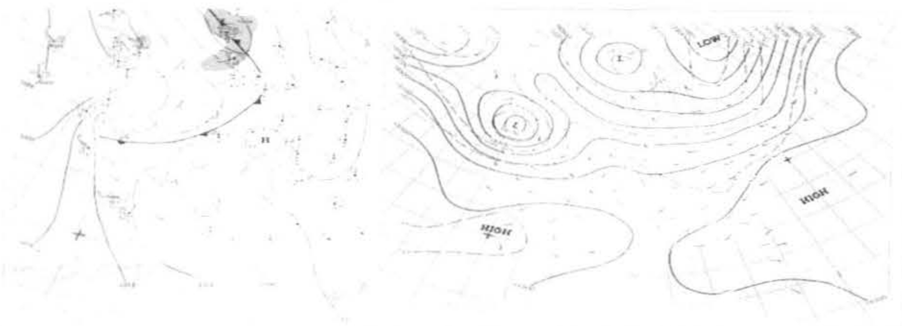


Figure 3b(4). Same as Figure 3b(3), but for 14 July 1982.

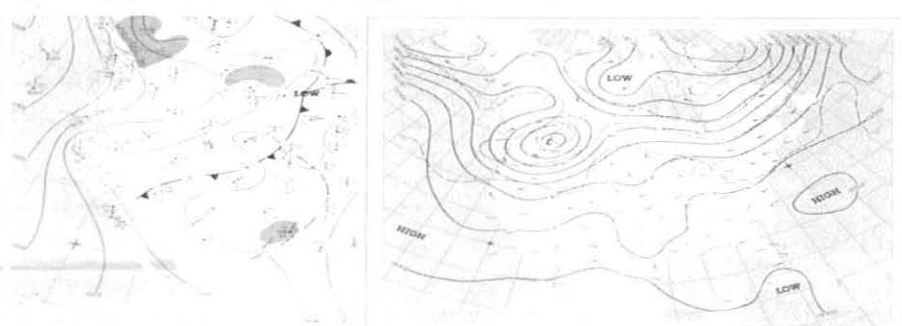


Figure 3b(5). Same as Figure 3b(3), but for 15 July 1982.

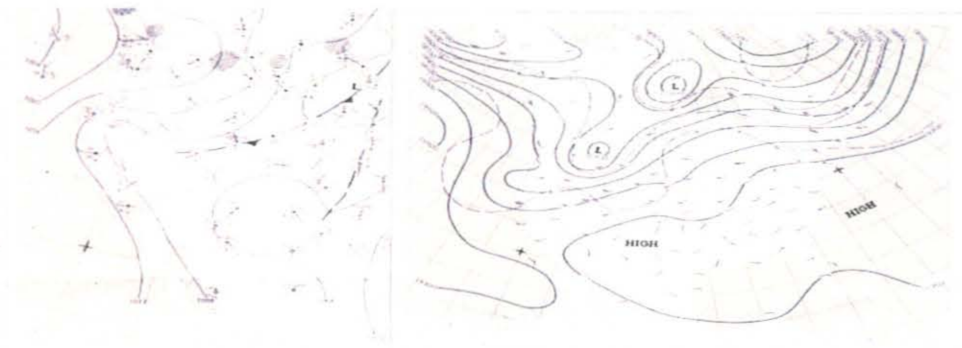


Figure 3b(6). Same as Figure 3b(3), but for 16 July 1982.

Table 3b. Time of peak amplitude and percent-variance explained by the first harmonics of wind speed and wave height (period = 24 hours) at buoy #46022 (13-16 July 1982).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	0336	79.7%	0542	60.6%
2	1730	66.0%	1800	66.6%
3	1224	78.7%	1430	43.5%
4	1042	86.5%	0812	67.2%
ALL	***1206***	***5.3%***	***1248***	***1.3%***

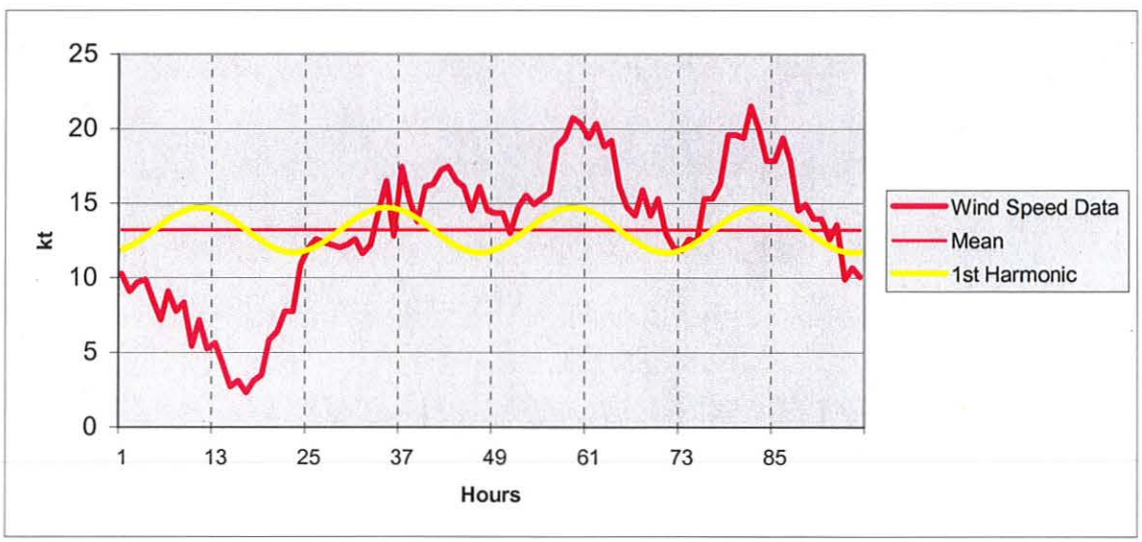


Figure 3b(7). Harmonic analysis of wind speed data, buoy #46022, 13-16 July 1982.

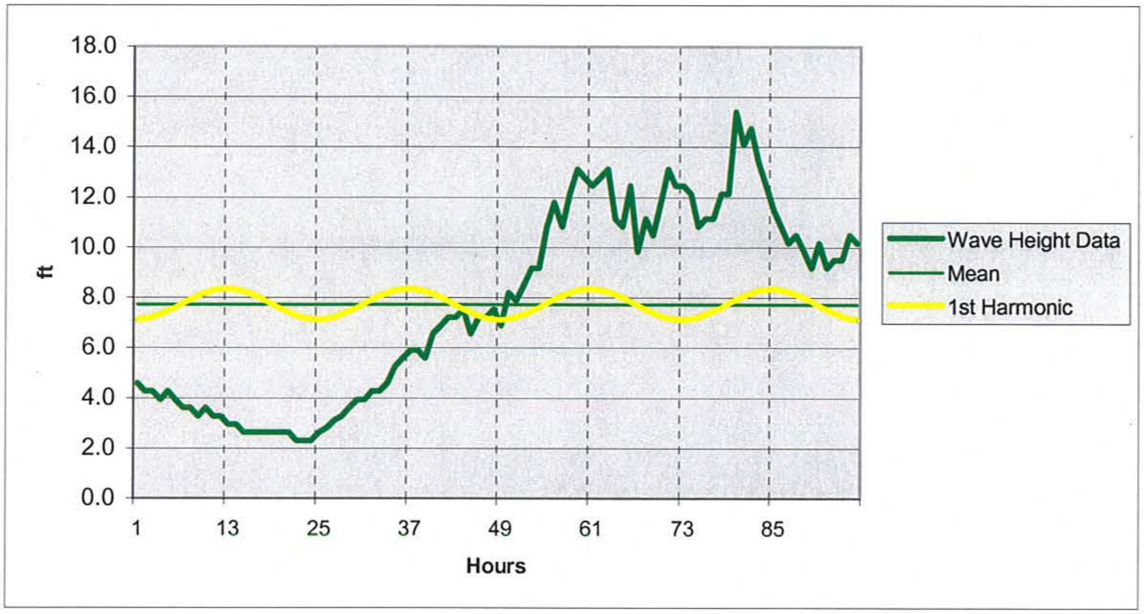


Figure 3b(8). Harmonic analysis of wave height data, buoy #46022, 13-16 July 1982.

c. Case #3. Rapid Rise Event: Buoy #46022 (9-20 September 1988).

(1) Event description: This 12-day event is actually two separate, but very similar events ("sub-events") which occurred only a few days apart (see Figures 3c(1) and 3c(2) for wind speed, direction, and wave height trends). Because of their similar characteristics and close separation, they are described together. Each of these sub-events was characterized by rapid increases in wind speed (up to12.2 knots/3 hours; 17.3 knots/6 hours) and sustained build-up of wave heights over periods of about 48 hours (with maximum rates of increase of up to 3.3 feet/3 hours and 4.6 feet/ 6 hours), followed by similarly rapid decreases. Each sub-event was about 3 days in duration. The first sub-event began late on day 1, with wind speeds rising from 2 knots late in the afternoon and through about 0600Z (2300 PDT) on day 2. Winds temporarily decreased during the following morning, then rose again, peaking at 28 knots during the afternoon and evening hours of days 2-3 (peak gusts to 36 knots). Winds then dropped sharply through about 1200Z (0500 PDT) on day 3, to 9-12 knots. Although another rise occurred later on day 3 (to near 20 knots), the overall trend in wind speeds was downward, falling back to around 3 knots early on day 4.

Wave heights, already 6 to 8 feet on the first day, built further -- peaking at 15.4 feet (with dominant periods of about 9 seconds) during the afternoon and evening hours on days 2-3. As the wind decreased overnight into day 3, wave heights also subsided rapidly, to near 5 feet by late on day 4.

Wind speeds remained lower on days 5 through 7 (maximum sustained wind speeds about 13-17 knots -- strongest late night and early morning hours), while wave heights continued to slowly subside from 5 to 3 feet. Sustained wind speeds then began another steady increase on day 8, rising more or less continuously from about 2 knots to a peak of 29.5 knots (gusts to 37.6 knots) late in the afternoon and early evening of day 9.

Wind speeds were strongest when from the north to north-northwest. When winds decreased (typically around 1200Z, or 0500 PDT), directions tended to turn to the north-northeast. Between the two major wind/wave peaks in this case, winds turned to the south-southwest and rose to 15-20 knots on days 5-6 as the thermal trough shifted off the coast.

Wave heights in this second sub-event (beginning on day 8) initially rose abruptly, then more steadily to 11-12 feet by 0000Z (1700 PDT) on day 9, then more gradually to a peak near 14 feet by 0300Z (2000 PDT) on day 10 (with dominant periods of 8.3 seconds, slightly shorter than the previous peak on days 2-3). Winds and waves then again fell rapidly, to about 2 knots and 3-4 feet on day 11. A third buildup of wind and waves apparently began on day 12, but is not described here.

(2) General Weather Situation: Figures 3c(3) through 3c(14) show the surface and 500 mb analyses for this event. As mentioned above, this case is really two separate events, and this is also clearly seen in the changing nature of the associated weather patterns. On day 1, an upper level trough was located just off the Pacific Northwest and far northern California coasts, with surface high pressure centered west of Washington state, and a weak thermal trough inland and near the coast over California. On days 2-3, the upper trough shifted inland and was replaced by a strongly amplified upper ridge over the northeast Pacific. As the upper ridge built, an associated surface ridge developed over the Pacific Northwest, while the thermal trough remained nearly stationary. Because of the surface ridge to the north, pressure gradients increased strongly over the far northern California and southern Oregon coasts. The upper ridge weakened on days 4-5, with the thermal trough moving to the California coast, and also northward off the Oregon and Washington coasts, thus relaxing the pressure gradients and ending the first of these two events. On days 5-6, another upper trough moved near the coast, then inland by day 8, and was again followed by a strongly amplified upper ridge over the northeast Pacific. The surface pattern for this second event also followed a similar sequence (compared to the first event).

(3) Harmonic Analysis of Wind Speed and Wave Height: Table 1 and Figures 3c(15) through 3c(16) show the harmonic analysis results (wind speed and wave height, period = 24 hours) for this event. Similar to Case #2, this pair of events was not characterized by strong diurnal trends overall, due to the changing weather patterns described above. For this case overall, the percent-variance explained by the first harmonic (wind speeds; period = 24 hours) was near zero. Again, though, individual days showed stronger diurnal character, between 60 and 80 percent on days 3, 7, 9, and 10 (September 11, 15, 17, and 18, respectively), and less than 50 percent on the other days. Overall, harmonic analysis showed no particularly favored time of day for stronger/weaker wind speeds -- again, likely due to the constantly changing weather pattern. Similarly, harmonic analysis of wave heights for this case showed no dominant trends. The percent-variance explained by the first harmonic was between 60 and 80 percent on days 3, 4, 8, and 10-12, and less than 40 percent on other days.

(4) Pressure Gradients: Figure 3c(17) shows the time-series of wind speeds at buoy #46022, along with pressure gradients (i.e. absolute magnitudes) between buoys #46027 and 46014, about 80 miles north and 120 miles south, respectively. The 46027-46014 pressure gradients rapidly increased during the *first* event (days 2-3), but lagged behind the increase in wind speed by several hours, peaking at 7.3 mb at 0700Z (midnight PDT) on day 3, or about 5-7 hours after the wind peak. In contrast, 46027-46014 pressure gradients during the *second* event began rising a few hours *before* the wind speed began rising, and continued to rise strongly through days 8-10, peaking at 9.3 mb at 0600Z (2300 PDT) on day 10. Despite the initial tendency for the 46027-46014 pressure gradient increases to precede the increases in wind speed in the second event, the peak pressure gradient eventually occurred about 5 hours *after* the peak in sustained wind speed, similar to the first event. It is also noteworthy to mention that the 46027-46014 pressure gradients observed during the second event in this case were among the strongest observed for *all* the cases analyzed in this study. For reasons noted previously, harmonic analysis of the pressure gradients was not conducted for this case.

(5) Upstream/Downstream Conditions: During the period of this case, strong winds also generated large waves at buoys 46027 (80 miles north) and 46014 (120 miles south). At buoy 27, winds were even stronger than at buoy 22 (this case); average sustained wind speeds were 15 knots, with peak sustained winds close to 35 knots, and peak gusts of more than 40 knots. Wave heights at buoy 27 averaged 6.5 feet, with peak wave heights of 11.8 feet. Given an average period of 8.3 seconds at buoy 27 (with waves ≥ 10 feet), this would indicate waves decaying only about 2 feet between buoys 27 and 22 (i.e. up to 8-10 foot decayed waves arriving at buoy 22). Assuming a 200 nautical mile fetch and a sustained wind speed of 25 knots (probably excessive for this case, but useful for illustration), the theoretical fully developed wave height would be about 10 feet after 24 hours, still about 5 feet less than the peak observed at buoy 22 for this case. It is possible that winds between buoys 27 and 22 could have been stronger, leading to larger waves upstream. It is also possible that long period swell from well outside the area could have contributed to the wave heights observed. Beginning on day 5 and continuing into day 6, a dominant period of around 14 seconds emerged, but the significant wave height at this time was only around 4 feet. Considering that, overall, wave heights rose as wind speeds rose (and vice-versa), it is probably reasonable to assume that the contribution from long period swell was negligible.

Downstream effects (contribution from waves generated near buoy 22 propagating south): Assuming a dominant period of 8.6 seconds at buoy 22 (average based dominant periods with wave heights ≥ 12 feet) and peak waves of 12 to 15 feet, waves up to 10-12 feet could be expected to arrive downstream at buoy 14. Sustained winds at buoy 14 during this period averaged slightly less than at buoy 22 (11.6 knots, with a peak of 29.1 knots, and peak gusts to 38.6 knots). Given average wave heights of 7.1 feet at buoy 14 (peak wave heights of 14.4 feet), the upstream contribution (from near buoy 22) would again help to explain the wave heights actually observed.

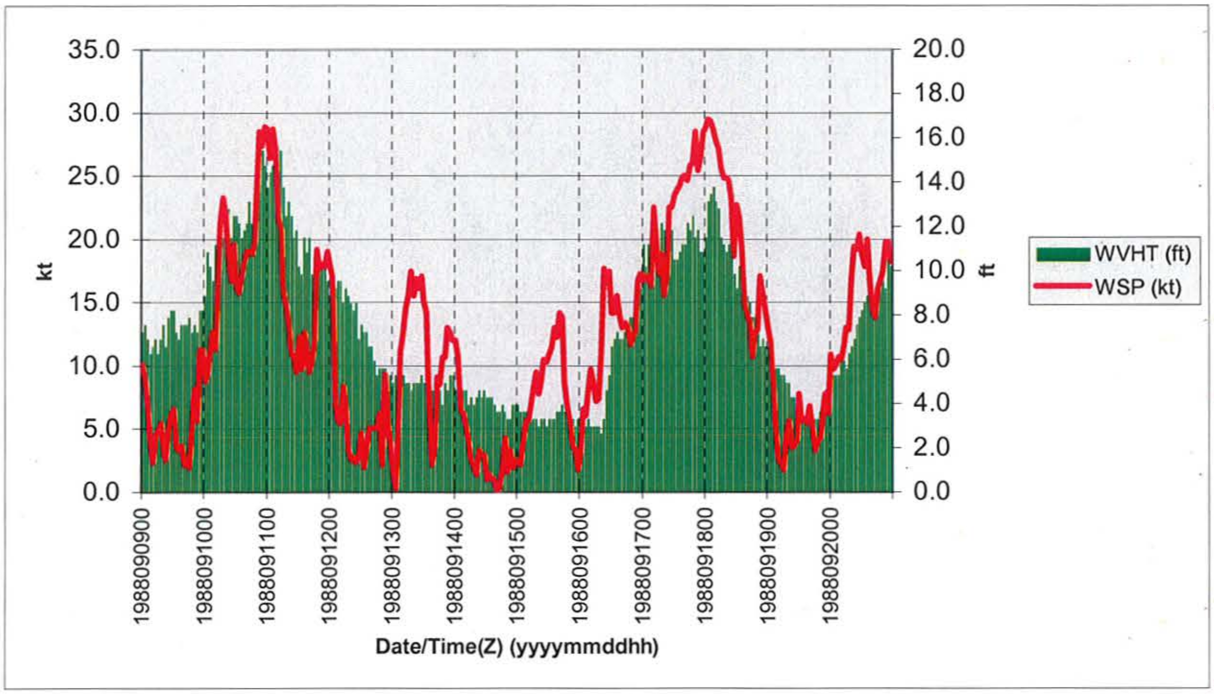


Figure 3c(1). Wind speed and wave height, buoy #46022 (9-20 September 1988).

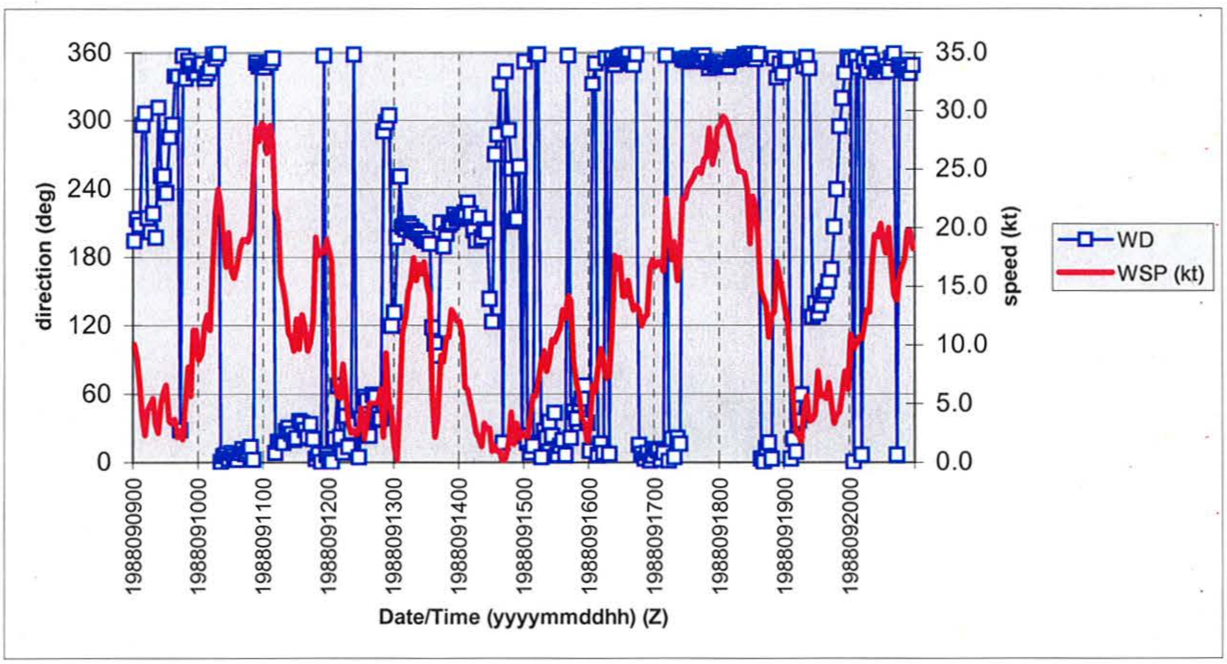


Figure 3c(2). Wind speed and direction, buoy #46022 (9-20 September 1988).

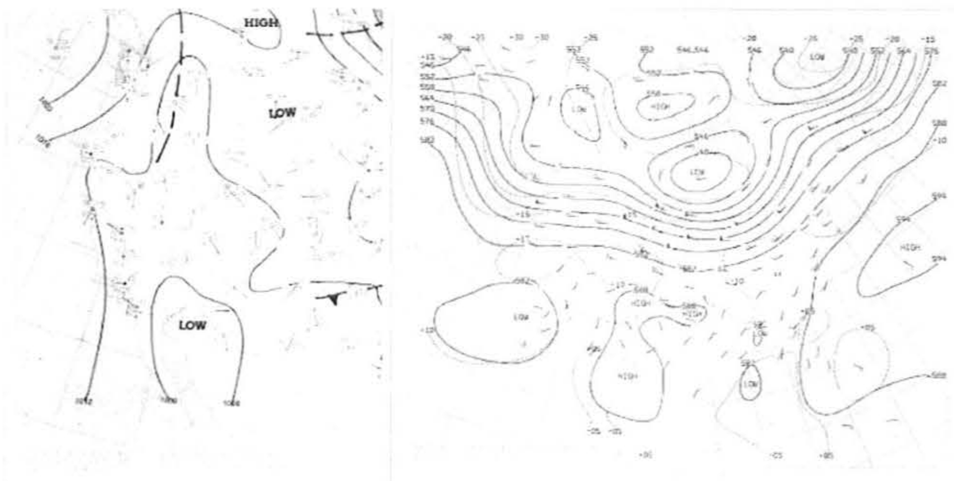


Figure 3c(3). Surface analysis (left) and 500 mb analysis (right): 1200Z, 9 September 1988.

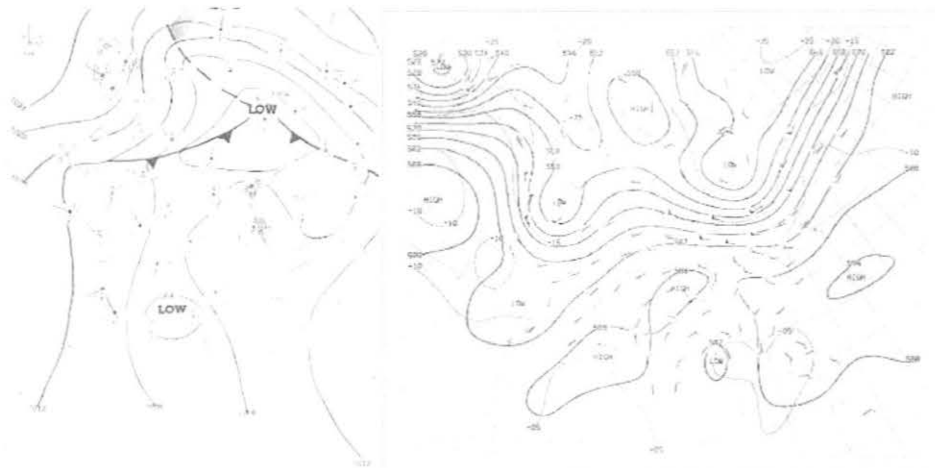


Figure 3c(4). Same as Figure 3c(3), but for 10 September 1988.

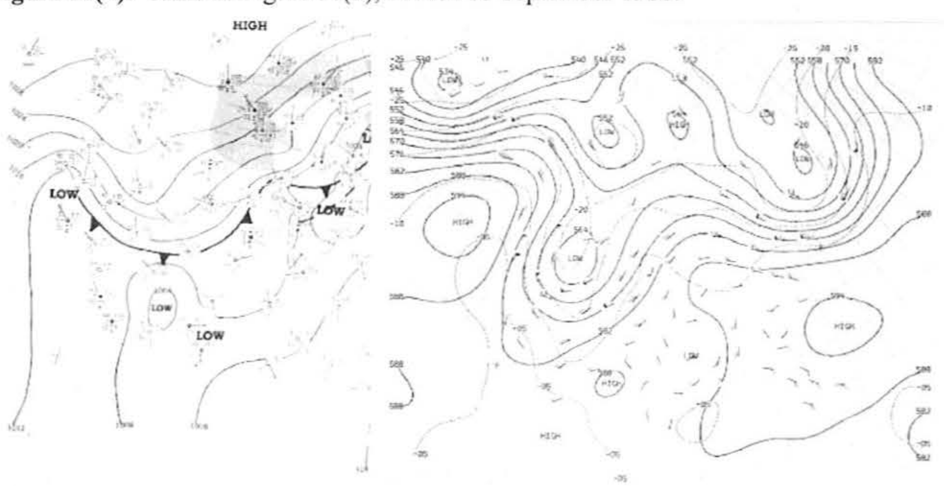
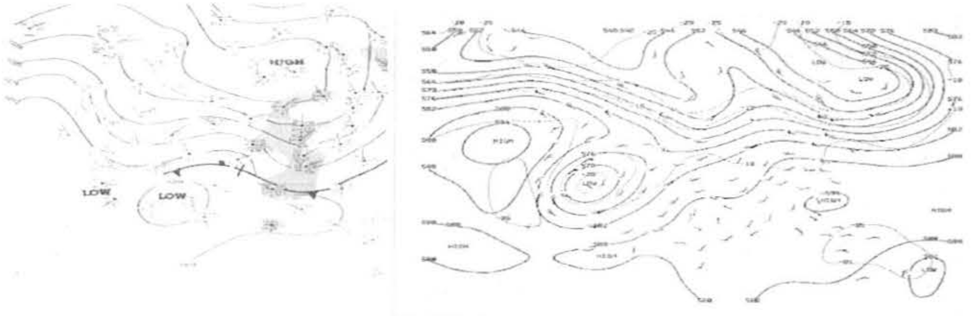


Figure 3c(5). Same as Figure 3c(3), but for 11 September 1988.



Sep 12, 1988

Figure 3c(6). Same as Figure 3c(3), but for 12 September 1988.

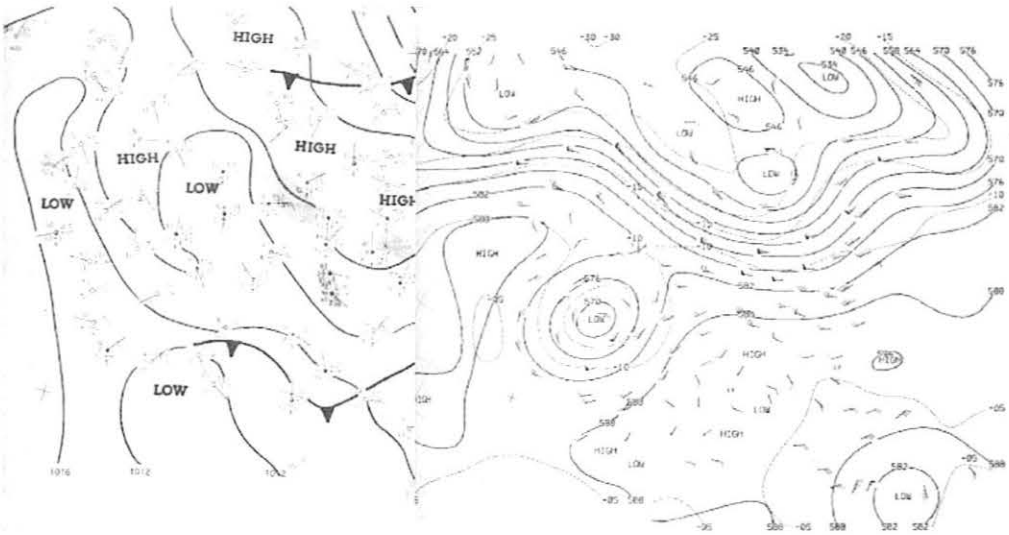


Figure 3c(7). Same as Figure 3c(3), but for 13 September 1988.

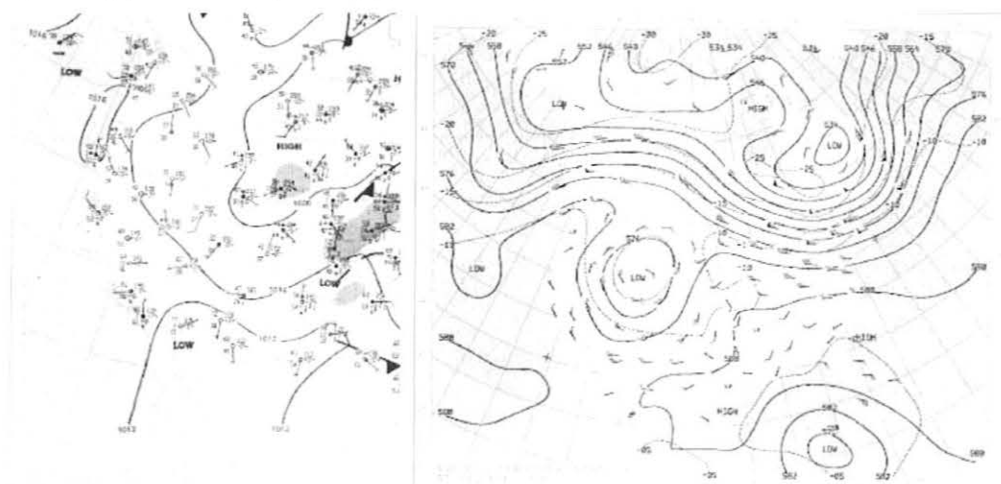


Figure 3c(8). Same as Figure 3c(3), but for 14 September 1988.

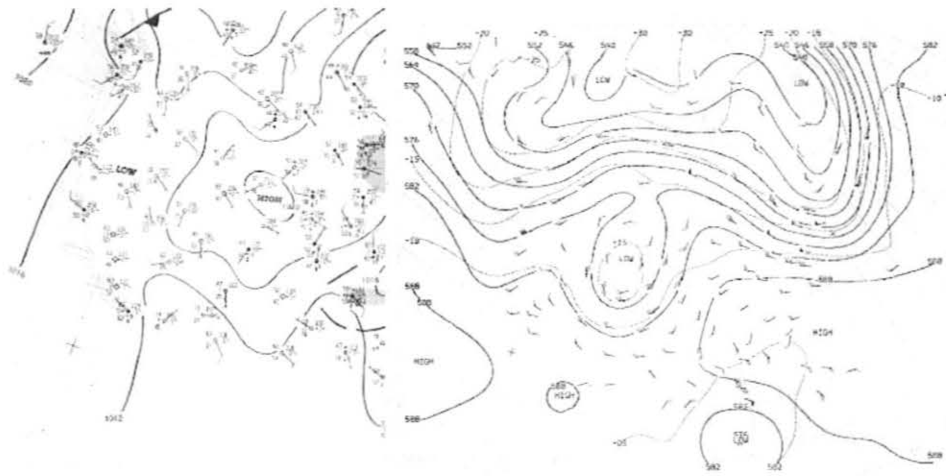


Figure 3c(9). Same as Figure 3c(3), but for 15 September 1988.

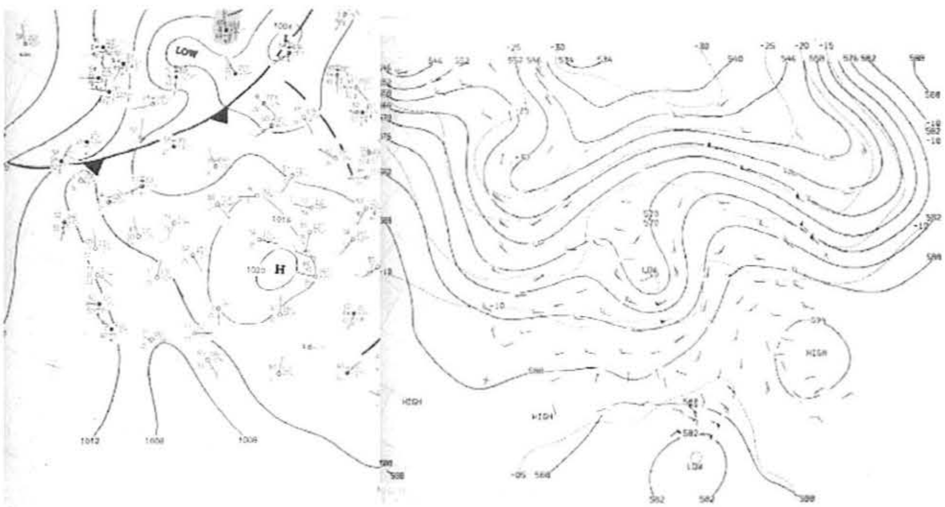


Figure 3c(10). Same as Figure 3c(3), but for 16 September 1988.

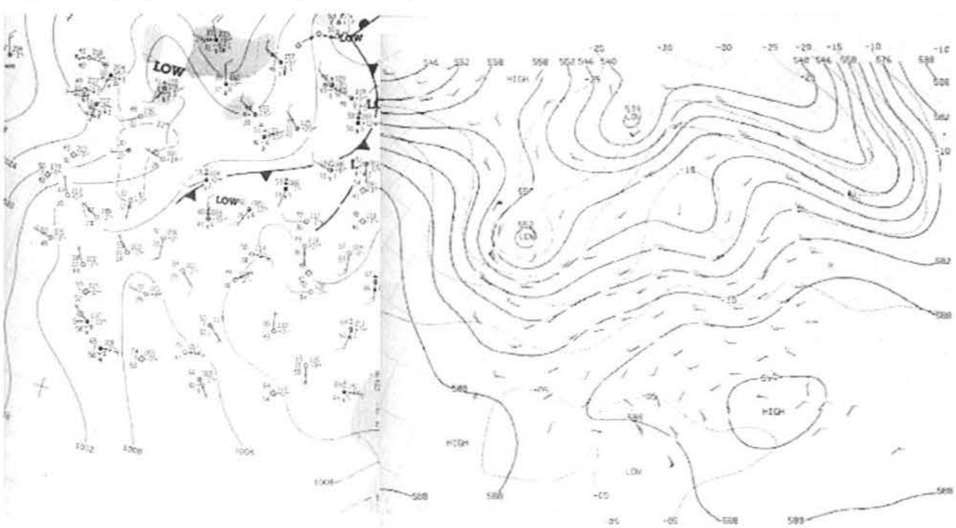


Figure 3c(11). Same as Figure 3c(3), but for 17 September 1988.

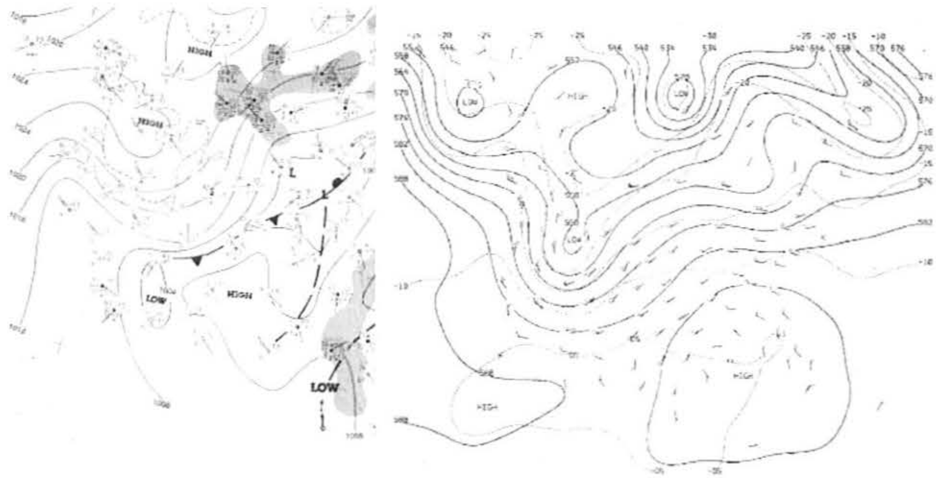


Figure 3c(12). Same as Figure 3c(3), but for 18 September 1988.

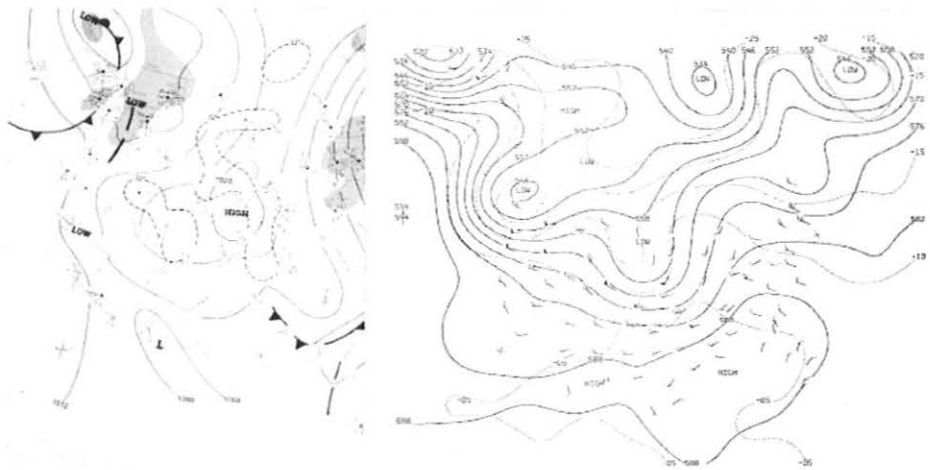


Figure 3c(13). Same as Figure 3c(3), but for 19 September 1988.

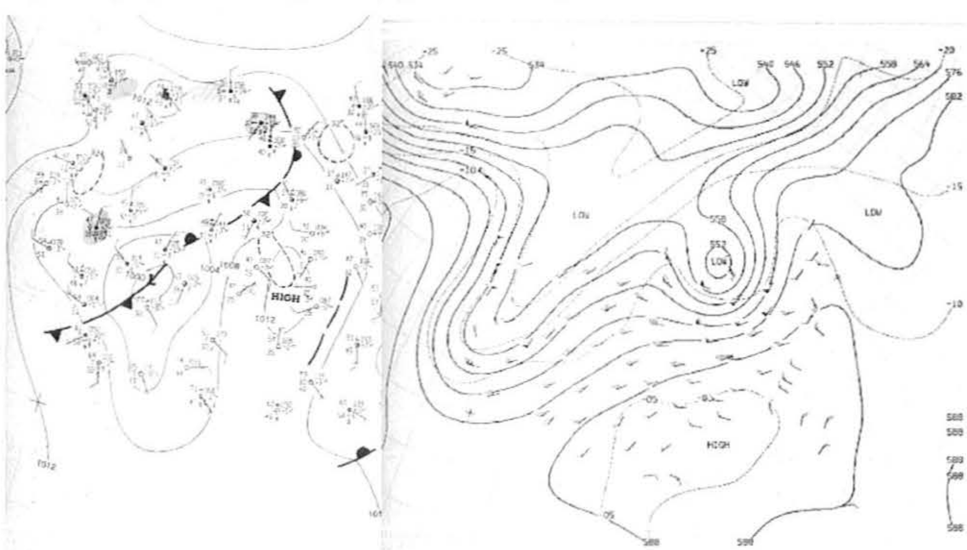


Figure 3c(14). Same as Figure 3c(3), but for 20 September 1988.

Table 3c. Time of peak amplitude and percent-variance explained by the first harmonics of wind speed and wave height (period = 24 hours) at buoy #46022 (9-20 September 1988).

	Wind Speed		*Wave Height*	
Day	**Time (Z)**	**Percent Variance Explained**	**Time (Z)**	**Percent Variance Explained**
1	1242	33.6%	1754	25.1%
2	1848	9.2%	1842	21.0%
3	0212	78.7%	0536	67.0%
4	0106	35.2%	0648	69.7%
5	0936	30.6%	0542	24.9%
6	0248	47.5%	0706	39.7%
7	1348	79.2%	2336	10.6%
8	1524	40.2%	1848	73.1%
9	1842	60.5%	1730	4.0%
10	0618	73.5%	0636	62.5%
11	2312	16.0%	0418	78.4%
12	1530	40.5%	1806	66.2%
All	***0206***	***0.2%***	***0424***	***0.1%***

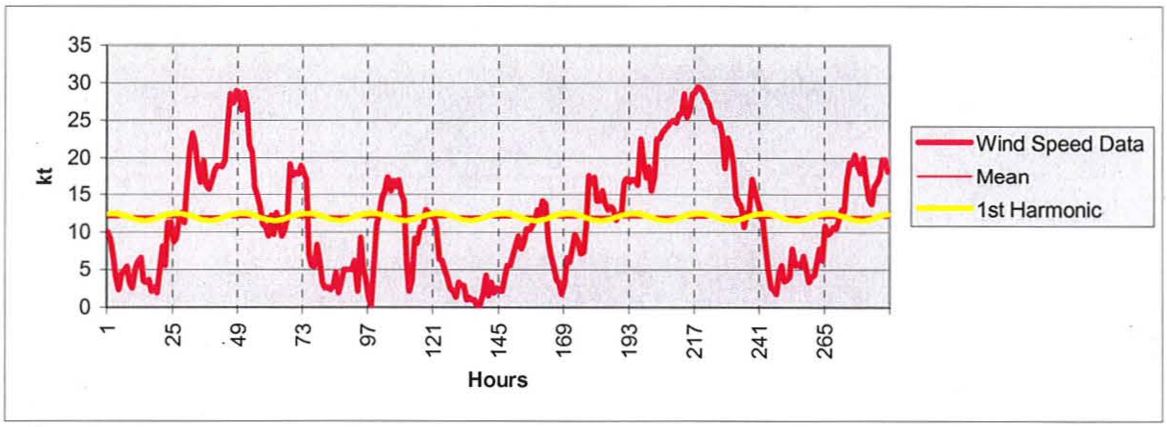


Figure 3c(15). Harmonic analysis of wind speed data, buoy #46022, 9-20 September 1988.

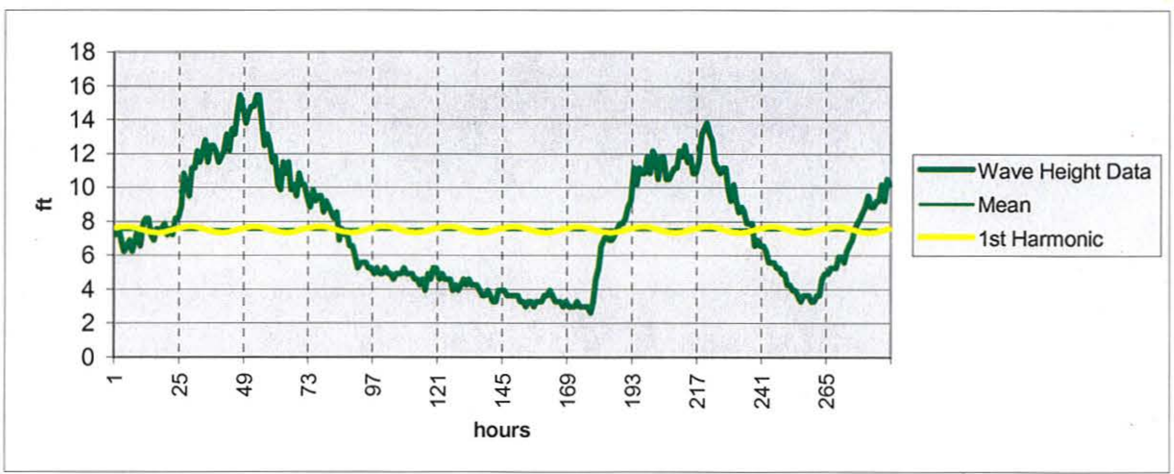


Figure 3c(16). Harmonic analysis of wave height data, buoy #46022, 9-20 September 1988.

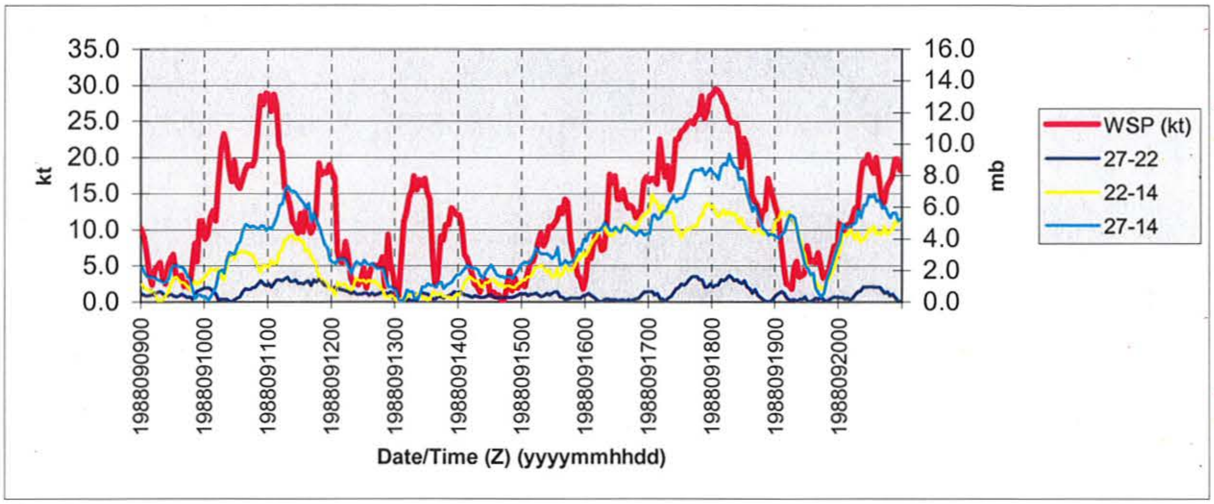


Figure 3c(17). Wind speed (buoy #46022) and pressure gradient (absolute magnitudes) for buoys #46027-46022, 46022-46014, and 46027-46014, 9-20 September 1988.

d. Case #4. Rapid Rise Event: Buoy #46022 (3-6 June 1991).

(1) Event description: Wind speed, direction, and wave height data for this event are shown in Figures 3d(1) and 3d(2). This event, although displaying only moderate rates of rise in wind speed and wave height, is nevertheless characterized as a "rapid rise event," one which culminated in the second-highest wave height (19.0 feet) of all the cases analyzed in this study, and among the highest observed for the entire period of study (maximum at buoy #46022: 22.3 feet). Wind directions remained consistently from the north to north-northwest through the period. Wind speeds initially increased during the overnight hours on day 1, from 10 to 25 knots in 10 hours. Wave heights also rose during the same time frame, from 8 to 13 feet. Wind speeds then leveled off for the next 18 hours (through the morning of day 2), averaging near 20 knots. Wave heights also leveled off, but only temporarily, remaining near 13 feet for about 9 hours (through the early evening on day 1), then again rising, to the overall peak of 19 feet at 0700Z (0100 PDT) on day 2. Wave heights then subsided, to near 13 feet on the afternoon of day 2. Even as the wave heights steadily came down, though, wind speeds steadily rose, from about 20 knots on the morning day 2 to a peak of 31 knots in the early evening (0100Z, or 1800 PDT) of day 3. About 6 hours after the winds began to rise, wave height trends also reversed, now rising again, from 13 feet in the afternoon of day 2 to 18.4 feet at 0400Z (2100 PDT) on day 3. As described below ("Upstream/Downstream Conditions"), even stronger winds upstream likely made a very significant contribution to those observed here.

(2) General Weather Situation: Surface and upper air analyses for this event are shown in Figures 3d(3) through 3d(6). An upper level low north of Vancouver Island moved slowly east on days 1 and 2, then dropped south on days 3 and 4, merging with a weaker upper low which had been moving east over the Pacific between 25 and 30 degrees north latitude, toward the Baja California coast. The surface thermal trough on day 1 was located well inland over northern California, but shifted west to the coast (south of Cape Mendocino) by day 2. To the north, a surface ridge built east over the Pacific Northwest, sharply increasing surface pressure gradients along the far northern California and southern Oregon coasts. As the (now merged) upper low drifted south into eastern Oregon on day 4, pressure gradients along the coast began to weaken.

(3) Harmonic Analysis of Wind Speed and Wave Height: Table 1 and Figures 3d(7) and 3d(8) show the harmonic analysis results for this case. For the four days as a whole, this case demonstrated only weak diurnal characteristics, with only 1.3 percent of the total variance explained by the first harmonic for wind speed (period = 24 hours), and 4.5 percent for wave height. On a day-to-day basis, however, the diurnal tendencies were much more obvious, with each individual 24 hour period having a percent-variance explained by the first harmonic of between 53 and 67 percent for wind speeds, and 51 to 81 percent for wave height. The times of maximum amplitude (overall) were near 17Z (1000 PDT) for wind speed and 05Z (0100 PDT) for wave height

(4) Pressure Gradients: Figure 3d(9) shows wind speeds and pressure gradients between buoys #46027 and #46014 (27-14) during this event. The 27-14 pressure gradients began rising a few hours before winds at buoy #46022 began increasing, but they temporarily leveled off near 3.4 mb. Simultaneously, pressure gradients fell between buoys #46027 and #46022, and between buoys #46022 and #46014. Even so, wind speeds continued to rise for the next 5 hours. At about 00Z (1700 PDT) on day 2, with wind speeds having been relatively steady near 20 knots for about 10 hours, the 27-14 pressure gradients again began to rise steadily. Wind speeds rose sharply about 12 hours later, on day 2 (at 1200Z, or 0500 PDT). Wind speeds then continued to rise, along with the 27-14 pressure gradients, until both peaked at 01Z (1800 PDT) on day 3, at 31 knots and 8.9 mb. From this point, the 27-14 gradients trended steadily downward until the evening hours on day 4. Here again, pressure gradients increased prior to the wind speeds, but this time only about 2 hours before. In this case, the 27-14 pressure gradients rose only moderately, from about 0.5 mb to 3 mb, while the wind speed increased from about 10 knots to 21 knots. The 27-14 pressure gradients and wind speeds then (both) continued downward.

(5) Upstream/Downstream Conditions: There appeared to be no significant contribution to wave heights from swell generated well outside the local area. There had been no hurricanes in the eastern Pacific, and there was no evidence of significant large swell from other sources. At buoy #46027 (about 80 miles north), winds were even stronger than the maximum 31 knots observed here. Winds at buoy #46027 during this period averaged 25.8 knots (compared to 18.3 knots at buoy #46022), with maximum sustained winds of 37.2 knots and gusts to near 47 knots (compared to 31.2 knots sustained and gusts near 40 knots at buoy #46022). Wave heights at buoy #46027 averaged 10.2 feet, with a dominant period of 7.8 seconds, compared to 12.3 feet at 9.2 seconds at buoy #46022). Maximum wave heights at buoy #46027 reached 14.1 feet at 8.3 seconds (dominant period at time of maximum wave height), compared to 19 feet at 10 seconds at buoy #46022. Assuming pure decay alone, these wave heights (at buoy #46027) would have produced waves of about 8 feet at 9 seconds (average) and about 12 feet at 9 seconds (maximum). Upstream winds had obviously built waves to much greater heights though, further building upon the already large waves moving into the area around buoy #46022 on day 2.

Downstream effects: Winds downstream at buoy #46014 (120 miles south) averaged 19.3 knots, slightly higher than at buoy #46022, but maximum sustained winds were considerably lower (28.5 knots with peak gusts to 35.5 knots). Waves averaged 11.2 feet at 9.5 seconds at buoy #46014, with peak waves of 15.4 to 15.7 feet at 9 to 10 seconds (dominant period at time of maximum wave height). Again, from a pure decay standpoint, waves arriving from upstream at buoy #46014 of approximately 10 feet at 10 seconds (average) and 16 feet at 11 seconds (maximum) could be expected. Conversely, from a purely local wave generation standpoint (assuming an average 20 knot wind speed for 24 hours and an upstream fetch of 120 miles), approximately 6-foot waves could be expected at buoy #46014. Adding these waves together, wave heights of about 16 feet could be expected, only slightly higher than actually observed.

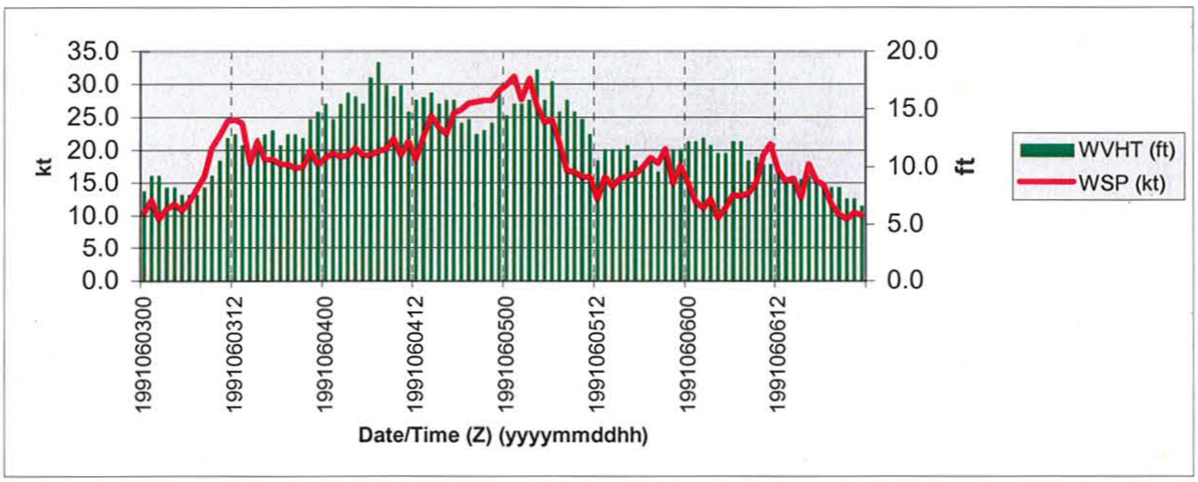


Figure 3d(1). Wind speed and wave height, buoy #46022 (3-6 June 1991).

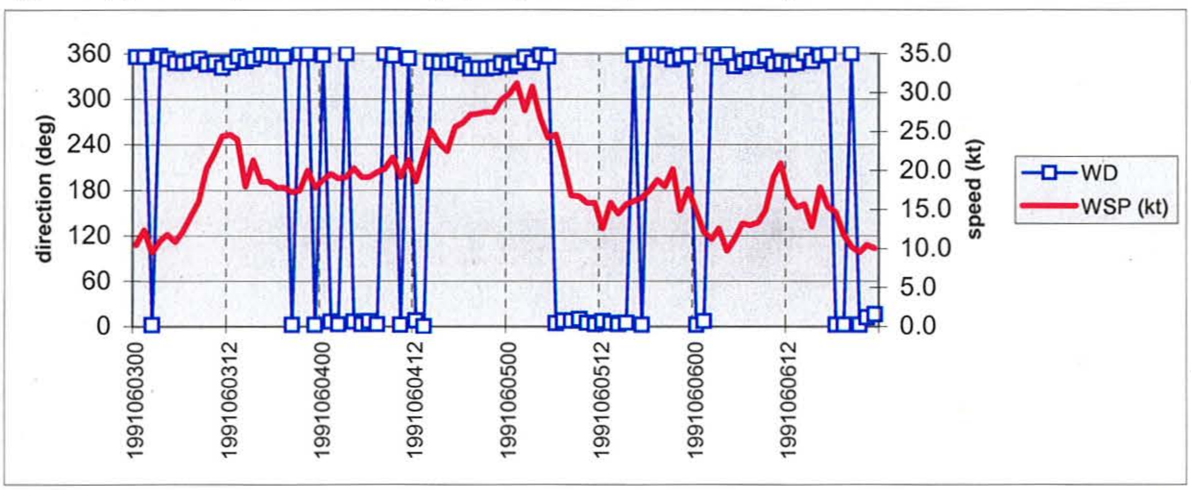


Figure 3d(2). Wind speed and direction, buoy #46022 (3-6 June 1991).

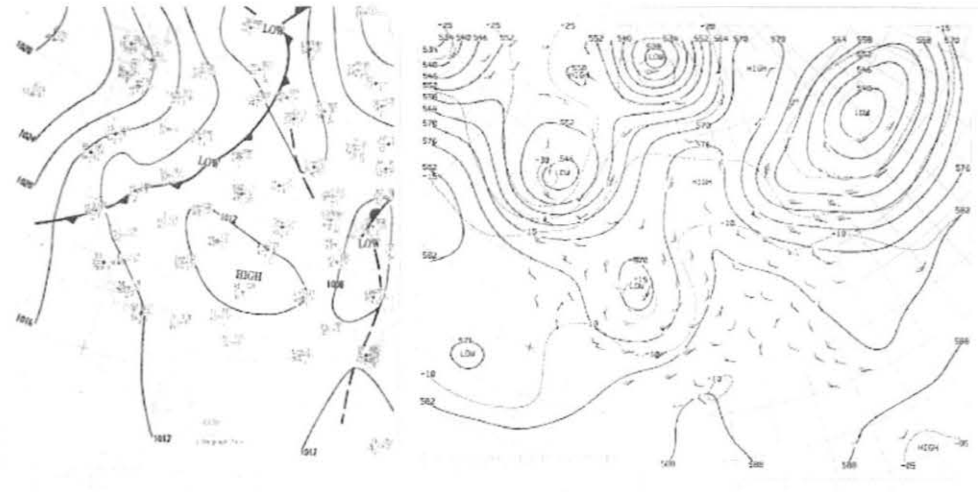


Figure 3d(3). Surface analysis (left) and 500 mb analysis (right): 3 June 1991.

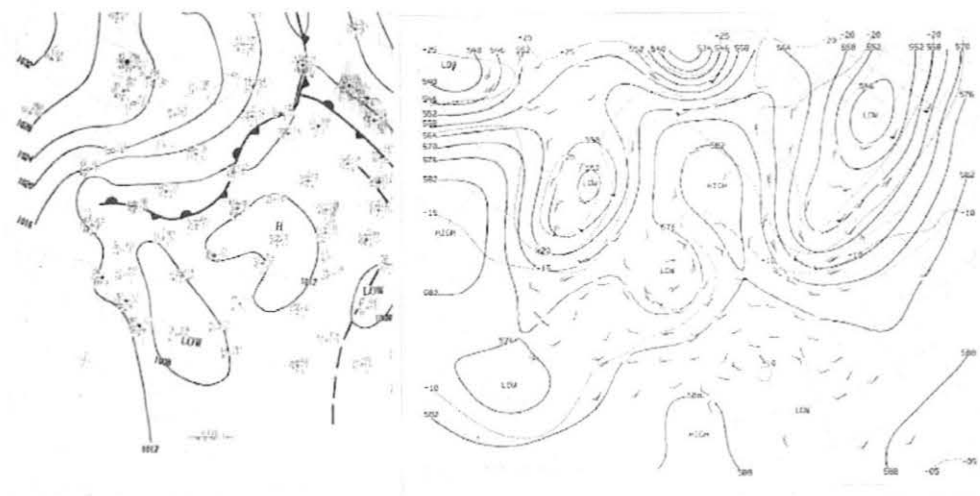
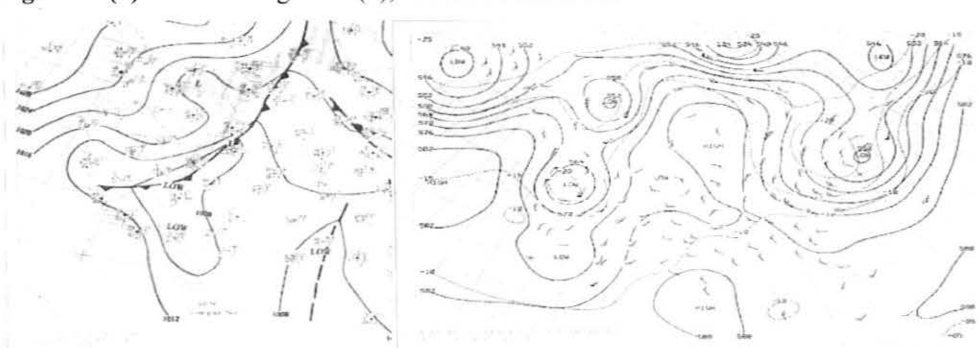


Figure 3d(4). Same as Figure 3d(3), but for 4 June 1991.



June 5, 1991

Figure 3d(5). Same as Figure 3d(3), but for 5 June 1991.

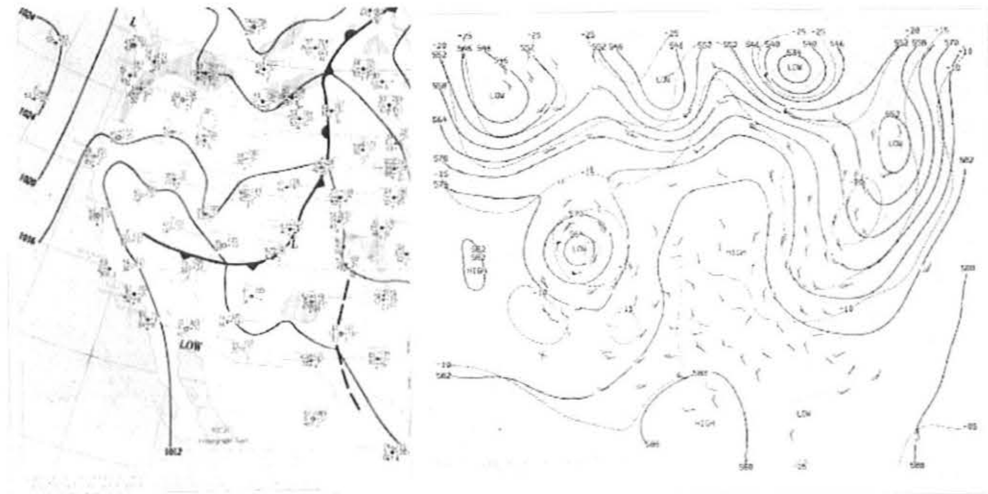


Figure 3d(6). Same as Figure 3d(3), but for 6 June 1991.

Table 3d. Time of peak amplitude and percent-variance explained by the first harmonics of wind speed and wave height (period = 24 hours) at buoy #46022 (3-6 June 1991).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	1506	66.1%	1830	66.1%
2	1954	61.5%	0900	51.7%
3	0318	67.0%	0606	81.1%
4	1306	53.7%	0642	57.3%
ALL	*1724*	*1.3%*	*0442*	*4.5%*

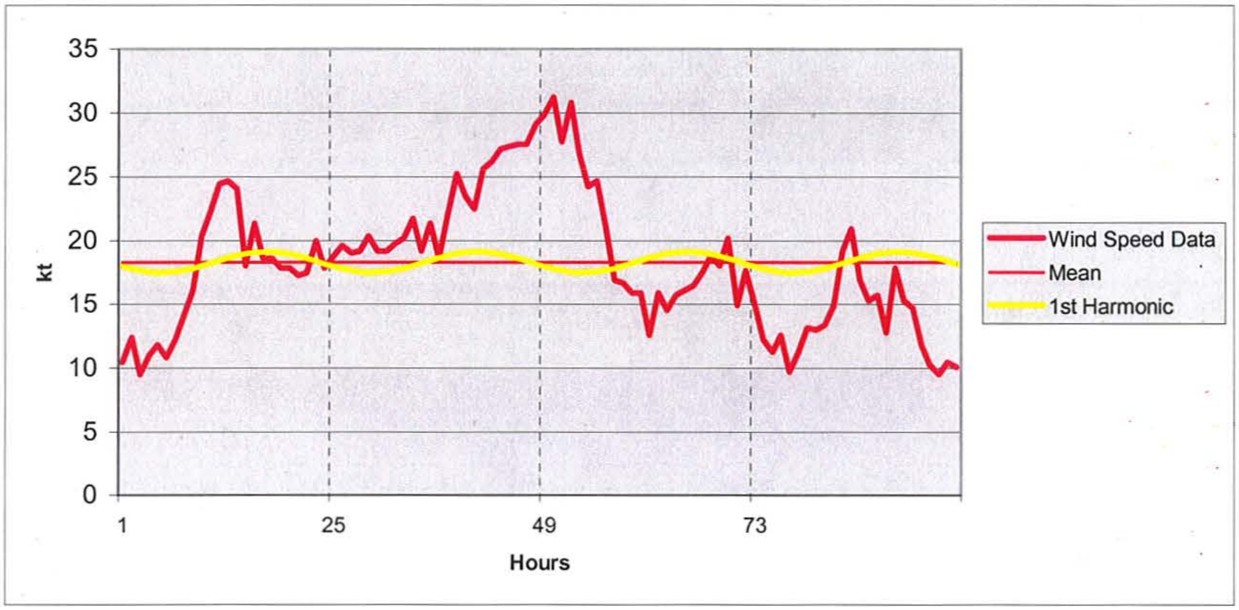


Figure 3d(7). Harmonic analysis of wind speed data, buoy #46022, 3-6 June 1991.

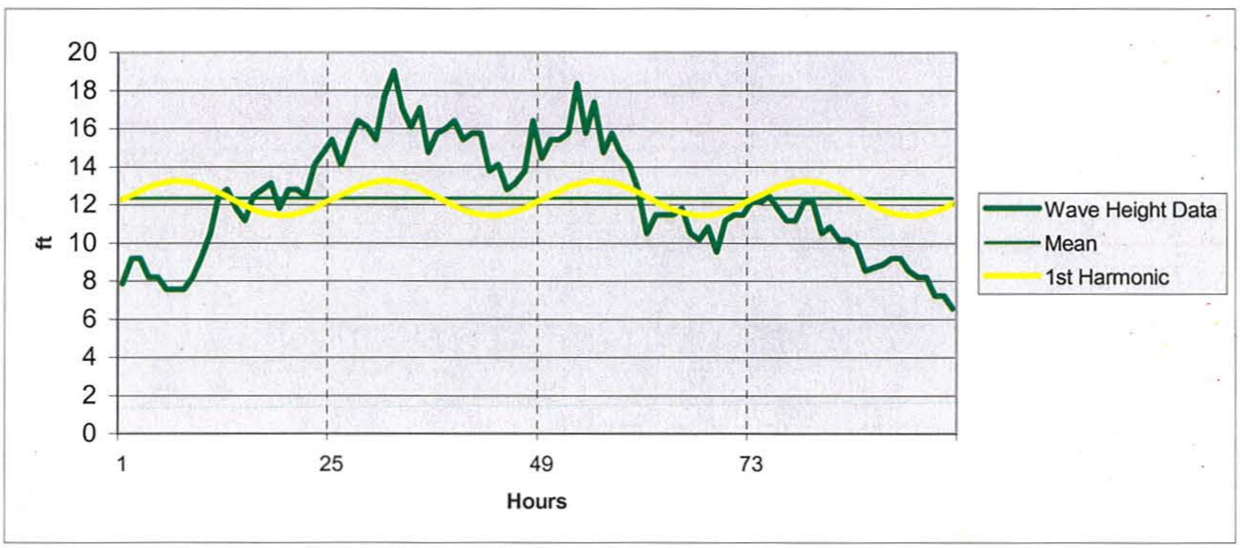


Figure 3d(8). Harmonic analysis of wave height data, buoy #46022, 3-6 June 1991.

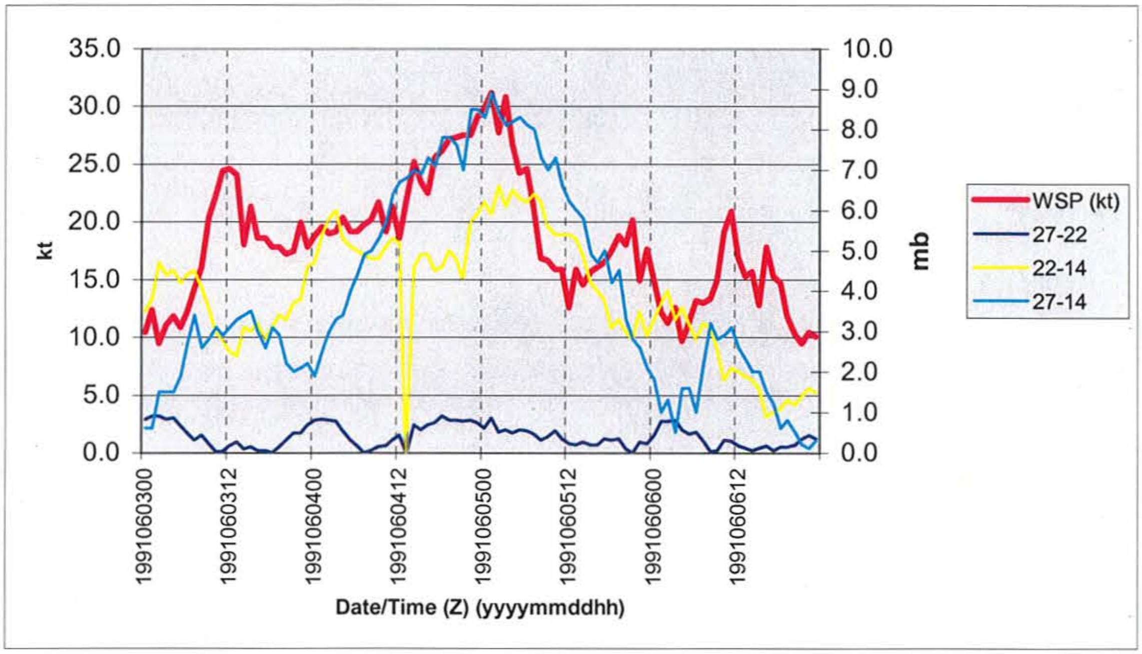


Figure 3d(9). Wind speed (buoy #46022) and pressure gradients (between buoys), 3-6 June 1991. Zero-values denote missing data.

e. Case #5. Periodic Event: Buoy #46022 (5-12 July 1993).

(1) Event description: Figures 3e(1) and 3e(2) show the wind speed, direction, and wave heights for this event. Similar to Case #1 (June 2001), this case is classified as a "periodic" event, due to its repetitive (diurnal) character. Peak sustained wind speeds over this 8-day event were not excessively strong (21.1 knots with peak gusts of 26.6 knots), but they followed a very similar pattern each day, typically rising overnight, from an early evening minimum of 4 to 8 knots to an early morning maximum around 20 knots. Speeds rose and fell rapidly on most days during the event (maximum 3-hour and 6-hour rates of increase: 10 knots and 16 knots, respectively). As with most other events evaluated, wind directions were predominantly north or north-northwest when moderate or strong wind speeds prevailed (late night and morning through afternoon). With lighter wind speeds (evenings), north-northeast directions were common.

Wave heights also typically followed a diurnal pattern, but to a lesser extent than the winds. Seas rose and fell moderately each of the first three days, with an overall upward trend, starting at about 8 feet on day 1, to an overall peak of 16.1 feet on day 3. As noted in previous cases at buoy 46022, the timing of rises and falls appeared to be strongly influenced by large waves generated upstream and propagating south along the coast, since the peak height on most days occurred *before* the wind peak. On days 4 through 7, the diurnal wave height trend was weaker, with a daily range of only 3 to 4 feet. A general downward trend then began about midway through day 7 and continued through day 8 (end of the event).

(2) General Weather Situation: Surface and upper air analyses for this event are shown in Figures 3e(3) through 3e(10). The upper air pattern for most of this event was characterized by a strong ridge over the east Pacific, with a broad upper trough located over the central United States. The surface pattern was also quite persistent, with the thermal trough near to, or just inland from the northern California coast, and ridging extending eastward from the east Pacific high across the Pacific Northwest. Moderate to strong pressure gradients prevailed along the far northern California and southern Oregon coasts. An upper low developed over southeast Alaska on day 5 and moved south along the British Columbia coast on days 6 and 7, then through the Pacific Northwest on day 8. By late on day 8, pressure gradients began to relax.

(3) Harmonic Analysis of Wind Speed and Wave Height: Table 1 and Figures 3e(11) and 3e(12) show the harmonic analysis results for wind speeds and wave heights during this event. For wind speeds over the entire eight days, the first harmonic (period = 24 hours) explained 56.5 percent of the variance. This figure is even higher than the overall 47 percent observed for Case 1 (buoy 27, June 2001). The percent-variance explained on individual days ranged from about 38 percent to about 89 percent (3 of 8 days exceeded 80 percent). According to the analysis, minimum wind speeds occurred at about 03Z (2000 PDT) and the maximum occurred at about 15Z (0800 PDT).

As noted previously, wave heights also showed diurnal character, but to a lesser extent than the local (buoy #46022) winds. Overall, the first harmonic explained only about 18 percent of the variance, but two of the days exceeded 70 percent. Maximum wave heights occurred between 09Z and 10Z (0200-0300 PDT) and the minimum occurred between 21Z and 22Z (1400-1500 PDT).

(4) Pressure Gradients: Pressure data from buoy #46027 (80 miles north) was missing during this event. Therefore, only the gradients between buoys #46022 and #46014 (120 miles south) were analyzed. Figure 3e(13) shows the wind speeds at buoy #46022 and the pressure gradients between buoys #46022 and #46014 (22-14), with their respective first harmonics superimposed. About 27 percent of the total variance in the pressure gradient data was explained by the first harmonic (period = 24 hours). Large changes in amplitude due to the stronger peaks near the beginning and end of the event (5.5 and 6.1 mb) likely contributed to the low overall percent-variance explained. Overall, the maximum amplitude occurred at about 05Z (2200 PDT), about 10 hours *prior to* each day's wind maximum. Referring back to Figure 19 (paragraph 2e), this appears to be consistent with the long-term correlation coefficients calculated between wind speed at buoy #46022 and the 22-14 pressure gradients. This figure indicated a *relative maximum* in correlation between the 22-14 pressure gradients and wind speeds *eight hours later*. It is difficult to say whether or not the daily 22-14 pressure gradient data could be used as a reliable predictor of subsequent wind speeds, however, as this case did not evaluate any additional data in the days just before or just after the 8-day event. Also, day-to-day increases/decreases in maximum 22-14 gradients were not consistently followed by higher/lower wind speeds. A more thorough evaluation of pressure gradients and wind speeds, including gradient data to the north (using buoy #46027) would be beneficial.

(5) Upstream/Downstream Conditions: Upstream data (from buoy #46027) was missing during this event. As implied by the sea level pressure analyses, however, it appears likely that strong winds developed to the north of buoy 46022 during this event (probably at diurnally-favored times, as described in Case #1). Local winds (at buoy #46022) were not sufficiently strong enough, or of long enough duration to generate waves of the heights seen here (up to 16 feet). As noted above, this seems to be supported by the fact that daily wave height peaks during this case *preceded* daily wind maxima by about 5 hours (according to the harmonic analyses).

Downstream conditions: Wind speeds at buoy #46014 (120 miles south) averaged 10.4 knots, about 2 knots less than at buoy 46022 during the same period. Peak winds were somewhat stronger, though (26.4 knots with gusts to 32 knots). Wave heights at buoy #46014 averaged 9.6 feet (with an average 9.6 second dominant period), and reached or exceeded 10 feet about 40 percent of the time (maximum 12.8 feet). These conditions are consistent with what would be reasonably expected, due to simple decay over the distance between buoys #46022 and #46014. If the timing (of higher wind speeds downstream from buoy #46022) were optimum, however, much higher waves than those observed *could* have developed downstream, building possibly by several feet on top of the (decaying) waves arriving from further upstream.

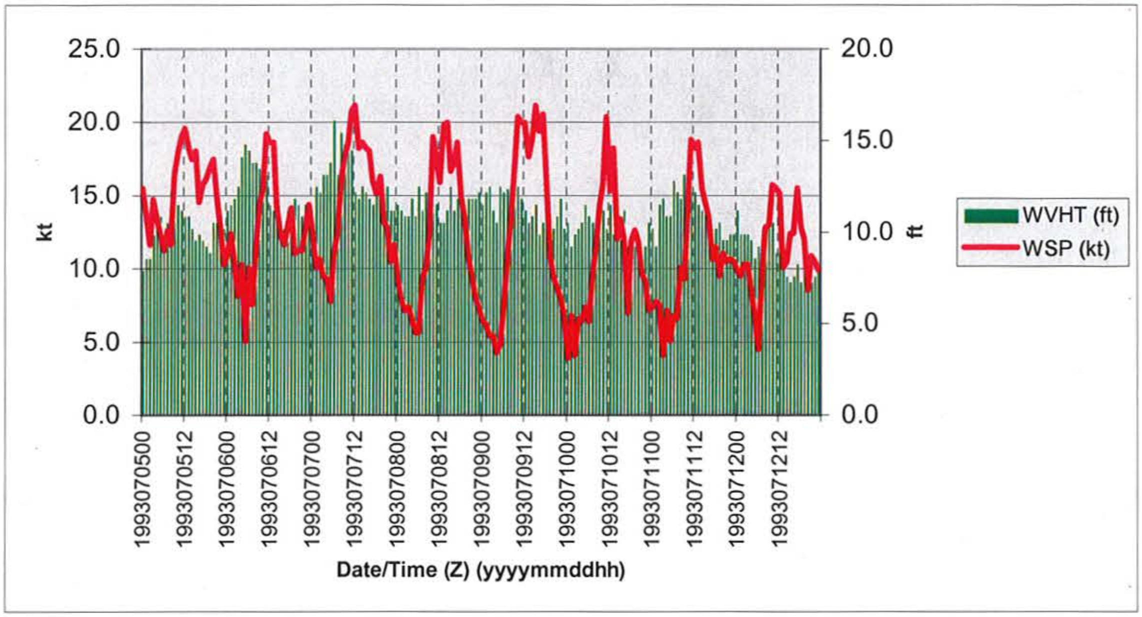


Figure 3e(1). Wind speed and wave height, buoy #46022 (5-12 July 1993).

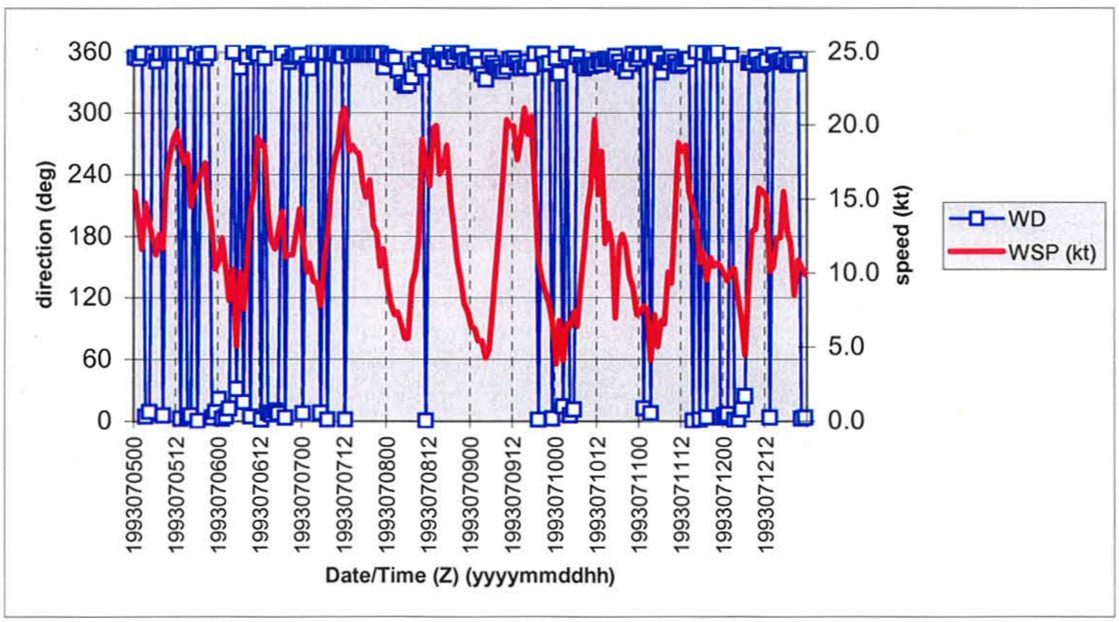
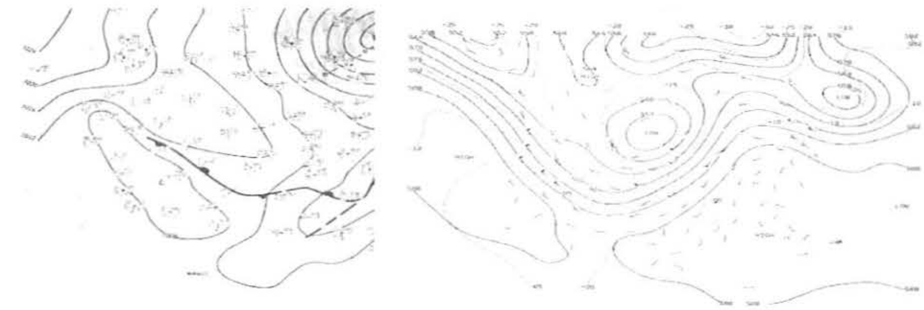
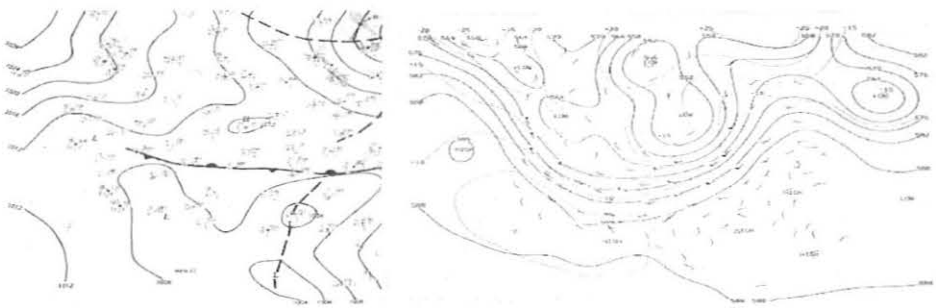


Figure 3e(2). Wind speed and direction, buoy #46022 (5-12 July 1993).



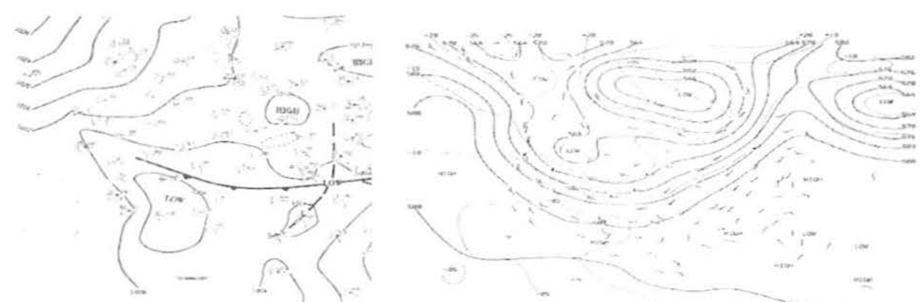
July 5, 1993

Figure 3e(3). Surface analysis (left) and 500 mb analysis (right), 5 July 1993.



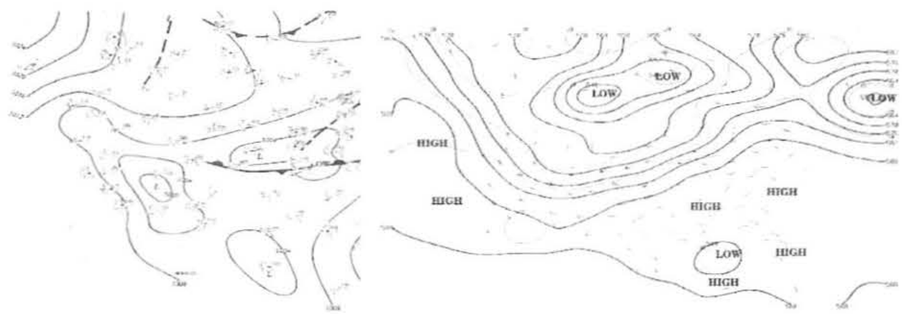
July 6, 1993

Figure 3e(4). Same as Figure 3e(3), but for 6 July 1993.



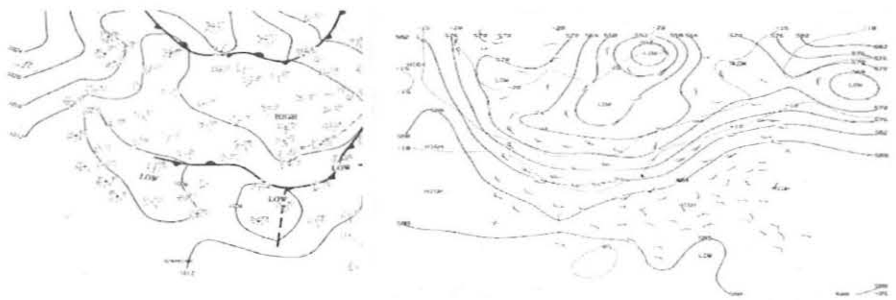
July 7, 1993

Figure 3e(5). Same as Figure 3e(3), but for 7 July 1993.



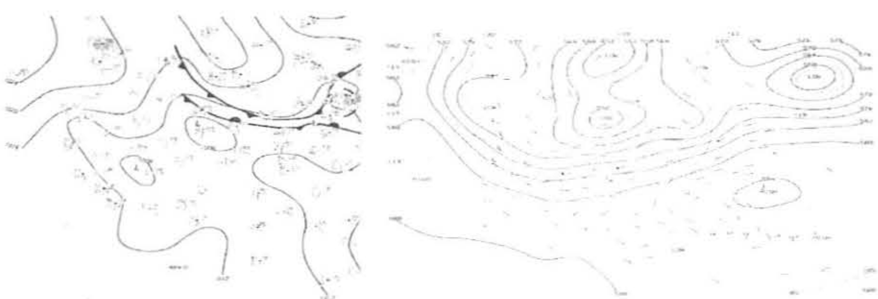
July 8, 1993

Figure 3e(6). Same as Figure 3e(3), but for 8 July 1993.



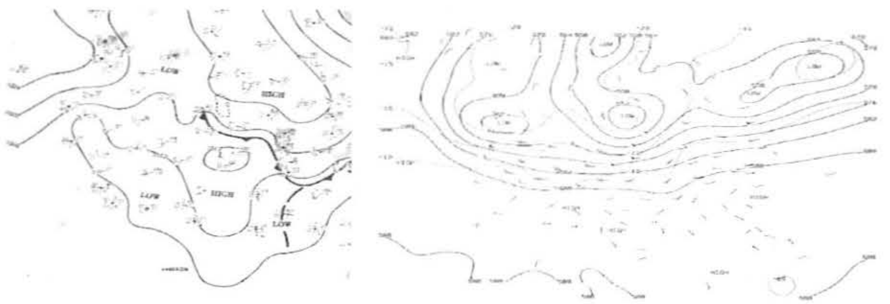
July 9, 1993

Figure 3e(7). Same as Figure 3e(3), but for 9 July 1993.



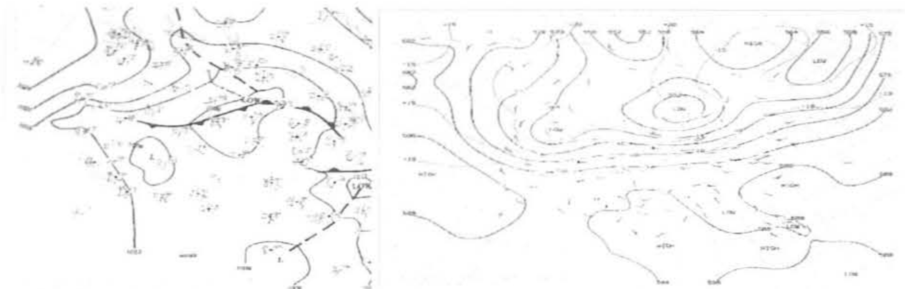
July 10, 1993

Figure 3e(8). Same as Figure 3e(3), but for 10 July 1993.



July 11, 1993

Figure 3e(9). Same as Figure 3e(3), but for 11 July 1993.



July 12, 1993

Figure 3e(10). Same as Figure 3e(3), but for 12 July 1993.

Table 3e. Time of maximum amplitude and percent-variance explained by the first harmonics of wind speed and wave height data (5-12 July 1993).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	1518	52.9%	1142	38.0%
2	1500	38.4%	0724	72.9%
3	1430	82.4%	0854	57.4%
4	1512	83.9%	1400	0.1%
5	1436	88.6%	0730	48.3%
6	1400	66.0%	0900	45.5%
7	1506	67.3%	1006	75.5%
8	1506	37.7%	0642	48.8%
ALL	***1448***	***56.5%***	***0936***	***18.3%***

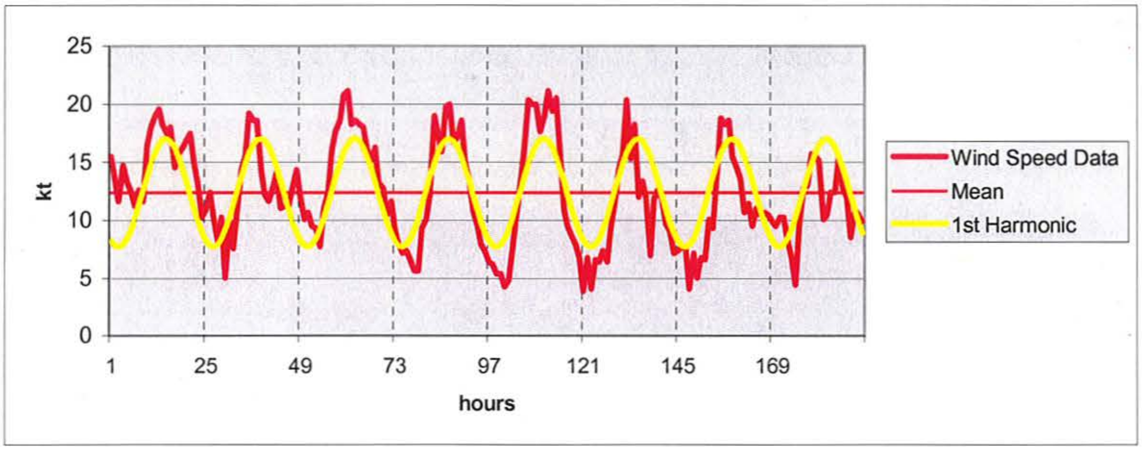


Figure 3e(11). Harmonic analysis of wind speed, buoy #46022 (5-12 July 1993).

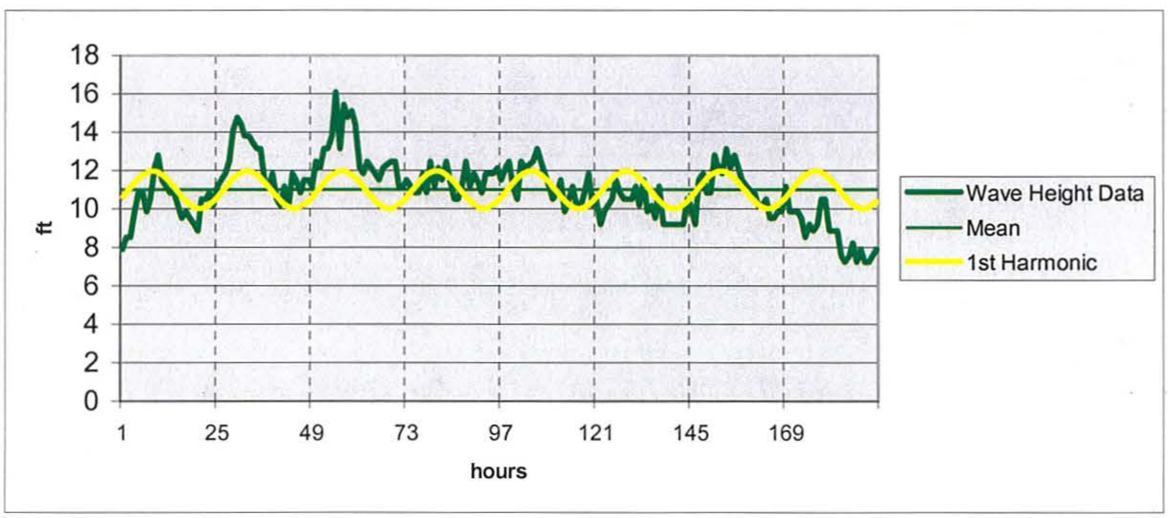


Figure 3e(12). Harmonic analysis of wave heights, buoy #46022 (5-12 July 1993).

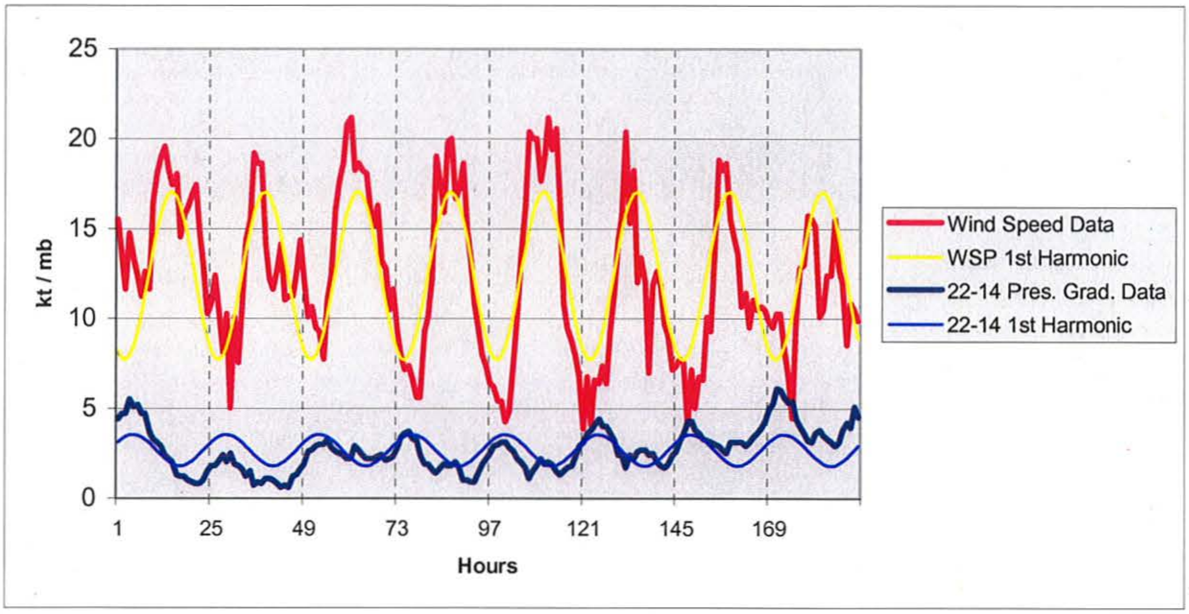


Figure 3e(13). Wind speeds (buoy #46022) and pressure gradients (absolute values) between buoys #46022 and 46014, with respective first harmonics superimposed (5-12 July 1993).

f. Case #6. Rapid Rise: Buoy #46014 (15-18 July 1987).

(1) Event description: Figures 3f(1) and 3f(2) show wind speed, direction, and wave heights for this event. This case is characterized by a sustained strong rise in wind speed and wave heights. Wind speed increases over 6-hour periods were the highest of any of the cases evaluated (maximum 19.2 knots). Although rates of increase in wave height were only moderate, the close coincidence and sustained nature of the increases in both wind and wave height are noteworthy. On day-1 of this event, winds were variable up to about 12 knots, and wave heights were steady around 5 feet. Beginning around 23Z (1700 PDT) on day 1, wind speeds rose sharply, then continued to rise to about 24 knots by 07Z (0000 PDT) on day 2. After briefly falling back to near 20 knots around 14Z (0700 PDT), winds again increased (through day 2), rising to a peak of 30-32 knots (gusts to 42 knots) from 23Z to 01Z (1600-1800 PDT) on days 2-3. Wave heights began rising about 6 hours before the initial wind speed increase (during the afternoon hours on day 1), then rose more rapidly, generally following wind speed trends, with maximum 6-hour increases of 4.3 feet. Wave heights peaked at 15.4 feet, at very nearly the same time as the peak wind. Wind directions followed similar trends compared to other cases, though tended to be more northwesterly with stronger wind speeds. At the end of the event, directions turned south to southwest (see "General Weather Situation, below").

(2) General Weather Situation: Figures 3f(3) through 3f(6) show the mean sea level pressure and upper air patterns for this event. The upper air situation on day 1 was dominated by a broad trough over northwestern Canada, with upper lows over southeast Alaska and northern Alberta. The southeast Alaska low briefly opened up to a trough on day 2 and shifted south to Vancouver Island and Washington state. On days 3 and 4, a cutoff upper low developed from this trough, then dropped further south, to the California-Oregon border. A surface cold front to the south of the upper trough was located over southwestern Canada on day 1, then dropped further south into the intermountain west on day 2. Pressure gradients began to increase (north to south) as ridging developed over the Pacific Northwest behind this front. By day 3, a strong surface low developed along the front (over northeast Nevada-southwest Idaho). Pressure gradients remained fairly strong, early, but were more west to east (onshore). By day 4, this low had begun to fill, with weaker pressure gradients prevailing. Another surface low then developed to the north, near Vancouver Island, further weakening pressure gradients and turning winds along the northern California coast to the south-southwest.

(3) Harmonic Analysis of Wind Speed and Wave Height: Figures 3f(7) and 3f(8) show the harmonic analysis results for wind speed and wave height for this event. Diurnal tendencies for both wind speed and wave height for this four-day event were quite weak, with less than 2 percent of the overall variance explained by the first harmonics (period = 24 hours). As the pressure gradients weakened and the event subsided on days 3 and 4 though, diurnal trends increased, with about 62 percent of the variance explained on each of those days. Overall, the time of peak wind speed amplitude occurred at about 06Z (2300 PDT) and the minimum occurred at 18Z (1100 PDT). Concerning wave heights, days 1 and 3, just before and after the peak wave height build-up, showed the strongest diurnal tendencies, with about 60 percent of the variance explained on those days. The overall peak wave height amplitude occurred near 00Z (1700 PDT), with the minimum about 12Z (0500 PDT).

(4) Pressure Gradients: Figure 3f(9) shows wind speeds along with the pressure gradients between buoys #46022 (120 miles north) and #46014 for this event. The 22-14 gradients provided a strong initial signal to the rising winds. About 6 hours prior to the first strong wind increase on day 1, 22-14 gradients rose steadily, from 1.3 mb to 6 mb, peaking about 4 hours before the first wind peak around 24 knots. Gradients (22-14) and wind speeds then began to slowly decrease overnight on day 2. These pressure gradients did not appear to offer an advance indicator of the second wind speed rise (from 20 to 32 knots later on day 2). Although 22-14 gradients did increase steadily during this subsequent rise, the wind speeds in this case actually preceded the gradient increase by about 2 hours. They did appear to signal the rapid decrease in winds, though, beginning on day 3. At 21Z (1400 PDT), 22-14 pressure gradients peaked at 5.3 mb, then began a steady fall to near zero by late morning on day 3 (except for a temporary rise in the early morning of day 3). Wind speeds also began to fall beginning about 3 hours later, from the peak near 32 knots to near calm by early morning on day 4.

(5) Upstream/Downstream Conditions: Data south of buoy #46014's location was not analyzed, so a description of downstream conditions is not provided here. To the north, (at buoy #46022), wind speeds during this event averaged about 13 knots, very close to average wind speeds at buoy #46014. Peak winds were about 10 knots less than observed here though. Wave heights averaged 9.9 feet with dominant periods averaging 9.9 seconds. Waves at buoy #46022 were 14 feet or higher about 18 percent of the total time, with dominant periods of 10-11 seconds for waves in this height range. Given these conditions, peak waves of 12-14 feet with periods of 11-12 seconds could be expected at buoy #46014 (due to simple decay), with a travel time of about 7 hours. Assuming an average 20 knot wind for 24 hours, over a fetch of 300 nautical miles (a reasonable assumption for this case), 6 foot waves could be expected to build. Given both of these (maximum) assumptions, the two would add up (using sums of squares) to about 15.2 feet, which is very consistent with conditions actually observed.

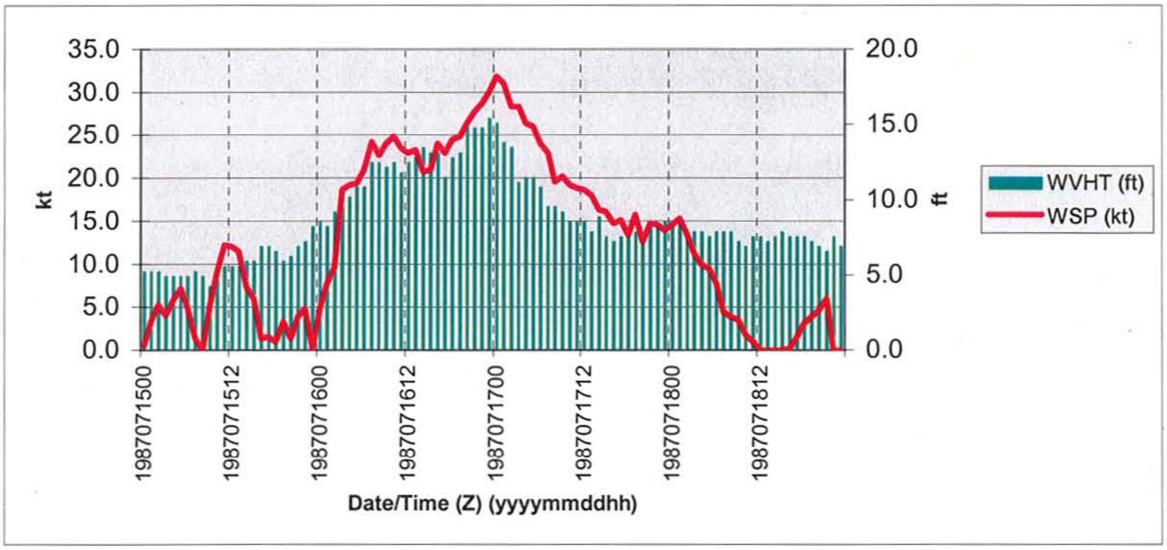


Figure 3f(1). Wind speed and wave height, buoy #46014 (15-18 July 1987).

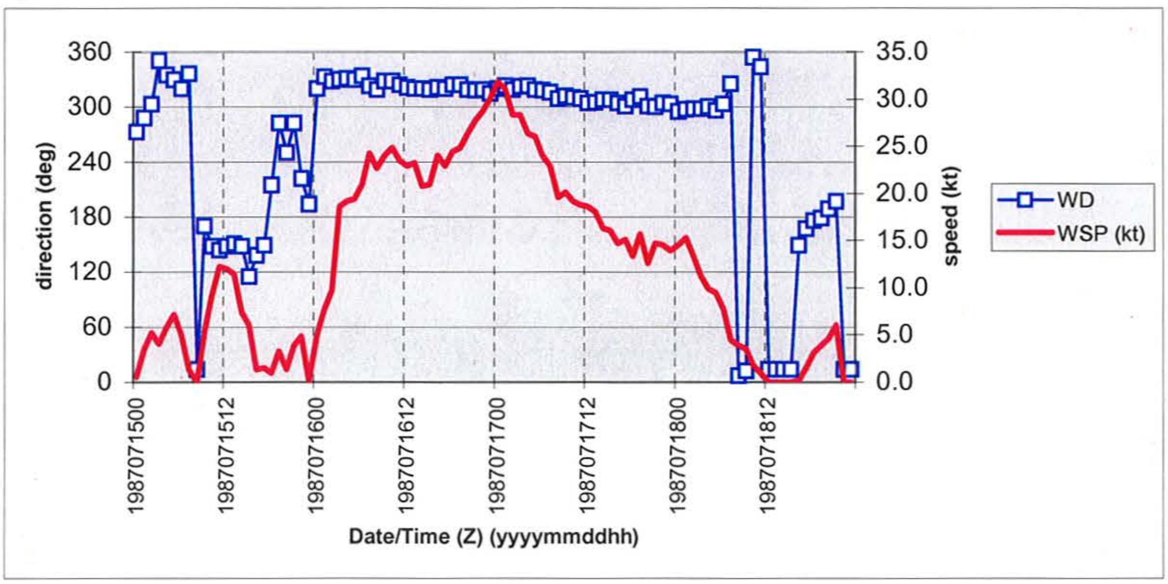
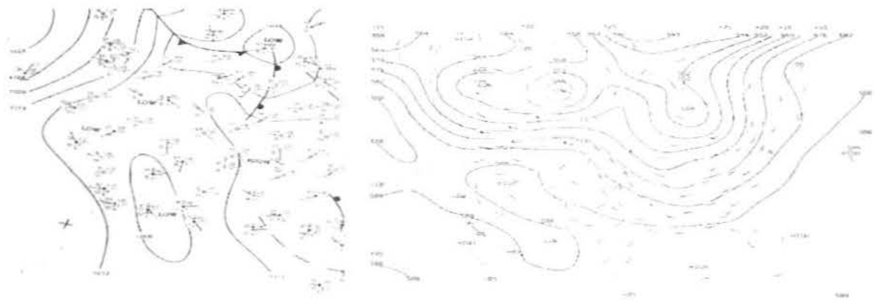
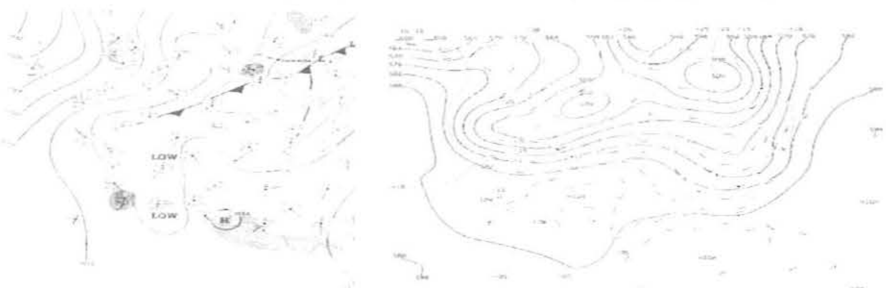


Figure 3f(2). Wind speed and direction, buoy #46014 (15-18 July 1987).



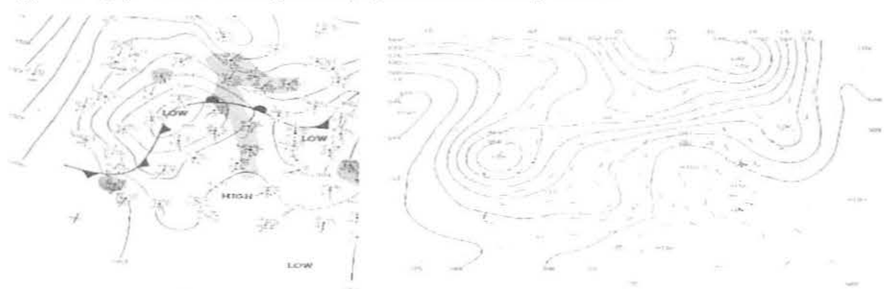
July 15, 1987

Figure 3f(3). Surface analysis (left) and 500 mb analysis (right), 15 July 1987.



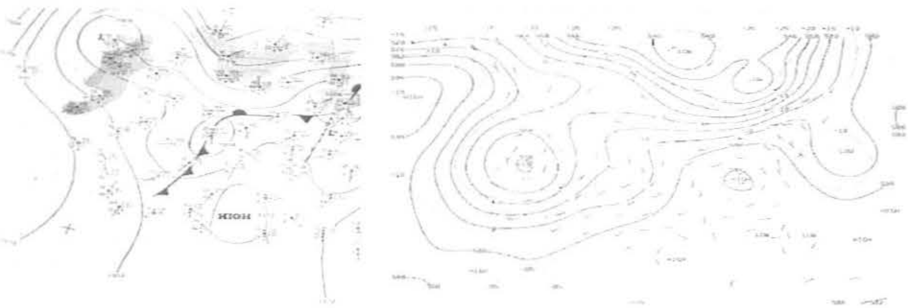
July 16, 1987

Figure 3f(4). Same as Figure 3f(3), but for 16 July 1987.



July 17, 1987

Figure 3f(5). Same as Figure 3f(3), but for 17 July 1987.



July 18, 1987

Figure 3f(6). Same as Figure 3f(3), but for 18 July 1987.

Table 1. Time of maximum amplitude and percent-variance explained by the first harmonics of wind speed and wave heights, buoy #46014 (15-18 July 1987).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	1218	32.7%	2012	60.1%
2	1600	19.6%	1730	32.4%
3	0512	61.0%	0406	60.1%
4	0318	62.7%	0512	16.3%
ALL	***0600***	***1.9%***	***2354***	***0.9%***

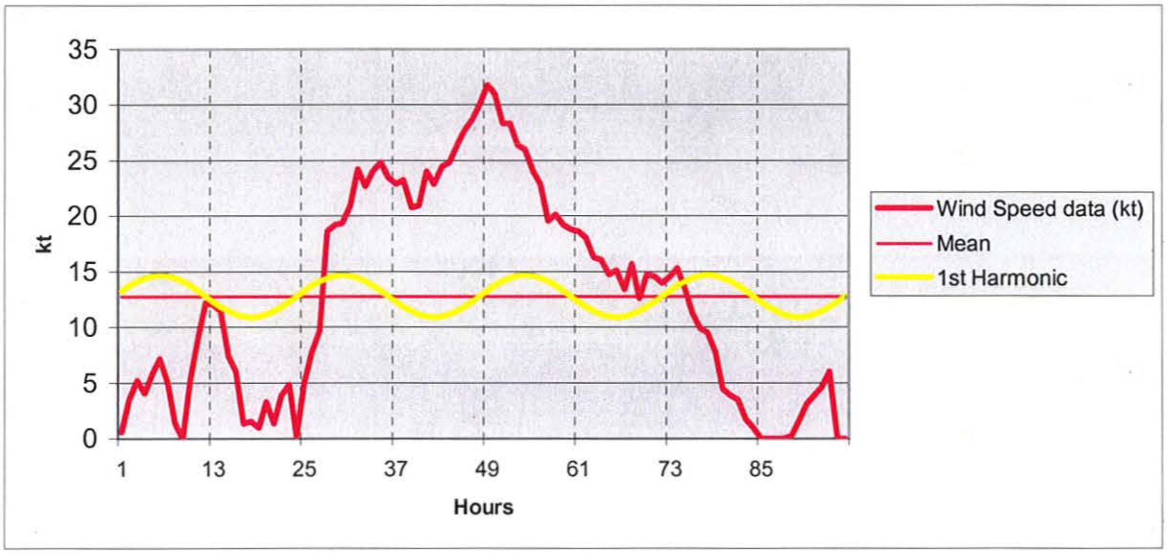


Figure 3f(7). Harmonic analysis of wind speeds, buoy #46014 (15-18 July 1987).

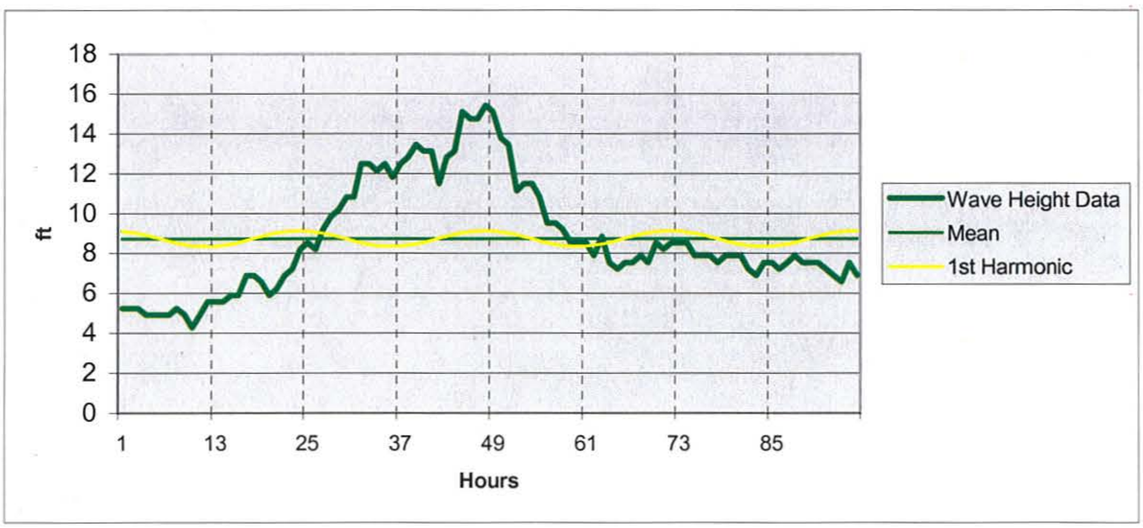


Figure 3f(8). Harmonic analysis of wave heights, buoy #46014 (15-18 July 1987).

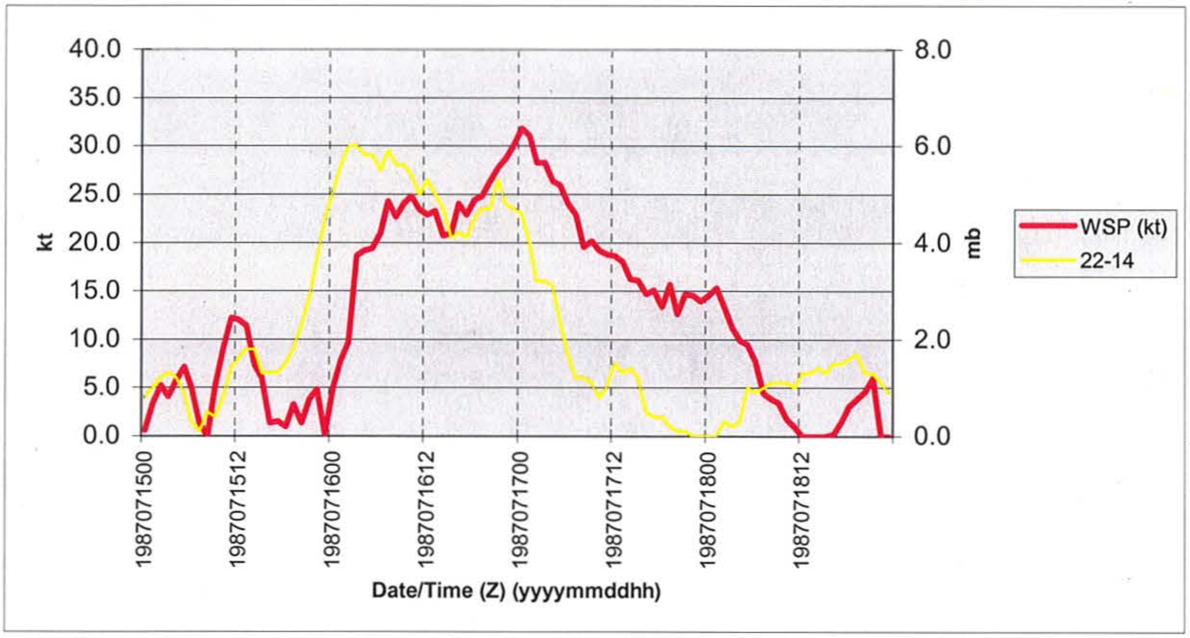


Figure 3f(9). Wind speed (#46014) and pressure gradients (#46022-46014), 15-18 July 1987.

g. Case #7. Rapid Rise: Buoy #46014 (15-17 September 1987).

(1) Event description: Figures 3g(1) and 3g(2) show the wind speed, direction, and wave height trends for this case. This case is characterized by rapidly increasing wind speeds (up to 15 knots/6 hours, with directions primarily from the north-northwest) and *very rapidly building wave heights*. Maximum wave height increases of 9.2 feet/6 hours were observed, which represents *the most rapid rise (over 6 hour periods) of any of the cases analyzed here*. As described below ("Upstream Conditions"), this case appears to have had a significant contribution to wave heights from an external (distant) source.

This event began with wind speeds between 5 and 10 knots (from variable directions, generally northwest to north-northeast) and steady wave heights around 3 feet. Wind speeds increased rapidly overnight on day 1, beginning about 04Z (2100 PDT), rising to 20 to 23 knots by the following morning. Wave heights began to rise about 4 hours later, building rapidly to around 10 feet by 15Z (0800 PDT) the following morning, then continued to rise, peaking at 17 feet at 19Z (1200 PDT) on day 1. After holding nearly steady for about 8 hours, wind speeds rose further, peaking at 27-28 knots (peak gusts to nearly 40 knots) between 00Z and 03Z (1700-2000 PDT) on day 2. Wind speeds then began a rapid decline overnight on day 2, falling to less than 5 knots (and becoming north-northeast) between 12Z and 18Z (0500-1100 PDT). The rate of decrease of wind speeds during this time (nearly 17 knots/6 hours) was the *most rapid (6-hourly) decrease* of any of the cases evaluated here. Wind speeds rose again during the afternoon of day 2, but only to 10-15 knots, then fell again to near calm by early morning on day 3. Wave heights also subsided, but at a much slower rate, remaining above 10 feet through the early morning hours of day 3, then gradually subsided below 8 feet in the afternoon of day 3.

(2) General Weather Situation: Figures 3g(3) through 3g(5) show the surface and 500 mb analyses for this event. An upper level trough was located along the west coast on day 1, with a ridge near 150° W. The upper trough shifted east (toward eastern Montana and Wyoming) through days 2-3, while the upstream ridge also moved east (to the Washington coast by day 3). A surface ridge had begun to build into the Pacific Northwest on day 1, behind a cold front which was moving east across the northern Rocky Mountains. Pressure gradients increased rapidly through day 1 (see "Pressure Gradients," below), as the surface thermal trough intensified along the coast and the ridge to the north strengthened. On day 3, pressure gradients relaxed, as high pressure over the Pacific Northwest weakened in association with a cold front approaching from the Gulf of Alaska.

(3) Harmonic Analysis of Wind Speed and Wave Height: Table 3g and Figures 3g(6) and 3g(7) show the harmonic analysis results for wind speed and wave height for this event. While only 7.7 percent of the wind speed variance was explained by the first harmonic (period = 24 hours), diurnal trends on individual days were much higher, ranging from 50 percent to about 85 percent (highest on day 2), with the overall maximum occurring about 04-05Z (2100-2200 PDT). Diurnal wave height trends were also weak for the 3 day period as a whole, but strong individually on days 1 and 3 (74 and 67 percent of the variance explained by the first harmonic, respectively), with the overall maximum occurring near 21Z (1400 PDT).

(4) Pressure Gradients: Figure 3g(8) shows the pressure gradient trends for buoys #46027-46014 (27-14) and for #46022-46014 (22-14), along with the buoy #46014 wind speeds. The 27-14 and 22-14 gradients began a steady rise 2-3 hours before wind speeds initially increased on day 1. Wind speeds then generally followed the increasing pressure gradient trends, peaking around 12Z (0500 PDT) the following morning, then leveled off. The 27-14 gradients then began to fall, even as wind speeds again increased to 25-28 knots through the late afternoon on day 1. The 22-14 gradients did rise during the afternoon, but not until *after* the winds began to increase again. Wind speeds and pressure gradients then generally fell through the remainder of the event, except on day 3 when a temporary rise occurred. Here again, though, pressure gradient trends lagged *behind* wind speed trends. Thus, while it appears that pressure gradients provided an advance indication of the initial wind speed increase, they were less valuable once the event was underway.

(5) Upstream Conditions: Data south of buoy 46014's location was not analyzed for this study, so a description of downstream conditions is not provided here. Upstream, at buoy #46022, winds were moderate, with peak sustained speeds of 21 knots (peak gusts to 27 knots). Wave heights reached a maximum of 17 feet (same as at buoy #46014 during this period). It is unlikely that waves as high as these could have been generated due solely to local/regional winds, so there had to be some external contributing source. Dominant wave periods provided some indication of this. With other cases analyzed in this study, dominant periods were typically 8 to 10 seconds, but in this case, dominant periods averaged 12 seconds, and were 14 seconds or longer nearly 40 percent of the time (at both #46014 and #46022). A similar set of dominant periods was also observed at #46027 during this period, with wave heights up to 15.4 feet. The source of the long-period swell is unknown, but it is nevertheless significant that such large waves could occur at this time of year, given only moderate to briefly strong wind conditions. Assuming a 250 nautical mile fetch, with an average 20-25 knot wind over 24 hours (reasonable values for this case), waves of 7 to 11 feet could be produced. In this case, though, waves from an apparently external source added several feet to what could have been expected to develop from purely local/regional sources.

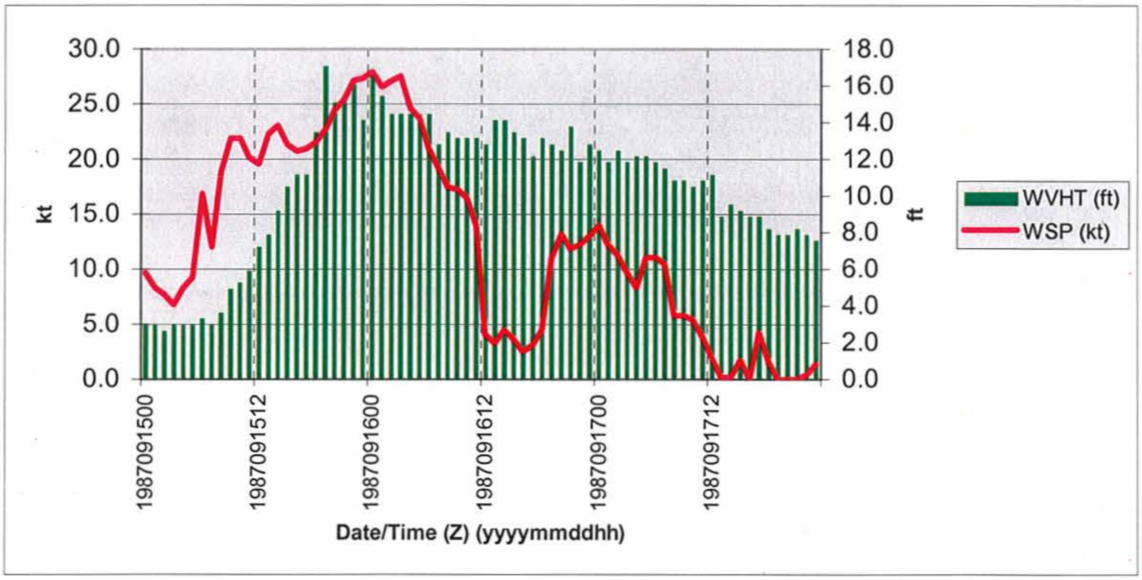


Figure 3g(1). Wind speed and wave height, buoy #46014 (15-17 September 1987).

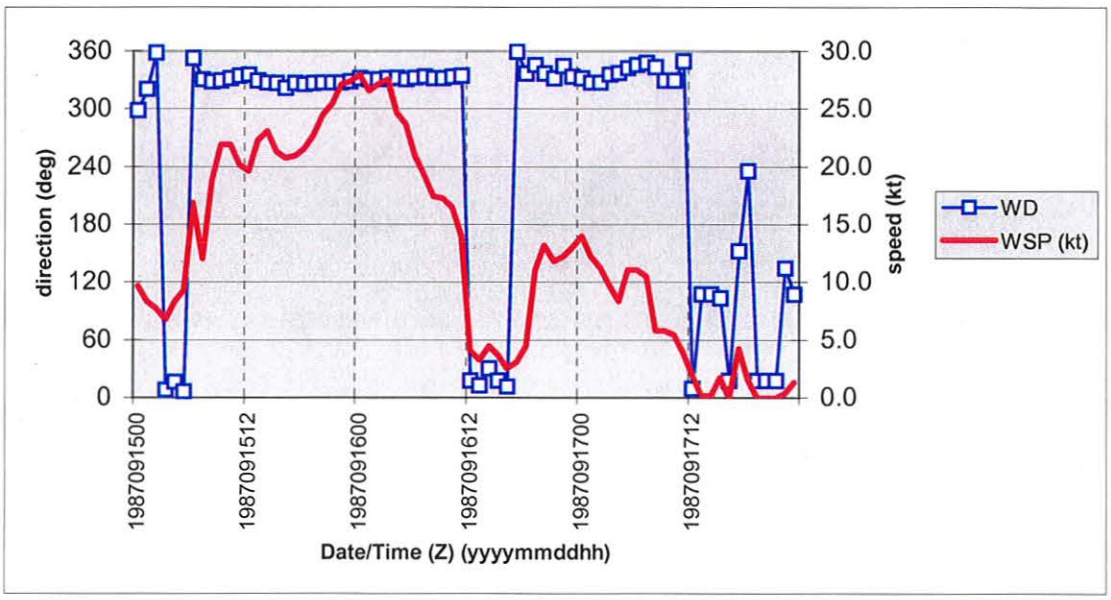
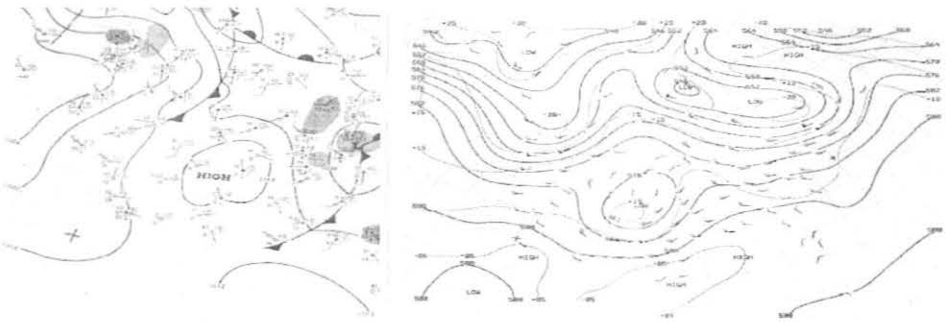
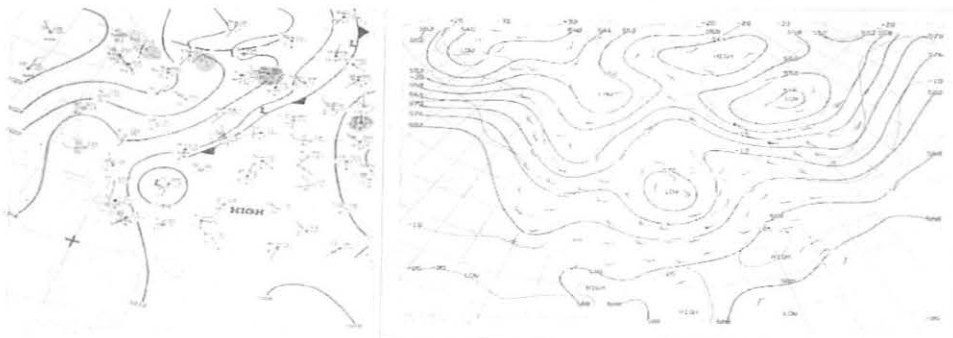


Figure 3g(2). Wind speed and direction, buoy #46014 (15-17 September 1987).



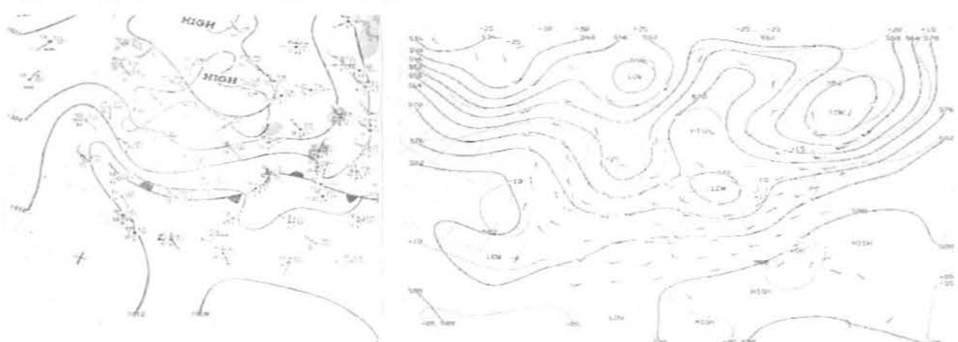
Sep. 15, 1987

Figure 3g(3). Surface analysis (left) and 500 mb analysis (right), 15 September 1987.



Sep. 16, 1987

Figure 3g(4). Same as Figure 3g(3), but for 16 September 1987.



Sep. 17, 1987

Figure 3g(5). Same as Figure 3g(3), but for 17 September 1987.

Table 3g. Time of maximum amplitude and percent-variance explained by the first harmonic of wind speed and wave height, Buoy #46014 (15-17 September 1987).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	1712	49.8%	1924	74.0%
2	0424	85.4%	0418	24.5%
3	0518	67.0%	0648	67.2%
ALL	***0424***	*7.7%*	***2118***	***5.2%***

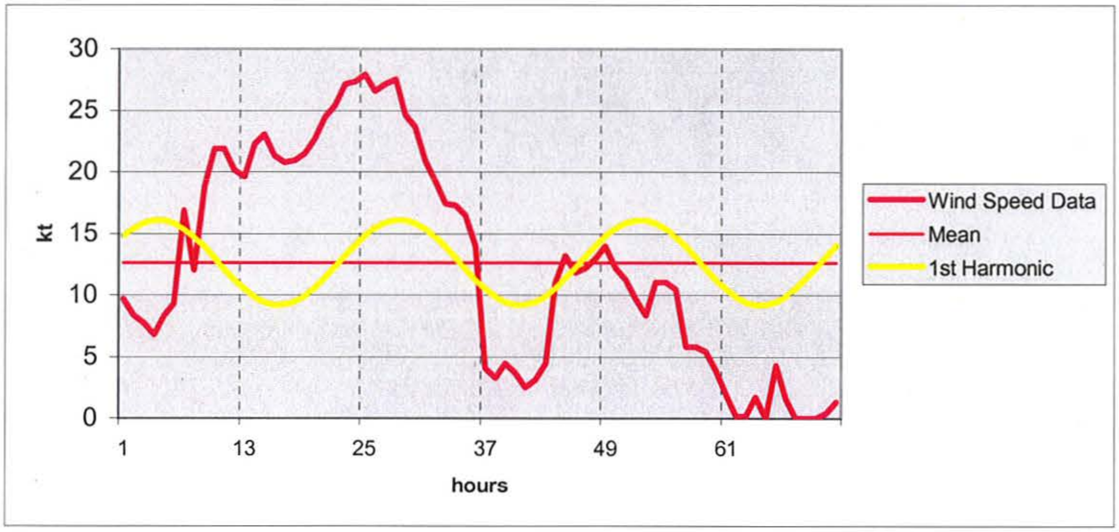


Figure 3g(6). Harmonic analysis of wind speed, buoy #46014 (15-17 September 1987).

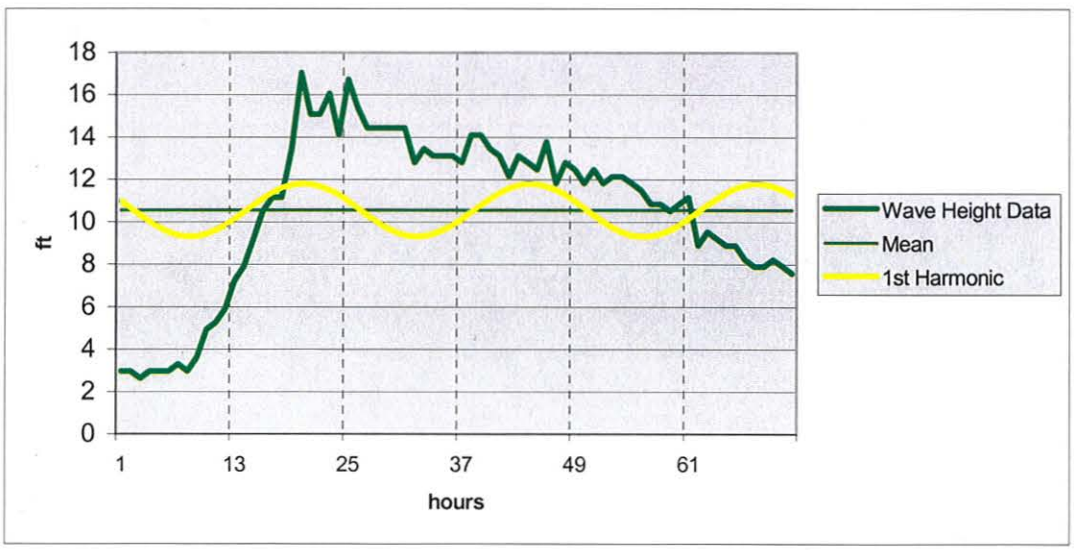


Figure 3g(7). Harmonic analysis of wind speed, buoy #46014 (15-17 September 1987).

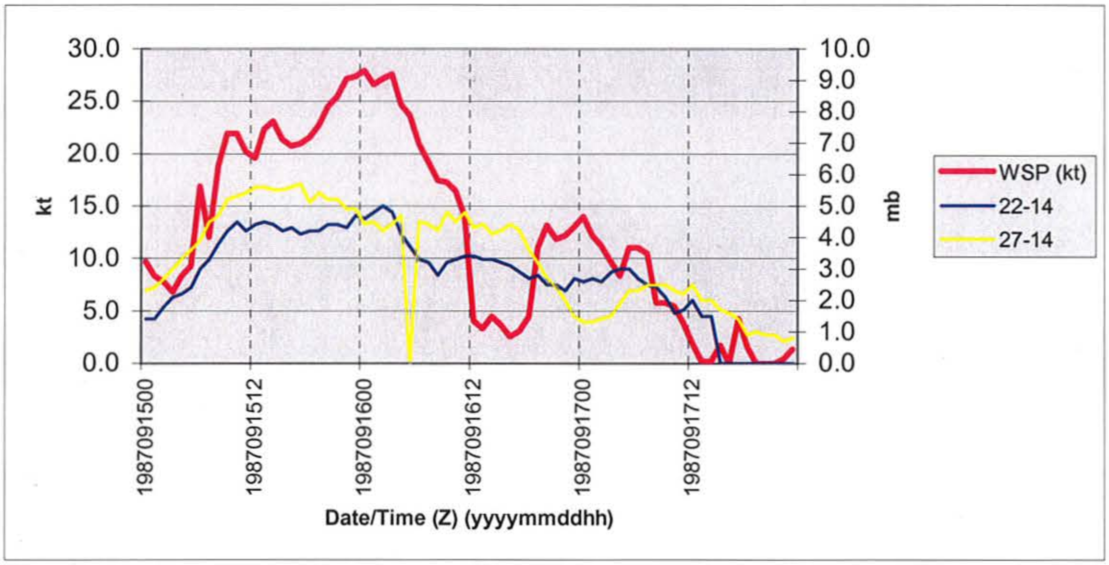


Figure 3g(8). Wind speed (buoy #46014) and pressure gradients (bouys #46027-46014 and #46022-46014), 15-17 September 1987. Zero-values denote missing data.

h. Case #8. Rapid Rise: Buoy #46014 (24-30 September 1997).

(1) Event description: Figures 3h(1) and 3h(2) shows the wind speed, direction, and wave height trends for this case. This case is characterized by a rapid increase in both wind speeds (up to 14 knots/3 hours, with directions primarily from the north-northwest) and *very rapidly building wave heights*. Maximum wave height increases of 7.4 feet/6 hours were observed (second-highest 6-hour rate of rise of the cases analyzed here). Over a 15-hour period, wave heights rose from about 7 feet to 19 feet, and ultimately to a peak of 19.4 feet, the highest overall wave height of all the cases analyzed here.[1] Similar to the previous case, this event appears to have had a significant contribution to wave heights early in the event from an external source, likely a distant north Pacific storm. Hurricane "Nora" was located south of Baja California early in this event, but based on the time of arrival of the initial long period swell (25 seconds) at buoys along the California coast, it appears that the primary source was not "Nora," but a storm to the northwest of the region. The long period swell arrived at buoys on the northern California coast in the early morning on day 1, and progressively later (by a few to several hours) at other buoys southward along the California coast. The second (larger) rise in wave heights in the middle of the event appears to be most closely related to an increase in coastal winds, due to the close similarity in wind speed and wave height trends, as described in more detail below.

Wind speeds from day 1 through the morning of day 3 were no higher than 12 knots. Wave heights however, began to rise early on day 1, from around 6 feet at 07Z (0000 PDT) to 12 to 14 feet between 01Z and 03Z (1800-2000 PDT) on day 2. This initial rise appears due primarily to an external swell source. Dominant periods, initially around 12 seconds through the overnight hours on day 1, abruptly increased to 25 seconds between 10Z and 14Z (0300-0700 PDT) on day 1. Wave heights then slowly subsided to around 8 feet through the afternoon of day 3, while dominant periods decreased to 14 seconds.

At 17Z (1000 PDT) on day 3, winds were calm. Through the afternoon and evening, wind speeds increased rapidly, rising to 20 knots by 05Z (2200 PDT) on day 4. Wind speeds remained about 20-22 knots overnight on day 4, then rose again to a peak of 26 knots with gusts to 32 knots at 01Z (1800 PDT) on day 5. Wave heights also rose rapidly (lagging behind the wind increase by a few hours), from 7 feet to 19 feet by 12Z (0500 PDT) on day 4, as described above. In the early morning hours on day 5, wind speeds rapidly decreased, and generally were 10 knots or less through the remainder of the event, except for a brief increase to around 15 knots overnight on day 7. Wave heights also steadily fell, though more gradually, from the peak of 19.4 feet on day 4, to below 10 feet on day 6, and then to below 5 feet on day 7.

(2) General Weather Situation: Figures 3h(3) through 3h(9) show the mean sea level pressure and upper air patterns for this event. Weak pressure gradients prevailed over the region on day 1, with a weak surface low just off the northern California coast. A strong ridge aloft was located over the western United States, with a deep upper trough over the Gulf of Alaska and a weak upper low off the central California coast. Hurricane "Nora" was located off the southern coast of Baja California, moving north. A similar surface and upper pattern prevailed on day 2, except that Hurricane "Nora" had moved into central and northern Baja California, and was continuing on a northward track. By day 3, the upper trough over the northeast Pacific shifted eastward to the west coast, and an associated cold front had swept into the Pacific Northwest. Hurricane "Nora" had continued to move north into the southwestern United States while weakening to a subtropical low. On day 4, pressure gradients increased, due to a strong surface ridge to the north (now having developed behind the cold front over the Pacific Northwest) and a thermal trough along the California coast. Pressure gradients remained strong on day 5, with strong surface high pressure over southeast Idaho, and a stronger thermal trough along the northern California coast. Pressure gradients weakened along the coast on days 6 and 7, as another upper trough and a surface cold front approached the Pacific Northwest.

(3) Harmonic Analysis of Wind Speed and Wave Height: Figures 3h(10) and 3h(11) show the harmonic analysis results for wind speed and wave height for this event. Except for days 1 and 5, wind speeds did not follow strong diurnal trends for this event. Overall, only about 2 percent of the total variance was explained by the first harmonic (period = 24 hours). Wave heights, overall, did not show strong diurnal trends either, with less than 1 percent of the variance explained by the first harmonic for the

---

[1] Wave heights at buoy 46022, 110 miles north, reached 20.4 feet at 08Z (0100 PDT), a few hours before the peak height at buoy 46014.

seven days as a whole. Individually, only days 1, 6, and 7 had more than 50 percent (with a range of 67-73 percent on these days).

(4) Pressure Gradients: Figure 3h(12) shows the pressure gradient trends for buoys #46022-46014 (22-14), along with the buoy #46014 wind speeds. Pressure data from buoy #46027 was not available for this period. The 22-14 gradients remained weak from day 1 through the first half of day 3, then began a steady increase in the afternoon on day 3. However, these gradients proved of little value as a predictor, as the initial increase occurred simultaneously with the wind speed increase, and the peak occurred shortly after the wind speed peak.

(5) Upstream Conditions: Data south of buoy #46014's location was not analyzed for this study, so a description of downstream conditions is not provided here. As noted above, buoy #46022 (110 miles north) also experienced the same rise in wave heights (apparently from a distant north Pacific storm). Peak wave heights during the initial buildup on days 1 and 2 reached 17 feet (with 17 second periods at time of peak height). The second wave height build up on days 3 and 4 reached 20.4 feet (again, with 17 second periods at peak height). Wind speeds were moderate to (briefly) strong on days 4 and 5, but less than at buoy #46014 during this time (peak of 21 knots sustained, with gusts to 25 knots). The wind speeds observed at buoys #46022 and #46014 were *not* sufficient (given the limited fetch along the coast, with north to northwest winds) to generate waves of this height. Nevertheless, given the observed height and period values at buoy #46022, only about 1 foot of decay would likely have occurred in traveling downstream (about 4 hours travel time) to buoy #46014. While the large waves from upstream obviously provided a major contribution to the conditions observed at buoy #46014, it is not clear what the ultimate source of these waves was. However, the wave buildup at buoy #46022 *preceded* the wind increase by several hours, so the source was clearly further upstream. Wind data further to the north (at buoy #46027) was not available during this time, however, so wave contributions from this part of the coast could not be evaluated.

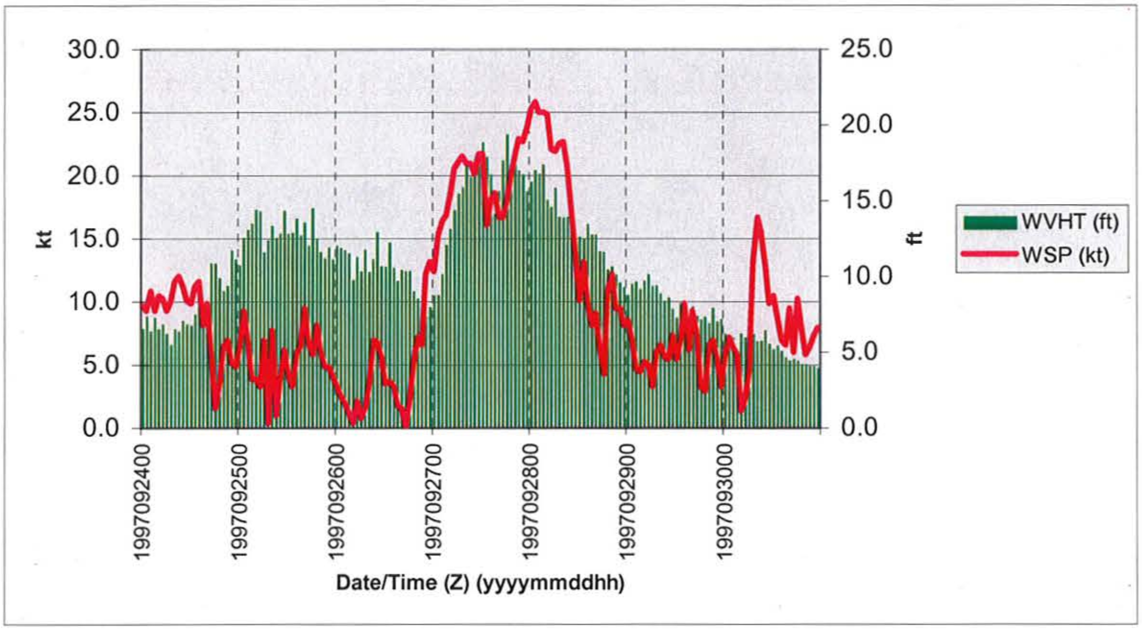


Figure 3h(1). Wind speed and wave height, buoy #46014 (24-30 September 1997).

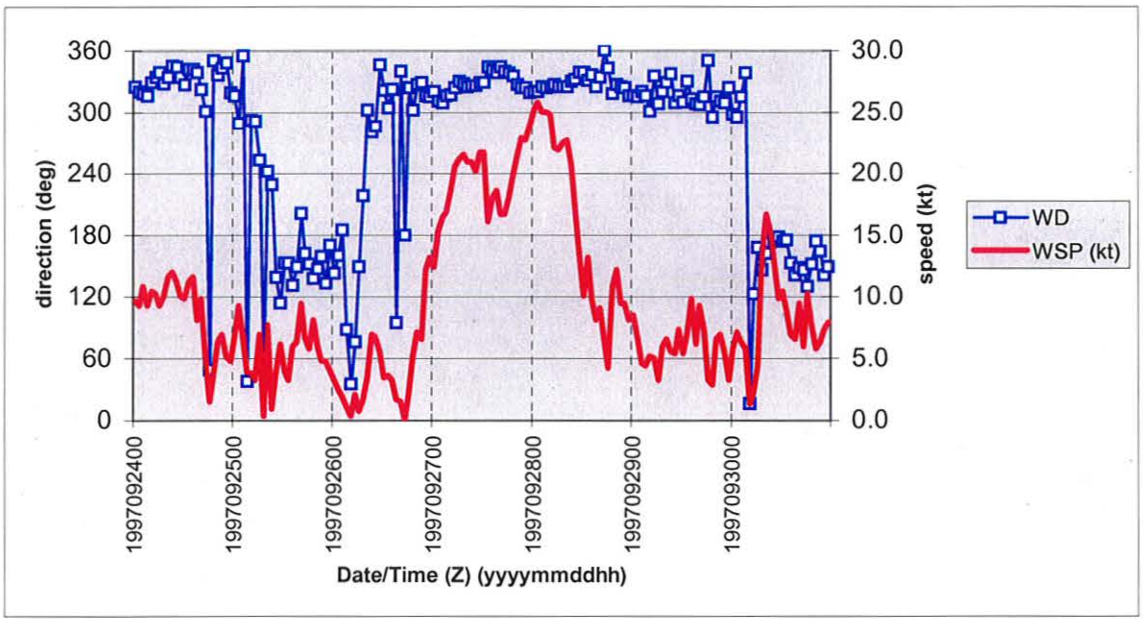
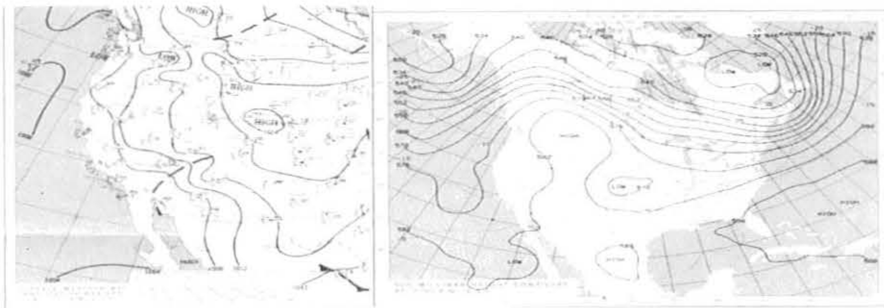
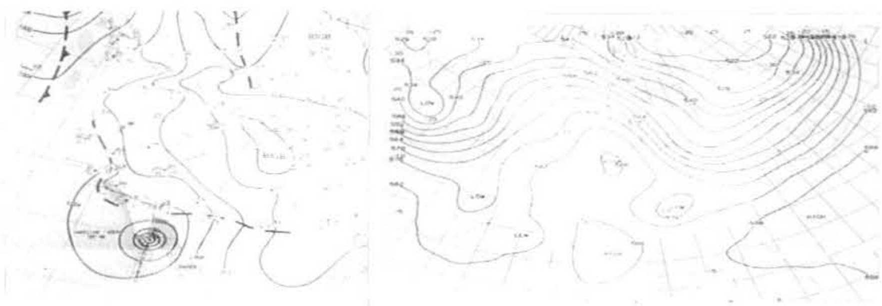


Figure 3h(2). Wind speed and direction, buoy #46014 (24-30 September 1997).



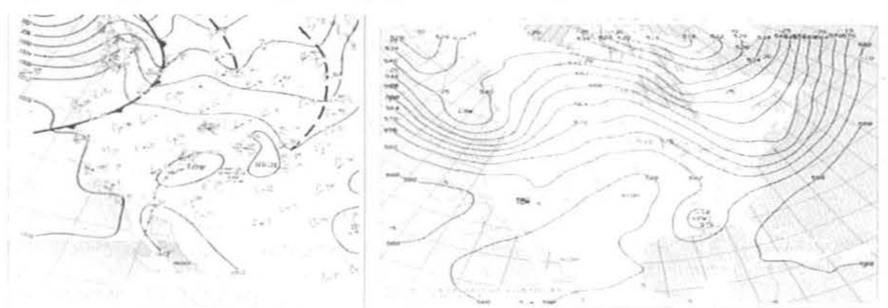
Sep. 24, 1997

Figure 3h(3). Surface analysis (left) and 500 mb analysis (right), 24 September 1997.



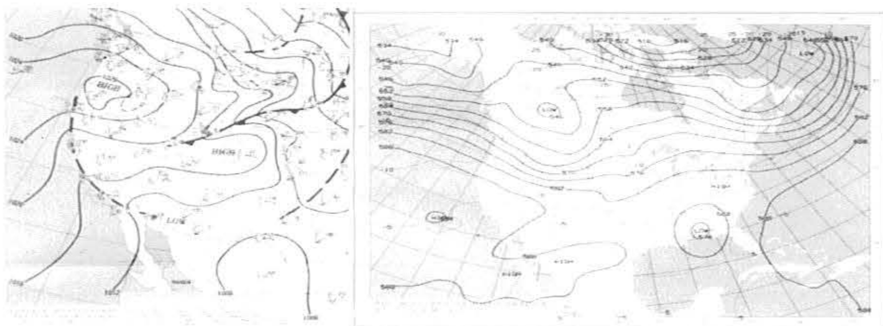
Sep. 25, 1997

Figure 3h(4). Same as Figure 3h(3), but for 25 September 1997.



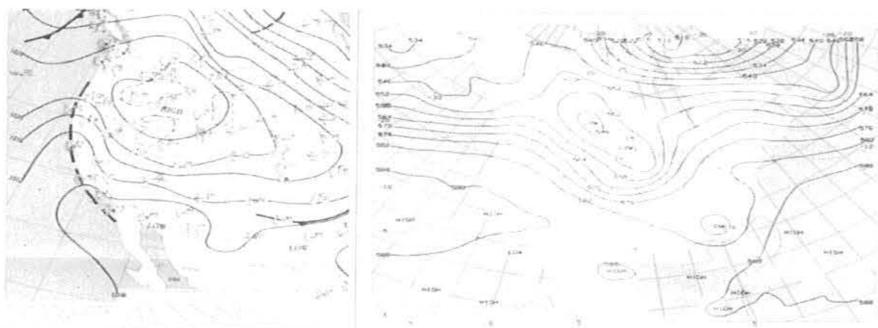
Sep. 26, 1997

Figure 3h(5). Same as Figure 3h(3), but for 26 September 1997.



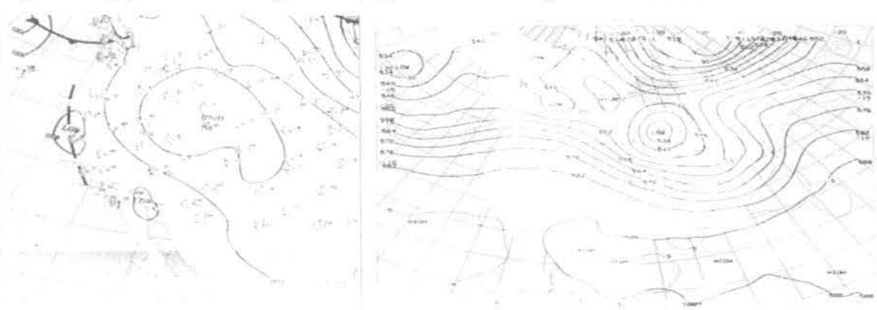
Sep. 27, 1997

Figure 3h(6). Same as Figure 3h(3), but for 27 September 1997.



Sep. 28, 1997

Figure 3h(7). Same as Figure 3h(3), but for 28 September 1997.



Sep. 29, 1997

Figure 3h(8). Same as Figure 3h(3), but for 29 September 1997.

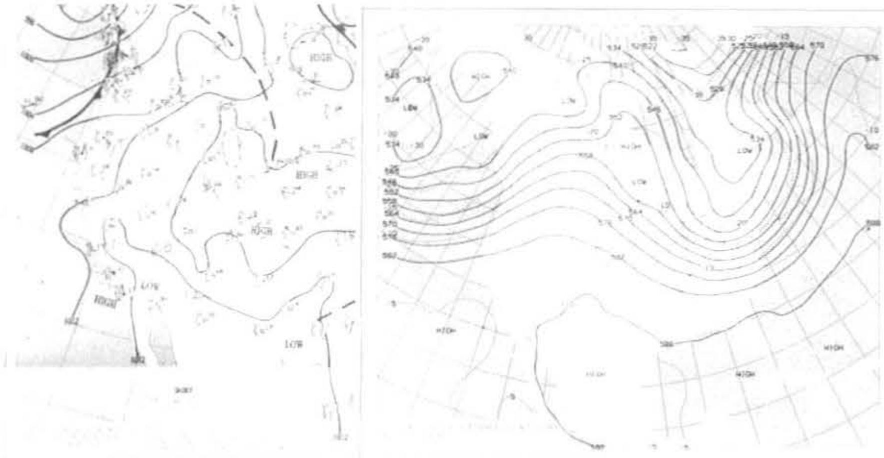


Figure 3h(9). Same as Figure 3h(3), but for 30 September 1997.

Table 3h. Time of maximum amplitude and percent-variance explained by the first harmonic of wind speed and wave height, Buoy #46014 (24-30 September 1997).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	0900	58.4%	2018	66.5%
2	2024	18.6%	1248	19.6%
3	2148	8.8%	0948	34.1%
4	1024	1.9%	1454	46.1%
5	0542	77.9%	0624	46.4%
6	1518	13.6%	0600	72.6%
7	1212	27.5%	0736	67.2%
ALL	***0824***	***2.1%***	***1106***	***0.9%***

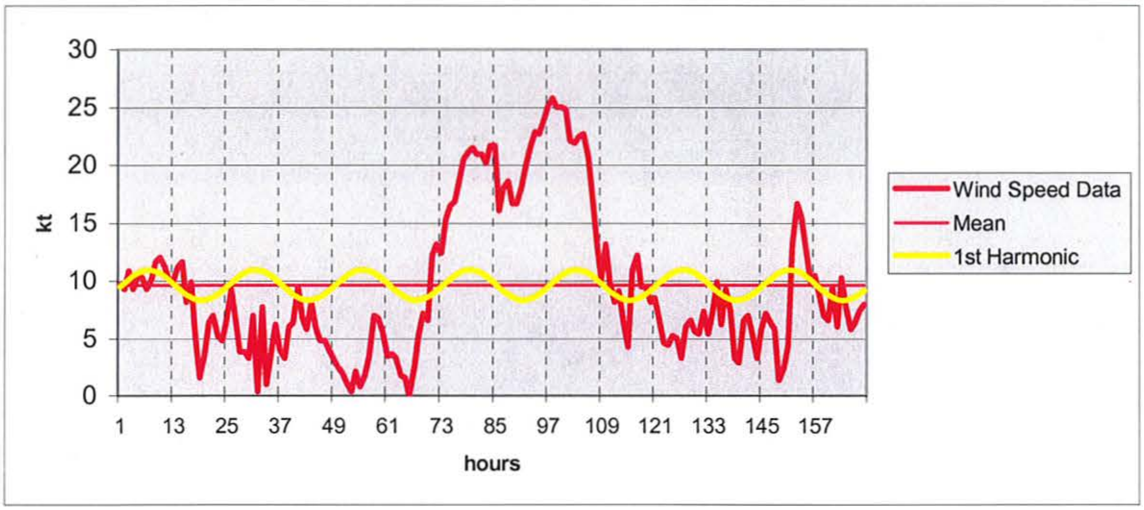


Figure 3h(10). Harmonic analysis of wind speeds (24-30 September 1997).

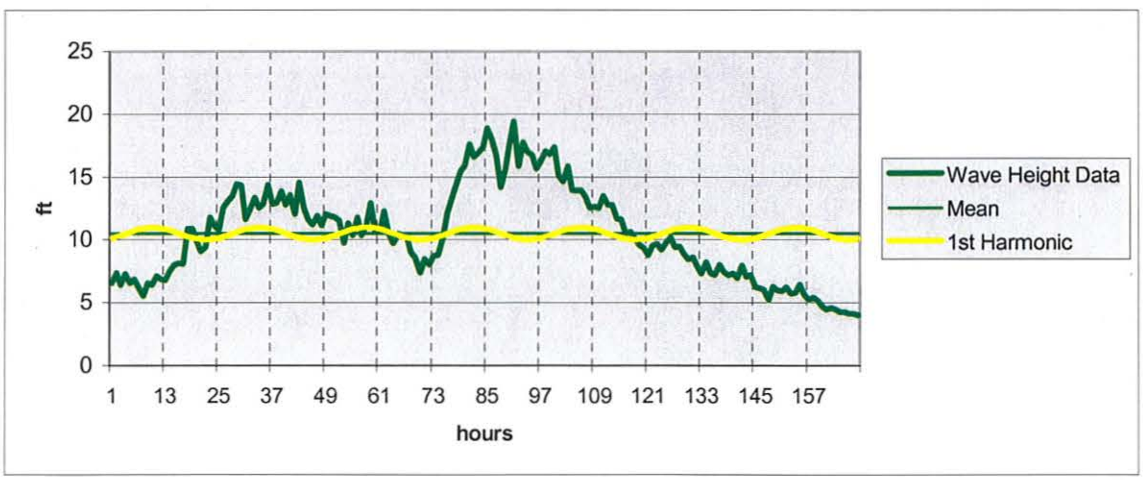


Figure 3h(11). Harmonic analysis of wave heights (24-30 September 1997).

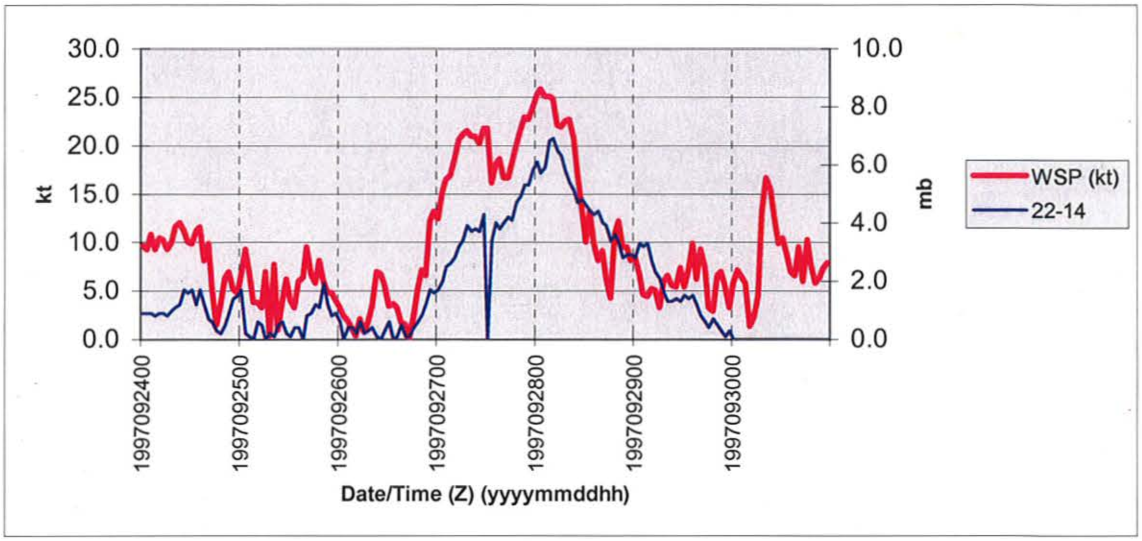


Figure 3h(12). Wind speeds (buoy #46014) and pressure gradients (#46022-46014) (24-30 September 1997). Zero-values denote missing data (gradients only).

i. Case #9. Periodic Event: Buoy #46014 (11-18 August, 2000).

(1) Event description: Figures 3i(1) and 3i(2) show the wind speed, direction, and wave height trends for this case. This 8-day event is classified as a "periodic event" due to its highly repetitive nature. Wind speeds and wave heights were moderate to (occasionally) high, overall. Wind directions were very consistently from the north-northwest (about 330 degrees), but tended to shift to the north during peak wind periods. Wind speeds on day 1 were light to moderate, no more than about 12 knots. Wave heights built steadily though, from 3 feet (initially) to 8 feet on day 1. Wind speeds on day 2 were slightly higher, averaging about 15 knots, while wave heights continued to rise slightly, up to about 9 feet. Beginning on day 3 and continuing through day 7, the wind and wave patterns were strongly diurnal in nature. Wind speeds were typically lowest, around 15 knots, in the late afternoon (about 00Z, or 1700 PDT). Wind speeds typically increased abruptly each evening, to between 22 and 27 knots, peaking about 3 to 6 hours later, around 03-06Z (2100-2400 PDT). In contrast to other events, which displayed a longer sustained rises in wind speed, the increases in this event were *strongest over short periods, i.e. less than 6 hours*. Maximum *one-hour* rates of rise were 11.4 knots, among the most rapid increases of any of the cases analyzed here. Each day showed progressively higher peak wind speeds, with an overall peak of 27 knots (peak gusts to 32 knots) on day 7.

Wave heights on days 3 through 7 followed a similar diurnal trend, driven primarily by the local winds. On day 3, wave heights peaked near 10 feet at very nearly the same time as the maximum wind. On days 4 through 7, wave heights continued to peak at about the same time as the winds, and were progressively (slightly) higher each day, with an overall peak for the event of 11.4 feet on day 7. After only a few hours (at most) near the peak, wave heights fell each day to about 7-8 feet, from early morning through afternoon.

(2) General Weather Situation: Figures 3i(3) through 3i(10) show the sea level pressure and upper air patterns for this event. Overall, the surface and upper air patterns showed little variation through the event. A weak upper trough persisted off the coast through the entire period, but intensified on days 7 and 8, as an upper low moved southeast near the British Columbia coast. At the surface, high pressure persisted over the northeast Pacific, with an associated ridge (of varying strength) extending into the Pacific Northwest, and a thermal trough just inland from the California coast. The event finally ended on day 8, as pressure gradients weakened due to a cold front approaching the Pacific Northwest.

(3) Harmonic Analysis of Wind Speed and Wave Height: Figures 3i(11) and 3i(12) show the harmonic analysis results for wind speed and wave height for this event. Overall, only about 6 percent of the variance in wind speed was explained by the first harmonic (period = 24 hours). This figure is (relatively) low, in part because of the overall increasing trends occurring on days 1 and 2, and also the decreasing trend on day 8. Limiting the harmonic analysis to days 2 through 7, which showed the strongest diurnal trends (time of maximum between about 10Z and 13Z), the overall percent-variance explained (first harmonic) increased to 23 percent. This figure would likely be even higher if the wind speed increases were not so strongly focused on a few hours each evening. Similarly, the percent-variance explained by the first harmonic on individual days appears deceptively low. Day 2 actually displayed the strongest percent-variance explained, about 81 percent. Days 3 through 7 ranged from 21 to 66 percent, but (again) these figures are lower because the stronger wind speeds are focused on only a few hours each evening. Harmonic analysis of the wave heights for this case showed similar results. Overall, only 5.6 percent of the variance was explained by the first harmonic. Similar to the wind speeds, this figure increased significantly (to 32 percent) when only days 2 through 7 were considered. Individual days ranged from 34 to 72 percent (all days), but as with the wind speeds, these figures would likely be higher if the daily wave height increases were no so narrowly focused on just a few hours each evening. Nevertheless, the wind and wave increases/decreases clearly followed a strong diurnal pattern.

(4) Pressure Gradients: Figure 3i(13) shows the pressure gradients for buoys #46022-46014 (22-14), #46027-46014 (27-14), and #46027-46022 (27-22), along with wind speeds at buoy #46014 for this case. It is not known why the 27-14 pressure gradients (i.e. absolute value of the differences) are smaller than the other two sets of gradients, given that the distance between buoys is greater. Perhaps there was a pressure sensor calibration error at one of the buoys. However, the *trends* in pressure gradients are more important (for purposes here) than the actual pressure values.

The 22-14 gradients tended to provide the best indication of wind speed increases, rising strongly (except for minor fluctuations) each day several hours before the initial wind increases. Further upstream, the 27-22 gradients also tended to increase prior to wind speeds, typically by about 6-8 hours. The 27-14 gradients, however, closely followed wind speed trends overall, thus providing little advance indication of increasing wind speeds. Regarding wind speed *decreases* at buoy #46014, the 27-22 pressure gradients seemed to provide the best indicator that wind speeds were near their peak, with the gradient peak typically occurring a few hours prior to the wind speed peak.

(5) Upstream Conditions: Wind speeds and wave heights upstream at buoy #46022 (110 miles north) were generally lower than at buoy #46014, averaging 9.1 knots (maximum 16.7 knots) and 5.2 feet (maximum 8.9 feet), respectively. At buoy #46014 during this period, wind speeds averaged 17.7 knots (maximum 27 knots) and wave heights averaged 7.9 feet (maximum 11.4 feet). Given the wave conditions at buoy #46022, about 2 feet of decay could reasonably be expected from the peak wave heights there, resulting in waves up to about 7 feet arriving at buoy #46014, which is consistent with observed conditions (daily minimum wave heights at #46014 were about 7-8 feet for all but the first and last days of the event).

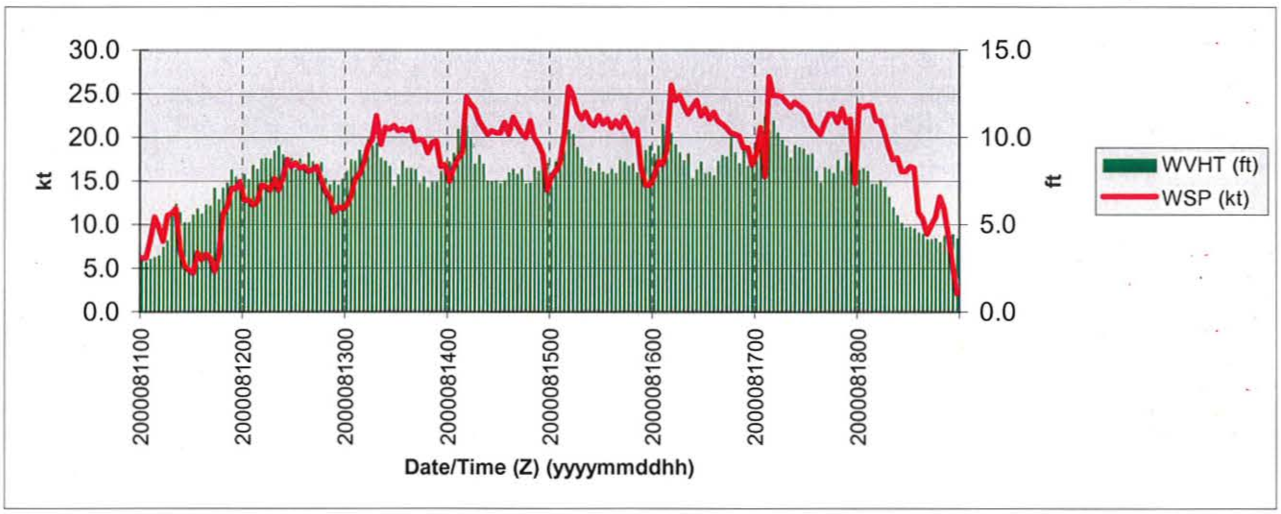


Figure 3i(1). Wind speed and wave height, buoy #46014 (11-18 August 2000).

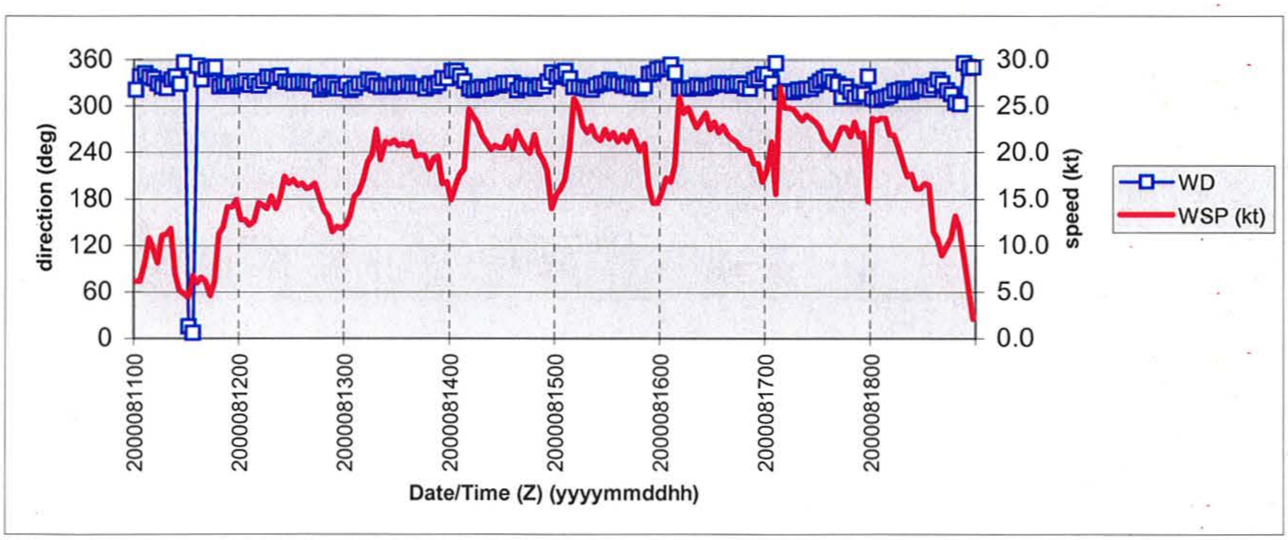
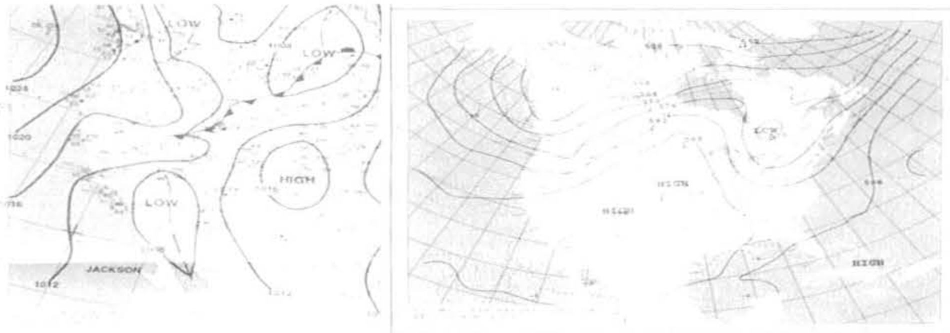
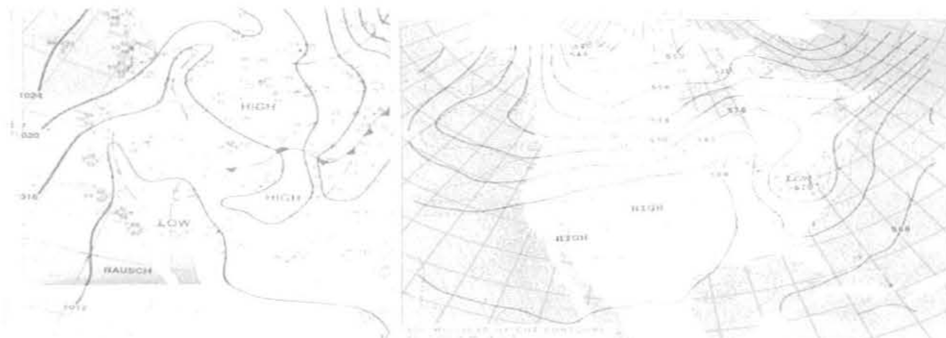


Figure 3i(2). Wind speed and direction, buoy #46014 (11-18 August 2000).



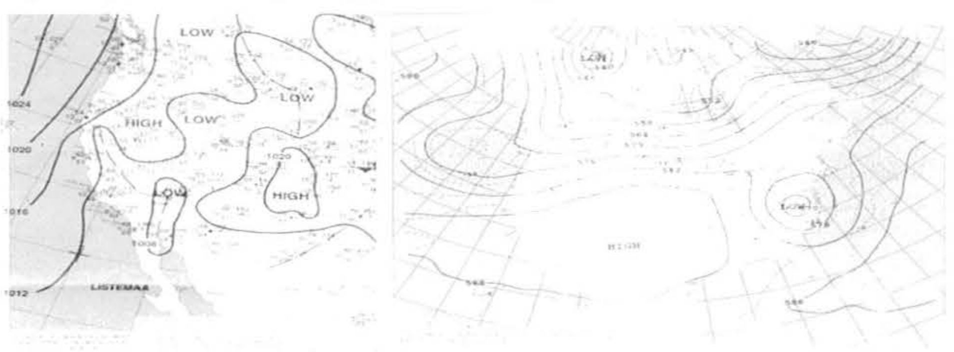
Aug. 11, 2000

Figure 3i(3). Surface analysis (left) and upper air analysis (right), 11 August 2000.



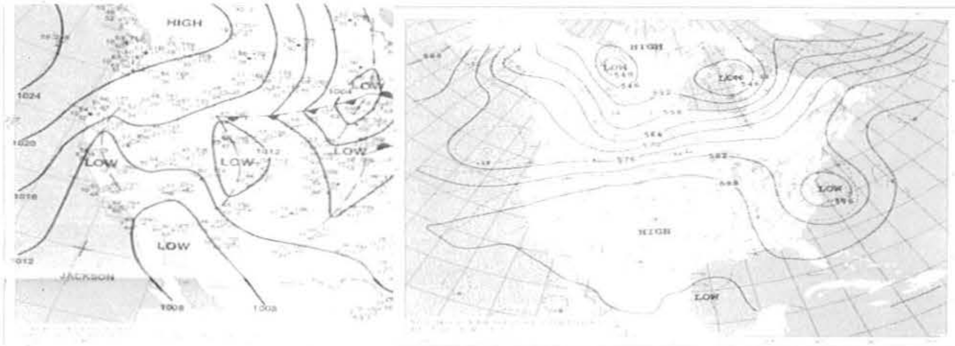
Aug. 12, 2000

Figure 3i(4). Same as Figure 3i(3), but for 12 August 2000.



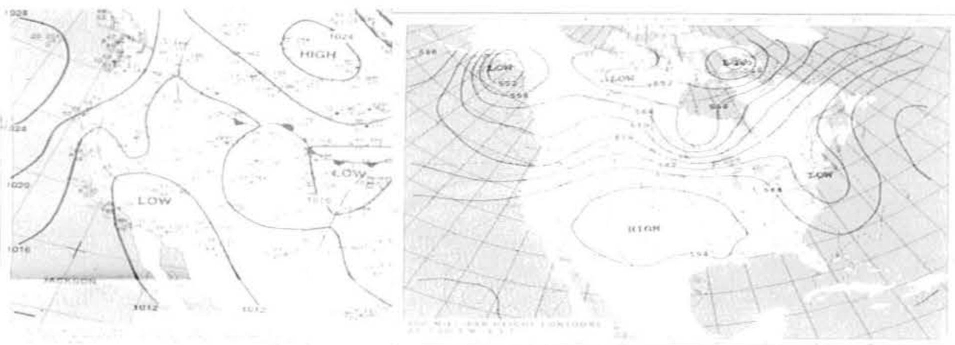
Aug. 13, 2000

Figure 3i(5). Same as Figure 3i(3), but for 13 August 2000.



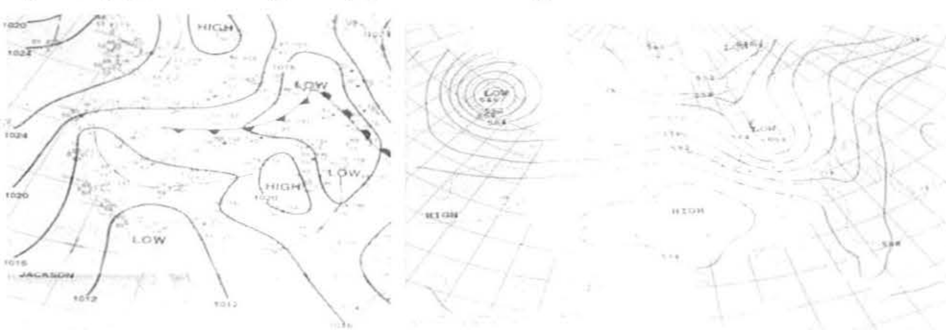
Aug. 14, 2000

Figure 3i(6). Same as Figure 3i(3), but for 14 August 2000.



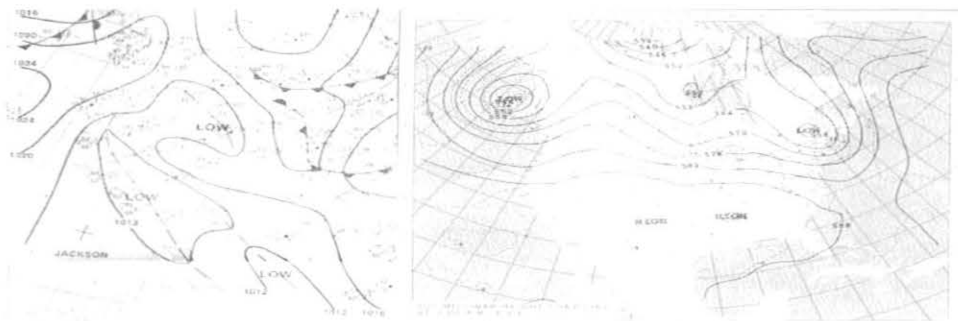
Aug. 15, 2000

Figure 3i(7). Same as Figure 3i(3), but for 15 August 2000.



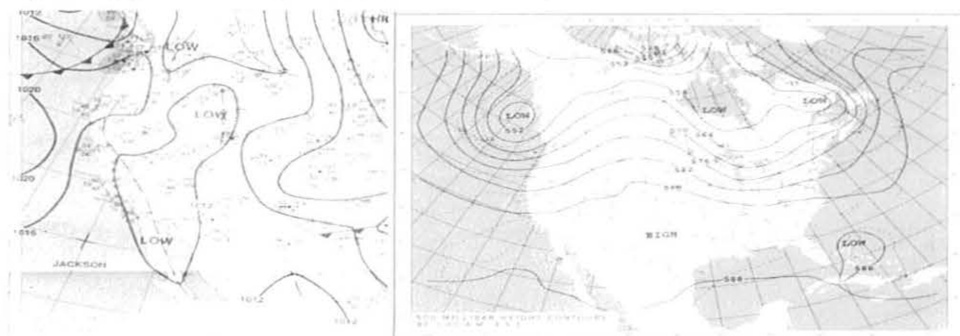
Aug. 16, 2000

Figure 3i(8). Same as Figure 3i(3), but for 16 August 2000.



Aug. 17, 2000

Figure 3i(9). Same as Figure 3i(3), but for 17 August 2000.



Aug. 18, 2000

Figure 3i(10). Same as Figure 3i(3), but for 18 August 2000.

Table 3i. Time of maximum amplitude and percent-variance explained by the first harmonic of wind speed and wave height, Case #9 (buoy #46014, 11-18 August 2000).

	Wind		*Wave*	
Day	**Time (Z)**	**Percent-Variance Explained**	**Time (Z)**	**Percent-Variance Explained**
1	0118	31.8%	0118	37.7%
2	1312	80.6%	1024	65.0%
3	1318	65.6%	0642	62.1%
4	1218	32.5%	0348	60.7%
5	1112	46.8%	0348	33.7%
6	1106	59.0%	0206	42.4%
7	0954	20.5%	0518	67.8%
8	0630	52.4%	0500	71.7%
ALL	***0206***	***6.2%***	***0812***	***5.6%***

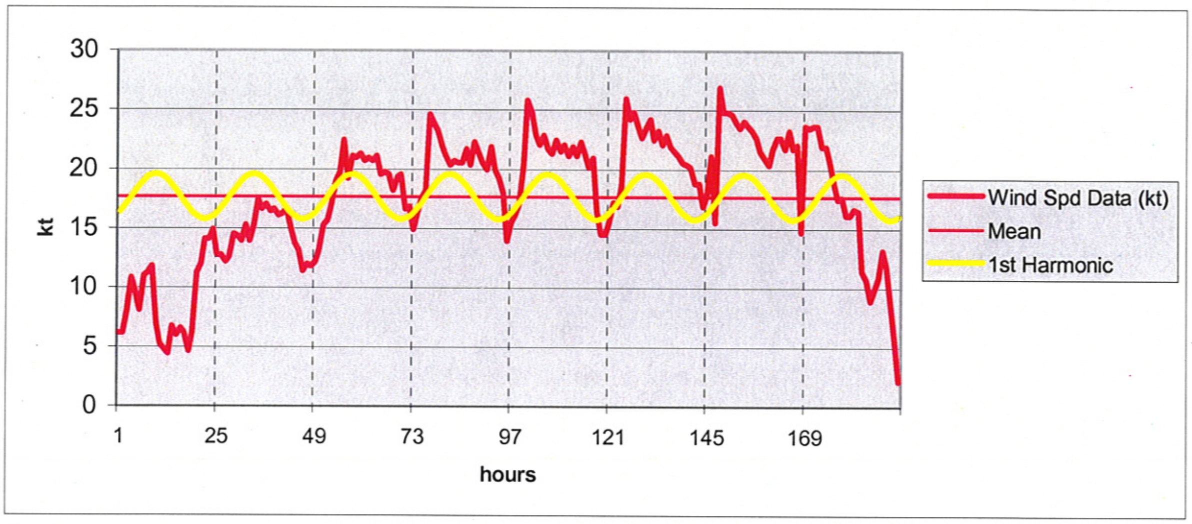


Figure 3i(11. Harmonic analysis of wind speed, buoy #46014 (11-18 August 2000).

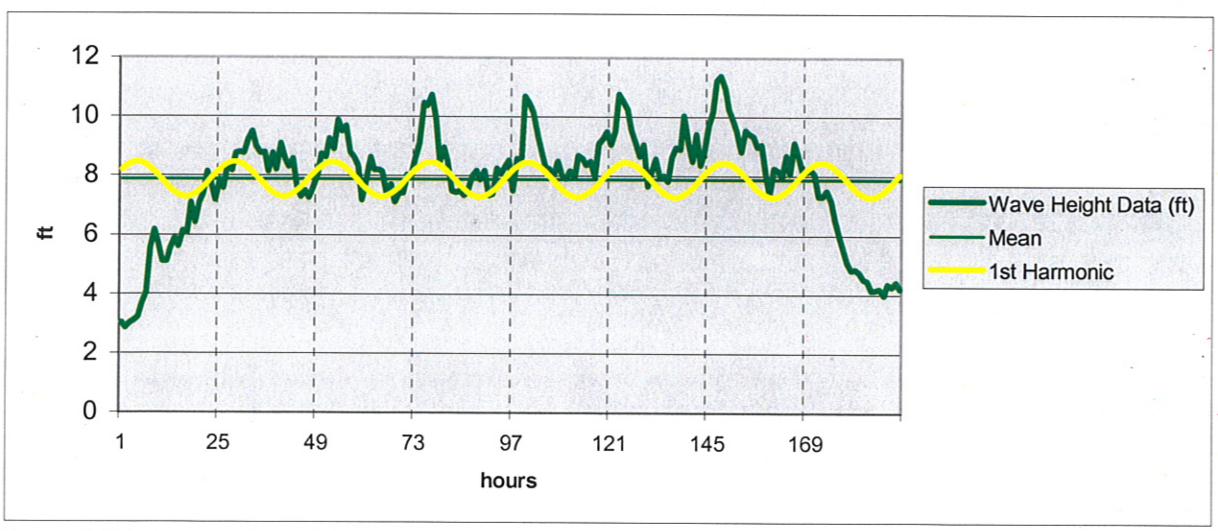


Figure 3i(12). Harmonic analysis of wave heights, buoy #46014 (11-18 August 2000).

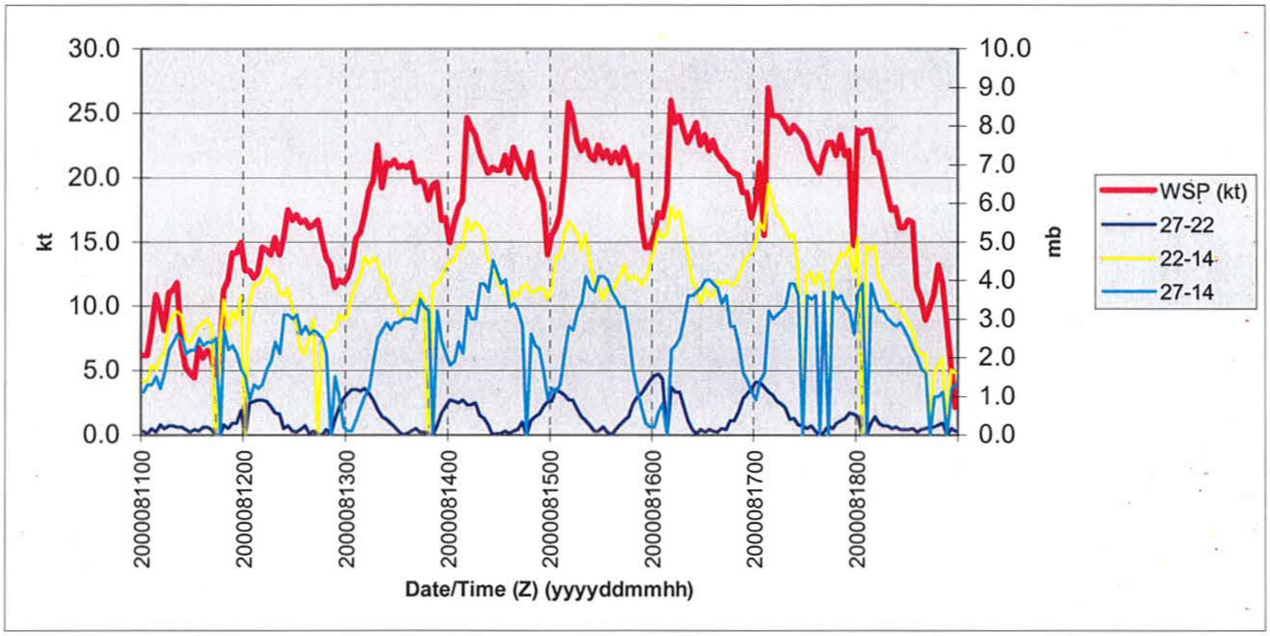


Figure 3i(13). Wind speed (buoy #46014) and pressure gradients (buoys #46027-46022, #46022-46014, and #46027-46014), 11-18 August 2000. Zero-values denote missing data (pressure gradients only).