INTENTSIFICATION OF NORTH PACIFIC WINTER CYCLONES 1948-98: IMPACTS ON CALIFORNIA WAVE CLIMATE

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In a recent paper Graham and Diaz (2001) document changes in North Pacific winter cyclones as seen in results from the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay et al., 1996) and *in situ* measurements. The results show a surprisingly regular trend towards increasing numbers of intense cyclones with associated increases in cyclone related wind speeds. In this note we discuss results of a 50-year wave hindcast covering the winters of 1947-48 through 1997-98 driven with 10-meter surface winds from the NCEP/NCAR reanalysis with a particular focus on changes in the eastern North Pacific and along the Southern California coast. The reader is also directed to the Wang and Swail (2000) who also present wave model hindcast results and analyses relating seasonal extreme wave and atmospheric circulation patterns for the North Pacific and North Atlantic Oceans covering 1958-1997.

The ocean wave hindcast data come from a simulation covering December-March 1948/49 through 1997/98 conducted by Pacific Weather Analysis using the WAVEWATCH III model (Tolman, 1999). The model was configured at a resolution of 1.5° latitude and 2° longitude using the 6-hourly 10-m winds from the NCEP reanalysis as forcing. The model was configured with 20 frequency bins and 72 directional bins. For comparison, the hindcast described by Wang and Swail (2000) covered 1958-97 and was conducted with their model had a spatial resolution of 1.25° latitude by 2.5° longitude with 25 frequency bins and 24 directional bins. The measured wave data shown in this note come from NOAA buoys 46011 (34.9°N 120.9°W), 46006 (40.9°N 137.5°W), 46013 (38.2°N 123.3°W) and 51001 (23.4°N 162.3°W). These data cover the late 1970s and early 1980s to present, with some gaps, and were obtained from the NOAA National Data Buoy Center (NDBC). Model data were taken from the model grid points closest to these locations.

Comparisons of the hindcast results with NOAA buoy wave data show good agreement with respect to both specific events and interannual variability. For example, Fig. 1 shows the fit between all coincident measured and hindcast H_S data (at 3-hour intervals) for the NOAA buoys noted above. For Buoy 46006 (Pt. Arguello) hindcast H_S tends to be slightly too low, though other analyses suggest that this is due in part to the fact that the model grid square used here is immediately adjacent to land resulting in too great a reduction in energy approaching from the northwest. The correlation at this site is 0.85. For Buoy 46013 (Pt. Reyes) the fit is better (R=0.88) and there is little apparent bias. For Buoy 51001 (Hawaii) the correlation is 0.81 and as at Buoy 46011 the hindcast values tend to be underestimated. At Buoy 46006 the fit is quite good (R=0.87) and little bias [see Tolman (1998) for a discussion of the tendency for such distributions to curve downward as measured heights increase as seen in the Pt. Reyes and 46006 results].

Figure 2 shows trends in annual December-March 99^{th} percentile 10-meter wind speed and trends in the zonal and meridional wind components for cases when speeds exceeded the 99^{th} percentile from the reanalysis data. For speed (Fig. 2A) positive trends are found over nearly all of the North Pacific, with negative trends found only in the northern Gulf of Alaska. The largest upward trends, on the order of 0.3- 0.6 ms^{-1} per decade, cover much of the North Pacific between 25°N and 35°N (the 95% significance level for the trends corresponds approximately to the 0.4 ms^{-1} contour). The wind components (Fig. 2B) show that the increasing speeds in this region have been associated with increasing westerlies, with trends in the zonal component on the order of 2 ms^{-1} per decade. Other analyses in GD2001 show that these increases the increased wind speeds and changes in wind direction are associated with the increased number and intensity of winter cyclones, and with a southward migration of thestorm track. As shown later, these increases in westerly winds across the sub-tropical North Pacific produce major increases hindcast extreme wave climatology along the coast of California and Baja California.

Another feature of note in Fig. 2B is the presence of large directional trends in the Gulf of Alaska. In this region, preferred wind directions during episodes of high wind speeds backed from west-northwest during the late 1940's and early 1950's to southwest during the latter part of the record. Up to 1980, these dramatic changes in direction are corroborated by measurements from Ocean Station Vessel P (see GD2001, Fig. 9A). Like the increasing sub-tropical westerlies, these changes in wind direction during high wind speed episodes also have clear impacts on the hindcast wave climate of the North Pacific.

The trends in hindcast 95th percentile December-March wave heights (Fig. 3) show the largest trends between 30° and 45° N where values range up to 2.4 meters in 50 years (approximately 0.48 m decade^{-1}).
In terms of percentage of the long term mean 99th percentile H_S, the trends represent increases of 20-35% with the largest values centered near 25°N and 140°W (see GD2001, their Fig. 11d). Along the coast of North America the largest upward trends in hindcast extreme H_S are found off Southern California where the trends amount to approximately 1.2 m decade^{-1}, representing an increase of about 25%. Consistent with the wind trends (Fig. 2), trend in extreme waves are much smaller in the Gulf of Alaska extending along the west coast of Canada and Pacific Northwest. The spatial pattern in Fig. 3 is similar the 90th percentile trends shown Wang and Swail (2000; their Fig. 8) though the percentage changes are larger in our results. These differences apparently arise from the different percentile used and the different years used - a separate analysis of 90th percentile wave heights over the 1958-97 period from our hindcast results (not shown) gives results quite similar to those of Wang and Swail (2000).

Figure 4 shows time series of measured and hindcast 95th percentile wave heights for the buoy locations described earlier. For the hindcast data, the long-term trends range from 0.22 m decade^{-1} (46011 - Pt. Arguello) to 0.15 m decade^{-1} (51001, Hawaii). In each case the trends are significant at above the 98% level (as measured by t-test). Also shown are the measured and hindcast data for those cases where measured data exist. The tendency for hindcast waves to be too low is again apparent for Buoy 46011 while the hindcast values appear biased high at Buoys 46006 and 46013 (Pt. Reyes) (to some degree this may reflect the effects of refraction and sheltering at the latter buoy). In any case, the buoy and hindcast data are generally in relatively good agreement (the correlations for annual values are 0.92 at 46006 and 0.84 at the other locations). This level of agreement suggests that the wave model results are of sufficient quality to resolve the observed upward trends.

Figure 5 shows the trends in directional wave spectra for 6 sites in the North Pacific (the four buoy locations noted above and points near the southern tip of Baja California and off the mouth of the Columbia River, respectively). The four sites in the mid-latitude eastern Pacific [Buoy 46011 (Pt. Arguello), Buoy 46013 (Pt. Reyes), Buoy 46006, and the Columbia River) each show a pattern of increasing energy approaching from the west-northwest to west-southwest, primarily in the period range centered near 15-17 seconds. They also show decreasing energy from the northwest at somewhat shorter period (12-14 seconds). For Buoy 51001 (Hawaii) and the Cabo San Lucas points the results show major positive trends from the 300° to 315° and centered at about 16-17 seconds. These patterns are consistent with the results presented earlier and indicate along the west coast of the US for larger, longer period extreme waves with more westerly approach directions. The Cabo San Lucas and Hawaii results are also consistent with the more intense wave generation in the lower mid-latitudes of the North Pacific.

To focus the implications of these results to conditions in the inshore waters of the Southern California Bight, Fig. 6A shows return period analyses for the Buoy 46006 hindcast data for 1948-49 through 1975-76 and for 1976-77 through 1997-98. (Note: A linear fit to a Fisher-Tippett Type I distribution applied to the upper 5% of the hindcast H_S values was used to calculate the 100-year waves for these analyses. Other distributions may give better fits so the values used here should be taken as indicators only). For the earlier period the estimated 100-year value of H_S is 7.6 meters for the earlier and later periods are 7.6 and 10.1 meters, respectively and the populations are very well separated. At this location the 100-year wave in the earlier period represents approximately a 5-year event in the latter period.

Figure 6B shows results from an analysis similar to that described above but in this case conducted for a point off Encinitas, CA, about 50 km north of San Diego. The back-refraction model of O'Reilly (1991) was used to provide energy and direction transfer functions for transforming hindcast deep water waves from a deep water point off San Diego to the shallow water point at approximately 23 m depth. For this site the 100-year waves for earlier and later periods are estimated to be 3.9 and 5.9 meters, respectively – and the 100-year wave for the earlier period becomes approximately a 1-year event during the latter period. These changes in statistics reflect not only the changes in deep water wave size, but the effects of more favorable (more westerly) approach directions and longer wave periods as well. The more westerly approach directions reduce the sheltering effects of Pt. Conception and the Channel Islands and give a more direct approach direction to the shore. The longer wave periods likely contribute to increased shoaling as well.

Conclusions

Results from analyses of the NCEP/NCAR reanalysis show major changes in winter storm climate over the North Pacific from 1948/49 through 1997/98 (GD2001). These changes include an increase in the number of intense cyclones and a southward shift in the storm track. These changes have resulted in substantial increases in westerly winds associated with strong storms across the lower mid-latitudes of the North Pacific. A winter wave hindcast using the WAVEWATCH III model and the surface winds from the reanalysis has been conducted to assess the impact of these circulation changes on the winter wave climate in the North Pacific. The results show that the hindcast wave climate tracks observed changes over the approximately 20 years for which wave measurements are available from NOAA buoys. The results also show that there have been substantial (25-35%) upward trends in extreme wave heights over much of the lower mid-latitude North Pacific since 1950. Analyses of deep water directional spectra from the hindcast show a consistent pattern for longer period extreme waves with from more westerly approach directions at sites off the US west coast over time and diminishing contributions from more northwesterly directions. A return period analysis for representative deep water and shallow water Southern California sites show that the upward trends in deep water wave heights have had major effects on estimated return periods over the past half-century. Even more extreme changes are found at the shallow water sites where the tendency for more westerly approach directions and longer periods for during extreme wave events reduces the estimated 100-year wave for 1948/49 through 1975/76 to approximately a 1-year event during 1976/77 through 1997/98.

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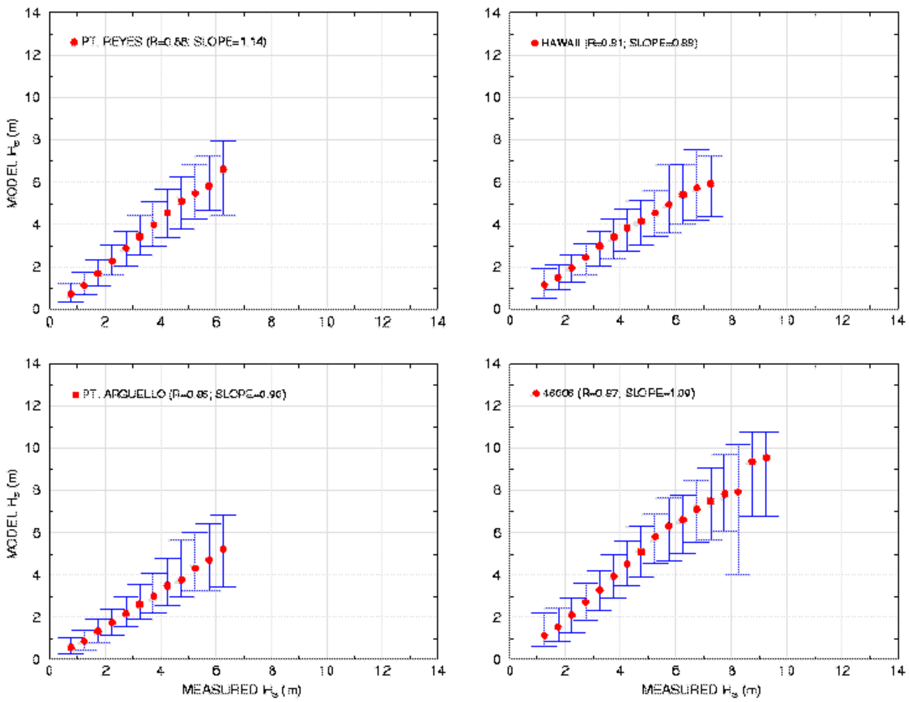

Fig. 1 – Median measured versus hindcast significant wave heights (solid circles) for 4 NOAA buoy locations in the North Pacific for 0.5 meter wide bins. Bars show 99% bounds for hindcast data. Proceeding clockwise from lower left plots are for Pt. Arguello (46011), Pt. Reyes (46023), Hawaii (51001), and 46006.

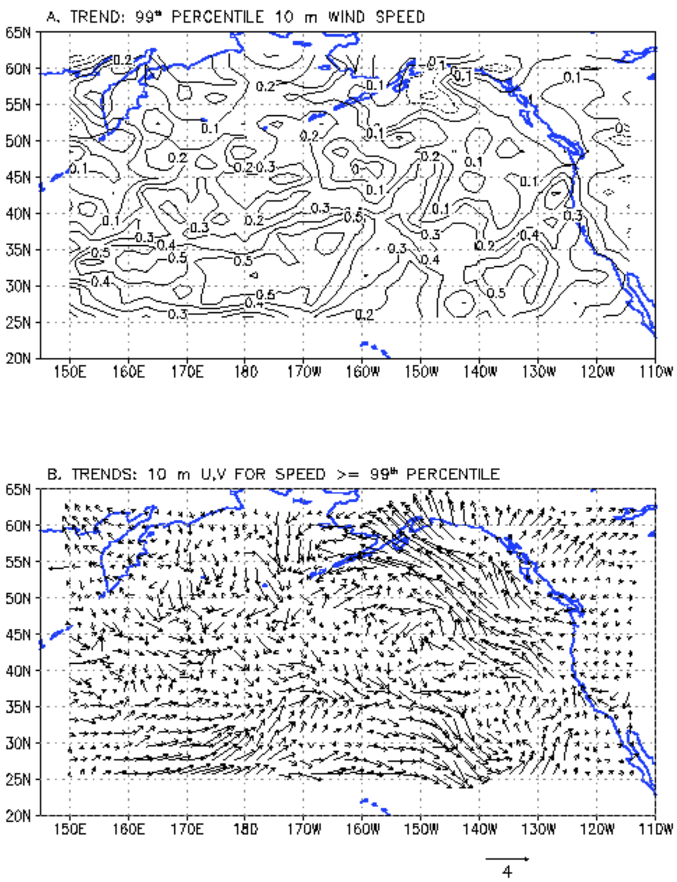

Fig. 2 – A. Trends in annual 99th 10-meter wind speeds from the NCEP/NCAR reanalysis for December-March 1948/49 through 1997/98. B. Trends in zonal and meridional 10-meter wind components for the same time period when 10-meter wind speeds exceeded annual 99th percentile. Values in both are ms^{-1} $decade^{-1}$.

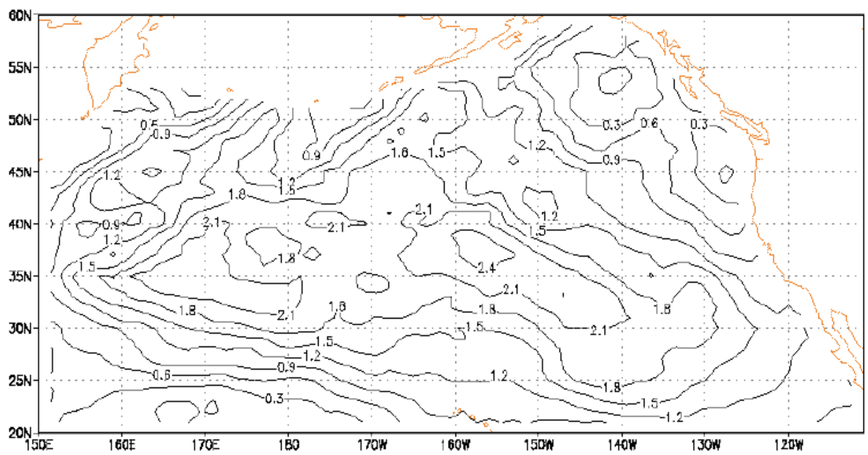

Fig 3 – Trends in hindcast 95th percentile wave height for December-March 1948/49 through 1997/98. Values are meters per 50 years.

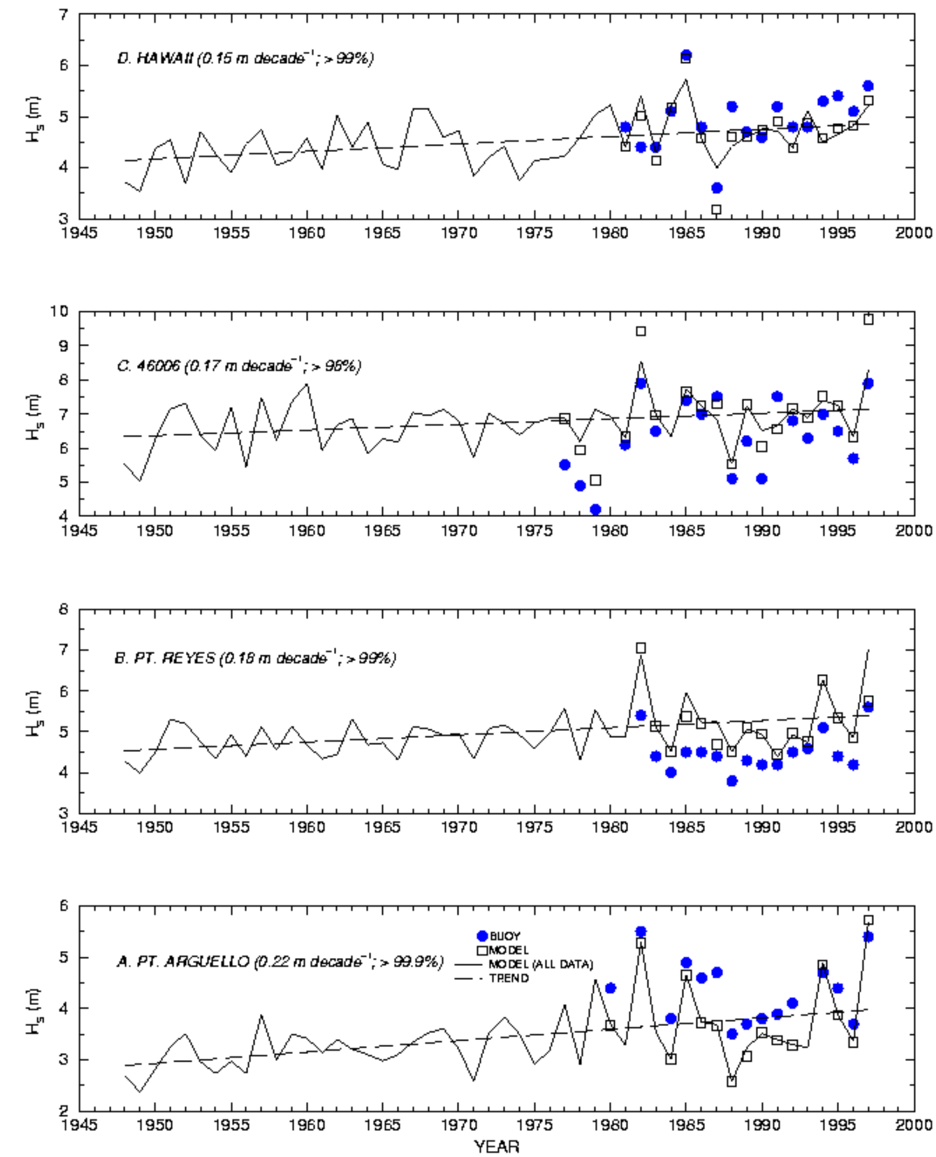

Fig. 4 – Time series of measured and hindcast 95th percentile significant wave heights for 4 locations in the North Pacific. Upward from the bottom the locations are Pt. Arguello (46011), Pt. Reyes (46013), 46006, and Hawaii (51001). Plots show hindcast data (solid line), trend in hindcast data (dashed line), measured values (solid circles), and hindcast values from data contemporaneous with observations.

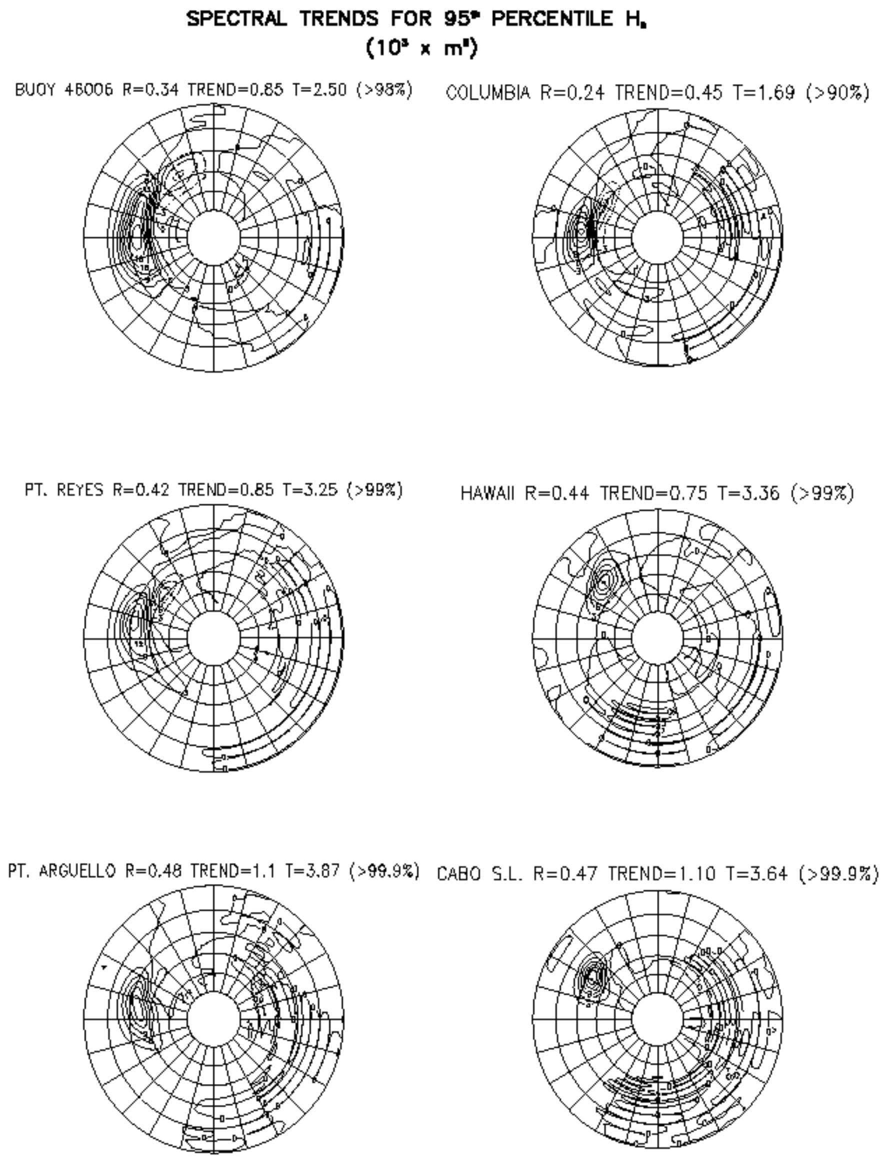

Fig. 5 – Trends in wave energy for bins in 2-D directional spectra. Directions indicate direction from; concentric circles indicate wave period starting at 27.5 seconds on the outside with 5 second decrements moving inward. Values are 10^3 x m^2 per 50 years. Proceeding clockwise from lower left locations are Pt. Arguello (46011), Pt. Reyes (46023), 46006, off the Columbia River mouth, Hawaii (51001) and off the southern tip of Baja California.

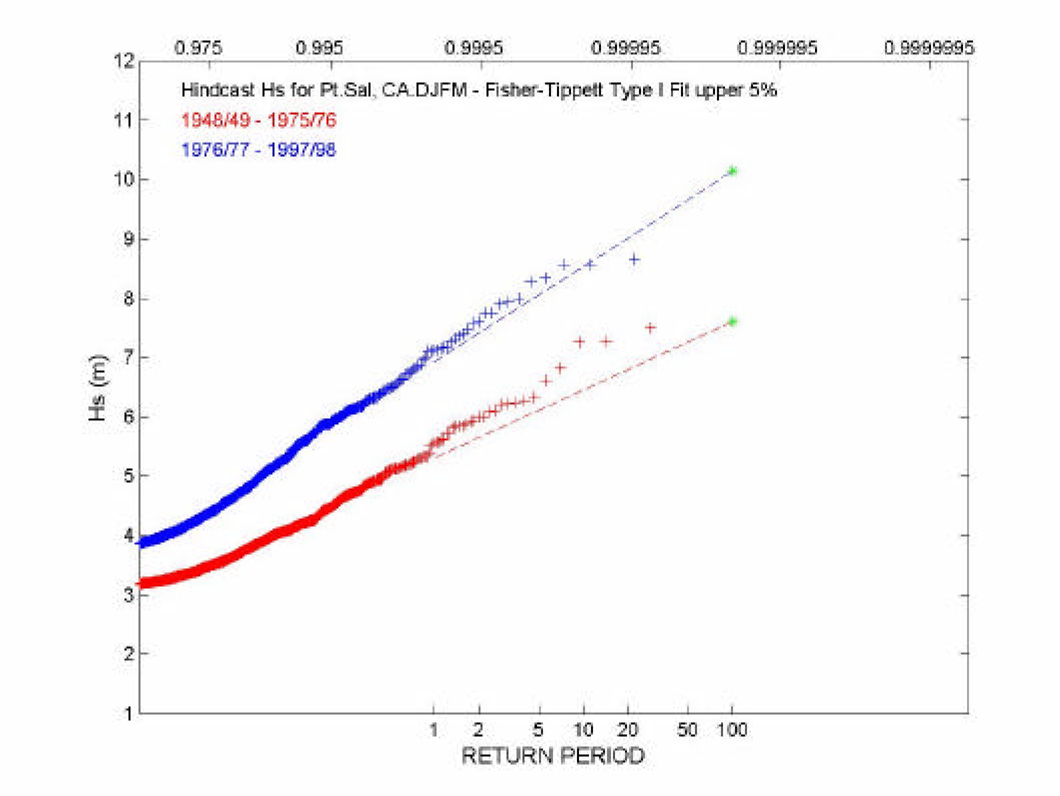

Fig. 6A – Return period analyses for upper 5% of hindcast December-March H_S 1947/48–1975/76 (lower curve) and for 1976/77–1997/98 (upper curve). Analysis is for deep water location off Pt. Arguello (near NOAA Buoy 46011).

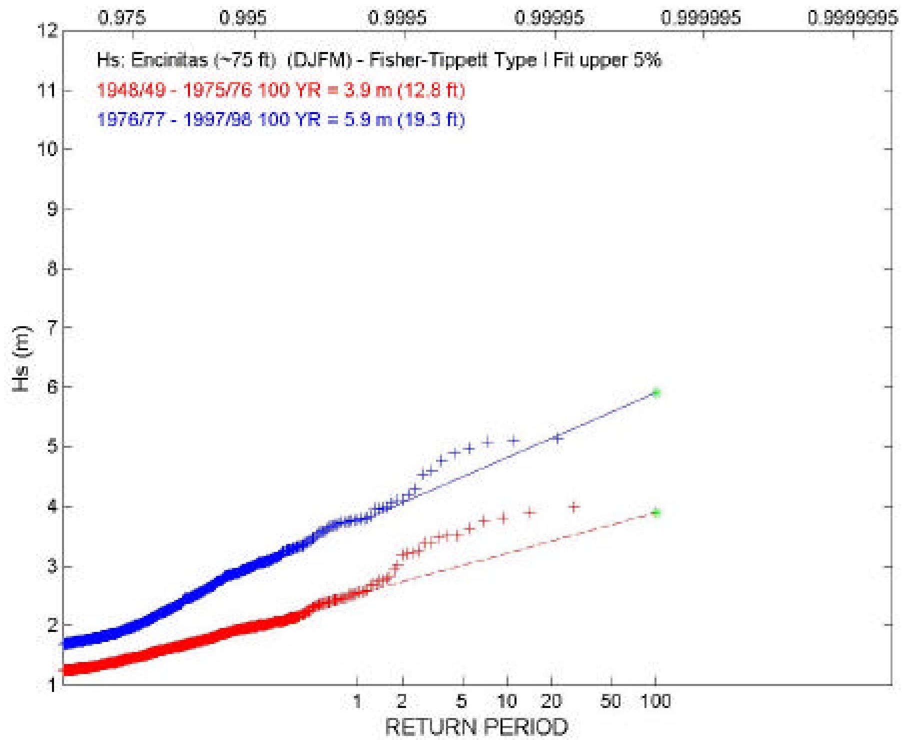

Fig. 6B – Return period analyses for upper 5% of hindcast December-March H_S 1947/48–1975/76 (lower curve) and for 1976/77–1997/98 (upper curve). Analysis is for a shallow water location off Encinitas, CA (see text).