Historical Wave and Wind Observations at Ocean Station P

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Abstract

An historical data set with 30 years of wave and wind observations from Ocean Weather Station P (50°N, 145°W) is described and validated against modern measurements. Observation biases are discussed and corrections are made where appropriate. Climate trends are explored, including a negative correlation between waves and the Pacific Decadal Oscillation. The validated historical data are deposited in a public archive with online access.

Introduction

Modern climate models require coupling between the ocean and atmosphere, and thus ocean waves are of growing interest in climate studies (*Bromirski et al*., 2013; *Cavaleri et al*., 2013). Interactions between the ocean and atmosphere form a complex feedback system of heat, energy, mass, and momentum, which is primarily facilitated by ocean surface waves (see, for example, *Large and Pond*, 1981; *Smith*, 1988; *Donelan*, 1993). Wave measurements are necessary to better understand and quantify these feedbacks and further refine the associated empirical models. With this motivation, scientists at the National Oceanic and Atmospheric Administration (NOAA) and University of Washington have been making continuous wind and wave measurements from buoys moored in the North Pacific since 2010. The mooring location, known as Ocean Station Papa (OSP; 50°N, 145°W), was originally occupied in the early 1940s as part of a U.S. military initiative to develop better weather prediction models for the Pacific Ocean. Adopted by the Canadian Coast Guard in 1951, the station remained occupied almost continuously by weather ships collecting meteorological and oceanographic measurements until the program was terminated in 1981 (*Freeland*, 2007).

Weather ship activity at OSP led to it becoming a popular location for field experiments in the North Pacific (e.g., *Martin and Fitzwater*, 1988; *Paduan and Niiler*, 1993). However, the historical data collected during the initial weather ship program have been largely forgotten. While attempting to recover these data, current OSP researchers identified numerous sources, but were unsure of the data's origin and quality. Long-term data sets that may be used to quantify climate trends are exceptionally valuable and, unfortunately, very rare. This makes the historical OSP data set especially important, as it contains wind and wave measurements spanning over 30 years. It also provides historical context for the ongoing work at OSP and an opportunity to explore the relationship of climate signals to wind and waves.

A growing body of research demonstrates the influence of climate cycles on wind and wave variability in the North Pacific (see, for example, *Gemmrich et al*., 2011; *Bromirski et al*., 2013). Some researchers have identified systematic problems with the use of buoys to determine long-period trends in wave data (*Gemmrich et al*., 2011). They also report that localized in situ measurements may be problematic when used to determine basin-wide characteristics. As a result, there has been a preference for using calibrated models and hindcasts to estimate long-term trends (*Bromirski et al*., 2013). While this assessment is generally true for wind measurements, it is less true for wave measurements. Though a wave height may be measured at a particular location, that measurement contains wave components that were generated on a much larger scale. Indeed, some waves are generated over spatial and temporal scales as large as the Pacific Ocean itself (*Snodgrass et al*., 1966). While less ideal than a basin-wide wave field, point wave measurements, such as those collected during the weather ship program, represent basin-scale forcing to some degree and are therefore valuable as scientific tools for assessing larger trends.

Our analysis of the historical data from the Canadian weather ship program had several components. First, numerous sources of historical data were analyzed and their relevance assessed. Second, the distribution of historical values was compared to the modern measurements. For this analysis, we compared wind speed, wave height, and wave period. These three parameters provide a general classification of the wave climate and the local wind forcing that contributes to wave generation. Third, a time series analysis was conducted to determine what, if any, trends exist in the historical data set. Fourth, after removing the mean seasonal fluctuation, the influence of long-period trends on wind and wave variability in the North Pacific could be studied. Finally, the validated time series of wind speed, wave height, and wave period were placed in a public database, available online via the University of Washington Libraries ResearchWorks Archive (http://hdl.handle.net/1773/25570).

Data Discovery and Synthesis

In the search for historical weather ship data, several different sources were discovered that have a direct connection to the original observation program. It was unclear which resource contained the original measurements. Some of these data were provided by employees at the Institute of Ocean Sciences (IOS), the current version of the government body originally charged with the weather ship program, while another set was found archived at the University Corporation for Atmospheric Research (UCAR). After an exhaustive comparison of numerous data transects from each source, it became clear that the UCAR archive represented the most original, error-free version of the data. It appears that the data obtained from IOS staff were derived from the UCAR archive source. Additionally, a cursory analysis of wave heights showed that the IOS data had been manipulated erroneously at some point without documentation, resulting in spurious jumps in the time series and distribution of values. Having determined a suitable primary source (UCAR), we proceeded to more direct analysis of wind speed, wave height, and wave period (Figure 1).

Comparison of historical and modern measurements required accounting for methodological differences. Historical wind speeds were collected using

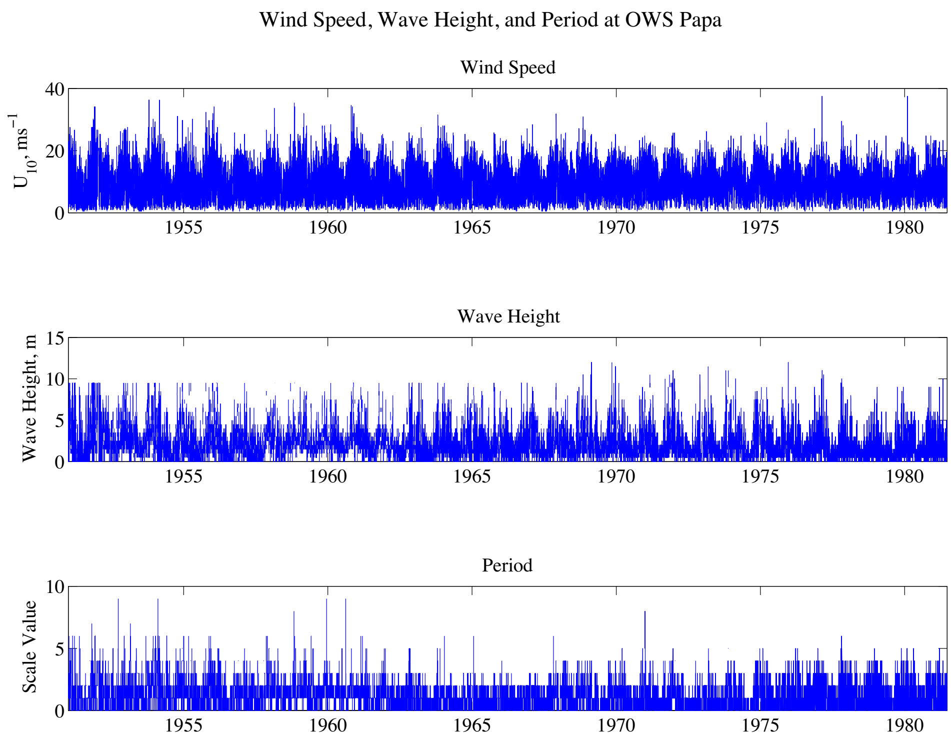

Figure 1. Full time series of wind speed, wave height, and wave period at OSP. *Note*: Period was reported using the following scale values: 0 (<5 s), 1 (6–7 s), 2 (8–9 s), 3 (10–11 s), 4 (12–13 s), 5 (14–15 s), 6 (16–17 s), 7 (18–19 s), 8 (20–21 s), 9 (>21 s).

mechanical anemometers mounted to the weather ships' mast, whereas modern measurements are collected with sonic anemometers at lower elevations. While these instruments are purportedly measuring the same quantity, it seems likely that systematic differences exist between reported wind speeds from different instruments. In fact, other researchers have noted systematic differences in wind data collected by different instrument types (*Winterfeldt et al*., 2010). However, this difference is generally small and statistical consistency is more important for comparative purposes. The elevation of the wind measurement is likely the key difference in methodology between data sets.

Over the thirty-year span of the Canadian weather ship program, four ships occupied OSP (*Freeland*, 2007). The first two, the CCGS *Stonetown* and *St. Catherines*, were in use until the mid-1960s and collected wind speeds at an anemometer height of 27 m. The second two, the CCGS *Vancouver* and *Quadra*, were in use from 1966 and 1967, respectively, until the end of the program and collected wind speeds from an anemometer height of 17 m. Notably, the UCAR data did not indicate which ship had been on station at which time. Fortunately, an employee at IOS had the foresight to add a ship identification field. By cross-referencing dates and measured wind speeds between IOS and UCAR data sets, we inferred which ship had collected the data point. Modern measurements are collected sonically at a height of 4 m.

After determining the height at which data were collected, we corrected the wind measurements to a common reference height of 10 m (U_{10}) to compare directly the modern and historical data sets. The correction utilized a standard logarithmic velocity profile and empirical coefficients determined by *Smith* (1988) to arrive at an iterative solution for U_{10}. Statistical distributions of U_{10} (Figure 2) indicate strong agreement between modern and historical wind measurements. The small difference in mean value and standard deviation may be attributed to greater variability in wind measurements in the historical data set. It may also be attributed to systematic differences between mechanical and sonic anemometers. The similarities in wind are strong enough to indicate that wind-generated waves should be expected to have a comparable correlation.

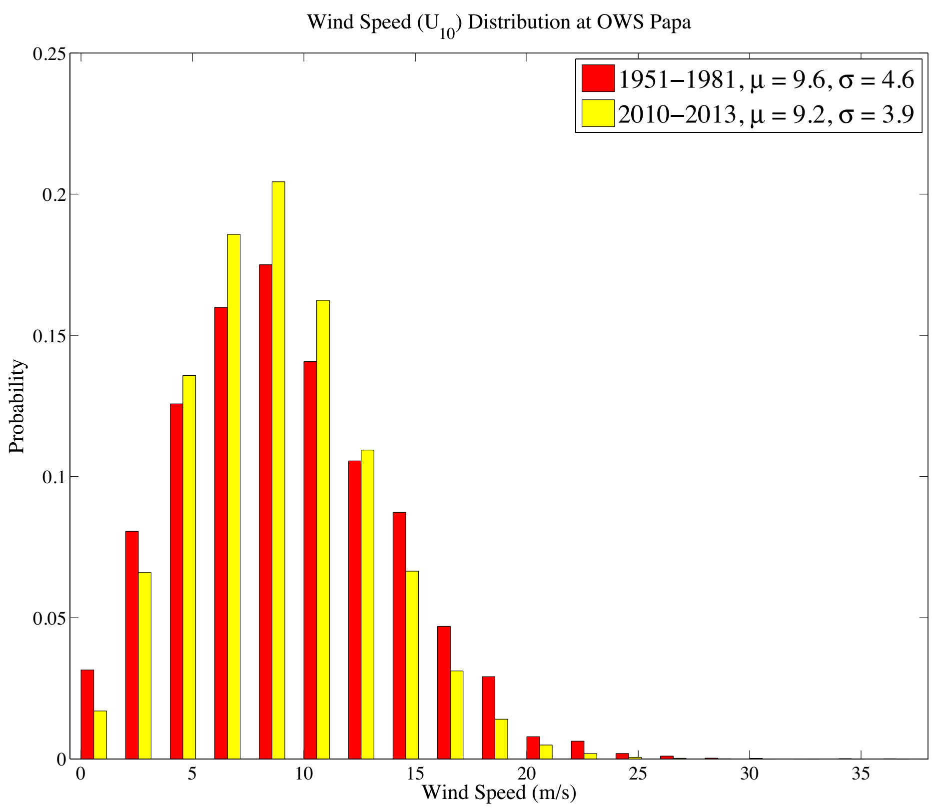

Figure 2. Statistical distribution of U_{10} speed at OSP. The statistical mean (μ) and standard deviation (σ) show close agreement between the historical data (red) and the modern data (yellow).

Wave height and period measurements are notably more complicated. Trained, shipboard observers collected the historical measurements as visual estimates, while a calibrated Datawell Directional Waverider buoy collects modern measurements. The historical data were also, on paper, separated into ‘swell’ and ‘wave’ (presumably wind-sea) measurements. Our research has thus far been unable to recover any documentation on how this was accomplished in the field. This is different from the spectral methods a modern buoy employs to determine the significant wave height. With buoy measurements, the convention is to compare the peak and average periods of wave spectra to determine whether the measured waves are predominantly swell or wind-sea. The historical measurements indicate different periods for swell and wave, but it is not obvious how to compare these notations with the modern conventions for peak and average period. Furthermore, most of the historical data set does not report these

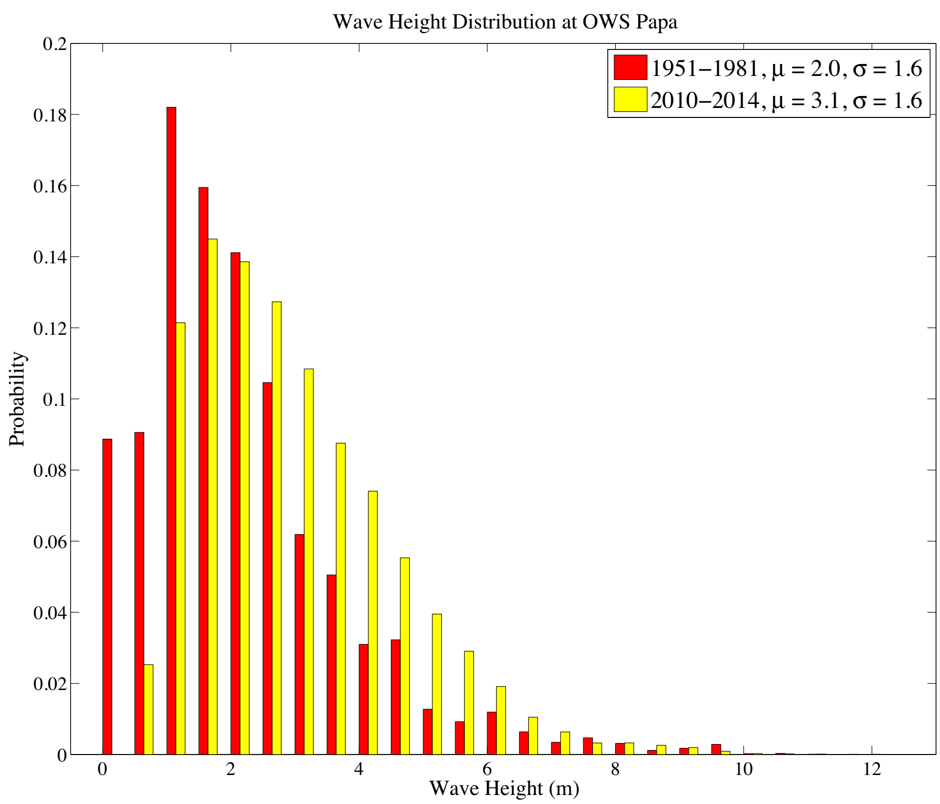

Figure 3. Statistical distribution of wave height at OSP. The mean (μ) values of the historical wave height (red) and the modern wave height (significant wave height; yellow) indicate differences introduced by data collection methods. Historical measurements were collected visually, whereas a buoy that calculates significant wave height from a wave spectrum collects modern measurements. It should be noted that similar standard deviation values (σ) indicate that visual estimates were systematic and, therefore, remain useful to this analysis.

values in tandem, often omitting the swell period altogether. It is unclear whether this omission was deliberate (i.e., no swell) or due to the lack of a measurement.

It is sometimes said that significant wave height is equivalent to what a trained observer would estimate visually. This statement has been attributed to the famed oceanographer Walter H. Munk, but has not been assessed rigorously. The statistical distributions of wave heights (Figure 3) reveal that visual estimates and buoy calculated values differ notably. The historical distribution is skewed by a high prevalence of zero and near-zero wave heights. This is likely the product of attempting to separate wind-sea and swell heights, namely that the 'wave height' field is likely meant to be only wind-sea. In addition, prior to 1969, wave height fields in observation logbooks had a maximum value of 9.5 m. Although the mean value of historical wave heights is obviously biased, it should be noted that the distribution of heights about those means have a similar standard deviation. The presence of an observational bias to a lower mean value does not necessarily exclude wave height from meaningful analysis. Distributional consistency indicates that wave height values, though subjectively determined by visual observations, were collected in a systematic manner and may be analyzed statistically. That is, direct comparison to other wave height data is problematic, but trends and signals within the historical data set may remain useful.

Modern wave periods are typically reported as an average or peak value, with explicit definitions relative to the measured wave spectrum, whereas the historical

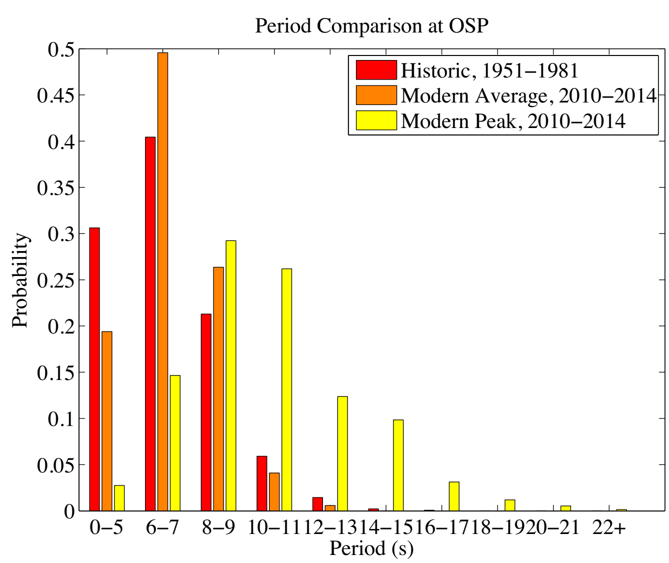

Figure 4. Historical and modern wave period values from OSP. The period of historical waves (red) agrees more strongly with the average period (orange) than the peak period (yellow) of modern waves.

data were only reported as 'period'. The historical values were also binned coarsely into intervals rather than given a distinct value. The modern average and peak period values were binned in a similar fashion and compared to historical values (Figure 4). The historical estimates of wave period lie primarily in the range 0–10 s, indicating that they are weighted towards the local wind waves. By contrast, spectral peak period measurements often pick out a swell component as the peak wave, so these values are more likely to be greater than 10 s. The historical observations are more closely aligned with modern average period measurements, which average over both swell and wind-sea wave components.

In summary, the compiled historical data from OSP are in reasonable agreement with modern measurements. Wind measurements are nearly identical and their slight difference is likely explained by differences in instrumentation. Wave information is less in agreement with modern data due to significant differences in collection methods. However, the distribution of measurements suggests a systematic approach to the visual approximation method and thus the historical data are worthy of further analysis.

Wind and Wave Relations to Climate Oscillations

There are two primary climate oscillations that have an impact on the Pacific region: the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Both oscillations have measureable impacts on sea surface and land temperatures, and yet they are also largely independent of each other. While derived from essentially the same measurements, researchers have identified distinctive interannual patterns (ENSO) and interdecadal patterns (PDO) (*Francis et al.*, 1998). It has also been demonstrated that ENSO effects have their strongest signal in the tropics and tertiary effects at higher latitudes, whereas PDO effects are the opposite. These characteristics led to our hypothesis that phase of the PDO may also have a measurable influence on wind and waves at higher latitudes, such as at OSP. Furthermore, the oscillations are highly correlated with climatic variability and their influence should therefore be observable in wind and wave variability.

Before variability was assessed, we established a mean state for both wind and waves at OSP. Visual analysis of daily averaged wind and wave time series shows an annual signal that is approximately sinusoidal. A second order Fourier series reproduces this seasonal signal well (Figures 5 and 6). This modeled seasonal signal was subtracted from the raw wind and wave data to produce a residual unencumbered by the average seasonal fluctuation. Centering the data about its

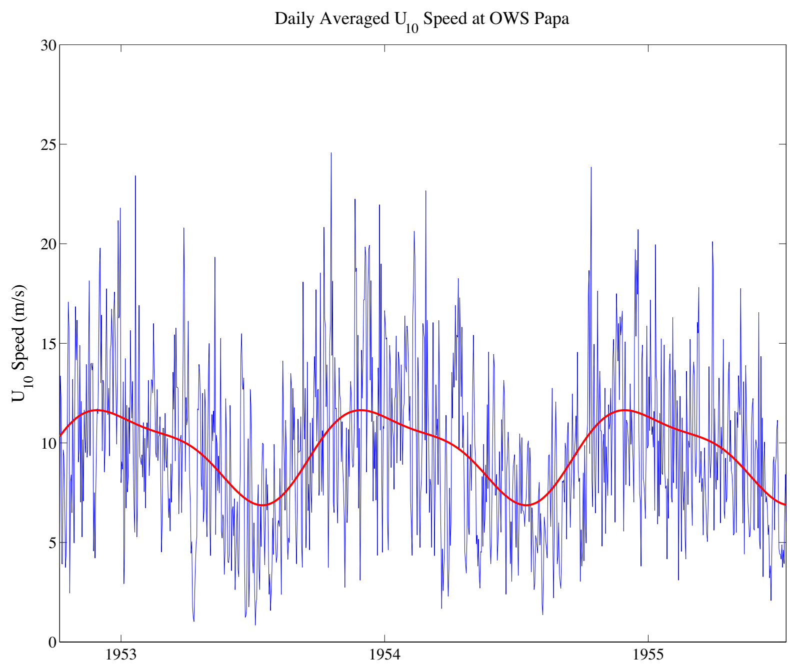

Figure 5. The modeled seasonal fluctuation in red aligns well with daily averaged U_{10} values.

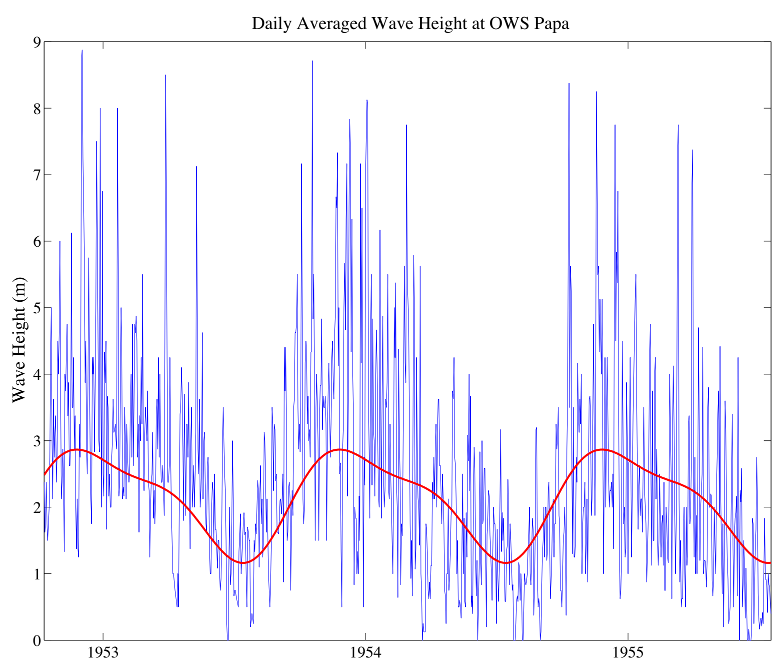

Figure 6. The modeled seasonal fluctuation in red aligns well with daily averaged wave height values.

seasonal component provides a clearer picture of the interannual variability by showing excursions from the mean state.

Variability in wind and wave data was defined using a 90th percentile-type value and the statistical variance of the seasonal residuals. It should be noted that the 90th percentile value was not defined relative to the standard deviation, since the distributions are not Gaussian. Rather, the 90th percentile wave height, H_{90}, (or wind speed, $U_{10,90}$) is defined here as the wave height that is nine-tenths of the way through the data set sorted in ascending order. The variance was defined by the usual method as the average of the square of the excursions from the mean. These values were calculated for each year and compared to the mean PDO index for that year.

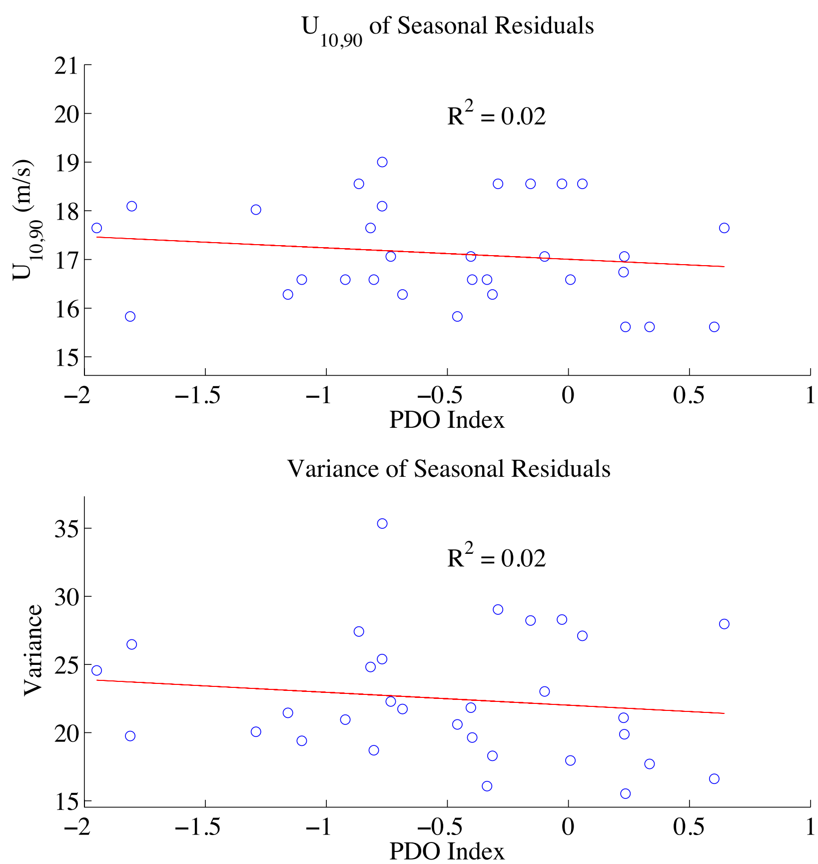

Figure 7. $U_{10,90}$ and seasonal residual variance versus PDO index. In both cases, a weak dependence on PDO phase is demonstrated.

Plotting H_{90}, $U_{10,90}$, and H and U_{10} variances against the PDO index (Figures 7 and 8) shows a weak dependence of each on the PDO phase. The low R^2 value for each linear least-squares fit indicates that a good deal of variability remains unaccounted for in our approach. This is not surprising, since we only attempted to quantify and control for the influence of seasonality on wind speed and wave height. In general, the cool phase of the PDO is weakly correlated with slightly greater wave heights and wind speeds, as well as greater variability. Similar findings are reported in *Bromirski et al.* (2013). Perhaps the most interesting feature of this analysis is that wave height demonstrates a stronger dependence than wind speed. This finding is parallel to our earlier assessment of wave generation as a basin-scale physical process.

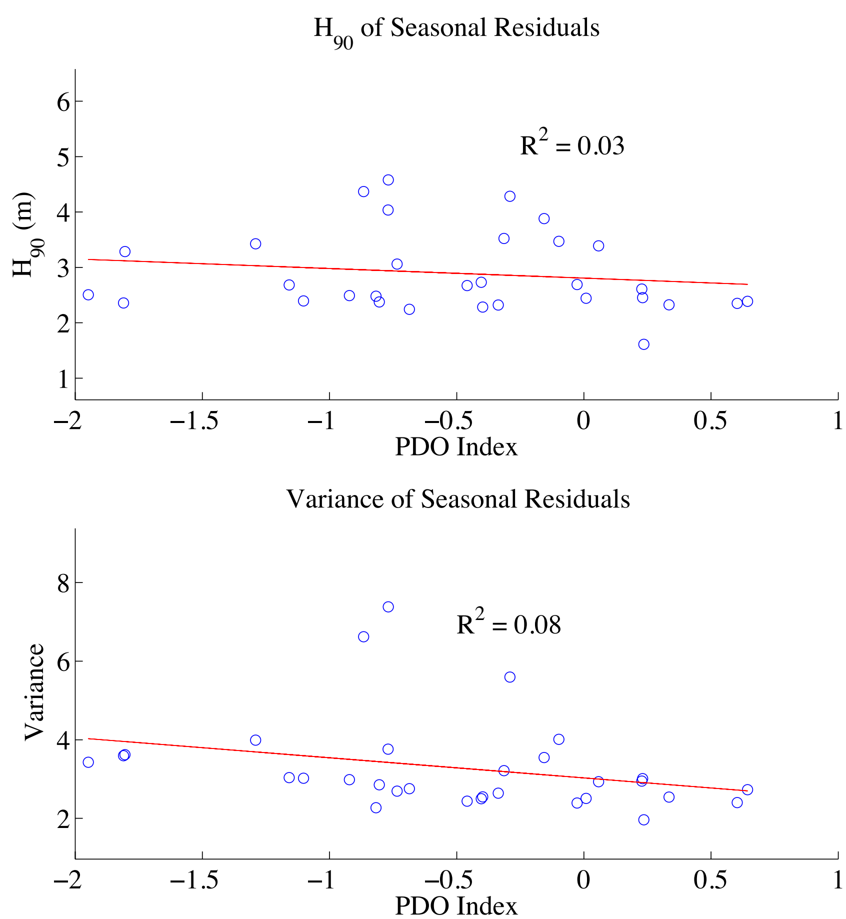

Figure 8. H_{90} and seasonal residual variance versus PDO index. In both cases, a weak dependence on PDO phase is demonstrated, though the dependence is stronger than observed in wind measurements.

Conclusions

The atmosphere and ocean are two parts of a complex feedback system that drives global climate. Physical understanding and quantification of those interactions is an important step toward better comprehension of how climate cycles, and future climate change, will impact other processes and potentially compound their effects. This understanding, especially with regard to ocean waves, will become increasingly important in the future as sea level continues to rise and coastal communities come under threat. Examining historical records such as these are useful tools not only in understanding basic processes, but also in developing extensive background information that will enable contemporary research to produce results more efficiently.

Our revival of an historical data set has provided some much-needed context for contemporary experiments and measurements at OSP. The interpretation of these historical data was complicated by instrumentation differences and the subjective manner in which some of it was collected. Accounting for those differences, it was still possible to utilize the historical measurements in general analyses that are less sensitive to imperfect data. We found a weak dependence of wind and wave variability on the phase of the PDO cycle, but ultimately links between North Pacific wind, waves, and climate trends remain unexplained. Further work in this area could consider other North Pacific oscillations, such as the Arctic Oscillation, to determine if those cycles are more strongly correlated (see, for example, *Thompson et al*., 2000). It should be noted that wind speed, wave height, and wave period are only three of the fields within the larger historical OSP collection. Other fields were also compiled as part of this project; all are now stored in readily accessible formats available online through the University of Washington Libraries ResearchWorks Archive (http://hdl.handle.net/1773/25570).

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