Title
California tides, sea level, and waves — Winter 2015-2016

Journal
Shore & Beach, 84(2)

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Publication Date
2016

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ABSTRACT

Tide predictions and wave and tide-gauge time series from San Francisco and La Jolla, CA, are used to characterize the sea level and wave height conditions of this El Niño winter spanning October 2015-March 2016. The early season timing of peak high "King" tides and monthly average high water levels served to decrease the probability of coincidences of extreme total water levels and large storm waves, especially in the south. Storminess in northern California helped ameliorate drought-related low reservoir levels and the Sierra snowpack.

Manuscript submitted 30 March 2016, revised and accepted 12 April 2016.

The El Niño of 2015-2016 was one of the strongest on record since 1950 in terms of the high equatorial Pacific Ocean temperature anomalies and trade wind reversals, the Southern Oscillation (pressure) Index, and other characteristics used to define these events (Becker 2016a). However, the impact on coastal California was below expectations for an event that was billed as a "Godzilla" El Niño in late 2015 by prominent climate scientist Dr. Bill Patzert of the National Aeronautic and Space Administration (NASA). The California Coastal Commission processed about 40 emergency and nine regular permits between October 2015 and early February 2016 (CCC 2016). Only two emergency permits were issued for the coast north of San Francisco. Most of the rest were for channel clearing to prevent inland flooding or for shoreline armoring and construction of sand berms in anticipation of flooding or damage. Several issued in January 2016 addressed coastal erosion, flooding, and damages, including cliff retreat and threats to public and private development in Pacifica, CA. Overall, however, damages were much less serious or widespread than during the comparable El Niños of 1982-1983 and 1997-1998.

Part of the explanation lies in the less than expected storminess due to the "ridiculously resilient ridge" (Swain 2013) of high atmospheric pressure that was parked over the southwestern U.S. for much of the winter (Swain 2016). This steered the mid-latitude jet stream along with numerous Pacific winter storms well north. Bromirski *et al.* (2003) described the climate of storminess variability along the California coast and how it depends on the broad-scale, mid-latitude eastern Pacific atmospheric pressure configuration, particularly the Aleutian Low and the Great Basin High.

California's precipitation situation did improve with El Niño 2015-2016, with numerous storms crossing at least the northern half of the state beginning in January 2016. In early March 2016 an "atmospheric river" (Dettinger 2013) from the tropical Pacific caused heavy rain and flooding in parts of northern California (Swain 2016). However, all this offered only modest relief from California's extended drought, now in its fifth year. For example, rainfall in San Diego from October 2015 through March 2016 was only 6.87 in, well below the 8.58 in average for 1850-2016. It was less than half of the total precipitation of 16.13 in and 15.08 in that fell over the same months during the 1982-1983 and 1997-1998 winters, respectively. As of March 2016 the El Niño was in decline with return to normal conditions expected by late spring (Becker 2016b).

This paper presents a quick-look at coastal ocean conditions during this past El Niño winter from October 2015-March 2016. Predicted tides and observed sea level and waves at San Francisco and La Jolla, CA are used to characterize these conditions. The approach follows Flick (1998) and Flick and Badan-Dangon (1989). Annual, monthly, and hourly sea level data from NOAA-NOS (2016) are used to show the contributions at each time scale to the total maximum water levels. Wave data from NOAA-NDBC (2016) and CDIP (2016) show the co-occurrences (or misses) of large wave events with peak high tides and high sea level anomalies.

Comprehensive multivariate or principal component analysis of all available data from the past winter and the recent strong El Niño winters of 1982-1983 and 1997-1998 is recommended to better define the temporal and spatial patterns observed in each event, and to highlight the differences between these events. Readily available data include: tide predictions, water level, wave height, period and direction, sea level atmospheric pressure, ocean temperature, and precipitation.

PREDICTED TIDES

Tidal water level changes are the ocean's response to the time-varying gravitational forces between the moon, sun, and earth. Different parts of the ocean respond differently to the same tidal forcing. Owing to the regularity of the astronomical motions, the tides are accurately predictable for practical purposes. Tide predications routinely include the non-astronomical "atmospheric" and oceanographic average seasonal cycles expressed by the constituents S_a and $S_{sa.}$[1]

Tides along the California coast are "mixed," with the diurnal constituents almost as large as the semidiurnal. This

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1) S_a and S_{sa} denote "Solar" (i.e. seasonal) annual and semi-annual average sea level cycles. These are calculated over a specific 19-year "tidal epoch," currently 1983-2001 and arise from seasonal changes in temperature, wind, atmospheric pressure, and other factors.

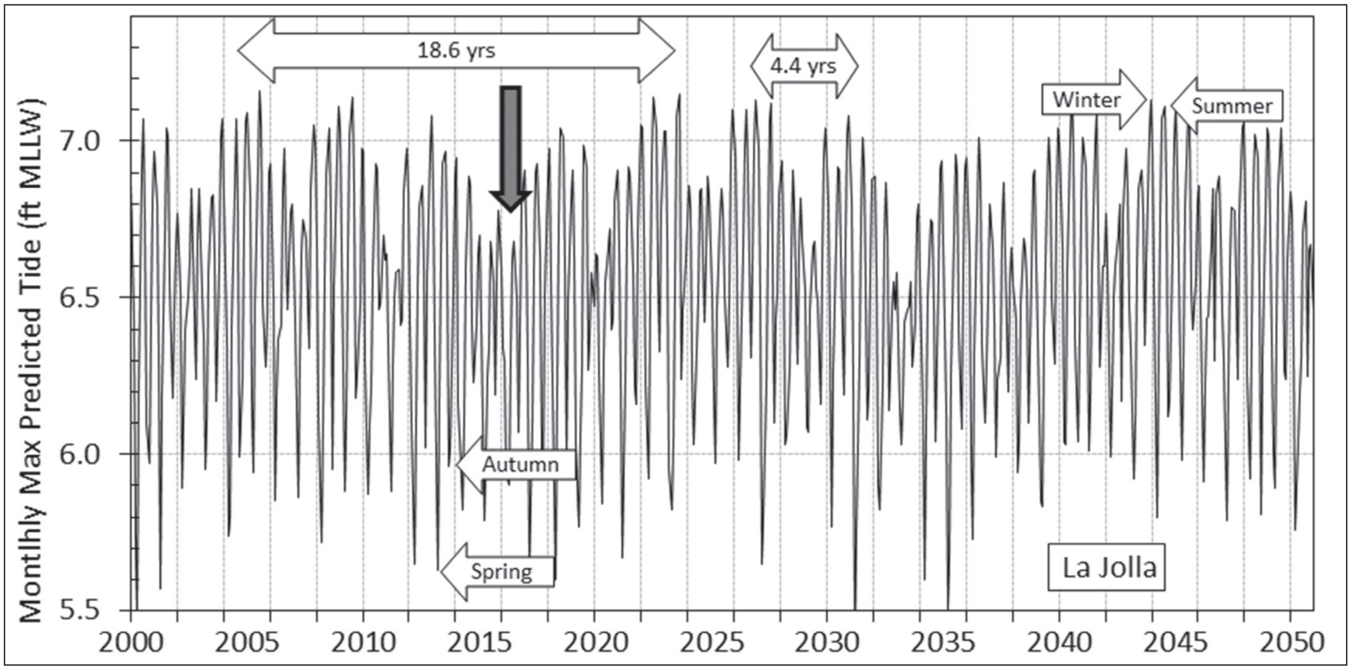
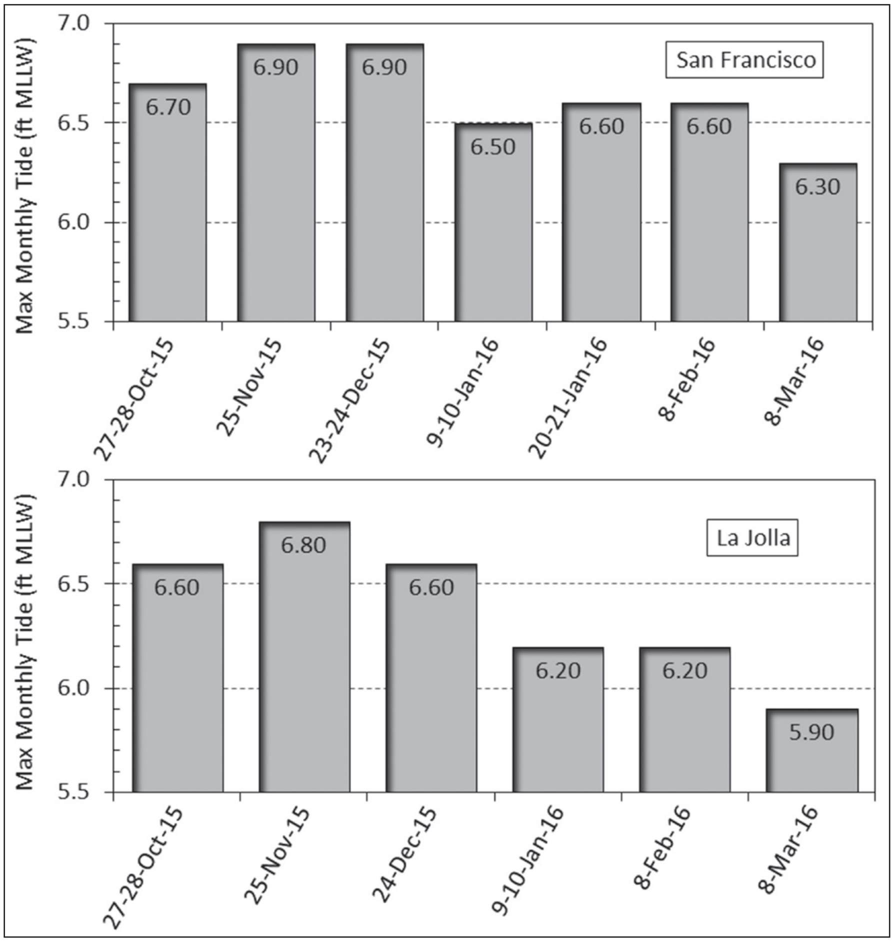


Figure 1. La Jolla maximum monthly predicted tides, 2000-2050. Note 18.6-yr and 4.4-yr modulations, higher summer and winter peak tides than those in spring and autumn, all owing to California's mixed tide regime. Dark vertical arrow points to 2015-16 winter, with its lower-than-average peak high tides.

Figure 2. Predicted monthly maximum tides at San Francisco for winter 2015-16 (upper) and La Jolla (lower). Winter tides peaked in November and/or December 2015, relatively early in the season.



leads to distinct patterns of high "King" tides (Zetler and Flick 1985a, 1985b), including peak ranges in winter and summer that exhibit 4.4-yr and 18.6-yr modulations,[2] along with the usual semi-diurnal twice-per-day and twice-per-month peaks. The winter-summer peaks are paced by the twice-yearly declination of the sun amplified by the twice-monthly declination and spring-neap variations in the moon's orbit. Declination effects are a characteristic of the diurnal contributions to the California tide regime. For example, in southern California the extreme monthly high tides always occur in the morning in winter, and in the evening in summer (Flick 2000). These variations are distinct from the spring-neap cycles that dominate semi-diurnal regimes, such as those on the east coast of the U.S.

Figure 1 shows the maximum monthly predicted high tide heights at La Jolla, CA, for 2000-2050. The variation between the lowest monthly peak tides in spring and autumn, and the highest in summer and winter ranges up to almost 2 ft (from 5.5-7.2 ft). Modulations associated with the 4.4-yr and 18.6-yr cycles reach over 0.5 ft (from 6.6-7.2 ft). The dark vertical arrow in Figure 1 indicates winter 2015-2016, with its relatively low peak high tides. Note that the prior episode of highest high tides at La Jolla occurred in 2012-2013, and the next one

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[2] The 4.4-yr variation derives from the 8.81-yr progression of the longitude of lunar perigee, while the 18.6-yr cycle arises from the regression of the lunar nodes. Both are prominent in mixed-tide regimes (Cartwright 1974).

is predicted for 2018-2019. Even more extreme highs are expected in 2022-2023 and 2025-2027.

Figure 2 gives the peak monthly high tide height details for San Francisco (upper) and La Jolla (lower) for the October 2015-March 2016 winter months. The seasonal maxima occurred in November-December 2105. In the south, the maximum tide heights decreased sharply from December through March. This substantially lowered the chances for co-occurrence of peak tides and high waves from big storms, which often occur in January or later in the season. In contrast, the devastating wave storms of late January 1983 happened to coincide with 7.2 ft peak high tides (La Jolla), the highest in about 19 years.

ANNUAL MEAN WATER LEVELS

Mean sea level, the background upon which all short-term fluctuations play out, is itself an increasingly important part of total regional water levels. For purposes of this paper, we consider annual averages shown in Figure 3 at San Francisco from 1855-2015 (upper) and La Jolla from 1925-2015 (lower) as the heavy lines marked with rhomboids. San Francisco is the longest continuous tide gauge record in the US. San Francisco and La Jolla respectively show similar trends of 0.54 and 0.64 ft/century (1.6 and 2.0 mm/yr) over their common period of record, 1925-2015 (light broken lines).

The San Francisco plot includes a reconstruction of global mean sea level from 1840-1993 (Jevrejeva *et al.* 2014) and satellite results from 1993-2015 (NASA 2016), as fluctuating light lines respectively adjusted to match the average measured mean sea level over each period. The near still-stand of global sea level prior to about 1850 (e.g. Kemp *et al.* 2011, Kopp *et al.* 2016) seems to have continued until about 1900 at San Francisco. San Francisco and La Jolla track the commonly cited 20th century global mean sea level rise of about 0.6 ft/century (2 mm/yr), which is illustrated by the solid light line from 1925-1980 in the La Jolla plot. Both records also show a two decade long "hiatus" in sea level rise from about 1980-2000 (horizontal light line in La Jolla plot), likely related to the "Pacific Decadal Oscillation" in the Pacific Ocean (Bromirski *et al.* 2011, 2012). Finally, the records also show this hiatus has ended with an apparent acceleration of sea level rise at La Jolla (solid sloping

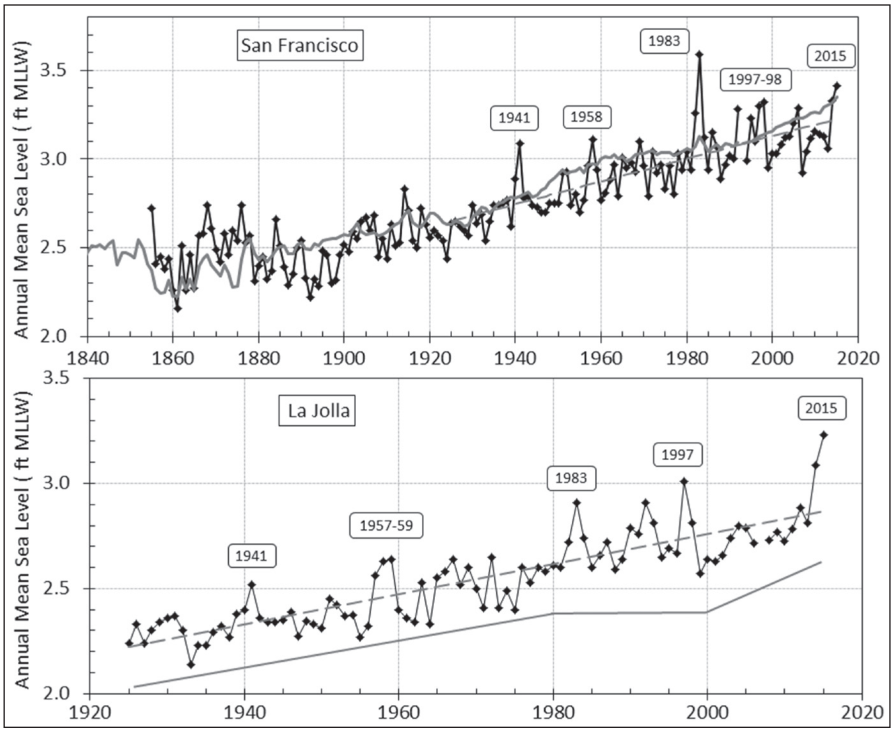
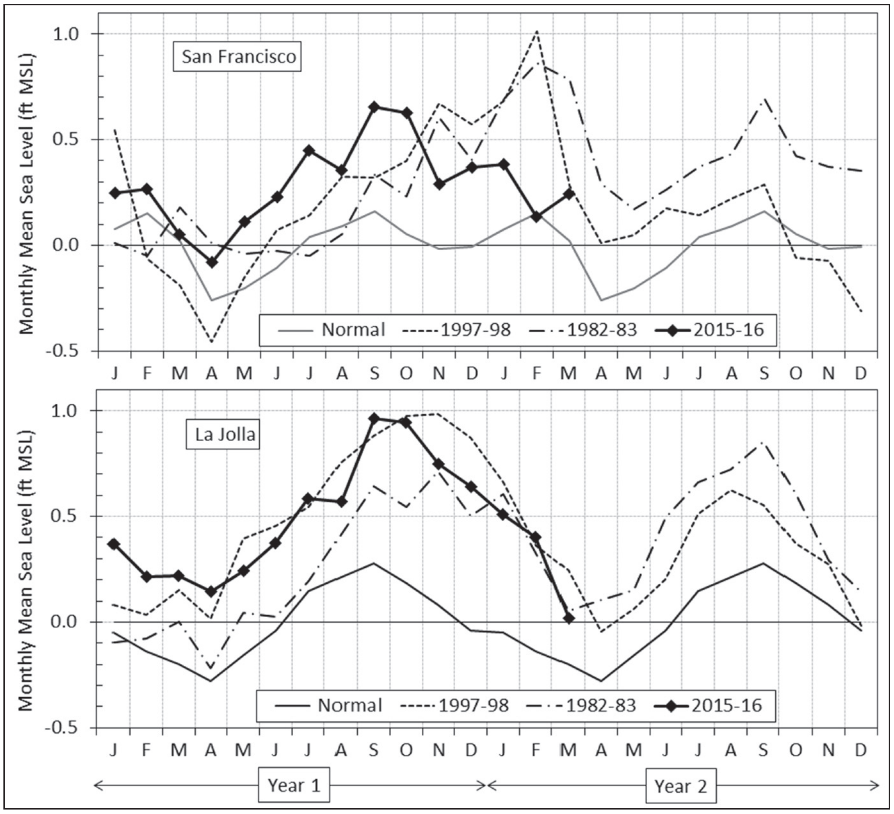


Figure 3. Annual average sea level (heavy black line with rhomboids) at San Francisco (upper) and La Jolla (lower). Years in boxes indicate strong El Niños. Broken light lines indicate trends from 1925-2015. Light fluctuating line in upper plot shows published 1840-2015 global mean sea level reconstruction. Light lines below La Jolla plot suggest apparent changes in sea level rise trends (see text).

Figure 4. Monthly average water level at San Francisco (upper) and La Jolla (lower) for several two-year periods as indicated, including El Niño years 1982-83 (dot-dash light lines) and 1997-98 (broken light lines), and October 2015-March 2016 (heavy lines with rhomboids).



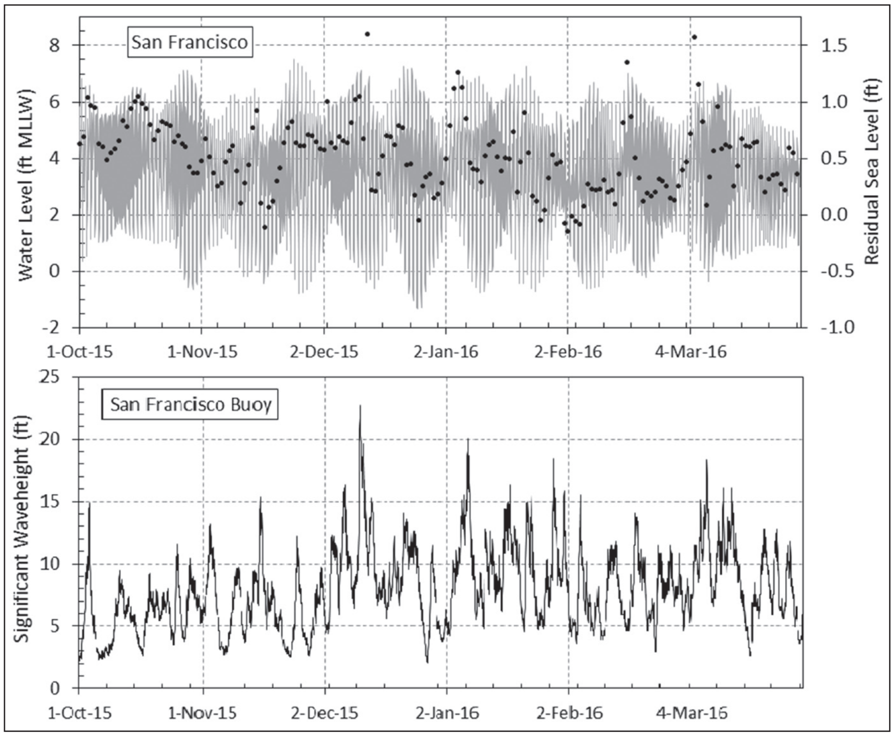
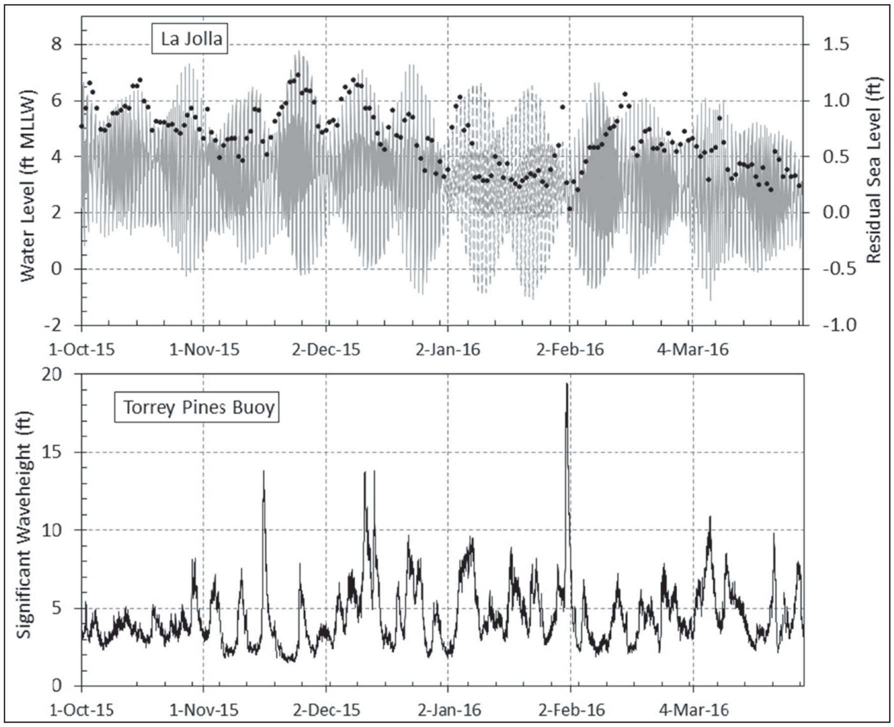


Figure 5. San Francisco hourly measured water level (light line) and maximum daily residual (dots) (upper), and hourly significant wave height (lower), October 2015-March 2016 (see text).

Figure 6. La Jolla (light solid line), and Los Angeles (light broken line) hourly measured water level and maximum daily residual (dots) (upper), and half-hourly significant wave height (lower), October 2015-March 2016 (see text).



line) to about 0.9 ft/century (3 mm/yr), which matches the recent global trend.

The San Francisco and La Jolla plots also call out the major El Niño years beginning with 1941 and including 1957-1959, 1982-1983, 1997-1998, and 2015. Mean sea level generally spikes higher in the south by several tenths of a foot, but the response is less consistent in the north. For example, San Francisco annual mean sea level was over 0.5 ft higher than normal in 1983, but was muted in 1997-1998 and in 2015 relative to the response at La Jolla during those years. It is notable that record high annual average sea levels were reached in 2014 and 2015 in the south.[3] This reflects widespread above-normal water temperatures in southern California over this time. For example, offshore of Oceanside average sea surface temperatures in 2014 and 2015 were 3.5° F and 4.1° F above normal, respectively. Average monthly temperatures reached 72.9° F in Aug 2015, while remaining at 72° F in Oct, 6.0° F above their 1997-2016 respective mean values (CDIP 2016).

MONTHLY MEAN WATER LEVELS

Monthly sea levels are useful for tracking the seasonal evolution of El Niño years, which generally present anomalously high sea levels for a year or two at a time. The seasonal timing of peak water levels varies from one El Niño to another and from location to location. Plotted in Figure 4 are monthly mean water levels at San Francisco (upper) and La Jolla (lower) for several two-year periods including the two most recent strong El Niños of 1982-1983 (dot-dash line) and 1997-98 (broken line), and October 2015-March 2016 (heavy line with rhomboids). Also shown for each location is the "normal" seasonal water level cycle defined as the respective monthly means over the current 1983-2001 National Tidal Datum Epoch (light solid line).[4]

San Francisco shows a twice-annual sea level cycle of about 0.5 ft in peak-to-peak height. The high in autumn (September) is related to ocean warming, and the second high in late winter (February) is caused by a combination of storm surge and enhanced estuary discharge of river water (Bromirski and Flick 2008). In contrast, La Jolla exhibits a slightly larger, strongly annual cycle mainly driven by warming and wind effects (Reid and Mantyla 1976). As mentioned above, these seasonal cycles are represented by the S_a and S_{sa} constituents in routine tide predications.

In San Francisco, 2015-2016 monthly mean water level maxima occurred in

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3) The record all-time highest instantaneous sea level elevation at La Jolla of 7.66 ft above MLLW occurred at 09:00 PST on 11 Jan 2005 as a combination of a 7.0 ft tide and 0.66 ft residual due to warming and storm surge during the weak El Niño of 2004-05.

4) The annual mean curve is repeated twice in each graph.

September-October 2015, much earlier than the peaks in either 1982-1983 or 1997-1998, which happened in February of those winters. The 2015-2016 heights of about 0.5 ft above normal were also lower than those of 1982-83 and 1997-1998, which reached about 0.8 ft above normal. At La Jolla, monthly maxima also occurred in September-October 2015, which was only slightly earlier than the corresponding highs of the earlier two strong El Niños, which peaked in October or November. By February and March 2016, monthly mean sea level at San Francisco had dropped back to normal or near-normal.

In the south, peak monthly heights reached those of 1997-1998, about 0.7 ft above normal, which were higher than observed in 1982-1983. Like the timing of the peak tides, the heights and timing of peak monthly average high water also served to decrease the probability of coincidences of high total water levels and large storm waves, which generally appear in December to March. As of March 2016, mean monthly sea level at La Jolla remained elevated by only 0.2 ft above normal.

HOURLY WATER LEVELS AND WAVE HEIGHTS

San Francisco

Figure 5 presents hourly measured total and daily maximum residual water levels (upper), and significant wave height (lower) observations at San Francisco (NOAA-NOS 2016, NOAA-NDBC 2016). The upper graph shows measured sea level (light line) and maximum daily residual (dots), defined as the difference between measured water level and the predicted tide. Several coincidences of high tide range and high residual water levels occurred, namely in mid-October, mid-November and mid-December 2015, and early January and mid-February 2016 with residual values of 1-1.5 ft. Maximum total water levels remained over about 7 ft and peak residuals exceeded 1 ft from late October 2015 through February 2016. Nevertheless, notably lower residuals occurred during the peak high "King" tides in late November and late December 2015.

Between 1982 and 2008, average significant winter wave heights ranged from about 5 ft in October to 7.5 ft in January-March. Maximum observed heights over this period range up to about 25-28 ft and occur in December and January (NOAA-NDBC 2016).

During winter 2015-2016 there were 14 or 15 episodes of waves exceeding 15 ft (Figure 5, lower), and two reaching or exceeded 20 ft. In early October 2015, 15-ft waves coincided with 6.8 ft total water levels. Four other co-occurrences of high water levels and large waves were observed, namely on 7 and 28 January 2016, and on 7 March and 11-14 March 2016. The maximum observed wave height reached about 23 ft on 10 December 2015. This large wave event coincided with a 7.0 ft tide and a 1 ft residual (upper), and brought a high surf and flood advisory along the north coast. However, reported damages were apparently due to the strong winds, heavy rainfall and inland flooding (ABC 7 News 2015).

"King Tides"

The term "King Tide" originated in Australia and New Zealand. It is an imprecise way to denote unusually high tides, or the very highest tides that occur only a "few times per year." While more descriptive terms like "peak annual," "peak seasonal," or "peak monthly high tides" are preferable, the vague "King Tide" moniker seems to prevail.

The term has also been used interchangeably with "perigean spring tides," which are specific high tides associated with the twice-monthly close approach of the moon to the earth (perigee) when earth, moon, and sun are lined up during new or full moon (spring). "Spring" in this context does not refer to the season, but as opposed to "neap" twice each month when earth, moon, and sun are in quadrature. Perigean springs dominant high tide patterns in semi-diurnal tide regimes.

While "spring" tides do enhance tide height twice per month on the mixed-tide California coast, its pattern of extremes is paced by the declination effects of the moon and especially the sun (see text). These influences are properly termed "tropic" high tides.

Even more confusing is a tendency to confound high water levels from non-astronomical causes with high astronomical tides by calling all high water events "high tides" or "King tides." For example, storm surge, high wave run-up, or enhanced sea levels associated with temporary warming from El Niño all contribute to total extreme water elevations, but are not tide related.

La Jolla

Figure 6 shows hourly measured total and daily maximum residual water levels (upper), and significant wave height (lower) observations at La Jolla.[5] Two coincidences of high water levels and large waves occurred, namely on 16 November and 11-14 December 2015, where tide heights were over 6 ft and residuals reached about 1.2 ft. In contrast to the north, maximum total water levels and peak residual heights at La Jolla decreased through March 2016 from their peak in late November 2015. This reduced the chance of coincidence of high water and large waves.

Average winter wave heights from 2001-2016 at the Torrey Pines buoy range from about 3 ft in October to 4 ft in December to March. The highest wave height observed was 18.8 ft on 1 February 2016 (Figure 6, lower). In winter 2015-2016, five episodes of waves exceeding 10 ft occurred, in mid-November and mid-December 2015, and on 1 February and 8 March 2016. Only two coincidences of high water levels and large waves occurred, namely those in mid-November and mid-December 2015. Notably, the large but brief wave-storm event in February coincided with a neap tide, where total water levels were only about 4.2 ft (Figure 6, upper). Beach sand losses at selected San Diego region locations are detailed in Ludka *et al.* (in press).

CONCLUSIONS

The strong El Niño winter of 2015-16 did not result in the anticipated coastal erosion, flooding, and damages that occurred during comparable events in 1982-1983 and 1997-1998. A combina-

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[5] The La Jolla tide gauge failed during January 2016. Water levels and residuals measured at Los Angeles, which is similar to La Jolla, were substituted (Figure 6, broken light line).

tion of favorable height and timing of peak high tides, seasonal water levels, and shunting of most winter storms to the north by a persistent ridge of high pressure spared southern California. There was more storminess in northern California, where occasional heavy precipitation did help improve low reservoir levels and the prior-year's deteriorated Sierra snowpack. However, less coastal erosion, flooding, and damages occurred because of similarly lower peak tides and smaller waves than those of other El Niño winters.

ACKNOWLEDGEMENTS

The support of the California Department of Parks and Recreation, Division of Boating and Waterways, is gratefully acknowledged. The author appreciates useful editorial comments and encouragement by Dr. Beth Sciaudone, Dr. Lesley Ewing, and Dr. Adam Young.

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