BC Storm Surge Forecasting System

2015-16 Storm Surge Almanac

Climate outlook and tidal elevations for fall/winter 2015

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Executive Summary

The tropical Pacific Ocean is currently experiencing very strong El Niño conditions that are trending towards the largest El Niño event since 1997-1998. In addition, persistently high sea surface height (SSH) and sea surface temperature (SST) anomalies continue to persist in the northeast Pacific Ocean as remnants of prior oceanographic/atmospheric forcing in 2014-15, pushing the Pacific Decadal Oscillation (PDO) index to its highest level in 18 years. Potential El Niño impacts include an increase in the number of extra-tropical storms and a possible southward shift of Pacific storm tracks associated with the strengthening of the Aleutian Low (Weng *et al*, 2009). Previous major El Niño events in 1982 and 1997 were responsible for two of the highest surge and total water level events on the coast of British Columbia. The 2014-15 storm surge season was very active in November and December, but tapered off in January with the onset of abnormally high pressure from the south moving in response to a strong meander in the jet stream (also responsible for bringing Arctic air down over eastern Canada and the United States). The maximum observed water level at Point Atkinson was 5.42 m (4.72 m tide + 0.70 m surge) during a series of storms from December 9-12, which brought isolated coastal erosion and flooding to the Lower Mainland and major flooding to communities on the east coast of Vancouver Island.

Annual coastal flooding risk is greatest during the seasonal perigean spring tides, which generate extreme high tidal levels during the winter months. This winter (2015-16) the highest tides for the Lower Mainland are expected to occur at the end of November, mid and late December, and mid January. For Victoria, the highest tides are expected in the fourth weeks of November and December.

Early storms in September 2015 caused major power disruptions, after a very warm dry summer left trees vulnerable to wind damage. The sail-effect of leaves on the trees during high winds exacerbates the damage early in the fall before leaves fall. Late summer storms so far have originated in Gulf of Alaska and propagated south; however, storm patterns are expected to change in the fall due to the deepening of the Aleutian Low which often accompanies the onset of El Niño.

The persistent 5-10 cm SSH anomaly off the west coast of British Columbia caused by “the Blob” of warm water in the northeast Pacific ocean appears to be diminishing (or fluctuating in amplitude), but could regenerate with El Niño. The El Niños of 1982 and 1997 gave rise to positive SSH anomalies of up to 20 cm. The evolving status of SSH, SST and El Niño will be discussed in the mid-season update in December.

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Overview

This document provides a summary of the current and forecasted meteorological and oceanographic conditions for southern British Columbia as they relate to the 2015-16 winter storm season. The focus is on total water level (tide plus surge), and the risk of total water level approaching or exceeding the historical maximum observed values at Point Atkinson (Vancouver) and Victoria.

The main factors that contribute to extreme water level are seasonal high tides ("king tides"), storm intensity (wind velocity and low sea-level pressure) and coastal sea level anomalies (departures from the long-term mean) due to basin-scale ocean climate phenomena such as the El Niño/Southern Oscillation (ENSO). Each of these risk factors is discussed in the following sections.

Climatological Factors

Large-scale climatological phenomena affect both the weather and climate. The statistics of synoptic scale meteorological conditions in a given year may be influenced by the larger scale atmospheric and oceanographic conditions that are often described in terms of select climate indices. Two indices of significance to the west coast of North America are the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation (ENSO). A description of these phenomena and a discussion of their potential relationship to the winter storm surge statistics for British Columbia are included in the Appendix.

In 2000, the PDO shifted away from the multi-decadal warm phase (1977-2000), to what has been a predominantly a cold phase (negative PDO) over the last 12 years. However, positive PDO values have been recorded since January 2014, and last winter's peak value of 2.5 was the highest since the 1997 El Niño. The winter of 2014-15 was characterized by a very persistent high pressure ridge centered over northern California, which dominated the south coast BC weather beginning at the end of January 2015. The resulting warm conditions led to the formation of an anomalously warm SST region in the northeast Pacific known colloquially as "the Blob". **The current PDO index (as of August 2015) is 1.56.**

The NCEP Climate Prediction Center (CPC) provides regular updates of the state of ENSO in the Pacific Ocean. As of September 10, 2015, the ENSO alert system is on El Niño Advisory. Consensus model forecasts published by CPC (Fig. 1) all point to strong El Niño conditions with a 95% chance of continuation through the Northern Hemisphere winter. The complete commentary is available at:

http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.pdf

From the CPC commentary of September 10, 2015:

"During August, sea surface temperature (SST) anomalies were near or greater than +2.0°C across the eastern half of the tropical Pacific (Fig. 1). SST anomalies increased in the Niño-3.4 and Niño 3- regions, were approximately unchanged in the Niño-4 region, and decreased in the Niño-1+2 region (Fig. 2). … . The atmosphere remained coupled to the anomalous oceanic warmth, with significant low-level westerly wind anomalies and upper-level easterly wind anomalies persisting from the western to east-central tropical Pacific. Also, the traditional and equatorial Southern Oscillation Index (SOI) were again negative, consistent with enhanced convection over the central and eastern equatorial Pacific and suppressed convection over Indonesia (Fig. 5). Collectively, these atmospheric and oceanic anomalies reflect a strong El Niño."

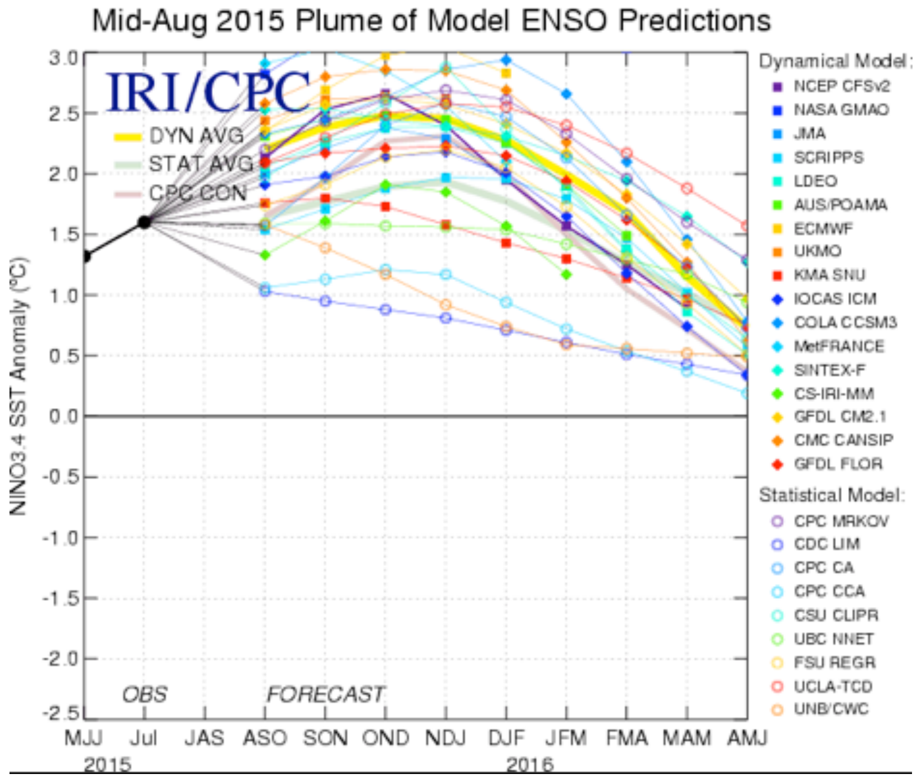

Figure 1: CPC numerical model consensus forecast for ENSO conditions for Fall 2015 to Spring 2016. The consensus is for a 95% chance of El Niño.

Temperature and precipitation effects of El Niño vary across North America. For the Pacific Northwest (including southern British Columbia), the general trends are towards warmer, drier winter conditions. Increasing precipitation for California is also expected as the winter storm track shifts south. Storms tend to form more frequently over the North Pacific Ocean during strong El Niños (Eichler and Higgens, 2006); therefore, regional coastal impacts will depend greatly on the exact nature of the shifted position of the Pacific storm track.

Eichler and Higgens (2006 - referred to hereafter as EH2006) compared North American extratropical storm activity to ENSO phases based on the NCEP reanalysis period of 1950-2002 and the European ECMWF 40-year reanalysis data from 1971-2000. They categorized years based on an ENSO Intensity Scale (EIS) equal to twice the “Oceanic Niño Index” (see Table 1).

Table 1: (From Eichler and Higgens (2006) Table 1)

EIS > 3	strong El Niño	1958, 1966, 1973, 1983, 1992, 1998, 2003
0 < EIS < 3	weak/moderate El Niño	1964, 1969, 1977, 1978, 1987, 1988, 1995
EIS = 0	Neutral	1952, 1953, 1954, 1959, 1960, 1961, 1963, 1967, 1970, 1979, 1980, 1981, 1982, 1986, 1990, 1991, 1993, 1994, 1997, 2002
-3 < EIS < 0	weak/moderate La Niña	1951, 1955, 1957, 1962, 1965, 1968, 1971, 1972, 1975, 1984, 1985, 1996, 2001
EIS < -3	strong La Niña	1950, 1956, 1974, 1976, 1989, 1999, 2000

Over the entire reanalysis period, EH2006 provide an average seasonal frequency of the number of storms in the northeast Pacific that impact the southern coast of British Columbia. Results show an average of three storms in the period spanning October to December (OND) and four in the period from January to March (JFM). When the storms were binned by ENSO phase (as described in Table 1), the JFM storm track frequency was shown to be highest (four or more) during a moderate or strong La Niña phase and during a strong El Niño phase. The lowest storm frequency in the region (4 or less) occurs, on average, during ENSO neutral or moderate El Niño conditions. This analysis was not done for the OND period so it is not clear from the discussion of EH2006 whether or not the storms have shifted earlier in the season, but it is assumed that the weakening of storm frequency in JFM during ENSO neutral to moderate El Niño occurs in all seasons.

The Pacific Ocean is currently experiencing strongly positive ENSO conditions, which are expected to evolve into a major El Niño. **Based on the forecast of strong El Niño conditions, combined with a positive PDO, an above average number of extra-tropical storms is predicted. The location of the winter storm track is generally expected to shift south (relative to the long term average) during El Niño, which is a marked departure from its tendency (strong northward shift) over the past two winters.**

Surge Statistics

Residual sea level (water level - tidal height) statistics for southern British Columbia are examined for Point Atkinson and Victoria from 1980 to present. This time period was chosen because it represents a modern era in the gauge data. One drawback of using this period is that the beginning coincides with the start of the 23-year PDO warm phase (1977-2000), and therefore may include climatological biases (weighted towards warm PDO conditions). The tides were calculated for both tide gauge stations and subtracted from observed water levels. The resulting water level residuals were binned in 5 cm bins; all residuals greater than 20 cm were retained for the analysis.

Point Atkinson

The maximum residual water level measured (1980-present) at Pt. Atkinson is **1.03 m in March, 1999**. For residuals > 20 cm, the 90th percentile corresponds to residuals >45 cm. The percentage and cumulative percentage represented for each 5-cm bin are shown in Fig. 2.

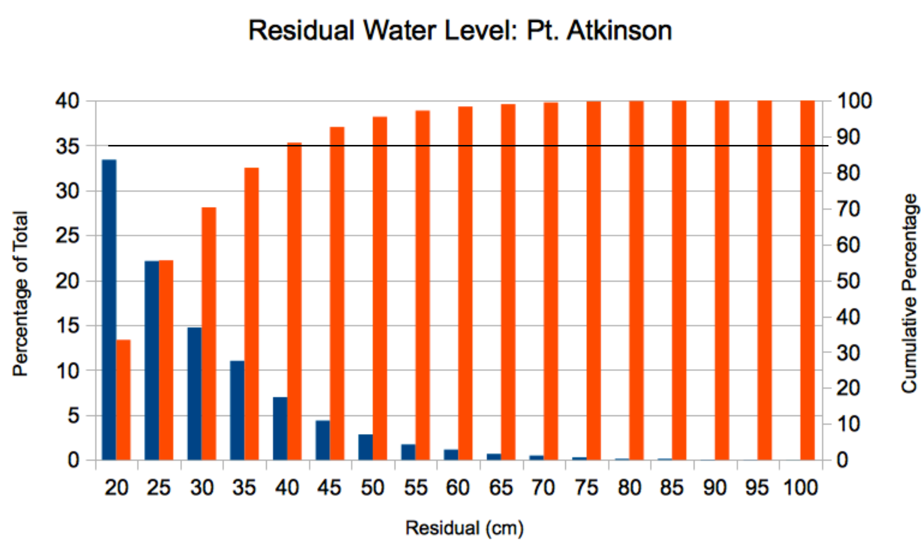

Figure 2. Residual water levels at Pt. Atkinson (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >45 cm lie within the 90th percentile (black line) of all residuals >20 cm.

Victoria

The maximum residual water level measured (1980-present) at Victoria is **0.80 m in January 1983**. The 90th percentile comprises all residuals >40 cm. The percentage and cumulative percentage represented for each 5-cm bin are shown in Fig. 3.

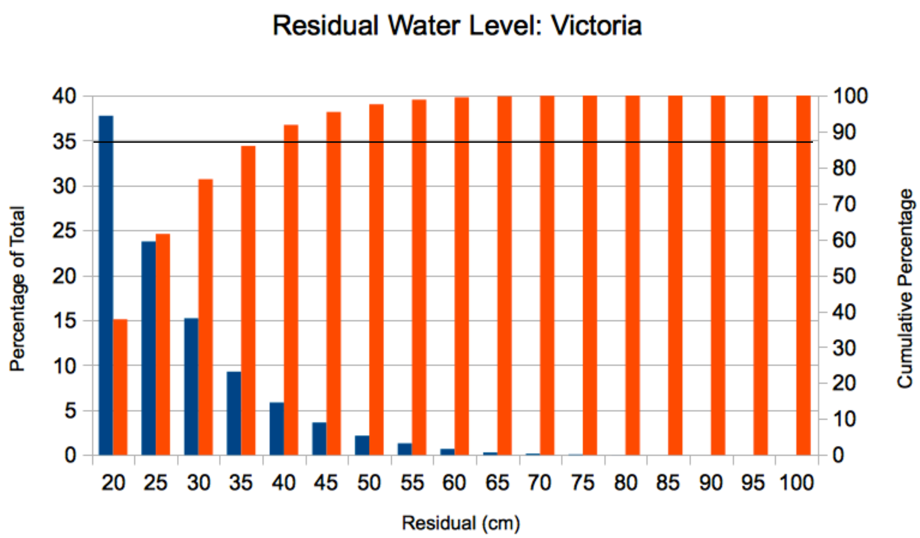

Figure 3. Residual water levels at Victoria (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >40 cm lie within the 90th percentile (black line) of all residuals >20 cm.

Tides

The highest tides of the year, known as the perigean spring tides, occur near the summer and winter solstices. High tides during this period reach (or slightly exceed) 5.0 m at Point Atkinson and 3.1 m at Victoria. Water levels of this magnitude leave coastal areas extremely vulnerable to flooding by storm surge. To illustrate the importance of these periods of extreme tidal height, a storm surge of 0.6 m (1.3 year return period) concurrent with peak winter tides would cause a total water level equivalent to the 1982 record high at Point Atkinson (and the 2003 record high at Victoria), even without the presence of El Niño-induced elevated coastal sea levels.

Point Atkinson

The historical recorded highest water level at Point Atkinson occurred on December 16, 1982 when the water gauge measured a total water level of 5.61 m (4.71 m tide + 0.90 m anomaly). The factors that led to the historical highest water level were a combination of high seasonal tide, strong winds, low atmospheric pressure and a coastal sea-level height anomaly of approximately 0.2 m driven by one of the most intense El Niño events on record.

Figure 4 highlights the dates when peak tides may exceed 4.7 m relative to station datum at Point Atkinson; these periods offer broad windows during which a moderate storm surge could result in extreme water levels. Days with predicted tides in the range of 4.7-4.8 m are shaded yellow, while those with tides in the range of 4.9-5.0 m above chart datum are shaded red. The periods to watch most closely occur during November 28-29, December 16-17 and 26-29, and January 12-15 inclusive.

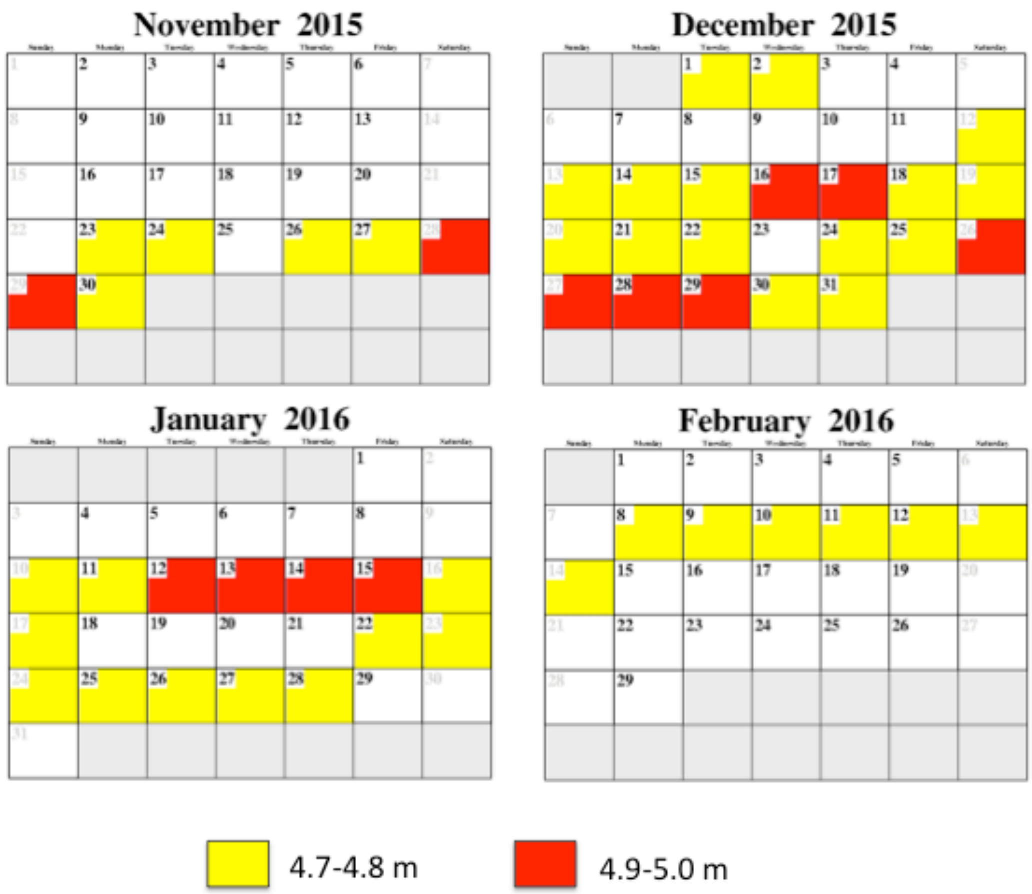

Figure 4. 2015-16 calendar dates for tides exceeding 4.7 m at Point Atkinson. The highest tides during this four month period occur near the end of November, mid and late December and mid-January.

Victoria

The historical maximum observed water level at Victoria of 3.71 m above chart datum (3.14 m tide + 0.57 m surge) occurred on January 2, 2003. This coincided with the time of highest seasonal tide and during a moderate El Niño.

Figure 5 highlights the dates when peak tides may exceed 2.8 m relative to station datum. Depending on the predominant wind direction, several regions around Victoria are at risk to storm surge damage including Fairfield (Ross Bay), Oak Bay and Cadboro Bay. This year (winter of 2015-16), the highest predicted tides occur during November 25-26 and December 22-25.

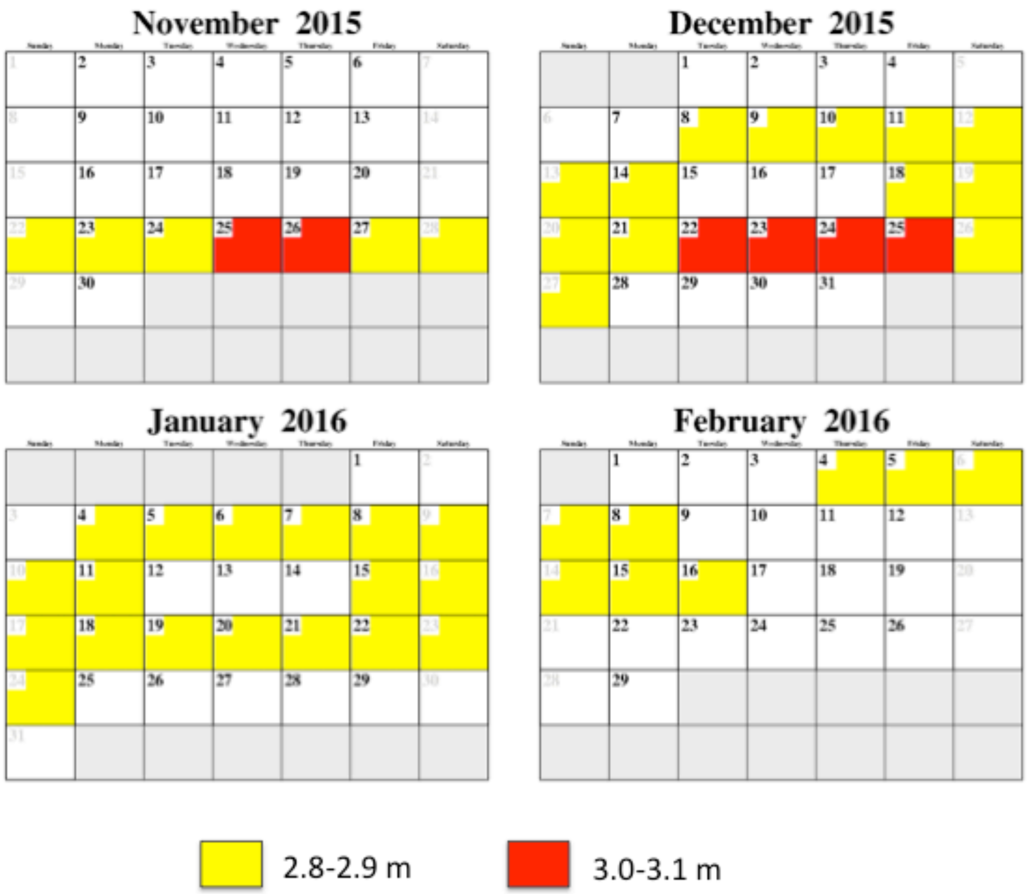

Figure 5. 2015-16 calendar dates for tides exceeding 2.8 m at Victoria. The highest tides during this four month period occur in late November and late December.

Sea Surface Height Anomaly

Sea surface height (SSH) anomalies derived from the JASON radar altimetry satellite are processed by the Jet Propulsion Laboratory (JPL) at the California Institute of Technology. The anomalies show the interannual variability of SSH after the mean and seasonal signals and the trend have been removed. The SSH anomalies are used to highlight large scale spatial trends, often caused by climatological phenomena such as ENSO. A major El Niño event, similar in magnitude to the 1997 event (the last “Super El Niño”), is presently underway. Equatorial SSH anomalies are well in excess of 20 cm with SSH anomalies along the west coasts of North and South America appearing similar to those in the fall of 1997. Currently, moderate 5-10 cm anomalies are present off the British Columbia coast (Fig. 6), likely resulting from steric effects associated with the positive sea surface temperature anomaly (“the Blob”) observed over the same region. El Niño conditions are forecast to remain strong through the northern hemisphere winter and begin weakening in spring.

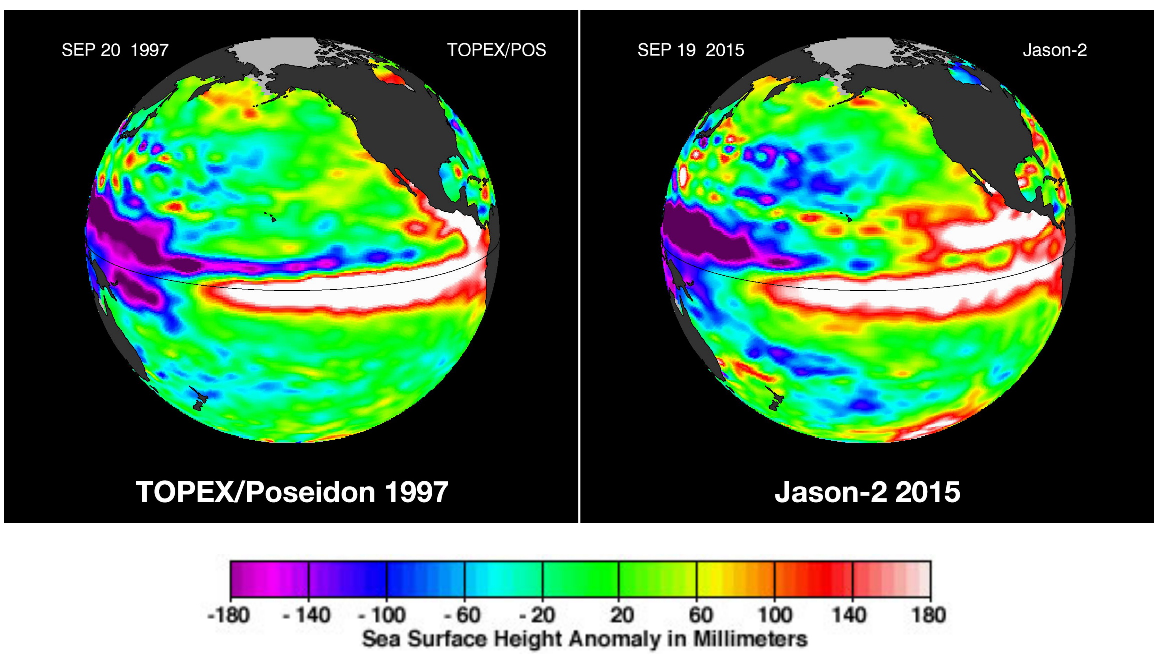

Figure 6. JPL image of 10-day averaged SSH anomalies over the Pacific Ocean on September 20, 1997 (left) and the latest image on September 19, 2015 (right). El Niño effects on temperature and precipitation across North America are expected to increase during winter before decreasing in spring.

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Summary

From the information available as of September 2015, the winter 2015-2016 storm season will be characterized by the following:

1. **ENSO**: A major El Niño forming in the equatorial Pacific will increase in intensity through the winter before decreasing in the spring of 2016. The intensifying El Niño conditions are expected to lead to increased frequency and intensity of storms in the northeast Pacific. (However, forecasting the exact storm impacts on the west coast of North America is difficult due to uncertainty in the projected location of the jet stream.
2. **PDO**: strongly positive. Positive PDO generally reinforces the effects of a positive ENSO (El Niño).
3. Peak tides **Victoria**: Late November and late December.
4. Peak tides **Vancouver:** Late November, mid and late December, and mid-January.
5. **SSH anomalies**: 5-10 cm anomalies are currently being detected, with the potential to due to coastal impacts of El Niño.

The 2015-16 storm surge season will be carefully monitored. The combination of positive PDO and strong El Niño conditions portend a very active storm system with the potential for enhanced persistent SSH anomalies along the west coast of North America. Peak tidal windows (within 20 cm of expected highest astronomical tide) are narrow this year, but the periods of higher tides (within 40 cm of expected highs) are broad. Conditions could change rapidly as the El Niño evolves, and an update on these conditions will be provided in mid December.

References

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Weng, H., Behera, S. K., & Yamagata, T. , 2009. Anomalous winter climate conditions in the Pacific rim during recent El Niño Modoki and El Niño events. *Climate Dynamics*, *32*(5), 663-674.

Wolter, K., and M. S. Timlin, 2011: El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *Intl. J. Climatology*, 31, 14pp., in press.

Appendix

Pacific Decadal Oscillation

The PDO, which represents the principal mode of variability of sea surface temperature in the Pacific Ocean, shifts between a positive (warm) and negative (cool) phase (Mantua and Hare, 2002). During a warm PDO phase, the waters off the west coast of North America exhibit warmer than normal temperatures, and wind velocity anomalies along the outer coast are directed northward (Fig. A1). The opposite is true during the cool phase. The time series of PDO index from 1900 to present (Fig. A2) shows that the oscillation between the warm and cool phase varies with a period of roughly 5-10 years, but can also stay predominantly in one mode for prolonged periods. The shift from a nearly 30-year cool phase to a warm phase in the late 1970s is considered by many to be an oceanic regime shift affecting both weather and biological ecosystems in the Pacific Ocean. After 1998, there was a return to the cool PDO phase.

The sea level pressure anomaly associated with the warm phase of the PDO acts to intensify the Aleutian low, and vice-versa during the cold phase. Gershunov and Barnett (1998) provide evidence of modulation of the ENSO signal by the PDO. For example, the climate impacts of El Niño may be intensified during a warm PDO phase since both contribute to a deepening of the Aleutian low pressure system. Conversely, a cold phase PDO could enhance the effects of La Niña over western North America.

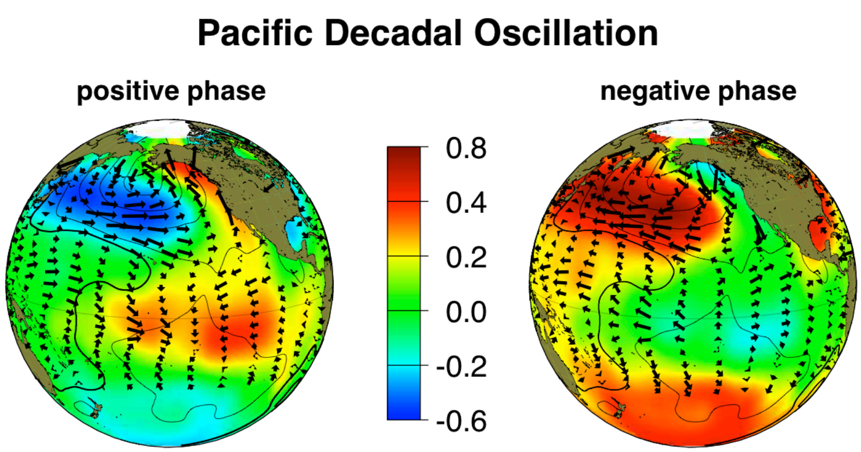

Figure A1. PDO warm and cool phases of sea surface temperature anomaly and associated wind anomaly patterns. Web image from Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington.

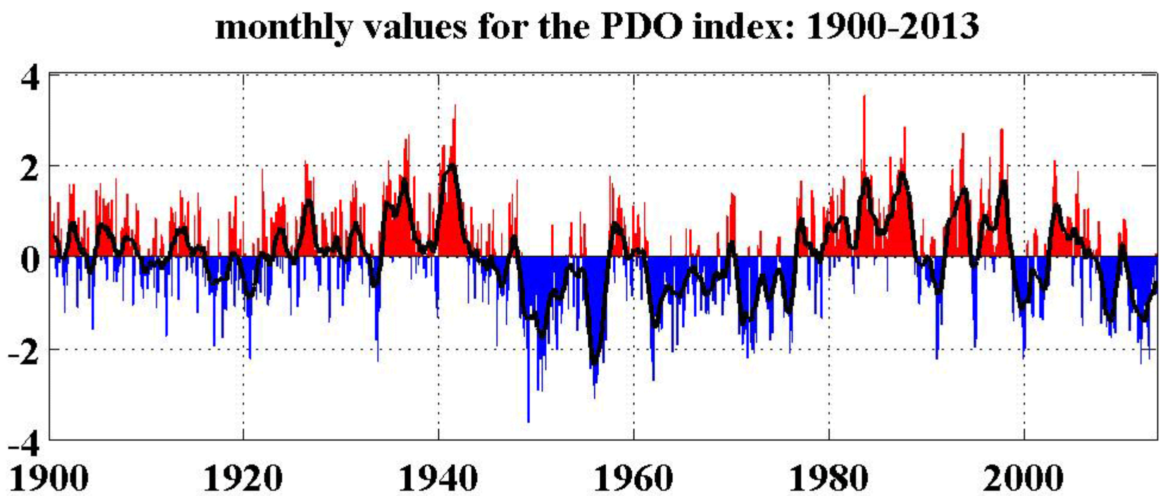

Figure A2. Monthly values of the PDO index from 1900-2012. Image from JISAO website.

El Niño/La Niña

The El Niño-Southern Oscillation is a coupled tropical atmospheric and ocean phenomenon that has extratropical influence over weather and oceanographic conditions. The Southern Oscillation is a quasi-periodic fluctuation in the atmospheric sea level pressure measured between Tahiti (central south Pacific) and Darwin, Australia. When atmospheric pressure is lower than normal over Tahiti and higher than normal at Darwin, the Southern Oscillation Index (departures from the mean difference) is negative and the normally easterly trade winds are reduced. This causes the warm water mass normally pushed to the western side of the Pacific Ocean to migrate towards South America. The occurrence of warm water off the coast of Peru is known as El Niño, and coincides with abnormally high coastal sea levels which suppress coastal upwelling and adversely affect marine biota through reduced deep water nutrient supply. Extratropical effects of El Niño include warmer ocean and air temperatures on the west coast of Canada, and more southern storm tracks. The opposite effect (a strengthening of the trade winds) results in La Niña conditions, which can result in colder air, more precipitation and a northward shift of the pacific storm track.

The impacts of El Niño/La Niña on sea levels off the coast of British Columbia can be significant. During the major El Niño years of 1982-83 and 1997-98, coastal sea level anomalies of 10-20 cm persisted for several months and contributed to a high occurrence of potentially damaging surges. La Niña can have the opposite effect (negative anomalies) but the anomalies are often more localized and of shorter duration. Figure A3 shows two images of residual sea surface height under both conditions.

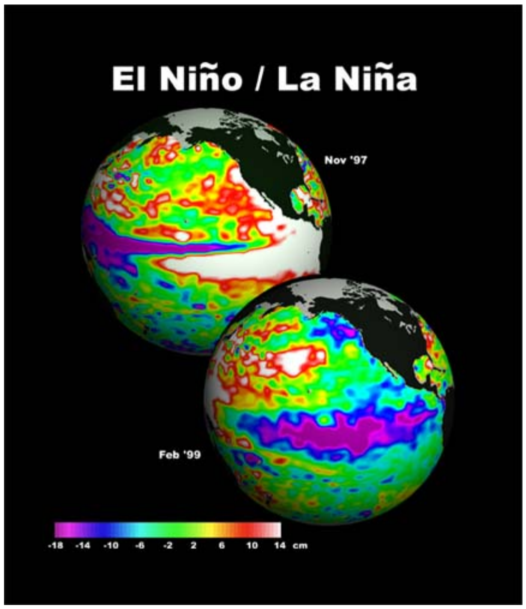

Figure A3. Residual sea surface height during the El Niño winter of 1997 and La Niña winter of 1999 (courtesy Jet Propulsion Laboratory). The positive SSH residual off the BC coast in 1997 is part of a larger feature stretching to the equator, while the negative SSH residual in 1999 is more localized. The magnitude of both is well in excess of 10 cm.

The Earth System Research Laboratory (ERSL) of the US National Oceanic and Atmospheric Administration produces a multi-variate ENSO index based on six oceanic and atmospheric variables: sea surface temperature, wind velocity components, sea level pressure, surface air temperature and cloudiness (Wolter and Timlin, 2011). The result is a monthly time series showing the interannual variability of ENSO strength (Fig. A4).

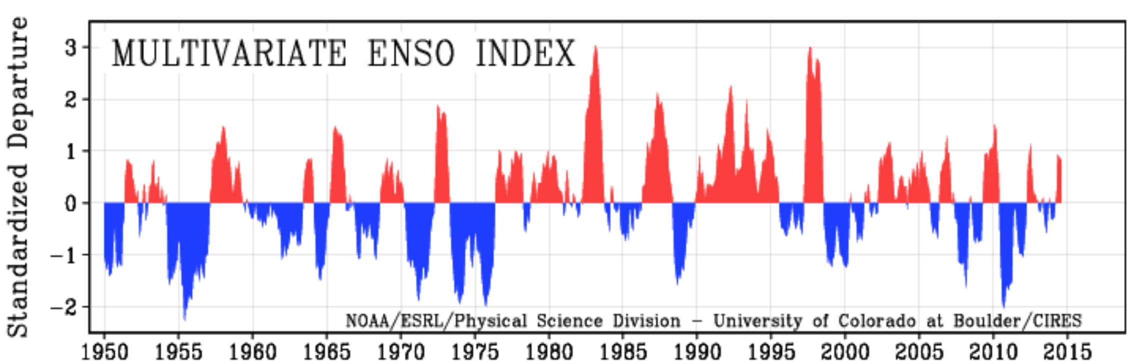

Figure A4. NOAA ERSL multivariate ENSO index from 1950 to present. Positive values indicate El Niño conditions, negative values indicate La Niña conditions.