BC Storm Surge Forecasting System

2016-17 Storm Surge Almanac

Climate outlook and tidal elevations for fall/winter 2016

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	PHONE	TWITTER	WEB
Author: Scott Tinis	250.886.5640	@SurgeBC	www.stormsurgebc.ca

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Executive Summary

The winter of 2015-16 was dominated by Elño-influenced weather, but the timing of storms rarely coincided with major high tides. One exception to this was very late in the season, when an early March storm arrived reminiscent of the February 2006 storm that caused damage in Boundary Bay. This storm was not well-characterized by weather models until 24 hours before landfall, and brought an 85 cm surge on top of a 4.70 m tide for the second highest total water level event recorded at Point Atkinson (March 10, 5.55 m). This year, developing La Niña conditions bring uncertainty to the general behaviour of weather for the upcoming winter season. Past La Niñas have bought a wide spectrum of conditions, ranging from persistent high-pressure (outflow winds) and cold weather (2008), to persistent onshore flows and repeated storms well into spring (1998-99). Table 1 shows the rank of maximum annual storm surges since 1997 at Point Atkinson out of the past 52 years; strong and weak La Niña phase appear both at the top and the bottom of the rankings.

Table 1. Rank of annual maximum storm surge at Point Atkinson (out of the past 52 years) for years since 1997 (current cold PDO regime). 1997 was inferred from other gauges due to missing data from the gauge. Year represents the start of the winter season.

Year	Rank (strength)	Surge (m)	ENSO Phase (red El Niño, blue La Niña)
1998	1	1.031	moderate-strong
2006	4	0.91	weak
2002	7	0.891	moderate
2015	8	0.85	very strong
2011	10	0.84	weak
2005	12	0.82	weak
2007	19	0.79	weak-moderate
2001	26	0.739	neutral
2009	28	0.72	moderate
2012	32	0.68	neutral

1997	35	0.655*	very strong
2010	37	0.65	moderate-strong
2004	43	0.571	weak
2003	44	0.571	weak
2013	48	0.549	weak
1999	49	0.533	strong
2000	50	0.455	weak
2008	52	0.44	moderate

Annual coastal flooding risk is greatest during the seasonal perigean spring tides, which generate extreme high tidal levels during the winter months. This winter (2016-17) the highest tides for the Lower Mainland are expected to occur at the mid-November, mid-December, and mid-January. For Victoria, the highest tides are expected mid- December and early to mid-January.

Early storms in October 2016 have already brought storm surges of 50-80 cm to British Columbia. The fall season looks to be dominated by the position of the north Pacific storm track, but may give way later in the season to arctic outflow depending on the influence of the developing La Niña in the equatorial Pacific Ocean.

The persistent 5-10 cm sea-surface height (SSH) anomaly off the west coast of British Columbia caused by “the Blob” of warm water in the northeast Pacific ocean was present over the summer, but appears to be diminishing into autumn. Current SSH anomalies are near zero.

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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 2016-17 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.

Disruptive weather systems have already begun to arrive on the south coast of BC. Between October 13th and 16th, three major storms brought tropical moisture and high winds, culminating with the re-emergence of the remnant of Typhoon Songda. Early forecasts were for extremely high winds and very low atmospheric pressure as the remnant reached the coastal waters. Ultimately, the final minimum pressure was measured at 974 mb and the storm was compact enough that wind damage and rain impacts were limited in scope. The peak surge at Point Atkinson was 70 cm, with secondary peaks of 50-60 cm and persistent high sea surface height anomalies present for several days during the event. None of the peak surges occurred during high tide, and tides were not yet approaching their winter season peaks.

The main factors that contribute to extreme water level are seasonal high tides ("king tides"), storm intensity (wind velocity and low atmospheric 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.

Pacific Decadal Oscillation

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 16 years, interrupted over the last two years by a major El Niño event. Recent strongly positive PDO values recorded between January 2014 and August 2016 are now beginning to retreat. **The current PDO index (as of September 2016) is 0.45.**

El Niño/Southern Oscillation

The NCEP Climate Prediction Center (CPC) provides regular updates of the state of ENSO in the Pacific Ocean. As of October 13, 2016, the ENSO alert system is on La Niña Watch. During the past El Niño event, the Multivariate ENSO Index (MEI) reached a peak of 2.53; **the current MEI level (as of September 2016) is -0.10.** Consensus model forecasts published by CPC (Fig. 1) all point to ENSO-neutral conditions with a 70% chance of La Niña developing during the Northern Hemisphere fall. The complete commentary is available at:

http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_oct2016/ensodisc.pdf

From the CPC commentary of October 13, 2016 (edited for space):

"ENSO-Neutral conditions were observed during September, with negative sea surface temperatures (SSTs) anomalies expanding across the eastern equatorial Pacific Ocean by early October (Fig. 1). All of the Niño regions cooled considerably during late September and early October, with the latest weekly value of Niño-3.4 index at -0.9°C (Fig. 2). […] The multi-model averages favor borderline Neutral-La Niña conditions (3-month average Niño- 3.4 index less than or equal to -0.5°C) persisting during the Northern Hemisphere fall and continuing into the winter (Figs. 6 and 7). Because of the recent cooling in the Niño-3.4 region and signs of renewed atmospheric coupling, the forecaster consensus now favors the formation of a weak La Niña in the near term, becoming less confident that La Niña will persist through the winter. In summary, La Niña is favored to develop (~70% chance) during the Northern Hemisphere fall 2016 and slightly favored to persist (~55% chance) during winter 2016"

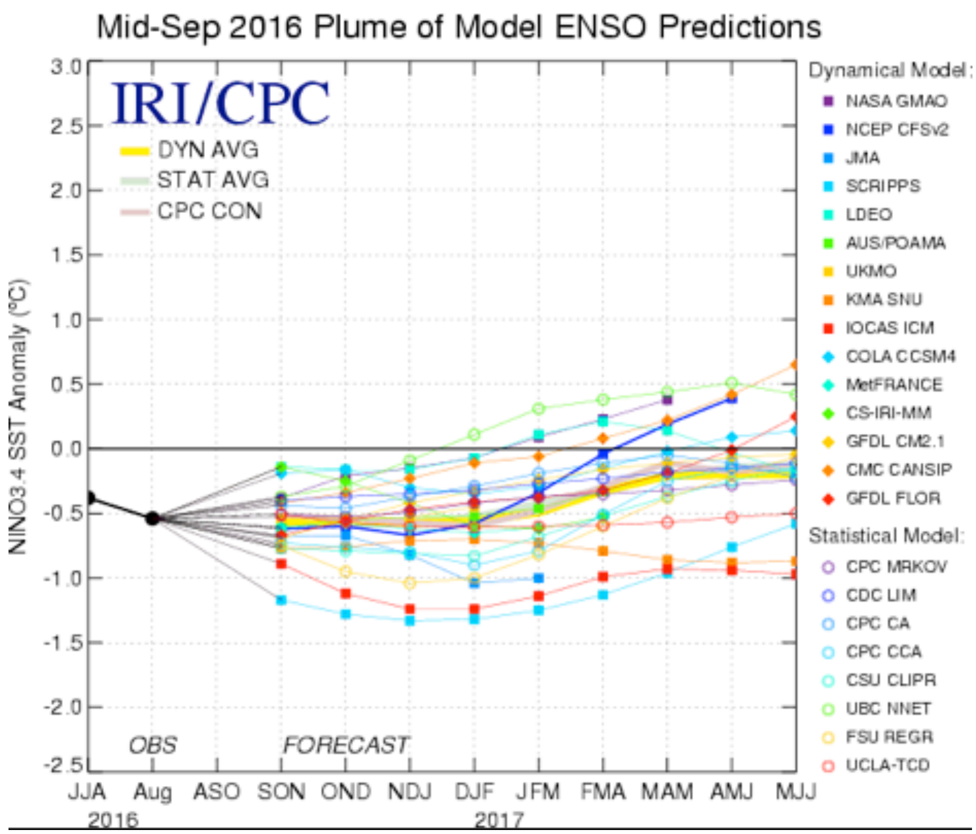

Figure 1: [CPC Figure 6] CPC numerical model consensus forecast for ENSO conditions for Fall 2016 to Spring 2017. The consensus is for a 70% chance of La Niña developing in the near term.

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 2).

Table 2: (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 2), 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.

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.

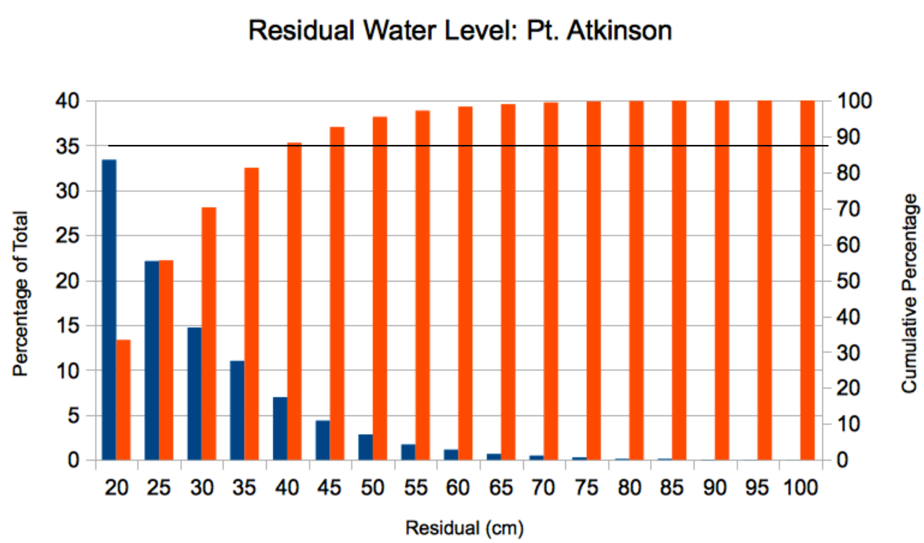

Figure 2. Residual water levels at Pt. Atkinson (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >45 cm lie within the 90th percentile (black line) of all residuals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

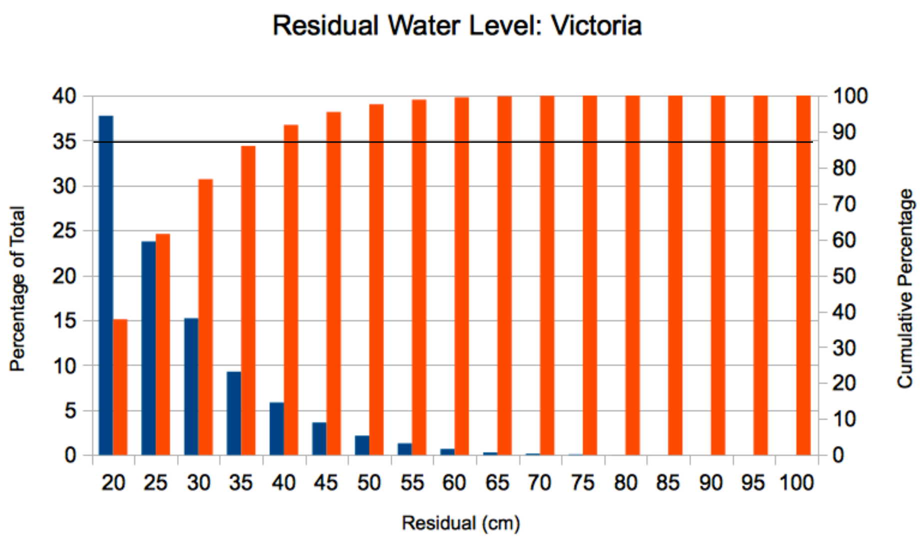

Figure 3. Residual water levels at Victoria (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >40 cm lie within the 90th percentile (black line) of all residuals >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 exceed 4.7 m relative to station datum at Point Atkinson; these periods offer broad windows during which a moderate or high 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 on November 17&18, and from December 14-19 and January 12-16 inclusive.

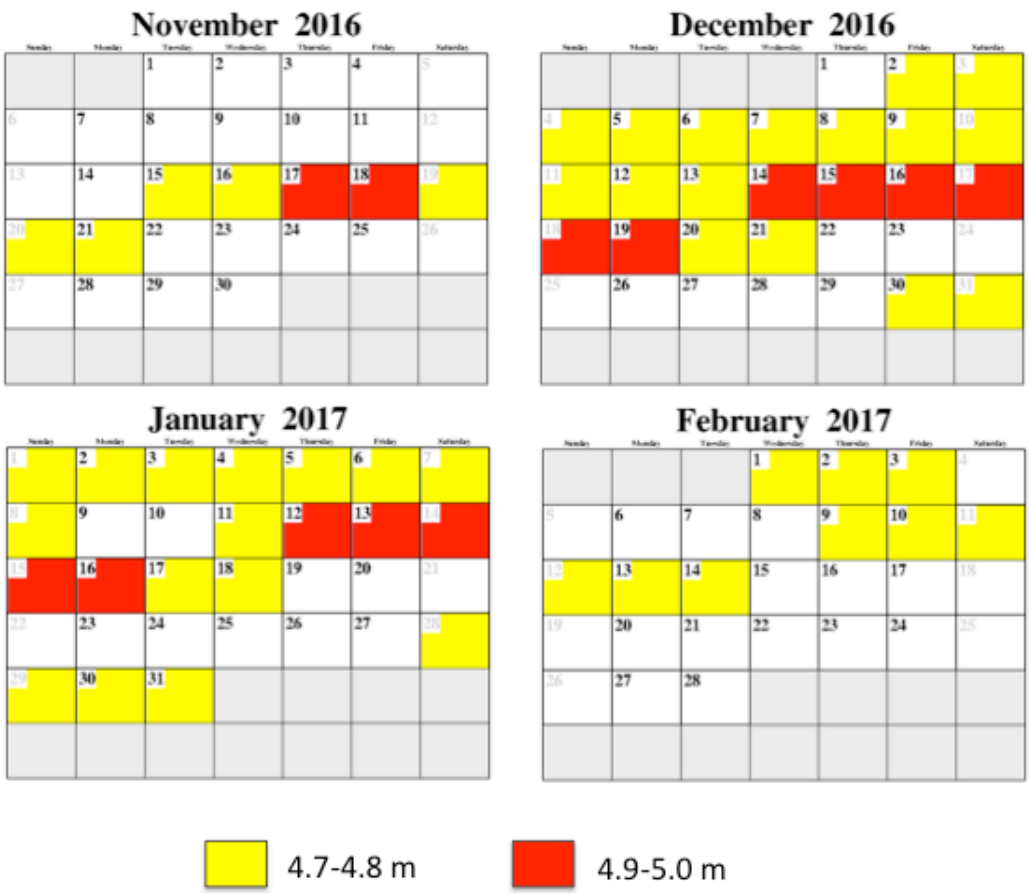

Figure 4. 2016-17 calendar dates for tides exceeding 4.7 m at Point Atkinson. The highest tides during this four month period occur mid-November, mid-December and mid-January.

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 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 2016-17), the highest predicted tides (>3.0 m) occur during December 11-15 and January 8-12.

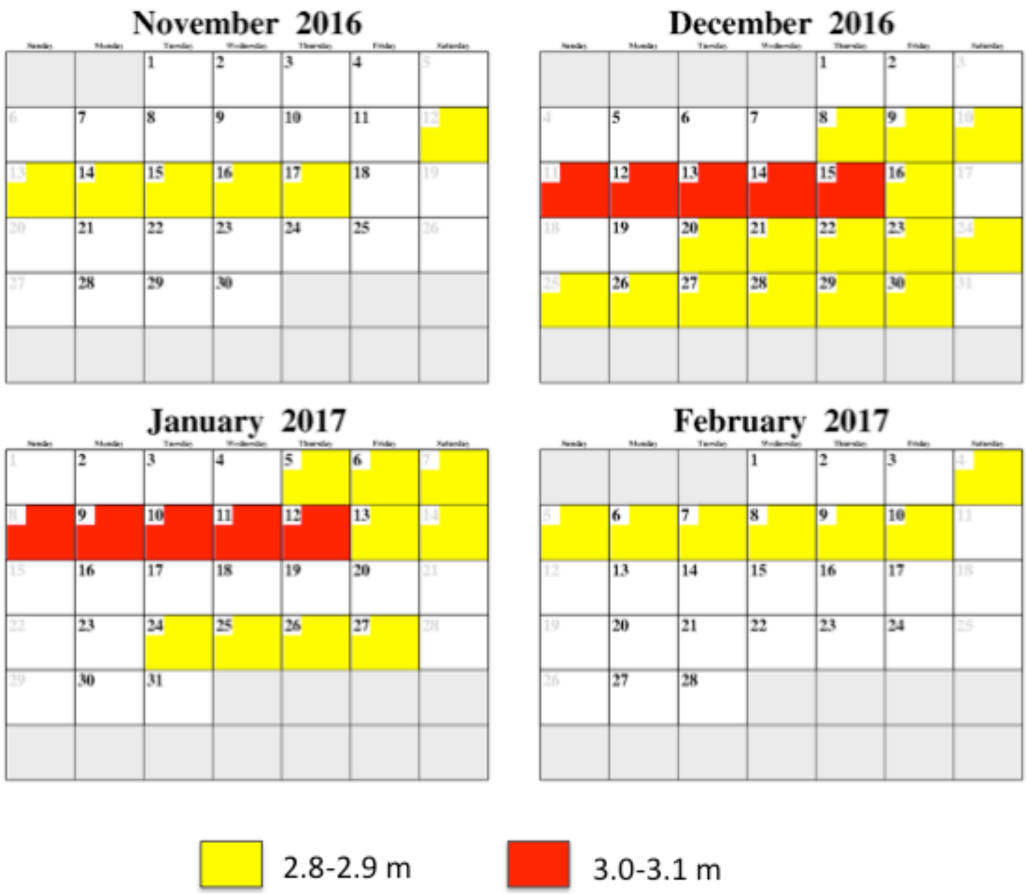

Figure 5. 2016-17 calendar dates for tides exceeding 2.8 m at Victoria. The highest tides during this four month period occur mid-December and in early January.

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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.

The El Niño event of 2015/16 is gradually dissipating and conditions are trending towards ENSO neutral. Equatorial SSH anomalies now clearly trending negative, consistent with ENSO neutral conditions. Positive SSH anomalies are still present in much of the tropical north Pacific, and some patches of positive SSH anomaly in the northeast Pacific. The moderate 5-10 cm anomalies still present off the British Columbia coast (Fig. 6) are likely from steric effects associated with the positive sea surface temperature anomaly observed over the same region.

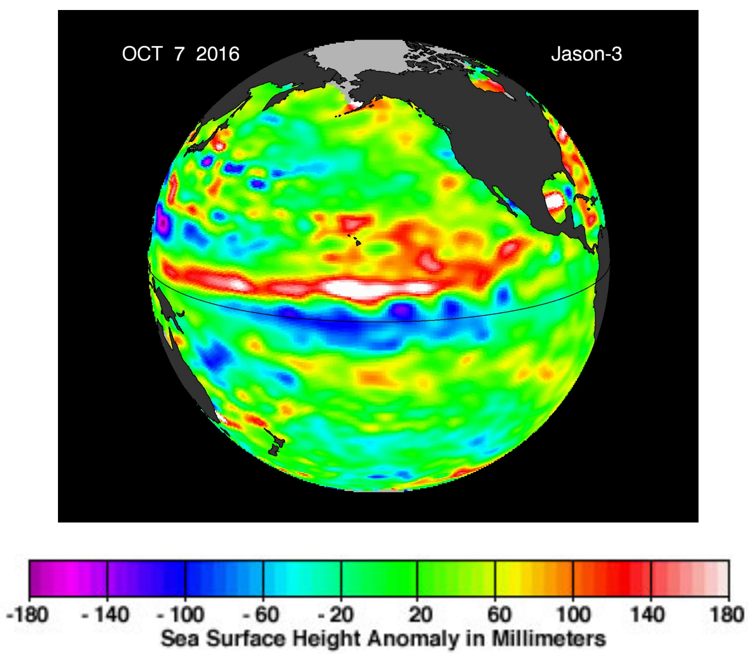

Figure 6. JPL image of 10-day averaged SSH anomalies over the Pacific Ocean on October 7, 2016. El Niño-influenced SSH anomalies have given way to slightly negative equatorial SSH anomalies consistent with ENSO-neutral conditions.

The seasonal (July-October) SST anomaly (Fig. 7) published by the Earth System Research Laboratory (ERSL/NOAA) shows positive temperature anomalies persisting in the northeast Pacific since July. However, the weekly anomlies in the same region (not shown) are not as clear.

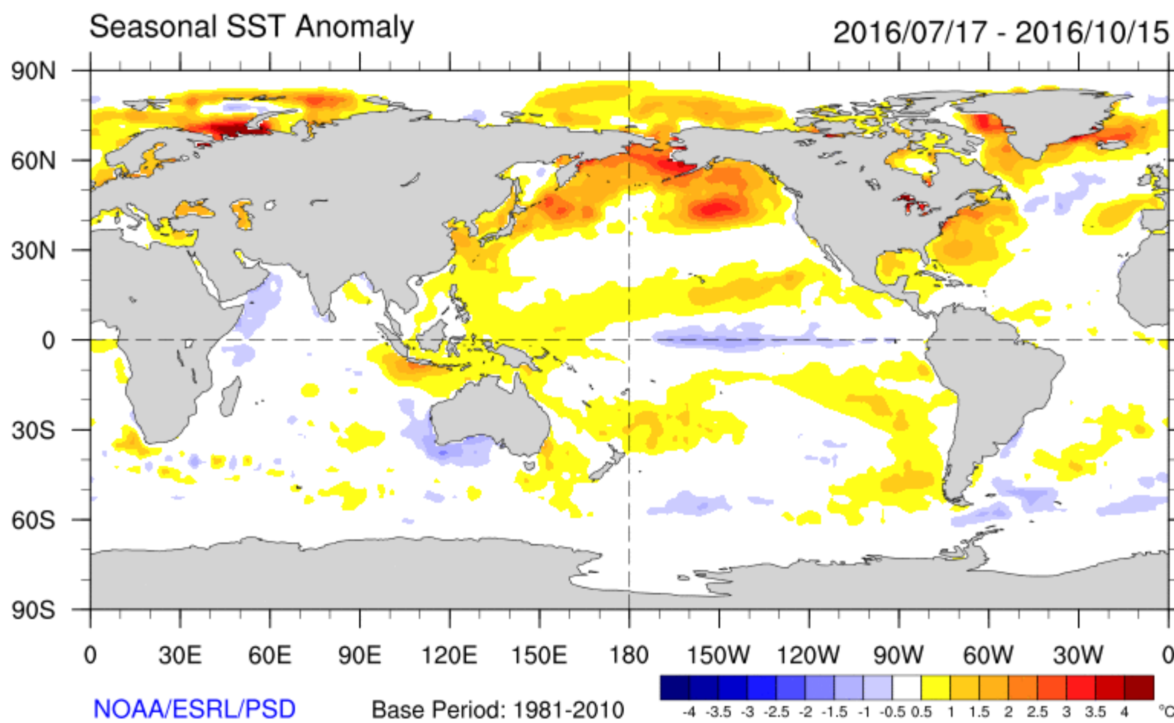

Figure 7. ERSL/NOAA seasonal SST anomaly for July 17-October 15, 2016.

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Summary

From the information available as of October 2016, the winter 2016-2017 storm season will be characterized by the following:

1. **ENSO**: The major El Niño of 2015/2016 is gradually giving way to ENSO neutral conditions. ENSO models are indicating that a La Niña may begin to develop early in 2017, but much uncertainty currently exists on both the strength of the impending La Niña and its expected impacts to the climate of western North America.
2. **PDO**: neutral and tending negative.
3. Peak tides **Victoria**: mid-December and early to mid-January
4. Peak tides **Vancouver:** mid-November, mid-December and mid-January.
5. **SSH anomalies**: Near zero.

Early indications are that the storm track is settling over southern British Columbia and the U.S. Pacific Northwest this Fall. Strong storms have already been seen, with surges up to 70 cm in the Strait of Georgia already realized. A short window of very high tides will appear in November for the Strait of Georgia, but the broader periods for both Victoria and the Lower Mainland/Strait of Georgia communities will be in mid-December and mid-January. Emerging La Niña conditions could bring a late-season change to conditions; however, while the La Niña of 1999 following the major El Niño of 1997 brought stormy wet conditions through the spring of 1999, the La Niña of 2008 brought very cold, predominantly high-pressure conditions.

References

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Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham and J. M. Oberhuber, 1994. The 1976-77 climate shift of the Pacific Ocean. *Oceanography*, 7, 21-26

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.

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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.

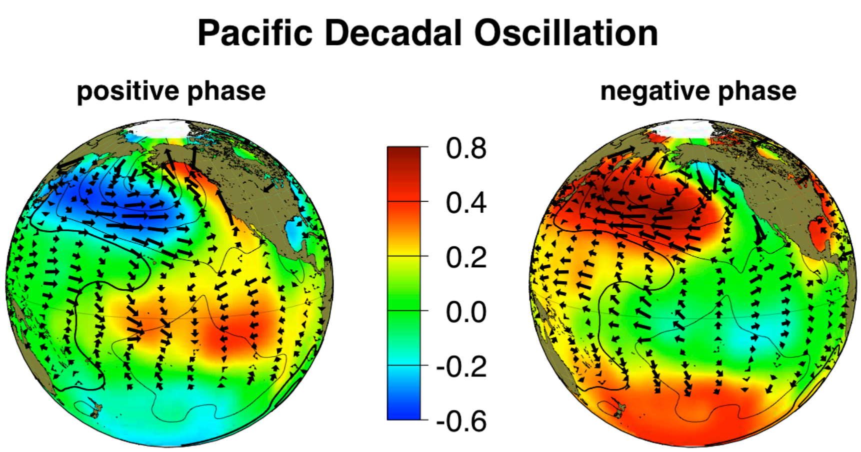

Figure A1. PDO warm and cool phases of sea surface temperature anomaly and associated wind anomaly patterns. Web image from Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington.

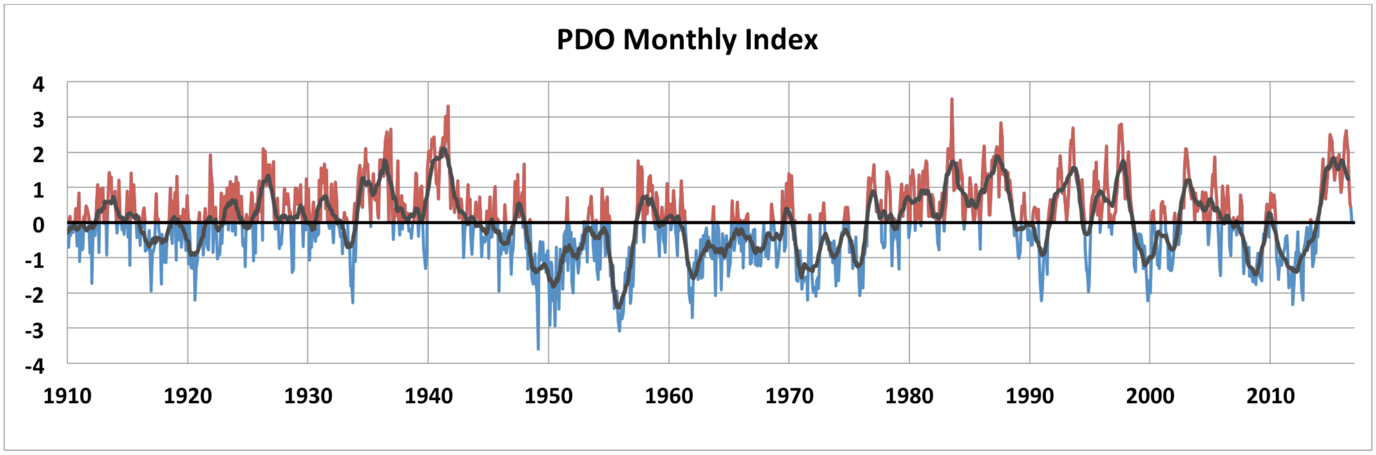

Figure A2. Monthly values of the PDO index from 1910-2016.

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.

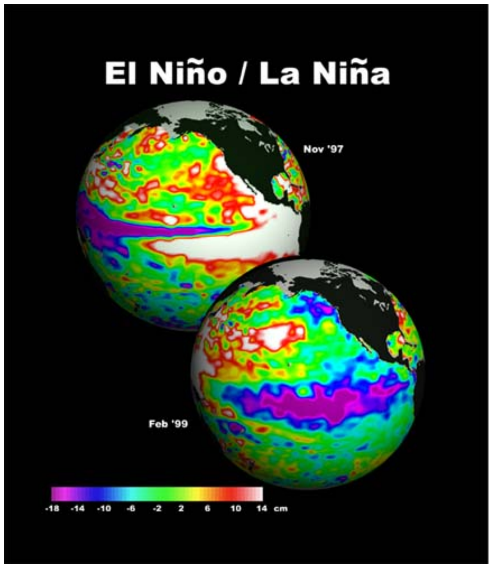

Figure A3. Residual sea surface height during the El Niño winter of 1997 and La Niña winter of 1999 (courtesy Jet Propulsion Laboratory). The positive SSH residual off the BC coast in 1997 is part of a larger feature stretching to the equator, while the negative SSH residual in 1999 is more localized.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

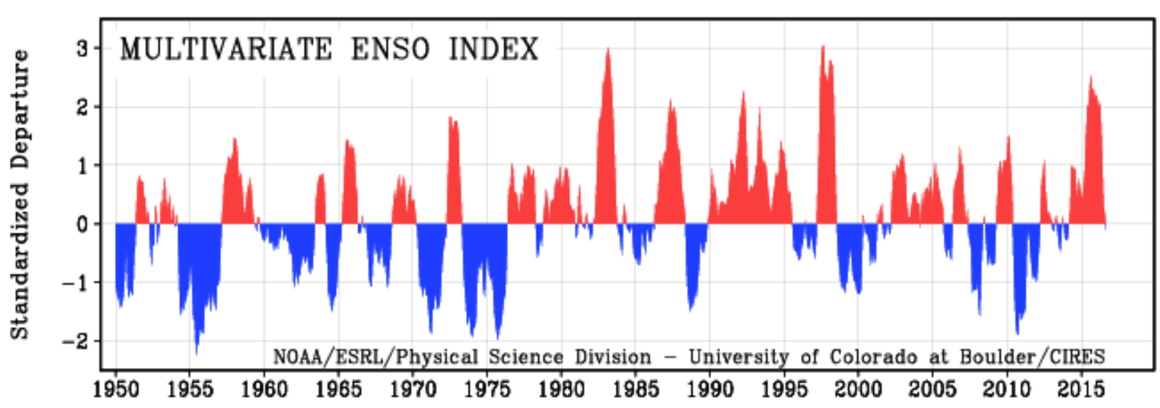

Figure A4. NOAA ERSL multivariate ENSO index from 1950 to present. Positive values indicate El Niño conditions, negative values indicate La Niña conditions.