BC Storm Surge Forecasting System

2017-18 Storm Surge Almanac

Climate outlook and tidal elevations for fall/winter 2017

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Executive Summary

The 2016-17 storm surge season was characterized by a series of intense storms in October, intermittent storms through November and the onset of arctic outflow conditions from December to the latter part of February. Intensifying La Niña conditions caused a gradual southward shift of the jet stream which focused the majority of onshore wind and moisture to the west coast of the United States (anomalously high rain and snowfall in northern California was significant enough to alleviate much of the drought condition accumulated over the past several years). **The 2017-18 season is currently experiencing ENSO neutral conditions in the equatorial Pacific Ocean, but is on a La Niña watch.**

On October 14, 2016, the remnant of typhoon Songda reached the BC coast and re-energized as it reached coastal waters bringing high winds and heavy precipitation. Two separate systems followed in Songda's wake within 48 hours. The three systems brought three out of the six highest atmospheric-induced sea surface anomalies of the entire season. While other significant weather systems occurred in early January and February, none of the systems arrived during spring tide, and consequently the highest total water level (TWL) (5.21 m on October 14) ranked in the bottom third of all TWL measurements in the last 54 years. As of the preparation of this almanac, a fall transition is underway along the BC coast with a series of storms that are bringing heavy precipitation but only moderate winds. **Similarities between ENSO conditions of last year and this year suggest that a similar storm season may be expected this winter.**

Table 1 shows the rank of maximum annual storm surges since 1997 at Point Atkinson out of the past 53 years; strong and weak La Niña phase appear both at the top and the bottom of the rankings. Note that although total water levels in 2016-17 ranked in the bottom third, the peak surge of 0.85 m ranked 9th out of the last 53 years, and 5th out of the last 20 years. It's important to note that strong surges can occur during any ENSO phase, and the most important variable is when they occur.

Table 1. Rank of annual maximum storm surge at Point Atkinson (out of the past 53 years) for years since 1997 (current cold PDO regime). 1997 was inferred from other gauges due to missing data from the gauge. Reference year represents the year at the start of the winter season.

Year	Rank (strength)	Surge (m)	ENSO Phase (red El Nino, blue La Nina)
1998	1	1.031	🟦 moderate-strong
2006	4	0.91	🟦 weak
2002	7	0.891	🟥 moderate
2015	8	0.85	🟥 very strong
2016	9	0.85	🟦 moderate
2011	10	0.84	🟦 weak
2005	13	0.82	🟦 weak
2007	20	0.79	🟥 weak-moderate
2001	27	0.739	🟦 neutral
2009	29	0.72	🟥 moderate
2012	33	0.68	🟥 neutral
1997	36	0.655	🟥 very strong*
2010	38	0.65	🟦 moderate-strong
2004	44	0.571	🟥 weak
2003	45	0.571	🟦 weak
2013	49	0.549	🟦 weak
1999	50	0.533	🟦 strong
2000	51	0.455	🟦 weak
2008	53	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 (2017-18) the highest tides for the Lower Mainland occur in the first weeks of December, January and February. For Victoria, the highest tides occur during the first and last weeks of both December and January.

Early storms in October 2017 have already brought some wind and moderate to heavy precipitation, but storm surges of only 30-40 cm to British Columbia. The north Pacific storm track is starting to establish itself over the central coast, 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, as it did in 2016.

The Pacific Decadal Oscillation is declining to near zero for the first time since 2014. Current coastal sea surface height (SSH) anomalies are near zero.

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Overview

This document provides a summary of the current and expected meteorological and oceanographic conditions for southern British Columbia as they relate to the 2017-18 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.

Typical fall weather systems have already begun to arrive on the south coast of BC, bringing moderate winds and heavy precipitation. Due to the very dry conditions experienced over the summer, water levels many watersheds and reservoirs are below normal. Storm surge can be a confounding factor during many late-fall and winter storms when hydro reservoir levels are near capacity. The additional barrier of high tide and surge at the mouth of rivers can adversely influence the ability to shed water at the time when discharge is most required.

The main factors that contribute to extreme marine coastal water levels 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.

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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)(Table 2). 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.

Table 2. Monthly Pacific Decadal Oscillation (PDO) and multi-variate ENSO index values from 2013-present.

Year	**2013**		**2014**		**2015**		**2016**		**2017**	
Index	PDO	ENSO	PDO	ENSO	PDO	ENSO	PDO	ENSO	PDO	ENSO
Jan	-0.13	0.10	0.30	-0.28	2.45	0.42	1.53	2.23	0.77	-0.06
Feb	-0.43	-0.08	0.38	-0.27	2.30	0.46	1.75	2.17	0.70	-0.06
Mar	-0.63	-0.13	0.97	0.03	2.00	0.67	2.40	1.96	0.74	-0.08
Apr	-0.16	0.07	1.13	0.25	1.44	0.97	2.62	2.07	1.12	0.77
May	0.08	0.15	1.80	0.98	1.20	1.58	2.35	1.70	0.88	1.46
Jun	-0.78	-0.17	0.82	0.98	1.54	2.05	2.03	1.00	0.79	1.05
Jul	-1.25	-0.36	0.70	0.88	1.84	1.95	1.25	0.31	0.10	0.46
Aug	-1.04	-0.48	0.67	0.95	1.56	2.37	0.52	0.18	0.09	0.03
Sep	-0.48	-0.13	1.08	0.59	1.94	2.53	0.45	-0.10	0.32	-0.45
Oct	-0.87	0.13	1.49	0.44	1.47	2.24	0.56	-0.38		
Nov	-0.11	-0.05	1.72	0.76	0.86	2.30	1.88	-0.21		
Dec	-0.41	-0.25	2.51	0.56	1.01	2.11	1.17	-0.12		

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 few years by a major El Niño event. Recent Strongly positive PDO values recorded between January 2014 and July 2016 retreated for a while last fall, but were resurgent throughout the winter and spring of 2017. The index is again in retreat: **the current PDO index (as of September 2017) is 0.32.**

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 12, 2017, 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 2017) is -0.45.** Consensus model forecasts published by CPC (Fig. 1) all point to ENSO-neutral conditions with a 55-65% 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_advisory/ensodisc.pdf

From the CPC commentary of October 12, 2017 (edited for space):

"During September, ENSO-neutral conditions were reflected in near-to-below average sea surface temperatures (SSTs) across most of the central and eastern Pacific Ocean …. The weekly Niño indices were volatile during the month, with negative values increasing to near zero during the past week in the Niño-4, Niño-3.4, and Niño-3 regions … . […] Overall, the ocean and atmosphere system remains consistent with ENSO-neutral, although edging closer to La Niña conditions."

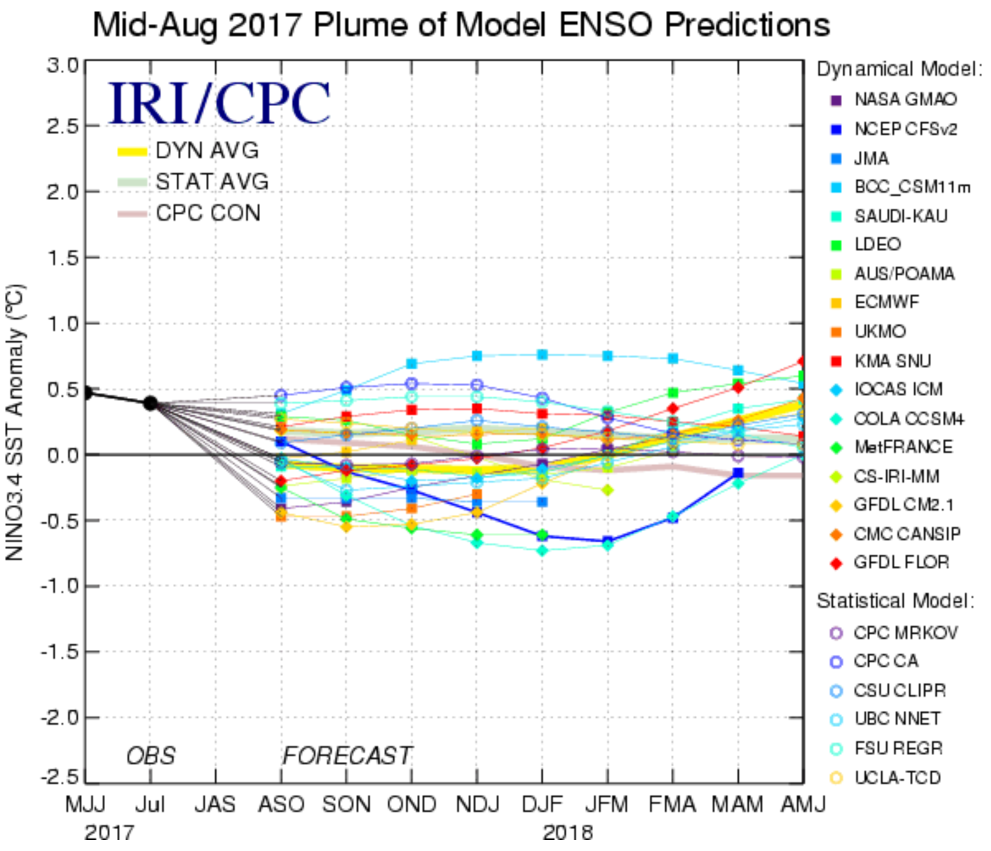

Figure 1: [CPC Figure 6] CPC numerical model consensus forecast for ENSO conditions for Fall 2017 to Spring 2018. The consensus is for a 55-65%% chance of La Niña developing in the northern hemisphere winter.

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 3).

Table 3: (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. **Winter 2017-18 is projected to be a weak/moderate La Niña, one of the more storm-active categories.**

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.

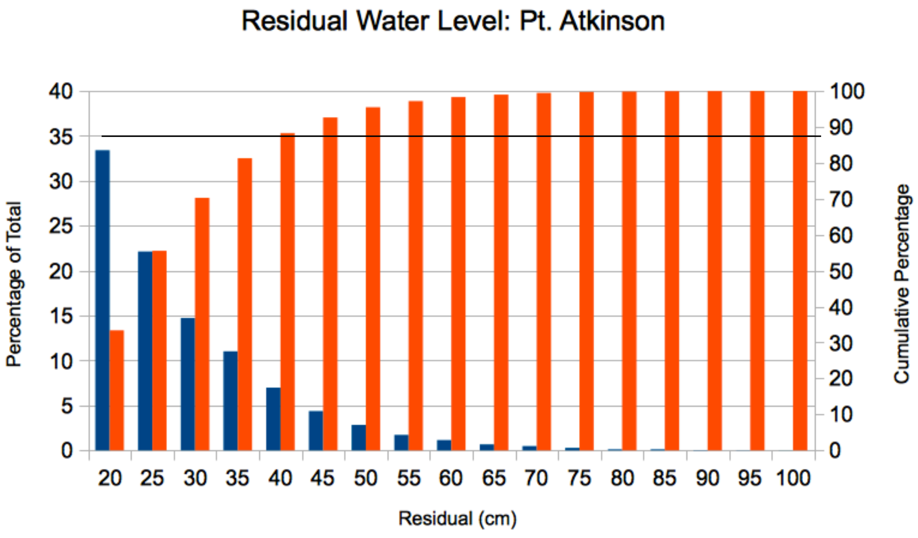

Figure 2. Residual water levels at Pt. Atkinson (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >45 cm lie within the 90th percentile (black line) of all residuals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

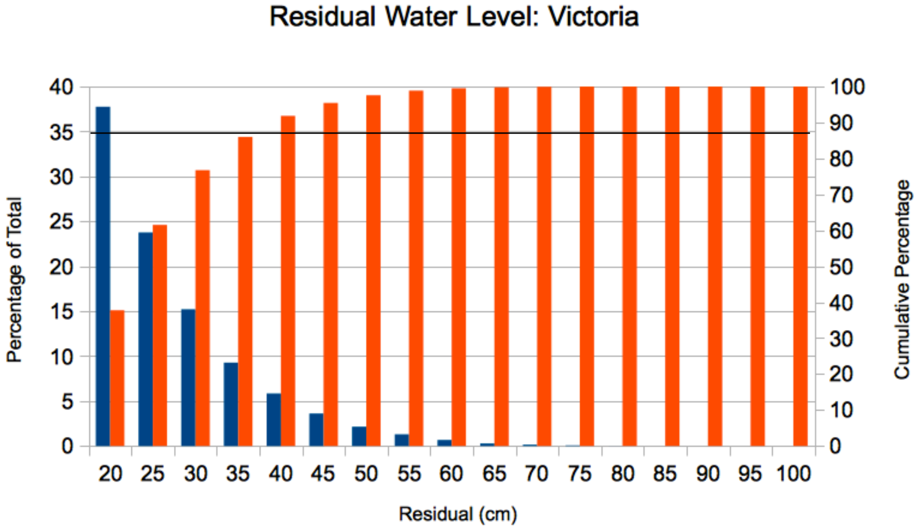

Figure 3. Residual water levels at Victoria (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >40 cm lie within the 90th percentile (black line) of all residuals >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 from December 5-9, January 2-7 and February 1-4**.

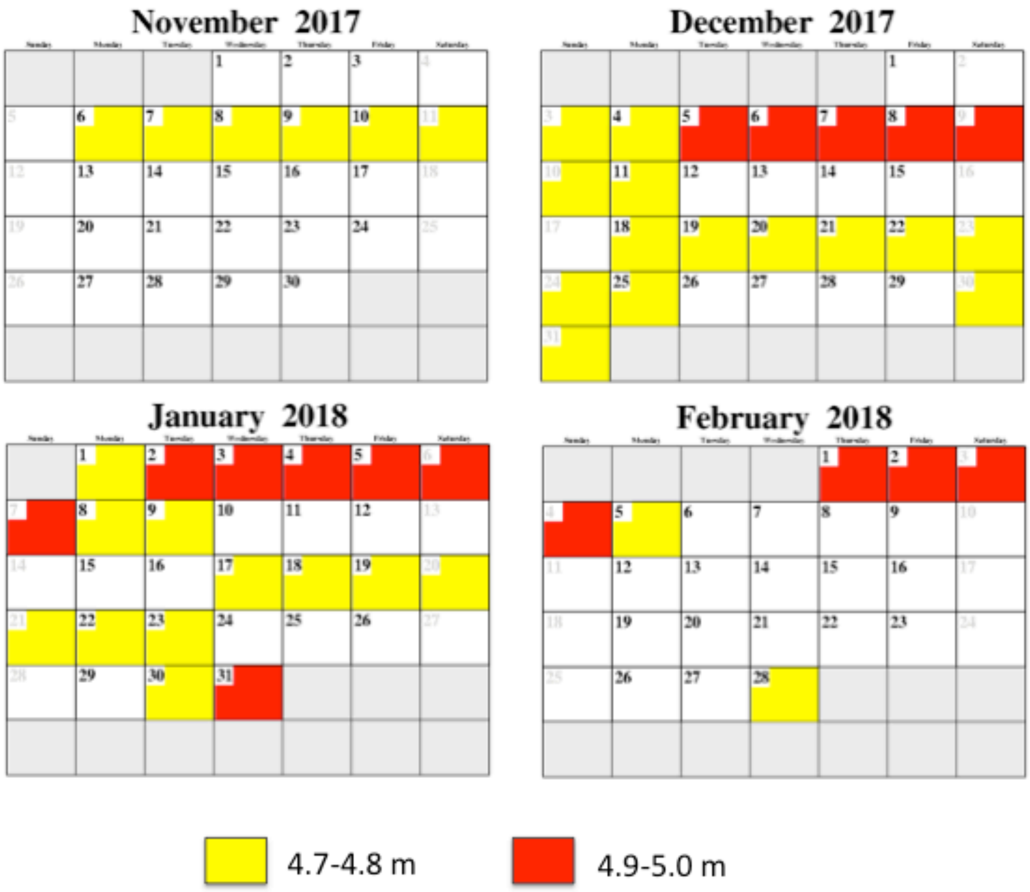

Figure 4. 2017-18 calendar dates for tides exceeding 4.7 m at Point Atkinson. The highest tides during this four month period occur in the first weeks of December, January and February.

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, **the highest predicted tides (>3.0 m) occur during December 2-5, December 30-January 3, and January 28-31**.

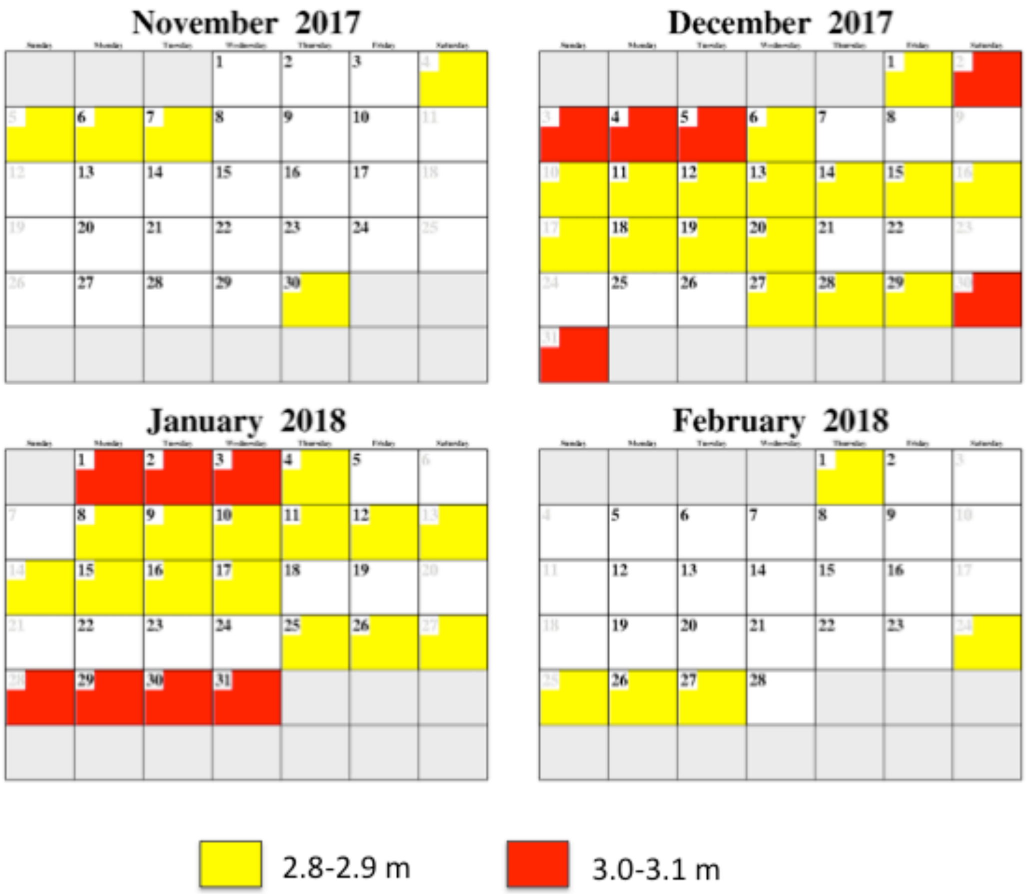

Figure 5. 2017-18 calendar dates for tides exceeding 2.8 m at Victoria. The highest tides during this four month period occur in the first and last weeks of December and January.

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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 La Niña conditions of 2016-17 retreated in summer 2017, trending towards ENSO neutral. Equatorial SSH anomalies are once again trending negative, consistent with ENSO neutral conditions. Patches of negative SSH anomalies are still visible in the extra-tropical northeast Pacific but anomalies are near zero all along the North American west coast (Fig. 6).

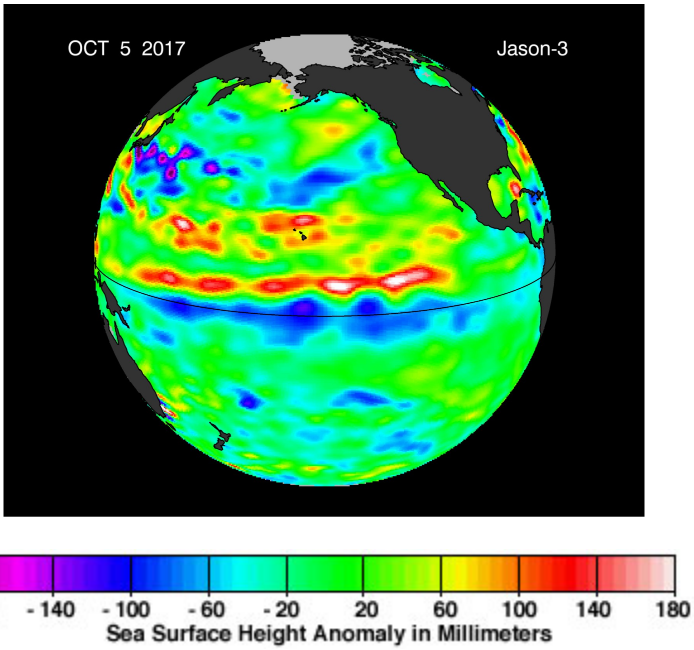

Figure 6. JPL image of 10-day averaged SSH anomalies over the Pacific Ocean on October 5, 2017. SSH Anomalies are consistent with ENSO-neutral conditions.

The seasonal (July-October) SST anomaly (Fig. 7) published by the Earth System Research Laboratory (ERSL/NOAA) shows slightly positive temperature anomalies persisting in the northeast Pacific. Compared to the same period in 2016, the SST anomarlies along the west coast of British Columbia are lower, which is consistent with the trend in the PDO index (from positive towards zero).

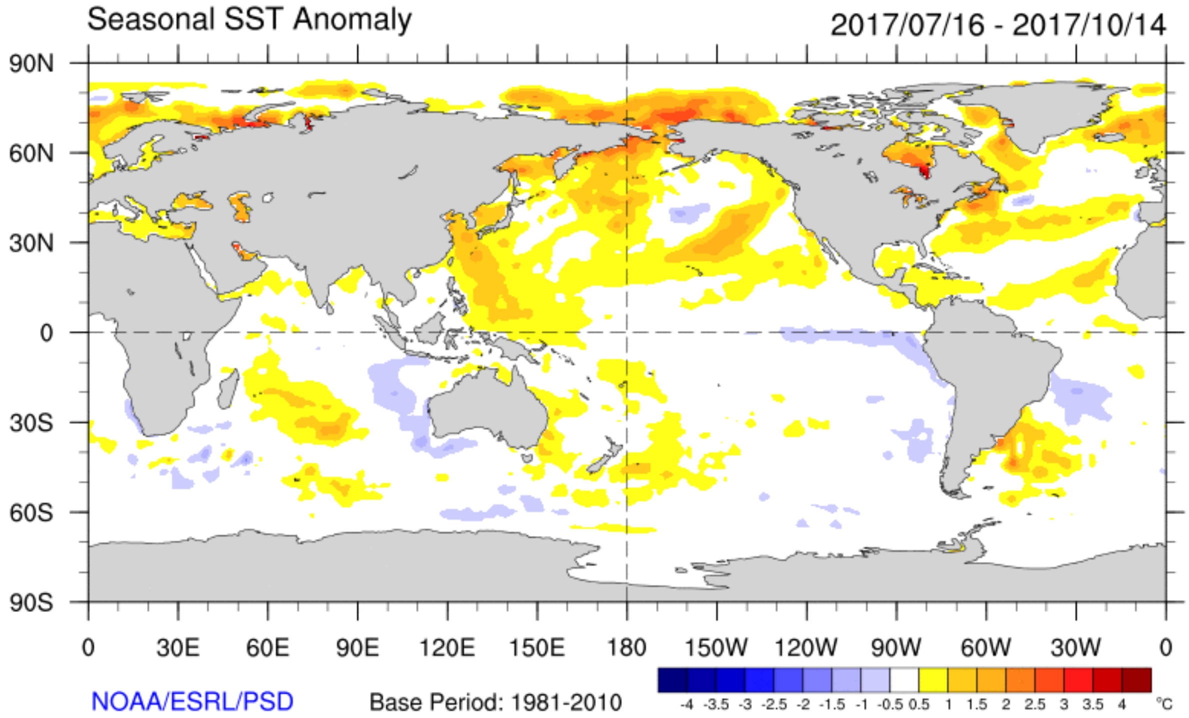

Figure 7. ERSL/NOAA seasonal SST anomaly for July 16-October 14, 2017.

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Summary

From the information available as of October 2017, the winter 2017-18 storm season will be characterized by the following:

1. **ENSO**: La Niña may re-develop early in 2018, 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**: December 2-5, December 30-January 3, and January 28-31.
4. Peak tides **Vancouver:** December 5-9, January 2-7 and February 1-4.
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. A series of moderate storms has marked the fall transition, with surges between 30-40 cm in the Strait of Georgia and around the southern and western shores of Vancouver Island. Seasonal high tides will not appear until December for all areas of the south coast. Emerging La Niña conditions last year brought a late-season change the south coast winter conditions when arctic outflow began to dominate the weather, interspersed with onshore flow from storms. This mixture brought an unusually large number of snowfall days to the region, and limited the number of days with high total water levels. Should this occur again, December will mark the period of highest risk of extreme total water levels, prior to a general shift to more arctic-dominated weather.

References

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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.

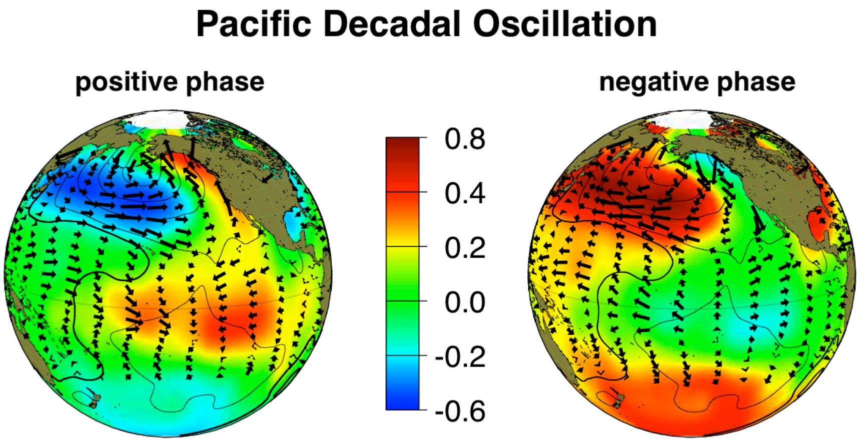

Figure A1. PDO warm and cool phases of sea surface temperature anomaly and associated wind anomaly patterns. Web image from Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington.

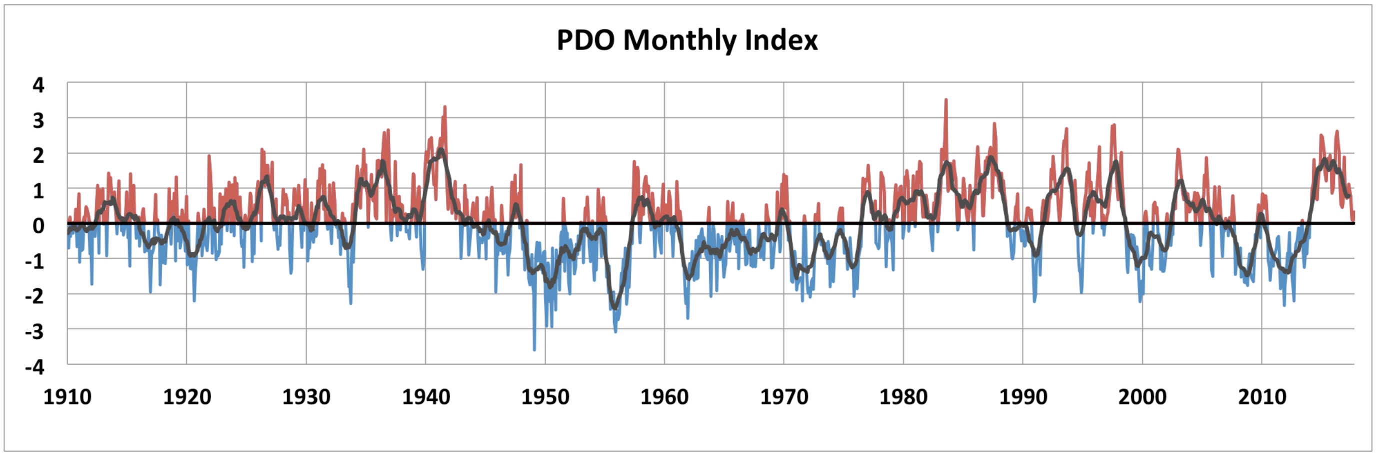

Figure A2. Monthly values of the PDO index from 1910-2017

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.

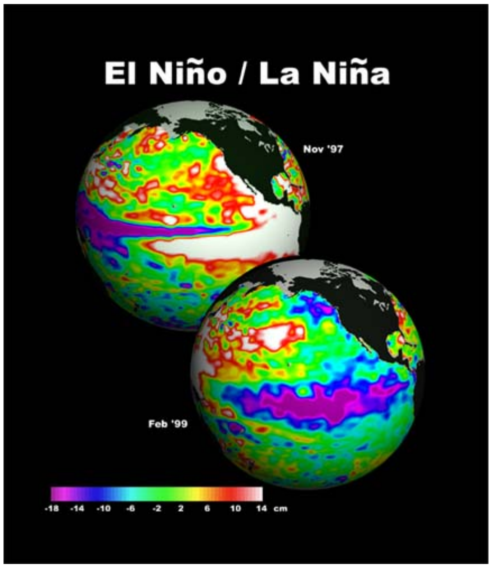

Figure A3. Residual sea surface height during the El Niño winter of 1997 and La Niña winter of 1999 (courtesy Jet Propulsion Laboratory). The positive SSH residual off the BC coast in 1997 is part of a larger feature stretching to the equator, while the negative SSH residual in 1999 is more localized.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

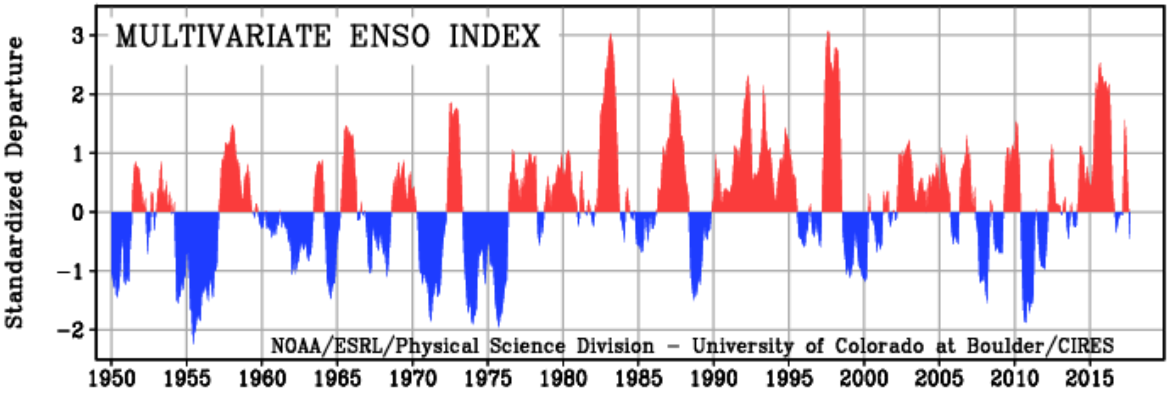

Figure A4. NOAA ERSL multivariate ENSO index from 1950 to present. Positive values indicate El Niño conditions, negative values indicate La Niña conditions.