BC Storm Surge Forecasting System

2018-19 Storm Surge Almanac

Climate outlook and tidal elevations for fall/winter 2018

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Executive Summary

The 2017-18 storm surge season began with a series of storms and atmospheric river events in October and November, followed by the onset of arctic outflow conditions from December to the latter part of February. Large meridional meanders in the jet stream brought distinctly northerly and southerly weather to the south coast of BC, which is a departure from our normal westerly and south-westerly weather patterns. Arctic outbreak conditions were felt all over North America last winter as a result of the meandering jet stream. The weather last year was characteristic of moderate La Nina conditions in the Pacific basin. **The 2018-19 season is currently expected to transition to El Nino conditions during the fall of 2018.**

Last year marked a very muted storm surge season due in part to the overlap of strong arctic air masses suppressing local sea levels during the periods of seasonal high tides. The strongest meteorologically-generated surge measured only 55 cm which ranked 50th of the last 55 years with a 1.1 year return period (Table 1). As of the preparation of this almanac, the blocking-high pressure system that has given the south coast dry clear and warm weather from the last week in September to mid-October is slowly giving way to more unsettled weather. **Developing El Nino conditions are likely bring more of the westerly storm systems that are characteristic of ENSO positive winters on the south coast.**

The north Pacific storm track is slowly starting to establish itself over the central coast, and is anticipated to bring more westerly weather due to the onset of El Nino conditions in the equatorial Pacific. Anomalously warm surface water in the north Pacific may also contribute to storm energy early in fall/winter, but may also disappear as increasing winds mix the upper ocean.

The Pacific Decadal Oscillation is hovering near zero for the first time since 2014. Current coastal sea surface height (SSH) anomalies are near zero at the coast, but somewhat elevated offshore and are likely related to the anomalously warm surface waters in the north Pacific.

Annual coastal flooding risk is greatest during the seasonal perigean spring tides, which generate extreme high tidal levels during the winter months. This winter (2018-19) the highest tides for the Lower Mainland occur in the final weeks of November, December, January and February. For Victoria, the highest tides begin during the third weeks of December and January.

Table 1. Rank of annual maximum storm surge at Point Atkinson (out of the past 55 years) ***for years since 1997*** *(current cold PDO regime). Reference year represents the year at the start of the winter season.*

Year	Rank (out of last 55 years)	Surge (m)	ENSO Phase (red El Nino, blue La Nina)
1998	1	1.03	moderate-strong
2015	3	0.95	very strong
2006	5	0.91	weak
2002	8	0.89	moderate
2016	9	0.85	moderate
2011	11	0.84	weak
2005	14	0.82	weak
2007	20	0.79	weak-moderate
2014	24	0.77	moderate
2001	27	0.74	neutral
2009	30	0.72	moderate
2012	34	0.68	neutral
1997	36	0.66	very strong*
2010	39	0.65	moderate-strong
2003	45	0.57	weak
2004	46	0.57	weak
2017	50	0.55	weak
2013	51	0.55	weak
1999	52	0.53	strong
2000	53	0.46	weak
2008	55	0.44	moderate

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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 2018-19 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 are beginning 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.

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 2014-present.

Year	**2014**		**2015**		**2016**		**2017**		**2018**	
Index	PDO	ENSO	PDO	ENSO	PDO	ENSO	PDO	ENSO	PDO	ENSO
Jan	0.30	-0.28	2.45	0.42	1.53	2.23	0.77	-0.06	0.70	-0.62
Feb	0.38	-0.27	2.30	0.46	1.75	2.17	0.70	-0.06	0.37	-0.73
Mar	0.97	0.03	2.00	0.67	2.40	1.96	0.74	-0.08	-0.05	-0.50
Apr	1.13	0.25	1.44	0.97	2.62	2.07	1.12	0.77	0.11	-0.43
May	1.80	0.98	1.20	1.58	2.35	1.70	0.88	1.46	0.11	0.47
Jun	0.82	0.98	1.54	2.05	2.03	1.00	0.79	1.05	-0.04	0.47
Jul	0.70	0.88	1.84	1.95	1.25	0.31	0.10	0.46	0.11	0.08
Aug	0.67	0.95	1.56	2.37	0.52	0.18	0.09	0.03	0.18	0.13
Sep	1.08	0.59	1.94	2.53	0.45	-0.10	0.32	-0.45	0.09	0.51
Oct	1.49	0.44	1.47	2.24	0.56	-0.38	0.05	-0.55		
Nov	1.72	0.76	0.86	2.30	1.88	-0.21	0.15	-0.28		
Dec	2.51	0.56	1.01	2.11	1.17	-0.12	0.50	-0.58		

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, and remained only slightly positive throughout the winter and spring of 2018. The index is currently hovering near zero: **the PDO index as of September 2018 is 0.09.**

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 (2015), the Multivariate ENSO Index (MEI) reached a peak of 2.53; **the current MEI level (as of September 2018) is 0.51.** Consensus model forecasts published by

CPC (Fig. 1) suggest strengthening positive ENSO indices with a 70-75% chance of El Niño 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 11, 2018 (edited for space):

"ENSO-neutral continued during September, but with increasingly more widespread regions of above-average sea surface temperatures (SSTs) across the equatorial Pacific Ocean []. Over the last month, all four Niño index values increased, with the latest weekly values in each region near +0.7°C []. Positive subsurface temperature anomalies (averaged across 180°-100°W) also increased during the last month [], due to the expansion and strengthening of above-average temperatures at depth across the equatorial Pacific []. […] Overall, the oceanic and atmospheric conditions reflected ENSO-neutral, but with recent trends indicative of a developing El Niño.

The majority of models in the IRI/CPC plume predict El Niño to form during the fall and continue through the winter []. The official forecast favors the formation of a weak El Niño, consistent with the recent strengthening of westerly wind anomalies and positive temperature trends in the surface and subsurface ocean. In summary, El Niño is favored to form in the next couple of months and continue through the Northern Hemisphere winter 2018-19"

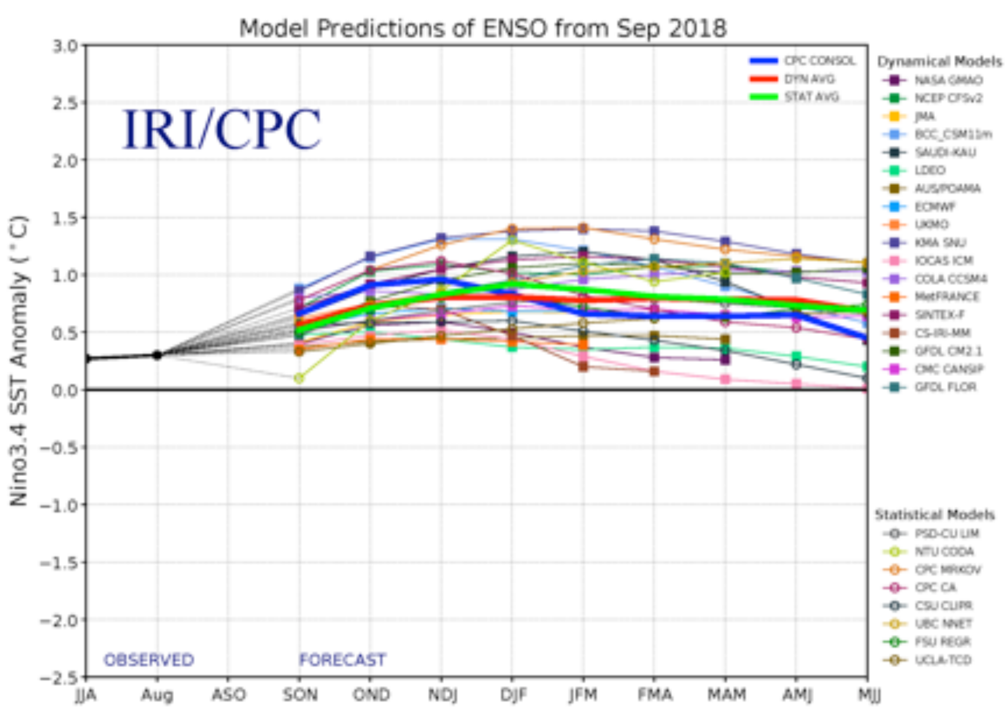

Figure 1: [CPC Figure 6] CPC numerical model consensus forecast for ENSO conditions for Fall 2018 to Spring 2019. The consensus is for a 70-75% chance of El Niño developing in the northern hemisphere winter.

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 2018-19 is under El Niño watch.**

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.

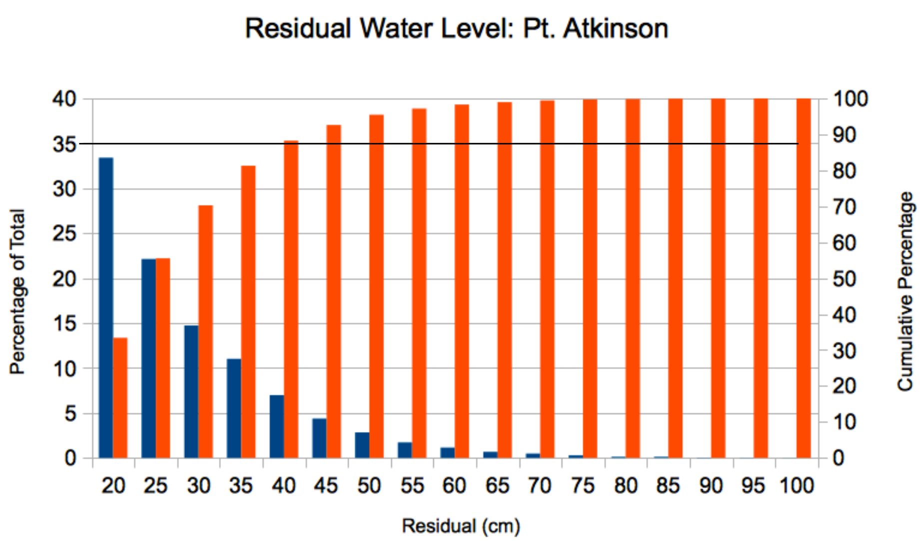

Figure 2. Residual water levels at Pt. Atkinson (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >45 cm lie within the 90th percentile (black line) of all residuals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

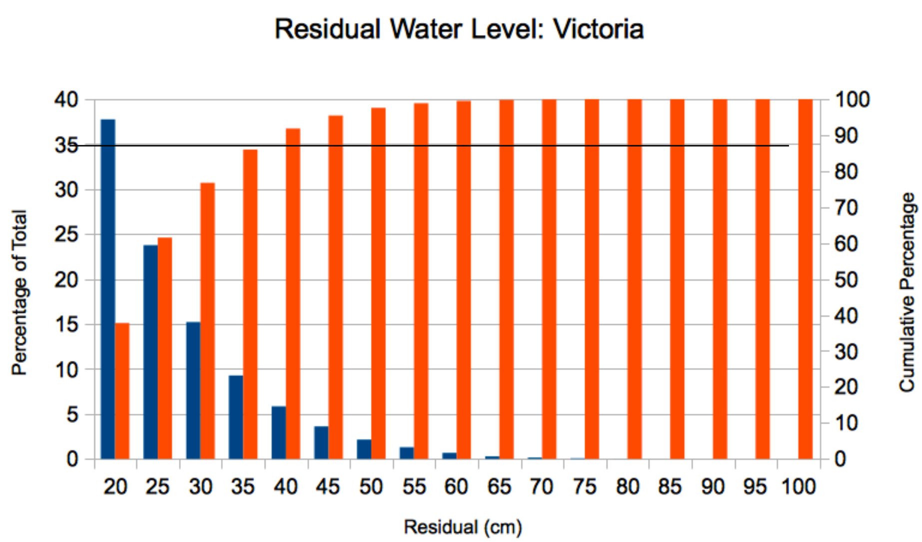

Figure 3. Residual water levels at Victoria (>20 cm) in 5-cm bins as a percentage of the total number of residuals >20 cm (blue) based on hourly observations. The cumulative percentage at each bin level is shown in orange. Residuals >40 cm lie within the 90th percentile (black line) of all residuals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

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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 November 27-28, December 24-29, January 21-26 and February 21**.

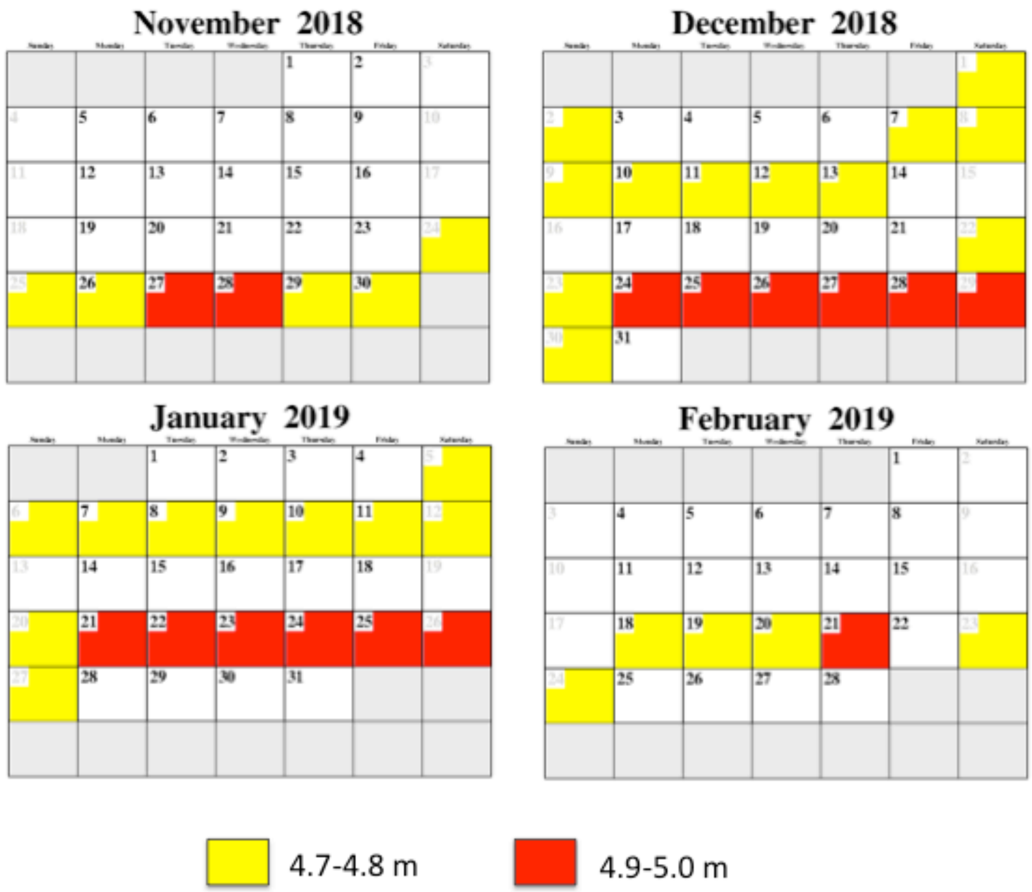

Figure 4. 2018-19 calendar dates for tides exceeding 4.7 m at Point Atkinson.

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 21-24 and January 18-22**.

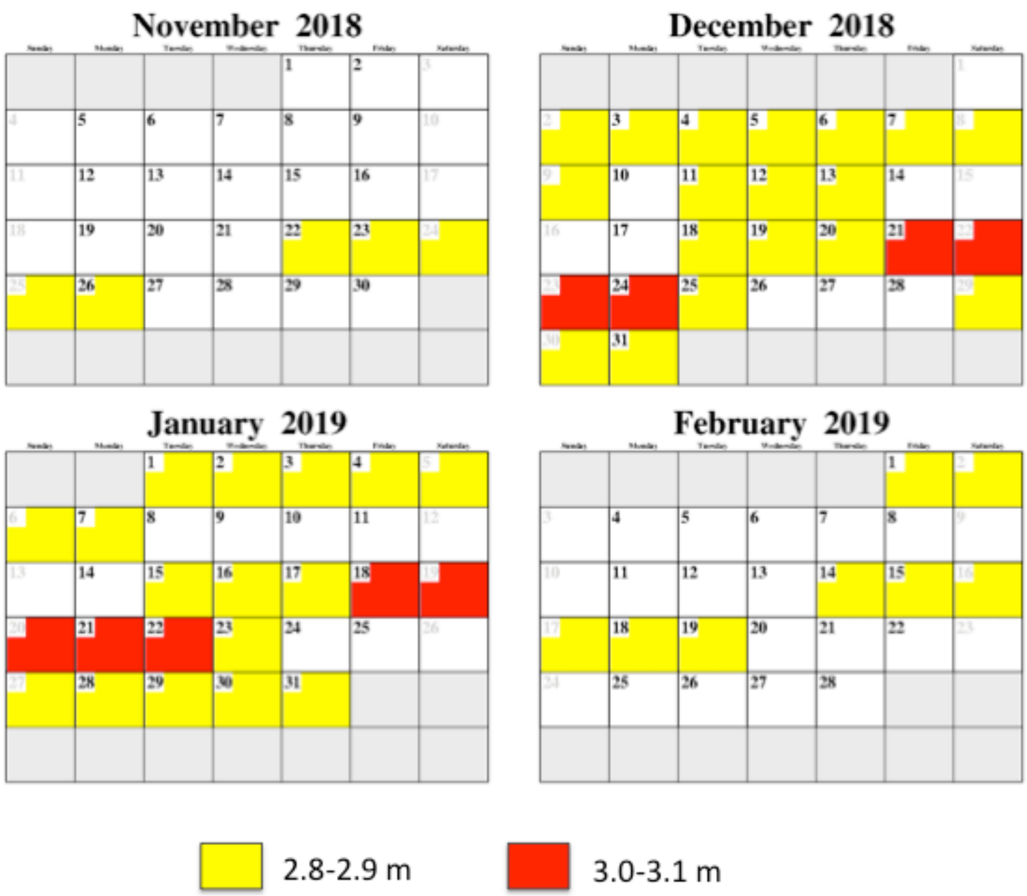

Figure 5. 2018-19 calendar dates for tides exceeding 2.8 m at Victoria.

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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 2017-18 have given way to ENSO neutral conditions. However, equatorial SSH anomalies are once again trending positive, consistent with an emerging El Nino forecast for fall 2018. Currently, SSH anomalies are near zero all along the North American west coast (Fig. 6), but a visible positive anomaly related to steric effects from surface warming due to warm early fall weather (with little wind) has formed in the north Pacific.

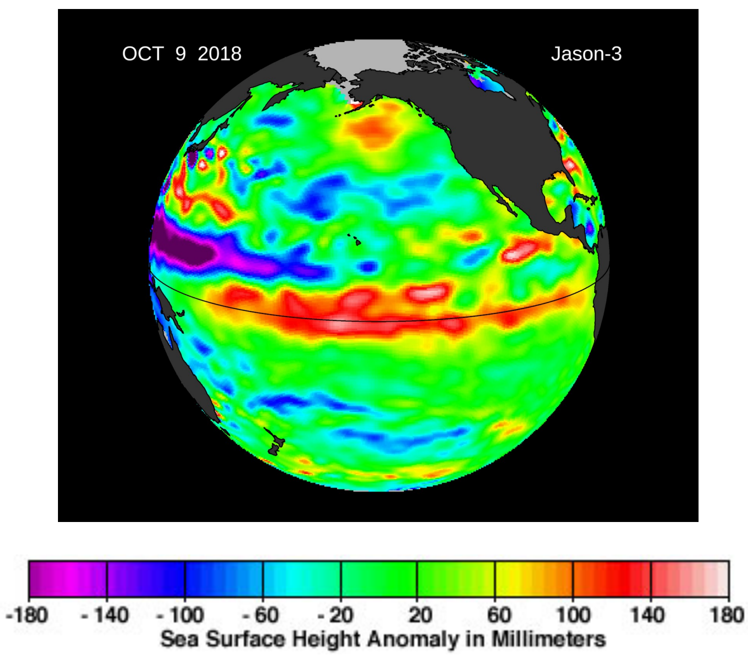

Figure 6. JPL image of 10-day averaged SSH anomalies over the Pacific Ocean on October 9, 2018. SSH Anomalies are consistent with emerging El Nino conditions.

The seasonal (June-September) 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 2017, the SST anomarlies along the west coast of British Columbia are lower, which is consistent with the declining trend in the PDO index (now near zero).

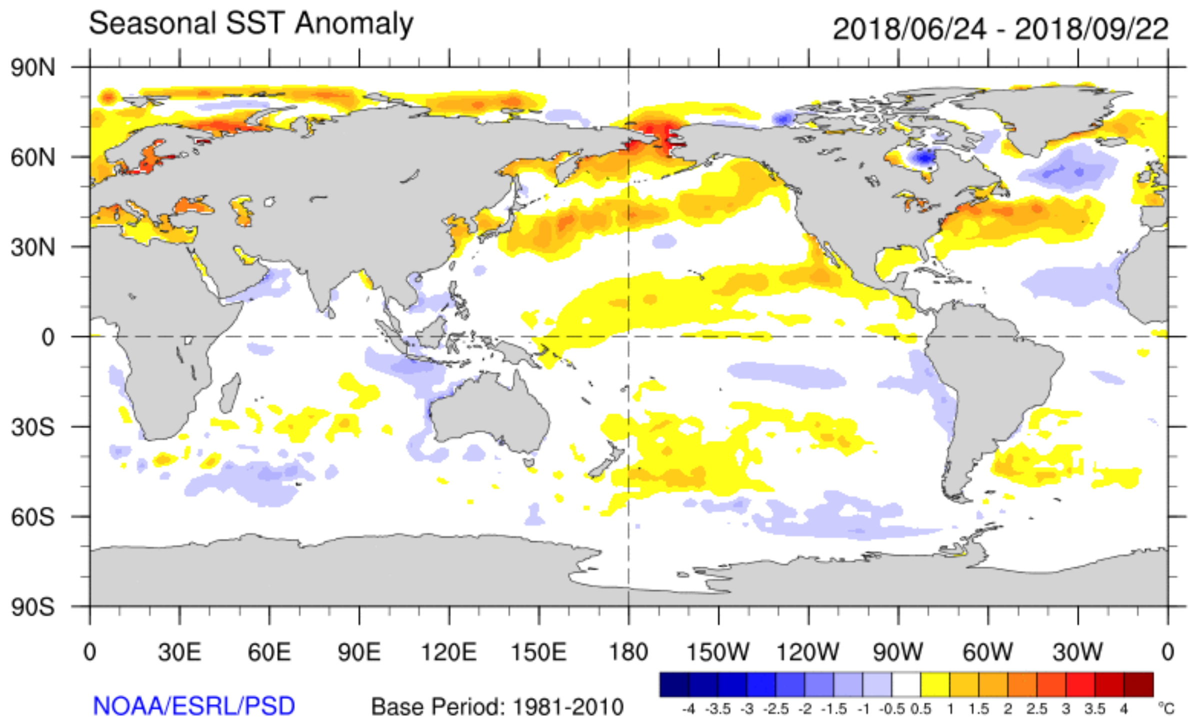

Figure 7. ERSL/NOAA seasonal SST anomaly for June 24-September 22, 2018.

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Summary

From the information available as of October 2018, the winter 2018-19 storm season will be characterized by the following:

1. **ENSO**: A developing El Niño will potentially influence the storm track, likely bringing more westerly flow and pulling the storm track more south than normal.
2. **PDO**: neutral.
3. Peak tides **Victoria**: December 21-24 and January 18-22.
4. Peak tides **Vancouver:** November 27-28, December 24-29, January 21-26 and February 21.
5. **SSH anomalies**: Near zero on the coast but positive offshore.

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 started in the Gulf of Alaska, but the fall transition in BC coastal waters has not yet started in earnest. Seasonal high tides will appear beginning in late November for the Lower Mainland, and be most prominent in late December and January for all areas of the south coast. Emerging El Niño conditions may influence the trajectory and frequency of storms to southern British Columbia; typical El Niño influences include a more zonal east-west storm track that is located further south than normal.

References

Eichler T. and W. Higgins, 2006: Climatology and ENSO-related variability of North American extratropical cyclone activity. *J. Clim* 19:2076-2093

Gershunov, A. and T. P. Barnett. 1998. Interdecadal modulation of ENSO teleconnections. *Bulletin of the American Meteorological Society* 79: 2715-2725

Mantua, N. J. and S. R. Hare. 2002. The Pacific Decadal Oscillation. *J. Ocean.* 58: 35-44

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.

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.

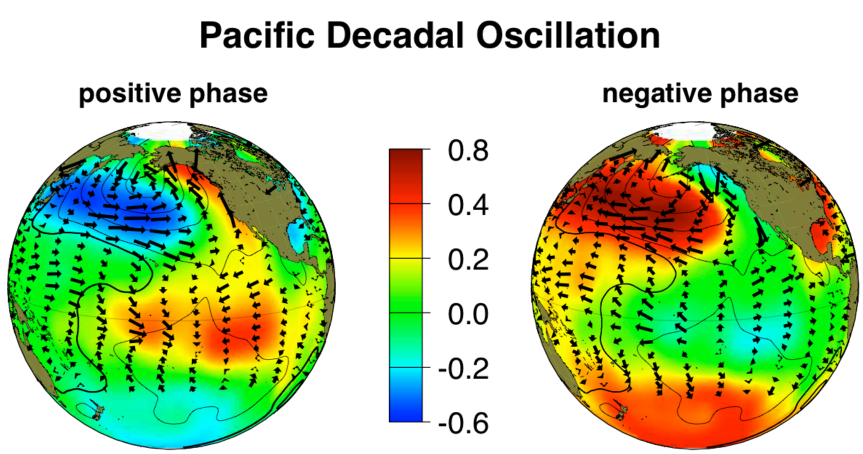

Figure A1. PDO warm and cool phases of sea surface temperature anomaly and associated wind anomaly patterns. Web image from Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington.

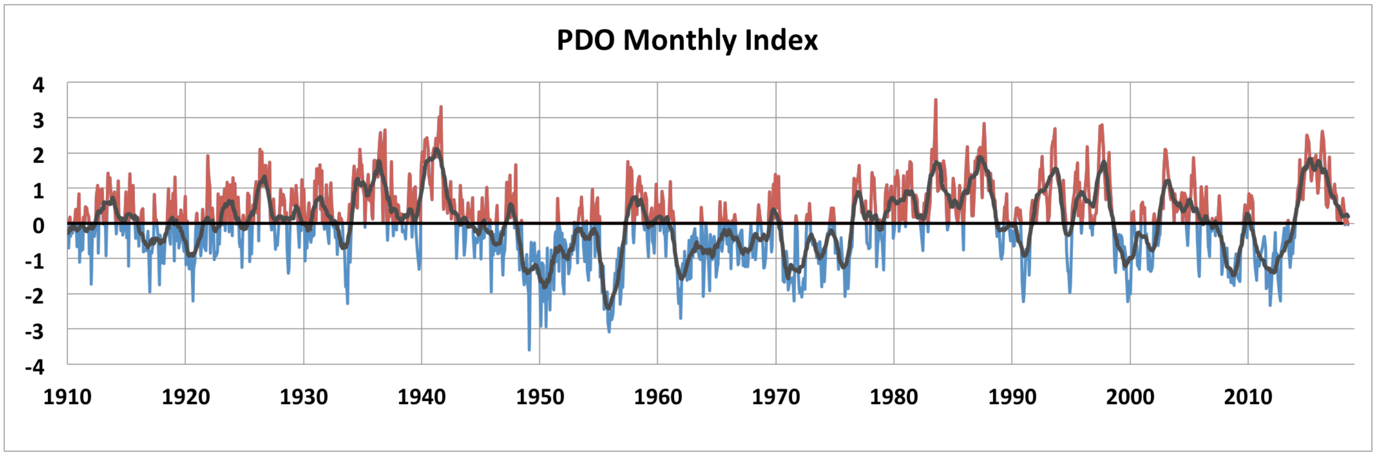

Figure A2. Monthly values of the PDO index from 1910-2018

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.

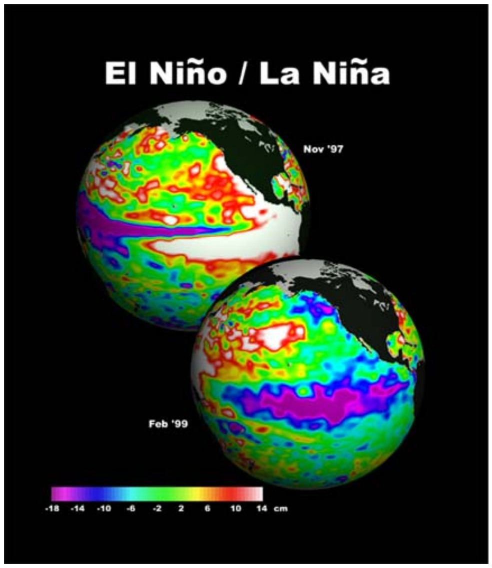

Figure A3. Residual sea surface height during the El Niño winter of 1997 and La Niña winter of 1999 (courtesy Jet Propulsion Laboratory). The positive SSH residual off the BC coast in 1997 is part of a larger feature stretching to the equator, while the negative SSH residual in 1999 is more localized.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

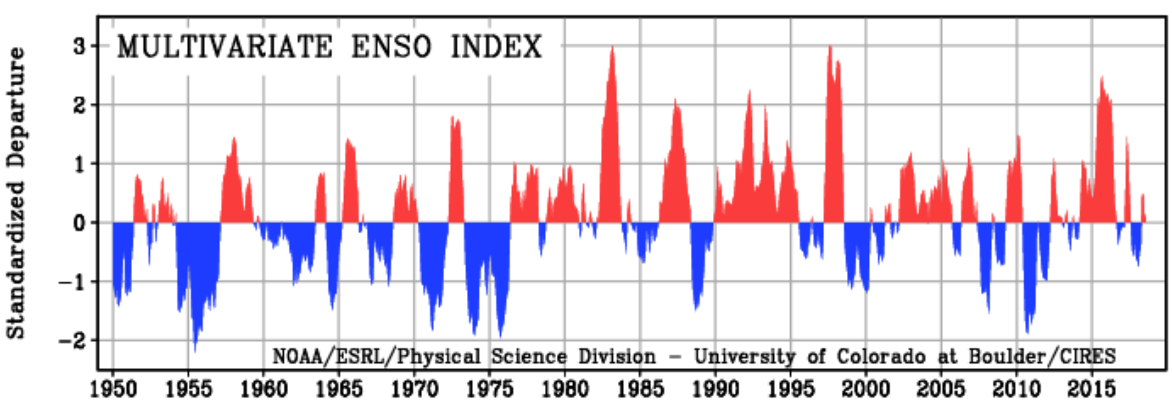

Figure A4. NOAA ERSL multivariate ENSO index from 1950 to present. Positive values indicate El Niño conditions, negative values indicate La Niña conditions.