

Numerical simulations of six major storm surge events in the southern Strait of Georgia and Boundary Bay

Isaac V. Fine and Richard E. Thomson

Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney, BC V8L 4B2

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NUMERICAL SIMULATIONS OF SIX MAJOR STORM SURGE
EVENTS IN THE SOUTHERN STRAIT OF GEORGIA AND
BOUNDARY BAY

By

Isaac V. Fine and Richard E. Thomson

Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney, BC V8L 4B2

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ABSTRACT

Fine, I.V., and Thomson, R.E. 2026. Numerical simulations of six major storm surge events in the southern Strait of Georgia and Boundary Bay. Can. Tech. Rep. Hydrogr. Ocean Sci. 412: v + 63 p.

Estimation of the risk from storm surge to the British Columbia coast is of considerable importance for broad, low-lying areas of the province such as Boundary Bay in the southern Strait of Georgia. A two-dimensional, nested-grid Princeton Ocean Model, with an implemented wetting-drying approach based on newly available high-resolution bathymetric and topographic data, was used to simulate storm surge heights in Boundary Bay for six historic storms that occurred in the Greater Vancouver area since 1981: November 14, 1981; December 16, 1982; January 27, 1983; January 01, 1997; February 04, 2006; and December 15, 2006. The main findings are: (1) modelled storm surge heights are close to values observed at the tide gauges at Point Atkinson, Vancouver and Cherry Point (Washington State), although in some cases the model underestimates the surge heights by 5-20 cm; (2) following a slight adjustment, the estimated historical storm surge amplitudes in Boundary Bay range from 0.91 m to 1.05 m above tidal level for all events; and (3) the distribution of storm surge amplitudes in Boundary Bay is non-uniform, with the highest amplitudes impacting the northeastern end of the region (Mud Bay). In the Semiahmoo area, amplitudes are as much as 5 cm lower than in the Mud Bay. The storm surge heights in this study are determined for Higher High Water Mean Tide; to determine the extent of coastal inundation during similar events in the future, the predicted tides for the time of the storm need to be considered.

RÉSUMÉ

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L'estimation du risque d'onde de tempête sur la côte de la Colombie-Britannique revêt une importance considérable pour les vastes zones basses de la province, comme la baie Boundary, dans le sud du détroit de Georgia. Un modèle océanique de Princeton bidimensionnel à grille imbriquée, intégrant une approche d'humidification-assèchement basée sur de nouvelles données bathymétriques et topographiques à haute résolution, a été utilisé pour simuler la hauteur des ondes de tempête dans la baie Boundary lors de six tempêtes historiques survenues dans la région du Grand Vancouver depuis 1981 : le 14 novembre 1981 ; le 16 décembre 1982 ; le 27 janvier 1983 ; le 1er janvier 1997 ; le 4 février 2006 ; et le 15 décembre 2006. Français Les principales conclusions sont les suivantes : (1) les hauteurs des ondes de tempête modélisées sont proches des valeurs observées aux marégraphes de Point Atkinson, Vancouver et Cherry Point (État de Washington), bien que dans certains cas le modèle sous-estime les hauteurs des ondes de 5 à 20 cm ; (2) après un léger ajustement, les amplitudes historiques estimées des ondes de tempête dans la baie Boundary varient de 0,91 m à 1,05 m au-dessus du niveau de la marée pour tous les événements ; et (3) la distribution des amplitudes des ondes de tempête dans la baie Boundary n'est pas uniforme, les amplitudes les plus élevées affectant l'extrémité nord-est de la région (baie Mud). Dans la région de Semiahmoo, les amplitudes sont jusqu'à 5 cm inférieures à celles de la baie Mud. Les hauteurs des ondes de tempête dans cette étude sont déterminées pour la marée moyenne des hautes eaux plus hautes ; pour déterminer l'étendue des inondations côtières lors d'événements similaires à l'avenir, les marées prévues au moment de la tempête doivent être prises en compte.



Storm surge at Boundary Bay on February 4, 2006 (from Patrick Forseth, 2012).

1. INTRODUCTION

Many coastal communities in the Strait of Georgia are at risk of flooding and property damage caused by storm-induced surges. During a passing storm, the low atmospheric pressure has an inverse barometer effect, elevating the sea level by roughly 1 cm for every fall in air pressure by 1 mb (Thomson and Fine, 2021). This effect, in combination with strong winds that push water up against the coast, can result in flooding, particularly if the storm occurs during a high spring tide. Forseth (2012) used tide gauge data from Point Atkinson in West Vancouver to compute dates of potential flooding for twenty-one storm surge events in the southern Strait of Georgia based on the highest measured sea levels. The author found that eight of the flooding events occurred between 1960 and 2011. Three of the events resulted in significant damage, with the surges of 16 December 1982 and 4 February 2006 responsible for damage of roughly \$2,000,000 (in 2011 Canadian Dollars). Given its low elevation and exposure to the sea, the Corporation of Delta experienced the greatest flooding and accounted for a majority of the damage reported (Forseth, 2012).

There are presently two storm surge models available for the southern Strait of Georgia. The Salish Sea storm surge model (Soontiens et al., 2015; <https://salishsea.eos.ubc.ca/>) produces a 48-hour forecast of marine conditions in the Strait of Georgia and Juan de Fuca Strait. The model uses a regional version of the 3-dimensional NEMO circulation model, with 40 vertical levels, to produce a storm surge hindcast, with a regular curvilinear mesh of 398 by 898 grid cells, corresponding to horizontal grid sizes of approximately 440 m by 500 m. The depth array of the model is smoothed to limit large changes in depth across grid cells, such that $\Delta h/h \leq 0.8$, where Δh is the difference in depth between two adjacent grid cells and h is their average depth. As a result, the effective bathymetric resolution is lower than specified in the model. In addition, bathymetric depths between 0 and 4 m are set to 4 m. The model uses the high-resolution Canadian atmospheric forecasting model (HRDPS; see section 2.3.2 below), and includes forcing by Fraser River discharge (as measured at Hope) and adds the astronomical tide (through boundary conditions) based on the northeast Pacific tidal model of Foreman et al. (2000).

A second model, the British Columbia storm surge forecasting system (<http://stormsurgebc.ca>), has been operating since 2007 using a two-dimensional (2D) nonlinear barotropic Princeton Ocean Model (POM) with a roughly 7 km spatial resolution. Originally developed through funding by Fisheries and Oceans Canada and the British Columbia Ministry of the Environment, this operational model provides online predictions out to seven days to emergency managers and public stakeholders, including the cities of Surrey, Richmond, and Delta. Zhai et al. (2019) used this POM forecasting system to generate a 37-yr storm surge hindcast for southern British Columbia (BC) from 1980 to 2016. Because barotropic models cannot determine baroclinic processes that affect seasonal and interannual sea level variability, Zhai et al. (2019) presented a procedure to account for these processes. The computed residual sea level variations were passed through a 40-hour low-pass filter to allow for comparison with observations at BC tide gauges.

In this study, we use a two-dimensional version of the Princeton Ocean Model that allows for wetting-and-drying of low-lying coastal areas to simulate storm surge in the southern Strait of Georgia. Focus is on Boundary Bay, which was originally selected as a “Case Study” region for the Flood Mitigation Canada Program funded by Defence Research and Development Canada (DRDC) and Natural Resources Canada (see the Acknowledgments for this study). The Princeton Ocean Model (Mellor, 2002) is a widely used ocean model with a terrain-following sigma-

coordinate system in the vertical and an orthogonal curvilinear coordinate system in the horizontal. Because of these features, and the fact that the model solves for the sea-level directly, POM is particularly well-suited for coastal ocean simulations. In particular, one of the earliest applications of POM was to simulate tides and their interaction with (river) buoyancy-driven flows in a bay (Oey et al., 1985).

The crest water level during a storm depends on two main factors: (a) The storm surge amplitude; and (2) the astronomical tidal level at time of the event. The risk of flooding increases when storm surge coincides with a high astronomical tide. However, because storm surge amplitudes only weakly depend on the astronomical tide, the strength of storm surges can be estimated separately by analysis of the residual (or de-tided) sea level. An analysis of the residual sea level at Point Atkinson, Vancouver, and Cherry Point tide gauges for 1981-2019 was presented in Fine et al. (2020). The study also provided a list of the strongest surges in the southern Strait of Georgia in past 40 years, ranked in order of the maximum crest level of the residual sea level at the Point Atkinson tide gauge. The goal of the current work is to model the six highest events observed in the area.

2. STORM SURGE MODEL

2.1 MODELLING STORM SURGE USING THE 2D POM WITH A NESTED GRID FORMULATION

As previously noted, this study uses a version of the 2D POM model with the wetting and drying (WAD) option. Wetting and drying are common and important phenomena occurring in low-lying coastal zones as well as coastal embayments and inlets. Falling air pressure and strong winds, combined with high astronomical tides, can lead to flooding and subsequent drying. The WAD algorithm in POM was developed by Oey et al. (2005).

Accurate numerical simulation of storm surge in the rapidly shoaling regions of British Columbia requires setting up the model domain as a series of nested grids of ever finer spatial and temporal resolution. The use of nested grids of smaller cell dimensions and time steps makes it possible to resolve waves as they propagate into the shallow coastal regions. Also, near-coast shallow areas are strongly affected by the wind and need special consideration. The principal requirements for numerical models using nested grids are as follows:

- Nested grid cell sizes are generally obtained by dividing the initial, large-scale coarse numerical grid by an integer, typically 3 to 5. Integers larger than this can lead to grid interface problems;
- Nested grids are needed in near-coastal areas; the coarse “parent” grid should be of sufficient extent to resolve possible feed-back effects that the nested grid may have on the parent grid during the simulation;
- A good interface between the inner and outer domains is required to avoid errors and model instability associated with point matching between the different grids. This should allow two-way fluxes without trapping of shorter period oscillations at the inner domain boundaries.

Because of the relatively long periods of storm surges of about a day, it is less important to have high resolution bathymetry than for other natural hazards, such as tsunamis. Consequently, we have limited our nested grid approach to outer and inner grid levels only. Parameters for the grids are listed in Table 1.

Table 1. Parameters of the numerical grids used in the storm surge model. Grid extent is along the x (eastward) and y (northward) coordinate directions and is presented in degrees ($^{\circ}$). Numerical grid cell sizes for Grids 1 and 2 are roughly 370 m and 61 m, respectively. Columns 2,3 and 4 are presented as x,y values. DEM denotes the Digital Elevation Model provided by Ocean Networks Canada; BC and BB stand for British Columbia and Boundary Bay, respectively. Note: 1° of latitude = 60 nautical miles (~ 111 km).

Grid No.	Extent (x, y) (degrees)	Array (number of grid points)	Cell size (degrees)	Source of data	Processing type
1	6.595, 4.2	1261, 1520	0.005, 0.00333	BC 3 arc-sec bathymetric DEM	Filtering and bilinear interpolation
2	0.74, 0.55	811, 889	0.0008333, 0.0005555	BB 1/9 arc second DEM	Filtering and interpolation

2.1.1. Outer grid (Grid 1)

Grid 1 covers the waters surrounding Vancouver Island and the northwest US coast (Figure 1). The location and coverage of the grid were chosen so that they covered all passes into the Strait of Georgia. This grid is also important for modelling of long waves and surge that penetrate into the Strait of Georgia through narrow straits, capturing the energy exchange between the deeper shelf waters and the much shallower coastal zone. The grid was created using the British Columbia (BC) 3 arc-second bathymetric Digital Elevation Model (DEM) (NOAA, 2017). Grid 1 has a resolution of 18 arc-seconds in the east-west direction and 12 arc-seconds in the north-south direction, corresponding to spatial scales (x,y) of approximately 370 m and 370 m, respectively (Table 1). The grid boundaries span 47.2° – 51.4° N, 129.8° – 122.2° W.



Figure 1. The region covered by the regional-scale coarse grid numerical model, which includes the coast of Vancouver Island, British Columbia and northwest Washington State (Grid 1). The insert shows the location of the nested grid (Grid 2), covering the coast of Metro Vancouver and Boundary Bay in the southern Strait of Georgia. The triangle denotes the location of Meteorological Buoy MB46206 (48.83° N, 126.00° W) on the continental shelf off southwest coast of Vancouver Island.

To comply with the Grid 2 bathymetry (see 2.1. 2), we replaced the bathymetric data in the Boundary Bay area for Grid 1 with data computed with a high-resolution digital model for Boundary Bay; the original 3-arc second data in the area are not satisfactory for that region.

2.1.2. Inner grid (Grid 2)

The second numerical grid covers the waters surrounding Metro Vancouver (Figure 2). This grid is of prime importance since it determines wave transformation in the vicinity of Boundary Bay. Model grid cells were created using the 1/9 arc-second Boundary Bay digital Elevation Model (BBDEM, 2020). The gridded data were subsequently re-interpolated to a geographical coordinate system (NAD83 standard) with a rectangular grid cell size of 3 arc-seconds by 2 arc-seconds (approximately 61 m by 62 m) in the east-west and north-south directions, respectively.

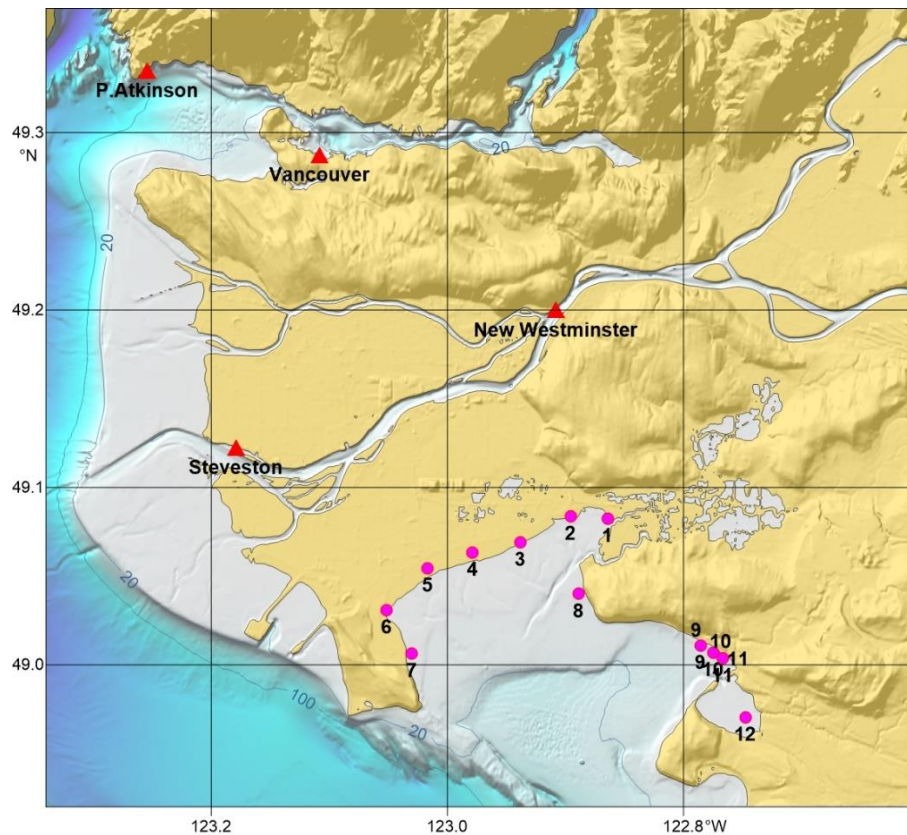


Figure 2. The coastal region covered by Grid 2, including the waters surrounding Greater (Metro) Vancouver. The x,y grid scales for this region are approximately 61 m and 62 m, respectively. Shown are the locations of the tide gauges (solid triangles) and the modelled sites (solid dots, numbers 1-12). The area above mean sea level is shaded yellow.

2.2. MODEL REFERENCE LEVEL

Model simulations are generally conducted for tsunami arrival times that coincide with times of Canadian Vertical Datum of Higher High Water Mean Tide (HHWMT). The National Tsunami Hazard Mapping Program of 2010 (Nikolsky et al., 2013) recommends that inundation maps be computed using high tide as the initial condition for modelling. Alaska University uses Mean Higher High Water (MHHW) as the initial condition (Suleimani et al., 2013), while the Washington State inundation map was created using Mean High Water (MHW) for the initial conditions (Eungard et al., 2018). The Canadian standard HHWMT is close to the US standard MHHW and has been used for several tsunami modelling projects in BC, including for Victoria (AECOM, 2013), for Victoria and Seal Cove (Fine et al., 2018), and for Prince Rupert (The City of Prince Rupert Tsunami Flooding Risk Assessment, 2019). Accordingly, to present values of highest risk, maps of maximum tsunami wave height and current speed in this report are referenced to HHWMT rather than to the mean tide or to a geodetic reference.

Table 2. Vertical datum values for tidal stations provided by the Canadian Hydrographic Service (CHS) and the US National Oceanic and Atmospheric Administration (NOAA). Latitude and longitude are in degrees and minutes. Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) are defined in two ways: (1) in Canada using tidal predictions derived from tide gauge records; and (2) in the United States using the observations from USA tide gauges. All values are referenced to Mean Sea Level (MSL), which by definition in this study is then zero (0.0). Here, CGVD 2013 denotes the Canadian Geodetic Vertical Datum.

Tide gauge ID	Name	Latitude (°N)		Longitude (°W)		CGVD 2013 (m)	MSL (m)	MHHW (m)	MLLW (m)
		Deg	Min	Deg	Min				
7795	Point Atkinson	49	20.25	123	22.42	-0.193	0.0	1.30	-1.94
7735	Vancouver	49	17.23	123	6.587	-0.180	0.0	1.32	-1.96
9449424	Cherry Point	48	51.80	122	45.50	-	0.0	1.18	-1.61

Higher High Water Mean Tide (HHWMT) is used as the primary reference level for most modelling results. For the Boundary Bay area, the closest permanent tide gauges are at Point Atkinson and Vancouver (Canadian Hydrographic Services) to the north and Cherry Point (NOAA) to the south. HHWMT is 1.30 m above Mean Sea Level (MSL) at Point Atkinson and 1.32 m above MSL at Vancouver; in comparison, MHHW used in the US is 1.18 m above MSL at Point Atkinson (see Table 2 below). For convenience, *a common reference value of 1.2 m* is added throughout the region for the tsunami modelling. Mean Sea Level (MSL) is 0.18-0.19 m above the Canadian geodetic datum CVD2013 (Table 2).

2.3. ATMOSPHERIC FORCING

Storm surge events in the Salish Sea have been forced using hourly time series of atmospheric pressure, wind velocity and other variables along the outer boundary of Grid 1. The two reanalysis datasets we applied to the model are the ERA5 data, provided by the European Centre for Medium Range Weather Forecasts, and corresponding data from Environment Canada's High Resolution Deterministic Prediction System (HRDPS). We also examined forcing by North American Regional Reanalysis (NARR) data produced by the National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996; Kistler et al., 2001) but found that the wind velocities on the outer coast and in Juan de Fuca Strait differed markedly from those provided by ERA5 and HRDPS. However, the HRDPS dataset is only available for recent years, starting from 2014, so that only the ERA5 data are acceptable for historical storm surge modelling.

In 2019, the European Centre for Medium Range Weather Forecasts (ECMWF) released a new, fifth, global high-resolution dataset named ERA5. The dataset provides hourly estimates of a large number of atmospheric, land and oceanic climate variables from 1979 to the present, covering the Earth on a 30-km grid and resolving the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 includes information on uncertainties for all variables at reduced spatial and temporal resolutions. The dataset combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems, and replaces the ERA-Interim reanalysis, which stopped being produced on 31 August 2019.

For the current modelling study, we extracted ERA5 data for 8 days around each historical event, including hourly atmospheric sea level pressure and hourly wind velocity (eastward and

northward components) at 10 m elevation. Horizontal resolution of the ERA5 data is 0.25 degrees in both directions (approximately 18 km by 28 km)

As mentioned in the Introduction, we have modelled six historical events, corresponding to the highest residual sea levels at the Point Atkinson tide gauge, according to the analysis in Fine et al. (2021). All events are associated with deep atmospheric low storms that crossed the BC coastline. These cyclonic wind systems are readily detected in the ERA5 data. Parameters of the storms estimated using the ERA5 fields are provided in Table 3; storm trajectories are shown in Figure 3.

The six storms (Table 3) are characterized by deep atmospheric depressions (with central pressures as low as 955 mb) and fast-moving speeds with a range of 30-80 km/h. The storms of November 1981 and January 27 arrived from the south, while the others storms arrived from southwest. All storms crossed the Vancouver Island coastline. Details of the atmosphere fields for each event are described Section 3 below.

Table 3. Dates and meteorological properties of historical cases involving the highest storm surge in the vicinity of Boundary Bay from 1979-2018. Values in the last two columns are approximations and meant to provide a characteristic value for the particular variable.

Case No.	Data	Minimum air pressure (mb)	Maximum wind speed (m/s)	Storm extent (km)	Storm travel speed (km/h)
1	November 14, 1981	963	24	400-500	35
2	December 16, 1982	967	26	500-800	30
3	January 27, 1983	971	26	300-400	50
4	January 01, 1997	955	25	600-800	~
5	February 4, 2006	966	25	500-700	30
6	December 15, 2006	975	27	300-700	50

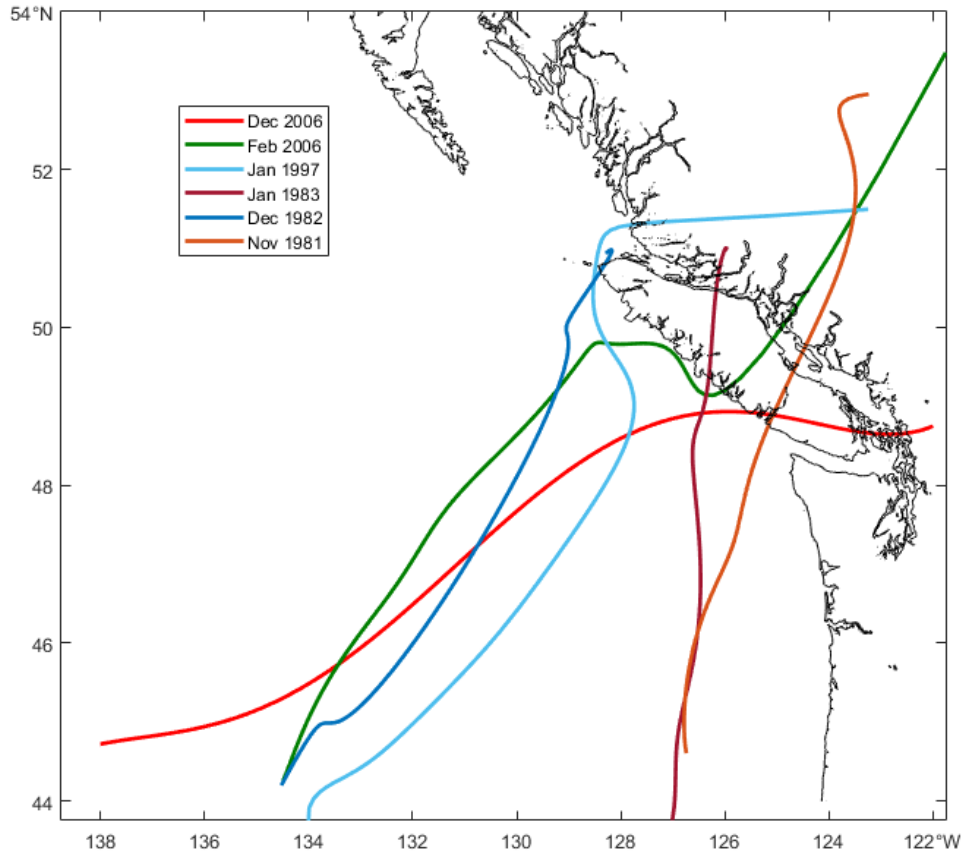


Figure 3. Trajectories of the six storms that caused the strongest surges from 1979 to 2018 at Point Atkinson, based on the atmospheric pressure data from the ERA5 reanalysis. The southern end of a trajectory corresponds to the time when the depression center entered the computational domain.

2.4. LATERAL BOUNDARY CONDITIONS

Specification of the prevailing oceanic conditions at the open ocean boundaries are important part of the model setup. In the case of hindcasting, we can use observed data or reanalysis data that are based on the observations. Here, we have used daily mean sea level anomalies provided through the ECMWF Copernicus portal <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview>. These conditions, in addition to the atmospheric forcing, are needed to accurately determine the storm surge component of the sea level response. The Copernicus dataset is mainly based on altimetry

observations and provides gridded global sea level data at a 0.25-degree resolution. The dataset does not include the inverse barometer effect or tides, but does include oceanic steric effects. We have used air pressure data to add sea level changes due to the inverse barometer effect at the boundary of the model to satisfy the simulation requirements, which apply the full barometric effect. To dampen imperfect reflection of barotropic waves at the outer boundaries, enhanced horizontal mixing was introduced along the boundaries (corresponding to a sponge layer) in addition to the usual outward radiation conditions. Introducing a sponge layer along the boundaries is standard methodology and is required to decrease incompatibilities of the boundary conditions with the sea level variations within the inner domain of the model. The sponge layer decreases artificial intensification of the processes along the boundaries.

3. CASE MODELLING

3.1. CASE 1: NOVEMBER 14, 1981. RANK NO. 5 AT POINT ATKINSON

The windstorm on 13-15 November 1981 was one of “Deadliest American disasters and large loss of life event” (Read, 2004). It was mentioned as “the strongest windstorm since the great Columbus Day storm of 1962 at the West Coast”. When the storm was approaching the Oregon coast, the pressure at the centre of the depression was as low as 956 mb. According to the reanalysis ERA-5 data, the minimum pressure had a compatible value of 963 mb (Table 1). At least 15 people lost their life because of the windstorm, and the total estimated damage in Pacific Northwest of the USA exceeded \$50 million <https://kcby.com/news/local/deadly-storm-hit-oregon-on-friday-the-13th-in-november-1981>. On the west coast of Vancouver Island, the 1981 storm created a strong surge, with the water level at Port Alberni reaching 4.4 m above Chart Datum (2.51 m above MSL) on November 14. Aside from tsunami waves from the 1964 Alaska earthquake, this is the highest level ever recorded at Port Alberni (waves from the 1964 tsunami were higher but were not recorded by a tide gauge).

Figure 4 shows the storm track computed from the reanalysis data. The centre of the storm crossed Vancouver Island in the Barkley Sound area. However, the strength of the pressure system significantly dropped when approaching the coast (see Figure 5), and the depression disappeared 3 hours after crossing the coastline.

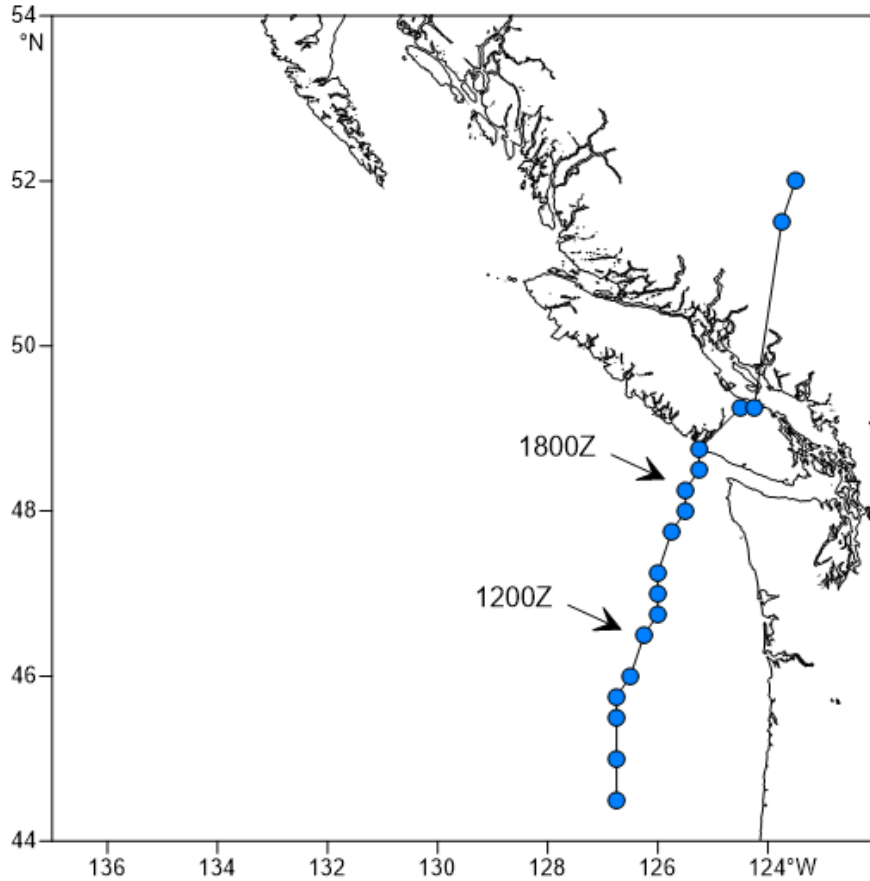


Figure 4. Path of the storm of November 14, 1981. Each point denotes the location of the storm centre at 1 hour time steps. Hours are in Greenwich Mean Time (Z) (i.e., Universal Coordinated Time, UTC).

According to the reanalysis data (see Figures 6-7), the atmospheric pressure at Boundary Bay dropped to 982 mb, which is less a drop than at the shelf break location (minimum of 973 mb). Accordingly, the wind speed at Boundary Bay was lower by up to about 13 m/s.

We used the 2D nested-grid POM to model the sea level variations for seven days, from November 12-18, 1981, using the described model parameters (Chapter 2). Figure 8 shows a comparison of the residual observed sea level and modelled records at Point Atkinson, Vancouver and Cherry Point. The model provides a good estimation of the storm surge at the sites, accurately capturing the times of maximum height and the basic characteristics of the storm surge, but underestimating the maxima values by ~8%. The distributions of the sea level maxima over the model domains are shown in Figures 9-10. The maxima of the modelled sea level at Boundary Bay vary from 0.82 m at the entrance to the bay to 0.9 m at the northeast corner.

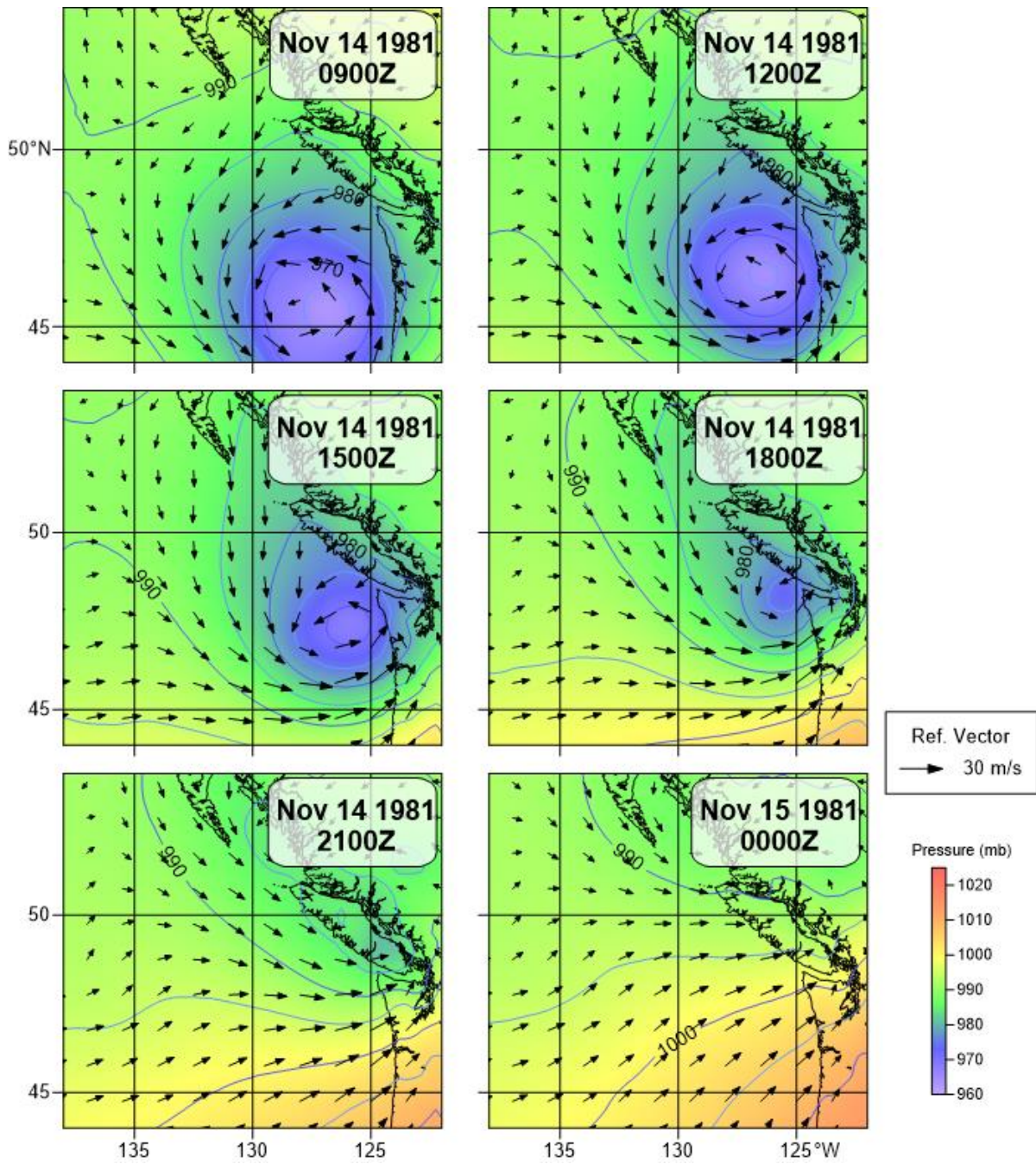


Figure 5. Atmospheric conditions on November 14, 1981, with hours in Greenwich Mean Time (Z).

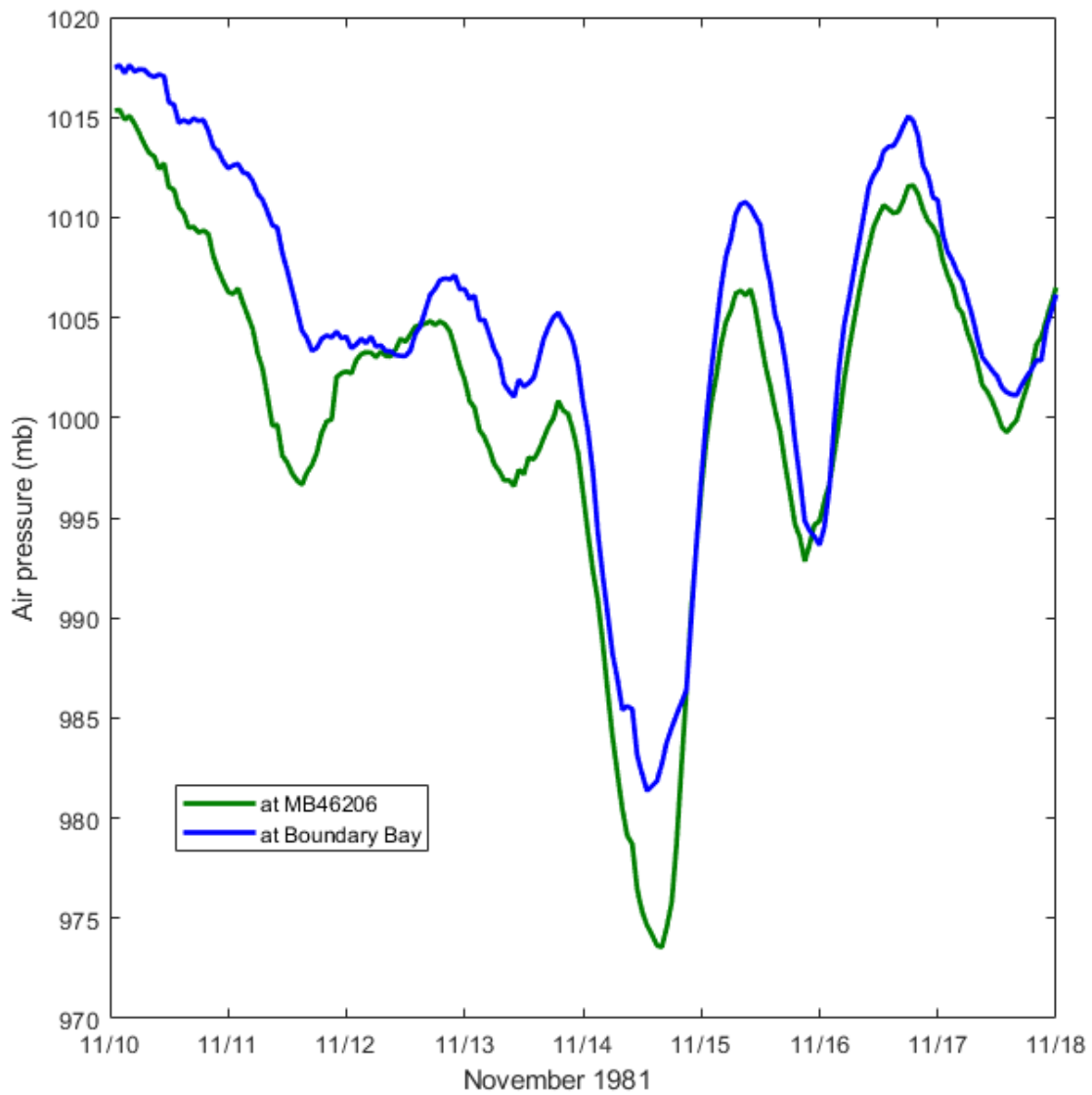


Figure 6. Atmospheric pressure in November 1981 at Boundary Bay and at meteorological buoy MB46206 off the southwest coast of Vancouver Island (see Figure 1 for location).

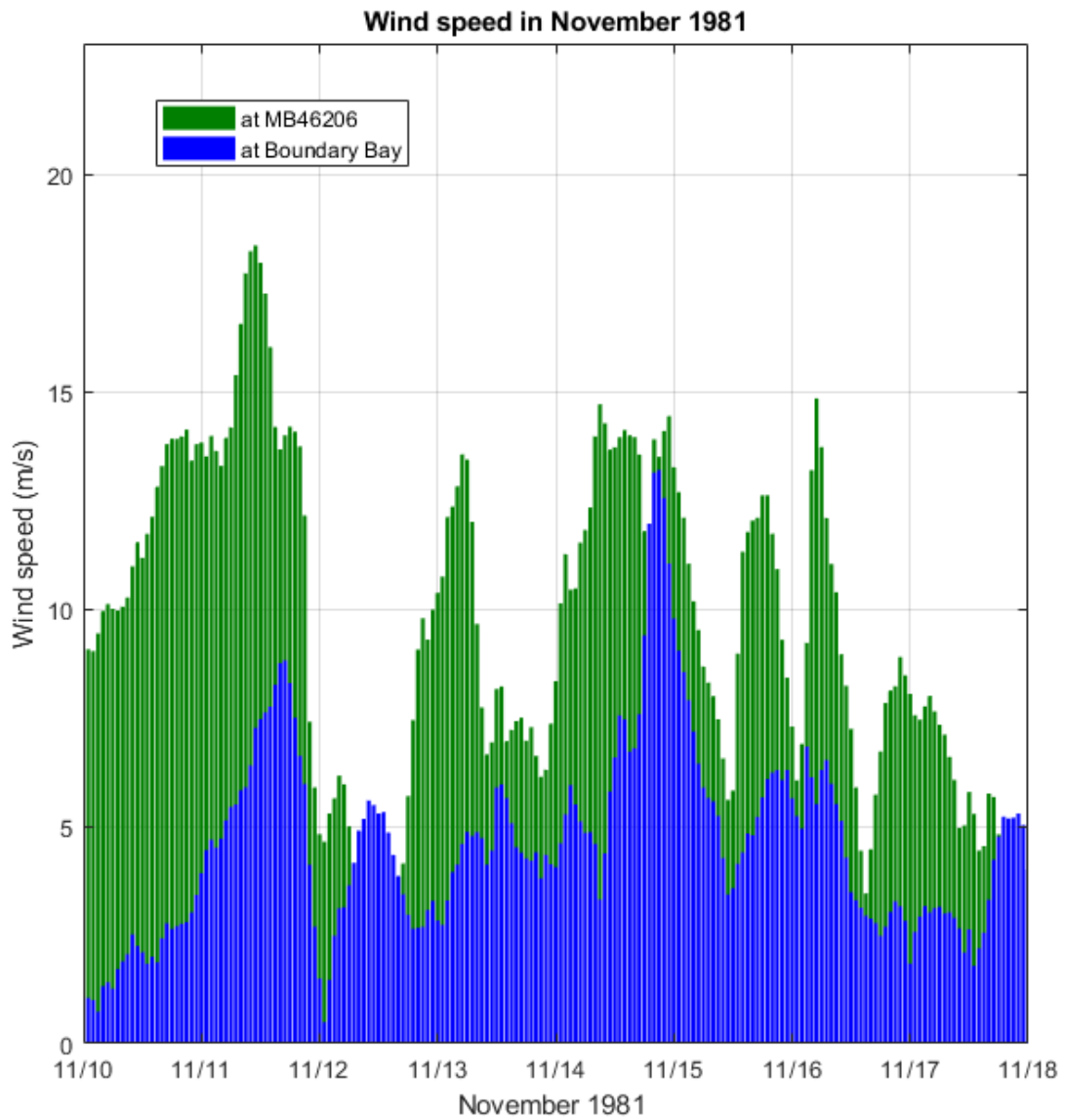


Figure 7. Wind speed in November 1981 at Boundary Bay and at meteorological buoy MB46206 (shelf break).

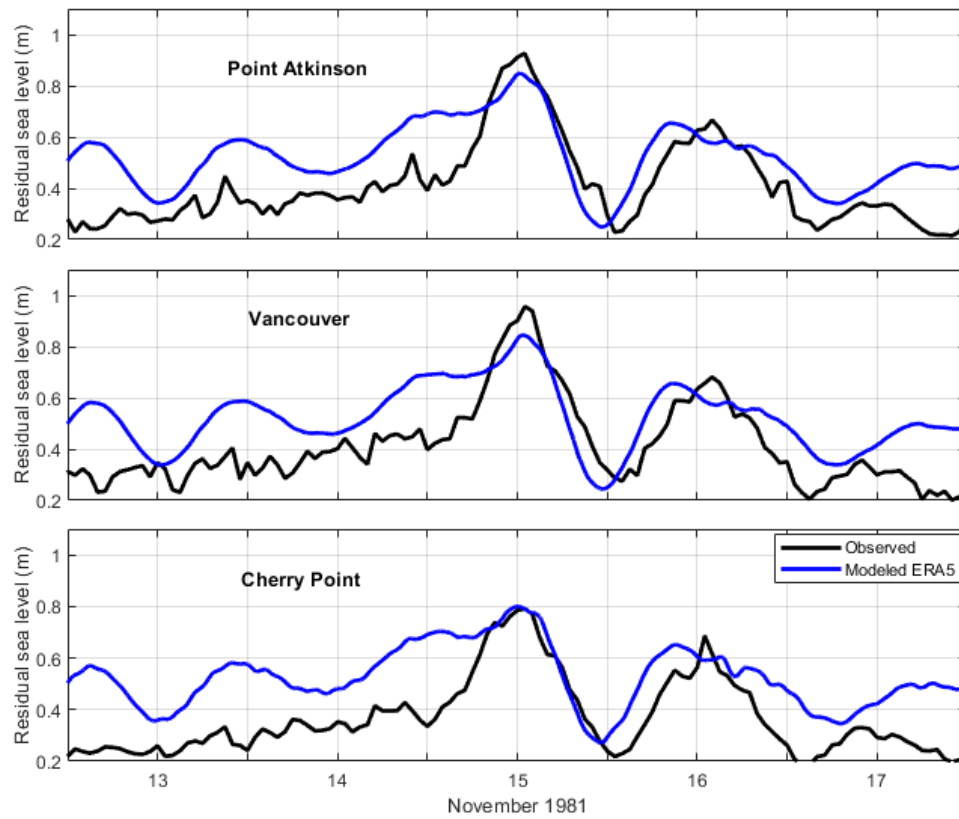


Figure 8. Comparison of the observed and modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of November 14, 1981, at the three tide gauge locations close to Boundary Bay.

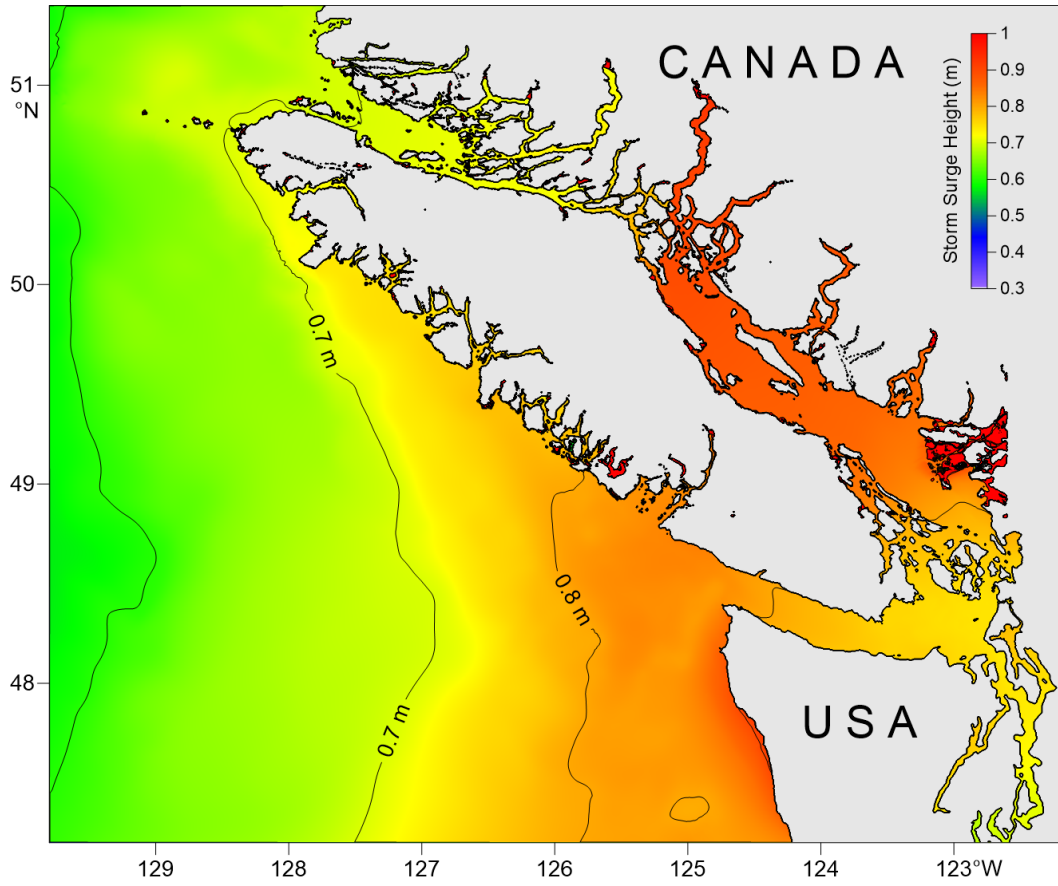


Figure 9. Distribution of the maximum residual sea level during the storm surge of November 14, 1981 for the outer domain encompassing the Vancouver Island area.

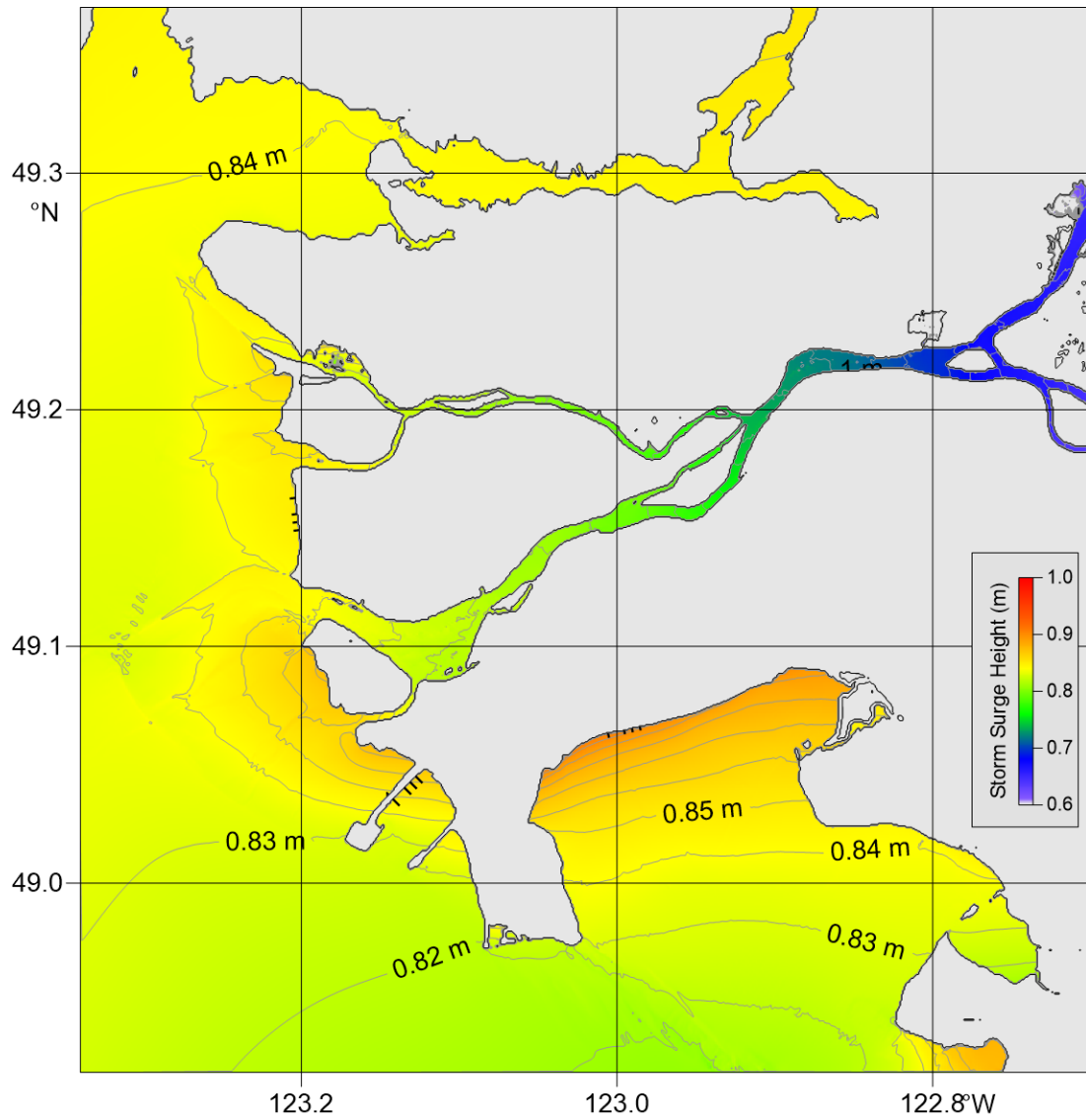


Figure 10. Distribution of the maximum residual sea level during the storm surge of November 14, 1981 for the inner domain (Vancouver and Boundary Bay areas).

3.2. CASE 2: DECEMBER 16, 1982. RANK NO 2 AT POINT ATKINSON

On December 16, 1982, Metro Vancouver experienced an extreme tide event that resulted in significant flooding. At Patricia Bay and Point Atkinson, the tide gauges recorded historical extreme sea levels of 4.38 m and 5.61, respectively. Peak water levels measured 5.55 metres at 700 and 800 PST (Forseth, 2012). Average wind speeds at Vancouver Airport measured 30 km/h from the south at 700 PST and 41 km/h from the southwest at 800 PST, under cloudy skies. The Vancouver Sun newspaper reported wind gusts of 100 km/h in Metro Vancouver. A report by the British Columbia Ministry of Environment (Kangasniemi, 2009) noted that the storm surge and high tide did not fully coincide.

Flooding occurred throughout many municipalities in Metro Vancouver. Storm surge and wave run up inundated Point Roberts, flooding basements and yards (Vancouver Sun, 1982). The Vancouver Sun observed a sail boat washed up on a sun porch. Residents reported damage to basements of the order of \$4,000 to \$30,000 and one shoreline cottage was washed off its foundation (Vancouver Sun, 1982). Surrey also experienced flooding, with water levels breaching dikes along the Serpentine and Nicomekl rivers, flooding Mud Bay and the King George highway (Vancouver Sun, 1982). The Vancouver Sun also reported flooding of a 65-hectare dairy farm and flood damage of an estimated \$100,000 to Art Knapp's, Surrey Garden Centre. A Ministry of Environment photograph provided further evidence of flooding in Boundary Bay (Kangasniemi, 2009), but there are no documented observations of the flooding effects. In total, the Vancouver Sun reported damages from flooding in the millions of dollars. The research provided no other information to verify or ascertain the flooding damage value.

The event of December 16, 1982 has been used as a “typical” example of the storm surge in British Columbia (Murty et al., 1995). The authors modelled the event using tide gauge records nearest to the boundary as boundary conditions and obtained satisfactory agreement between observations at points inside Juan de Fuca Strait and the model predictions.

Figure 11 shows the path of the centre of the depression on December 16, 1982. The storm trajectory was located to the north of that from the 1981 event. Based on the pressure maps (Figure 12), the atmospheric low was wide enough to affect the entire region, from southern Vancouver Island to Queen Charlotte Sound in the north. The system weakened as it crossed the coastline.

Off the west coast, the pressure at the centre of the system was as low as 967 mb, but diminished to 977 mb at the shelf break, and by Boundary Bay, the depression depth had increased

to 985 mb (see Figure 13). Winds reached 20 m/s at the shelf break but had fallen to 13 m/s by the time the storm reached Boundary Bay (Figure 14).

We modelled the sea level variations for eight days using the 2D nested grid POM over the period December 11 to December 19, 1982. Model parameters are outlined in Section 2. Figure 15 shows a comparison between the observed residual sea level and the modelled sea level at the same three sites as the previous case, namely, Point Atkinson, Vancouver and Cherry Point. The modelled records fit the observation well, and only marginally underestimate the observed storm surge values by roughly 5 %. The distributions of the maximum storm surge heights over the domains are shown in Figures 16-17. The peak modelled sea level at Boundary Bay varies from 0.89 m at the entrance to 0.98 m at the northern edge of the bay.

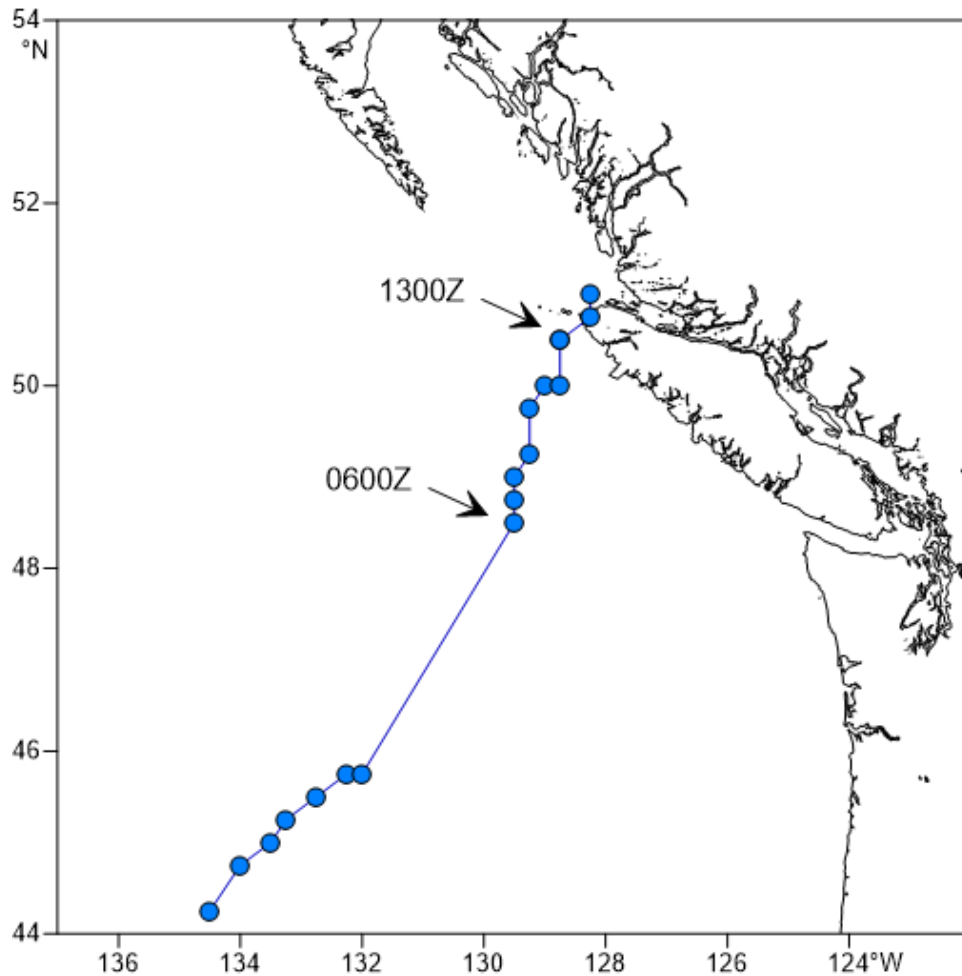


Figure 11. Path of the storm of December 16, 1982. Each point represents the location of the low-pressure centre with a 1-hour time step. Times are in Greenwich Mean Time (Z).

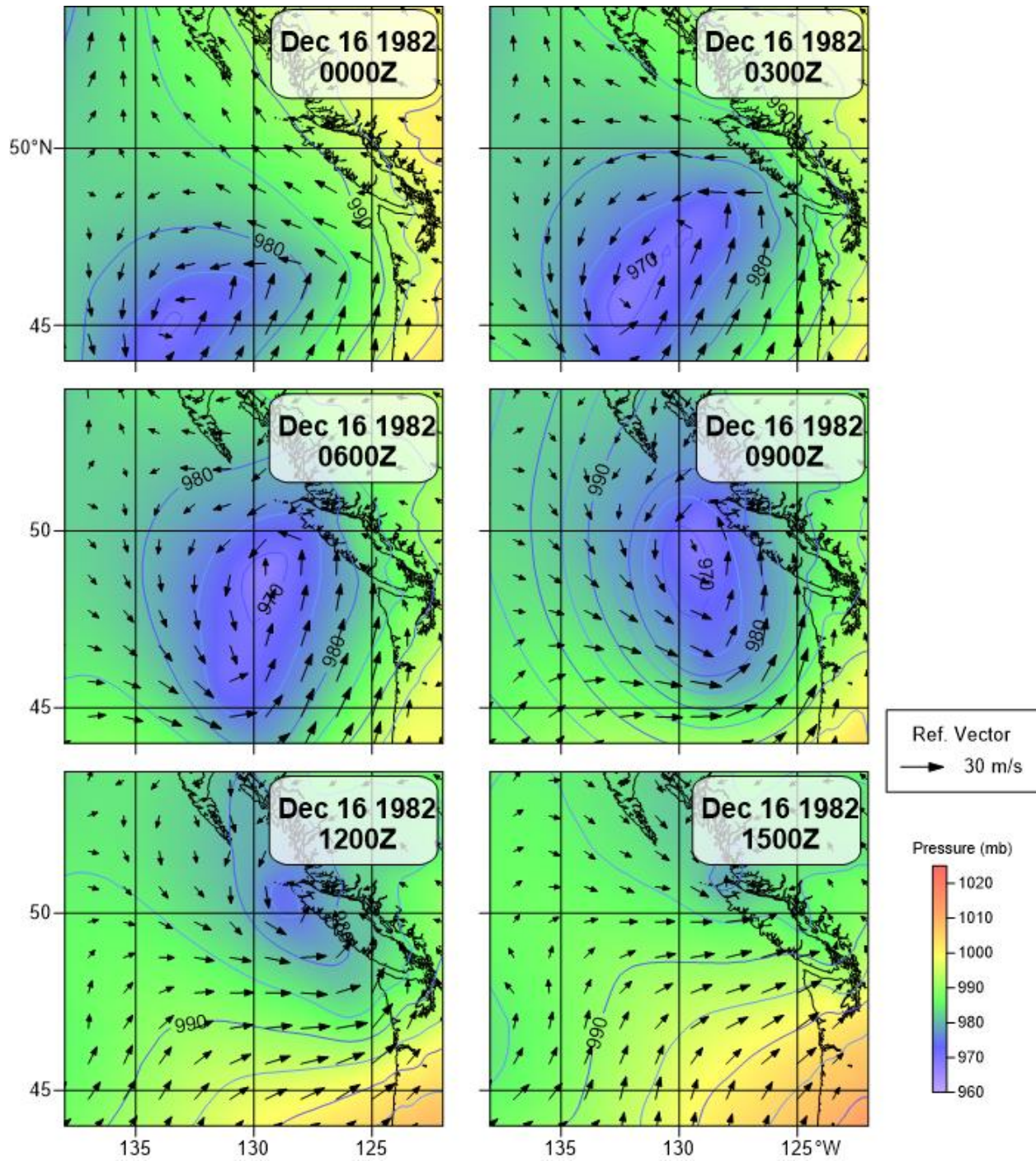


Figure 12. Wind velocity and surface air pressure conditions at three-hour time steps on December 16, 1982.

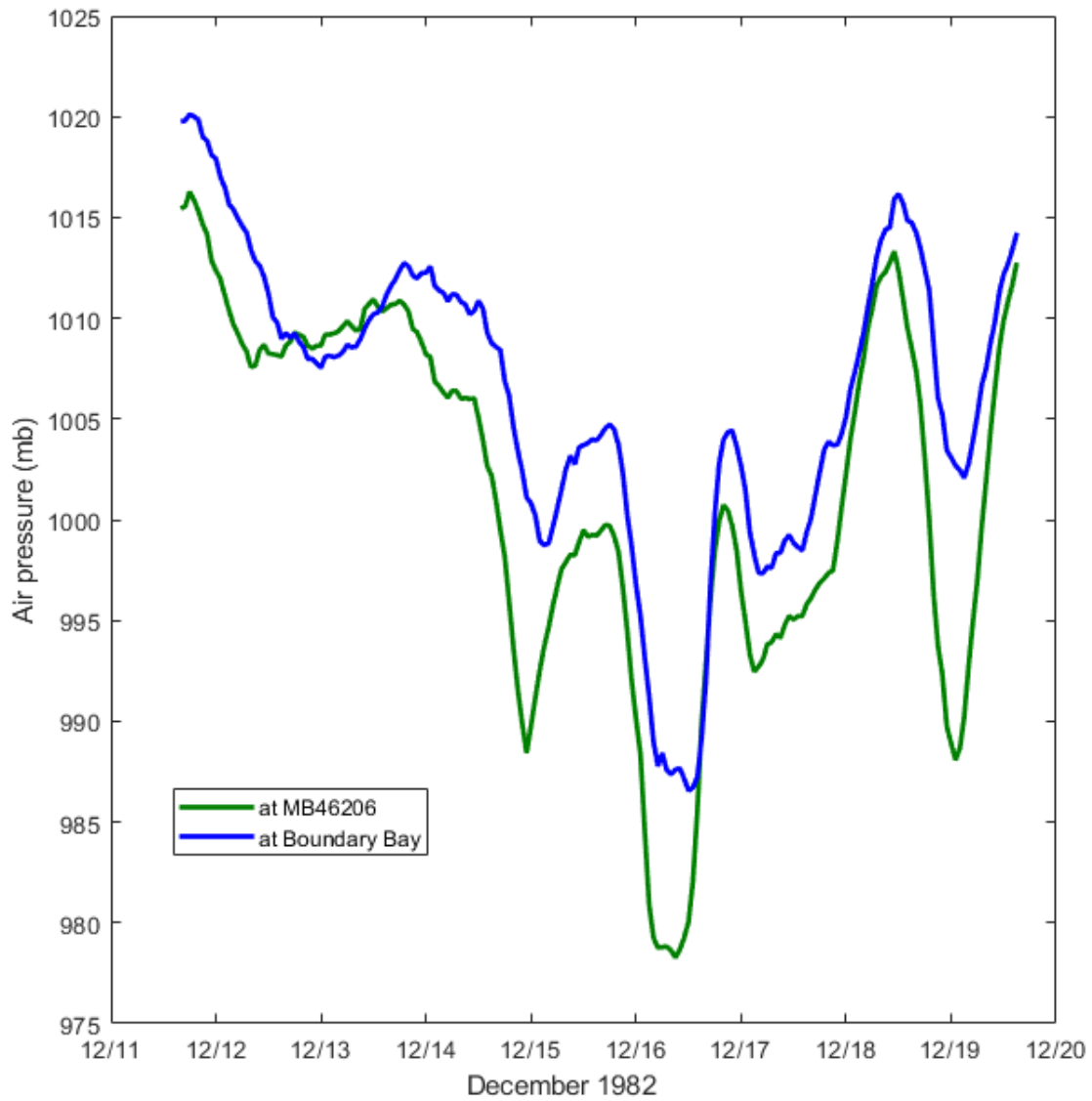


Figure 13. Atmospheric pressure in December 1982 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

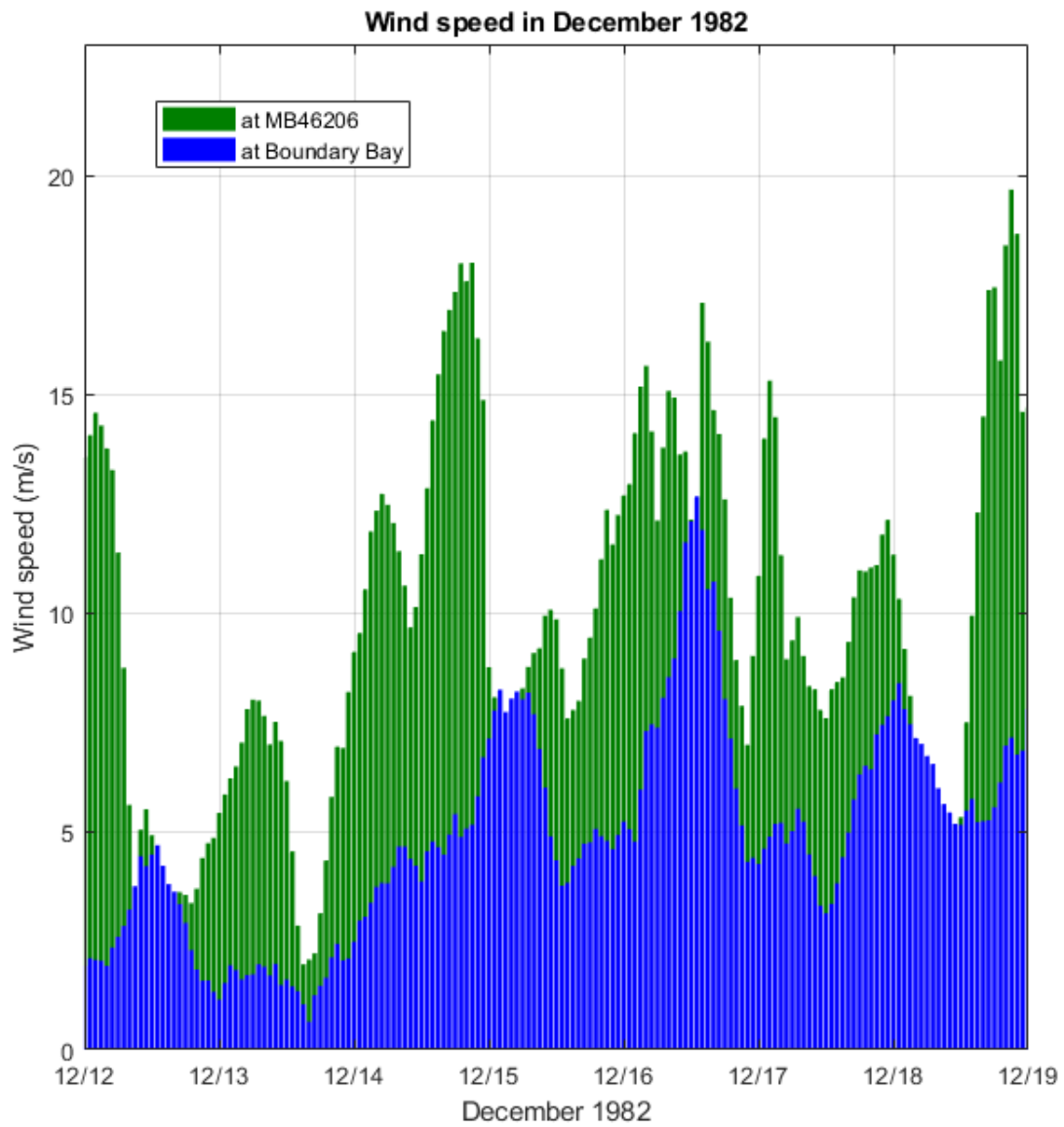


Figure 14. Wind speed in December 1982 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

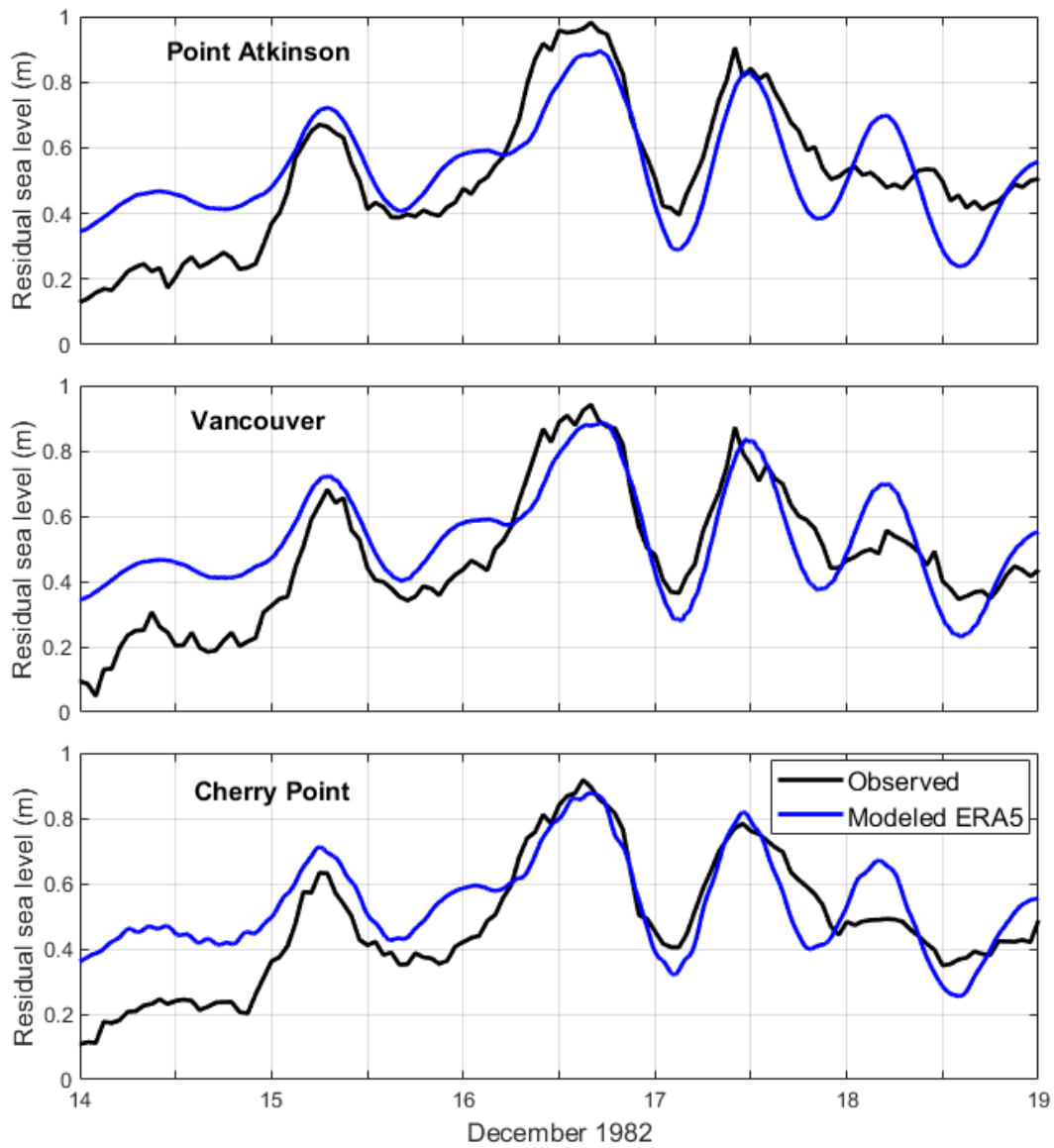


Figure 15. Comparison between the observed and modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of December 16, 1982 at the three tide gauge locations close to Boundary Bay.

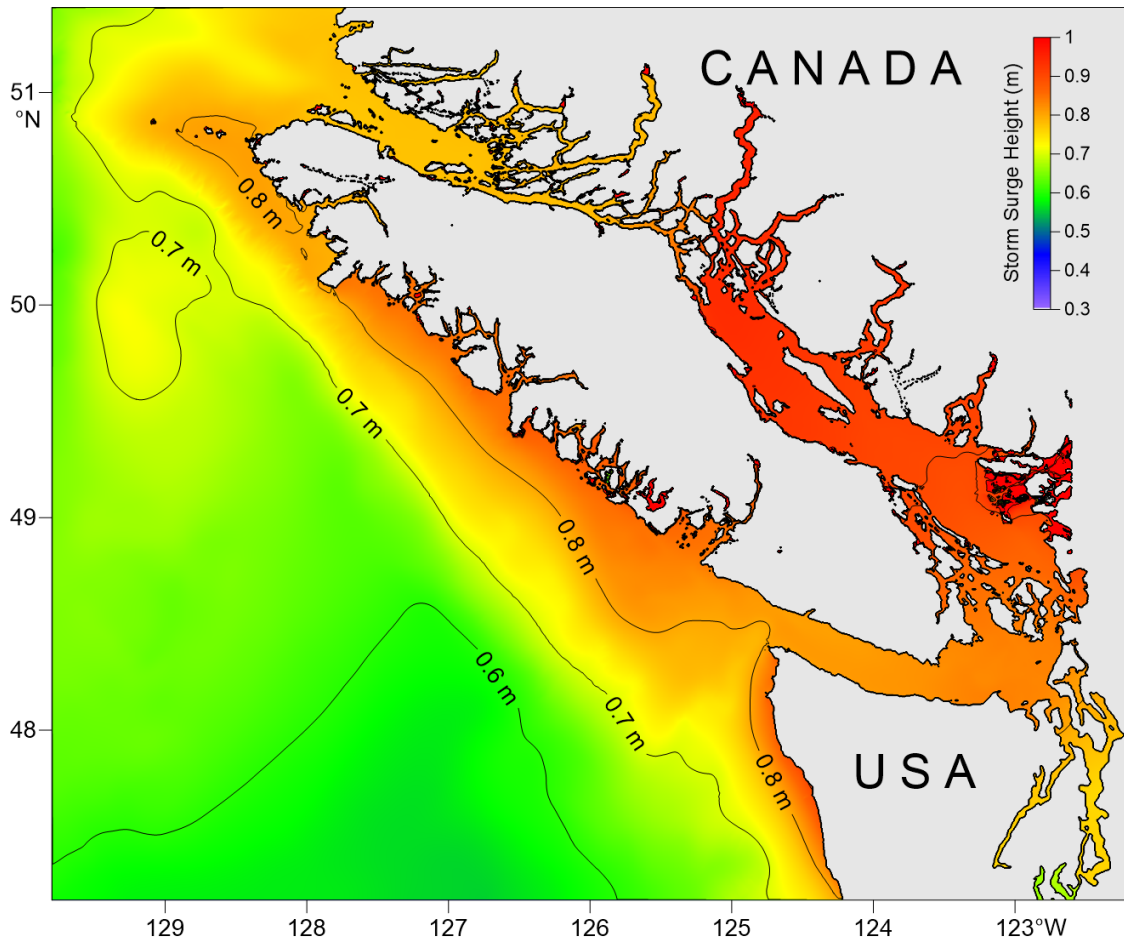


Figure 16. Distribution of the maximum residual sea level during the storm surge of December 16, 1982 at the outer domain.

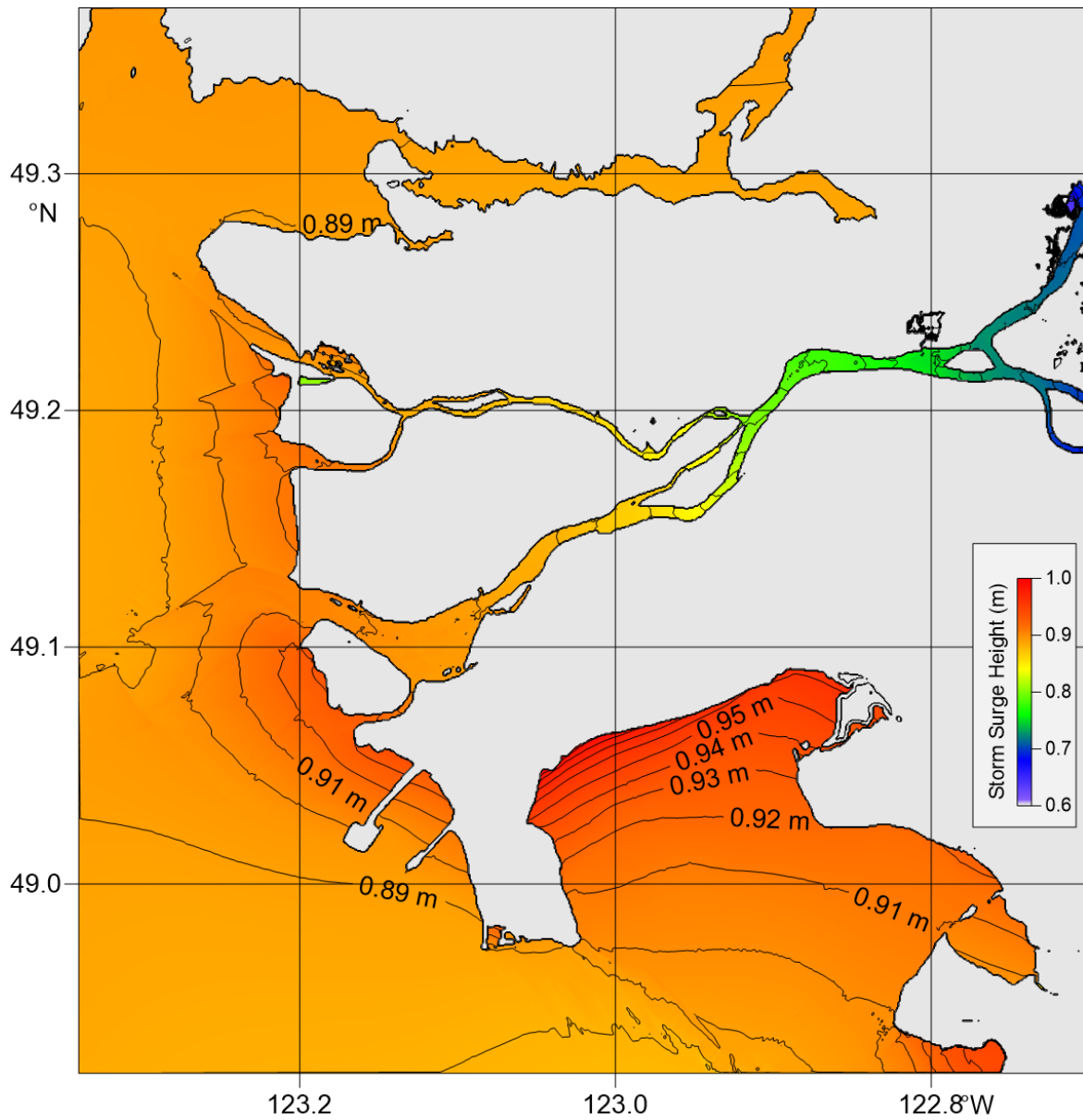


Figure 17. Distribution of the maximum residual sea level during the storm surge of December 16, 1982 at the inner domain (Vancouver and Boundary Bay area).

3.3. CASE 3: JANUARY 27, 1983. RANK NO. 1 AT POINT ATKINSON

On January 27, 1983, Metro Vancouver experienced an extreme tide event but no significant flooding. The peak water levels measured 5.48 metres at 500 PDT at Point Atkinson (Forseth, 2012). Weather conditions at the time of the peak water levels were rainy, with average wind speeds of 7 km/h from the southeast. There is no other specific information on this event. Because of the low wind speeds, the event was not related to a “windstorm”. The parameters of the depression (Table 1) show that the event was characterized by a small spatial extent and fast movement, whereby the dynamic pressure effect was of primary importance in generating the water level response.

The storm trajectory (Figure 18) shows that the system moved from the south, similar to the 1981 event, and crossed the central region of Vancouver Island. The pressures maps (Figure 19) reveal that the low had a small size and was superimposed on an existing low-pressure background. A sharp change in the atmospheric pressure at the shelf break and at Boundary Bay is seen in Figure 20. At meteorological buoy MB46206 (shelf break), the pressure was as low as 970 mb, but was not associated with strong winds, which were of weak-to-moderate at both locations (Figure 21).

The event was modelled using an eight-day simulation with the 2D nested-grid Princeton Ocean Model for the period 23 to 30 January, 1983, with model parameters described in Section 2. Figure 22 presents a comparison between the observed residual sea level and the modelled sea level at Point Atkinson, Vancouver and Cherry Point. It is evident that the model strongly underestimates the observed storm surge at all sites by ~ 20 cm (i.e., by 25-30%). The distributions of the maximum storm induced sea level variations over the grid domains are shown in Figures 23-24. The maximum modelled sea level surge at Boundary Bay and at Vancouver coast is distributed nearly uniformly, with values of 0.79-0.80 m. In contrast, the observations reveal that the storm surge reached ~ 1 m at Vancouver and Point Atkinson.

It is not immediately clear why the model underestimates the storm surge heights for this event. Because the event had the smallest size among the six case studies, it is possible that the grid was too coarse (a quarter degree step) for the atmospheric reanalysis to accurately represent the pressure field. Moreover, the pressure system was moving quite rapidly, which may have increased the dynamic effects of the pressure field, while limiting the ability of the model to reproduce the sea level response based on the 1-hour time step of the reanalysis field.

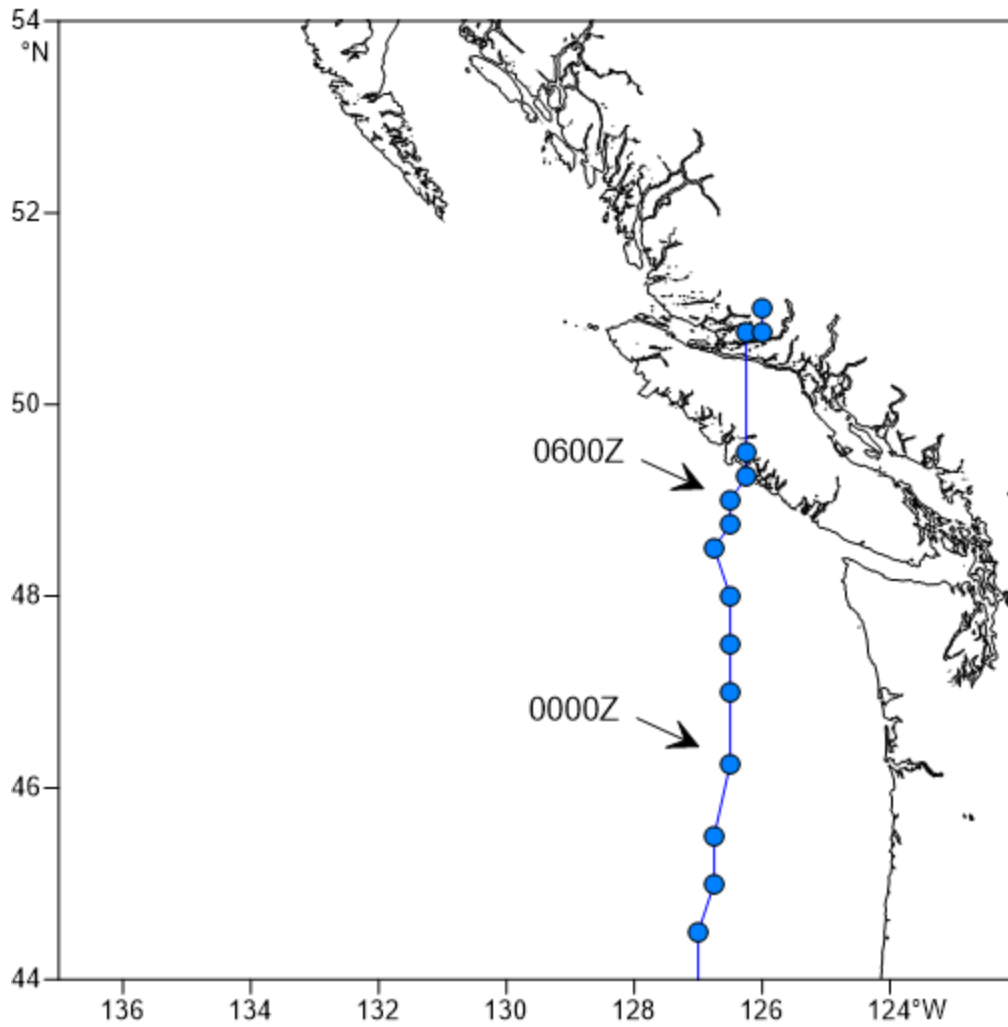


Figure 18. Path of the storm on January 27, 1983. Each point denotes the location of the low-pressure centre with a 1-hour step. Times are every hour in Greenwich Mean Time (Z).

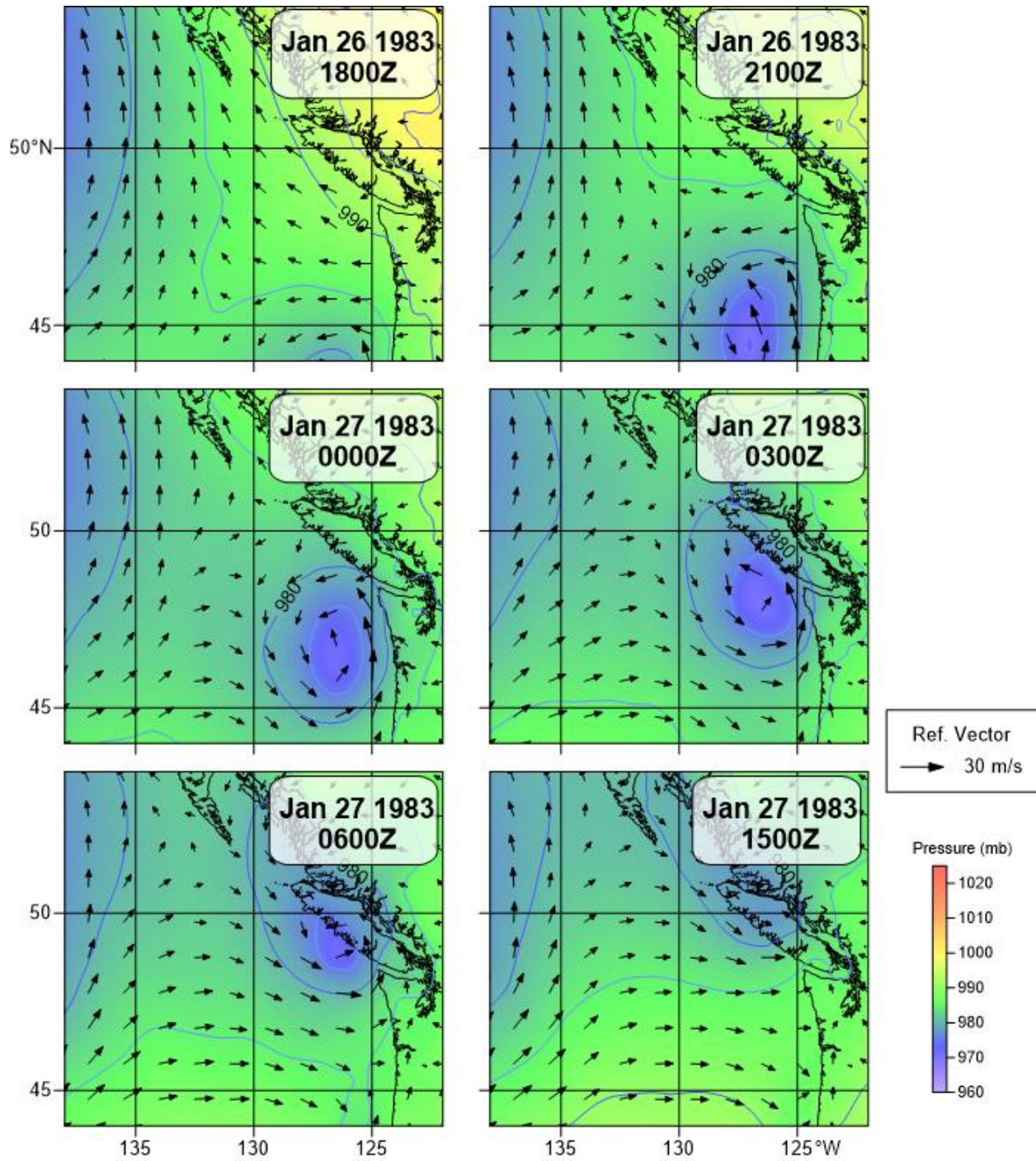


Figure 19. Wind velocity and sea level pressure conditions on January 27, 1983.

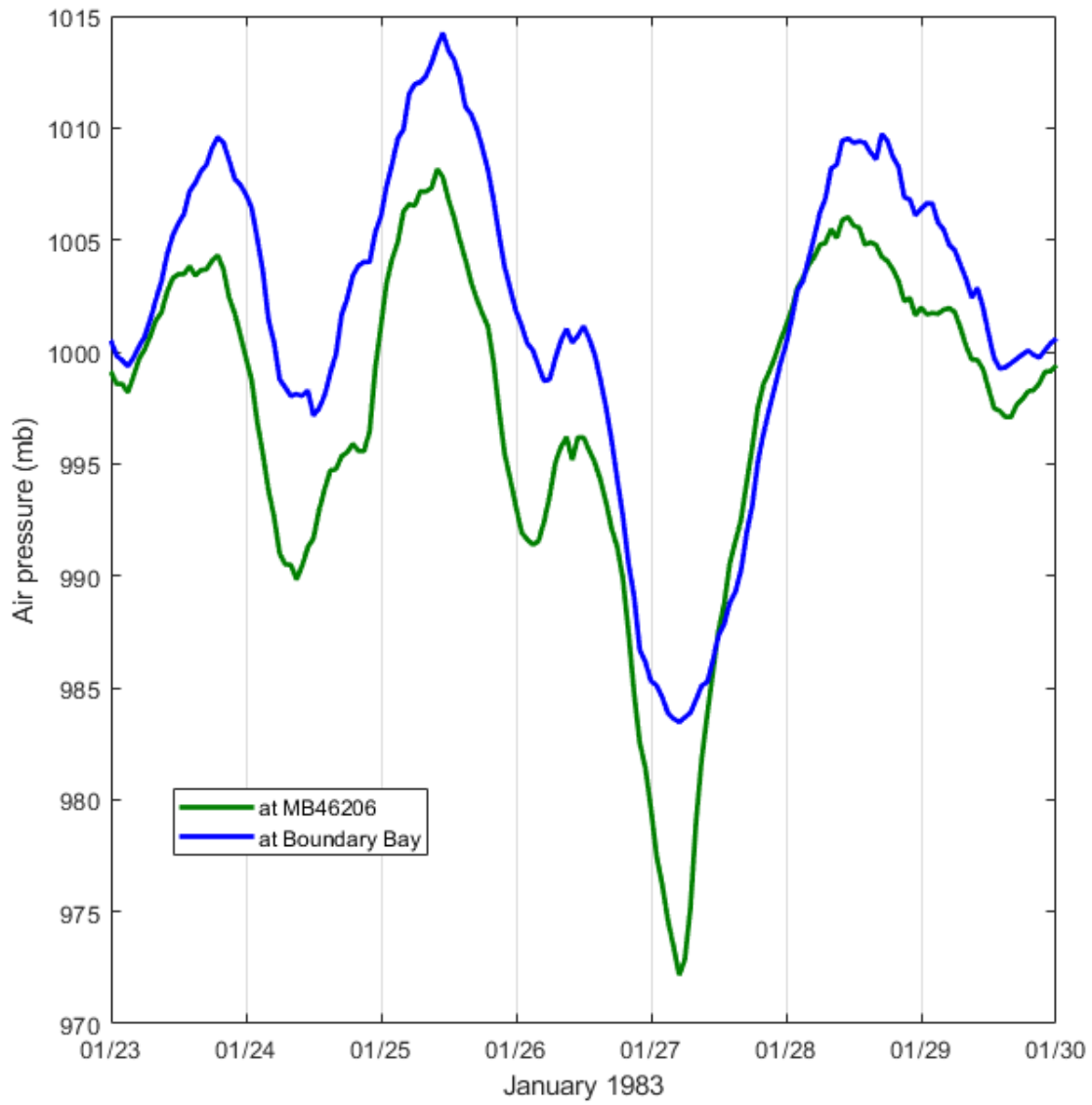


Figure 20. Atmospheric pressure in January 1983 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

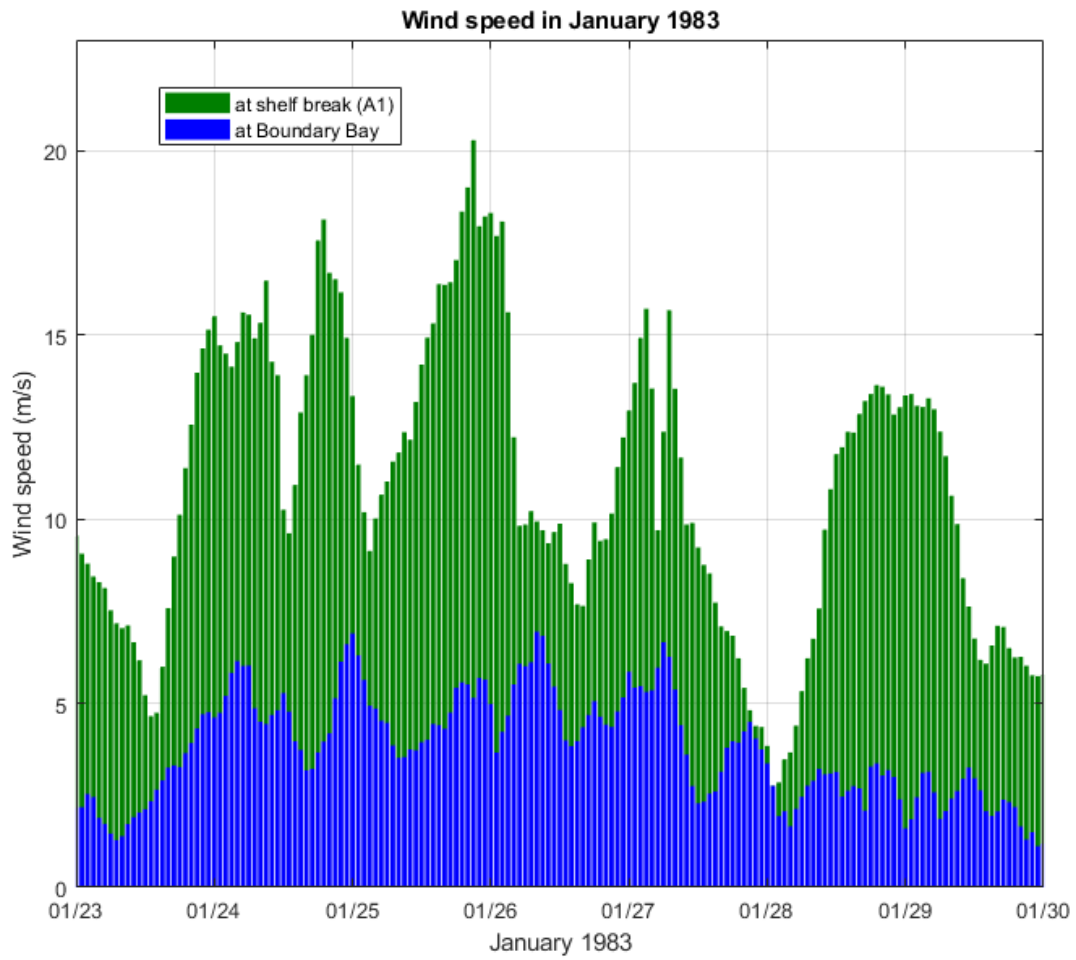


Figure 21. Wind speed in January 1983 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

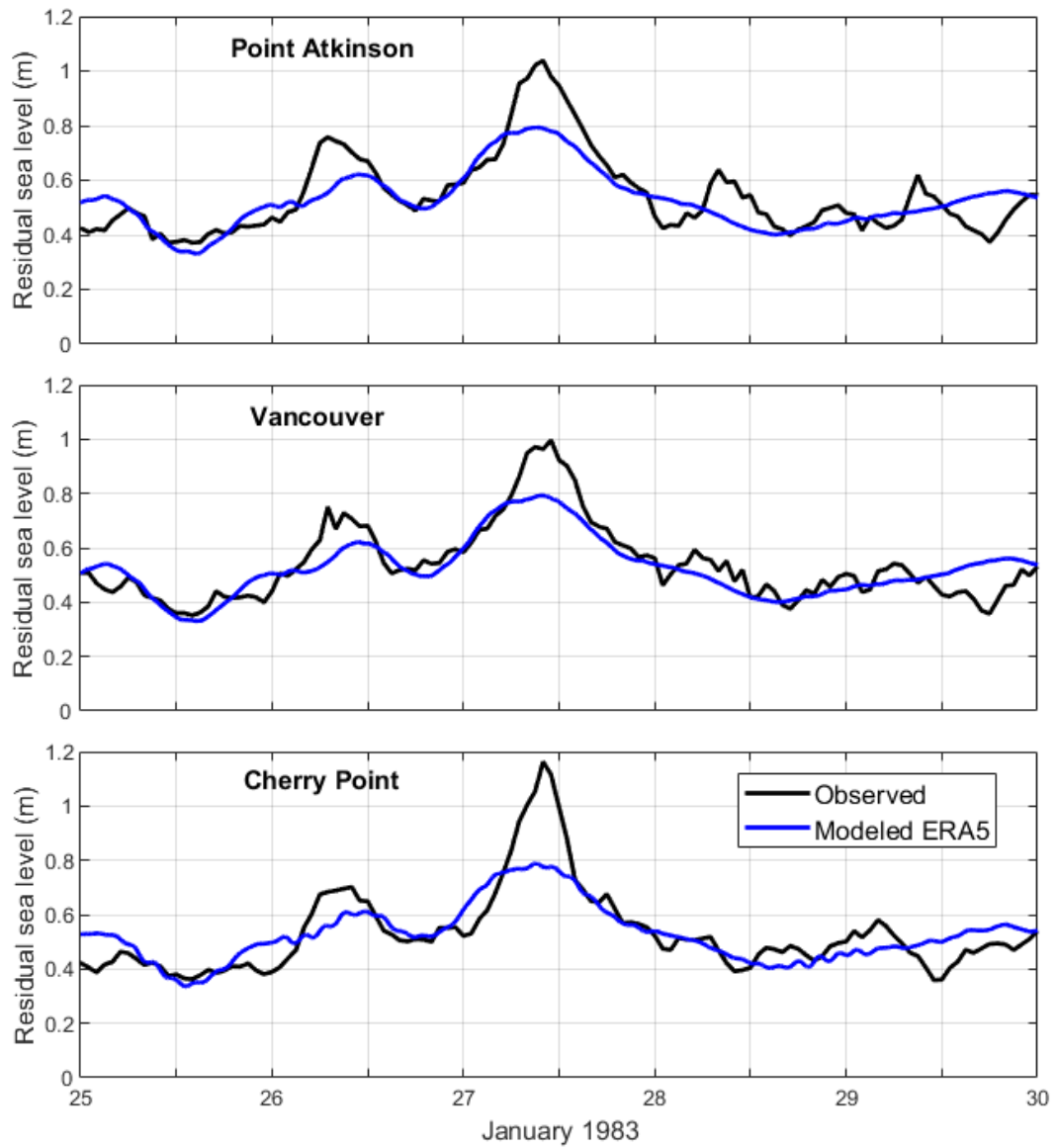


Figure 22. Comparison of the observed versus the modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of January 27, 1983 at three tide gauge locations close to Boundary Bay.

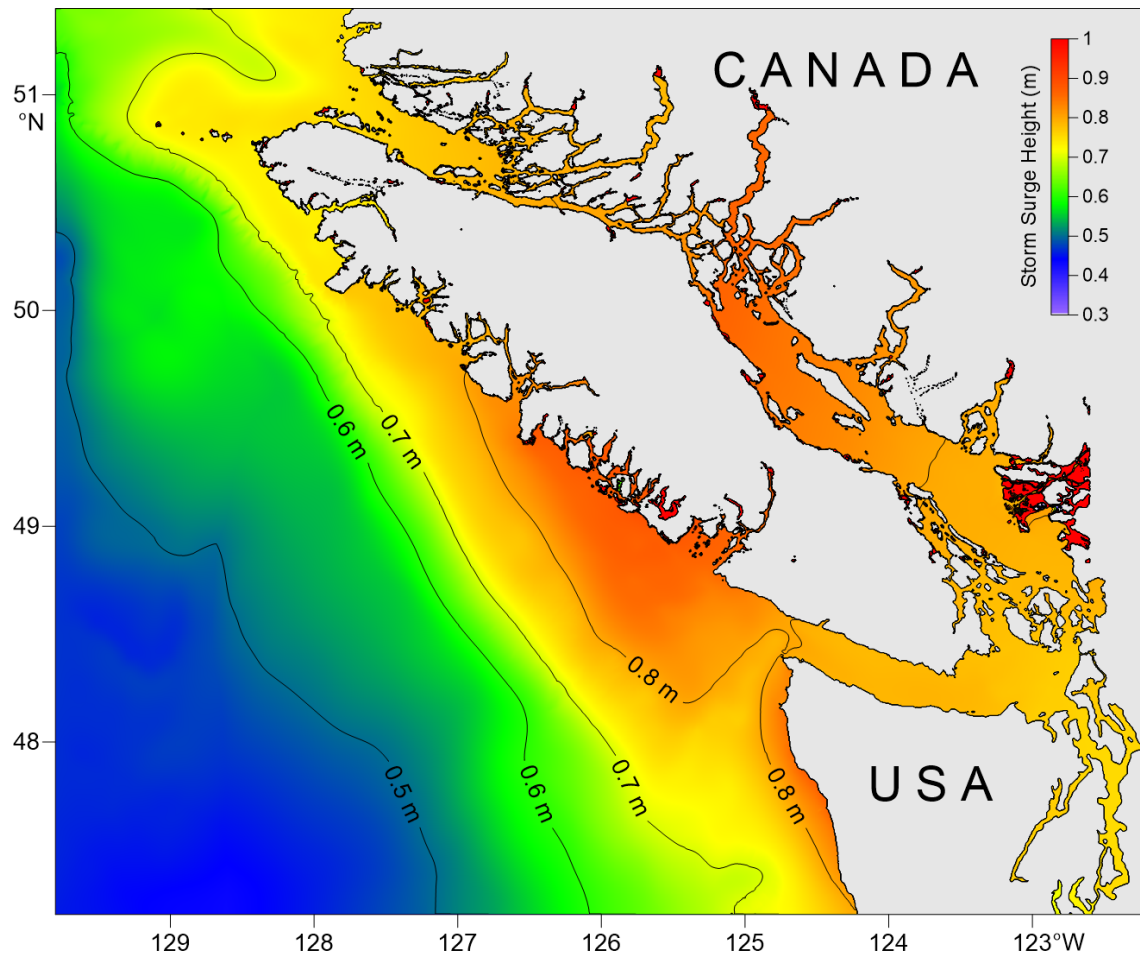


Figure 23. Modelled distribution of the maximum residual sea level during the storm surge of January 27, 1983 for the outer coastal domain.

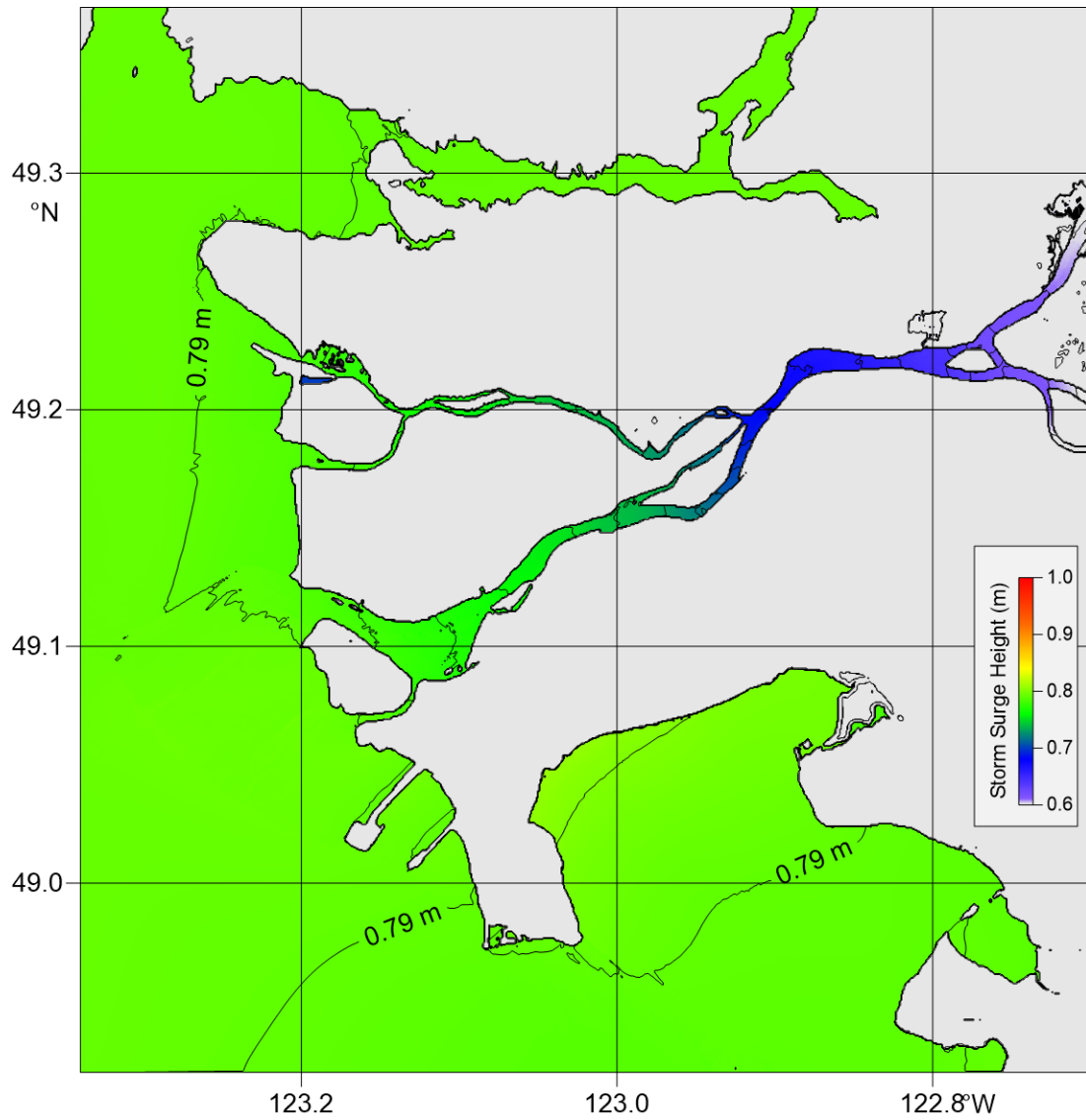


Figure 24. Modelled distribution of the maximum residual sea level during the storm surge of January 27, 1983 for inner domain (Vancouver and Boundary Bay areas).

3.4. CASE 4: JANUARY 1, 1997. RANK NO 3 AT POINT ATKINSON

The New Year's storm of 1997 caused no flooding in the Vancouver area as it was not coincident with an astronomical high tide. In his literature review, Forseth (2012) does not even mention the event, although the residual sea level from the storm was one of the highest in 40 years. In addition to the contributions from the inverse barometer effect and wind, the high residual level was partially due to the high sea surface setup associated with the major 1997-98 El Niño in the Pacific Ocean. The 1997 New Year also associated with an extreme snowfall event in Victoria during the last days of December 1996, which damaged island properties in the range of millions of dollars. The event was mentioned in the report by Read (2008) as one of the “major” windstorm events (i.e., when average peak wind gusts exceed 55 mph) in the 1996-2005 decade.

The sea surface air pressure associated with the storm fell to a very low minimum of 955 mb over a large area (Table 1, Figures 25-26). Remarkably, the trajectory of the depression (Figure 25) coincided with that of 1982 event, which also occurred during a major El Niño event. As with the 1982 and 1983 events, the atmospheric pressure drop at the shelf break (meteorological buoy MB46206) was much deeper than over Boundary Bay (Figure 27). The recorded winds also were markedly stronger at MB46206 than at Boundary Bay (Figure 28).

An eight-day simulation of the event was performed using the nested-grid 2D POM model. Figure 29 compares the modelled records with the observations at two nearby located tide gauges, Point Atkinson and Vancouver. As indicated, the model accurately predicts the high surge amplitudes, albeit with time lags between the model and observed records.

Figures 30 and 31 shows the distribution of the surge crests over the outer and inner model domains. High surge crests (more than 0.8 m) are obtained around Vancouver Island, with smaller surge values in the deep offshore regions. The modelled storm surges at Boundary Bay vary between 0.95 m and 1 m.

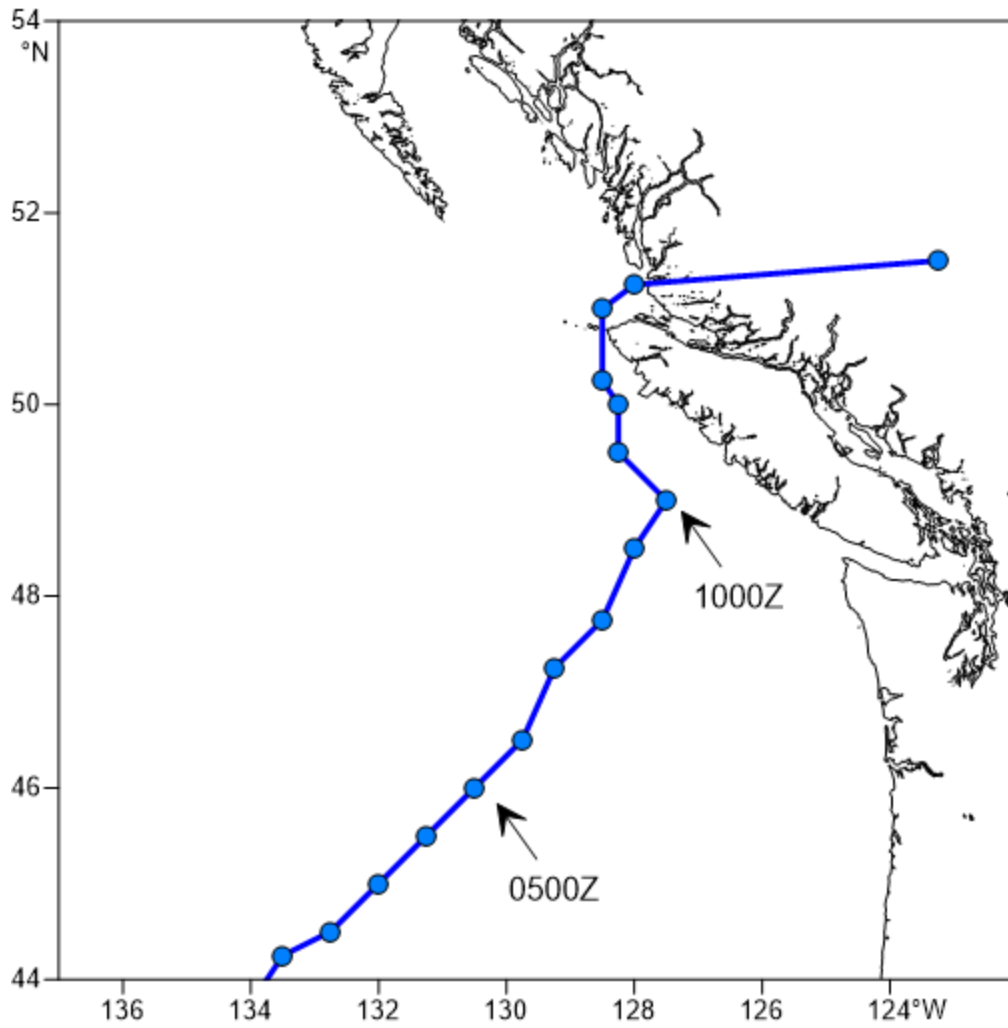


Figure 25. Path of the storm of January 01, 1997. Each point denotes the location of the cyclonic wind centre at 1-hour time steps. Times are in Greenwich Mean Time (Z).

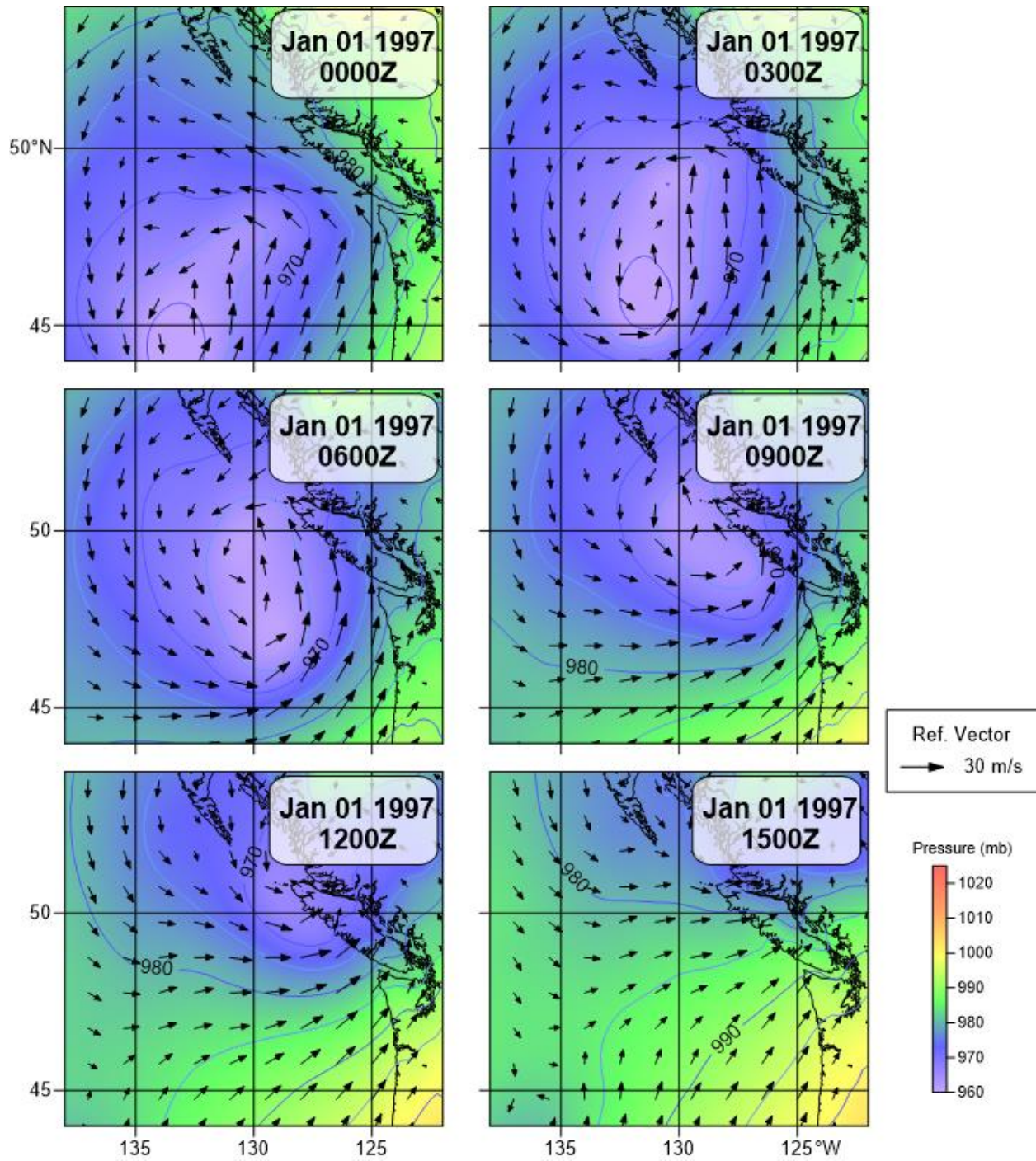


Figure 26. Surface wind velocity and air pressure conditions during January 01, 1997.

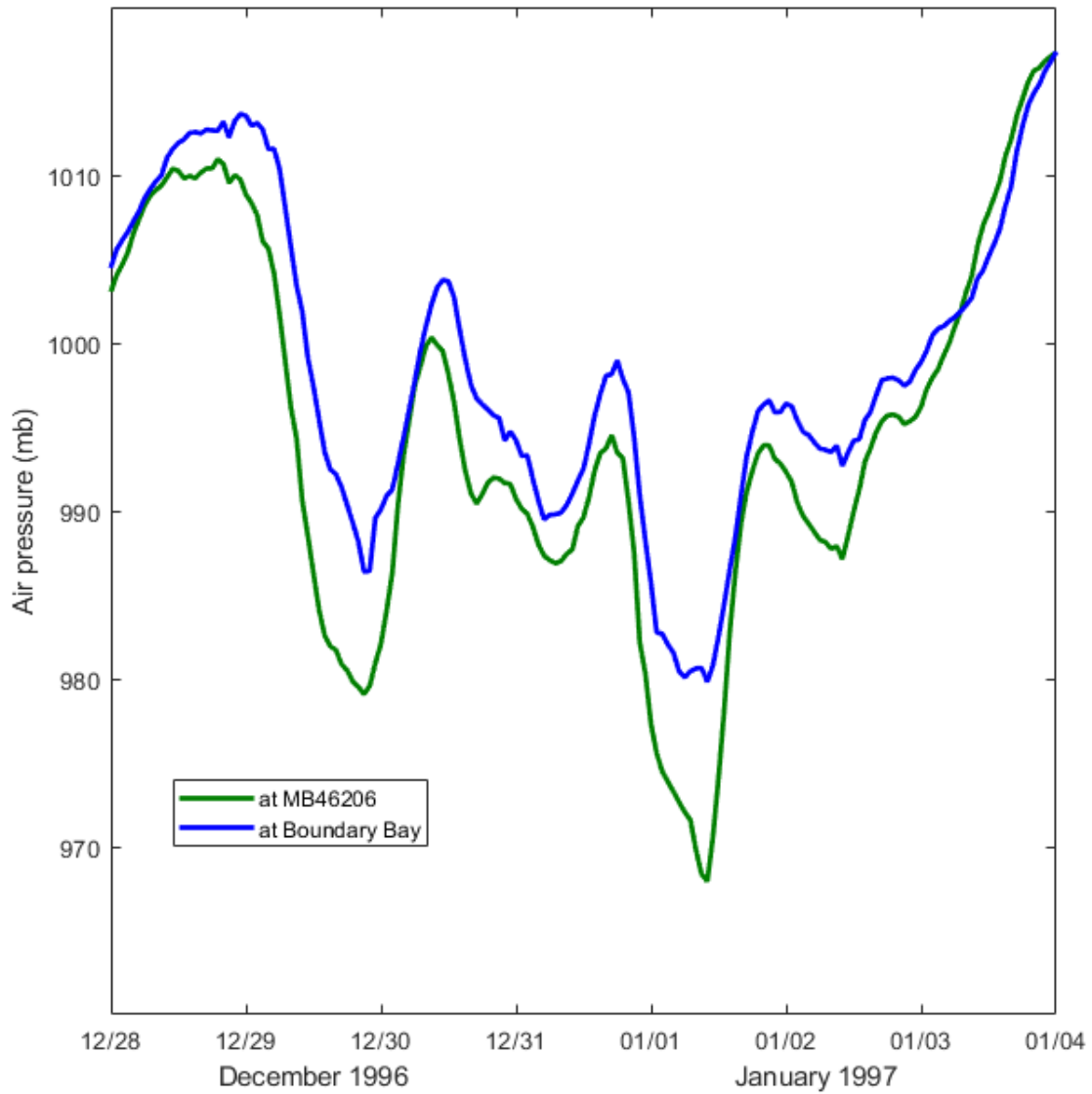


Figure 27. Atmospheric pressure in December 1996-January 1997 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

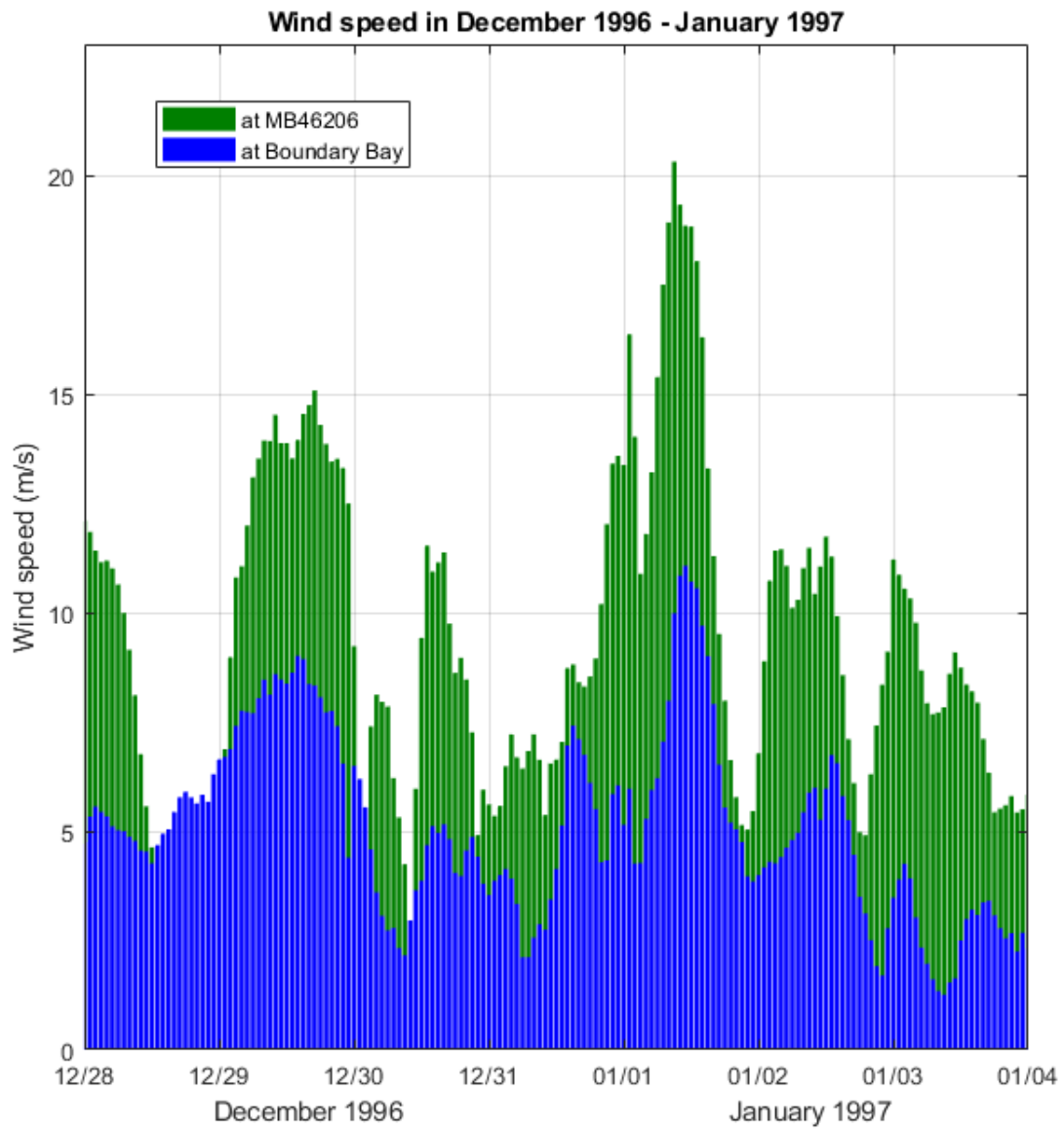


Figure 28. Wind speed from December 1996-January 1997 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

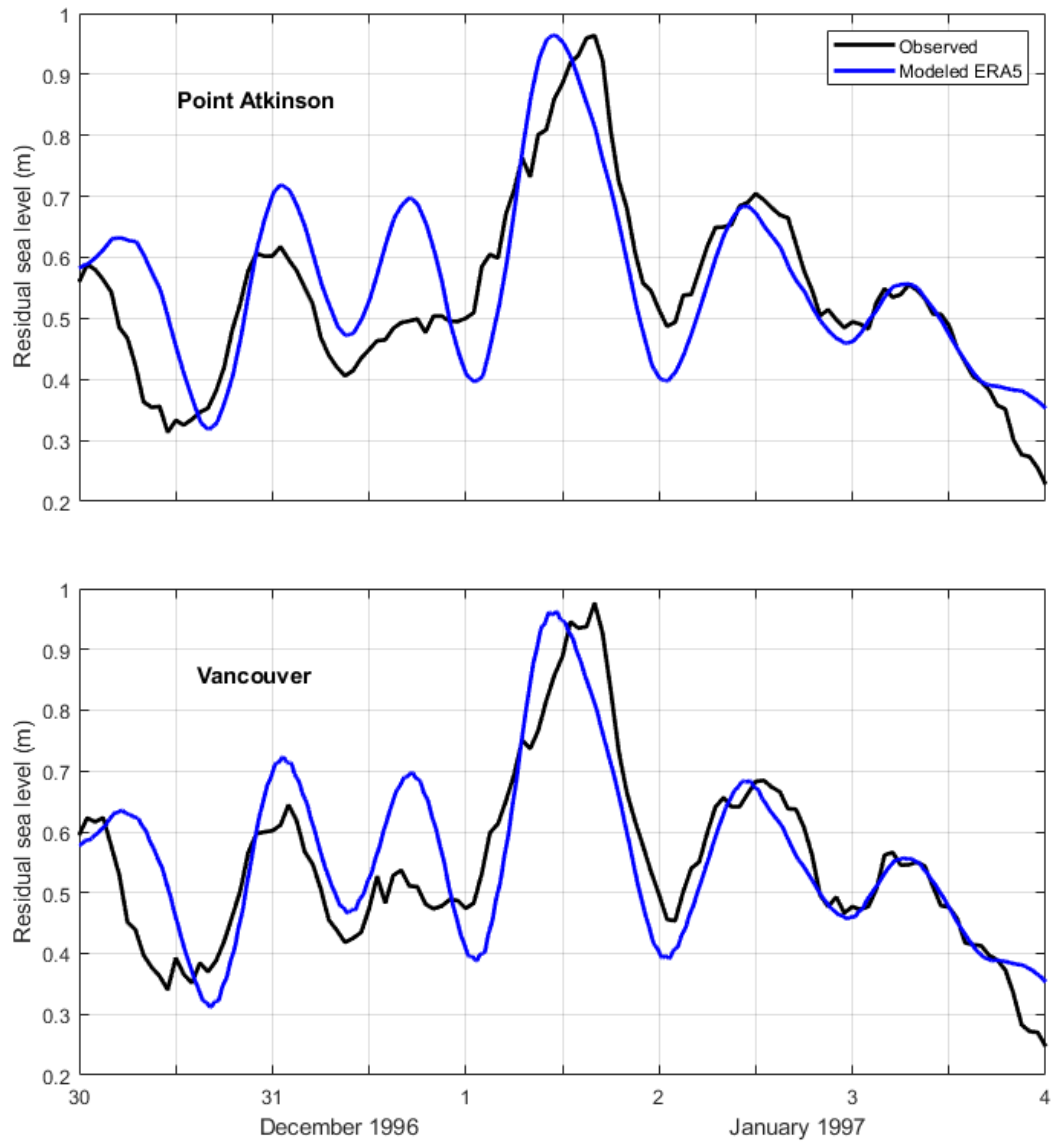


Figure 29. Comparison between the observed with modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of January 1, 1997, at two tide gauges located close to Boundary Bay.

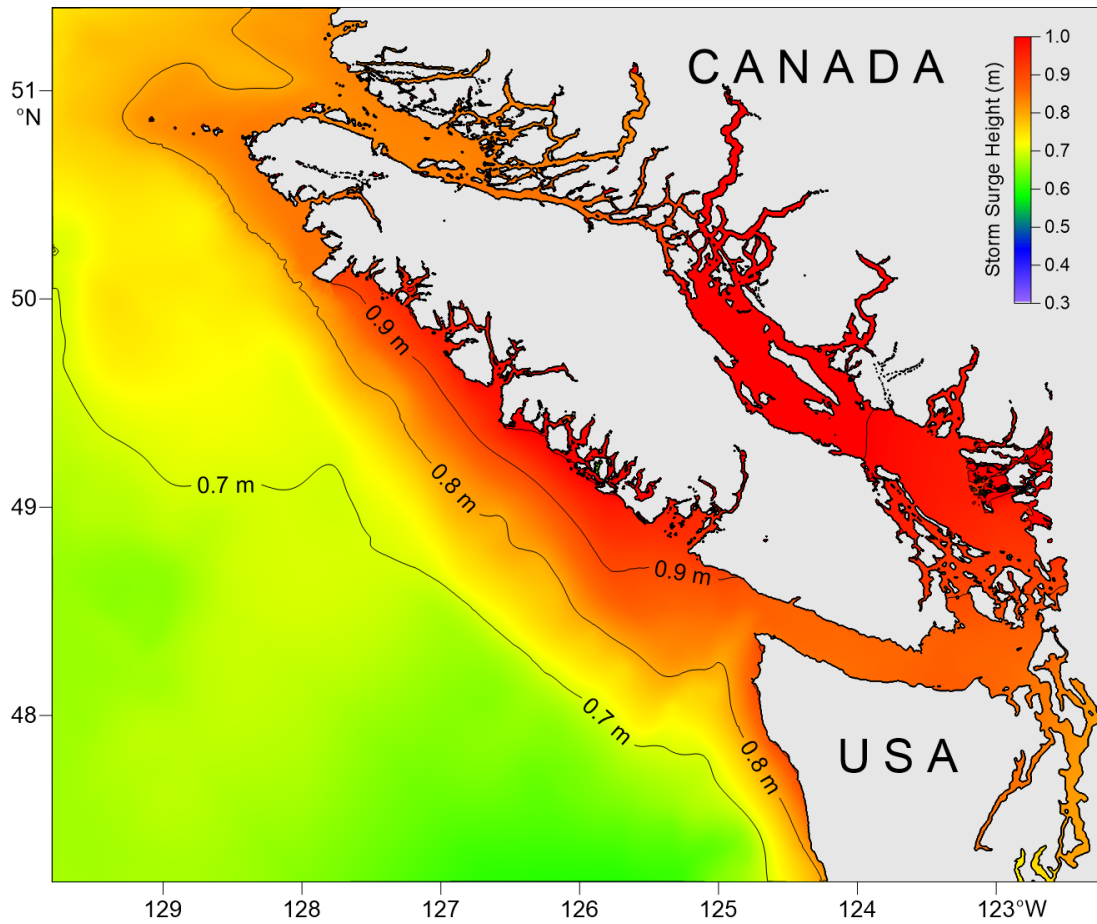


Figure 30. Modelled distribution of the maximum residual sea level during the storm surge of January 1, 1997 for the outer coastal domain.

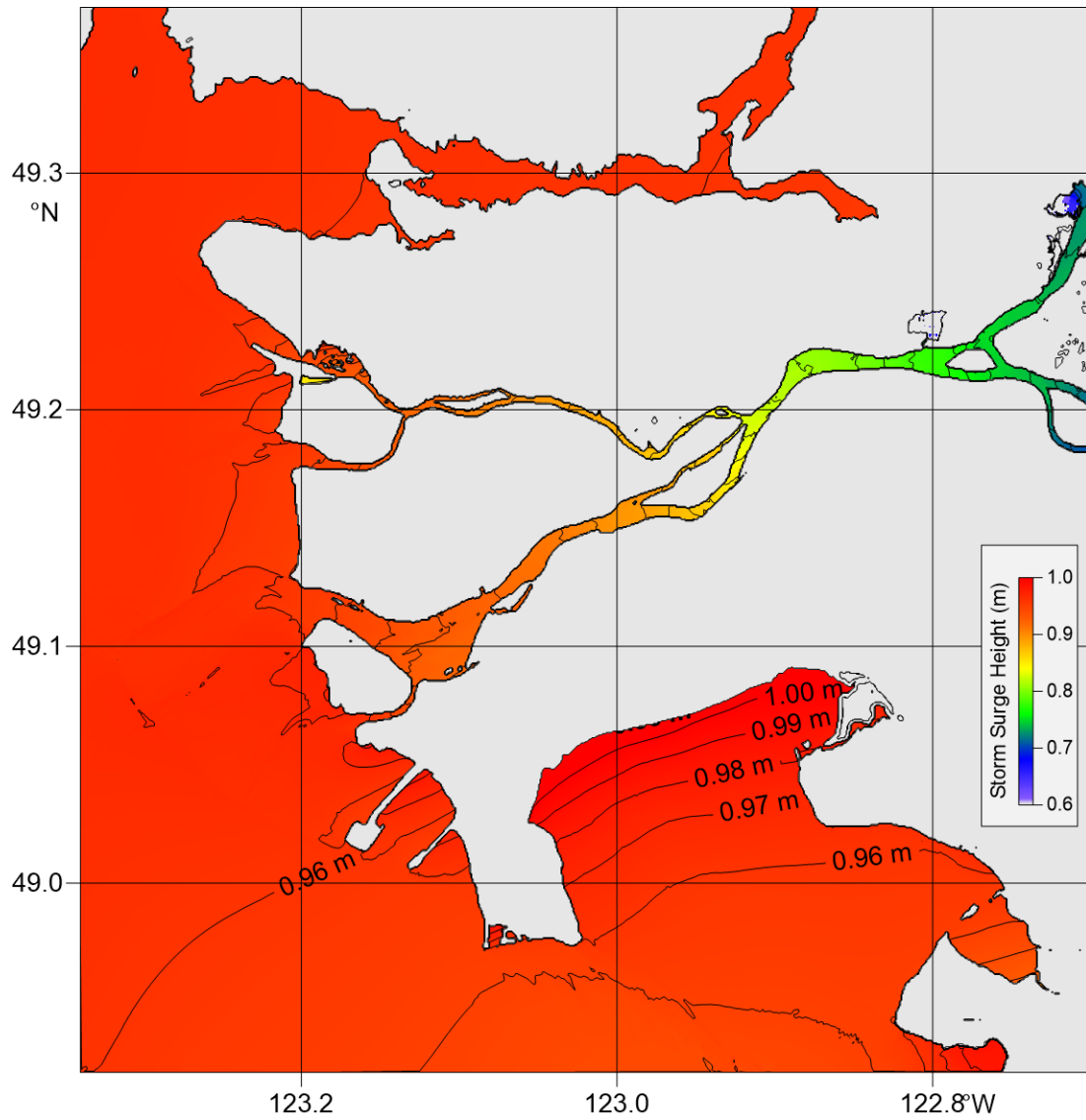


Figure 31. Modelled distribution of the maximum residual sea level during the storm surge of January 1, 1997 for the inner model domain (Vancouver and Boundary Bay areas).

3.5. CASE 5: FEBRUARY 4, 2006. RANK NO 6 AT POINT ATKINSON

On February 4, 2006, a vigorous storm packing winds of 60 to 100 km/h tore through southwestern BC. The storm closed bridges, cancelled ferries and flooded entire neighbourhoods in South Delta. The combination of high tides and vicious winds left yards under water. The mayor declared a state of emergency and some locals described it as the worst storm in 50 years. In addition to the flooding in Delta, the storm created problems in other parts of the Lower Mainland and Vancouver Island, felling trees and damaging power lines. BC Hydro reported that more than 80,000 homes across BC's southwest corner lost power.

The peak water level 5.446 m above Chart Datum (CD) coincided with an extreme high tide and flooding in Delta, affecting 150-200 homes (Forseth, 2012).

The initial path of the storm was among the more northern paths we investigated, arriving at Vancouver Island at its northern corner (Figure 32). Atmospheric pressures within the depression centre were as low as 966 mb (Figure 33), and along with a high-pressure background, created impressive pressure variations and, accordingly, a major windstorm. The minimum air pressure at the shelf break was 981 mb, and at Boundary Bay it was above 990 mb (Figure 34). Strong winds of up to 21 m/s were observed at the shelf break, while at Boundary Bay, wind speeds were up to 12 m/s (Figure 35).

The event was previously modelled by Soontjens et al. (2016) as one of five storm surge events of 2006-2012. They used a 3D MEMO model, which has ~500 m horizontal resolution and lateral boundary conditions forced by the actual sea level observations at Tofino and Port Hardy. The model provides a good estimation of the storm surges observed at the Victoria, Patricia Bay, Point Atkinson, and Campbell River tide gauges.

For this project, we modelled the sea level variations using the 2D nested-grid POM for the eight-day period from January 31 to February 7, 2006, using the model parameters outlined in Chapter 2. Figure 36 is a comparison between the observed residual sea level and the modelled sea level at Point Atkinson, Vancouver and Cherry Point.. The modelled records fit the observations through much of the event, although the central peak of the storm surge on February 4 was underestimated. Figures 37 and 38 show the distributions of the maximum sea level over the model domains. Modelled sea level maxima at Boundary Bay vary from 0.74 m at the entrance of the bay to 0.79 m at its northern edge.

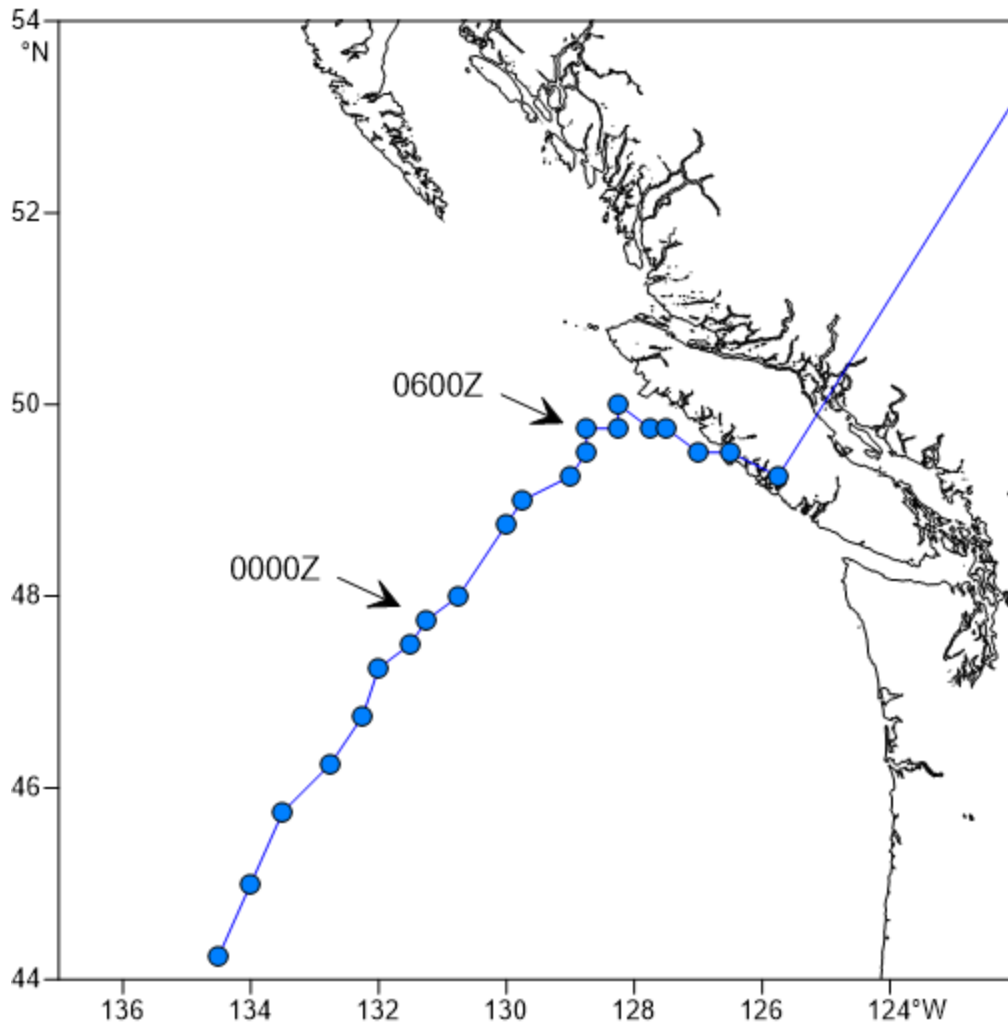


Figure 32. Path of the storm of February 4, 2006. Each point denotes the location of the storm centre at 1-hour time steps. Z denotes Greenwich Mean Time.

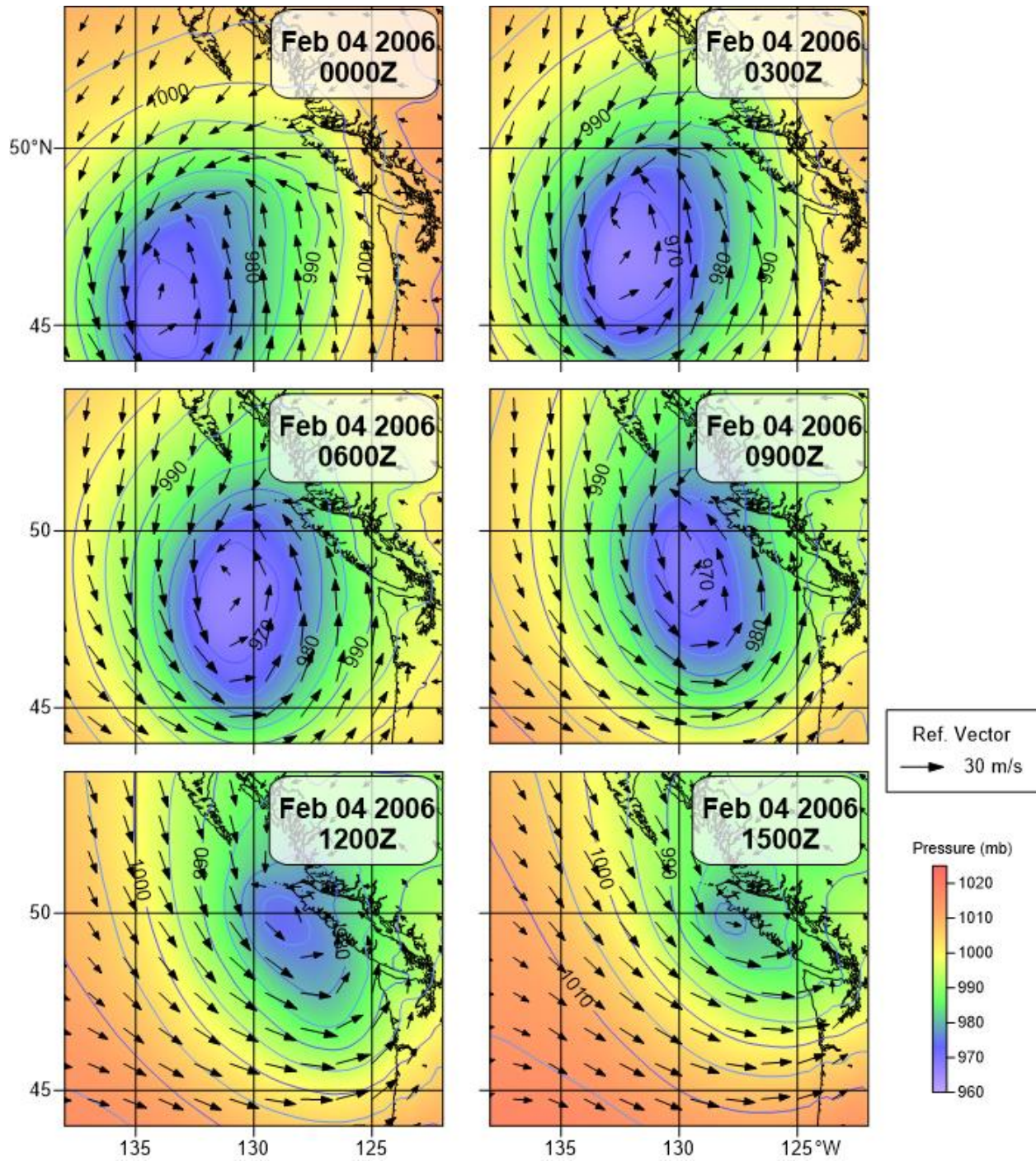


Figure 33. Wind velocity and sea surface air pressure on February 04, 2006.

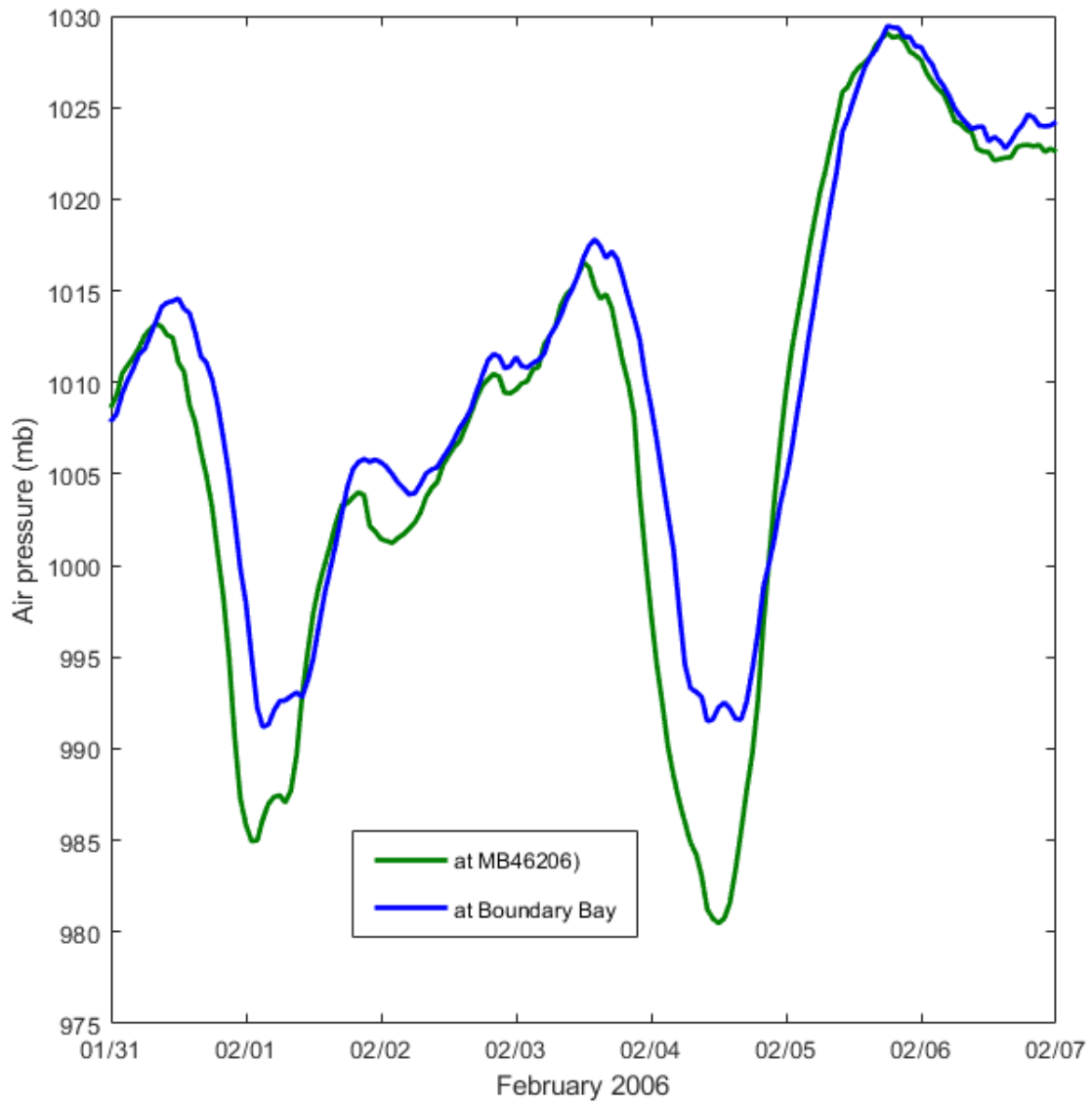


Figure 34. Atmospheric sea level pressure on February 2006 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

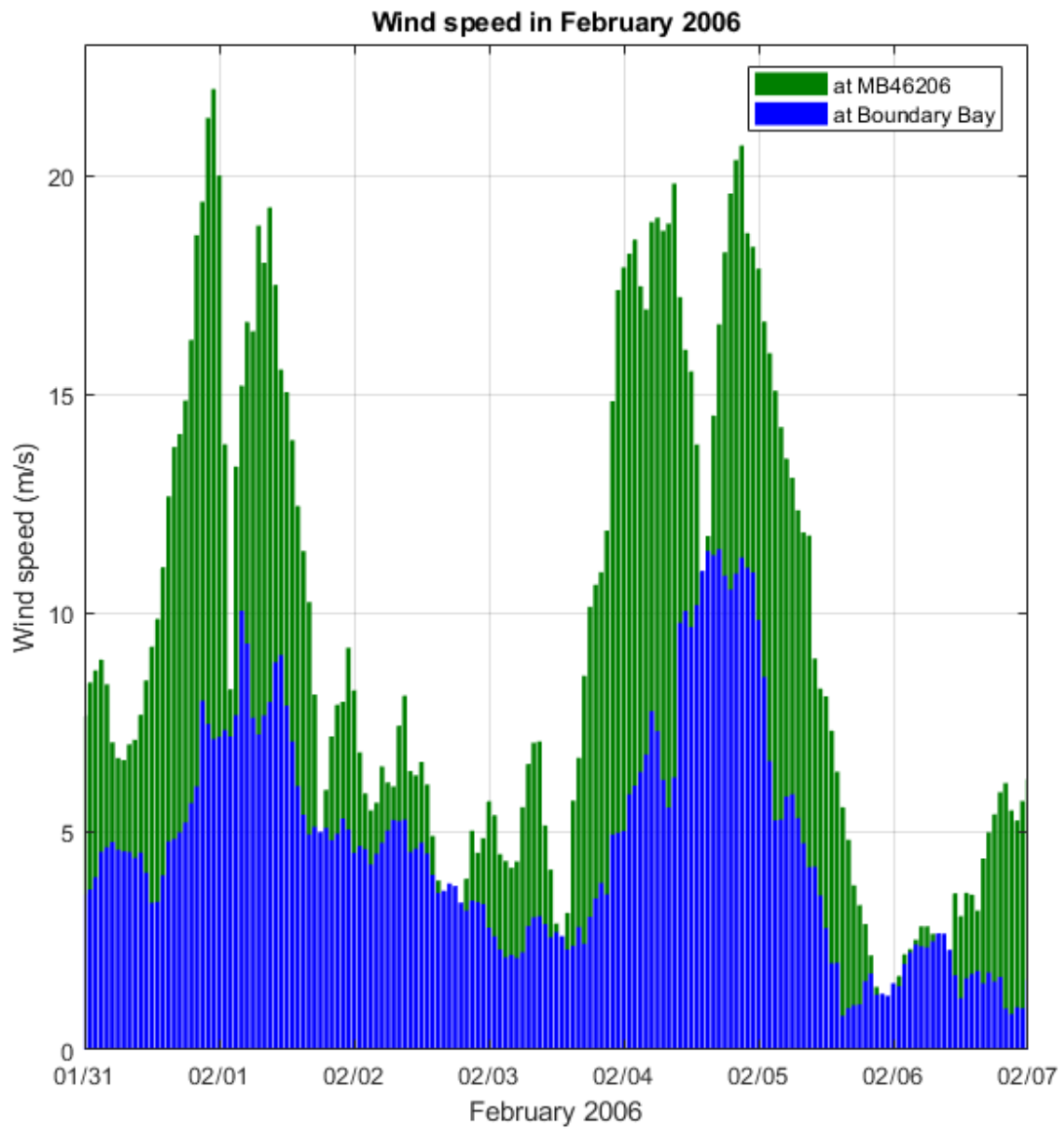


Figure 35. Wind speed in February 2006 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

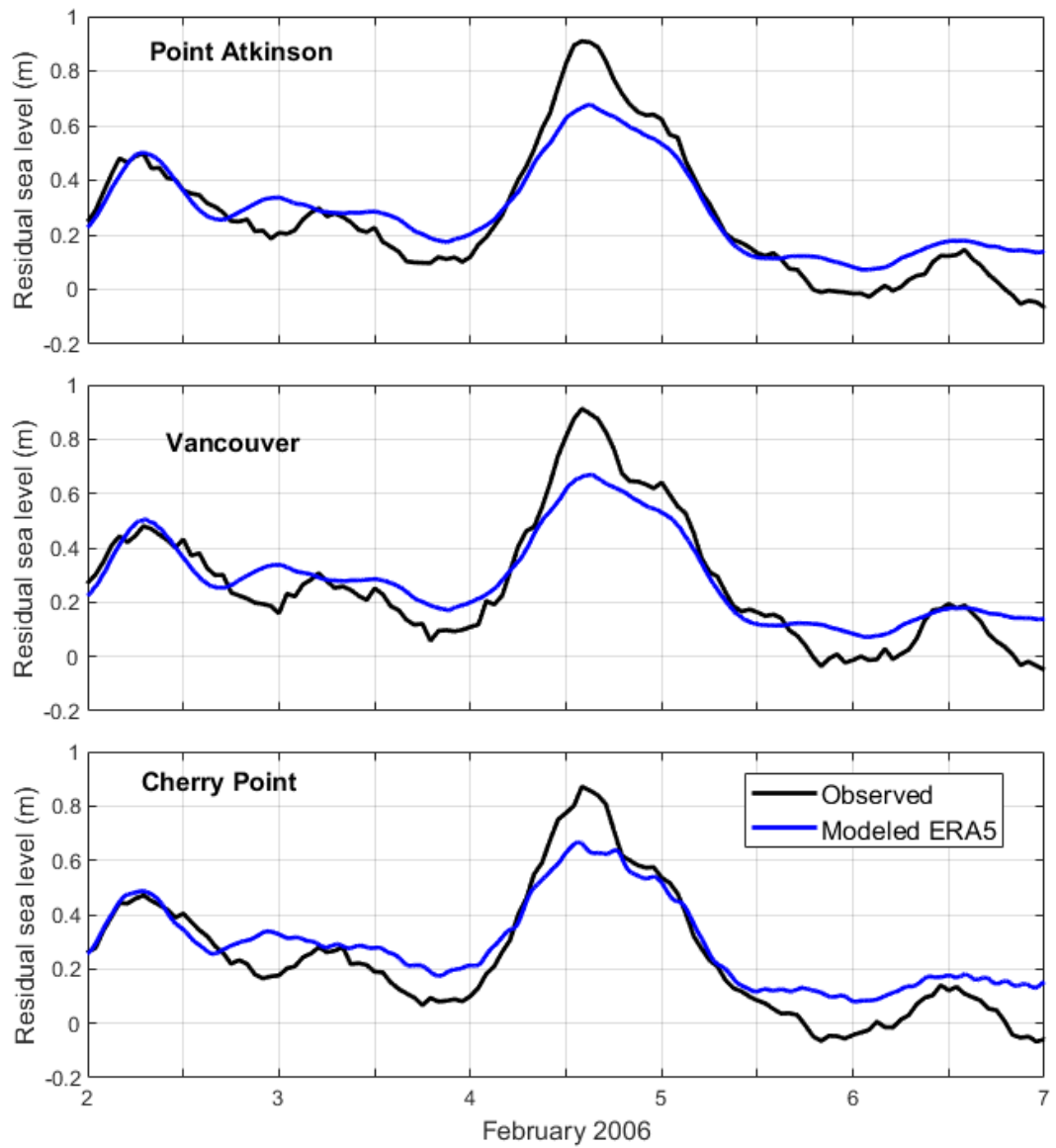


Figure 36. Comparison of the observed with modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of February 04, 2006 at three tide gauge locations close to Boundary Bay.

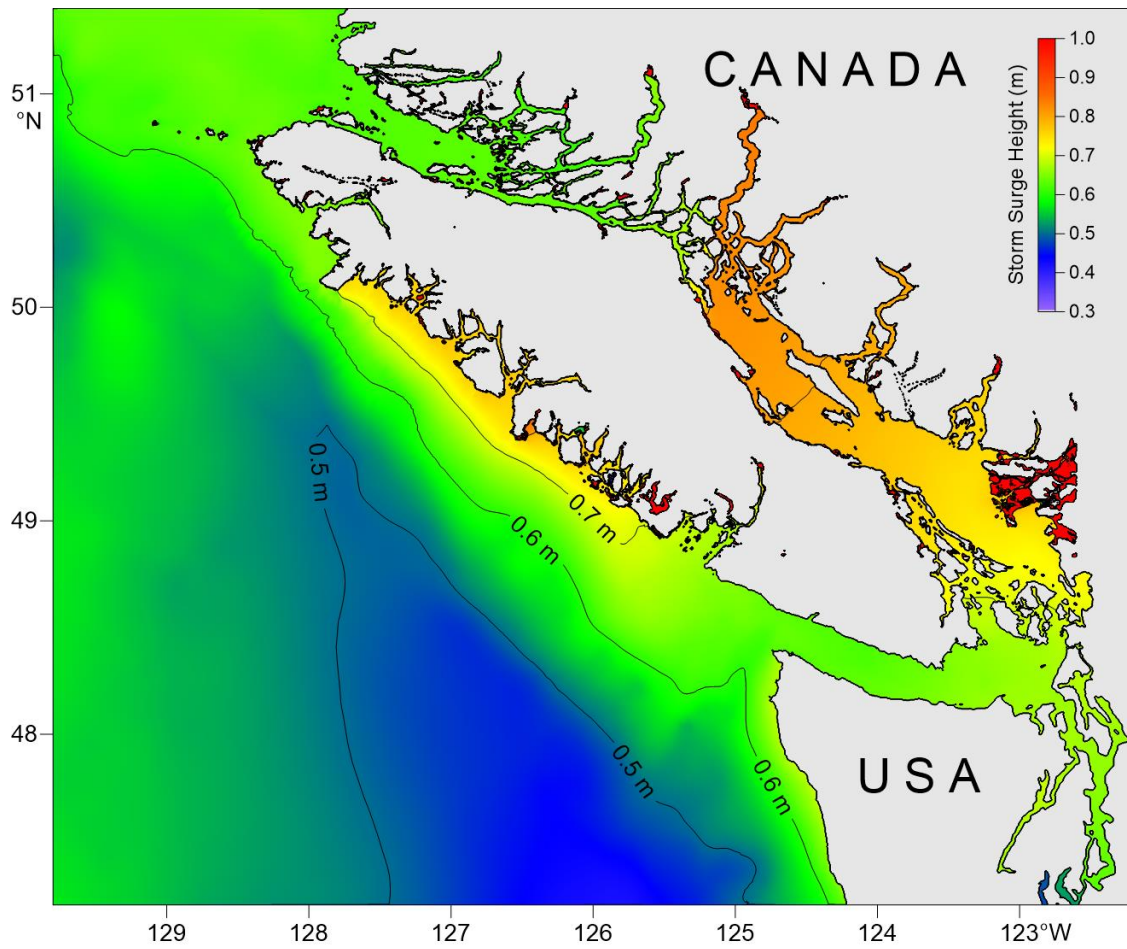


Figure 37. Modelled distribution of the maximum residual sea level during the storm surge of February 04, 2006 for the outer coastal domain

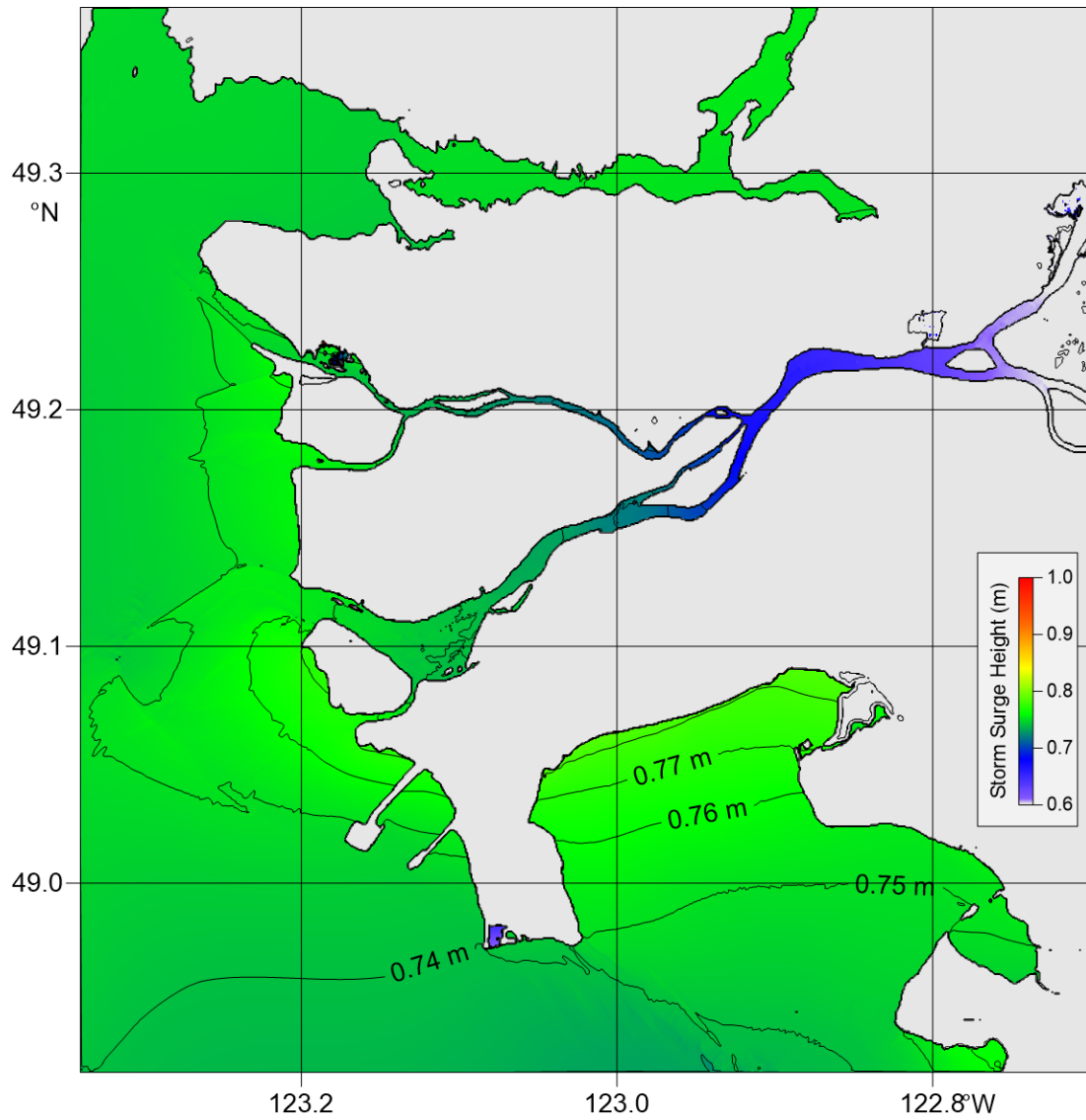


Figure 38. Modelled distribution of the maximum residual sea level during the storm surge of February 04, 2006 for the inner domain (Vancouver and Boundary Bay areas).

3.6. CASE 6: DECEMBER 15, 2006. RANK NO 4 AT POINT ATKINSON

The fall storm season of 2006 finished with a major windstorm on 15 December 2006, named the as “Hannukah Eve storm”. The windstorm caused major damage, as Washington and Oregon reported about \$220 million in insured damage, while in British Columbia the total damage was about 80 million (https://en.wikipedia.org/wiki/Hanukkah_Eve_windstorm_of_2006). Washington State reported 18 deaths related to the windstorm.

The windstorm caused significant damage throughout Metro Vancouver, most notably in Stanley Park, but there are no records of flooding or inundation (Forseth, 2012). Peak water levels reached just over 4.48 m at 400 PDT, which is about 1 m less than for the pervious event. The lower peak is due to the fact that there was not a high astronomical tide at the peak of the storm surge.

The storm moved in the northeastern direction, crossed Vancouver Island and on December 15 arrived at the mainland coast of southern British Columbia (Figures 39 and 40). Reanalysis pressure and wind data show that the storm had a minimum pressure of 975 mb and maximum wind speeds of 27 m/s (Table 2). At the shelf break, pressure fell to 976 mb, and at Boundary Bay to 980 mb (Figure 41), indicating that the system was still strong when it entered the Vancouver area. However, the reanalysis data show that the wind speed in Boundary Bay was below 9 m/s (Figure 42). The weak wind speeds provided by the reanalysis records are contrary to the wind observations at Vancouver and to the major damage in the area from the windstorm.

The event was previously modelled in Soontients et al. (2016) as one of five storm surge events in 2006-2012. Based on the observations, the authors estimated a residual sea level at Point Atkinson of 0.94 m, but the model provided only a 0.7 m surge. No explanation for this discrepancy was provided.

Here, we have modelled the sea level variations using the 2D POM for the eight days from 11 to 18 December, 2006. Figure 43 shows a comparison between the observed residual sea level and the modelled sea level at Point Atkinson, Vancouver and Cherry Point. The modelled seas levels closely fit the observations over much of the records, although the central peak of the storm surge on December 16 is underestimated. Figures 44 and 45 show the distributions of the maximum sea level residual over the model domains. In this case, maximum modelled sea level residuals at Boundary Bay vary from 0.80 m at the entrance of the bay to 0.82 m at northern edge.

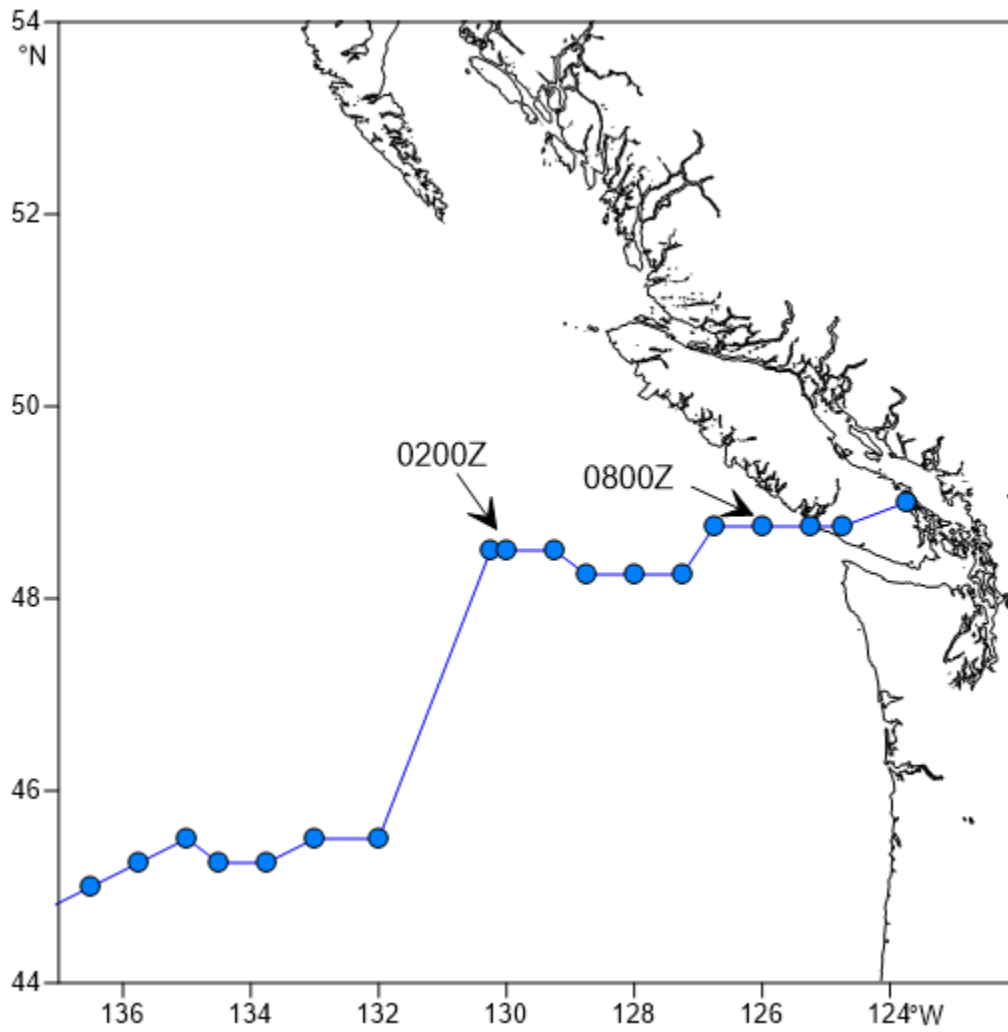


Figure 39. Path of the storm of December 15, 2006. Each point denotes location of the storm centre at 1-hour time steps. Z is Greenwich Mean Time.

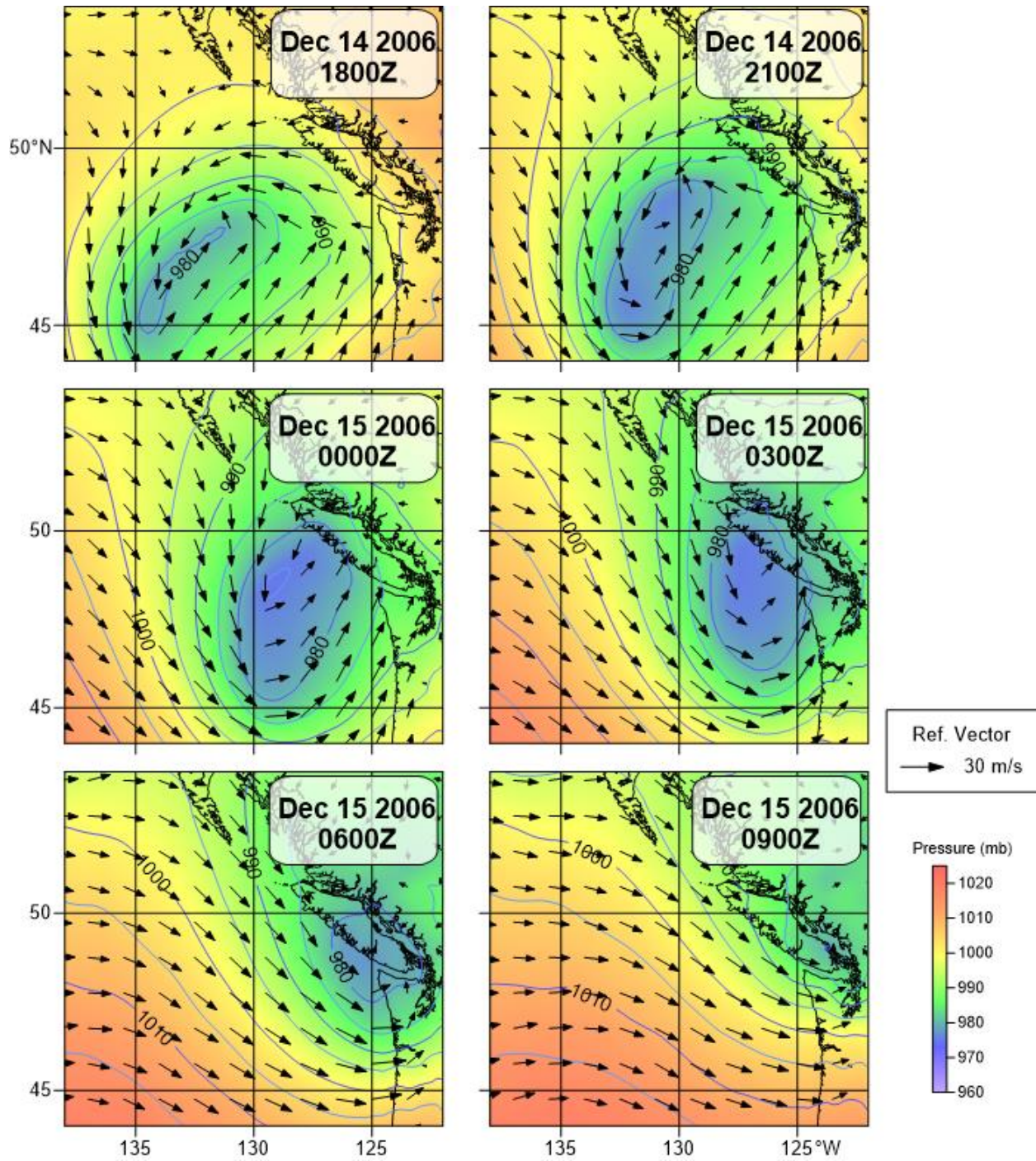


Figure 40. Wind velocity vectors and surface air pressure on December 15, 2006.

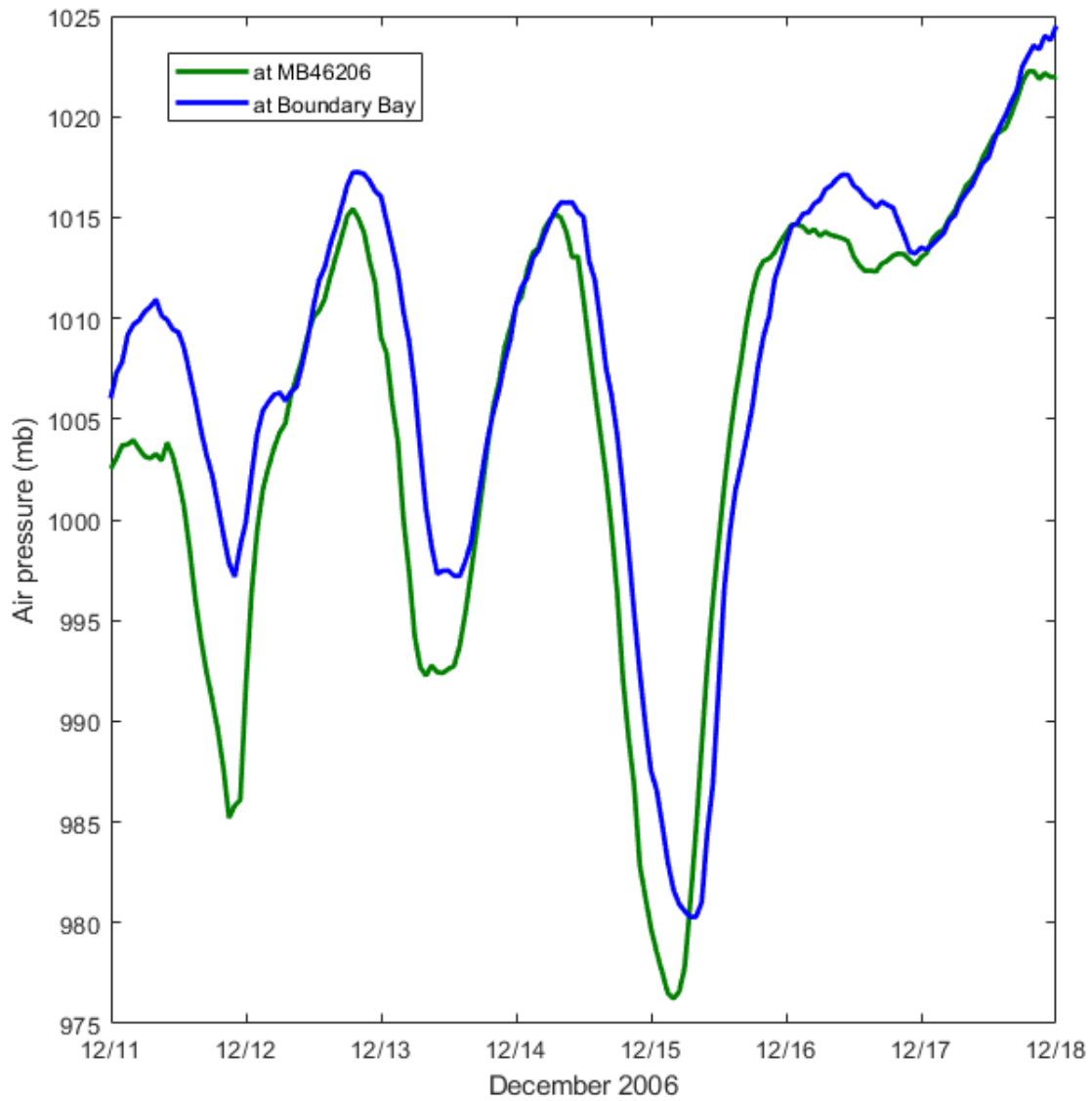


Figure 41. Atmospheric pressure in December 2006 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

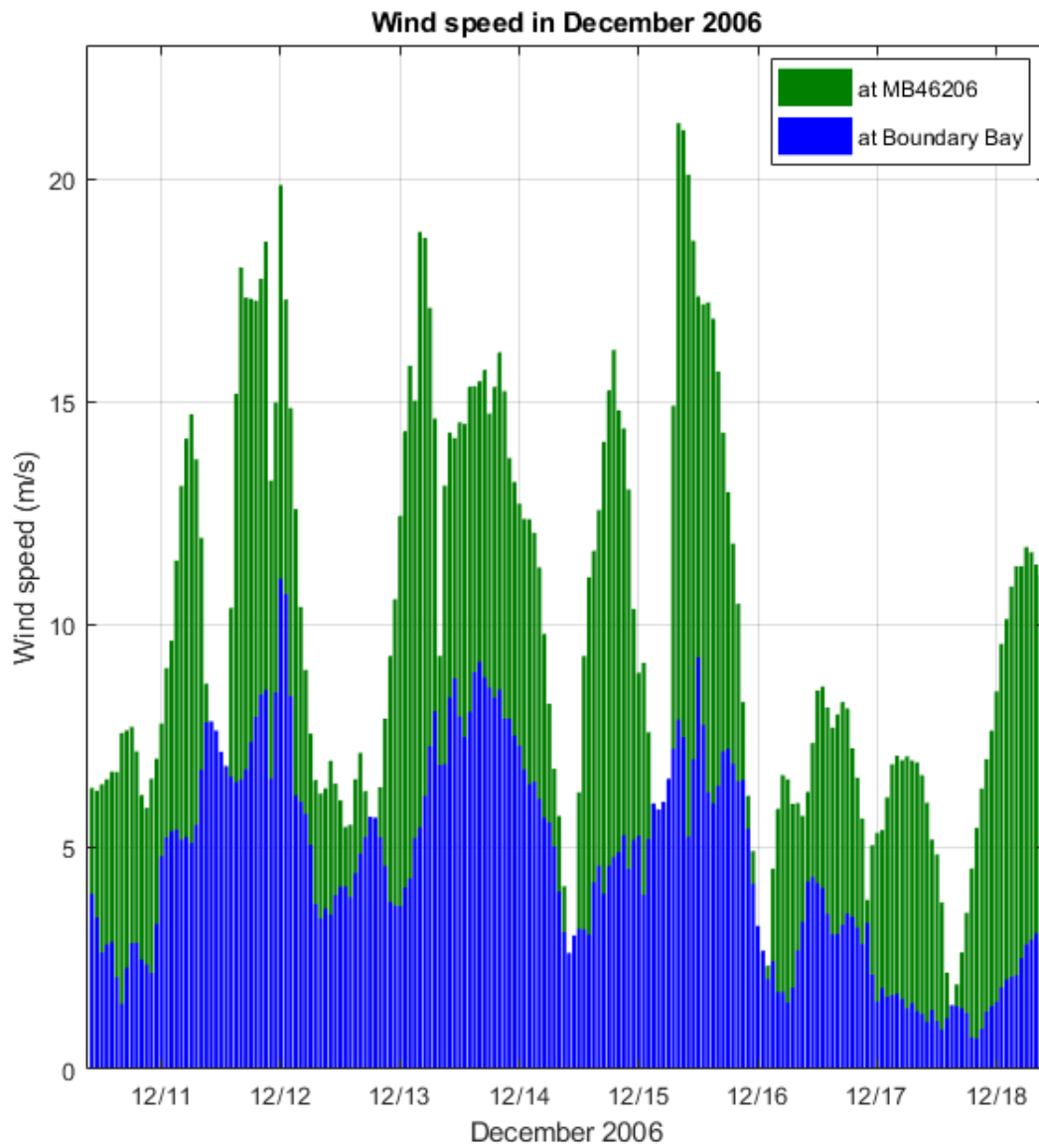


Figure 42. Wind speed in December 2006 at Boundary Bay and at meteorological buoy MB46206 (continental shelf).

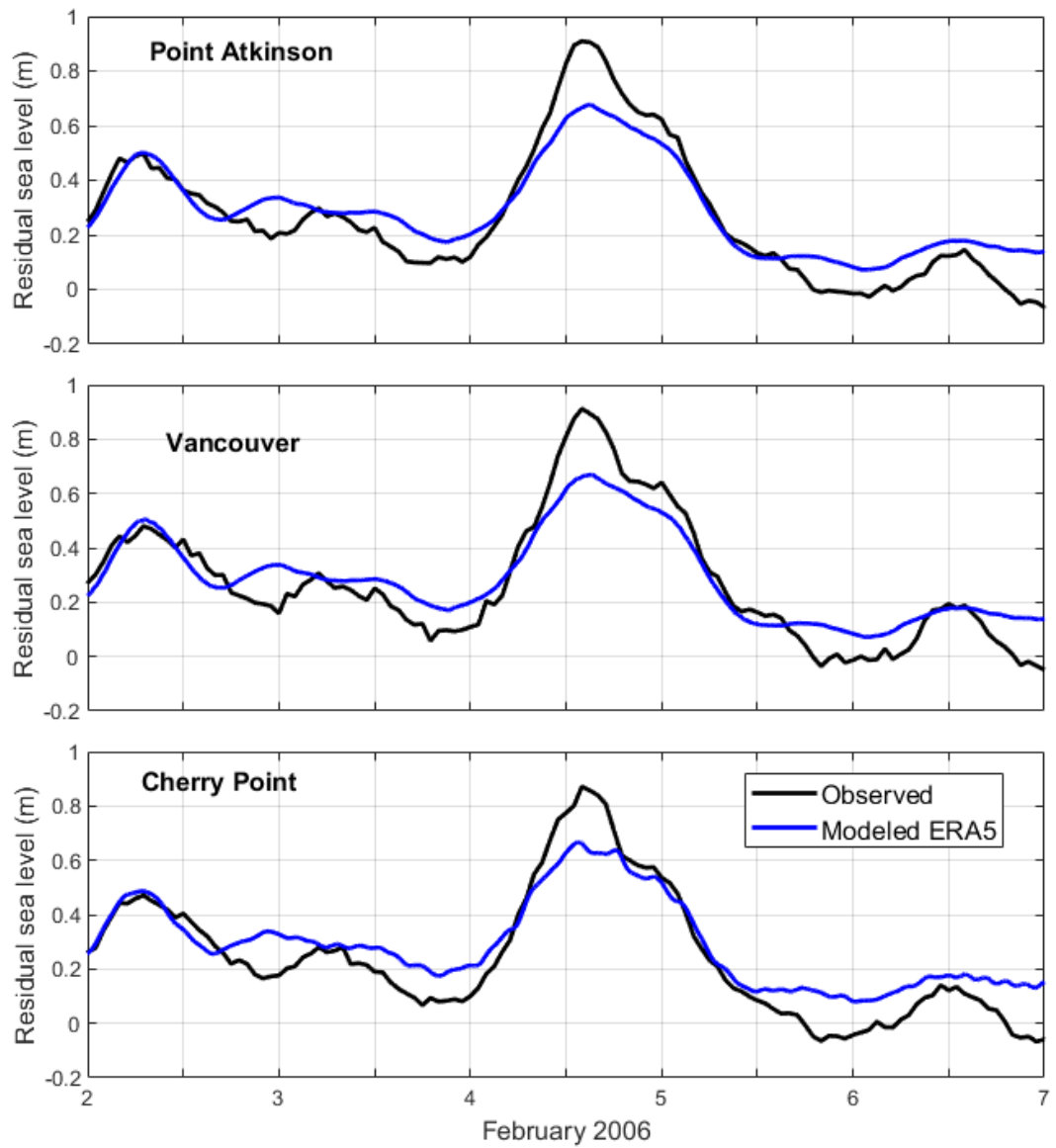


Figure 43. Comparison of observed and modelled (forced by ERA5 reanalysis) residual sea level series during the storm surge of December 15, 2006 at three tide gauge locations close to Boundary Bay.

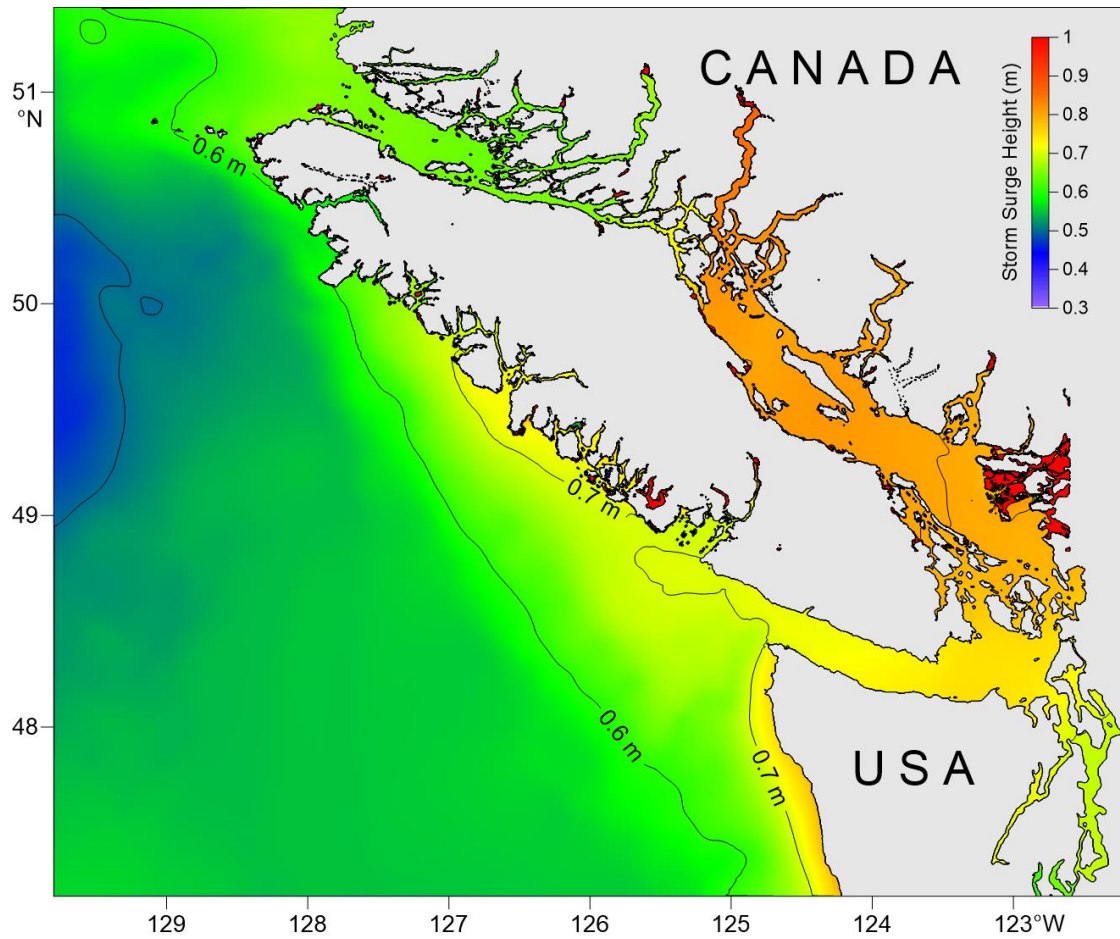


Figure 44. Modelled distribution of the maximum residual sea level during the storm surge of December 15, 2006 for the outer coastal domain.

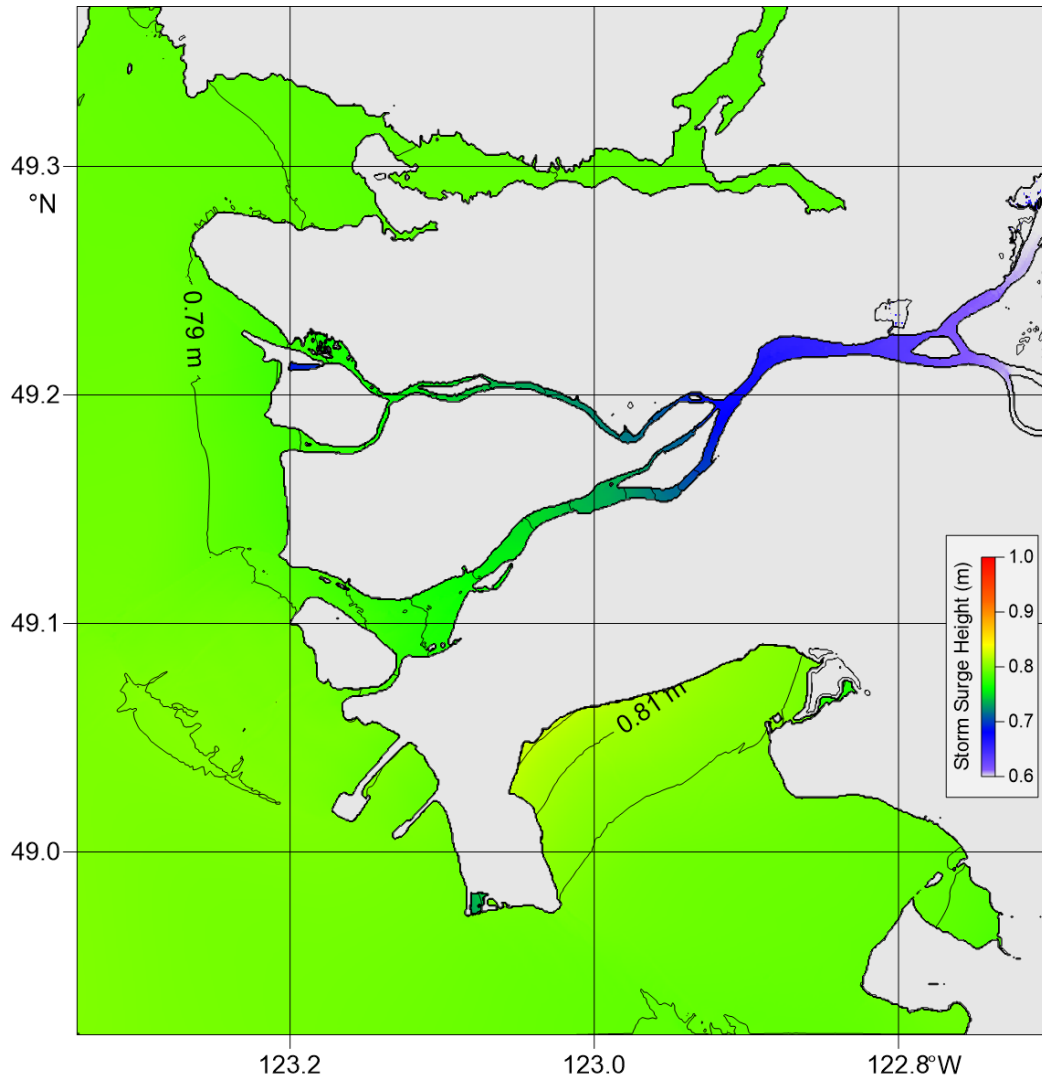


Figure 45. Modelled distribution of the maximum residual sea level during the storm surge of December 15, 2006 for the inner model domain (Boundary Bay and Vancouver areas).

4. SUMMARY AND CONCLUSIONS

A two-dimensional, nested-grid Princeton Ocean Model with an implemented wetting-drying approach based on newly available high-resolution bathymetric and topographic data was used to estimate the storm surge heights within Boundary Bay for six historic storms that occurred in the Greater Vancouver area since 1981. The specific case studies for the specific time of Higher High Water Mean Tide (HHWMT) are for the storms of November 14, 1981, December 16, 1982, January 27, 1983, January 1, 1997, February 4, 2006, and December 15, 2006. In general, the numerical model accounts for the main features of the storm surges and the distribution of peak crests over the study area, although in some cases the model underestimates the amplitudes of the surges. Table 4 provides a summary of the modelled and observed storm surge heights for three tide gauge sites in the southern Strait of Georgia and the six storm events. Possible reasons for the underestimates of the storm surge heights are

- 1) Underestimation of the wind speeds in the reanalysis atmospheric forcing, arising from the fact that ERA5 produces smoothed atmospheric fields at a horizontal resolution that is insufficient to resolve features of the relatively narrow basins of Juan de Fuca Strait and the Strait of Georgia;
- 2) Smoothing of the remote forcing to 5-day averages in sea level, used as a boundary condition for the model, are likely too smooth to resolve specific features of the response, which is to a considerable degree, controlled by oceanic and meteorological processes with larger scales than the model domain;
- 3) Secondary physical processes, such as stratification, river discharge and wind wave setup are not included in the model. However, inclusion of such effects would significantly increase the complexity of the model.

To adjust the model results to better coincide with observations, we have scaled the numerical values using coincident recordings from nearby tide gauges. Table 5 shows the modelled storm surge crest values, together with the adjusted value, using a factor equal to the ratio of observed and modelled values at Point Atkinson for each of the six case studies. Following application of this factor, the surge crest values at Boundary Bay ranged from 0.91 m to 1.05 m for all six events. To obtain the full extent of coastal inundation for future events similar to those

examined in this study, the storm surge heights need to be added to the predicted tides for a given location.

Table 4. Crest levels (m) of residual sea levels for the six historical storm surge cases between 1980 and 2018. Obs = Observed and Mod = Modelled. There are no tide gauge data for Boundary Bay.

Case No	Date	Rank	Point Atkinson		Vancouver		Cherry Point		Boundary Bay (modelled)
			Obs	Mod	Obs	Mod	Obs	Mod	
1	Nov. 1981	5	0.93	0.85	0.96	0.84	0.79	0.80	0.91
2	Dec. 1982	2	0.98	0.90	0.94	0.89	0.92	0.88	0.98
3	Jan. 1983	1	1.04	0.79	1.00	0.79	1.16	0.79	0.81
4	Jan. 1997	3	0.96	0.97	0.98	0.97		0.94	1.02
5	Feb. 2006	6	0.91	0.75	0.91	0.75	0.87	0.73	0.79
6	Dec. 2006	4	0.94	0.79	1.03	0.79	0.92	0.79	0.82

Table 5. Modelled (mod) and tide-gauge corrected modelled (corr) residual sea level crests (m) at sites 1 to 12 in Boundary Bay during the storm surges of 1980-2018. Numbers listed with the storm surge rank denote the time in day.month.year.

No.	Rank 5 14.11.1981		Rank 2 16.12.1982		Rank 1 27.01.1983		Rank 3 01.01.1997		Rank 6 04.02.2006		Rank 4 15.12.2006	
	Mod	Corr	Mod	Corr	Mod	Corr	Mod	Corr	Mod	Corr	Mod	Corr
1	0.88	0.96	0.96	1.05	0.80	1.05	1.00	0.99	0.78	0.95	0.80	0.95
2	0.89	0.97	0.95	1.03	0.80	1.05	1.00	0.99	0.78	0.95	0.80	0.95
3	0.88	0.96	0.95	1.03	0.80	1.05	1.00	0.99	0.78	0.95	0.81	0.96
4	0.89	0.97	0.97	1.06	0.80	1.05	1.00	0.99	0.78	0.95	0.81	0.96
5	0.89	0.97	0.97	1.06	0.80	1.05	1.01	1.00	0.78	0.95	0.82	0.98
6	0.87	0.95	0.96	1.05	0.80	1.05	1.00	0.99	0.77	0.93	0.82	0.98
7	0.84	0.92	0.92	1.00	0.80	1.05	0.97	0.96	0.76	0.92	0.81	0.96
8	0.85	0.93	0.93	1.01	0.79	1.04	0.97	0.96	0.76	0.92	0.80	0.95
9	0.84	0.92	0.92	1.00	0.79	1.04	0.96	0.95	0.75	0.91	0.79	0.94
10	0.84	0.92	0.92	1.00	0.79	1.04	0.96	0.95	0.75	0.91	0.79	0.94
11	0.84	0.92	0.92	1.00	0.79	1.04	0.96	0.95	0.75	0.91	0.79	0.94
12	0.82	0.90	0.91	0.99	0.79	1.04	0.94	0.93	0.75	0.91	0.79	0.94

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