Appendix V5-7E

Doris North Gold Mine Project:
2011 Numerical Simulation of Roberts Bay Circulation

TMAC RESOURCES

Hope Bay Mining Limited

DORIS NORTH GOLD MINE PROJECT 2011 Numerical Simulation of Roberts Bay Circulation

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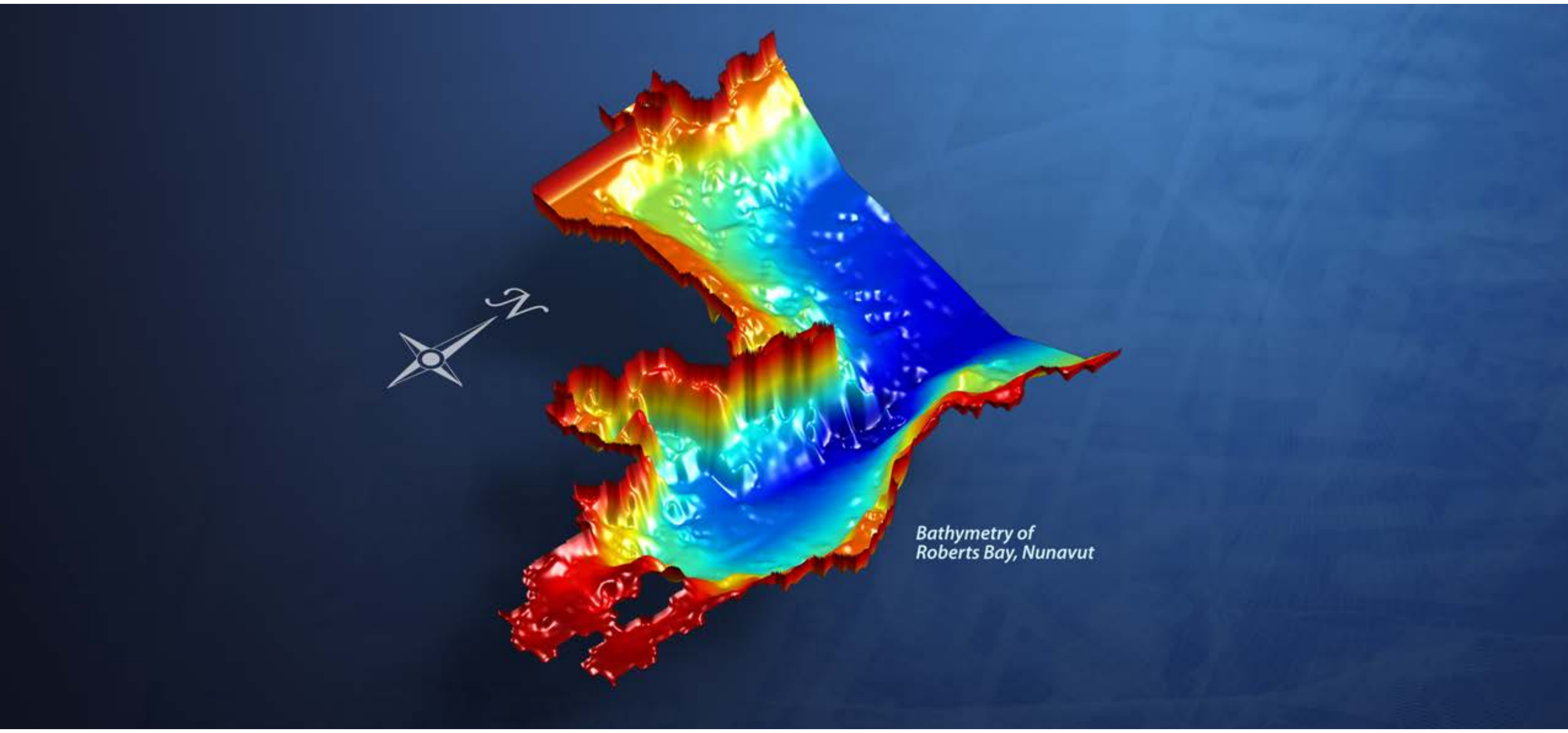

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June 2012

DORIS NORTH GOLD MINE PROJECT

2011 NUMERICAL SIMULATION OF ROBERTS BAY CIRCULATION

June 2012
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Hope Bay Mining Limited

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Executive Summary

Executive Summary

The 2011 Roberts Bay Numerical Simulation Circulation study was conducted by Rescan Environmental Services Ltd. (Rescan) on behalf of Hope Bay Mining Ltd. (HBML), for the Doris North Gold Mine Project. The Doris North Property is located approximately 125 km southwest of Cambridge Bay, Nunavut, on the south shore of Melville Sound.

This report was written to supplement the results of the 2011 Roberts Bay Physical Oceanography program (Rescan 2012b). The primary objective of the field program was to collect physical oceanographic data (i.e., water column structure and current velocities) relevant to the proposed discharge of treated water from the Tailings Impoundment Area (TIA) into Roberts Bay. The TIA effluent waters could potentially influence the water quality around the discharge location; therefore, knowledge of the effective flushing rate of the bay was required to estimate future dilution rates in Roberts Bay. Numerical simulations of the bay circulation were undertaken to provide higher levels of predictive refinement, and results of this modelling are presented in this report.

The MIKE3 3D hydrodynamic model by the Danish Hydraulic Institute (DHI) was used to run the simulations. The main results of the modelling work are summarized below.

<u>2011 Baseline Circulation Simulation</u>

The model was able to reasonably reproduce the conditions observed in the 2011 Roberts Bay Physical Oceanography Baseline Report. The circulation pattern alternated between two-layered positive- and negative-type estuarine flows, in agreement with the observations in Rescan (2012b). The thermohaline structure was adequately simulated for all summer months, and the currents were of the same magnitude order as the field observations.

<u>Roberts Bay Flushing Times</u>

The time required to flush Roberts Bay at the Melville Sound boundary was computed for the 2011 summer season and various other climactic scenarios. The baseline simulation took 7 to 18 days to flush, depending on the transect height used to calculate the flushing rate. During the runs of various scenarios it was found that large wind magnitudes and southern wind directions lowered the flushing times of the bay, whereas increased flushing times resulted from greater freshwater input and north-westerly winds. The maximum flushing time recorded for the bottom waters of the bay was just below 30 days.

Based on the numerical simulation presented here, it is predicted that Roberts Bay could be flushed several times over the course of the summer season by Melville Sound waters. This would lead to strong dilution rates in the vicinity of the proposed TIA discharge.

Acknowledgements

Engineers and Scientists

Acknowledgements

This report was prepared for Hope Bay Mining Limited by Rescan Environmental Services Ltd. The modelling work was conducted by Philippe Benoit (M.Sc.). The report was written by Philippe Benoit and was reviewed by Mike Henry (Ph.D.) and Deborah Muggli (Ph.D., M.Sc., R.P.Bio.). The project was managed by Deborah Muggli.

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DORIS NORTH GOLD MINE PROJECT
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Glossary and Abbreviations

Glossary and Abbreviations

Terminology used in this document is defined where it is first used. The following list will assist readers who may choose to review only portions of the document.

ADCP	Acoustic Doppler Current Profiler
Baroclinic/Baroclinity	Characteristic of a stratified fluid that has misaligned pressure and density gradients, a fundamental requirement for the generation of eddies.
Current velocity	Speed of the water movement at a given water depth. By convention, the direction of a current (in degrees) is given as the direction towards which the current is heading.
CTD	Conductivity, temperature, and depth profiler
Density	Weight of water per unit volume (kg/m^3); calculated from temperature, salinity and pressure.
HBML	Hope Bay Mining Limited
Lagrangian	In fluid dynamics, refers to the frame of reference where an observer follows an individual fluid parcel as it moves through space and time (see Kundu [1990] for details).
'Negative' estuary	An estuary where freshwater losses from evaporation or ice formation exceed freshwater additions (e.g., river discharge, rain, ice melting). This leads to a landward longitudinal density gradient, which drives a strong surface volume inflow from the ocean in response to the freshwater scarcity, and a correspondingly weaker near-bottom seaward outflow.
NIRB	Nunavut Impact Review Board
NWB	Nunavut Water Board
"Positive" estuary	An estuary where freshwater additions (e.g., river discharge, rain, ice melting) exceed freshwater losses from evaporation or freezing. This leads to a seaward longitudinal density gradient, which drives a strong surface volume outflow to the ocean in response to the supplementary freshwater, and a correspondingly weaker near-bottom inflow of seawater.
Pycnocline	Depth zone where density changes sharply.
PSS	Practical salinity scale
RBW	Roberts Bay West station
Salinity	Dimensionless (i.e., no units) scaling used to represent the total mass of solid material dissolved in a sample of water divided by the mass of that sample. The scaling used is based the PSS-78 standard, which relates the conductivity ratio of a seawater sample to a KCl solution (for additional details see UNESCO [1985]).
ST	Summer transect
TIA	Tailings impoundment area

UNESCO	United Nations Educational, Scientific and Cultural Organization
Thermocline	Depth zone where temperature changes sharply.
Thermohaline	Relating to temperature and salinity
V	Velocity (e.g., Vnorth refers to the velocity in the northern direction)
Wind Velocity	Speed of wind, generally standardised at an altitude of 10 metres. By convention, the direction of a wind (in degrees) is given as the direction from which the wind is blowing.
WT	Winter transect

1. Introduction

1. Introduction

The Doris North Gold Mine Project (the Project) is located approximately 125 km southwest of Cambridge Bay, Nunavut, on the south shore of Melville Sound. The nearest communities are Omingmaktok (75 km to the southwest of the property), Cambridge Bay, and Kingaok (Bathurst Inlet; 160 km to the southwest of the property). Figure 1.1-1 provides a general location map for the Doris North Project.

HBML recently considered expanding the Doris North Project as per the Doris North amendment package submitted to the NWB and NIRB in November 2011 (HBML 2011). The amendment included expanding the mine life by accessing additional resources via the Doris North Portal, and also included the potential discharge of treated water from the Tailings Impoundment Area (TIA) to Roberts Bay. The TIA water would potentially be saline in nature, and the amendment application requested a change from the currently-permitted discharge location in Doris Creek to Roberts Bay. However, as of February 1, 2012, HBML plans to transition the Doris North Project to Care and Maintenance.

This report was written to supplement the results of the 2011 Roberts Bay Physical Oceanography program (Rescan 2012b). The primary objective of the field program was to collect physical oceanographic data (i.e., water column structure and current velocities) relevant to the proposed discharge of treated water from the Tailings Impoundment Area (TIA) into Roberts Bay. The TIA effluent waters could potentially influence the water quality around the discharge location; therefore, knowledge of the effective flushing rate of the bay was required to estimate future dilution rates in Roberts Bay. Numerical simulations of the bay circulation were undertaken to provide higher levels of predictive refinement, and results of this modelling are presented in this report.

If Roberts Bay was effectively flushed into Melville Sound during the summer season, the waters would eventually achieve large dilution ratings, thus minimizing the potential accumulation of the treated TIA discharge in Roberts Bay. Hence, the two primary objectives of this report were to:

1. develop and calibrate a model for the circulation and flushing of Roberts Bay based on 2011 field data; and
2. calculate the range of likely flushing times in Roberts Bay based on different climactic scenarios.

This report details the methodology used in the numerical model, and compare its output to the data acquired during the 2011 Physical Oceanography Baseline program. Chapter 2 describes the theory and methodology used for the numerical model construction, Chapter 3 presents the graphical displays and analysis of the simulation results, and Chapter 4 summarizes the model findings in terms of the generally observed circulation and flushing times of Roberts Bay.

Figure 1-1

Doris North Project Location

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2. The Numerical Model

2. The Numerical Model

2.1 MODEL GENERAL DESCRIPTION

The Roberts Bay summer circulation and flushing rate was modelled using the Danish Hydraulic Institute (DHI) MIKE3 hydrodynamic model (DHI 2010). MIKE3 is a three dimensional baroclinic fluid model, which can simulate unsteady discretized flows while accounting for density variations, bathymetry and external forcings such as tides, boundary currents and meteorological inputs. Other built-in features of the model include flooding and drying of coastal land, sediment bed resistance, turbulence modelling, sources/sinks of external waters and heat exchange with the atmosphere.

The MIKE3 model is based on the numerical solution of the three dimensional Reynolds-averaged Navier-Stokes fluid equations invoking the Boussinesq and hydrostatic assumptions (Gill 1982; Kundu 1990; also see DHI 2010). Thus, the model consists of the continuity, momentum, temperature, salinity and density equations and the non-linear equations are resolved by a turbulent closure scheme. The free surface and gravity waves are evaluated using a sigma-coordinate transformation approach.

The spatial discretization of the primitive equations is performed using a cell-centered finite volume method (e.g., see Patankar 1980). The spatial domain is discretized by subdivision of the fluid continuum into non-overlapping elements or cells. An unstructured grid is used in the horizontal plane while a structured mesh is used in the vertical. The elements can either be prisms with triangular horizontal faces or bricks with quadrilateral horizontal faces.

The model solves the pertinent time-dependent hydrodynamic and thermodynamic equations over the discretized regional grid. It therefore produces computed values of variables, such as temperature or current, in each grid cell throughout the model domain for each time step. The model's physical system is driven by environmental inputs comprised of time-series of winds, air temperatures and freshwater discharges. Other inputs are derived from the latitude of the domain such as incoming solar radiation.

The utility of a sophisticated modelling tool like MIKE3 is that, after the initial model setup, it is subsequently straightforward to evaluated varying scenarios, such as different wind or discharge magnitudes.

2.2 MODEL DEVELOPMENT FOR ROBERTS BAY

This section provides a summary of the 2011 field results, which were used to calibrate the numerical model.

2.2.1 Ice-covered Conditions (February to June 2011)

During the ice-covered season of 2011, a 1 to 2 m thick ice layer forms that shelters Roberts Bay waters from atmospheric winds. Over time, the under-ice convection generated from the ice growth leads to the formation of a two-layer thermohaline structure with weak stratification in the water column, and a colder, fresher layer of 25 to 30 m thickness atop a more saline, warmer layer extending to the bottom.

Under-ice currents, as measured by an Acoustic Doppler Current Profiler (ADCP), were generally very weak, with mean horizontal current velocities between 1 and 2 cm/s. Deep currents, which were driven either by density gradients formed through ice formation/brine release or advection of waters from Melville Sound, had generally stronger velocities. This was particularly apparent for the more southern bay measurements, which had recorded mean currents between 4 and 5 cm/s with a maximum of 7.91 cm/s.

The denser waters tended to slowly pool and accumulate in the deep basin of Roberts Bay, where they remained relatively isolated from other water sources. The dense downwelling waters appeared to be replaced by advecting surface currents from the middle region of Roberts Bay. The overall circulation pattern in the surface waters appeared to be a sluggish clockwise flow, with occasional larger currents recorded directly under the sea ice, particularly in shallow areas where brine rejection flows were likely to occur. Tidal ebb and flow currents were found across the bay, but they had very low velocities of around 0.1 cm/s.

2.2.2 Open-water Conditions (July to October 2011)

In early summer, the increased sunlight and warming atmospheric temperatures eventually caused the ice cover to melt in early July, flooding the surface of Roberts Bay with a large volume of fresh, warm water. After the ice cover breakup, wind forcing on Roberts Bay waters contributed to a significant increase in current velocity and variability, particularly near the surface.

The addition of freshwater from ice melting, combined with the mixing due to wind generated currents and warmer temperatures, progressively lead to the formation of an alternate two-layered thermohaline structure with a warmer, fresher wind-mixed layer atop a colder more saline bottom layer. The surface mixed layer was much shallower than that found in the winter months, with the top layer initially at 5 to 10 m thickness, but increasing to over 25 m depth in the fall.

The current variability changed dramatically during the summer, with a ten-fold increase in water exchange rate estimated at the mouth of Roberts Bay where the current measurements were obtained. Mean horizontal current velocities in the deep layer ranged from 1 to 5 cm/s, but with maximum of around 30 cm/s during periods of large flow. Similarly, while horizontal currents in the upper water column had mean velocities between 1 and 6 cm/s, maximum values of over 30 cm/s were sometimes recorded above 10 m depth.

The general circulation within Roberts Bay was assumed to be anticyclonic (clockwise) for both top and bottom layers. The combination of southern/easterly winds and freshwater inputs resulted in a positive-type two-layered estuarine circulation for roughly 70% of flow measurements, where the top layer flowed seaward and the deeper waters flowed into Roberts Bay from Melville Sound. For the other ~30% of the time, the general estuarine circulation reversed, depending on the prevailing wind conditions and strength of incoming flow from Melville Sound.

A map of the different sampling stations for Roberts Bay in 2011 is shown in Figure 2.4-1.

2.3 MODEL USAGE

The first objective for this work (i.e., see Section 1) was to simulate the 2011 conditions in Roberts Bay using the observed field measurements as reported in the physical oceanography baseline report (Rescan 2012b; also see Section 2.2). The following assumptions were used in the 3D hydrodynamic model:

- no ice-cover period was modelled. The simulations were thus restricted to the open-water season only;
- a warm-up period of roughly one month was implemented prior to the start of the summer simulation, in order for the thermohaline structure of the bay to stabilize adequately; and
- only three measured data inputs were used within the model: winds, freshwater discharges, and atmospheric temperatures. All other climactic and oceanographic variables were taken as either constants or were modelled using physical models.

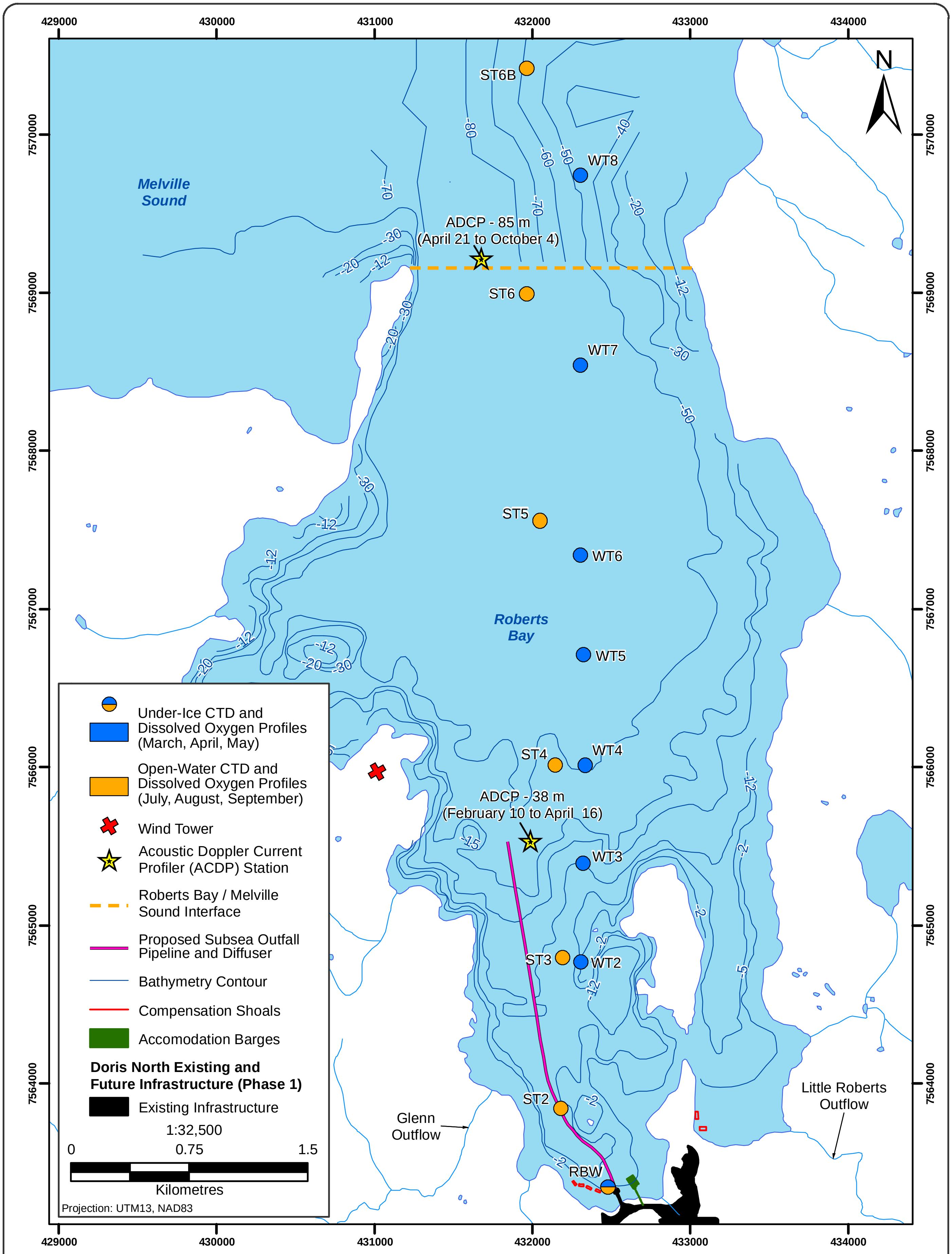

Figure 2.2-1

Roberts Bay Physical Oceanographic Sampling Stations, Doris North Project, 2011

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Flushing rates for Roberts Bay could then be extracted from the modeled currents. The second objective involved measuring how the flushing rates varied when either the winds or freshwater discharge rates were changed from the 2011 baseline conditions. These additional scenarios showed how differing climactic conditions affected the Roberts Bay system. The results for all simulation scenarios are detailed in Section 3.

2.4 SPECIFIC MODEL DETAILS

This section provides additional information on the parameters needed to construct the Roberts Bay numerical model.

2.4.1 Bathymetry

Depths within the model domain were digitized with bathymetric data from field surveys previously conducted by Rescan (see Rescan 2011 and Rescan 2012b). Figure 2.4-1 shows the model region and bathymetry data used for the simulations, as well as the Roberts Bay – Melville Sound boundary and the near-field (end of the proposed TIA discharge pipeline at 38 m depth) and far-field (exchange point with Melville Sound at 85 m depth) locations sampled for currents in Roberts Bay (Rescan 2012b).

For the Roberts Bay simulation, a three dimensional rectilinear grid was used, covering the complete bay area and part of the surrounding Melville Sound. The grid cells were selected at 100 m square dimensions, and ten parallel vertical layers were used to represent the water column, with the first nine being 4 m deep while at the lowest layer depth was permitted to vary. This arrangement was the best configuration found that reproduced reasonably well the bay stratification while maximizing computational efficiency.

2.4.2 Winds

The wind data from 2011 were available from a wind sensor established on the southern shore of the bay, as shown in Figure 2.2-1. Winds measured at this site were applied across the entire model domain. Further details on the winds can be found in Rescan 2012b; wind data from 2011 is summarized in Figure 7 of the Appendix.

2.4.3 Freshwater Influx

Two freshwater discharge points were implemented in the model: the Glenn Lake and Little Roberts Outflows situated in the southern part of Roberts Bay. The Doris and Roberts Outflow 2011 datasets, as described in detail in Rescan 2012b, were combined to form the Little Roberts Outflow time-series in the model. No data was available for the Glenn Outflow in 2011; however, based on data acquired in previous sampling years (e.g., see Rescan 2011), the flow rates for Glenn Outflow were set at 50% of the Doris Creek flow.

2.4.4 Other Meteorological Inputs

The relative air humidity was assumed to be 75%, and the air temperature was allowed to vary daily between roughly 10ºC and 20ºC in accordance with the 2011 Meteorology Baseline Report (Rescan 2012a).

2.4.5 Stratification

Background salinity was assumed to be initially constant at 27 and then allowed to stabilize itself according to meteorological inputs and freshwater flows. Similarly, the initial background temperature was set at 0ºC. Both temperature and salinity were set to vary spatially and temporally.

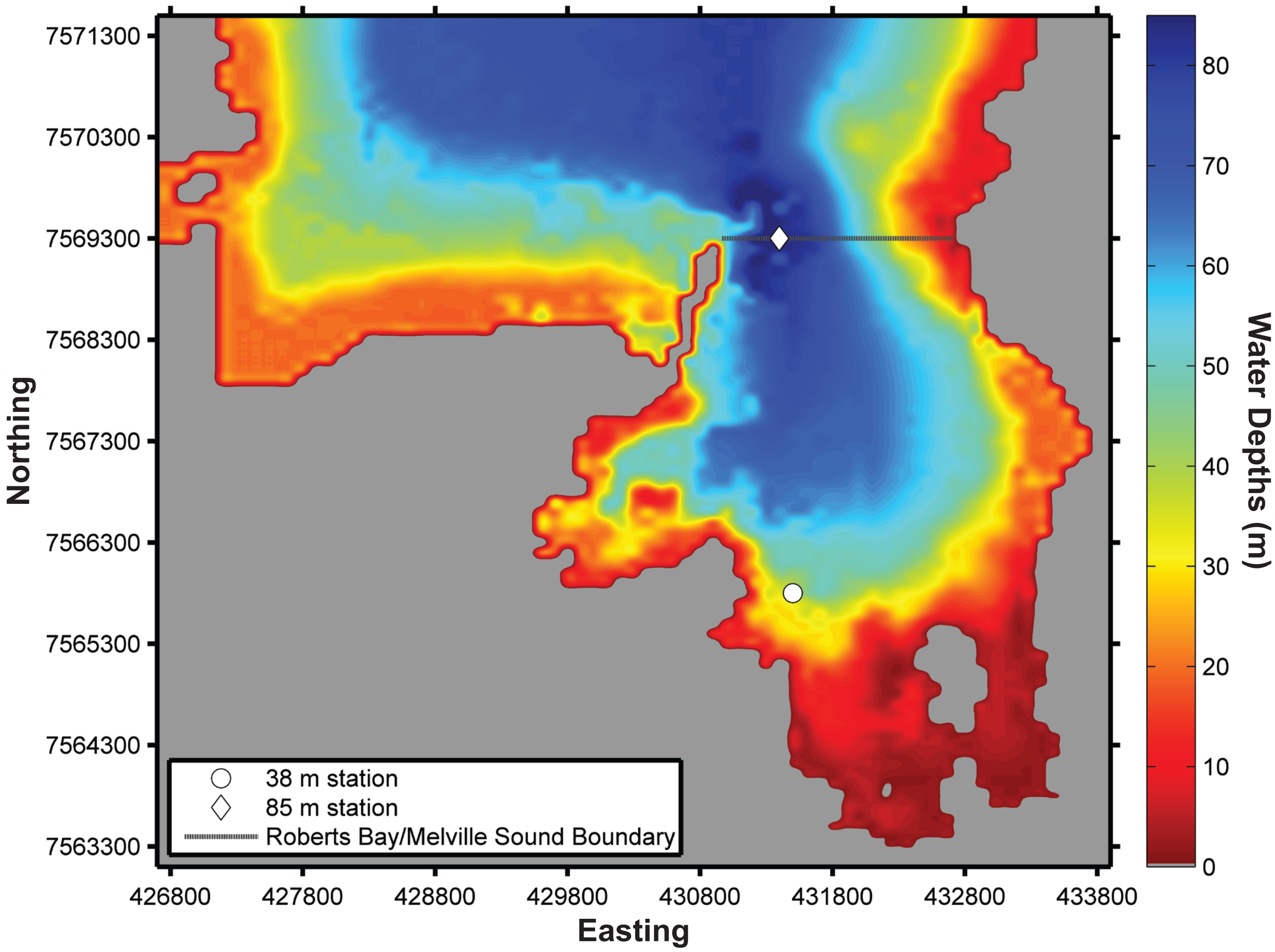

Figure 2.4-1

Roberts Bay and Melville Sound Bathymetry Used in the Numerical Model

2.4.6 Tides

Tidal heights and currents were previously found to be very weak within Roberts Bay when compared to wind-driven currents (see Rescan 2012b for details), so tides were not included for this model to save on computational time.

2.4.7 Model Time: Calibration and Simulation Periods

The model was set to run at a 5 s time step for 118 days between June 6 and October 8, 2011. The first month of modelling was defined the calibration period, during which the stratification adjusts itself to a stable state which replicated reasonably well the conditions measured in Roberts Bay for 2011 (see Section 2.2). The first month of computed data would have been unrealistic otherwise, given the entire month of June was frozen over in Roberts Bay in 2011. The remainder of the model time is defined as the simulation period, where the calculated model currents can be compared to the measured field data.

2.4.8 Turbulence Scheme

The Smagorinsky formulation (Smagorinsky 1963) was chosen, which involves the eddy viscosity being linked to a filter size (i.e., the grid spacing) and the velocity gradients of the resolved flow field. Further details of the inner workings of turbulence within MIKE3 can be found in DHI (2010).

2.4.9 Other Model Parameters

Table 2.4-1 summarizes the inputs and model parameters used in the hydrodynamic model.

Table 2.4-1. Important Model Input Parameters

Parameter Name	Values	Comment
Horizontal Grid Size	100 m	
Vertical Grid Size	4 m	Bottom layer varies
Number of Layers	10	
Time Step	5 s	
Simulation Duration	118 days	
Bed Roughness Length	0.05 m	
Smagorinsky vertical coefficient	0.176	
Horizontal Eddy Viscosity Limits	0.01 to 33.3 m^2/s	Smagorinsky formulation
Vertical Eddy Viscosity Limits	0.0001 to 0.003 m^2/s	Smagorinsky formulation
Wind Friction	0.0016 to 0.0026	Drag coefficient
Relative Humidity	75%	
Initial Background Salinity	27	
Initial Background Temperature	0°C	

3. Simulation Results and Discussion

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3.1 2011 BASELINE SIMULATION

3.1.1 Thermohaline Structure

The comparison of temperature and salinity profiles between measured data and model results for Roberts Bay stations (see Figure 2.4-1) are shown in Figures 3.1-1, 3.1-2 and 3.1-3 for July, August and September 2011. For July 2011, station profiles were reproduced fairly well in the model, the notable exception was station ST2, which was shallow and more difficult to reproduce given the coarse numerical grid. The values modelled at shallow depths (i.e., above 20 m depth) had generally the greatest departures from the measured data, with differences in temperatures of greater than 3ºC at stations ST5 and ST6, and between 1-2 for salinity. The deeper water column was much better reproduced, with differences generally less than 1ºC in temperatures and less than 1 in salinity. Overall, the stratification and layering of the water column was reasonably reproduced, particularly in view of the assumptions by the model. The difference in mixed layer depth between the model and data was at most ~5 m.

Model temperature and salinity profiles for August 2011 (Figure 3.1-2) reproduced the measured data reasonably well, but not as effectively as July 2011. The major differences were in the top 10 metres of the water column, where the model continuously underestimated temperatures and overestimated salinity. This was particularly apparent at stations ST5 and ST6 where modelled and measured salinity differed by over 3 at 5 m depth. There are two possible reasons for this discrepancy: (1) the model physics slightly overestimated the vertical mixing in the first few metres of the water column, or (2) the land freshwater input to Roberts Bay is underestimated in August, particularly in the northern region of the bay. Deeper than 20 m, both model and measured results varied less than 10% of each other.

In September 2011 (Figure 3.1-3), profiles replicated the Roberts Bay stratification more accurately than in August 2011, with a few notable exceptions: station ST3 temperatures showed a deeper top layer in the model than that measured at 8 m, while station ST6B conversely had a mixed layer 10 m deeper in the observations than in the model.

3.1.2 Currents and Circulation

Model current velocities were plotted versus ADCP observations at four different depths for the 85 m station in the northern (Figure 3.1-4) and eastern (Figure 3.1-5) directions. The model's effectiveness at simulating the measured currents varied during the whole simulation length. This was to be expected given the multiple assumptions taken in the model formulation, and the fact that the measured wind from only one location is applied over the complete model domain; in reality, wind and wave strength/direction can vary at the sub-metre scale. Despite some dissimilarities, there are several periods within the run where measured and modelled data correlated extremely well, such as between September 8 and September 10 in Figure 3.1-4 or the eastern currents at 4 m depth in Figure 3.1-5. Furthermore, the magnitudes of the model currents are on the same scale (i.e., averages < 5 cm/s) as the ADCP measurements, suggesting that the model output currents are a reasonable approximation to the observed dataset.

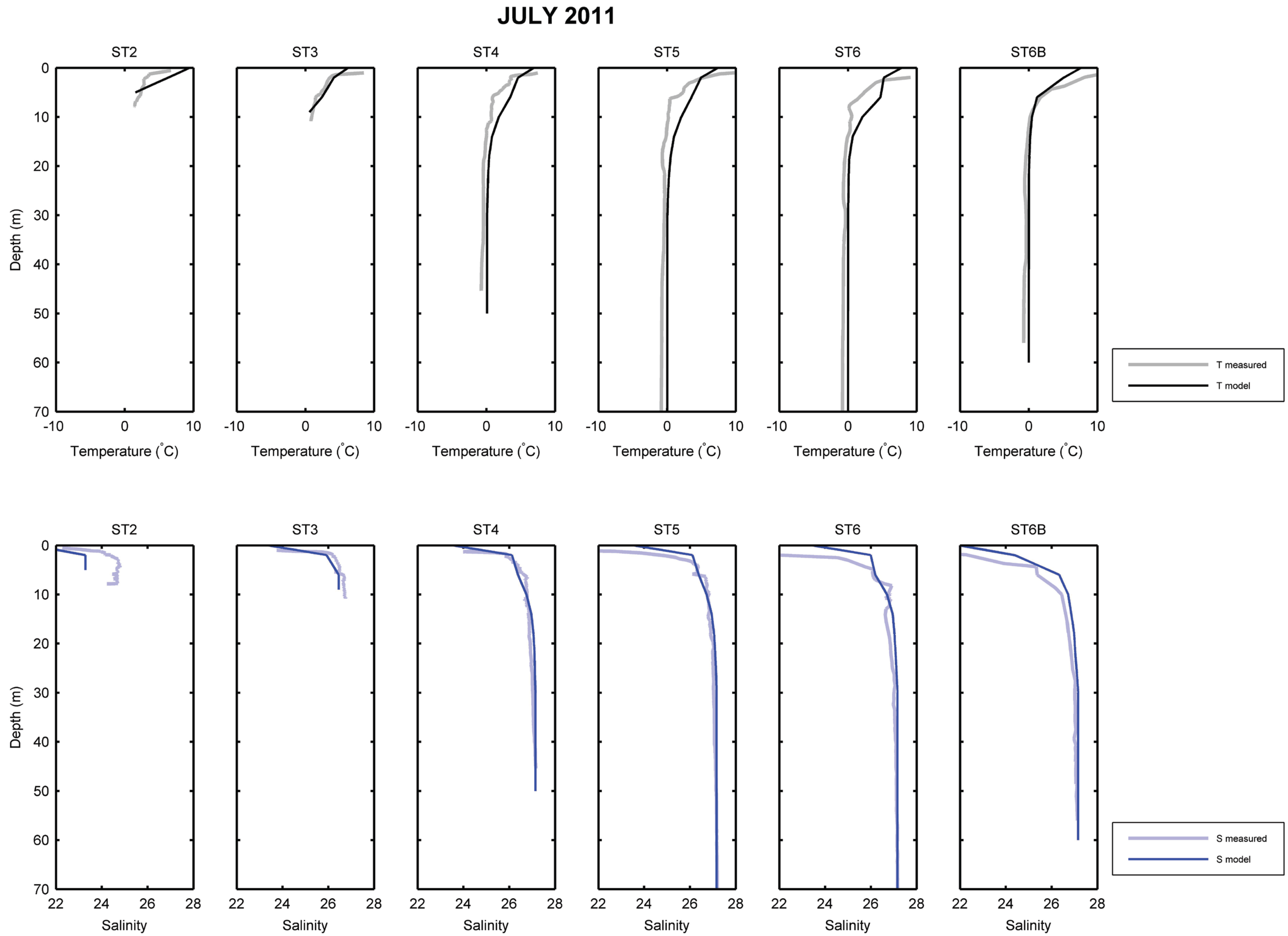

Figure 3.1-1

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Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, July 2011

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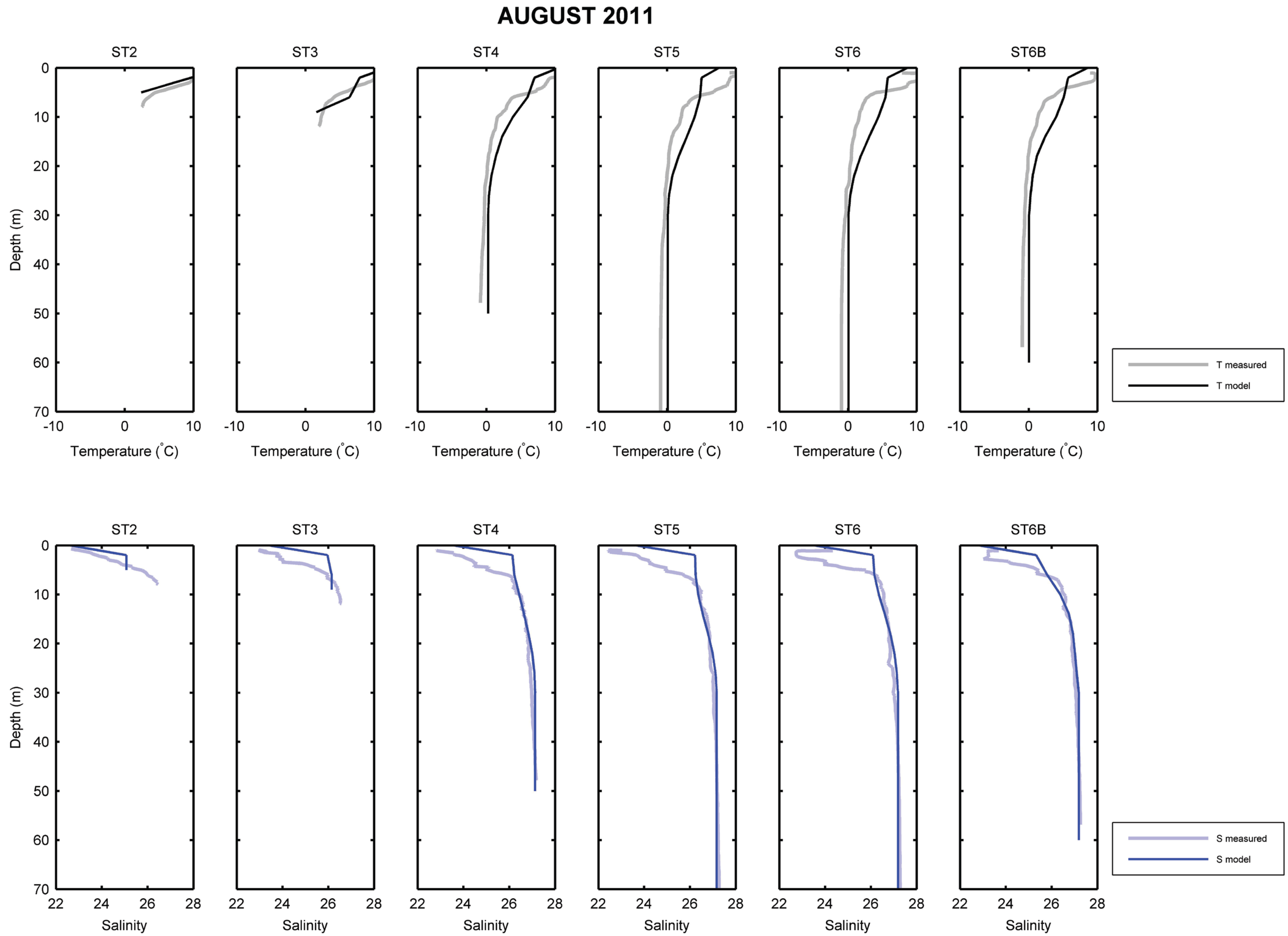

Figure 3.1-2

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, August 2011

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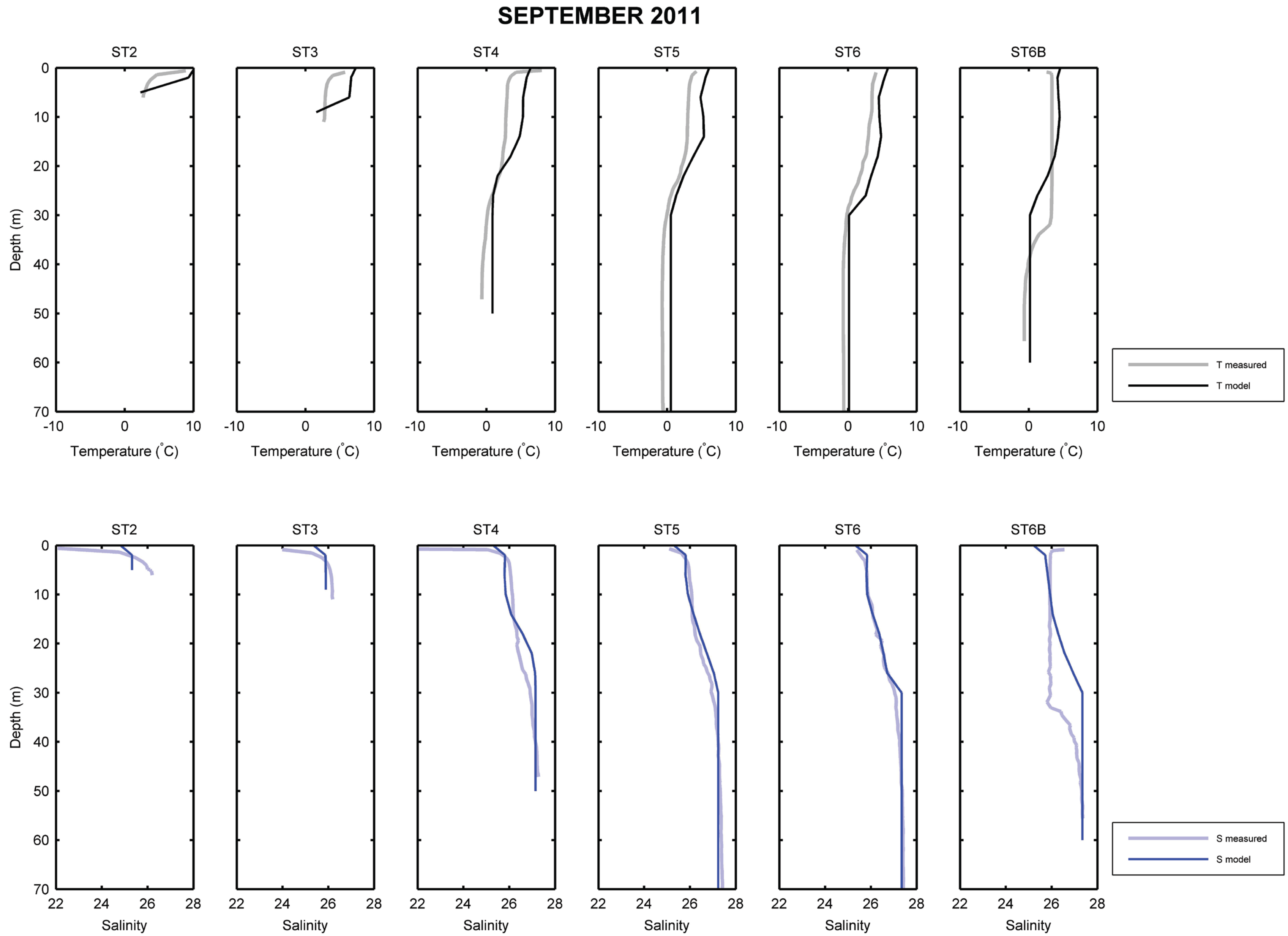

Figure 3.1-3

Temperature and Salinity Comparison between Measured and Modelled Data in Roberts Bay, Doris North Project, September 2011

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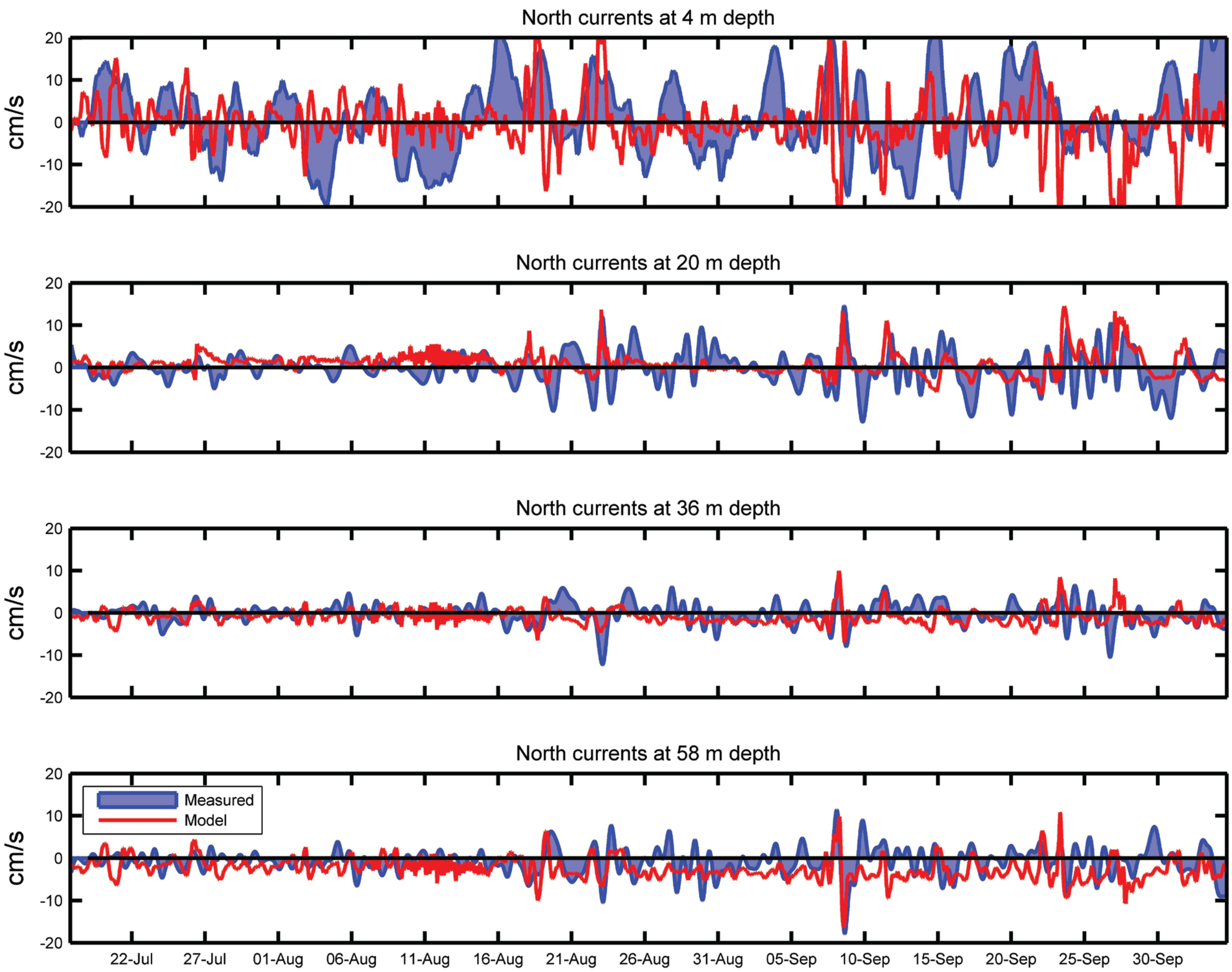

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Comparison of Northern Current Velocities between Measured and Modelled Data, 85 m Site, July to September 2011

Figure 3.1-4

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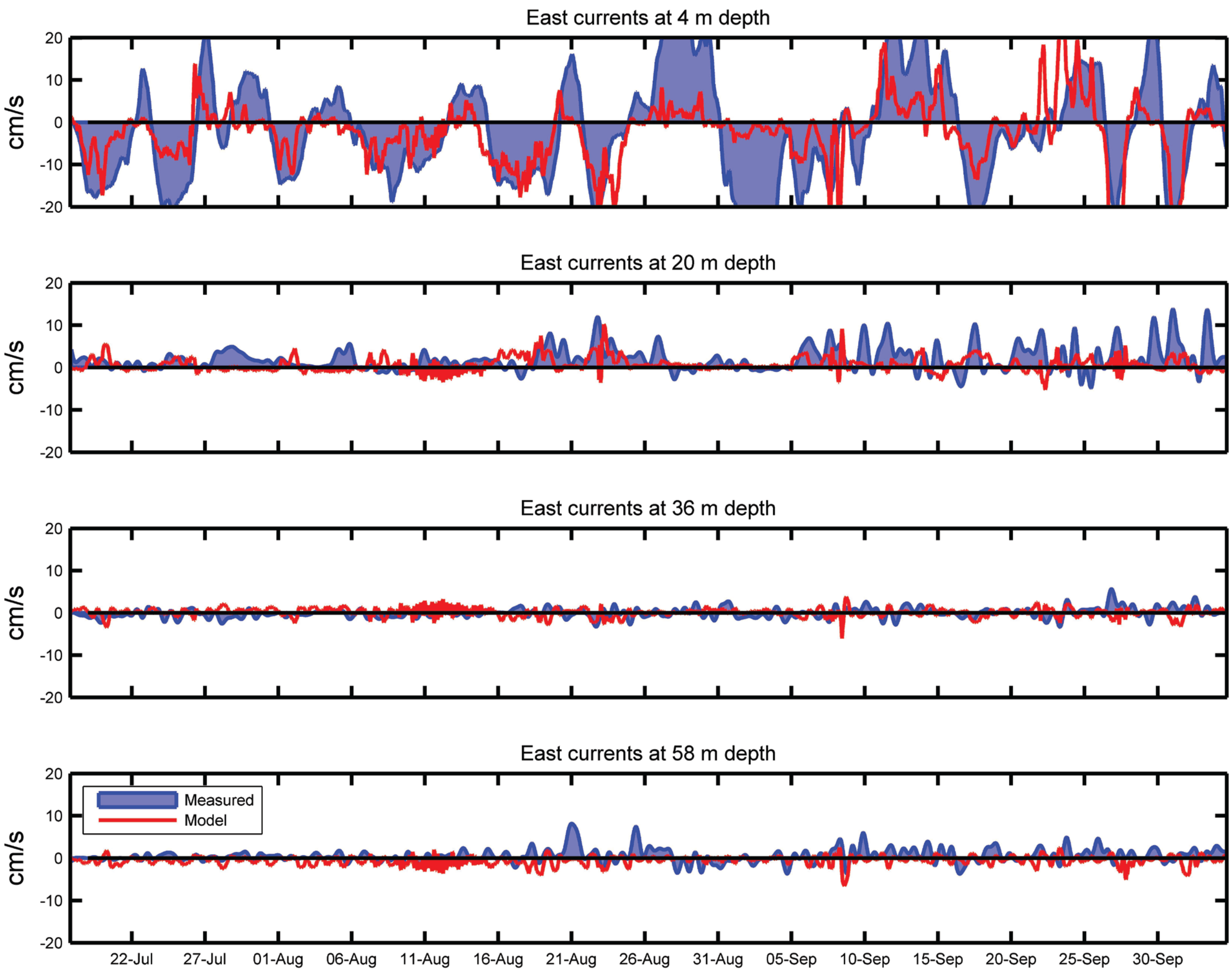

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Comparison of Eastern Current Velocities between Measured and Modelled Data, 85 m Site, July to September 2011

Figure 3.1-5

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The model circulation varied extensively during the simulation run; the system was extremely sensitive to the wind input, as discussed in the 2011 Roberts Bay Physical Oceanography Baseline Report (Rescan 2012b). In that report, the general circulation observed in the bay for approximately 70% of the time was that of a positive-type estuary, where the surface layer has a seaward flow and the bottom layer flows landward. This flow characteristic was frequently recorded in the model simulations and is depicted in Figure 3.1-6; this shows the mean current velocity between July 1 and July 7, 2011 at 4 and 36 m depths. During that period, clockwise flow was observed in both layers, and seaward currents dominated the top layer, varying between 0.04 to 0.08 m/s within Roberts Bay to beyond 0.12 m/s at the Melville Sound boundary. Conversely, the bottom layer flowed landward to compensate for the surface circulation, with current velocities between 0.02 to 0.06 m/s. These flow observations are in excellent agreement with the conclusions made in Rescan (2012b).

However, it should be emphasised that the bay circulation system was not locked into a positive-type estuary mode. Figure 3.1-7 shows the mean currents between August 5 and 8, 2011, and the circulation is typical of a negative estuary, with the bottom layer having seaward flows of up to 0.05 m/s, and the top layer currents flowing southward towards the shallow bay shelf with velocities between 0.045 and 0.1 m/s at the Melville Sound boundary. By varying back and forth between these two major modes of circulation, the surface and bottom layers of the bay were rapidly flushed with Melville Sound waters, as is detailed in the following section.

3.2 ROBERTS BAY FLUSHING

3.2.1 Flushing Time Definition

The main objective of this study was to determine the length of time needed, from the start of the ice-off period, to completely mix Roberts Bay waters with Melville Sound inflow, thereby diluting the waters of the bay and the proposed TIA discharge. For the model to calculate this flushing time, the northern transport flow rate was calculated over the whole area of the Roberts Bay—Melville Sound boundary (see Figure 2.4-1). This transport rate was integrated over time at different depth intervals to verify the contributions of top and bottom layers.

The flushing time was started at July 4, the approximate date of ice cover break-up in the bay, and ended once the complete volume of the bay passed northward through the boundary (approximately 5.12×10^8 m^3). This calculation was done for the 2011 baseline simulation and several other scenarios, which included simulations using the winds recorded in 2005, 2007 and 2009, simulations using double or quadruple times the freshwater input than the baseline model, and simulations done with the 2011 wind magnitudes but wind directions locked into one of the four cardinal points (i.e., north, south, east and west).

The results are displayed in Table 3.2-1 and described in detail in the following sections.

3.2.2 2011 Baseline Simulation

For the 2011 year, a volume of water equivalent to the Roberts Bay total passes through to Melville Sound within seven days of the ice breakup date. Most of this flushing occurs in the top 10 to 20 m of the water column, since surface currents were much stronger than their lower depth counterparts due to the wind forcing proximity. Hence, the bottom waters in 2011 (i.e., the 30 m to bottom transport area) only flush the equivalent volume in roughly 17.5 days in the circulation model. These values are extremely conservative estimates when calculating the bottom water section, since the complete bay water volume is used instead of the actual 30 m to bottom volume.

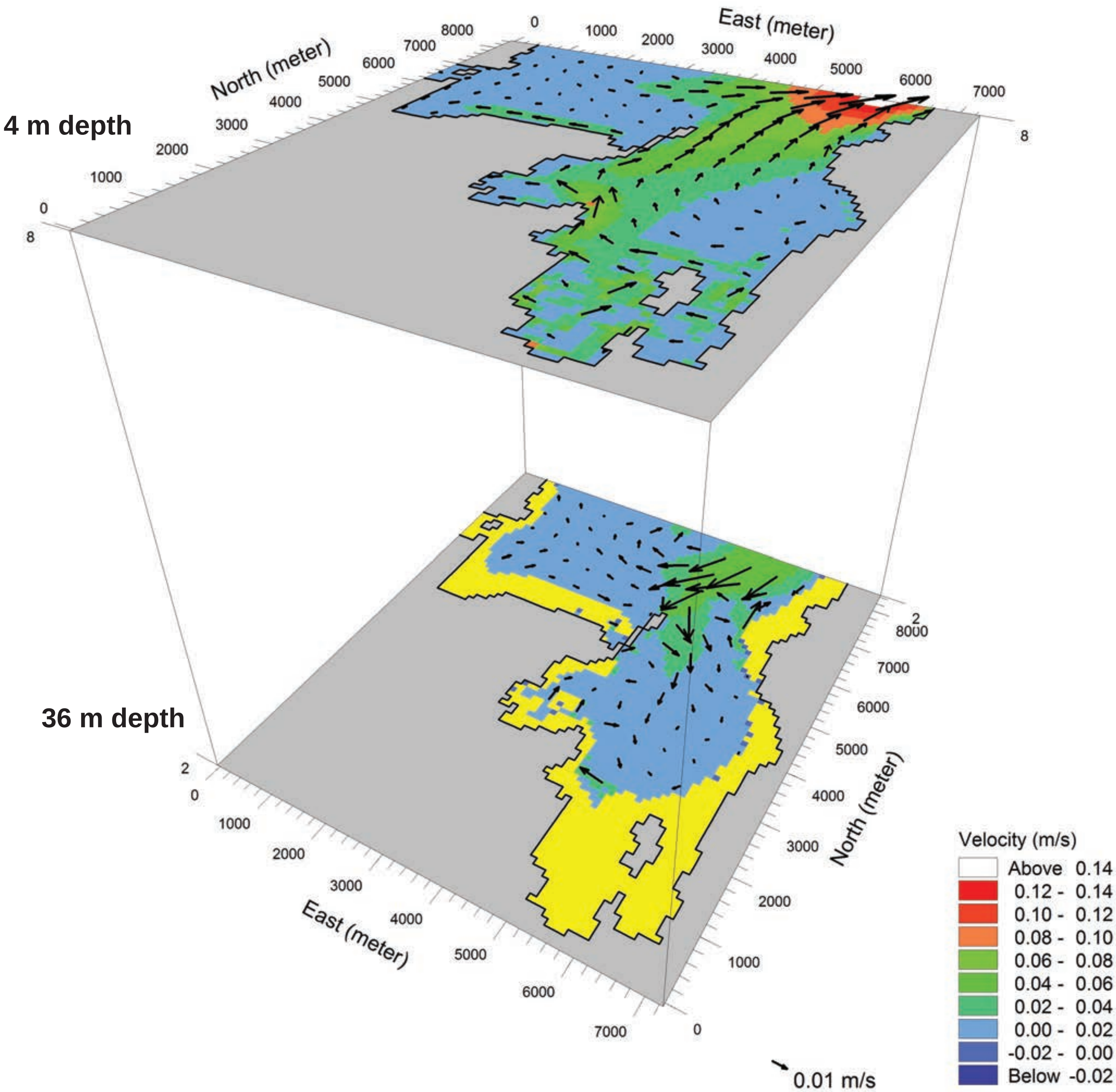
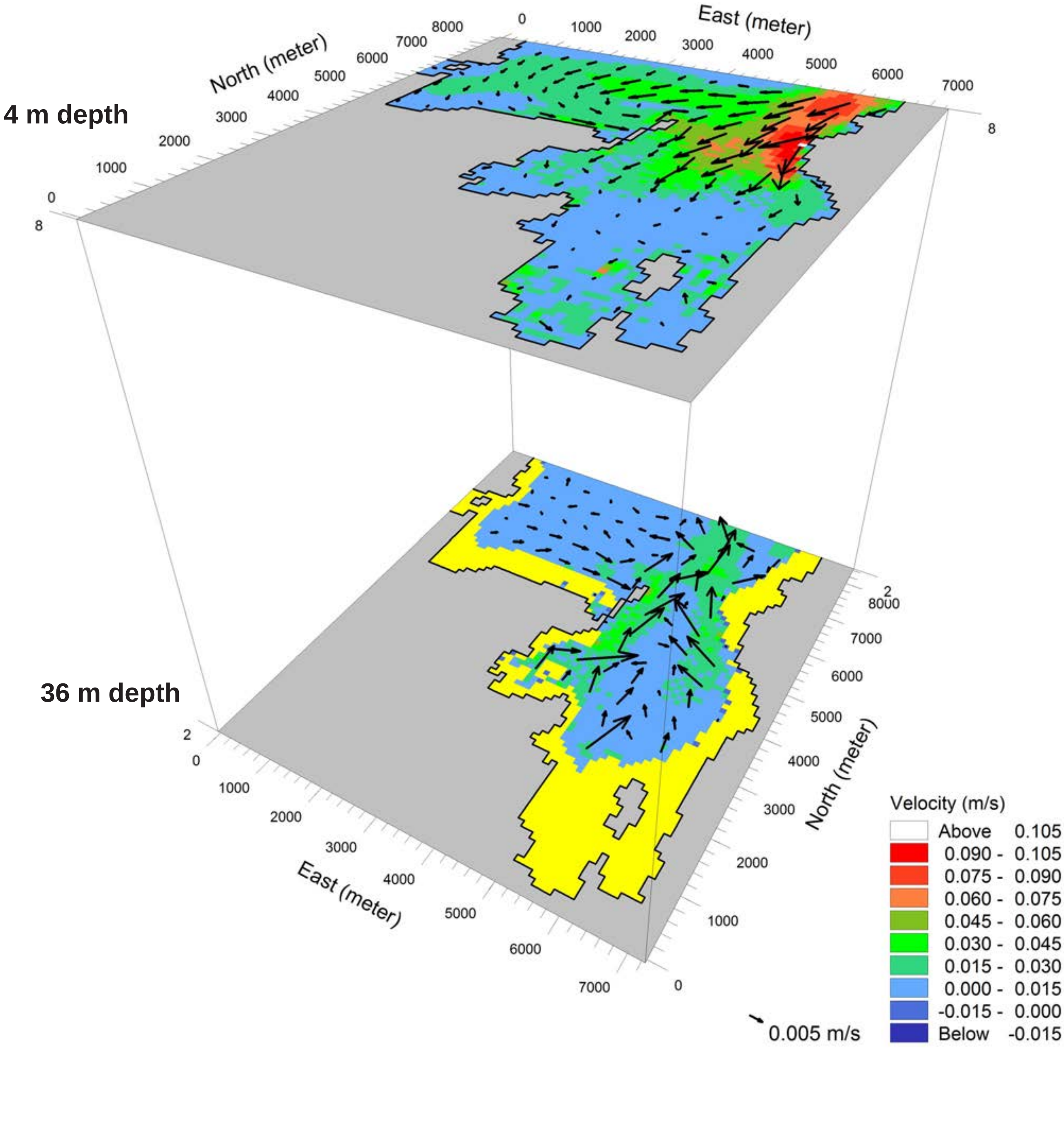


Figure 3.1-6

Mean Model Current Velocities and Directions at 4 and 36 m Depths, July 1 – July 7, 2011



NEWMONT NORTH AMERICA

Mean Model Current Velocities and Directions at 4 and 36 m Depths, August 5 – August 8, 2011

Figure 3.1-7

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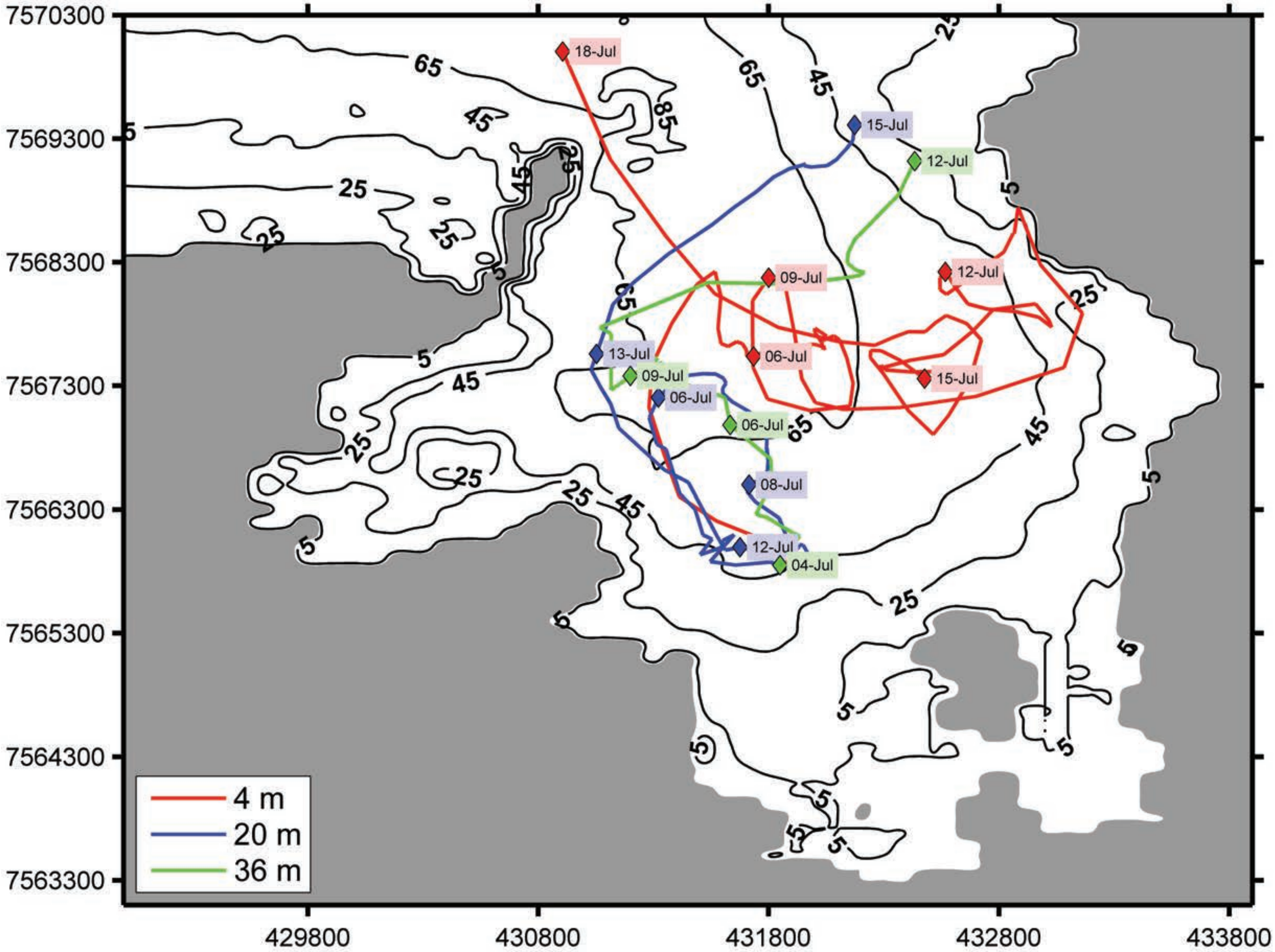
Table 3.2-1. Flushing Rates of Roberts Bay (in days) at the Melville Sound Exchange Location for Different Water Column Sections and Modelling Scenarios

Model Scenarios	All Depths	10 m Depth to Bottom	20 m to Bottom	30 m to Bottom
2011 Baseline	6.71	8.58	15.00	17.58
2009 Winds	6.92	8.54	18.38	25.13
2007 Winds	8.83	11.54	19.04	26.33
2005 Winds	7.75	10.04	18.75	27.71
Double Outflow	6.95	10.08	16.67	21.08
Quadruple Outflow	7.33	12.38	22.33	28.50
North Winds	6.29	7.05	14.83	23.54
South Winds	5.25	6.63	7.92	9.96
East Winds	6.49	8.42	17.63	24.25
West Winds	6.79	8.71	17.67	25.50

The flushing rate considered in Table 3.2-1 only takes account of northern flowing waters; thus, there is the possibility that some of the water exchange is simply the result of back and forth circulation at the Melville Sound boundary, and not Roberts Bay entirely flushing into Melville Sound. An important question is whether or not waters at the southern part of the bay actually reach Melville Sound. While tracking all discrete water parcels at every time step in the model could easily solve this issue, such calculations are numerically intensive and well beyond the scope of this report. Instead, parcels at three specific depths (4, 20 and 36 m) were recorded using a Lagrangian description during the simulation, starting at the 38 m station (i.e., the potential TIA discharge point). For this experiment, the parcels were assumed to be uniformly affected by the currents at each grid and followed their depth isoclines during the model run (i.e., no vertical mixing). While this latter assumption is sometimes unrealistic, particularly during episodes of large upwelling/downwelling (e.g., storms, boundary regions, collapsing fronts), generally it is reasonable given that the horizontal currents are more than an order of magnitude larger than vertical currents.

The results of the tracking experiment for each layer are plotted in Figure 3.2-1. In general, parcels at all three depths followed a clockwise pattern around Roberts Bay before reaching Melville Sound, as had been observed in the 2011 Roberts Bay Physical Oceanography Baseline Report (Rescan 2012b). The shallowest parcel at 4 m depth traveled a much greater distance than the others within Roberts Bay, as it was subjected to stronger, more variable currents. This is clearly apparent around the dates of July 5-6, where the parcels suddenly shifted eastward and then northward, skirting the coast and nearly exiting the bay, before moving back towards the middle of the Bay around July 12. Afterwards, wind/wave interactions subjected the parcel to a couple of cyclonic motions before being ejected out of the bay at the western end of the Melville Sound boundary shortly before July 18. The deeper parcels underwent comparatively more straightforward trajectories: at 20 m depth, the waters went through a small clockwise eddy before exiting the bay around July 15, while at 36 m depth, the parcel simply circulated anticyclonically before entering Melville Sound on July 12.

Given that each tracked parcel flushes out of Roberts Bay within two to three weeks of circulation, the flushing rates displayed in Table 3.2-1 are surmised to affect the complete regional volume of the bay within a few weeks of open water circulation.



NEWMONT NORTH AMERICA

Water Parcel Model Trajectories at 4, 20 and 36 m Depths Starting July 4, 2011

Figure 3.2-1

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3.2.3 Yearly Wind Scenarios

Since winds were deemed the single most important driving force in generating the Roberts Bay circulation (see Rescan 2012b), it was useful to complete simulations with different wind regimes to assess how the flushing rate could vary on a year-to-year basis. Although wind data for the summer months were available yearly from 2005 onwards (see Figures 1 to 7 in the Appendix for wind rosettes), simulations were done only for odd years. The rest of the input data (initial temperatures and salinity, freshwater discharges, etc.) were the same as the 2011 simulation. The results for the flushing rates are again shown in Table 3.2-1. All wind scenario simulation resulted in longer flushing rates (i.e., longer residence times) than the 2011 year; the differences were low when considering the transport rate at all depths (maximum of 2.22 days between 2011 and 2007), but increased significantly when considering only the bottom layer (maximum of 10.13 days between 2011 and 2005). The rapid flushing for 2011 is attributed mainly to the higher wind magnitudes found during that year, since stronger winds result in deeper, more intense currents (Gill 1982).

3.2.4 Freshwater Flow Scenarios

The freshwater discharge from the Little Roberts and Glenn outflows were secondary contributors to the circulation within Roberts Bay, but the impact of their variability is difficult to assess simply by looking at the 2011 baseline model run. Given that the total riverine input is not well known for Roberts Bay, and that the values used in the numerical model likely underestimated the true freshwater input to the system, two different scenarios were run through the model where the freshwater flow was doubled and quadrupled. These scenarios highlighted one of the main advantages of numerical modelling, the potential to analyze the sensitivity of one distinct parameter (i.e., freshwater discharge rate) within a complex system.

The resulting flushing times are shown again in Table 3.2-1. Since the general mean circulation in the bay is positive estuarine, the expected response to an increase in freshwater discharge in the southern bay would be a greater seaward density gradient, enhanced flows out of the bay and thus lower flushing times. However, larger flushing times were recorded at all transect depths for both scenarios; relatively minor differences when considering the complete water column depth (< 0.5 day increases), but fairly important when only considering the bottom waters, with a difference of over 10 days between the 2011 baseline and quadruple flow simulations. During the model runs, the increased freshwater input served to lower the water salinity and temperatures in the top 10 m of the water column, hence increasing the stratification and limiting the transfer of wind energy between the surface and deep waters. This in turn led to slightly lower current velocities and changes in circulation patterns, resulting in the lower flushing times within the model.

3.2.5 Wind Direction Scenarios

Another significant difference in the wind data between the 2011 and previous years was the generally more southerly wind directions, particularly in July. Since southerly winds naturally push waters out of the bay, this should contribute to faster flushing rates. To verify the impact each cardinal wind direction has on the Roberts Bay system, four test simulations were initiated where the winds had the same magnitudes as in 2011, but the directions were constantly northern, eastern, southern or western (i.e., direction of 0°, 90°, 180° or 270°). These scenarios, although physically implausible, help to isolate the impact of each wind direction with respect to the bay's flushing. As displayed in Table 3.2-1, the results for flushing times indicate very little difference between north, east or west directions. The northern scenario had slightly lower flushing times, since the wind direction impedes the natural positive-estuarine flow. The southern wind scenario resulted in the lowest flushing times of all simulated runs, with only roughly 10 days for the bottom layer calculation. This result agrees with the hypothesis that the 2011 flushing times in July were faster due to more southerly winds.

4. Summary and Conclusions

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4.1 GENERAL CIRCULATION PATTERN

A 3D hydrodynamic coastal model (MIKE3 by DHI) was used to reproduce the 2011 baseline marine conditions for Roberts Bay as reported in Rescan (2012b). Despite the many simplifying assumptions made during model construction, the simulations were able to reasonably reproduce the two-layered thermohaline structure and current velocities of the bay, with layer delimitations generally within 5 to 10 m of the measured data.

The current depth structures modelled at the ADCP locations differed from what the instrumentation measured, but the velocity magnitudes were of the same order. The emergent circulation pattern in the bay was that of a positive estuarine-type flow with strong seaward flow and lower, more diffuse bottom water landward flow. This is in agreement with the observations detailed in Rescan (2012b). However, predicted current directions varied extensively with wind input, and the circulation pattern sometimes shifted into negative-type flow where the bottom layer had seaward flow and vice versa for the top layer.

4.2 ROBERTS BAY FLUSHING TIMES

The time required by the model to flush all waters from the bay at the Roberts Bay/Melville Sound transect boundary, starting from the complete disappearance of the ice cover on July 4, was computed for the 2011 baseline simulation and several other scenarios. The results are summarized below:

- For the 2011 baseline simulation, it took less than a week for a total volume of water equivalent to Roberts Bay to transport out into Melville Sound. This time increased to nearly 18 days when only calculating from 30 m depth to the water bottom.
- The minimum flushing times were obtained by forcing all winds to be from the southern direction, thereby enhancing all flow out of Roberts Bay into Melville Sound. This resulted in a flushing time for the bay of slightly above 5 days when considering the complete water column, and a time of approximately 10 days when calculating from 30 m to the water bottom.
- The maximum flushing times using realistic winds were obtained by running the 2011 simulation with 2007 winds, taking nearly 9 days to flush the bay out over the complete water column, and more than 26 days when considering the 30 m to bottom layer.
- The absolute maximum flushing for the 30 m to bottom section resulted from the quadruple freshwater outflow scenario for 2011.
- Overall, stronger winds and more southerly wind directions lowered the flushing times of the bay, while increased flushing times resulted from greater freshwater input and north-westerly winds.

In summary, a conservative estimate for the flushing time of the bottom waters (i.e., 30 m +) of Roberts Bay at the onset of summer 2011 is approximately 3 weeks, and when considering various circulation scenarios the maximum flushing time is estimated at nearly a month. Thus, it is surmised from the modelling results that Roberts Bay will be effectively flushed multiple times with Melville Sound waters during the f-month long summer season.

References

References

Definitions of the acronyms and abbreviations used in this reference list can be found in the Glossary and Abbreviations section.

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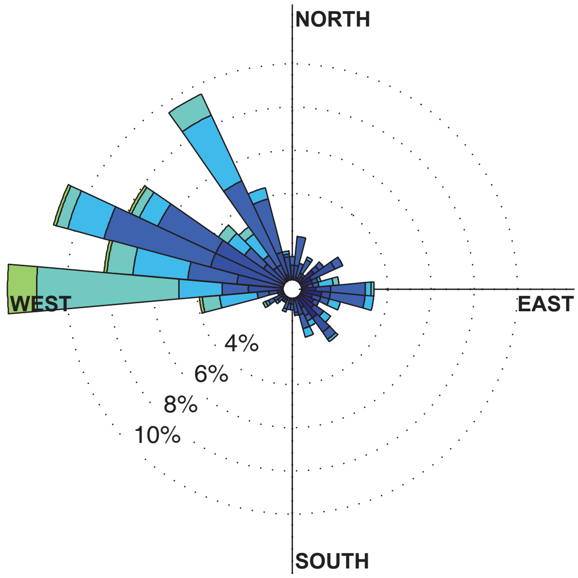
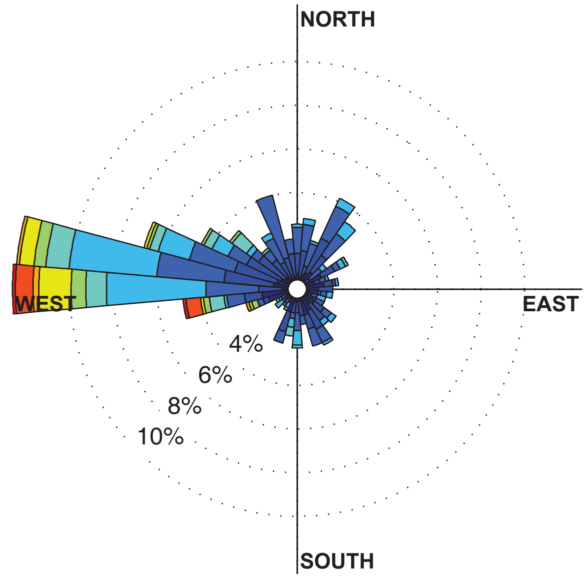
Appendix 1

Monthly Wind Roses at Roberts Bay, Doris North Project, July to October, 2005-2011

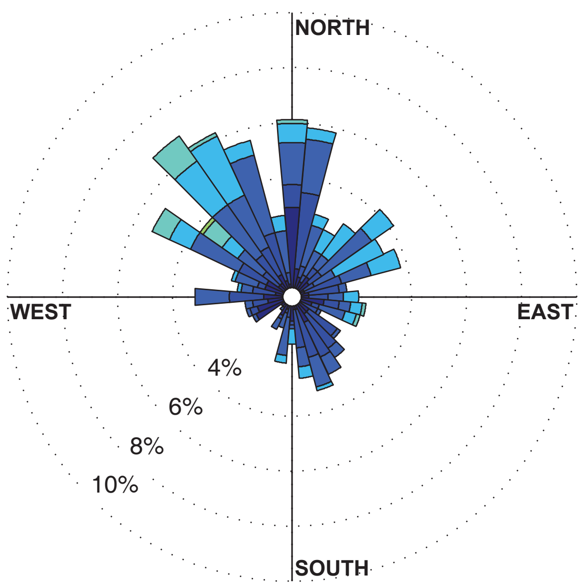
July 2005



August 2005



September 2005



October 2005

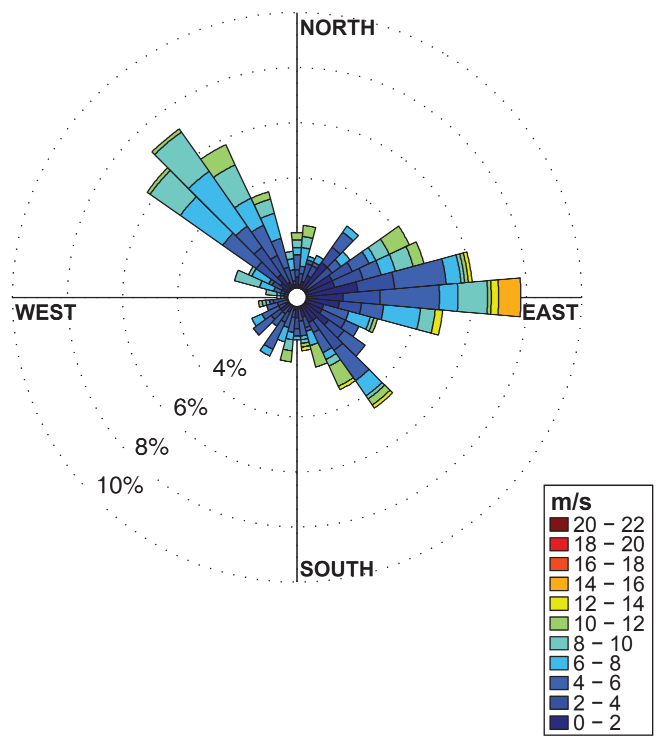


Figure 1

2005 Windroses

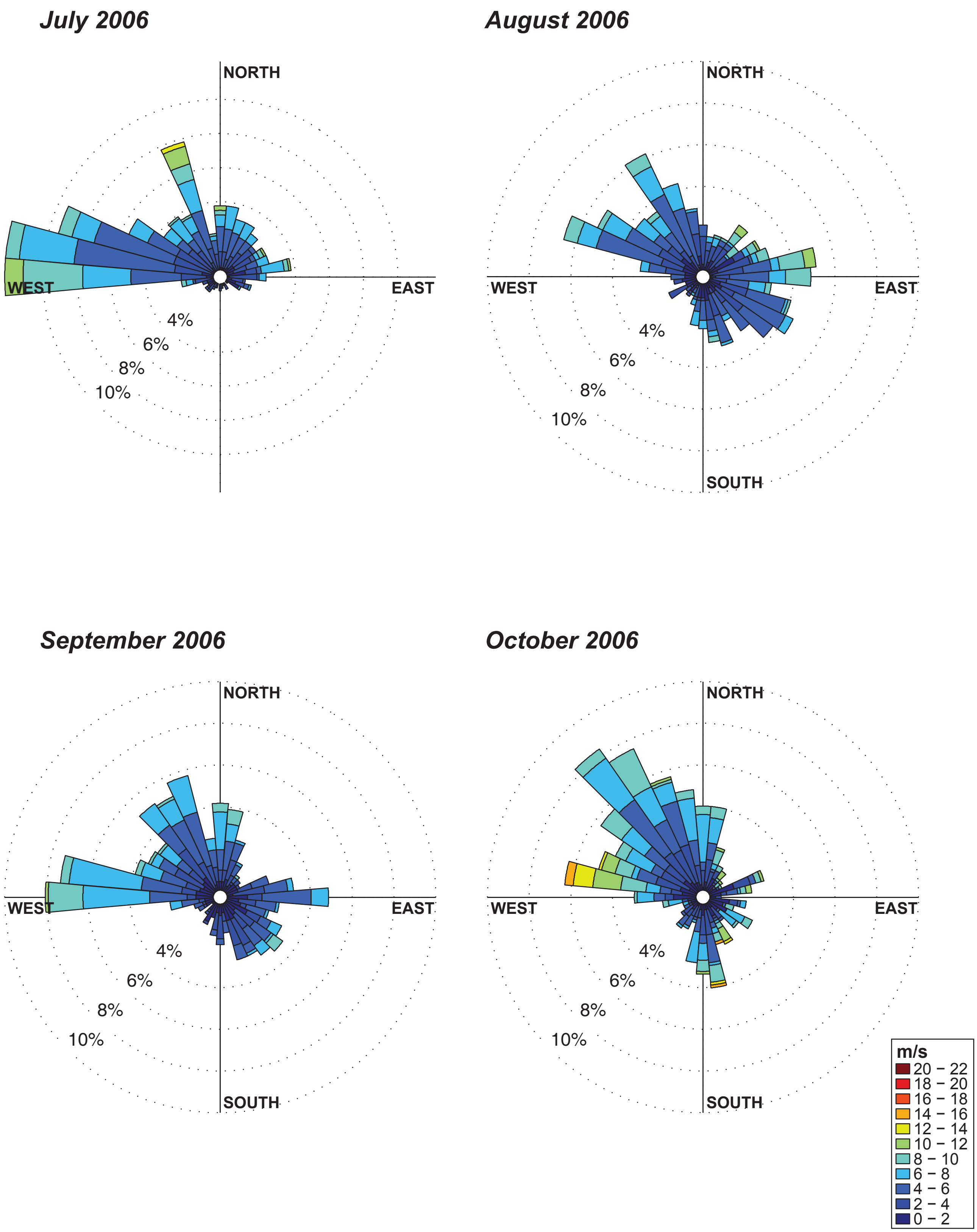
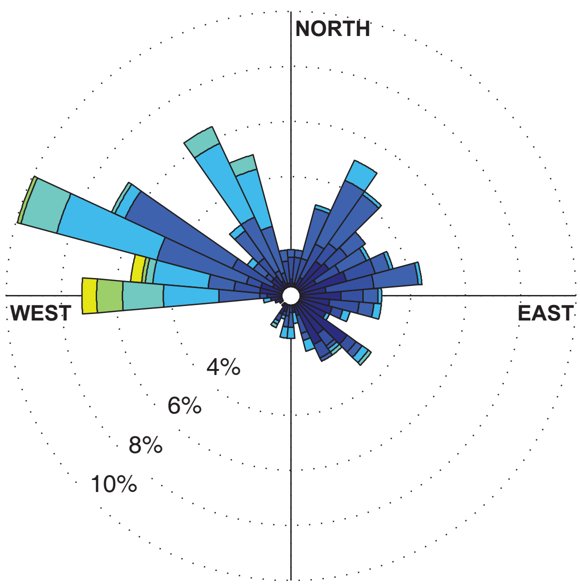


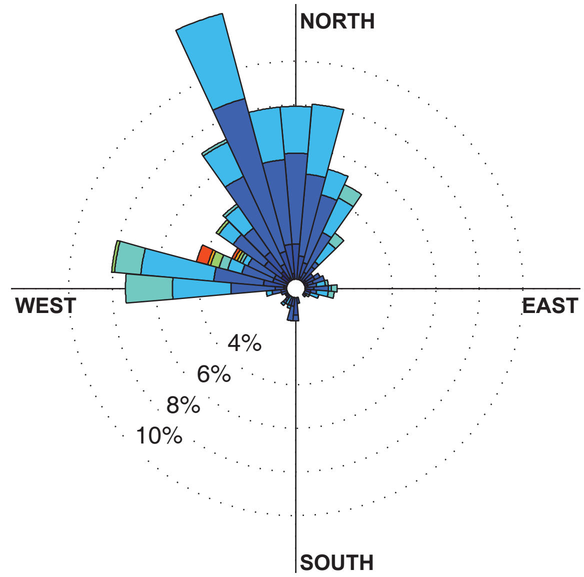
Figure 2

2006 Windroses

July 2007



August 2007



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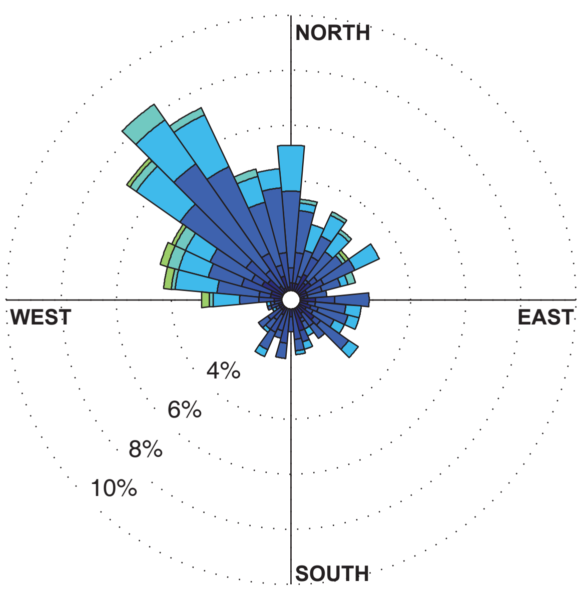

October 2007

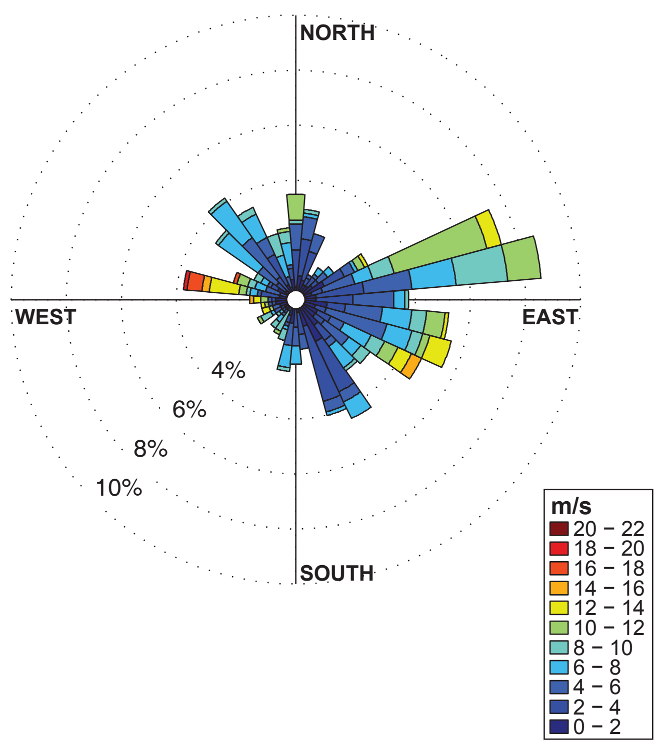

Figure 3

2007 Windroses

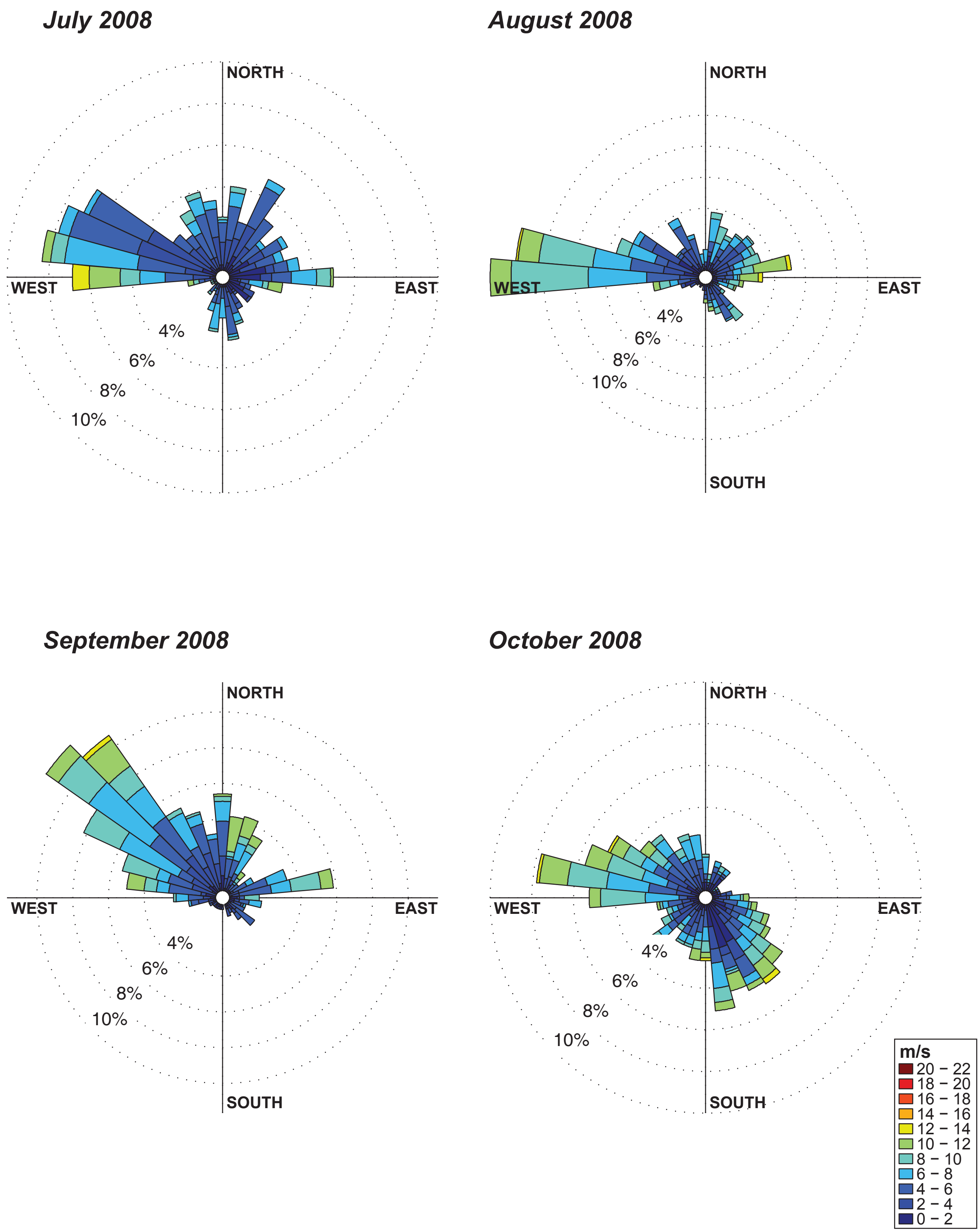

Figure 4

2008 Windroses

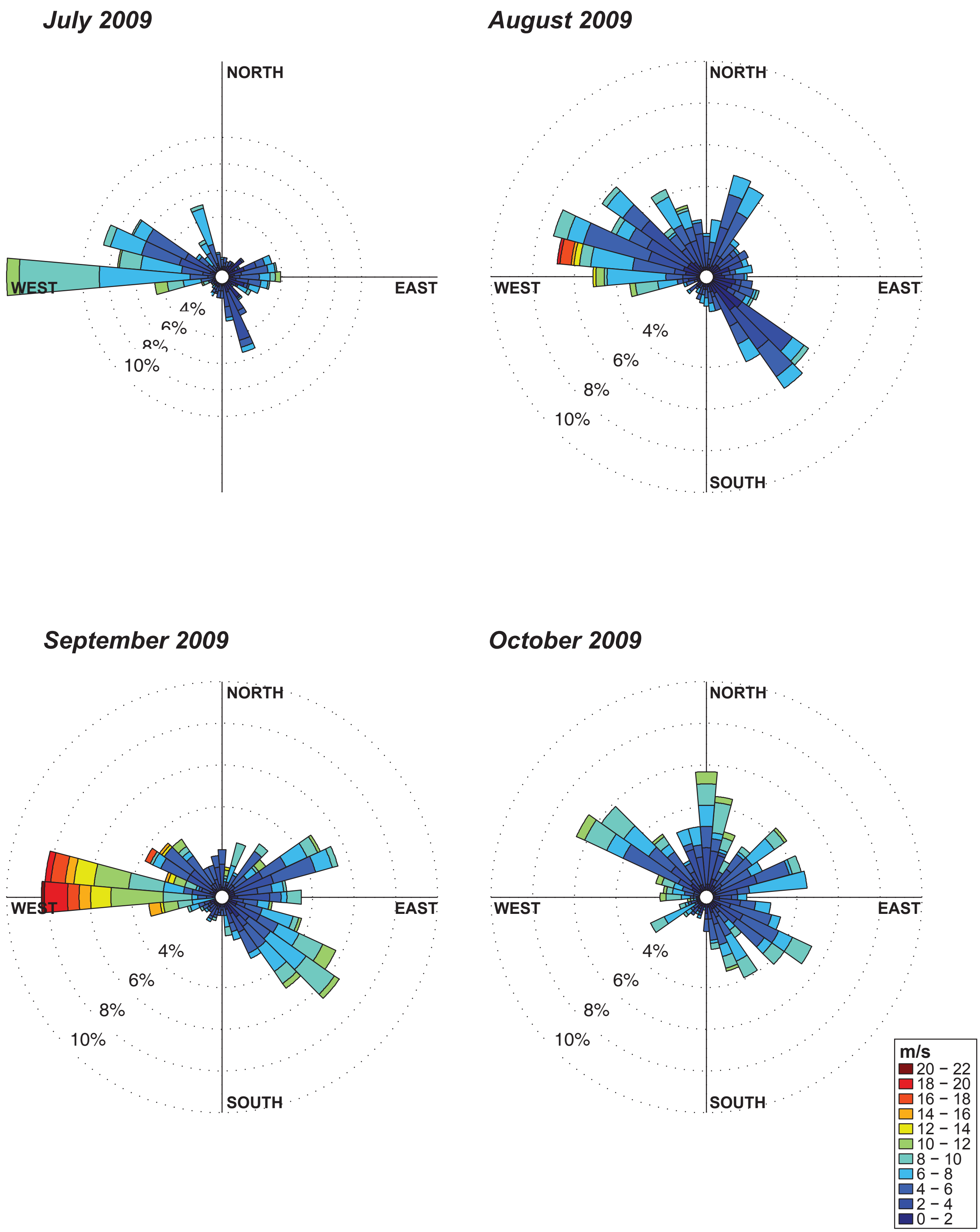

Figure 5

2009 Windroses

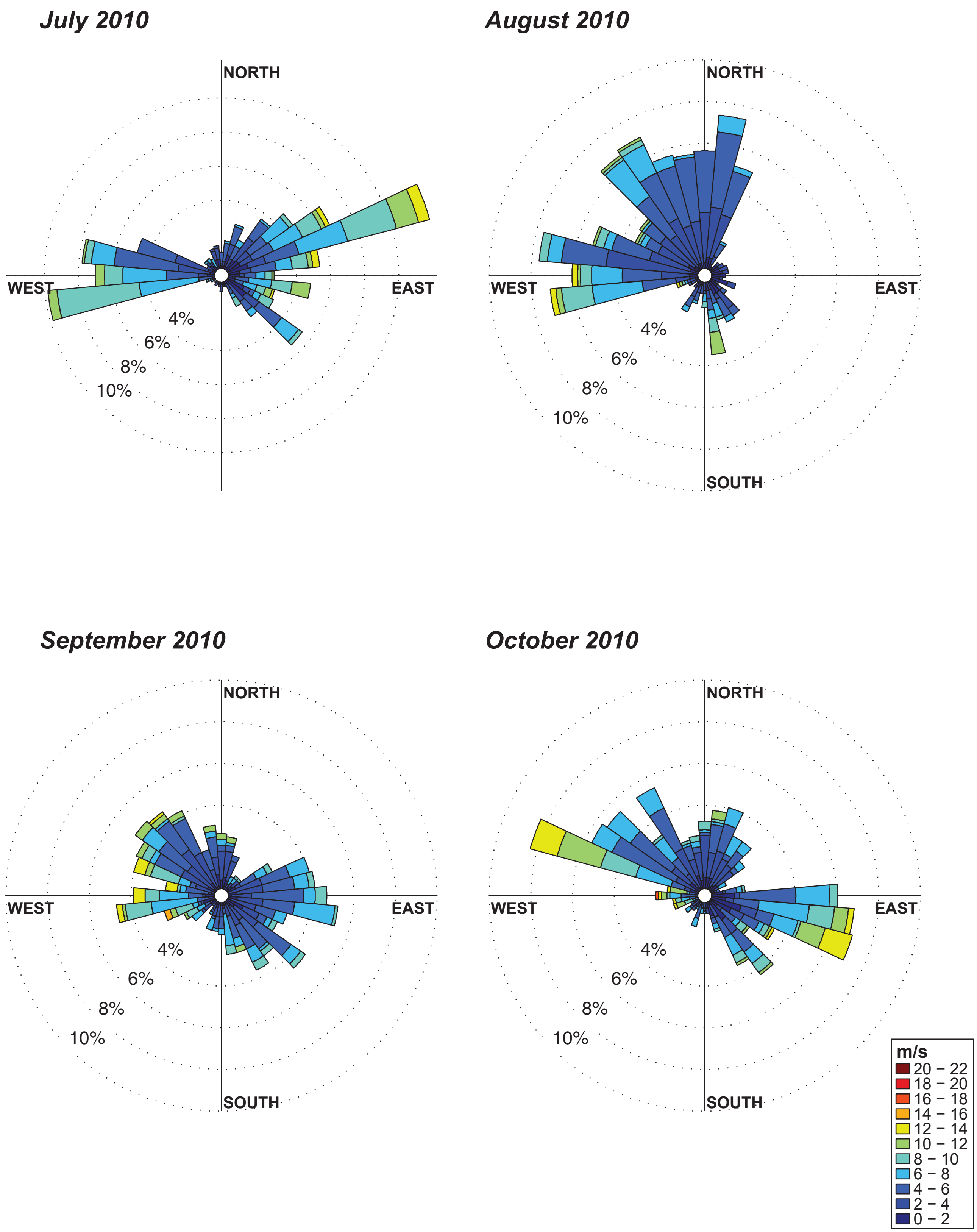

Figure 6

2010 Windroses

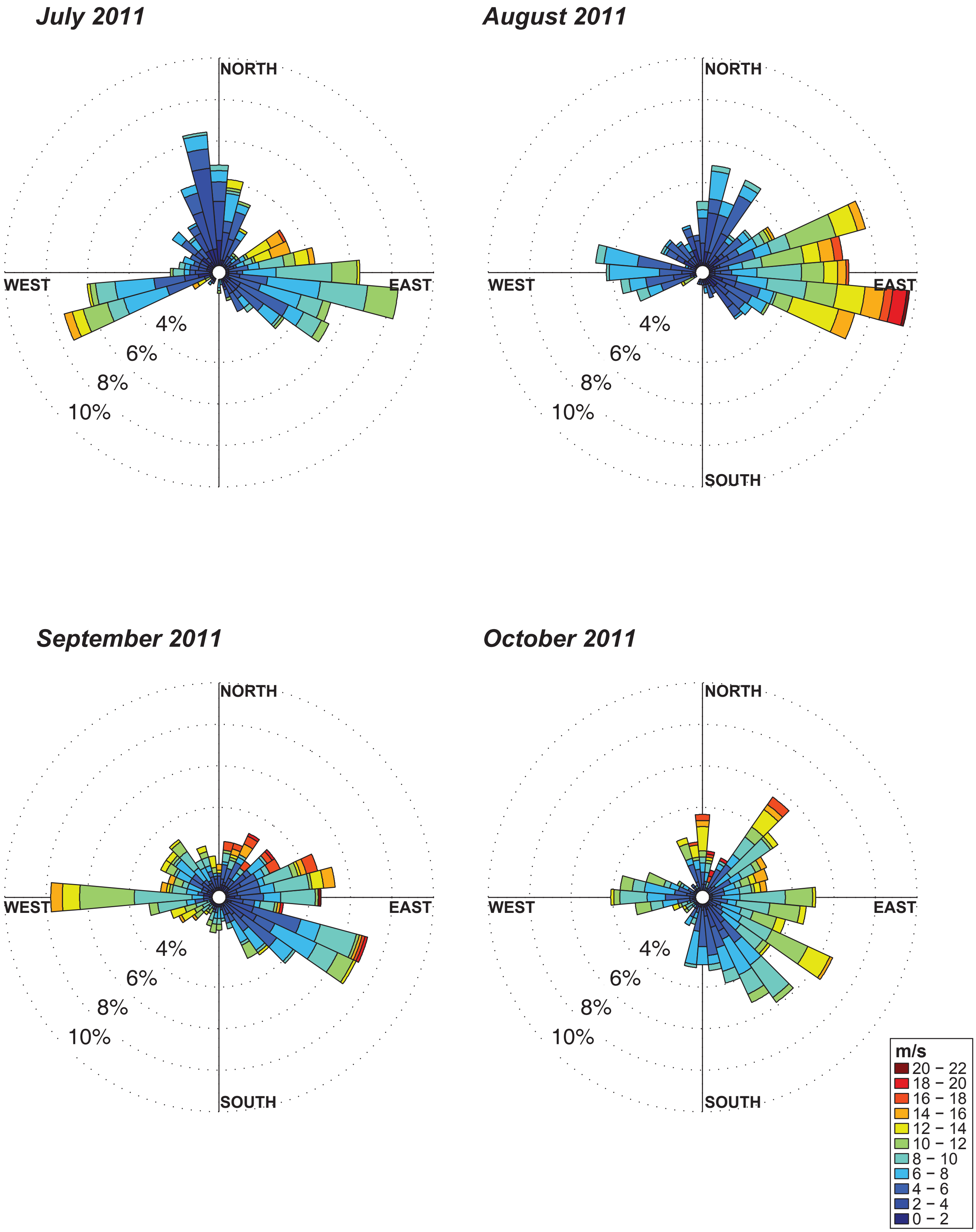

Figure 7

2011 Windroses