Port Valdez Weather Buoy Analysis 2019 - 2021

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Contents

List of acronyms 2
Executive summary 2
Introduction 2
Data operations, notes, and quality assurance/quality control (QA/QC) 4
A primer on the visualization of vector data 4
Results and discussion 5
Air and sea surface temperature 5
Relative humidity 6
Barometric pressure 6
Solar radiation 6
Wind speed and direction, wind gusts 6
Wave height and direction 7
Temperature climatology 8
Surface currents 9
Conclusions 11
Literature cited 13
Figures 14
Appendix 1: Table of averages and minimum/maximum values at the VMT buoy, by month. 37
Appendix 2: Table of averages and minimum/maximum values at the Duck Flats buoy, by month. 38

List of acronyms

CO-OPS	Center for Operational Oceanographic Products and Services (NOAA)
FAA	Federal Aviation Administration
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PWS	Prince William Sound
PWSRCAC	Prince William Sound Regional Citizens' Advisory Council
QA/QC	Quality Assurance / Quality Control
VDZA2	NOAA tide station in Valdez Harbor
VMT	Valdez Marine Terminal
WMO	World Meteorological Organization

Executive summary

This report summarizes two years of meteorological and oceanographic measurements made by two buoys deployed in Port Valdez, one adjacent to the Valdez Marine Terminal (VMT) and one near the Valdez Duck Flats. Time series at each of the buoys were analyzed for seasonal, intra-, and interannual patterns. Air and water temperatures, and solar radiation all showed a cyclical seasonal progression typical to subarctic regions, with minima in February and maxima in August. Relative humidity was high, as befits a coastal region with a large amount of annual precipitation, and tended to follow temperature trends. Air pressure, driven by large scale atmospheric circulations, was similar between the two sites. Winds were primarily from the east in autumn and winter, again driven by the large-scale atmospheric patterns that create a low pressure system over the Gulf of Alaska during that time. In late spring and summer, daily westerly sea breezes were common. A 113-year-long temperature climatology was constructed for the Valdez region, which showed a steady and persistent warming trend. Temperatures in 2019 tended towards warmer than average and transitioned towards cooler than average in 2020 and 2021, as did much of the North Pacific, in response to a La Niña event. The influence of winds, tidal currents and river discharge on surface currents were examined. All were weakly correlated with surface currents but parsing out each influence proved difficult. Cross covariance analysis comparing the timing of currents at the buoys compared to the tides at the Port Valdez tide station showed that surface currents tended to lag the tides by approximately 45 minutes to 1 hour, 15 minutes.

Introduction

The Prince William Sound Regional Citizens' Advisory Council (PWSRCAC) operates two weather buoys in Port Valdez, one offshore of the Valdez Marine Terminal (VMT) at Jackson Point that was deployed in May 2019, and one adjacent to the Valdez Duck Flats that was deployed in September 2019 (fig. 1). Both buoys have been uploading meteorological and oceanographic observations on an hourly basis (with some interruptions due to hardware/software failures and service visits) since their deployment.

Standard equipment on each buoy includes an anemometer, relative humidity sensor, three temperature thermistors (one dedicated for air temperature, a secondary included in the relative humidity sensor, and one to measure sea surface temperature mounted ~1 meter (m) below the waterline), barometer, radiometer, Acoustic Doppler Current Meter (for surface currents), and a wave sensor (only on the VMT buoy at present). An onboard electric compass is used to measure the buoy heading to adjust direction measurements (wind, waves, and current) to true north. The measured parameters of interest, their units, and recording period are listed in table 1.

Table 1: Meteorological and oceanographic parameters collected by the buoys.

Parameter	Instrument Make/Model	Units	Recording period
Wind speed	RM Young 05103-L	m/s	6 minutes
Wind gust speed	RM Young 05103-L	m/s	6 minutes
Wind direction	RM Young 05103-L	Deg. True	6 minutes
Air temperature	Campbell Scientific 109	°C	15 minutes
Relative humidity	Campbell Scientific HC2S	%	15 minutes
Barometric pressure	Setra CS100-QD	mbar	15 minutes
Solar Radiation	Hukseflux LP02	W/m^2	15 minutes
Current speed	Nortek Aquadopp 2 MHz	m/s	20 minutes
Current direction	Nortek Aquadopp 2 MHz	Deg. True	20 minutes
Significant wave height	Axys TriAXYS	m	Hourly
Maximum wave height	Axys TriAXYS	m	Hourly
Wave period	Axys TriAXYS	s	Hourly
Wave direction	Axys TriAXYS	Deg. True	Hourly

The high frequency of sampling by the buoys has already created large archive of observations, approximately 6.9 million primary data points for the VMT buoy and 6.5 million data points for the Duck Flats buoy, plus a similar amount of associated metadata. The purpose of this report is to provide an analysis of some of the seasonal and higher frequency patterns found in the data.

This report is structured around the different data types produced by the buoys. Following discussion with PWSRCAC staff and committee members, the basic averaging period was decided to be monthly. In some cases higher frequencies have been used where appropriate to provide a higher level of detail. Given the very broad backgrounds of the many PWSRCAC stakeholders, technical jargon has been avoided where possible to provide a plain language interpretation for that large and diverse audience; where necessary, definitions of technical terms are provided. Rather than the usual methods/results/discussion format featured in the scientific literature, a more narrative structure was adopted, and explanations of methods, highlighting of the results, and discussion of them have been done all at the same time for the many different data collected. The metric units used by the buoys have also been mostly converted to imperial units. Graphical presentations of the data have been used as much as possible and a tabular compilation of monthly averages at both buoys has also been included in appendices.

Data operations, notes, and quality assurance/quality control (QA/QC)

All data was downloaded directly from the buoy servers. Each time series was examined with automated and manual methods for anomalous spikes. Relative humidity values prior to January 2020 at the VMT were removed (the sensor was damaged) and occasional bad water temperature observations at the buoys (<28°F) were removed. On or about March 11, 2020, the VMT buoy had a power issue which tripped the main fuse from the battery, which resulted in intermittent daytime-only data (when the solar panels produced enough voltage to power up the data logger) until the buoy was repaired on April 29, 2020.

A primer on the visualization of vector data

Meteorological and oceanographic data are either scalar observations (magnitude only, e.g., temperature) or vector observations (magnitude and direction, e.g., winds). Scalar data may be visualized with a standard x-y plot that should be familiar to most. Vector data, having two components, is more complicated to visualize and average. A vector may be visualized as an arrow, with the direction indicated by the direction the arrow is pointed, and the magnitude indicated by the length of the arrow (fig. 2A). When doing mathematical operations on a vector, vectors are usually broken up into components that correspond to the dimensions of the vector. The red and blue arrows in figure 2A indicate those two components for the two-dimensional vector shown: there is a horizontal component and a vertical component. Those components are usually designated as 'u' and 'v' in the technical literature, and in the context of meteorological data are referred to as the zonal (i.e., "east-west") and meridional (i.e., "north-south") components. In this context positive numbers mean one direction and negative numbers mean the opposite. For example, on the east-west axis in figure 2, a positive number is eastward and a negative number is westward. Figures showing vector components in this report have annotations indicating the east/west and north/south directions to aid the reader.

Averaging of vector observations is usually done on the components and then may be visualized in a number of ways. The two methods used in this report are roses and quiver plots. A rose is a good way to summarize a large number of observations and may be thought of as something similar to a bar chart, but arranged in a circle to indicate directions. An example of a rose plot is shown in figure 2B, which represents all the wind observations made by the VMT buoy in the month of June 2020. The wind directions (the direction the wind is blowing from) are broken up into 10° "bins" that are shown by the bars. The length of the bars is proportional to the frequency of winds blowing from that direction and the colors indicate bins of wind speeds, which are shown on the color scale to the right. Figure 2B shows us that most of the winds in June 2020 were primarily in the east-west direction. The median wind direction (i.e., the most frequent, shown by the longest bar) was just south of westerly. The four largest bars showing westerly to southwesterly winds can be summed up on the circular scale and shows that something like half (50%) of winds were in those westerly to southwesterly directions. The color scale shows that the strongest winds were westerlies, with a small proportion blowing 15-20 knots (green bars), slightly more blowing 10-15 knots (cyan bars) and more still blowing 5-10 knots (light blue bars). One can also see that easterly winds were generally weak, being mostly 0-5 knots (dark blue bars). In this report, rose plots are used only for the most recent year of data (2021), because showing multiple years results in very small roses or multi-page figures that are difficult to interpret.

Quiver plots allow examining finer scale patterns that would be impractical with rose plots and show a vector as an arrow or a line. An example quiver plot is shown in figure 2C, again using wind data from June 2020 at the VMT buoy, but with daily average wind speed and direction shown. Each arrow in the plot is the daily average wind velocity, with the angle of the stick showing the direction of the wind vector and the length of the stick indicating the wind speed. The axis is scaled such that the length of the stick is proportional to the ticks on the bottom axis. Because the winds, waves, and currents in Port Valdez are primarily oriented in the east-west direction, the plots were produced with time shown vertically. Arrowheads are shown in the example plot, but are not shown in the rest of the plots in this report because they show a great deal more data and the arrowheads tended to add clutter and make the plots more difficult to read. Quiver plots are more data-dense, and the entire time series from each buoy is shown (instead of the most recent year) to give a sense of the entire time series collected so far.

Meteorologists and oceanographers use different conventions when speaking of directions: meteorologists speak of the direction that winds are coming from (e.g., a northerly wind is coming from the north), while oceanographers speak of the direction water is traveling to (e.g., an eastward current is travelling to the east). This convention has been adhered to in this report for the rose plots, but has not for the quiver plots, because the quiver plots are a direct representation of the vector in question (the average movement of the air or water). This is why the rose in figure 2B has bars pointing to the left ("winds from"), while the quiver plot in figure 2C has vectors pointing to the right ("direction air is moving to"). In the text of this report both "from" and "to" notation is used depending on the convention (meteorological vs oceanographic) to distinguish between the conventions.

Results and discussion

Air and sea surface temperature

Monthly air and water temperatures at both buoys showed the typical sinusoidal seasonal cycle expected in a subarctic environment (figs. 3, 4), with maxima in August and minima in February and considerable day-to-day departures from monthly means. Air temperatures tended to be slightly higher at the VMT buoy (fig. 3) than at the Duck Flats buoy (fig. 4), which may indicate a slightly more terrestrial influence at the Duck Flats buoy (e.g., downsloping winds from the Valdez Glacier Valley, see winds discussion below). Water temperatures were also slightly cooler at the Duck Flats, likely reflecting potential source waters from the Lowe and Valdez Glacier Rivers which can be expected to be cooler than seawater given the presence of year-round ice in their watersheds.

Relative humidity

Relative humidity was variable at both sites (figs. 3, 4). Much of the time relative humidity was quite high, greater than 70%, as expected in the coastal climate both buoys are measuring. Part of the data record from the VMT buoy was removed for data quality issues, but both buoys have an almost complete record from 2020 and 2021, and the patterns between them are quite similar. Relative humidity was highest in August and lowest in March, following the temperature cycle.

Barometric pressure

Air pressure was very similar between both sites, as would be expected because air pressure is largely driven by large scale atmospheric circulations (figs. 3, 4). There was not a strong seasonal cycle in air pressure. Air pressure in summer 2019 was quite high and likely driven by a large-scale atmospheric ridge that set up over the north Gulf Coast that year (Amaya et al., 2020). A similar pattern set up in 2020. Air pressure during the summer months of 2021 tended to be higher than in 2020 and appears to have been similar to 2019. Pressure was more variable in the autumn months, with the onset of so-called “Equinox weather” which tends to feature large cyclonic circulations driven by the Aleutian Low, which usually sets up in the Gulf of Alaska in autumn and winter and determines the storm tracks to the region (Rodionov et al., 2007).

Solar radiation

As to be expected given the latitude of the sites, solar radiation was strongly seasonal, peaking in June and with a nadir during the winter months (figs. 3, 4). Both buoys are shaded by the mountains fringing Port Valdez during the late autumn and winter months, which has created some power issues (both buoys are powered by solar panels), particularly at the VMT location. The intermittent values in March and April 2020 (collected only during days when the solar panel energized the logger) resulted in spuriously large averages for those months because only daytime values were collected and those data were omitted from the averaging.

Wind speed and direction, wind gusts

Winds are summarized as monthly wind roses for 2021 in figures 5 and 6, and (following meteorological convention) are shown as the direction the wind is blowing from (i.e., an east wind blows from the east). The anemometers on the buoys are very sensitive and usually move slightly in all but the calmest conditions. They are also subject to freezing up after heavy snow and rain events followed by freezing temperatures. This manifests as a zero wind speed from exactly true north (vector multiplication on the 0 wind speed results in a direction of 0 as well) and can be seen on the wind roses as a spike in observations at the 0° band only. Those spikes may be used as an indicator of the frequency of calms during summer months and freeze-up events in winter.

Both the roses and the quiver plots (figs. 7, 8) show that most winds were easterly during autumn and winter, and transitioned to westerlies from May until August at both buoys. The strongest winds were easterlies, during the autumn and winter months, likely driven by outflow winds caused by the large-scale atmospheric features that set up in autumn/winter (the Aleutian Low offshore and high pressure over the interior). The summer westerlies are a daily sea breeze caused by localized heating and cooling that is familiar to mariners in the region (Lethcoe and Lethcoe, 2009). During the day, the sun heats the land faster than the ocean, creating upward convection and low air pressure over land; this draws air in from the ocean and creates a landward breeze (from the west in Port Valdez). At night, the land cools faster than the ocean, creating convection in the opposite direction. To illustrate this, hourly average winds in the east-west direction at the VMT buoy are depicted in figure 9 (patterns were identical at the Duck Flats buoy). Westerly winds are depicted with a green color scale and easterly winds are depicted with a blue color scale. The figure shows that the “westerly season” in Port Valdez begins in late April or early May, and extends into August. During the westerly season, winds on most days were easterly from midnight until approximately 10 a.m., then switched to westerlies into the afternoon and evening. There were occasional short episodes where the westerlies were disrupted by summer storms with strong easterly winds (fig. 7).

The roses and quiver plots also show that wind directions were not completely symmetrical, as there was a northerly component as well, regardless of if the winds were primarily from the east or west. That slight northerly tendency may have been caused by topographic steering of the winds by the steep terrain of Port Valdez, with westerly winds blowing out of Shoup Bay to the northwest. The northeastern direction of easterly winds may indicate that winds from Valdez Glacier Valley tend to predominate over those of the Lowe River Valley at the Duck Flats location.

Following the World Meteorological Organization (WMO) standard, the buoys also recorded a running 3-second average wind speed and reported the maximum of that 3-second average in each 6-minute wind recording period as the wind gust speed. Upon examination, a number of unrealistic (>200 knots) gust observations were found in the gust time series. Those values have been traced to an incorrect setting in wind measurement lines in the original data logger program which was corrected in February 2021. The wind gust time series at the buoys in 2021 (fig. 10) followed the same pattern as sustained winds, with maximums during the winter months and elevated gusts during the summer westerly season. Summer gust speeds were in the 15-20-knot range and 30-40-knot gusts occurred during autumn and winter storms.

Wave height and direction

Wave observations have also been summarized as roses (fig. 11) and quiver plots (fig. 12) at the VMT buoy. No wave measurements were made at the Duck Flats buoy in 2021, and discussion of the short time series of observations at that buoy was done in the buoy analysis report for that year (Campbell, unpubl.). Wind makes waves and the wave observations reflect the wind observations, with most waves, and the largest waves, from the east at the VMT buoy during the winter months and from the west in spring and summer.

The largest maximum wave height observed in the time series was an observation of just under 7 feet in March 2020 (fig. 13) and similar wave heights were recorded in early and late 2021. Maximum summertime wave heights were between 1 and 3 feet and wave heights were slightly higher during winter storms.

Temperature climatology

Although the buoys have a fairly short time series, to put the buoy observations into a climatological context it is possible to convert observations into anomalies (i.e., departures from the long-term average) using observations from nearby stations, with the assumption that they are reasonably similar. There is a National Oceanic and Atmospheric Administration Center for Operational Oceanographic Products and Services (NOAA CO-OPS) weather and water level station in Valdez harbor, named VDZA2, which has a record of water temperatures that goes back to 2008. An average annual temperature cycle based on weekly averages was created from the VDZA2 time series (fig. 14) to use as a long-term average.

Water temperatures at the buoys may then be averaged by each week and subtracted from the weekly averages at VDZA2 to produce an anomaly plot (fig. 15), which depicts the departure of observations from the long-term average seasonal cycle (only the VMT buoy is shown because patterns are essentially identical at the Duck Flats buoy). The anomaly plot shows that relative to the 2008-2020 average, surface waters were much warmer than average in the early summers of both 2019 and 2020 at the VMT buoy but tended to be cooler than average in autumn in both years. This matches with larger-scale oceanographic patterns seen elsewhere, including a Gulf of Alaska wide marine heat wave in 2019 (Amaya *et al.* 2020) and warm surface waters observed in Prince William Sound (PWS) in 2020 (Campbell, *unpubl. obs*). A La Niña event began in late 2020, and continued through 2021 (NOAA CPC 2021). La Niña events are usually correlated with cooler surface temperatures in the North Pacific (Papineau, 2001; Newman et al., 2016), but PWS tends to lag the Gulf of Alaska by about a year in terms of temperature responses (Campbell, 2018). Near surface water temperatures in Port Valdez tended towards cooler than average in 2021, with some warm stanzas of ~8 weeks duration in late winter/spring.

Although the water temperature record is comparatively short, a longer climatology is available for monthly average air temperatures in Valdez that was compiled by the Berkeley Earth database (http://berkeleyearth.org/). The Berkeley Earth time series spans from 1908 to 2013, using data from several National Weather Service (NWS) and Federal Aviation Administration (FAA) weather stations that have existed in the Valdez area over the years. To bring the climatology all the way to present day, the VDZA2 air temperature time series was appended to the Berkeley Earth series. The Berkeley Earth climatology overlaps with the VDZA2 time series for several years, which permits examining for offsets between the two time series. A linear regression comparing monthly averages at the VDZA2 station to the Berkeley Earth averages showed a very tight relationship between the two (excepting one outlier), but with a significant slope and offset (fig. 16). This suggests that although the two data sets showed the same pattern, there were slight differences in the temperatures that they estimated. The Berkeley Earth averages were therefore adjusted with the slope and intercept to make them consistent with the contemporary VDZA2 record.

The complete time series of air temperature anomalies from 1908 to 2021 (fig. 17) shows a consistent warming trend of just under a half a degree Fahrenheit per decade over the last 113 years, an overall increase in average temperatures of ~5 degrees. This is consistent with trends observed elsewhere in the region (e.g., Campbell, 2018). A pattern of cold winters and the occasional warmer than average summer early in the 20th century has transitioned to both warmer winters and summers, with occasional short stanzas (3-4 months) of cooler temperatures. Air temperatures in 2021 began above average, trended towards below average for much of the year, but became warmer than average by the end of the year.

Air temperature anomalies at the buoys (fig. 18) showed a similar pattern to water temperatures, with warm anomalies trending towards cooler in late 2019, and again in late 2020. 2021 began cool, trended towards slightly warmer than average, then cool again. The patterns between the buoys were similar, but again offset, with anomalies lower at the Duck Flats buoy. Again, that offset was partially because air temperatures tended to be cooler at the Duck Flats buoy (figs. 3, 4); if that offset is considered the overall pattern can be seen to be similar. The difference between the buoys is interesting given their relatively close proximity (3.5 miles), one explanation is that the VMT buoy reflects a more oceanic temperature regime, while the Duck Flats buoy, being more directly in line with the Lowe River and Valdez Glacier Valley is more land-influenced.

Surface currents

Surface currents at the VMT buoy were as high as 1.5 knots and considerably smaller at the Duck Flats buoy (fig. 19), which is not surprising given the different locations. The Duck Flats buoy is deployed in shallow water near the head of Port Valdez (where motions will be more vertical), while the VMT buoy is deployed in deeper water over a steeply-sloped bottom mid-Port, where tidal currents will be stronger as the tides slosh back and forth.

Tide heights from station VDZA2 are routinely overlaid on the current data at both buoys on the buoy websites (e.g., http://www.pwswx.pwssc.org/VMT/VMT.html). There is clearly a correlation between current direction and stage of the tide, as is to be expected given the large tidal ranges that are a feature of the region. In addition to the semidiurnal (i.e., twice daily) tidal circulations, there can also be longer period flows driven by winds and buoyancy currents (currents driven by freshwater entering saltwater under the influence of Coriolis forcing) and wind effects. The predecessor to this report (Campbell, *unpubl.*) attempted to de-tide the current observations to look for longer period residual flow, but the analysis was not very successful: it was suggested that wind influences might be overriding the tidal ones and confounding tidal analysis. For this report, the analysis focus was shifted to examine the effect of winds and tides on surface currents. This analysis focused on the VMT buoy, because the 2021 analysis (Campbell, *unpubl.*) showed that current velocities at the Duck Flats buoy are much weaker and less coherent.

In order to directly compare wind (measured every 6 minutes) and current (measured every 20 minutes) observations, the time series of average wind speed was downsampled by linear interpolation to the same 20-minute time points as the current observations. Comparisons of wind and current velocities in the east-west and north-south components (fig. 20) showed no obvious relationship between the two in the north-south direction (presenting as two point clouds centered on zero). There was the suggestion of a relationship between winds and surface currents in the east west direction (where winds are strongest): during strong easterlies (>10 knots), there was a weakly positive relationship between surface currents and winds, while during calmer winds or during westerlies winds and tidal currents were essentially uncorrelated.

Comparing surface currents to expected tidal currents is more difficult, there is a tide height gauge in Valdez harbor, but turning those observations to an expected current is nontrivial. NOAA produces a tidal current prediction at depth in Valdez Narrows that may however be used as a baseline expectation for tidal flow. Those predictions are based on tidal harmonics derived from both nearby water level stations and from in-water measurements of current velocities. As a proxy for tidal currents, NOAA current predictions in Port Valdez at a 133-foot depth (station PWS0745) were downloaded from the NOAA CO-OPS system and 6-minute predictions linearly interpolated into the 20-minute intervals of the current observations. Comparisons of tidal currents to observed surface currents showed a weak correlation between the two on the east-west axis (fig. 21), and a weaker still correlation on the north-south one. It could be expected that tidal currents might predominate during periods of low winds, but when the same comparison was made looking at times when winds were less than 0.2-knot (the lowest ~8% of wind observations) the overall correlation improved (fig. 22). However, many of the observations were still centered on the lowest current speeds (i.e., centered on zero).

There are two streams entering the head of Port Valdez, the Lowe River the Valdez Glacier Creek. Both are gauged and the hydrograph of the two streams (fig. 23) is typical of the region: flow increases in spring with break-up, is maximal in mid-summer, and decreases into autumn. Superimposed over the general pattern is considerable variability caused by precipitation events and occasional large spikes that may be due to ice damming or jökulhlaups (glacier outburst floods). Circulation in Port Valdez is influenced in part by freshwater inputs: surface freshwater inputs are less dense than saltwater and tend to ride above saltwater for some distance before eventually being mixed in. In the northern hemisphere the Coriolis force will act upon freshwater flows and turn them to the right, which tends to create counterclockwise circulations in enclosed basins like Port Valdez. Prior work with drifters and vessel mounted current meters did show an eastward circulation along the southern shore (Gay, 2018).

To examine the relationship between freshwater discharge and surface currents, the discharge measurements from the Lowe River and Valdez Glacier Creek were summed, and linearly interpolated onto the time points of the surface current observations so that discharge and current speeds could be compared (fig. 24). Current speeds at the VMT buoy were slightly correlated with discharge, but the correlation at the Duck Flats buoy was much weaker. This is a somewhat unexpected result; one might expect that the Duck Flats location, being "downstream" of the rivers, would be more closely correlated to discharge. Coriolis is a weak "force" and does take some time/distance to influence currents; the Duck Flats buoy, being very close inshore, may miss the direct influence of the freshwater inputs. The stronger correlation at the VMT buoy may reflect larger scale phenomena; discharge at the Lowe River and Valdez Glacier Creek are likely correlated with outflows at other points in the region, so the correlation there may be due to the regional freshwater circulation.

In order to examine how the timing of currents at the two buoys varied compared to the water height observations at the VDZA2 tide station, a cross covariance analysis was done. The covariance between two quantities measures how much in concert the quantities change (i.e., "if one goes up how much does the other go up" and vice-versa). In a cross-covariance analysis the covariance between the quantities is examined at several different times to see if one lags or leads the other. The results of the cross-covariance analysis (fig. 25) showed that the surface currents at the VMT buoy tended to lag the tidal height by about 1 hour and 15 minutes and the Duck Flats tended to lag by 45 minutes.

The surface current analysis done here highlights the complexity of the surface currents in Port Valdez. Currents are impacted by winds, tidal variations, and discharge in complicated ways, and a simple descriptive (i.e., statistical) analysis such as done here cannot tease apart the various influences easily. Surface currents in Prince William Sound often manifest as a "Spirograph" type pattern, where tidal ellipses are superimposed over mean flows (Okkonen and Belanger, 2008), which are difficult to tease of a single location. A better description of current variability can be accomplished with a more dynamical approach where the various components are explicitly modelled (e.g. see Wang et al., 2012); that kind of study involves much more time and effort than was done here.

Conclusions

The analysis done here shows the patterns one would expect of meteorological and oceanographic observations in a subarctic region with a large tidal range. The main observations may be summarized as follows:

- Air and water temperatures, and solar radiation followed a seasonal sinusoid with maxima in August and minima in February. Temperatures were slightly cooler at the Duck Flats buoy than at the VMT buoy.

- Relative humidity was high at both sites and followed the seasonal temperature pattern.
- Air pressure was similar between both sites and driven by large-scale atmospheric circulations.
- Winds were mostly from the east in autumn and winter, with maximum gust on order of 25 knots, and transitioned to weak easterly and stronger westerly sea breezes during the summer months.
- Wave directions tended to match wind directions. The highest waves were observed during autumn/winter storms and were of considerable size, just under 7 feet tall; spring/summer sea breeze generated waves were on order of 1-foot.
- A temperature climatology was constructed that shows a persistent warming pattern over the past 113 years.
- Air and water temperatures at the buoy sites were warmer than average in 2019 and tended towards cooler than average in 2020 and 2021, likely reflecting large scale climate fluctuations.
- Surface currents in Port Valdez are complex and result from the interplay of winds, tides, and freshwater inputs. Surface currents were correlated with winds when wind speeds were high (>10 knots) and weakly correlated with expected tidal currents in Valdez Narrows. Surface currents were uncorrelated with river discharge.
- Cross covariance analysis comparing the timing of currents at the buoys compared to the tides at the Port Valdez tide station showed that surface currents tended to lag the tides by approximately 45 minutes to 1 hour and 15 minutes.

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Figures

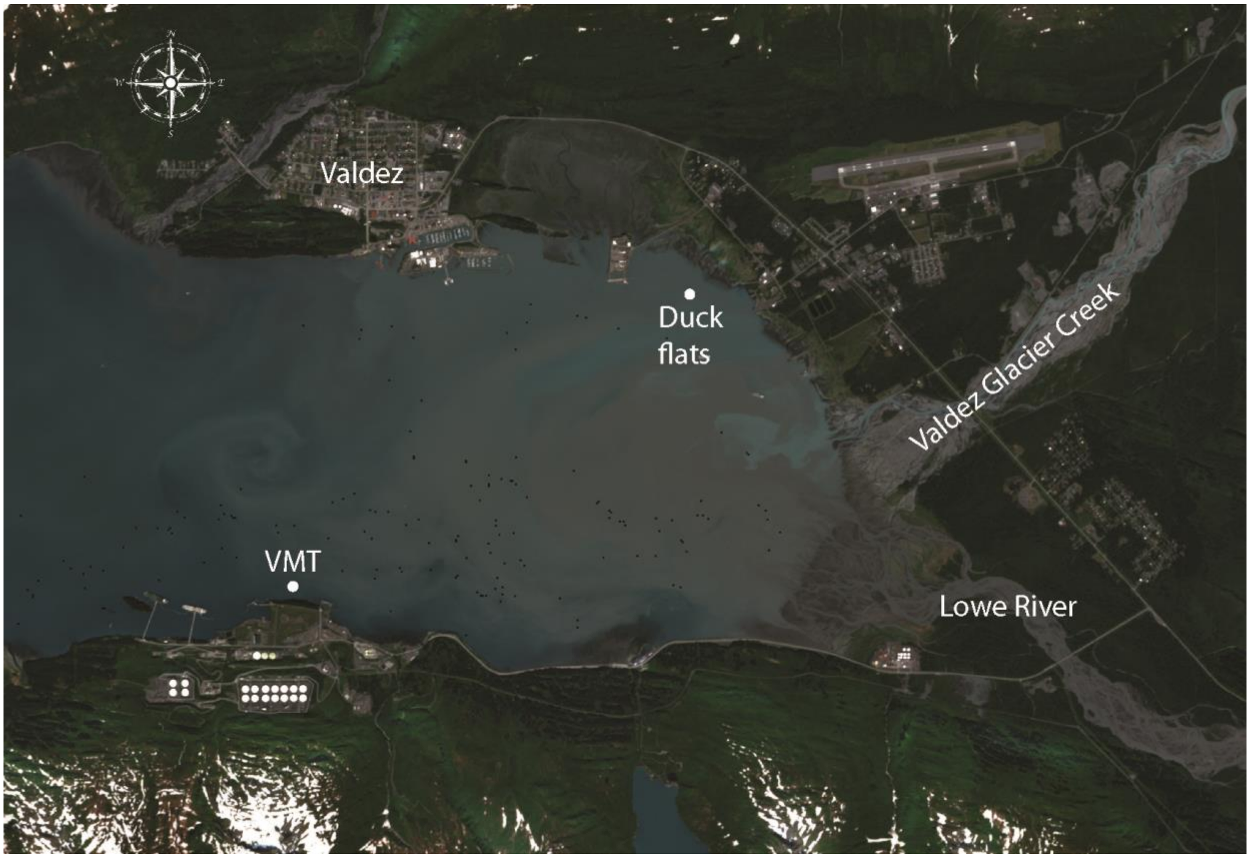

Figure 1: Sentinel 2 satellite image of Port Valdez (taken June 22, 2022) showing the location of the two buoys and other geographic locations mentioned in the report.

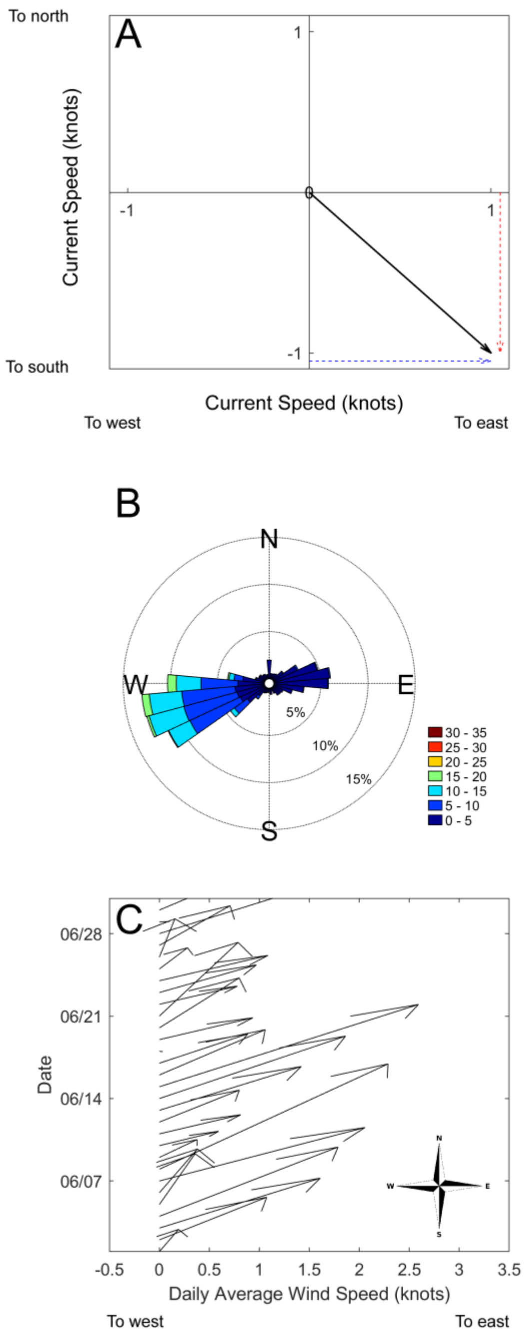

Figure 2: Examples of the visualization of vector data. Panel A: An example of a vector observation, for example a 1-knot current to the southeast. The vector may be broken up into two components, an east-west component (blue arrow) and a north-south component (red arrow). Panel B: An example wind rose summarizing wind observations made in June 2020. The bars indicate 10° bands of wind directions (direction from), the lengths of the bars indicate frequency (how often winds in each band were observed), and the color encodes wind speeds. Panel C: An example of a quiver plot, showing daily average wind vectors (direction in which the air is traveling) for June 2020. The angle of the arrow indicates the

direction on the compass rose, and the length of the arrow indicates average wind speed, scaled to match the bottom axis.

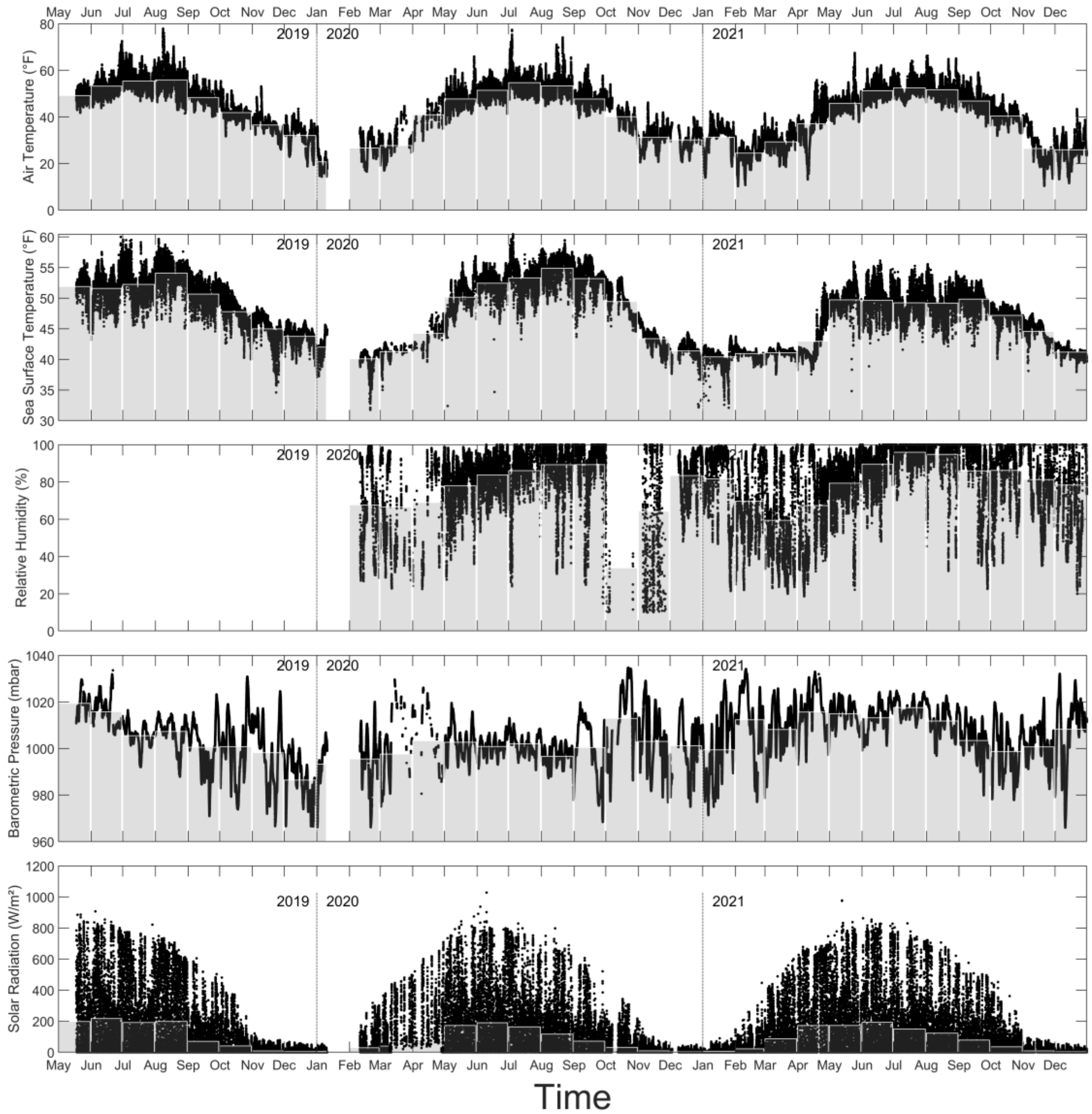

Figure 3: Scalar observations at the VMT buoy, including air (top panel) and water (2nd panel) temperatures, relative humidity (3rd panel), barometric pressure (4th panel), and solar radiation (bottom panel). Black dots are observations, bars indicate monthly averages.

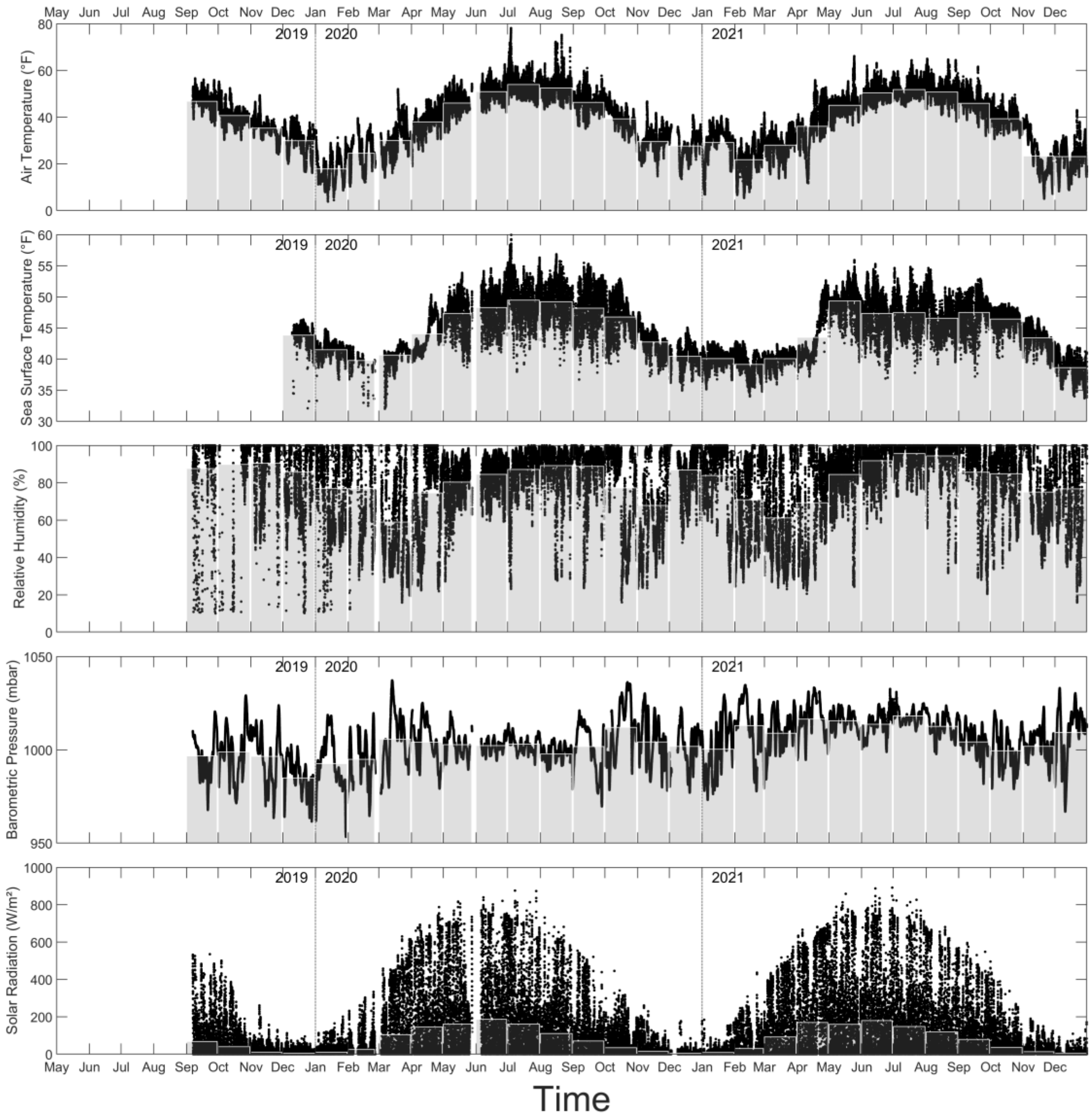

Figure 4: Scalar observations at the Duck Flats buoy, including air (top panel) and water (2nd panel) temperatures, relative humidity (3rd panel), barometric pressure (4th panel), and solar radiation (bottom panel). Black dots are observations, bars indicate monthly averages.

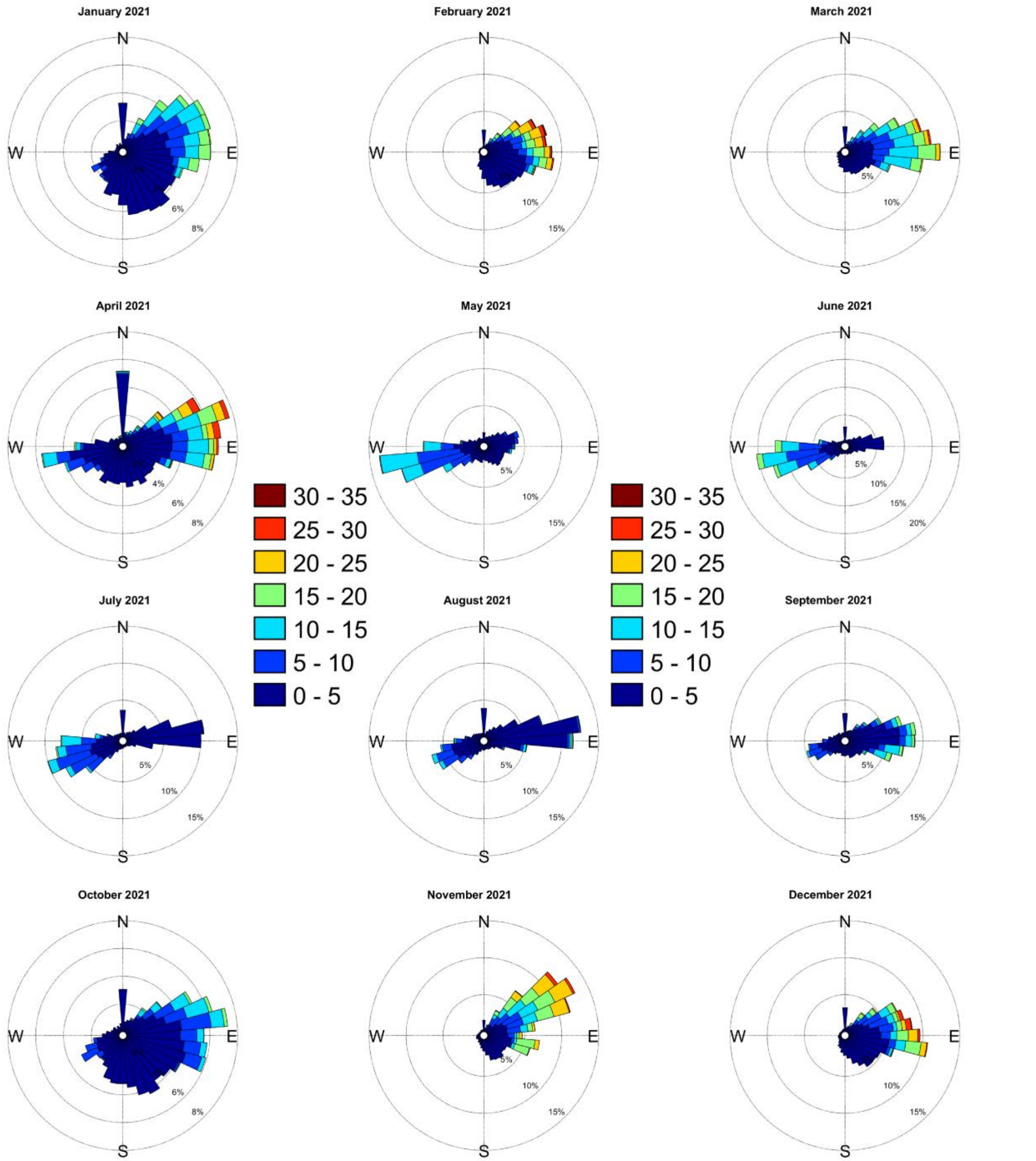

Figure 5: Monthly wind roses at the VMT buoy. Bars indicate the direction from and the color scale indicates wind velocities. Color scale is equivalent among the figures (i.e., all the figures are directly comparable).

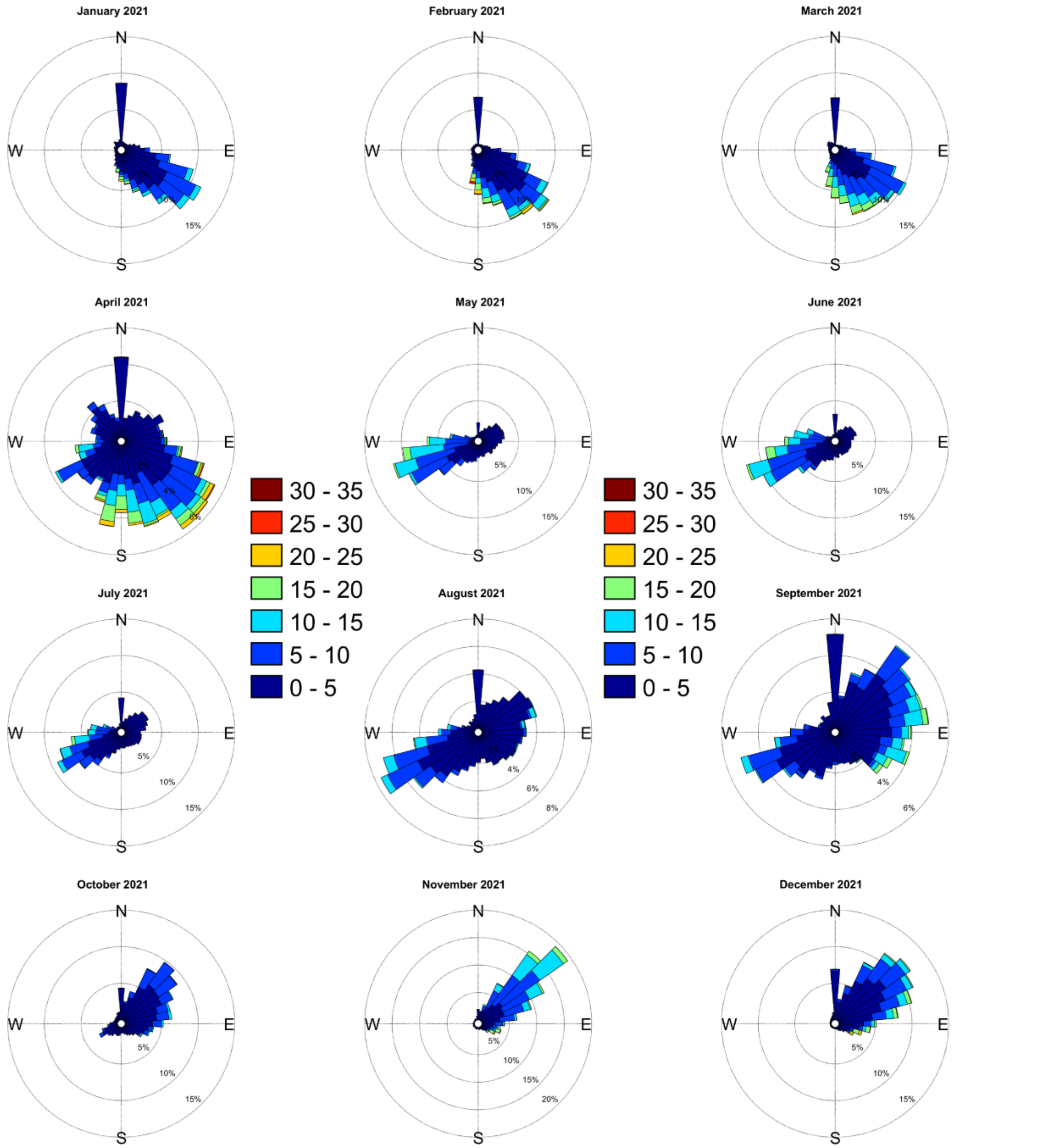

Figure 6: Monthly wind roses at the Duck Flats buoy. Bars indicate the direction from and the color scale indicates wind velocities. Color scale is equivalent among the figures (i.e., all the figures are directly comparable).

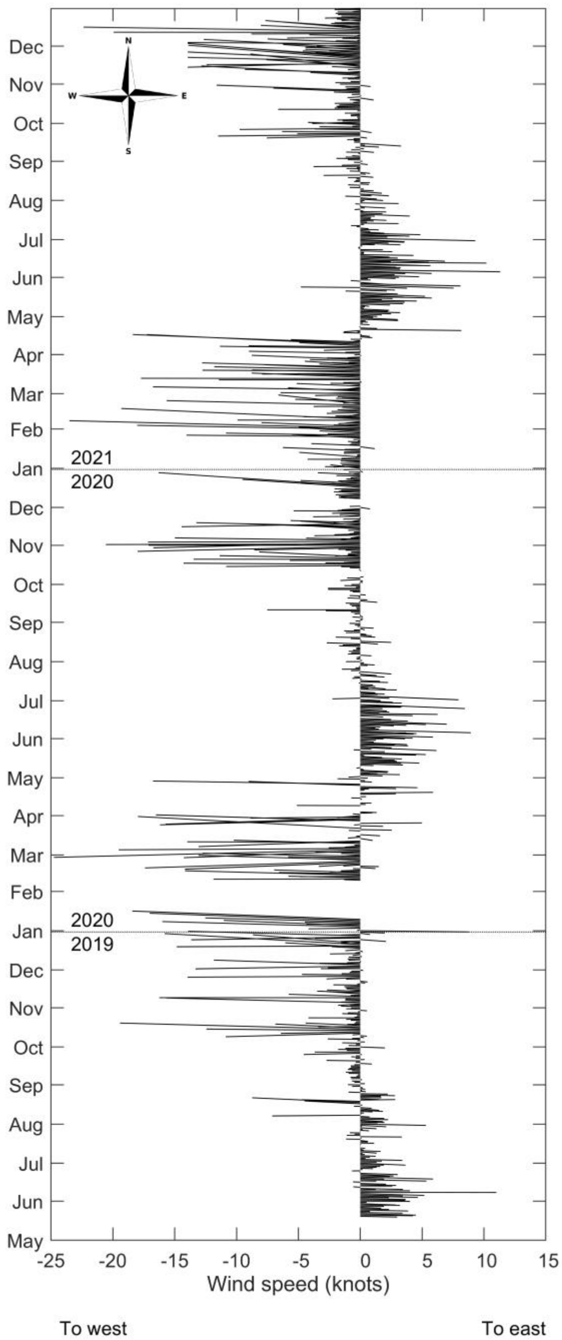

Figure 7: Quiver plot of average daily wind vectors at the VMT buoy. The length of each stick indicates wind speed and the angle indicates the direction from.

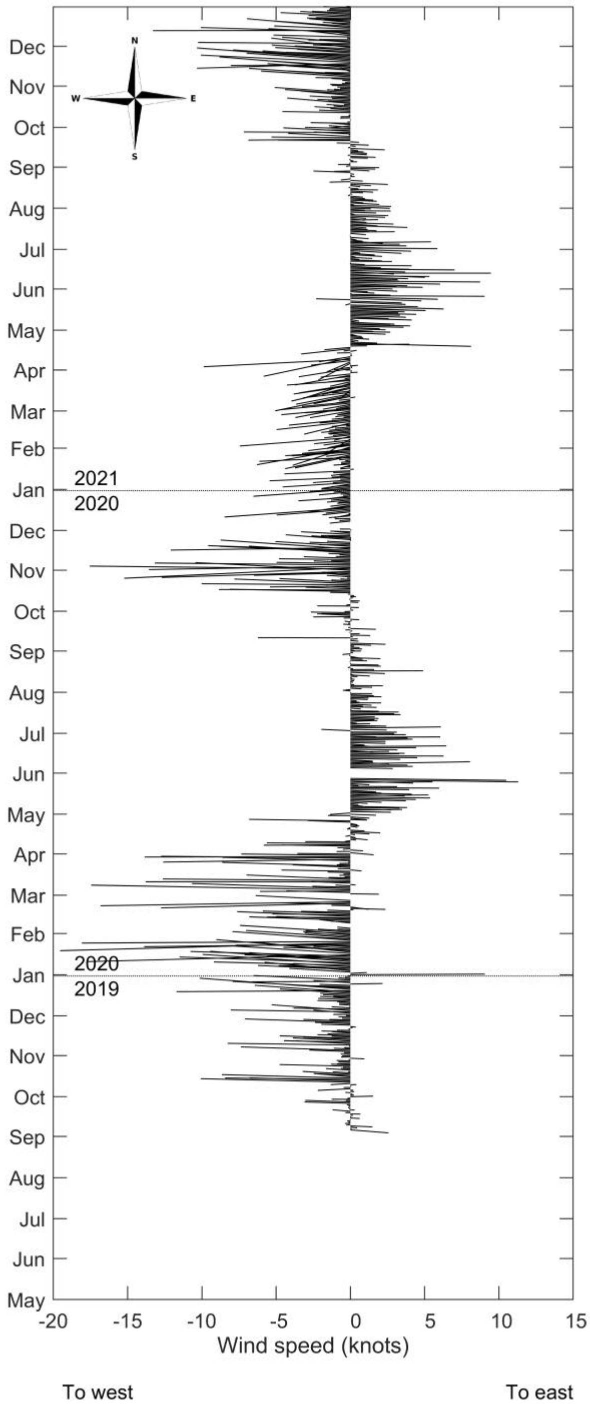

Figure 8: Quiver plot of average daily wind vectors at the Duck Flats buoy. The length of each stick indicates wind speed and the angle indicates the direction from.

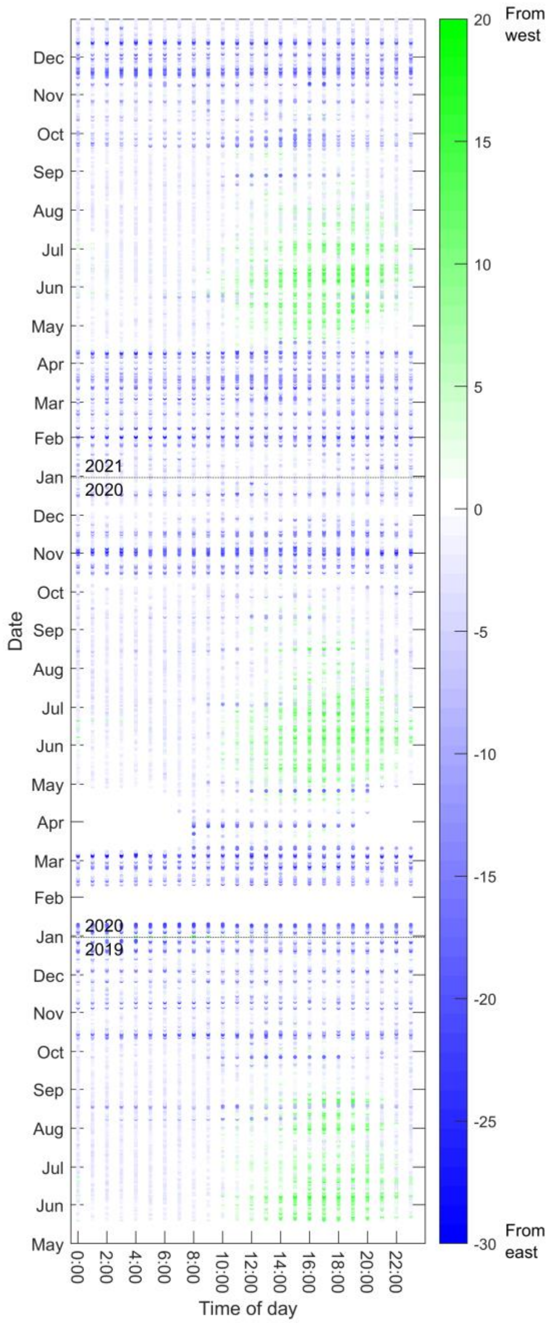

Figure 9: Daily east-west winds at the VMT buoy. Only the east-west component of the winds are shown, green colors scale with the strength of westerly winds, and blue colors scale with the strength of easterly winds.

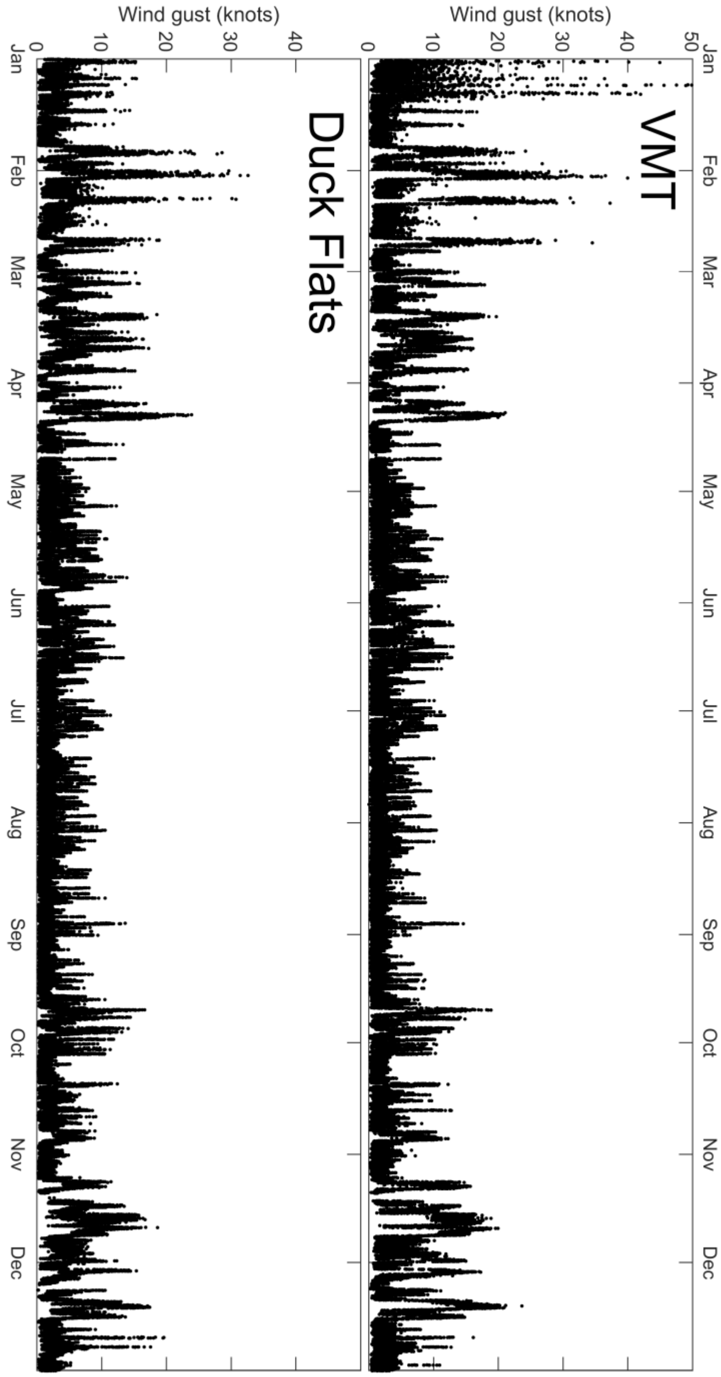

Figure 10: Wind gust time series at the VMT (top panel) and Duck Flats (bottom panel).

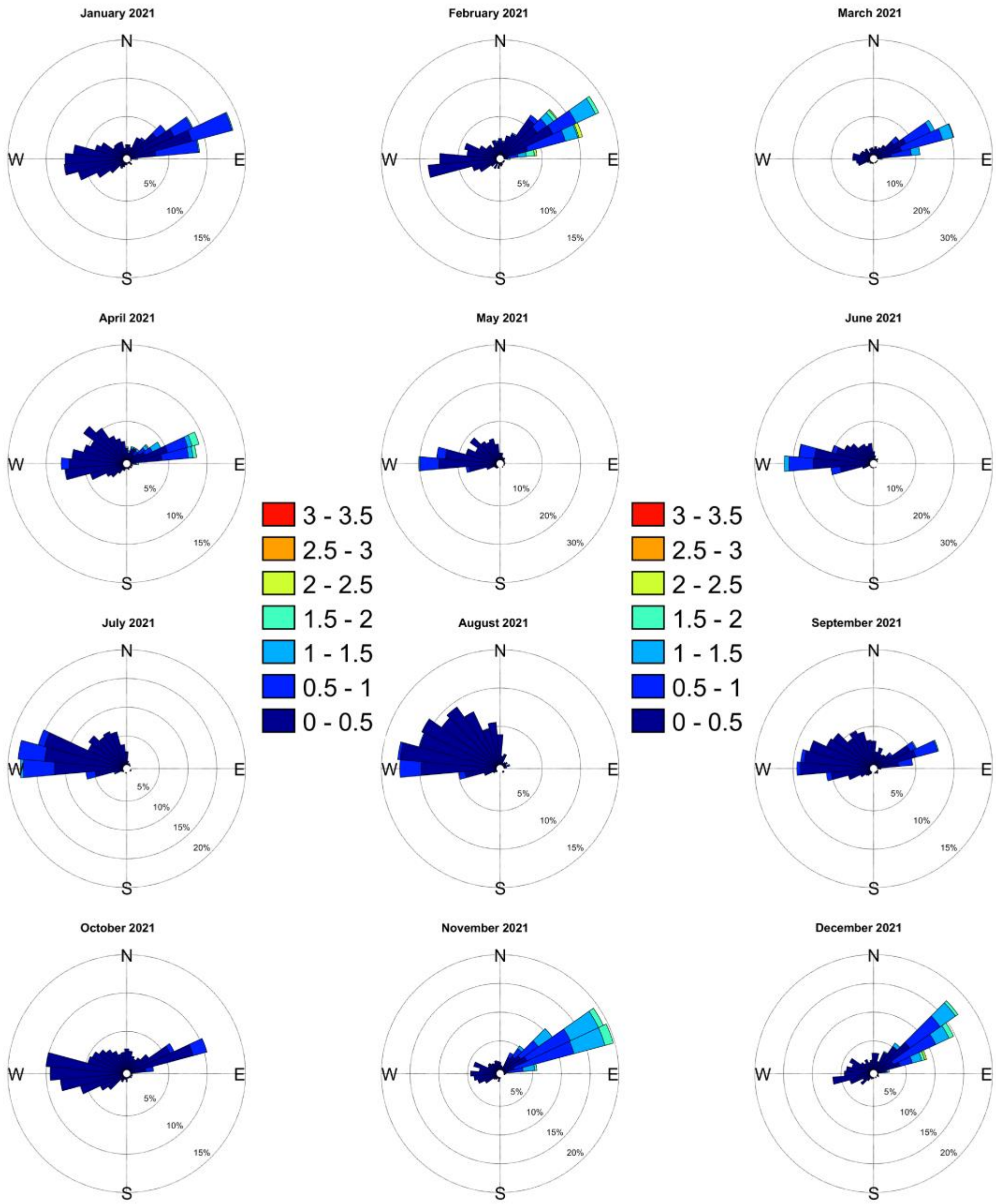

Figure 11: Monthly wave roses at the VMT buoy. Bars indicate the direction to and the color scale indicates significant wave heights. Color scale is equivalent among the figures (i.e., all the figures are directly comparable).

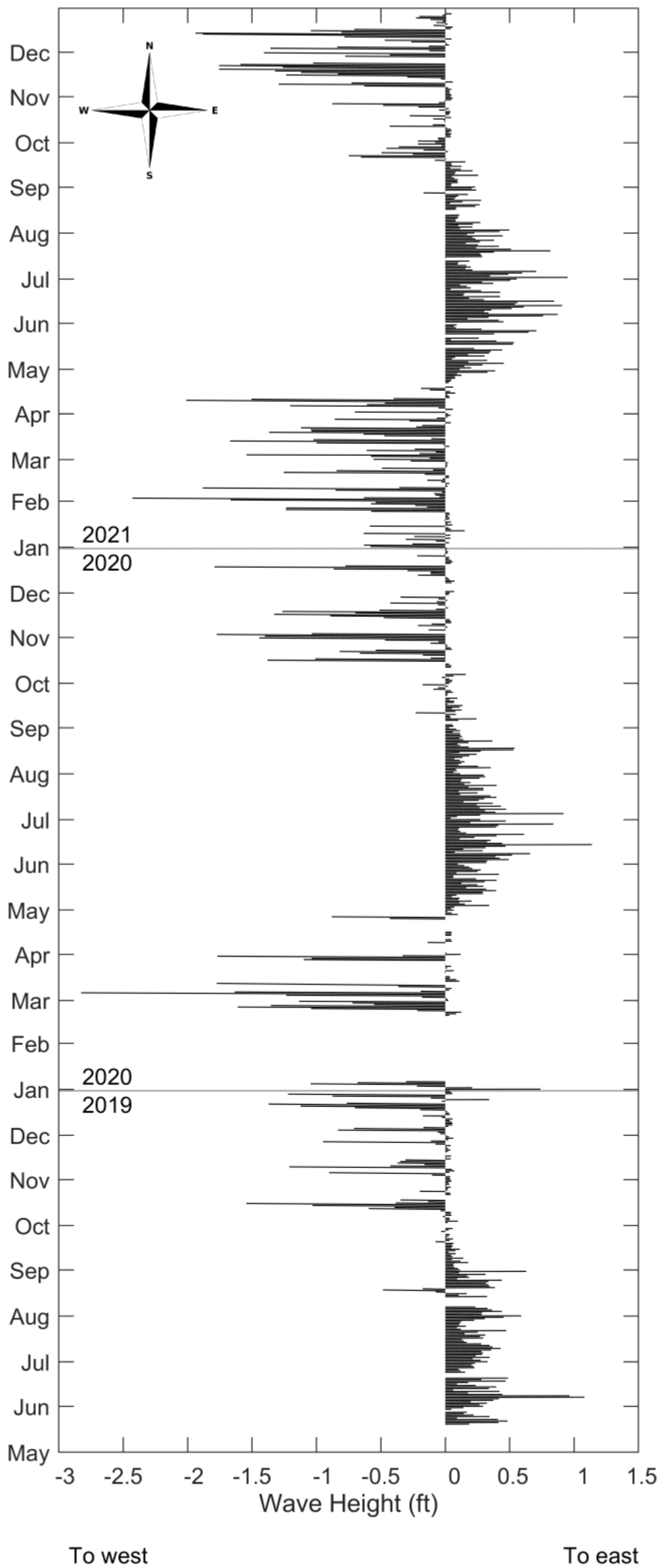

Figure 12: Quiver plot of average daily wave vectors at the VMT buoy. The length of each stick indicates wave height and the angle indicates the direction to.

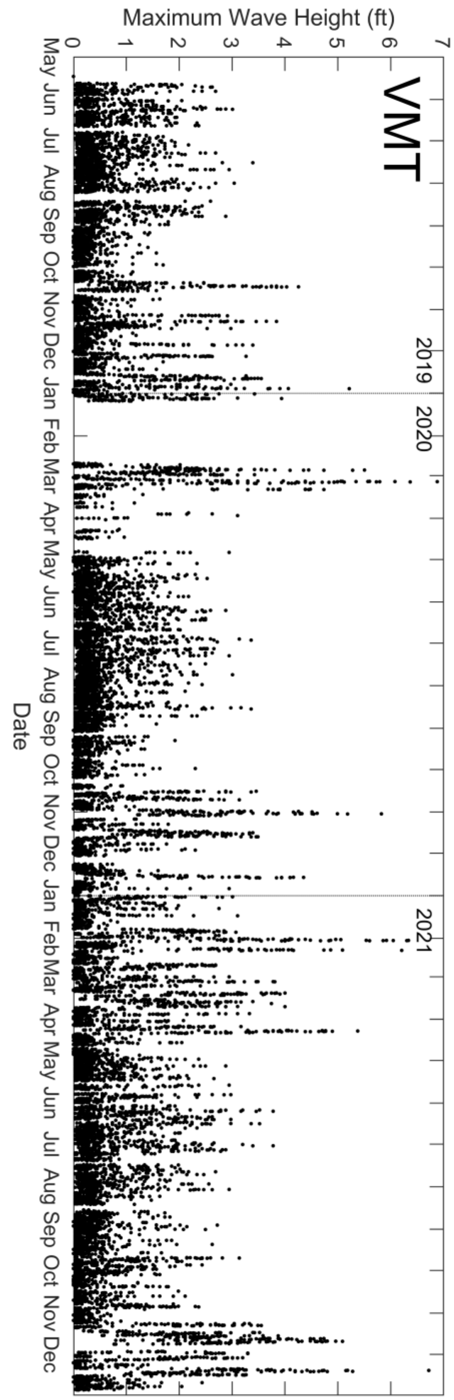

Figure 13: Time series of maximum wave heights observed at the VMT buoy.

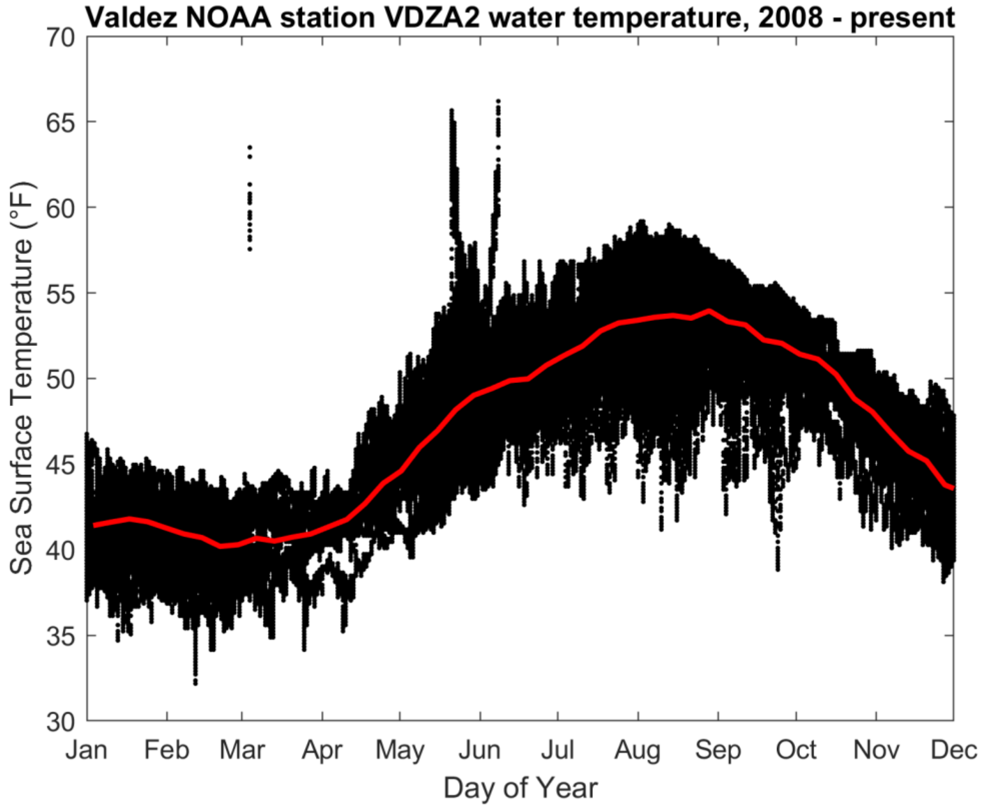

Figure 14: Annual average temperature cycle at the NOAA tide station VDZA2 in Valdez harbor. Air temperature data was overlaid from all years (2009-present) by day of year. Dots indicate observations and the red line indicates the weekly average.

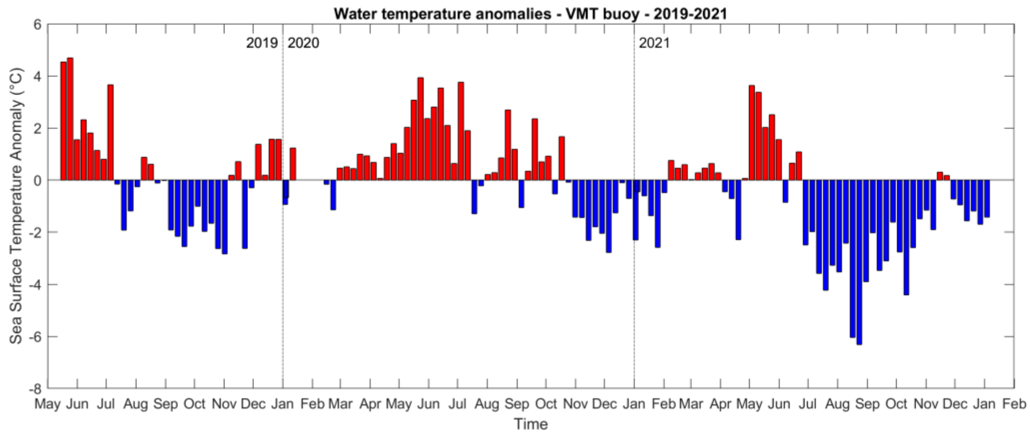

Figure 15: Weekly sea surface temperature anomalies at the VMT buoy. Anomalies are the departure of weekly average temperatures from the weekly average at the VDZA2 tide station.

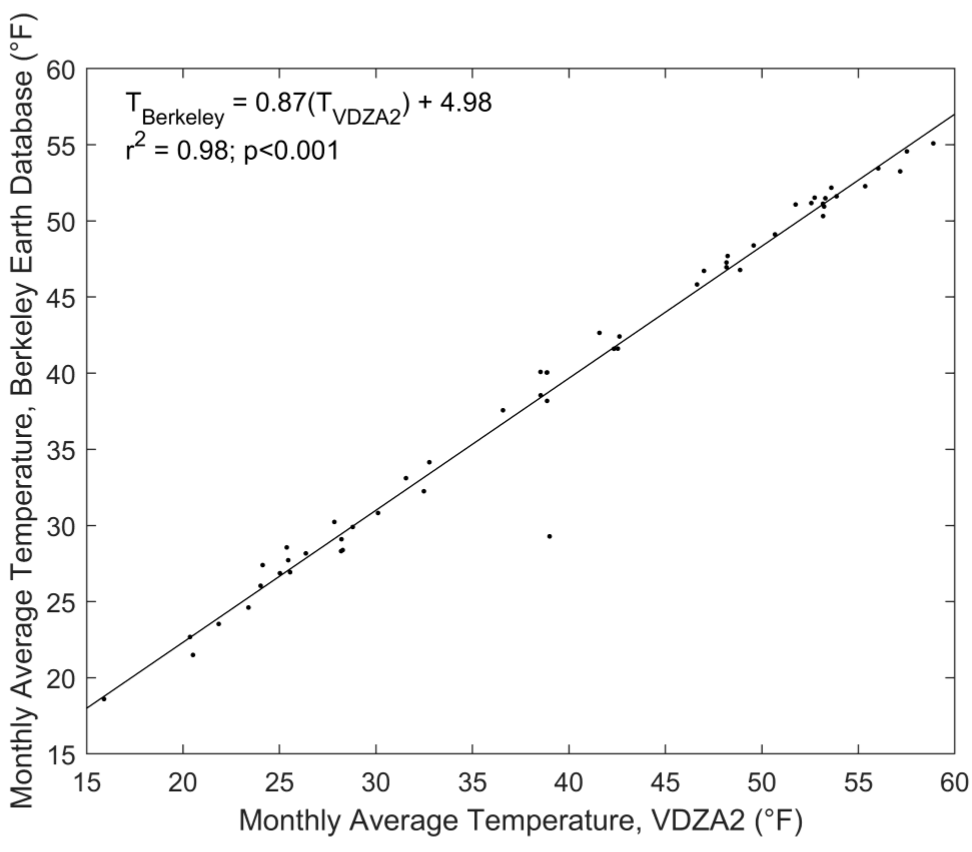

Figure 16: Comparison of monthly average air temperature estimates from the Berkeley Earth database and monthly average temperatures calculated at the VDZA2 station on months where the two time series overlapped (2009-2013). The regression line was fit by least squares.

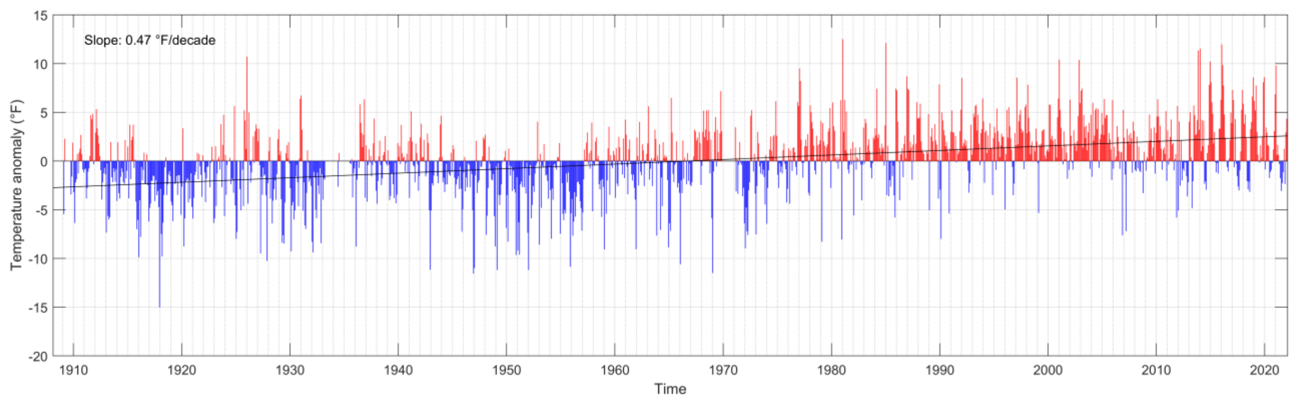

Figure 17: Air temperature anomalies from the combined Berkeley Earth database/VDZA2 monthly temperature estimates, 1908 - 2021.

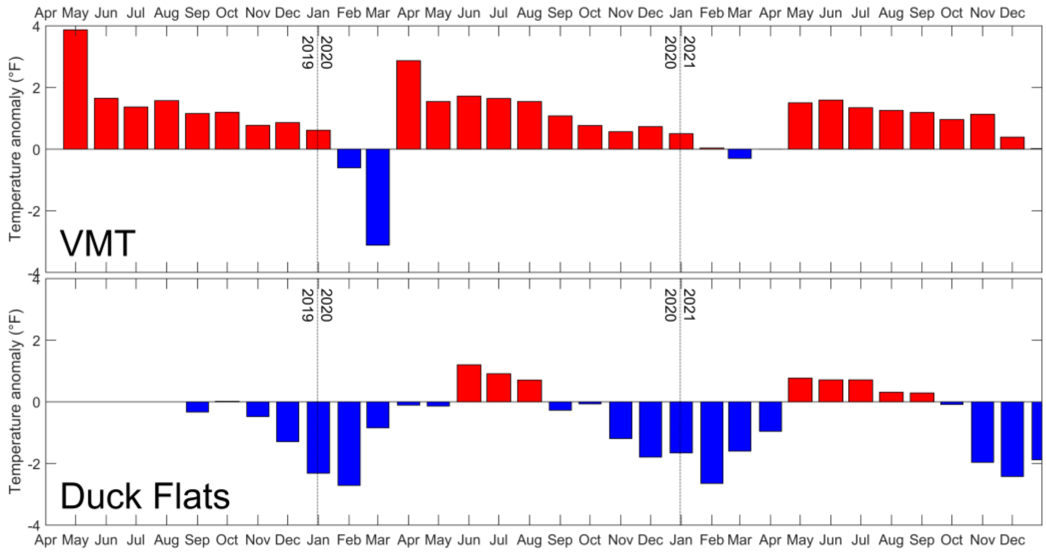

Figure 18: Monthly average air temperature anomalies at the VMT (top panel) and Duck Flats (bottom panel) buoys using the Berkeley Earth/VDZA2 climatology.

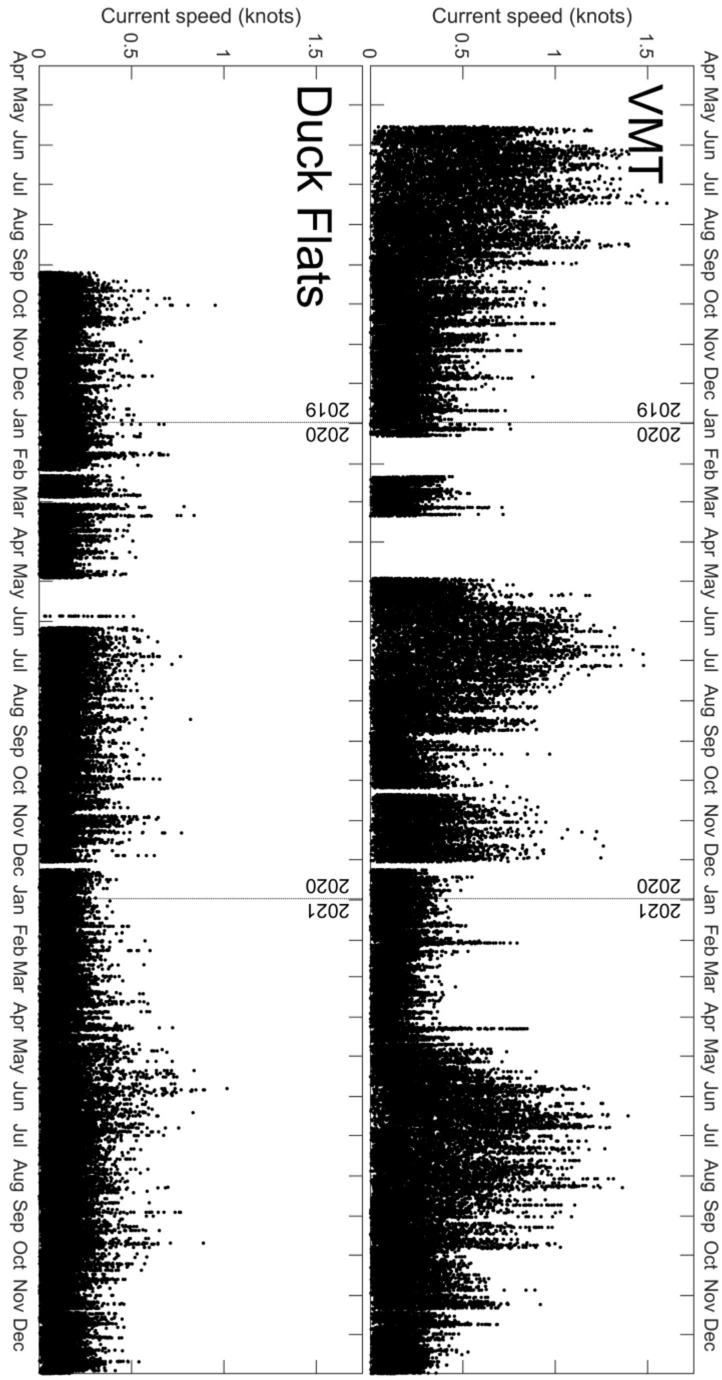

Figure 19: Current speed time series at the VMT (top panel) and Duck Flats (bottom panel).

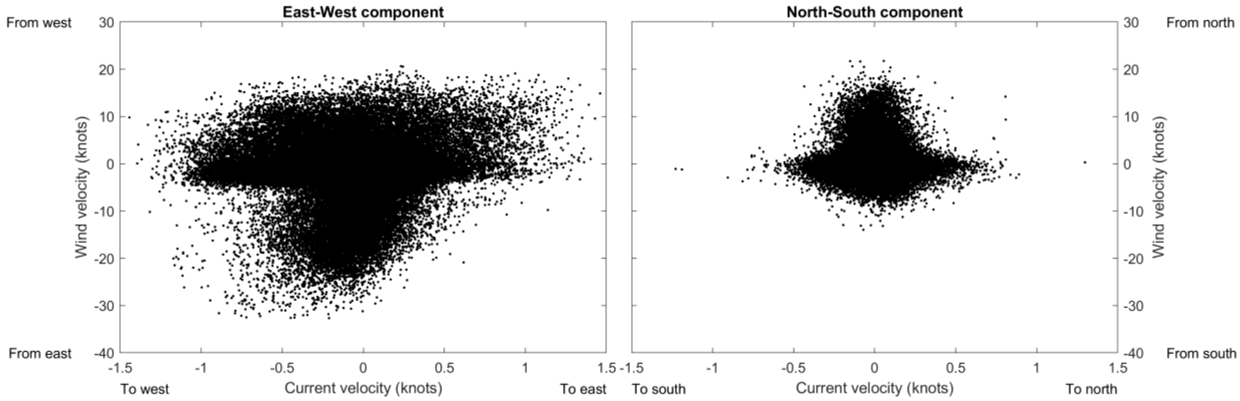

Figure 20: Comparison of wind velocities and current velocities at the VMT buoy, broken out into the east-west (left panel) and north-south (right panel) components.

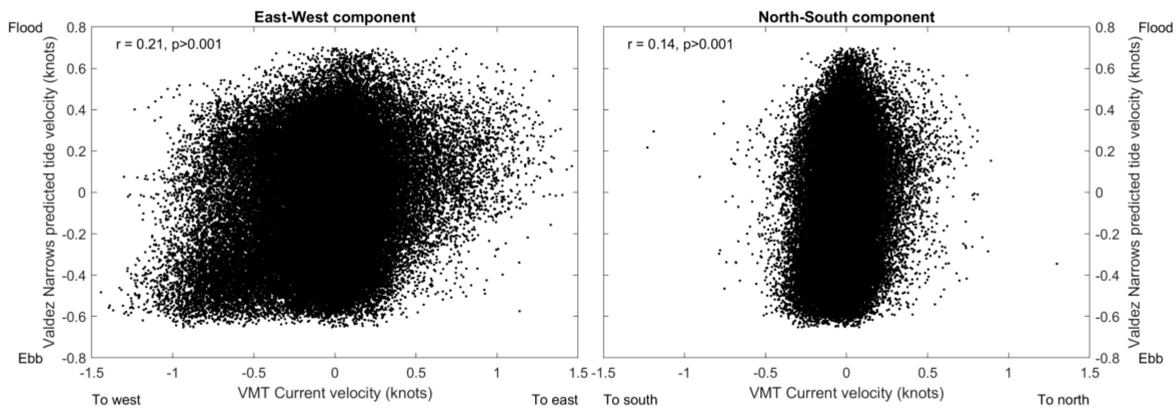

Figure 21: Comparison of current velocities at the VMT buoy (broken out into east-west and north-south components) and expected tidal currents at the Valdez narrows at 133-foot depth (NOAA station PWS 0745).

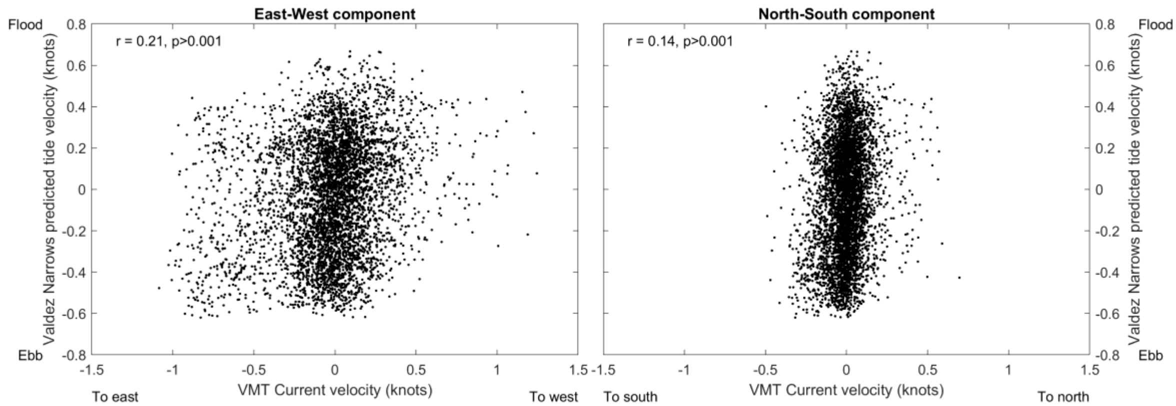

Figure 22: Comparison of current velocities at the VMT buoy and expected tidal currents at the Valdez narrows at 133-foot depth (NOAA station PWS 0745) during times when wind speeds at the VMT buoy were less than 0.2 knots.

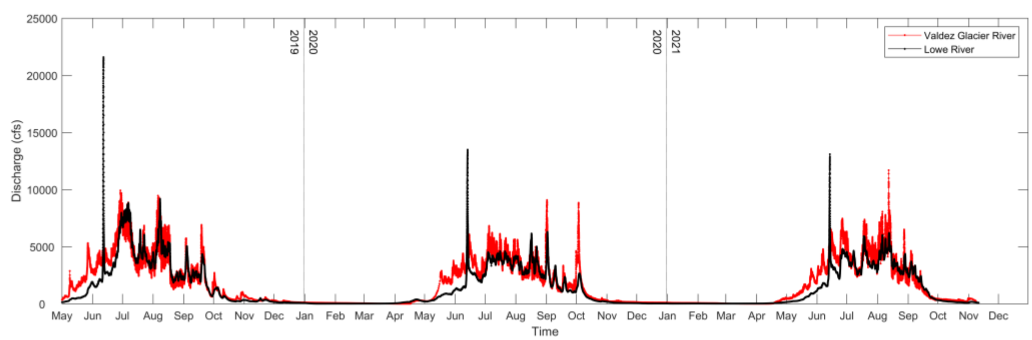

Figure 23: Hydrograph of discharge at the Lowe River (USGS station 15226620) and Valdez Glacier River (USGS station 15227090). Discharge data was downloaded from waterdata.usgs.gov.

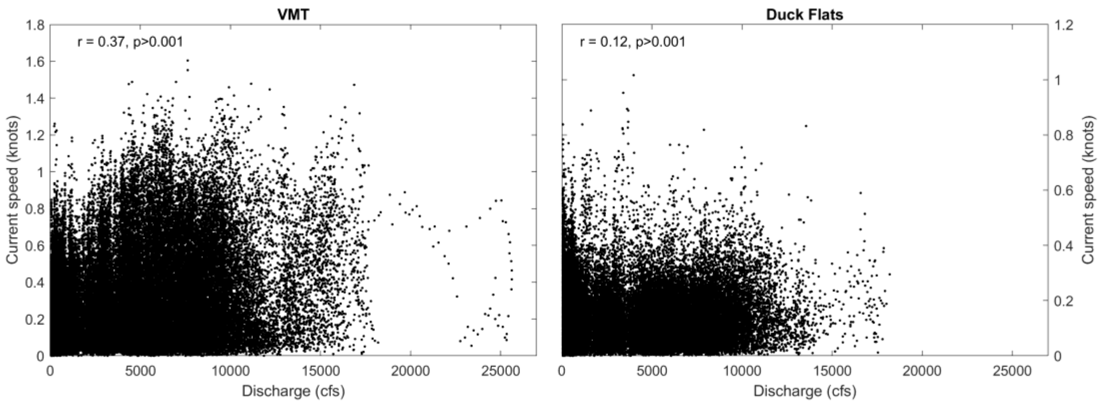

Figure 24: Comparison of current velocities at the VMT (left panel) and Duck Flats (right panel) buoys and combined discharge of the Lowe River and Valdez Glacier Creek.

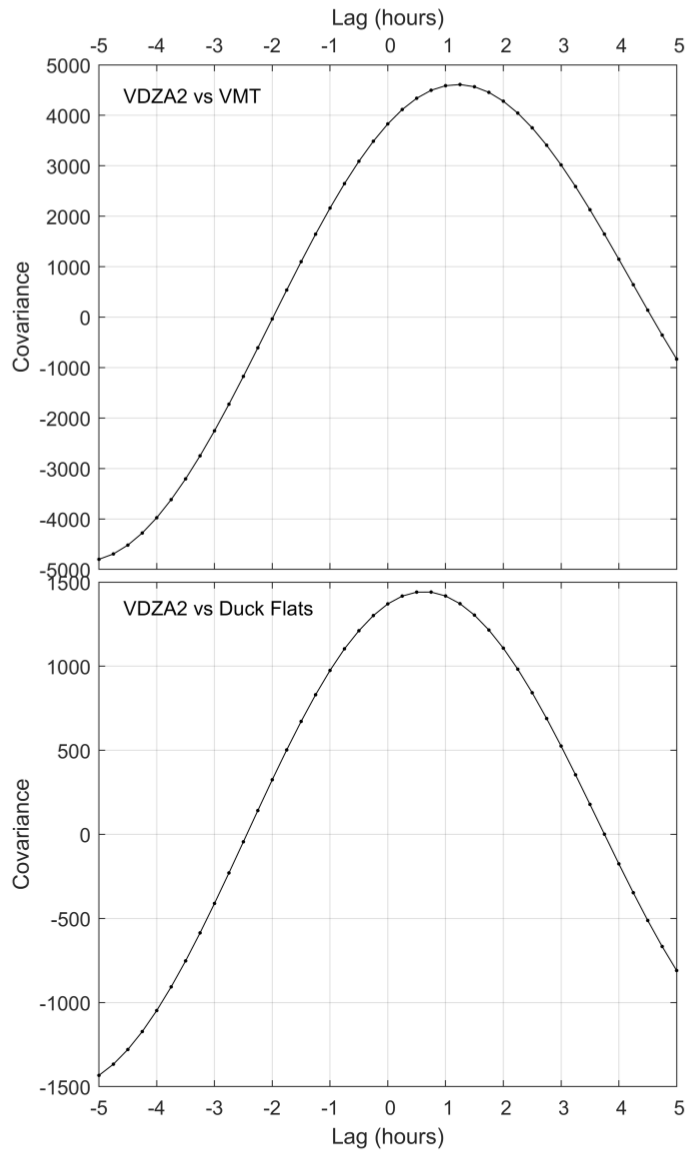

Figure 25: Cross covariance between tidal currents at the VMT (top panel) and Duck Flats (bottom panel) buoys and water heights at station VDZA2. Lags are relative to the time at VDZA2.

Appendix 1: Table of averages and minimum/maximum values at the VMT buoy, by month.

Month	Air Temperature (°F)	Water Temperature (°F)	Relative Humidity (%)	Barometric Pressure (%)	Solar Radiation (W/m^2)	Wind Speed (knots)	Wind Gust (knots)	Significant Wave Height (ft)	Max. Wave Height (ft)	Current Speed (knots)
January	27.29	40.24	87.29	1001.67	4.55	6.09	10.90	0.53	0.93	0.18
	5.77 - 42.34	32.10 - 45.64	21.51 - 100.00	966.18 - 1033.57	0.00 - 146.88	0.00 - 31.49	0.00 - 58.29	0.00 - 3.87	0.00 - 7.20	0.00 - 2.24
February	26.86	39.09	78.85	1007.79	14.20	4.83	8.46	0.41	0.74	0.14
	10.24 - 41.53	31.75 - 43.71	13.28 - 100.00	966.15 - 1034.95	0.00 - 446.49	0.00 - 34.77	0.00 - 58.29	0.00 - 3.58	0.00 - 6.34	0.00 - 0.80
March	29.51	40.61	67.97	1006.21	71.89	5.58	8.86	0.53	0.95	0.12
	16.99 - 44.64	31.90 - 42.80	20.02 - 100.00	975.08 - 1037.95	0.00 - 599.92	0.00 - 34.77	0.00 - 58.29	0.00 - 3.78	0.00 - 6.88	0.00 - 0.72
April	37.81	43.22	67.64	1013.16	172.05	4.63	7.99	0.36	0.67	0.16
	13.14 - 55.80	37.56 - 52.48	18.65 - 100.00	980.56 - 1033.04	0.00 - 746.60	0.00 - 30.25	0.00 - 57.54	0.00 - 3.14	0.00 - 5.38	0.00 - 0.85
May	47.19	50.30	78.63	1010.76	176.82	4.12	8.67	0.27	0.52	0.33
	36.80 - 67.44	32.38 - 56.86	22.19 - 100.00	988.68 - 1029.65	0.00 - 976.98	0.00 - 18.02	0.00 - 58.16	0.00 - 1.79	0.00 - 2.98	0.00 - 1.20
June	51.97	51.23	86.67	1009.93	199.75	4.86	9.84	0.37	0.69	0.49
	41.35 - 72.50	34.67 - 59.99	48.10 - 100.00	991.38 - 1033.57	0.00 - 1027.90	0.00 - 19.98	0.00 - 58.24	0.00 - 2.08	0.03 - 3.78	0.00 - 1.49
July	54.17	51.59	91.47	1008.37	168.15	3.50	7.98	0.32	0.60	0.38
	44.72 - 77.36	41.58 - 60.44	24.08 - 100.00	990.72 - 1024.78	0.00 - 829.64	0.00 - 21.23	0.00 - 58.24	0.00 - 2.21	0.03 - 3.78	0.00 - 1.61
August	53.64	52.69	92.08	1005.36	146.08	3.49	8.76	0.27	0.51	0.30
	41.47 - 77.86	42.14 - 59.65	30.71 - 100.00	977.82 - 1022.69	0.00 - 797.59	0.00 - 22.66	0.00 - 58.29	0.00 - 2.08	0.00 - 3.36	0.00 - 1.40
September	47.59	51.22	87.59	1001.46	73.26	3.00	7.69	0.15	0.31	0.20
	35.94 - 62.37	42.15 - 57.07	14.78 - 100.00	968.33 - 1023.27	0.00 - 606.41	0.00 - 22.98	0.00 - 57.91	0.00 - 1.76	0.00 - 3.14	0.00 - 1.09
October	40.81	48.06	85.27	1003.62	35.91	4.22	9.86	0.24	0.45	0.22
	28.14 - 55.35	40.02 - 53.44	10.22 - 100.00	973.84 - 1034.70	0.00 - 480.61	0.00 - 28.59	0.00 - 58.29	0.00 - 2.59	0.00 - 4.51	0.00 - 1.00
November	31.53	44.30	77.04	1000.63	8.69	6.54	12.27	0.51	0.90	0.22
	10.38 - 53.08	34.60 - 48.60	10.01 - 100.00	966.61 - 1029.09	0.00 - 192.75	0.00 - 33.98	0.00 - 58.29	0.00 - 3.23	0.00 - 5.82	0.00 - 1.26
December	29.31	42.15	80.53	998.46	3.71	5.17	10.63	0.41	0.73	0.15
	11.57 - 43.48	32.16 - 46.51	19.97 - 100.00	965.98 - 1032.07	0.00 - 65.93	0.00 - 31.88	0.00 - 58.29	0.00 - 3.36	0.00 - 6.72	0.00 - 0.75

Appendix 2: Table of averages and minimum/maximum values at the Duck Flats buoy, by month.

Month	Air Temperature (°F)	Water Temperature (°F)	Relative Humidity (%)	Barometric Pressure (%)	Solar Radiation (W/m^2)	Wind Speed (knots)	Wind Gust (knots)	Significant Wave Height (ft)	Max. Wave Height (ft)	Current Speed (knots)
January	23.46	40.08	81.02	1000.38	7.80	6.41	10.68	0.50	0.90	0.13
	0.54 - 40.45	33.20 - 44.83	10.86 - 100.00	953.29 - 1032.19	0.00 - 200.66	0.00 - 31.94	0.00 - 80.90	0.00 - 2.69	0.00 - 4.99	0.00 - 0.70
February	25.06	37.93	75.48	1007.89	22.04	4.15	6.86	0.29	0.52	0.11
	5.36 - 41.92	32.01 - 42.88	10.12 - 100.00	964.57 - 1035.96	0.00 - 436.39	0.00 - 28.61	0.00 - 66.17	0.00 - 2.14	0.00 - 3.71	0.00 - 2.83
March	29.27	39.56	60.01	1008.46	88.72	5.72	9.48	0.22	0.41	0.12
	13.73 - 51.96	32.02 - 43.13	10.14 - 100.00	976.47 - 1042.24	0.00 - 630.10	0.00 - 31.10	0.00 - 78.30	0.00 - 1.73	0.00 - 3.07	0.00 - 1.32
April	37.01	43.77	71.96	1010.23	157.68	4.26	7.43	0.09	0.18	0.11
	11.71 - 55.80	37.20 - 52.63	20.59 - 100.00	979.17 - 1033.37	0.00 - 787.33	0.00 - 28.38	0.00 - 46.42	0.00 - 1.06	0.00 - 1.70	0.00 - 0.72
May	45.50	48.43	82.64	1009.84	160.18	4.64	7.98	0.37	0.68	0.16
	33.36 - 66.11	38.69 - 55.90	24.36 - 100.00	989.29 - 1024.44	0.00 - 858.38	0.00 - 23.97	0.00 - 54.04	0.03 - 1.34	0.06 - 2.18	0.00 - 1.02
June	50.64	47.77	88.47	1008.49	182.71	4.78	7.67	-	-	0.16
	41.26 - 63.16	36.88 - 55.27	55.49 - 100.00	994.11 - 1032.61	0.00 - 891.69	0.00 - 23.83	0.00 - 54.35			0.00 - 0.83
July	52.88	48.46	91.42	1010.69	154.36	3.53	5.75	-	-	0.14
	43.56 - 78.12	37.80 - 59.95	23.19 - 100.00	991.91 - 1030.98	0.00 - 875.80	0.00 - 22.12	0.00 - 55.24			0.00 - 0.72
August	51.59	47.86	91.86	1005.34	114.69	2.90	4.57	-	-	0.14
	38.17 - 75.22	38.99 - 56.84	27.67 - 100.00	978.77 - 1023.76	0.00 - 731.37	0.00 - 25.42	0.00 - 53.90			0.00 - 0.82
September	46.31	47.84	87.31	1001.18	72.70	2.94	4.91	0.06	0.11	0.13
	31.99 - 61.57	36.72 - 55.45	10.09 - 100.00	967.75 - 1021.05	0.00 - 595.51	0.00 - 21.67	0.00 - 54.04	0.00 - 0.51	0.00 - 1.15	0.00 - 0.89
October	39.75	46.60	82.37	1003.44	36.68	3.66	5.85	0.11	0.20	0.12
	25.21 - 55.20	39.26 - 52.92	10.84 - 100.00	971.36 - 1036.23	0.00 - 500.47	0.00 - 25.31	0.00 - 61.40	0.00 - 1.47	0.00 - 2.56	0.00 - 0.95
November	29.51	43.08	77.83	1000.84	12.67	5.56	8.36	0.07	0.14	0.12
	5.05 - 49.33	37.27 - 47.50	13.65 - 100.00	963.49 - 1030.19	0.00 - 260.51	0.00 - 30.98	0.00 - 65.72	0.00 - 0.86	0.00 - 1.73	0.00 - 3.95
December	26.81	40.56	82.85	998.48	4.39	4.29	7.48	0.13	0.25	0.12
	8.22 - 42.92	32.07 - 46.36	10.22 - 100.00	961.57 - 1033.08	0.00 - 176.74	0.00 - 25.31	0.00 - 65.91	0.00 - 1.66	0.00 - 3.10	0.00 - 0.54