1.0 EXECUTIVE SUMMARY

The Prince William Sound Science Center (PWSSC) conducted a study of circulation for the Prince William Sound Regional Citizens' Advisory Council (PWSRCAC) to describe and quantify the currents within Port Valdez, Alaska, and to address concerns regarding the potential dispersal of contaminants, such as spilled oil, within the fjord basin. PWSRCAC felt this research would help the oil spill response community to understand the fate and transport effects of oil, gather specific decision making information related to chemical dispersant use, and assist with prioritization and tactics related to sensitive area protection strategies. The knowledge gained from this study would also aid in designing and validating any future models of oil movement and general circulation applied to Port Valdez, including the oil spill contingency and response (OSCAR) model, the general NOAA oil modeling environment (GNOME) and regional ocean modeling system (ROMS).

The study was conducted during three seasons including early summer (June), early fall (September) and late winter (March). Each season was selected to best characterize how the circulation was affected by differing levels of meteorological variables, such as solar heating and freshwater input, and forcing by winds, tides and spatial variations in water density (i.e. geostrophic flows). The data consisted of Lagrangian flows (i.e. water parcels moving through a flow field) measured by tracking drifter buoys with drogues set to four different depths: surface, 1*m*, 10*m* and 40*m*. Measurements of the flow field were made using a towed acoustic Doppler current (ADCP) profiler and vertical profiles of temperature and salinity were collected using a tethered conductivity, temperature and depth (CTD) instrument lowered by a ship's winch. Ancillary meteorological and tidal data were obtained from archives of local NOAA weather assets located in Valdez, Alaska and historical records[1].

The ADCP data were collected along nine transect lines extending from the inner basin to the central region of the fjord and ending ~ 2*km* (1.08*nm*) west of the Security Zone (SZ). The lines were set up to obtain as much information as possible within the timeframe of the semi-diurnal tides. The instrument was towed at a depth of 2 to 3*m* but since the instrument has a blanking distance of 4*m* the currents in the upper 6 to 7*m* could not be measured. The data were collected in 8*m* depth bins, starting at ~ 7*m* and ending at a maximum depth of ~ 207*m*. The hydrography (CTD) profiles were collected during each repeated run of ADCP transects.

The drifters used in the study consisted of surface oil spill response buoys (ispheres) and subsurface type drifters with drogues centered at 1*m*, 10*m* and 40*m*. In June drifters were deployed singly at first, then as groups of three during dispersion experiments. In September and March all deployments were conducted to measure dispersion in groups of either two or three. Units were released at various regions of the middle and inner basin at points along the ADCP transects. The surface and 1*m* drifters were typically retrieved in one day or less depending on whether grounding occurred or if they had exited the study area, which included the entire fjord up to a western boundary located just north of the Narrows.

All data were quality checked using both standard oceanographic data methods and techniques developed by the author and a prior colleague at the Prince William Sound Science Center (PWSSC). In addition to basic descriptive statistics, more advanced analyses were performed including estimates the forcing of currents by winds, measurements of flow patterns and the magnitudes of currents forced by horizontal variations in mass or water density and principal axes of variation, which describe the directions along which most of the variation in flow occurs.

---

[1] Archives were from the NOAA Center for Operational Oceanographic Products (CO-OPS) and the Global Historical Climatology Network (GHCN) published online by the NOAA National Environmental Information Center.

The results showed that the patterns of circulation differed significantly between seasons, with circulation modes in the upper meter driven in the summer and fall primarily by winds and horizontal variations in the density (mass) field created by spatial differences in solar heating, freshwater input from cold, glacial sources and limited vertical mixing. The currents were significantly moderated by up-fjord and down-fjord winds, which caused changes in circulation modes on the order of hours from open and closed counterclockwise (cyclonic) and clockwise (anticyclonic) modes to linear flows oriented primarily along the main channel (i.e. east-west in direction). In late winter, the entire upper 80*m* of the water column were driven primarily by strong down-fjord winds. However, when a period of quiescence ensued the circulation modes returned to the prominent eddy modes observed in the previous months.

In all seasons a westerly (outflow) current was observed along the northern side of the fjord, driven by varying seasonal forcing mechanisms. In the summer and fall, for example, the outflows were related to estuarine currents due to freshwater runoff that caused marked horizontal changes in density stratification (i.e. layering) in the upper few meters. These flows were either impeded by daily, westerly sea breezes or enhanced by down-fjord, northeast winds from the interior in June and September respectively. In late winter the water column had nearly uniform physical properties due to vertical mixing from winds and the sinking of dense, salty surface water known as thermohaline convection[2]. At this time, the westerly outflow was generated by strong southeasterly winds transporting water to the northern side of the fjord, thus setting up a basin-scale counterclockwise (cyclonic) circulation extending to at least 80*m* in depth.

In many cases the ADCP data verified the 10*m* and 40*m* subsurface drifter flow patterns. For example, in June the 10*m* currents exhibited counterclockwise (cyclonic) circulations in the mid to outer fjord and northern inner basin at average speeds of 6 to 10$cm\ s^{-1}$ (0.12 to 0.19*kts*) and 5 to 7$cm\ s^{-1}$ (0.1 to 0.14*kts*) respectively, and clockwise (anticyclonic) flows at slightly slower speeds (3 to 4$cm\ s^{-1}$) in the southeastern inner basin. In contrast, the water at 40*m* moved very slowly and exhibited mostly small east-west oscillations at along-channel velocities consistent with the tidal currents (~1 to 2 $cm\ s^{-1}$). At times, however, the 40*m* flows in June accelerated to speeds of ~ 10$cm\ s^{-1}$(0.19*kts*).

In September the ADCP currents increased in to speeds of 25 to 35$cm\ s^{-1}$ (~ 0.5 to 0.7*kts*) and 25 to 30*m* in depth due to partial mixing and deepening of the seasonal vertical temperature and salinity gradients known as the thermocline and halocline[3]. The ADCP data also showed persistent counterclockwise (cyclonic) currents extending from 7 to 23*m* in depth that were traced by the 10*m* drifters, but only during the initial deployments on September 21st to the 23rd. In contrast, the currents at the surface and 1*m* were primarily driven by combinations of estuarine (geostrophic) flow and down-fjord winds. Geostrophic currents are caused by horizontal variation in the density field, and in September these gradients extended deeper into the subsurface water (upper 20*m*) causing nearsurface currents ranging from 45 to 100$cm\ s^{-1}$. Also, the highest velocities occurred for stations close to large sources of freshwater discharge, such as the Lowe River and Valdez Glacier Stream.

The first half of the March survey was conducted under the influence of strong winds ranging from 12 to 15$m\ s^{-1}$ (23 to 29*kts*) coming from either the southeast (Lowe River Valley) or from the northeast (Valdez Glacier Valley). The surface drifters initially moved to the northwest at speeds ranging from 30 to 45$cm\ s^{-1}$ (0.6 to 0.9*kts*) during the southeast wind events and to the southwest at speeds of 20 to 27$cm\ s^{-1}$ (0.4 to 0.5*kts*) during northeast winds. Based on Ekman layer dynamics and given that the surface drifters were directly driven at 3% to 5% of the wind speed, the surface currents during the above wind events probably

---

2 Thermohaline convection occurs in the winter when freshwater input is negligible and maximum surface cooling causes the formation of dense, salty surface water that sinks and mixes of the upper water column over time. In PWS this process can cause mixing to ~100*m* in depth by late March.

3 The seasonal thermocline and halocline are vertical gradients caused respectively by solar heating and freshwater inputs from direct precipitation and runoff.

ranged from 10 to 14*cm* s^{-1} (0.2 to 0.27*kts*) and 6.5 to 8.5*cm* s^{-1} (0.13 to 0.17*kts*) respectively due to winds and tidal currents. The latter were negligible during the first segment and estimated at only 1.0 to 1.5*cm* s^{-1} (~0.03*kts*) based on the approximate changes in tidal volume and cross-sectional area near the mouth.

The nearly continuous winds in March also affected the deeper flows as well, and forced drifters at all depths to initially move northwest. However, due to the long-shore flow developed by wind transport all the subsurface drifters then moved steadily westward at maximum speeds ranging from 20 to 25*cm* s^{-1} (0.4 to 0.5kts) for the 1*m* drifters and 12 to 15*cm* s^{-1} (0.23 to 0.29*kts*) for the 10*m* drifters. During the second half of the survey, however, the winds diminished and eventually a one-day period of quiescence began. At this time the drifter speeds decreased significantly and their motions showed highly varied tracks including open and closed cyclonic and anticyclonic modes similar to previous months.

In all seasons the north-south (cross-channel) flows were also important and frequently resulted in drifter groundings along the shoreline. In June and September, for example, cross-channel flows were responsible for grounding 100% of the surface drifter that exhibited retention; with retention being inferred by a net eastward movement of these drifters. Drifters exhibiting a net westward movement were considered to be flushing, and in the same months 67% and 40% of flushing surface buoys also grounded inside the fjord and thus were considered to be retentions by default. The 1*m* drifters, by contrast, were driven ashore in only two deployments in June, and in September none of the 1*m* drifter deployments exhibiting flushing ended in grounding inside the fjord. However, four of the latter cases were considered questionable due to the drifters grounding on the western shoreline beyond Shoup Bay.

In June the average east-west (along-channel) drifter movement generally inferred that retention occurred for 93% of the surface water and 75% of the flows at 1*m*. The subsurface currents showed 66% retention at 10*m* and a net eastward motion at 40*m* indicated that the deep, subsurface water in the inner basin had 100% retention. Conditions in the fall and winter favored flushing, but in September retention of the surface drifters was still relatively high (62%) due to grounding, whereas 85% of the 1*m* flows showed complete flushing. In late winter 45% of the surface flows exhibited flushing, but in all cases the drifters grounded before exiting the fjord. In contrast, 72% of the flows at 1*m* exhibited complete flushing and in only three cases water at 1*m* moved back into the fjord. Retention of water at 10*m* in the fall decreased only slightly with respect to June (55% vs. 66%), but in late winter this layer exhibited 90% flushing. However, in two of the 10*m* deployments in late winter three of the drifters snagged the bottom along the northern shore. The water would have continued to flush westward but partial retention could be considered due to the currents striking the sub-tidal zone. The flows at 40*m* exhibited 100% flushing also along the northern shoreline in both the fall and late winter, but in September two of these drifters also made contact with the northern subsurface benthic zone in the outer fjord.

Port Valdez and PWS share some common oceanographic characteristics. However, they also differ significantly in certain properties that drive circulation. For example, eddy circulations in Port Valdez occur from mesoscale turbulence caused by local vorticity in the flow field, as opposed to closed geostrophically balanced eddies that occur in central PWS. As such, these features in Port Valdez are highly ephemeral and frequently occur as open counterclockwise (cyclonic) and clockwise (anticyclonic) turns. Lateral dispersion due to turbulence is also generally limited in both systems but also highly variable depending on the prevailing conditions of winds, estuarine (geostrophic) flows and lateral shear in the flow field. Although dispersion in Port Valdez typically increased when flows reached the shore as expected, during periods of low winds the large-scale turbulence in the system created mesoscale eddies that gradually dispersed material, but also caused longer retention in comparison to flushing by currents forced by wind and estuarine driven currents. The maximum flushing should therefore occur for the surface and 1*m* layers, as they exhibited the most rapid down-fjord motions that periodically entered Valdez Arm. In contrast, the deeper flows at 10 and 40*m* were typically much slower and dispersion at these depths occurred later in the deployments.

Conclusions

Early Summer:

1) Oil spilled within the fjord in early summer (June) could be held within the system for long periods depending on the prevailing meteorological and oceanographic conditions. For example, surface oil dispersing into the central fjord basin could either contaminate the southeast shoreline in as little as 9*hr* or flush from the fjord in less than half a day (7*hr*) depending on whether diurnal, westerly winds forced inward retention or if oil became entrained into an outflow along the northern side of the fjord that is enhanced by weak, down-fjord winds at night.

2) A caveat is that due to strong, reversing actions of westerly winds in combination with flood tides at the Narrows oil that flushed from the fjord at night could return the following day and contaminate the northern shoreline in about one day (25*hr*).

3) In other cases, retention of oil could occur for as long as 64 to 66*hr*, and result in contamination of multiple areas due to wide oscillatory motions within the fjord, or oil could move directly into the inner basin and contaminate the eastern to northeastern shorelines.

4) If dispersants were applied allowing the oil to vertically mix then flushing at 1*m* in depth in June could occur in 17 to 27*hr*. However, oil in this layer could also undergo oscillatory motions similar to the surface water and hence remain in the fjord indefinitely until prolonged flushing conditions returned.

5) Oil mixed to depths of 10*m* and 40*m* would very likely remain within the fjord for long periods (5 to 16 days). At 10*m* it would move in large counterclockwise (cyclonic) motions before possibly contaminating various subtidal zones around the fjord. In certain cases, however, the oil in this layer may also be caught in mesoscale counterclockwise (cyclonic) eddies in the outer fjord basin and either eventually flush from the system or gradually move eastward towards the inner basin over 4 to 5 days time due to action of diurnal, westerly winds.

6) Oil mixed to 40*m* that reached the inner basin would remain there indefinitely, whereas in the outer basin the average flows may cause it to gradually flush out of the fjord.

Early Fall:

1) In September strong northeast winds could flush surface oil from the central fjord in six to 21*hr*, but even under the influence of weak, variable winds the strong estuarine outflows during this season could assist in flushing oil out in about 10 to 14*hr*.

2) A caveat is that surface oil moving slowly outward (e.g. 18 to 22*hr*) can be affected by strong cross-channel flows, resulting in contamination of the outer fjord shorelines. Also, retention may ensue due to resumption of eastward along-channel velocities forced by periodic shifts to diurnal, westerly winds. Under such conditions shorelines in the eastern (inner) fjord could be affected by oil in 9 to 21*hr*.

3) At 1*m* the frequency of total flushing was the highest of all depths and all seasons (85%), and under the action of strong, northeast winds flushing could occur in as little as 12 to 16*hr*. Also, out of four of the cases exhibiting retention (15%), two initially showed flushing but drifters either turned back into the fjord in the outer basin or grounded along the southeastern shoreline when exiting the inner basin.

4) The subsurface water at 10*m* and 40*m* exhibited very long residence times in the fall, ranging from 5 to 10 days respectively, but whereas the upper layer at 10*m* exhibited more variability in flushing due to

effects of mesoscale turbulence (SD = 41*hr*), the 40*m* flows moved steadily outward at 5$cm\ s^{-1}$ resulting in much lower variation in flushing times (SD = 16*hr*). Under indirect effects of strong, northeast winds, however, flows at 40*m* could also strike the deep benthic regions on the northern side of the fjord.

Late Winter:

1) Flushing in late winter (March) was very strong due to the action of easterly winds, but little effects of density driven flows occurred since the water column physical properties were relatively homogeneous.

2) Marked cross-channel flows from wind and wave action invariably led to grounding of surface drifters, and under the action of strong southeasterly winds from the Lowe River Valley, for example, the northwestern shoreline could be contaminated by surface oil in as little as 10 to 11*hr*.

3) The water at 1 to 40*m* would move in the same general direction as the surface flows, but any oil at these depths would flush outward due to a long-shore current developed by piling of water along the northern shore from wind driven transport.

4) In contrast, when winds shift to the northeast surface oil could contaminate the southwestern shoreline in 20 to 31*hr*, but oil at 1*m* could either flush from the fjord in 45*hr* or be retained for nearly 8 days due to extremely small negative along-channel velocities.

5) Under the conditions of very weak winds or quiescence, however, water at both the surface and 1*m* would exhibit moderate to long residence times ranging from 70*hr* before surface flows reached the inner basin to nearly 14 days prior to flushing for water at 1*m*.

6) Under both sets of easterly winds, the flows at 10*m* would flush outward over the course of 2 to 5 days, but when the winds weaken the flows at this depth would begin moving in cyclonic eddies due to mesoscale turbulence. Flushing times under the above conditions exhibited extreme variations ranging from 3 to 20 days, the latter being essentially indefinite.

7) In contrast, the flows at 40*m* would move steadily outward under all conditions at average speeds similar to September (~ 5 $cm\ s^{-1}$), and would flush from the fjord in 86 to 93*hr*.

8) A final conclusion of the study regards areas in the fjord especially at risk of contamination from oil, particularly if dispersants were applied allowing it to mix vertically in the water column. Although these sites varied somewhat with the season and depth of the flows, there was significant overlap in the upper meter, particularly for the early summer and fall periods. In June, for example, thirteen locations were identified and included various points along the northern shoreline extending from east of Shoup Bay to Gold Creek and Mineral Creek Deltas and along the peninsula one nautical mile to the east; the eastern shoreline from the Valdez Glacier Stream northwards to the 'Duck Flats' region; the southeast region from the Lowe River to Solomon Gulch; the southwest shoreline east of Anderson Bay and at Entrance Island; and the entire western shoreline south of Shoup Bay (see Fig. 67a).

In the fall, the sites included the southwest shorelines at Valdez Narrows, Entrance Island and points east of Anderson Bay; the western shoreline south of Shoup Bay; the northwest shoreline between Shoup Bay and Gold Creek delta; the northeast shoreline both west and east of the harbor entrance and potentially the 'Duck Flats' and nearby islands; the eastern shoreline north of the Valdez Glacier Stream; and southeast shoreline near Solomon Gulch (see Fig. 67b).

In late winter, potential 'sensitive sites' during high easterly wind events were distributed mainly along the entire northern shoreline extending from one nautical mile east of Mineral Creek all the way to Shoup

Bay. During the northeast wind events various points between the Security Zone and Anderson Bay were at risk from surface oil, but during periods of calm or weak westerly winds flows at 1*m* also turned southwards, and potentially could contaminate the southern side of the fjord (see Fig. 67c).