Exxon Valdez Oil Spill
Restoration project Final Report

3-D Ocean State Simulations for Ecosystem Applications from 1995-1998 in Prince William Sound, Alaska

Restoration Project 00389
Final Report

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Study History: Project 00389 was an extension of the 3-D PWS circulation model (Wang et al., 2001) of the SEA project 97320-J to include four continuous years (1995-1998) instead of one year (1996). Project 00389 was a two-year project that collected physical forcing data of 1995-1998, conducted a four-year continuous run and sensitivity studies to determine key components of physical forcing, and numerical experiments of oil spill trajectory of the four years.

Abstract:

Using 3-D circulation model and buoy station data in the central sound, a four-year (1995-1998) simulation was conducted under combined forcing of monthly heat flux, freshwater discharge of a line source, daily wind, Alaska Coastal Current inflow/outflow and tide.

The seasonal cycle of the circulation in the sound matches well with field observations. The simulated monthly mean sea surface temperature (SST) matches well with the observed seasonal cycle of 1995-1998 at NOAA Station 46060.

Sensitivity studies were conducted to identify the key environmental parameters of the model forcing: wind, tide, Alaska Coastal Current inflow/outflow, and surface temperature and salinity restoring. All of these forcings were proven to be important.

A sixty-day oil drift trajectory simulation was conducted for each year. The drifters were released outside Bligh Reef on March 24 of each year. The numerical experiments show large interannual variability of possible oil spill trajectories. Most of the oil spill remained in the sound after 60 days in 1995, 1997 and 1998. Most of the oil spill drifted out of the sound from Montague Strait into the Gulf of Alaska in 1996.

Key Words: Circulation, *EXXON Valdez* Oil Spill, Prince William Sound, 3-D PWS model, sensitivity study.

Project Data: *Description of data* - buoy data at NOAA station 46060 and 46061, meteorological data at coast stations: Valdez, Whittier, Potato Point and Bligh Reef from 1995-1998. The buoy data have half-hourly wind, surface temperature and salinity, and the coast stations include just half-hourly wind. The data from simulation include 3-D current and temperature, salinity field. *Format* – All observation data is in ASCII text format, simulation data is in binary. *Custodian* – Contact Jia Wang and Meibing Jin, 122 O'Neill Building, University of Alaska, Fairbanks, AK 99775-7220, tel: 907-474-6877, fax: 907-474-7204, email: jwang@iarc.uaf.edu and ffjm@uaf.edu. *Availability* – All available.

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Tables of Contents

List of Tables

List of Figures

Fig. 7. Monthly mean sea surface temperature (top), salinity (middle) and elevation (bottom) at Station 46060. Solid-simulated, dot-observed.

Fig. 8. Simulated temperature (top), salinity (middle) and sigma-t (bottom) time series vs. depth at Station 46060.

Fig. 9. Surface circulation in April (left panel) and October (right panel) of sensitivity study case 1 (no wind, upper panel) and case 2 (no tide, lower panel).

Fig. 10. Fig. 10. Depth (0m – 80m)-averaged transport in October of control run (upper panel) and sensitivity study case 1 (no wind, middle) and 2 (no tide, lower panel).

Fig. 11. Density time series of control run (upper) and sensitivity study case 1 (no wind, middle) and case 2 (no tide, lower) at Station 46060.

Fig. 12. Depth-integrated transport (m2/s) of sensitivity study cases 3 (double ACC, upper), 4 (half ACC, middle), and 5 (no ACC, lower panel) in October.

Fig. 13. Vertical density time series of sensitivity study cases 3 (double ACC, upper), 4 (half ACC, middle), and 5 (no ACC, lower panel) at Station 46060.

Fig. 14. Simulated surface circulation of case 6 (no restoring), 7 (restoring T only) and 8 (restoring S only) in April (left column) and October (right column).

Fig. 15. Simulated oil spill tracks of a) 1995, b) 1996, c) 1997, and d) 1998. "+" is releasing position, color bar denotes the days from release.

Executive Summary

Using 3-D PWS (Prince William Sound) circulation model developed from the SEA (Sound Ecosystem Assessment) project and buoy station data in the central sound, a four-year (1995-1998) simulation of the circulation in the sound was conducted under combined forcing of monthly heat flux, freshwater discharge of a line source, daily wind, Alaska Coastal Current (ACC) inflow/outflow and tide. The seasonal cycle and interannual variability of the circulation patterns and thermohaline structures were examined.

The seasonal cycle of the circulation in the sound compares well with observations. Similar seasonal circulation patterns in the four years were characterized by an anticyclonic gyre in the central sound in January to April, and strong cyclonic gyre in the central sound in September to December, while summer was the transition period of the two circulation regimes. The size, position and strength of the gyres and thermohaline depth in the central sound showed small interannual variability. But the size, position and magnitude of the gyres in the central sound indicate interannual variability. In 1995 and 1998, in addition to a cyclonic gyre, there was one small anticyclonic gyre on the northwest corner. The outflow from Montague Strait was strong for all four years.

The simulated monthly mean sea surface temperature (SST) compares well with the observed seasonal cycle of 1995-1998 at NOAA Station 46060. The SST was lowest in February and highest in July for all four years. The observed SST ranges from 3.7 to 15.6°C, while the simulated SST ranges from 4.1 to 12.5°C. The difference of the low temperature in summer is due to the fact that the simulated data represents the mean temperature in the surface layer with certain thickness, while the observation is of the surface skin temperature that is usually higher in the summer when the weather was calm and the sea was well stratified. The simulated sea surface salinity (SSS) at Station 46060 shows similar seasonal cycles for the four years. The SSS ranges from 28.2 to 30.7, with the high in June and low in September or October. The simulated sea surface elevation at Station 46060 shows similar seasonal patterns for 1995 and 1996, with large interannual variability in 1997 and 1998. The elevation ranges from 0.01m to 0.08m with the high in November or December and low in April. The low and high in sea level are related to the magnitude of ACC inflow and outflow and the circulation patterns in the sound.

Sensitivity studies show that all the forcings of wind, tide, Alaska Coastal Current inflow/outflow, heat flux, and freshwater flux applied in the model via surface temperature and salinity restoring are important to the simulated results in the following ways:

1) Wind has more impacts on the vertical temperature and salinity structure and circulation of the surface layer than deep water. Without wind, the surface current became weaker and the thermocline became shallower.

2) Tidal current is a major current in the sound and important to surface and bottom mixing, while residual tide current just contribute a small part to the mean circulation. Without tide, the thermocline depth would be shallower.

3) The magnitude of the ACC inflow determined the outflow current through Montague Strait. Doubled ACC inflow could change the cyclonic circulation pattern in October in the case of normal or less ACC inflow into a northward jet with a small accompanying anticyclonic gyre, which would strongly flush the west sound in addition to the central sound. Also, double ACC inflow would increase the mix-layer depth significantly

4) The surface T, S restoring is critical to maintain T, S seasonal cycle and surface circulation patterns. Salinity was the most important factor determining the central sound

cyclonic circulation patterns in autumn, due to freshening around the sound.

The numerical oil spill drift experiments showed that in 1995-1997, the western sound was impacted by the oil spill. Most of the oil spill remained in the sound after 60 days in 1995, 1997 and 1998. Most of the oil spill drifted out of the sound from Montague Strait into the Gulf of Alaska in 1996. This result indicates a large interannual variability of possible oil spill trajectories.

Introduction

Prince William Sound (PWS or the Sound) is located in the southern coast of the Gulf of Alaska (Fig. 1). PWS is a combination of fjords and tidewater glaciers along the coast of Alaska that was formed by a combination of preglacial erosion, glacial excavation, and tectonism. A systematic numerical simulation (study) of the physical oceanography and ecosystem in the region is essential to provide scientific knowledge and information to the state government, local community, etc. because of its rich resources in sea birds, mammals, salmon, forage fish, and many other animals.

Because the *Exxon Valdez* Oil Spill on March 24 1989 severely damaged the ecosystem in PWS and the adjacent waters, such as Cook Inlet and Kachemak Bay, extensive observational programs have been carried out in PWS. The SEA (Sound Ecosystem Assessment) project supported by EVOS is a major effort. This interdisciplinary project started in 1994 with major focus on pink salmon, Pacific herring habitat, ecology, and physical oceanography. As the physical component, the effort was placed on field program and numerical modelling.

The circulation in the sound is strongly mediated by seasonal and interannual variations in winds and freshwater runoff as well as by local topography. After the implementation of 3D-PWS model and a passive tracer simulation were accomplished (Mooers and Wang 1998; Deleersnijder et al 1998), a seasonal simulation (12 consecutive months) has been followed up by Wang et al. (2001) using the SEA observations of 1996.

Nevertheless, the following questions still remain: 1) Are the seasonal circulation patterns and thermocline structure in the sound similar each year? 2) How large is the interannual variability? 3) What are the possible oil spill trajectories if the oil spill occurs under wind of different years? 4) What is the major forcing that maintains the circulation in the sound?

This study was an attempt to answer the above questions by implementing a continuous four-year, 3-D simulation of ocean current velocity, ocean temperature, salinity and mixing coefficients for the resource managers, the fishing industry and for biological applications. This simulation uses the observed data collected from 1995-1998 in PWS, including tides, coastal current inflow/outflow, freshwater discharge, and wind. Besides the 4-year simulation, sensitivity studies were conducted to identify the key environmental parameters from the model forcings of wind, heat flux and freshwater flux via surface temperature and salinity restoring, Alaska Coastal Current inflow/outflow, and tide. A sixty-day oil spill simulation was conducted for each year from 1995-1998. The oil spill drifters were released at the place where *Exxon Valdez* grounded, on March 24 of each year. The oil spill particles were treated as passive drifters driven by surface currents, turbulence diffusion, and wind.

Objectives

1. To use the 3-D PWS model to simulate circulation, and T, S structure for 1995-1998. The model results were validated with observations during the four years.

2. Sensitivity studies were conducted to identify the key environmental parameters from the model forcing of wind, tide, Alaska Coastal Current inflow/outflow, heat flux, and freshwater flux (via surface temperature and salinity restoring). This objective was not in the original proposal, but it was suggested by reviewers of our manuscripts.

3. Simulation of zooplankton overwintering was replaced by simulation of oil particle drifting of 1995-1998, because the amount of overwintering zooplankton of 1995, 1997 and 1998 were unknown.

4. Provide biologists and resource managers the 3-D fields of velocity, T, S etc. of 1995-1998.

5. Collect meteorological data from coastal weather stations and offshore buoy stations within and beside Prince William Sound. Establish a web site to make our research results to public and data available to the research community of Prince William Sound ecosystem.

Methods

1. The 3-D circulation model

A modified version of Blumberg's (1991) ECOMSI (Estuarine and Coastal Ocean Model with Semi-Implicit scheme) is used, with a newly-implemented predictor-correct scheme for time integration (Wang and Ikeda, 1997). The model has the following similar features to the Prince Ocean Model (POM; Mellor, 1991): (1) horizontal curvilinear coordinates (not used here); (2) an Arakawa grid; (3) sigma (terrain-following) coordinates in the vertical with realistic bottom topography; (4) a free surface; (5) a level 2.5 turbulence closure model for the vertical viscosity and diffusivity (Mellor and Yamada, 1982); and (6) a mean flow shear parameterization for horizontal viscosity and diffusivity (Smagorinsky, 1963). Differing from POM, ECOMSI uses: (1) a semi-implicit scheme for the shallow water equations (Blumberg 1991); and (2) a predictor-correct scheme for the time integration to avoid inertial instability (Wang and Ikeda, 1996, 1997; Wang et al., 2001). The model equations, time integration method, and boundary conditions were described by Wang et al. (2001).

The model domain includes the entire sound with two open boundaries, one at Hinchinbrook Entrance and the other at Montague Strait (Fig. 1), allowing water exchange with the Gulf of Alaska coastal waters (Schmidt, 1977; Mooers and Wang, 1998). The model grid (Fig. 2) spacing is 1.2 km, which is eddy-resolving because the internal Rossby radius of deformation is about 5km in winter (50km in summer; Niebauer et al. 1994). There are 15 vertical sigma levels, with a relatively high resolution in the upper 50m to resolve the upper mixed layer.

2. Model forcing and initialization

The model forcing includes monthly heat flux, freshwater discharge of a line source, daily wind, Alaska Coastal Current (ACC) inflow/outflow, and tide.

The monthly heat flux from COADS (Comprehensive Oceanic and Atmospheric Data Sets) was applied uniformly in PWS, together with restoring the surface temperature to the CTD-observed seasonal SST during 1995-1996 (Vaughan et al., 1997).

The monthly freshwater runoff that was calculated from hydrological Digital Elevation Model (DEM, Simmons, 1996) was specified at the surface along the coast of PWS as a rate of precipitation, together with restoring boundary condition to the CTD-observed seasonal SSS during 1995-1996 (Vaughan et al., 1997). This combination is an effective way to physically describe freshwater runoff as a line source along the coast, as did Wang et al. (2001).

The daily averaged wind data was mainly from NOAA buoy Station 46060 in the central sound, modified by available local weather stations (location in Fig. 1) at some coastal areas to include strong local orographic effects, especially at channels between mountains. The longitude and latitude of the stations are listed in the following Table 1:

Table 1. Longitude and latitude of the stations

Station	Latitude	Longitude
46061	60.22 N	146.83 W
46060	60.58 N	146.83 W
Bligh Reef	60.84 N	146.88 W
Potato Point	61.06 N	146.70 W
Valdez	61.18N	146.40W
Whittier	60.75N	148.60W

Alaska Coastal Current (ACC) inflow/outflow was specified according to observations at Hinchinbrook Entrance. The seasonal variability of the transport during 1995-1996 was calculated (Fig. 3). The inflow from Hinchinbrook Entrance was balanced by the outflow through Montague Strait by using a radiation boundary for the normal velocity (with self-adjusted outflow of the same amount as the inflow). The inflow and outflow were assumed maximum at the surface and to linearly decrease to zero at 200m or at the bottom. This inflow and outflow boundary condition was applied uniformly across the open boundaries of the 3-D velocity grid points, while the vertical and lateral integration must be equal to the observed volume transport. The open boundary condition for temperature and salinity at Montague Strait is free-advecting, while at Hinchinbrook Entrance, the CTD-observed T and S profiles during 1995-1996 (Vaughan et al., 1997) were specified over the seasonal cycle.

The tidal harmonic constants for amplitude and phase (Schwiderski, 1980) at both Hinchinbrook Entrance and Montague Strait were prescribed for surface elevation. Here, only the M_2 tidal component, the major tidal component in PWS, was considered.

Initial temperature and salinity fields used are based on a typical spring profile observed in the central sound in March 1995 (T/S ranges from 4°C/31.2 PSU at surface to about 6°C/32.3 PSU at 400m; Wang et al., 2001). These were specified to be horizontally uniform. The model was spun-up for two years from these initial conditions under seasonal forcing. The restart file was saved for use as initial conditions for the 4-year (1995-1998) prognostic runs. Vertical viscosity diffusivity was determined at each time step and each grid point from the Mellor-Yamada 2.5 turbulence closure model. The model forcing includes freshwater runoff of a line source, heat flux, ACC throughflow, wind, and M_2 tide. In the 4-year continuous run, only wind is changed every year by using the buoy data from central sound Station 46060.

3. Numerical experiments

There are three parts of numerical experiments in this study:

1) To investigate interannual variability of the thermohaline and circulation patterns in the sound, a 4-year (1995-1998) continuous model run was performed under all the forcing including monthly heat flux, freshwater discharge of a line source, daily wind, Alaska Coastal Current (ACC) inflow/outflow and tide. In this run, only the daily wind field was different every year, with other forcings held the same for each year.

2) In order to determine the role of each forcing on the circulation in the sound, the following sensitivity studies were performed for one year (1996) run (Table 2). The anomalies (sensitivity study minus control run in 1996) were analyzed.

Table 2. Sensitivity studies. The blank space means that the parameter is included in the model.

Case	1	2	3	4	5	6	7	8
Wind	None							
Tide		None						
ACC throughflow			Double	Half	None			
Surface T, S restoring						None	T only	S only

3) A 60-day oil spill drift simulation was conducted for each year. The oil spill drifters were released at the place where the spill occurred on March 24 of each year. The oil particles were treated as passive drifters driven by sea surface current and wind.

$$\vec{V}_{oil} = \vec{V}_{sea} + \alpha \cdot \vec{V}_{wind} + \vec{v}'$$

where $\vec{V}_{oil}, \vec{V}_{sea}, \vec{V}_{wind}$ are the speed of oil spill particles, sea surface current and wind, respectively; α is a constant coefficient of 3%; $\vec{v}'$ is turbulent random walk speed which the complex and inherent motion that occurs at spatial and temporal scales much smaller than the predominant scales of mean current and wind drift surface current. This turbulent velocity is provided by a random number generator obeying Gaussian distribution, with a mean of zero and a variance of unity. The turbulent velocity has only statistical meaning in contrast to the deterministic large-scale motion and wind drift motion. The random flight model that satisfies a well mixed (homogeneous) condition and Gaussian turbulence can be described as follows (Wang, 2001):

$$d\vec{v}' = -\frac{1}{T}\vec{v}'dt + K^{1/2}d\xi$$

where T is the Lagrangian integration timescale (or turbulence decorrelation time) and the Lagragian correlation function is exp(-t/T), $K = 2\sigma^2/T$ is the turbulence diffusion coefficient, σ^2 is the variance of turbulence, and $d\xi$ is the stochastic kick received by the particle. For more details on this random flight statistical approach, see Thomson (1987) and Dutkiewicz et al.

(1993).

The trajectory of the oil spill particle is of Lagrangian type (Wang, 2001):

$$\vec{x}(t) = \vec{x}(t_0) + \int_{t_0}^{t} \vec{V}_{oil} \, dt$$

where t_0 is the initial time, and t is the present time.

Results and Discussion

Objective 1: Seasonal cycle and interannual variability during 1995-1998

1.1 Seasonal cycle and interannual variability of winds during 1995-1998

There were six stations (Table 1) in the sound with half-hourly wind data from 1995-1998. We averaged them into daily mean wind (Fig. 4.1-4.6). Some missing periods of data are replaced by the other-year mean value of the same station and same periods.

The most unique features of the winds in the sound are that in the fjords, channels, and inlets areas, the wind directions are channeled by the local orography. These orographic effects can be seen in most coastal stations (Fig. 4.3-4.6). Stations Bligh Reef and Potato Point show NNE wind prevailing all seasons in all four years, while Station Whittier has SSW wind prevailing all the time. The wind is calm at Valdez because it is surrounded by mountains. Although directions at variable channels are different, they are directed from the channel toward the basin.

In the basin area and open ocean, the wind directions are diversified, but the annual mean wind directions are E or EEN. This kind of wind direction, along with those in the channels and the Alaska Coastal Current flowing through the sound, constitutes a strong strength to drive surface drifters out of the sound from Montague Strait.

The magnitudes of wind in the sound are diversified at different stations. For Stations Bligh Reef and Potato Point, the wind is calm in spring and summer (around day 100 to 230) and strong in other periods of the year. For other stations, there is no obvious seasonal variation. Although there was some small interannual variability in the wind field, there were no systematic trends in the interannual variability for both wind speeds and directions at all the stations. The wind at Station 46060 showed some interannual variability. For instance, the x-component of the wind in the spring of 1997 and 1998 was much stronger than 1995 and 1996, and the y-component of the wind was negative (southward) for the whole winter season in 1995-1997, but in the winter of 1998, the period of southward wind was much shorter and mixed with periods of northward wind.

1.2 Seasonal cycle and their interannual variability of the circulation during 1995-1998

The simulated mean surface circulation (averaged over a M_2 tide cycle) of 1995-1998 shows strong seasonal patterns and relatively small interannual variability. The magnitude of mean circulation also shows seasonal and interannual variations which have significant effects on retaining or dispersing organisms in the sound and the water exchanges between the Gulf of Alaska and the sound.

In the winter season, such as in January (Figure 5.1), there existed strong ACC throughflow entering from Hinchinbrook Entrance and flowing out of the sound from Montague Strait. The inflow from Hinchinbrook Entrance flew into the left side of the central sound and then was divided into two branches, one going farther north and the other turning left and flowing out of the sound from Montague Strait. The current in Valdez Arm was directed toward the central sound because of the local persistent NE wind in winter. All these currents coming into the central sound formed a complicated circulation pattern there. In January of each year, there was an anticyclonic gyre in the central sound. In 1996, the gyre was weaker than those of the other years, because more inflow has turned left into the Montague Strait under the relatively stronger southward wind in January. These gyres in the central sound had a significant role on the water exchange between ACC inflow with the inner sound and inlets. Some of the water entering the sound became involved in the gyres and had a longer residence time in the sound.

In the spring, the ACC throughflow gradually became small. In April (Figure 5.2), the gyres in the central sound were still anticyclonic but much weaker than those in January. This anticyclonic regime was captured by observations using towed ADCP (Vaughan et al., 1997). The circulation in April of 1998 was quite different from the other three years: the northward current was much stronger because the mean northward wind in April of 1998 was stronger.

In summer, the ACC throughflow gradually increased, but was still weak. While freshwater runoff started to build up, the circulation patterns in the central sound were in a transition period. In July (Figure 5.3), there were two gyres in the central sound: one anticyclonic and one cyclonic. The location, size and strength of the gyres varied from year to year.

In autumn, freshwater runoff reaches maximum and the increased ACC throughflow flushes the entire sound (Figure 5.4). There was a strong cyclonic gyre in the central sound which was revealed by observations (Niebauer, 1994, Vaughan et al., 1997). The simulated cyclonic gyre in the central sound in September in 1996 was very close to that observed (Fig. 6b). In 1995 and 1998, in addition to a cyclonic gyre, there was one small anticyclonic gyre on the northwest corner. The outflow from Montague Strait was strong for all four years.

1.3 Seasonal cycle and their interannual variability of the temperature, salinity and sea surface elevation during 1995-1998

The simulated monthly mean sea surface temperature (SST) compared well with the observed seasonal cycle of 1995-1998 at NOAA Station 46060 (Fig. 7). The SST had a minimum in February and maximum in July for all the four years. The observed SST ranges from 3.7 to 15.6°C, while the simulated SST ranges from 4.1 to 12.5°C. The difference of the high temperature in summer is because the simulated data represents the mean temperature in the surface layer with certain thickness which might be larger than the surface mixed layer in the summer. The simulated sea surface salinity (SSS) at Station 46060 (Fig. 7) shows similar seasonal cycle for the four years. The SSS ranges from 28 to 31 with the high in May or June and low in September or October. The simulated sea surface elevation at Station 46060 (Fig. 7) shows similar seasonal patterns for 1995 and 1996, with large interannual variability in 1997 and 1998. The elevation ranges from -0.02m to 0.05m with the high in November and December and low in the other month. The changes of elevation are related to the magnitude of ACC inflow and outflow (Fig. 3a) and the circulation patterns in the sound. The lower elevation in September of 1997 was because Station 46060 was in a stronger cyclonic gyre in September than the other years.

The temperature, salinity and density (Fig. 8) vertical structures at Station 46060 show similar seasonal cycles from 1995-1998. The surface thermocline was first formed by rising surface temperature in spring due to solar heating, and was dominated by low surface salinity in the autumn.

Objective 2: Sensitivity studies

2.1 The impact of wind

When there was no wind (case 1), the surface current in April and October all became weaker but still had the same pattern (Fig. 9) as the control run in the central sound. The depth (0-80m)-integrated transport (in this report, the unit of the transport is $Sv=10^{6}\ m^{3}s^{-1}$) in October still has the same pattern as the control run in the central sound (Fig. 10), although the magnitude of the depth integrated circulation decreased by 30%, or 0.05Sv. Also, the shape of the gyre was changed, becoming less northward and more westward. Another impact without wind is that the depth of the mix-layer seen from the vertical density time series at Station 46060 (Fig. 11) is much shallower than that of the control run, because wind stirring is one of the important factors of surface mixing. This means wind is important to the vertical temperature and salinity structure and the circulation in the surface layer.

2.2 The impact of tide

When there was no tide (case 2), the surface circulation patterns (Fig. 9) were similar to the control run in both April and September, but the magnitude and direction of the current had slightly changed, which reflected the impact of residual tide current. The depth (0m - 80m) integrated transport kept the same pattern as the control run in the central sound in October (Fig. 10). The magnitude of the transport was 10% or 0.02Sv smaller, which suggests that the residual tide current in the central Sound is also cyclonic and has a transport of about 0.02Sv. The surface mix-layer depth (Fig. 11) was shallower than the control run, but deeper than case 1 (no wind). Thus, the tide current also played an important role on surface mixing layer (Wang et al., 1999), although it was less important than wind.

2.3 The impact of ACC throughflow

In cases 3, 4, and 5 (the ACC throughflow is set to be double, half and zero of the control run), the inflow through Hinchinbrook Entrance and outflow through the Montague Strait showed a proportional change as seen from the depth (0m - bottom) -integrated transports in October (Fig. 12). In case 3, the doubled inflow entered the central sound like a jet and was divided into three branches: one main branch went north until the coast and turned into the western sound, flushing the western sound water out through Montague Strait; the other two were small branches: one turned left into Montague Strait and flew out of the sound, and one turned right and formed a small anticyclonic gyre. In cases 4 and 5 (half ACC inflow and no inflow), the central sound had a cyclonic gyre similar to the control run with small outflow through Montague Strait in case 4 and no outflow in case 5. So, the central sound circulation would be a cyclonic gyre in October in normal or less ACC inflow, but in the case of strong ACC inflow, the circulation in the central sound could be changed to a straight northward flow with a small accompanying anticyclonic gyre. Also, both the central sound and western sound would be strongly flushed under strong ACC inflow, while only the central sound was flushed in normal or less ACC inflow.

The simulated vertical density time series at Station 46060 (Fig. 13) showed that the vertical mixing in case 3 (double ACC inflow) was much deeper than those in cases 4 and 5. This indicates that an increase of ACC inflow will largely increase the mixed layer depth, while a small ACC inflow does not affect much of the mixed layer depth.

2.4 The impact of surface T and S restoring

Surface T and S restoring are used in the control run along with surface heat flux and salt flux to reproduce seasonal cycle. The vertical structures of temperature in case 7 (restoring T only) and salinity in case 8 (restoring S only) are similar to those of the control run, but still drifting slightly with time and depth (not shown here). The surface restoring of the temperature can only control the seasonal cycle of the surface temperature, but the drifting in salinity will affect the circulation and gradually affect the vertical structure of temperature. The same applies to salinity restoring only.

The impacts of the surface temperature and salinity restoring on surface current and depth-averaged transport vary between restoring S or not. In case 8 (restoring S only), surface circulation patterns (Figure 14) in April and October still displayed similarity to the control run. While in cases 6 (no restoring) and 7 (restoring T only), the surface circulation patterns are totally different from the control run. Thus, salinity was a major factor determining the surface circulation patterns in the central sound

Objective 3: Interannual variability of the oil spill drift trajectories during 1995-1998

Oil spill particles were released outside Bligh Island ("+" point in Figure 15) on March 24 (the date when Exxon Valdez Oil Spill occurred) of each year. The 60-day simulation showed that most of oil spill particles were advected out of the sound from Montague Strait in 1996, but remained in different parts of the sound for the other three years. The oil spill affected areas also showed large interannual variability caused by wind and surface current. In 1995-1997, the western sound was impacted by oil spill. But in 1998, the oil spill was almost restrained in the northern sound. The reason is the wind turned northward earlier than the other three years.

The total percentage of particles advected out of the sound after 60 days are 1995: 2.5%; 1996: 75.8%; 1997: 0.3%; 1998: 0%. This result indicates a large interannual variability of possible oil spill trajectories.

Objective 4: Application to biological research

The simulated 3-D field of current, T, S was successfully used in several biological studies: 1) A 3-D simulation of overwintering zooplankton drifting from February to June of 1996 (Cooney, 1999); 2) Larva drift in Prince William Sound (Norcross, et al., 2001); 3) Larva transport and retention in Prince William Sound (Brown, 2001); 4) Plankton dynamics: Observed and modelled responses to physical forcing in Prince William Sound, Alaska (Eslinger et al., 2001); and 5) Coupled physical-biological modelling the spring phytoplankton bloom in Prince William Sound (Jin et al., 2002).

Objective 5: Web site to distribute data and model results

Meteorological data from coastal weather stations and offshore buoy stations within and beside Prince William Sound were collected. A web site was established to make our research results and datato public and data available to the research community of Prince William Sound ecosystem, with the help of Mr. Stephen Bodnar. The address of the web site is linked to IMS web site: www.ims.uaf.edu.

Conclusions

The observed wind data suggests that orographic complexity gave the wind in the sound a large geographic variability: unique wind directions in the fjords, channels and inlets, and diversified wind directions in the central sound. The wind of coastal stations has a strong seasonal cycle. The wind of Station 46060 showed some interannual variability significant to the circulation and oil spill trajectory: the x-component of the wind in the spring of 1997 and 1998 was much stronger than 1995 and 1996; the y-component of the wind was negative (southward) for the whole winter season in 1995-1997, but in the winter of 1998, the period of southward wind was much shorter and mixed with a period of northward wind.

The four-year (1995-1998) simulation compared well with field observations of circulation and sea surface temperature at NOAA Station 46060 of 1995-1998. Similar seasonal circulation patterns in the four years were characterized by anticyclonic gyre in the central sound in January to April, and strong cyclonic gyre in the central sound in September to December, while summer was the transition period of the two circulation regimes. The size, position and strength of the gyres and thermohaline depth in the central sound showed small interannual variability.

The numerical oil spill drift experiments showed that in 1995-1997, the western sound was impacted by the oil spill. Most of the oil spill remained in the sound after 60 days in 1995, 1997 and 1998. Most of the oil spill drifted out of the sound from Montague Strait into the Gulf of Alaska in 1996. This result indicates a large interannual variability of possible oil spill trajectories.

Sensitivity studies showed that all the model forcings, such as wind, tide, ACC inflow/outflow, and surface temperature and salinity restoring were important to the model results in different ways: 1) wind has more impact on the surface circulation and mixed layer depth. Without wind, the surface current became weaker and the thermocline became shallower; 2) tidal current is a major current in the sound and important to surface and bottom mixing. Without tide, the thermocline depth became shallower; 3) the magnitude of the ACC inflow determined the outflow current through Montague Strait. Doubled ACC inflow could change the cyclonic circulation pattern in October in the case of normal or less ACC inflow into a northward jet with a small accompanying anticyclonic gyre, which would strongly flush the west sound in addition to the central sound. Also, double ACC inflow would increase the mix-layer depth significantly; 4) the surface T, S restoring is critical to maintain T, S seasonal cycle and surface circulation patterns. Salinity was the most important factor determining the central sound cyclonic circulation patterns in autumn, due to freshening around the sound.

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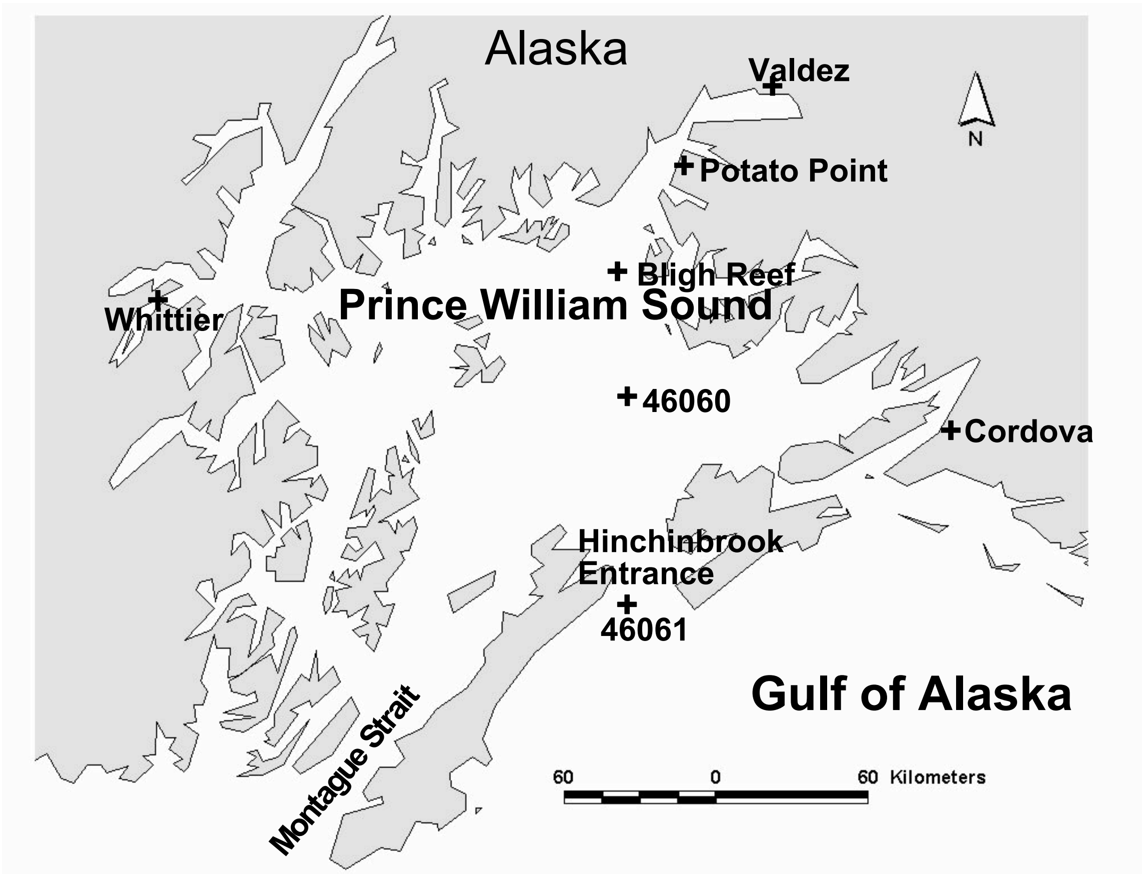


Fig 1. Geographical location of the model area and observation stations in Prince William Sound

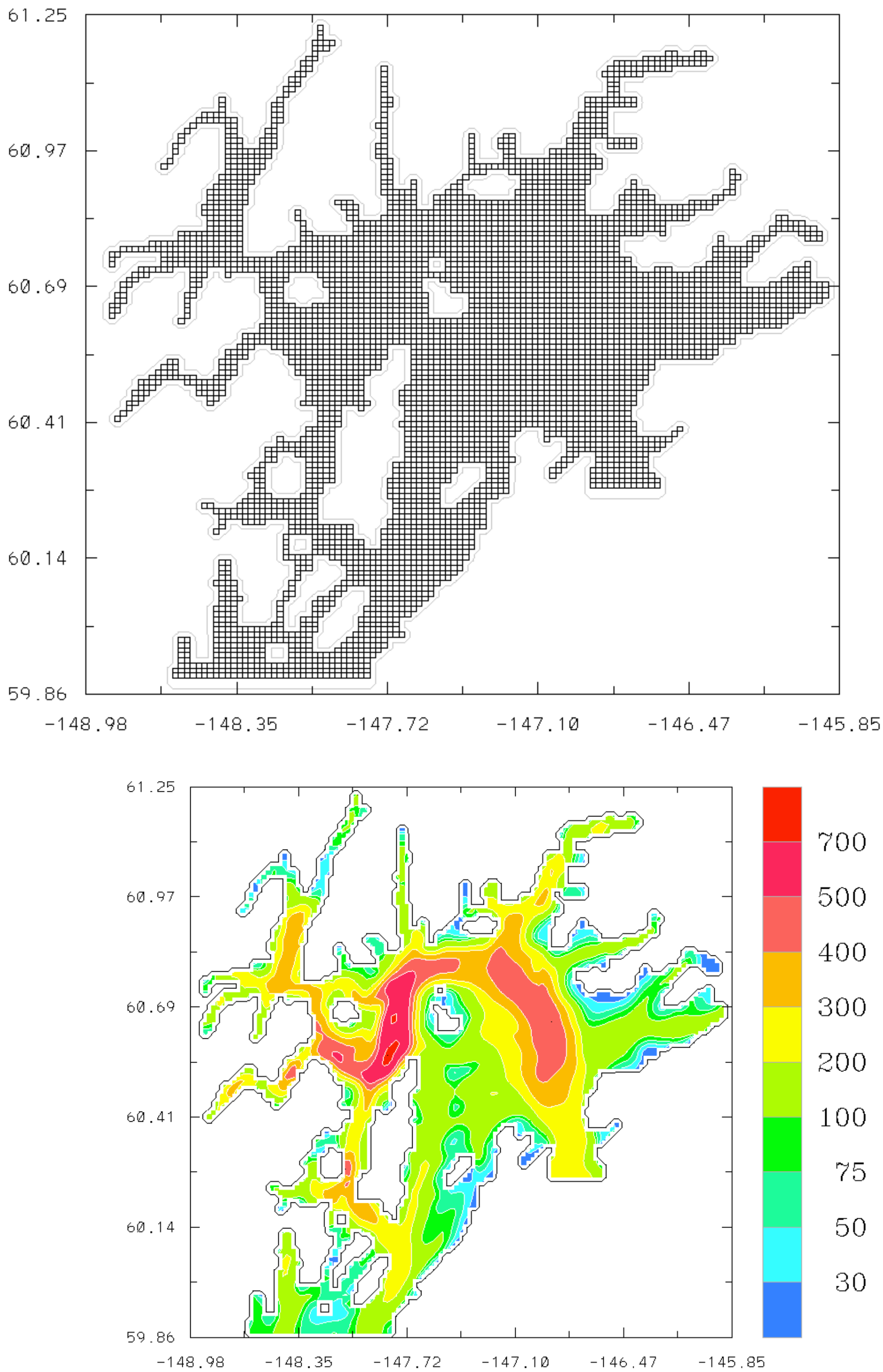


Fig. 2 Model grid (upper) and topography of Prince William Sound (lower)

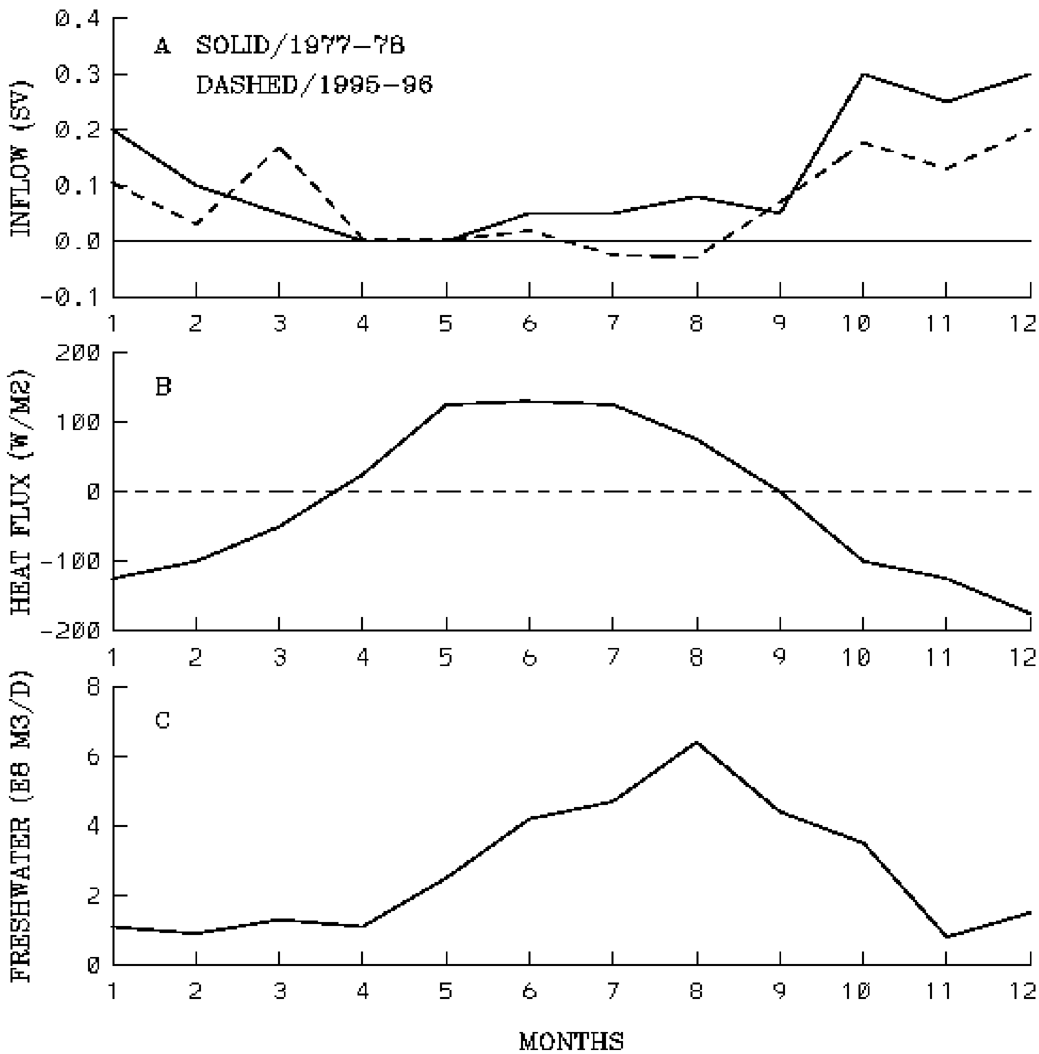


Fig 3 The time series of (A) inflow from the Hinchinbrook Entrance: the solid line is the data from Niebauer et al. (1994) and dashed line is from the SEA observation, (B) heat flux from COADS, and © freshwater runoff.

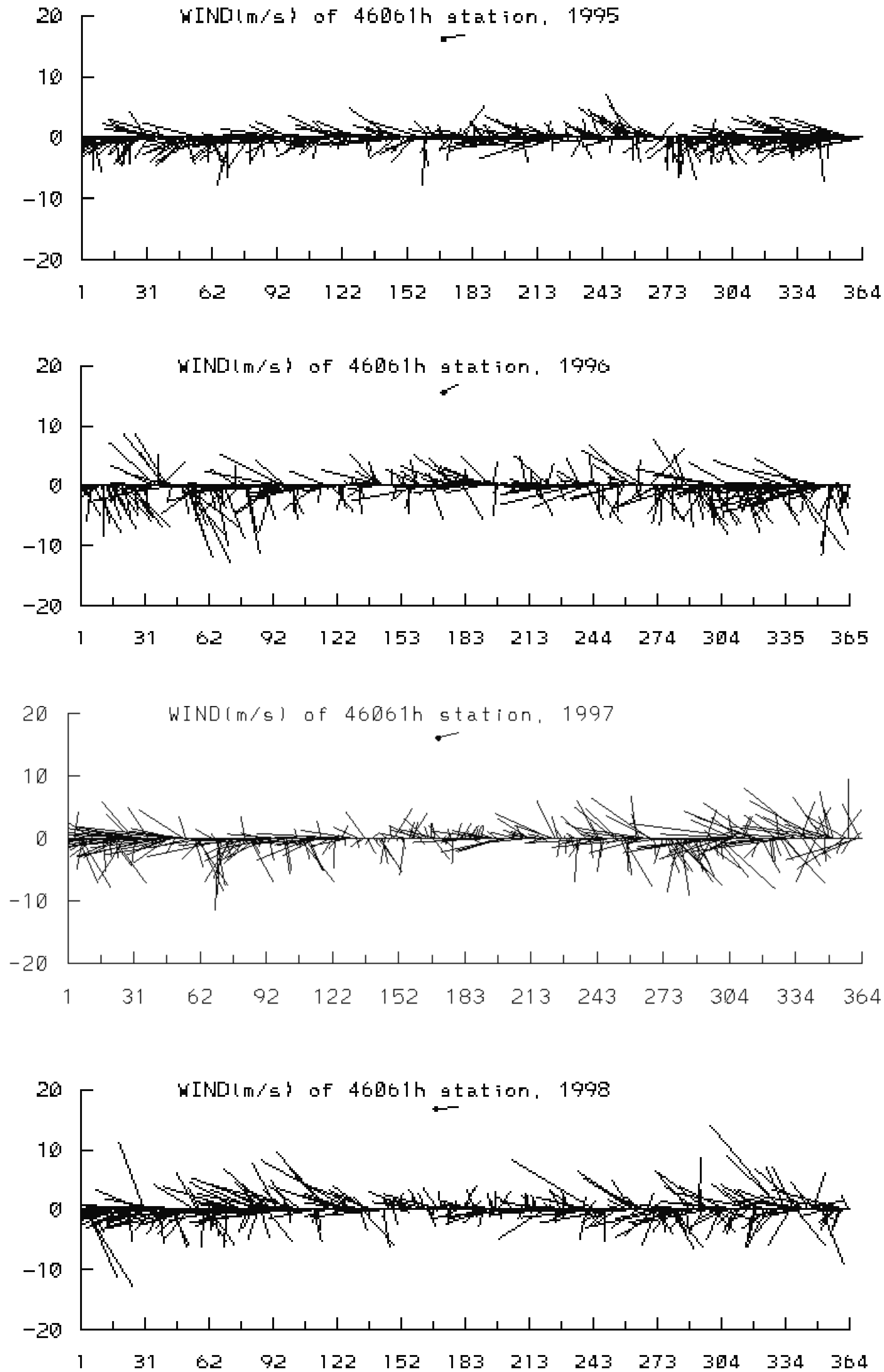


Fig. 4.1. Daily wind time series at Station 46061. The line with dot denotes the annual mean wind velocity. Upward is north.

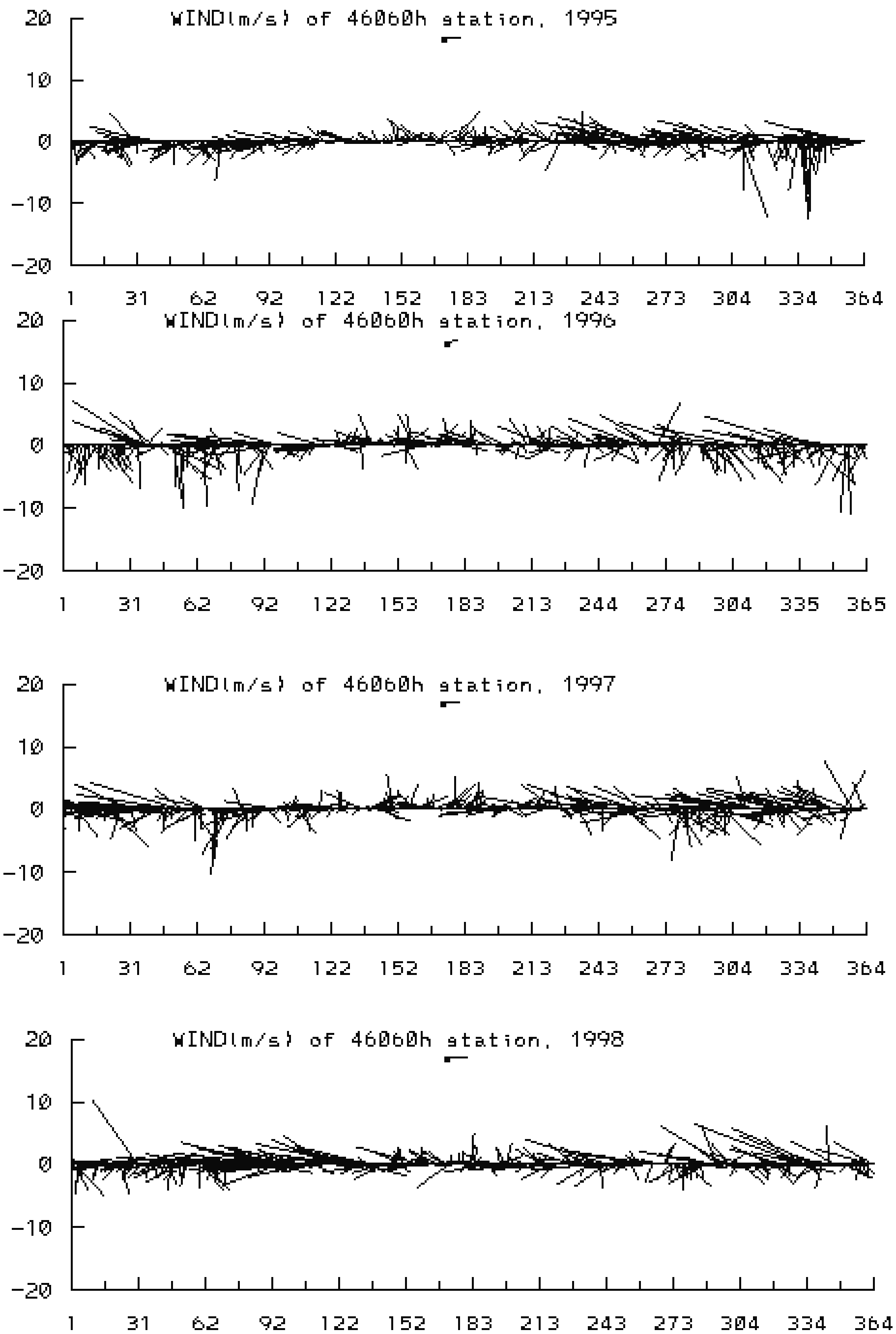


Fig. 4.2. Same as Fig. 4.1 except at Station 46060.

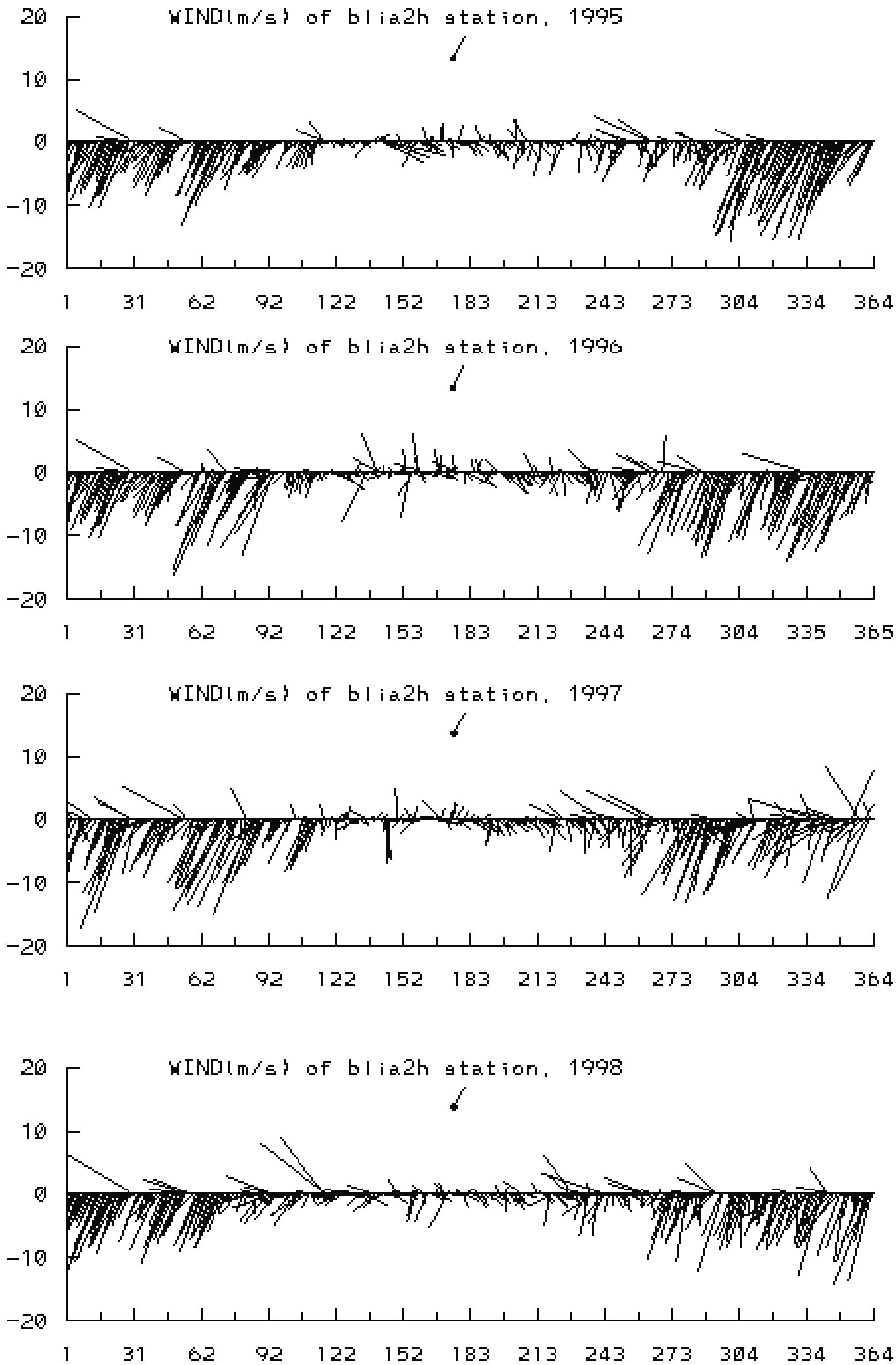


Fig. 4.3. Same as Fig. 4.1 except at Station Bligh Reef.

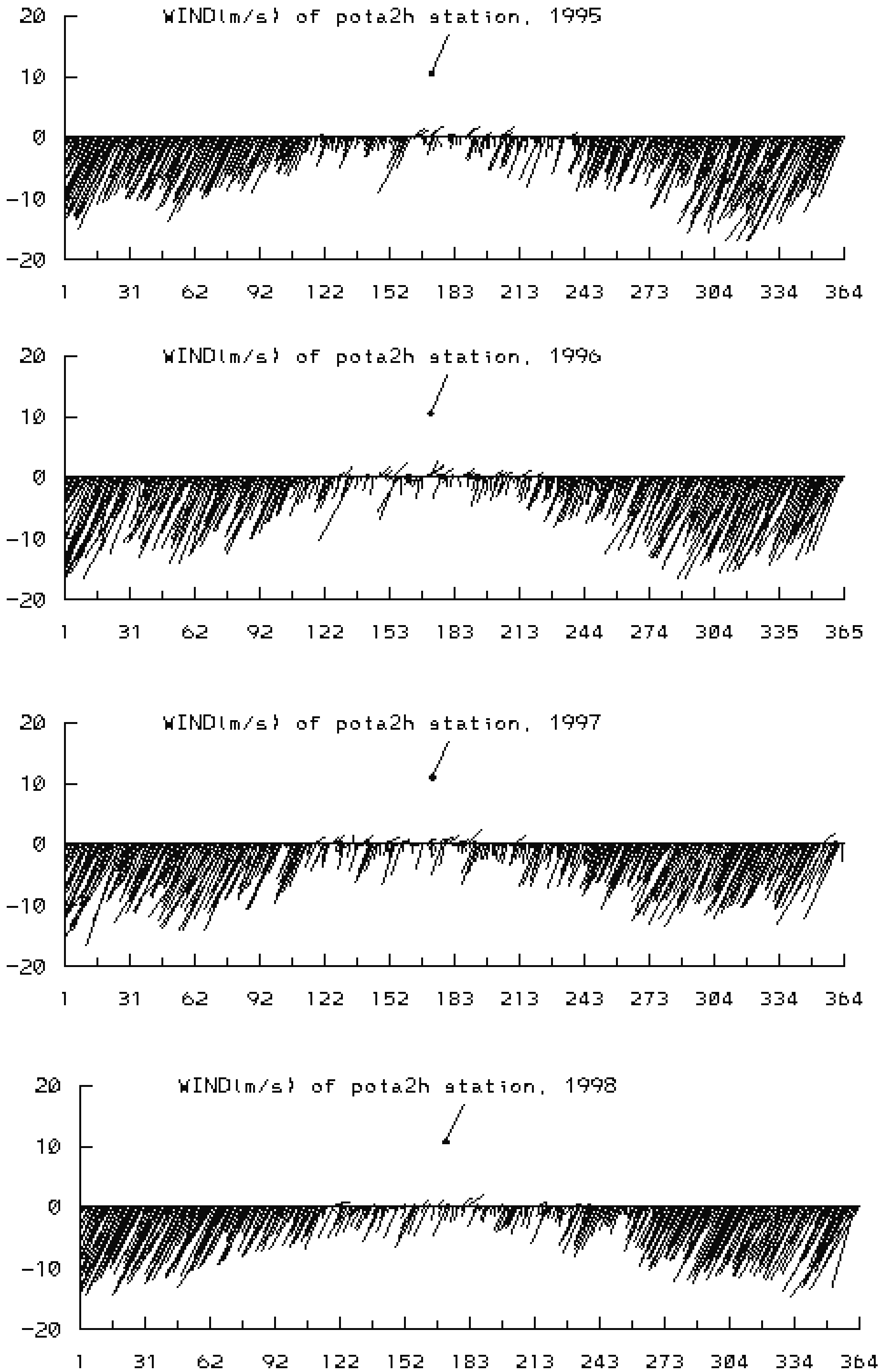


Fig. 4.4. Same as Fig. 4.1 except at Station Potato Point.

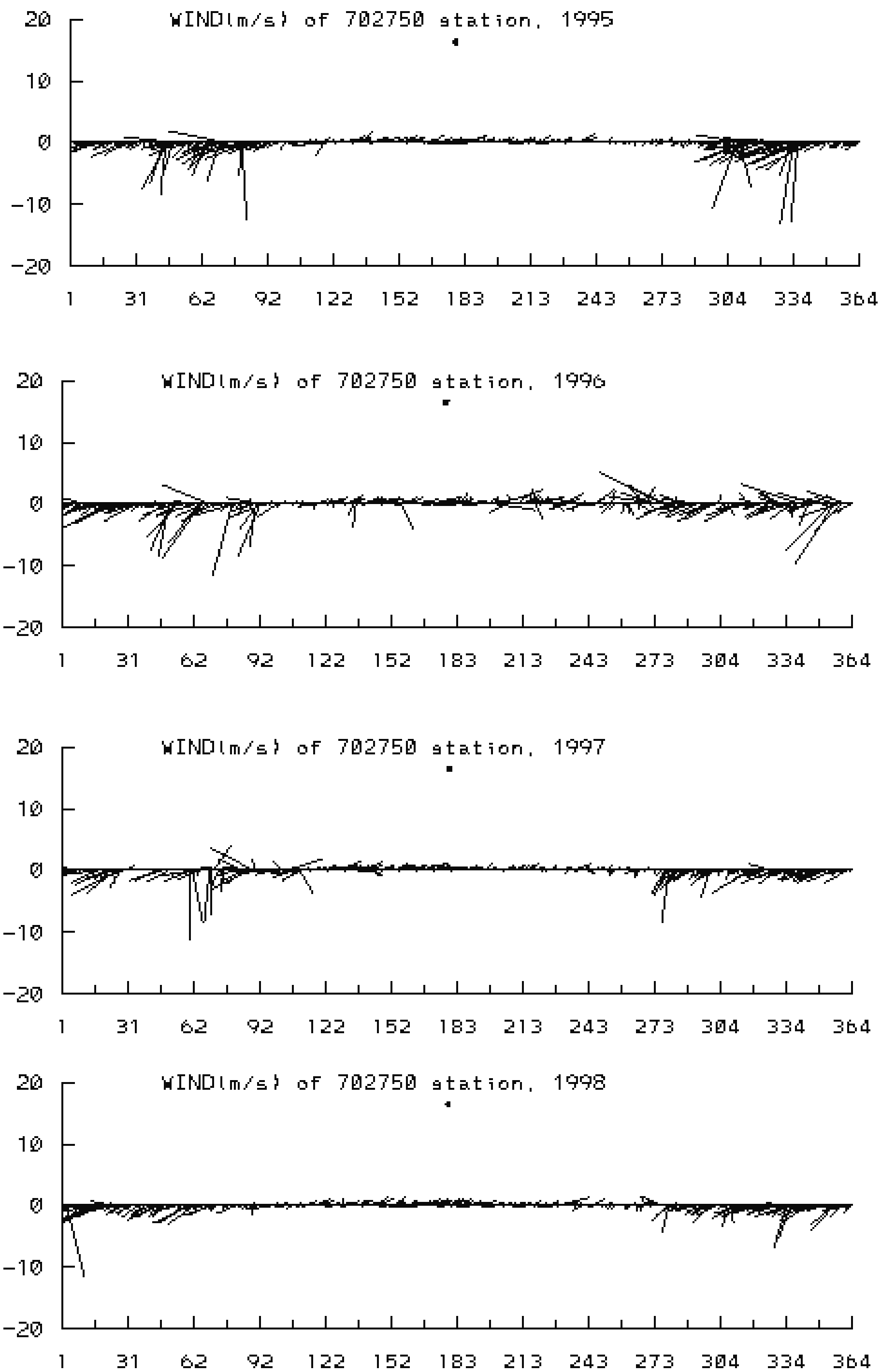


Fig. 4.5. Same as Fig. 4.1 exceot at Station Valdez.

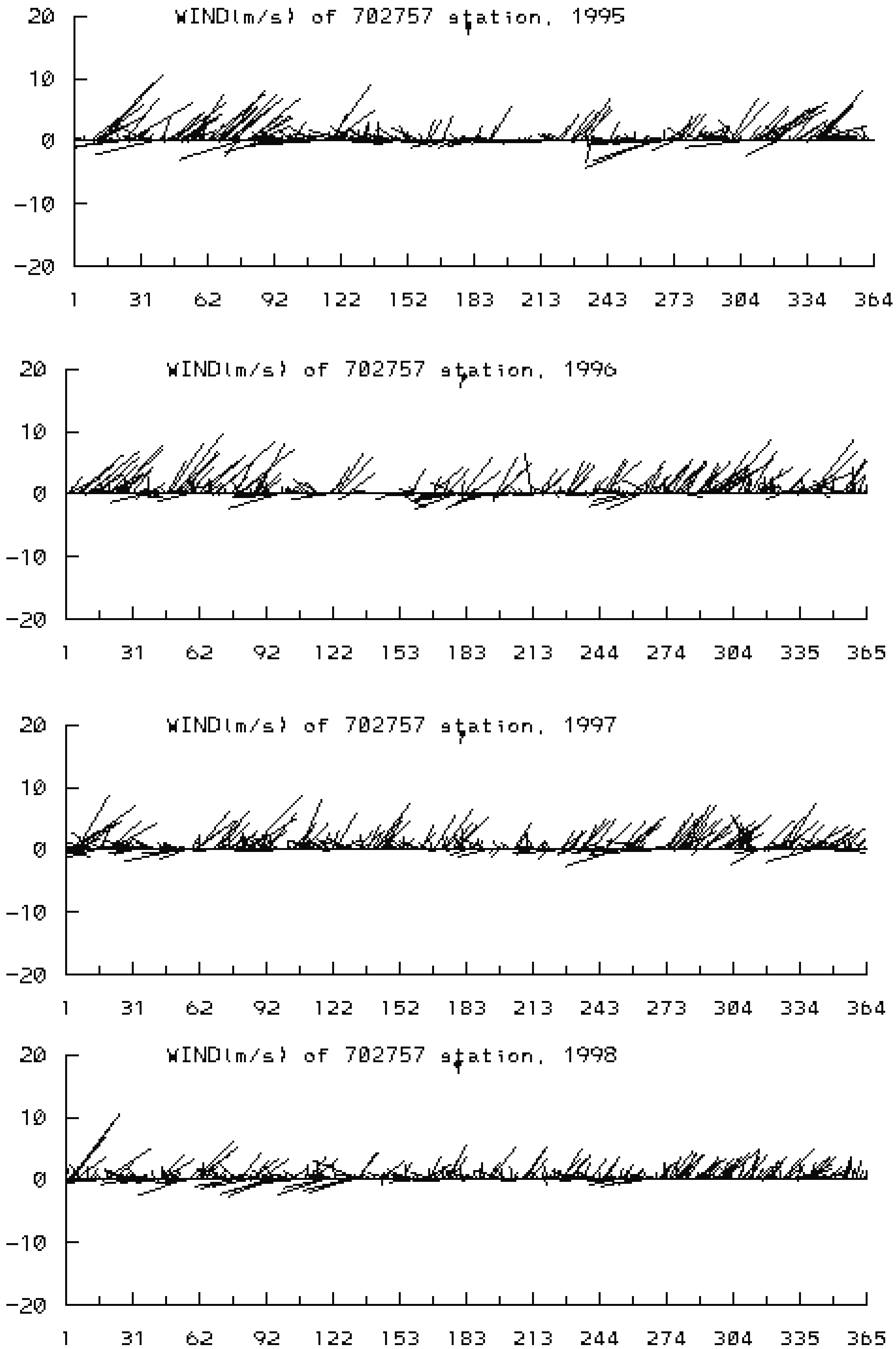


Fig. 4.6. Same as Fig. 4.1 except at Station Whittier.

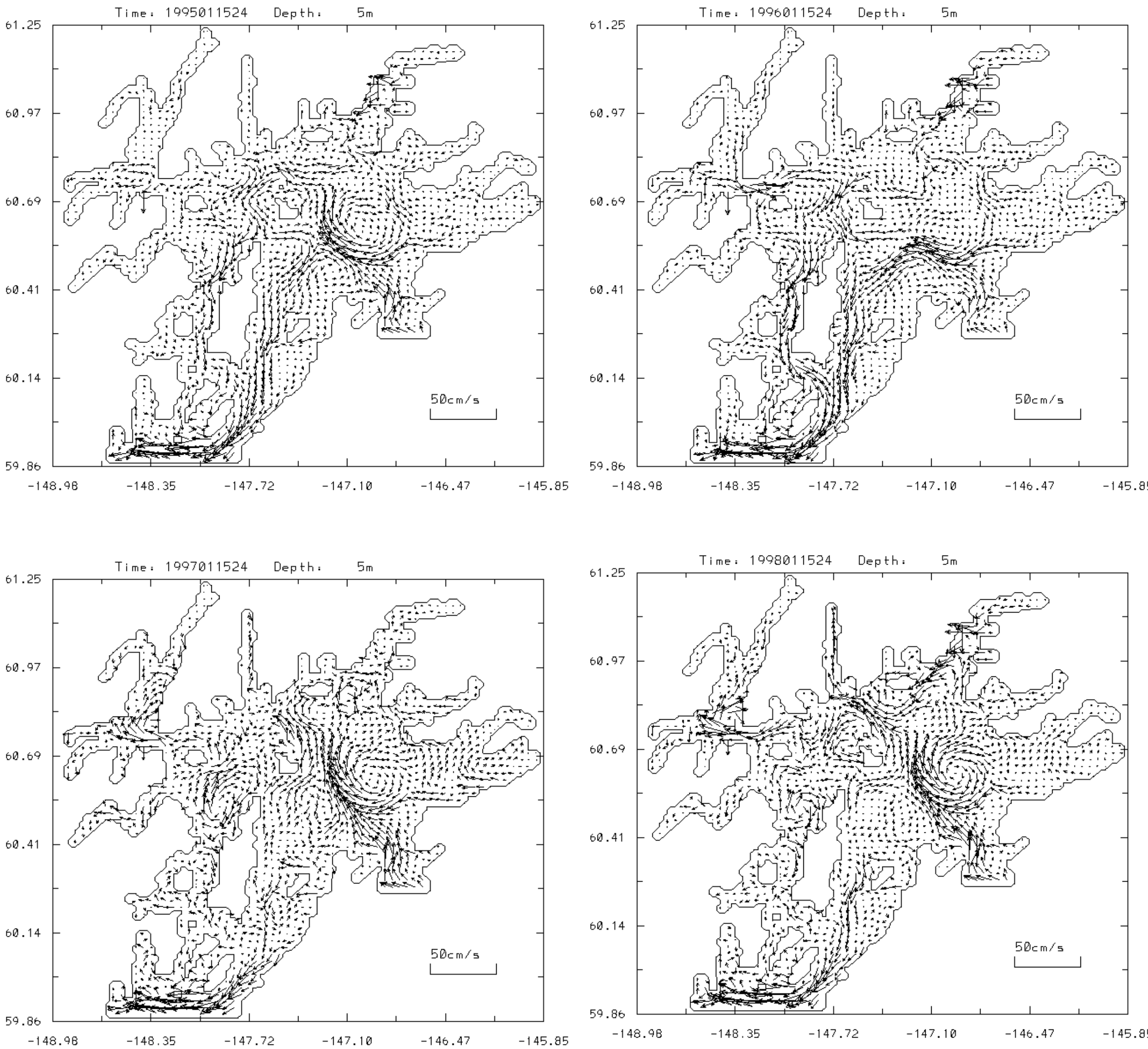


Fig. 5.1. Simulated surface circulation patterns in January of 1995 (upper left), 1996 (upper right), 1997 (lower left), and 1998 (lower right).

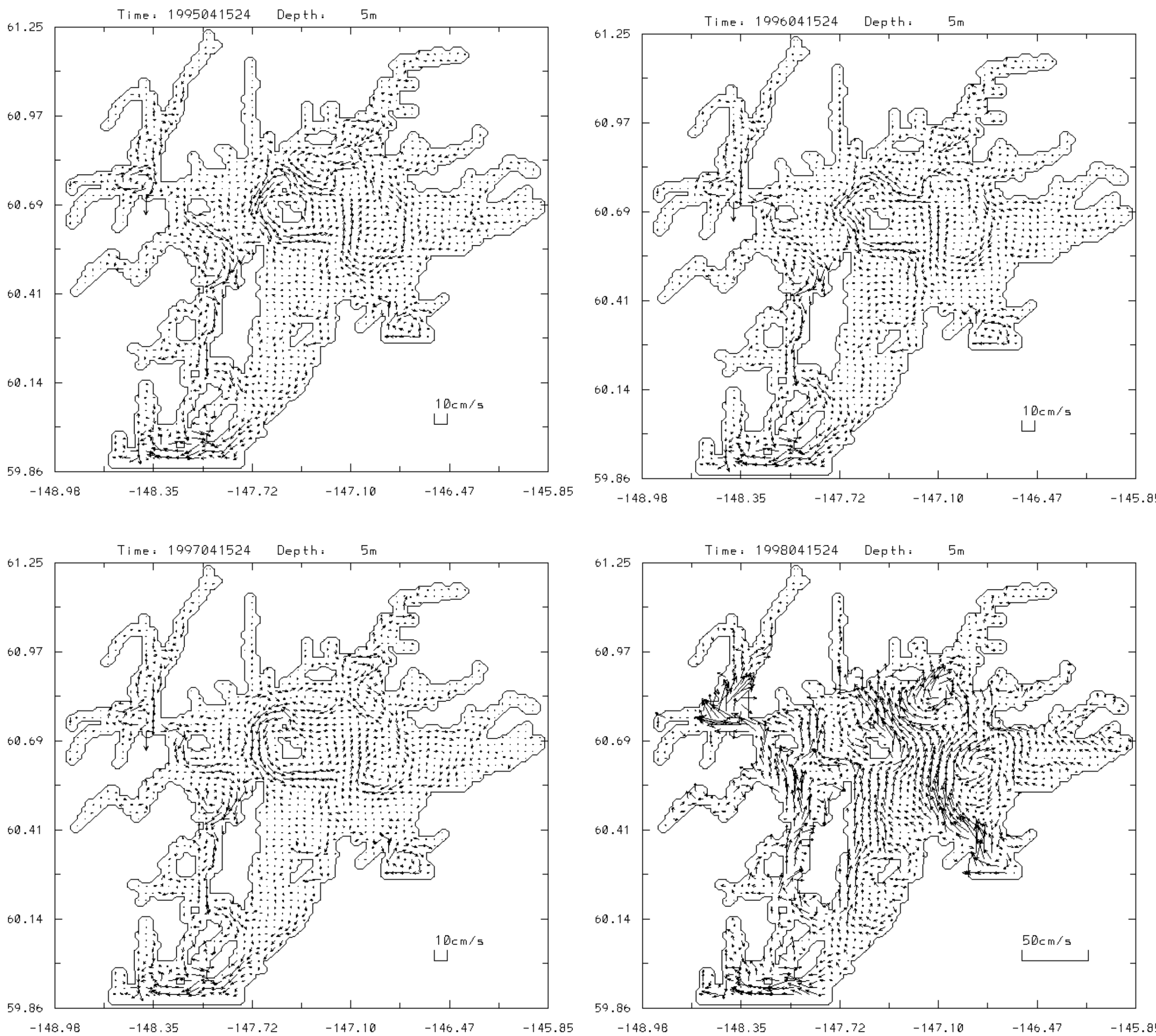


Fig. 5.2. Same as Fig. 5.1 except in April.

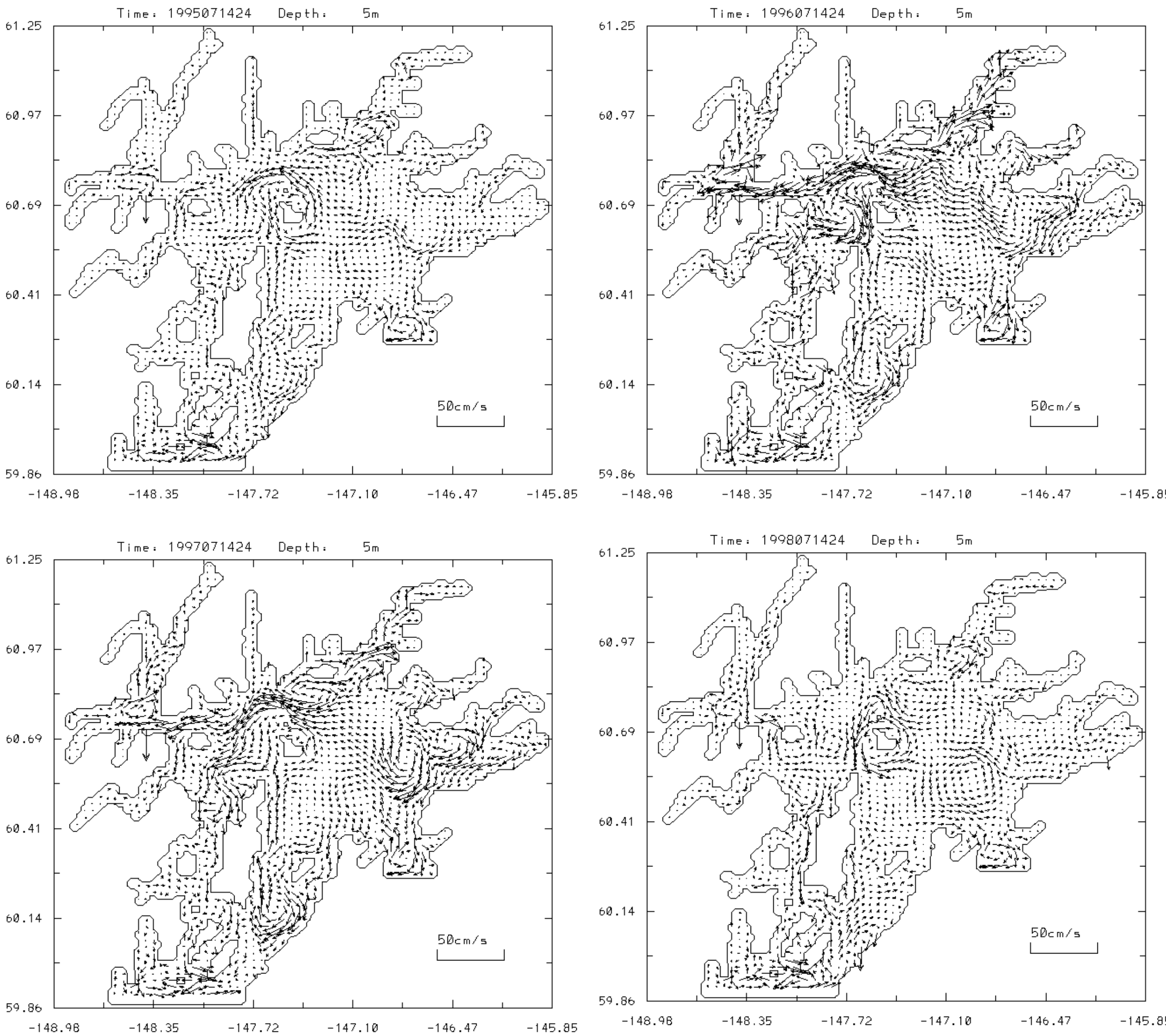


Fig. 5.3. Same as Fig. 5.1 except in July.

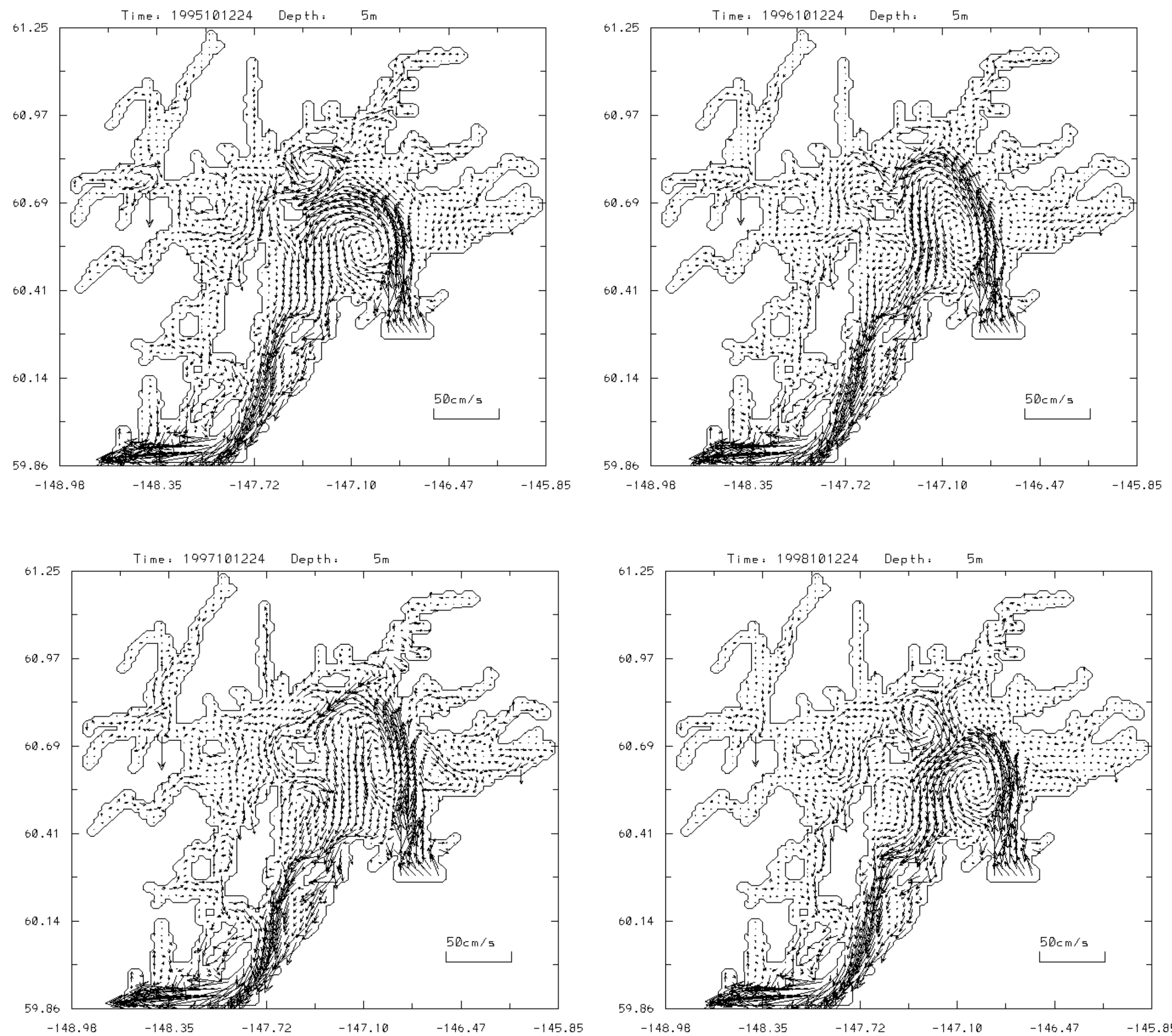


Fig. 5.4. Same as Fig. 5.1 except in October.

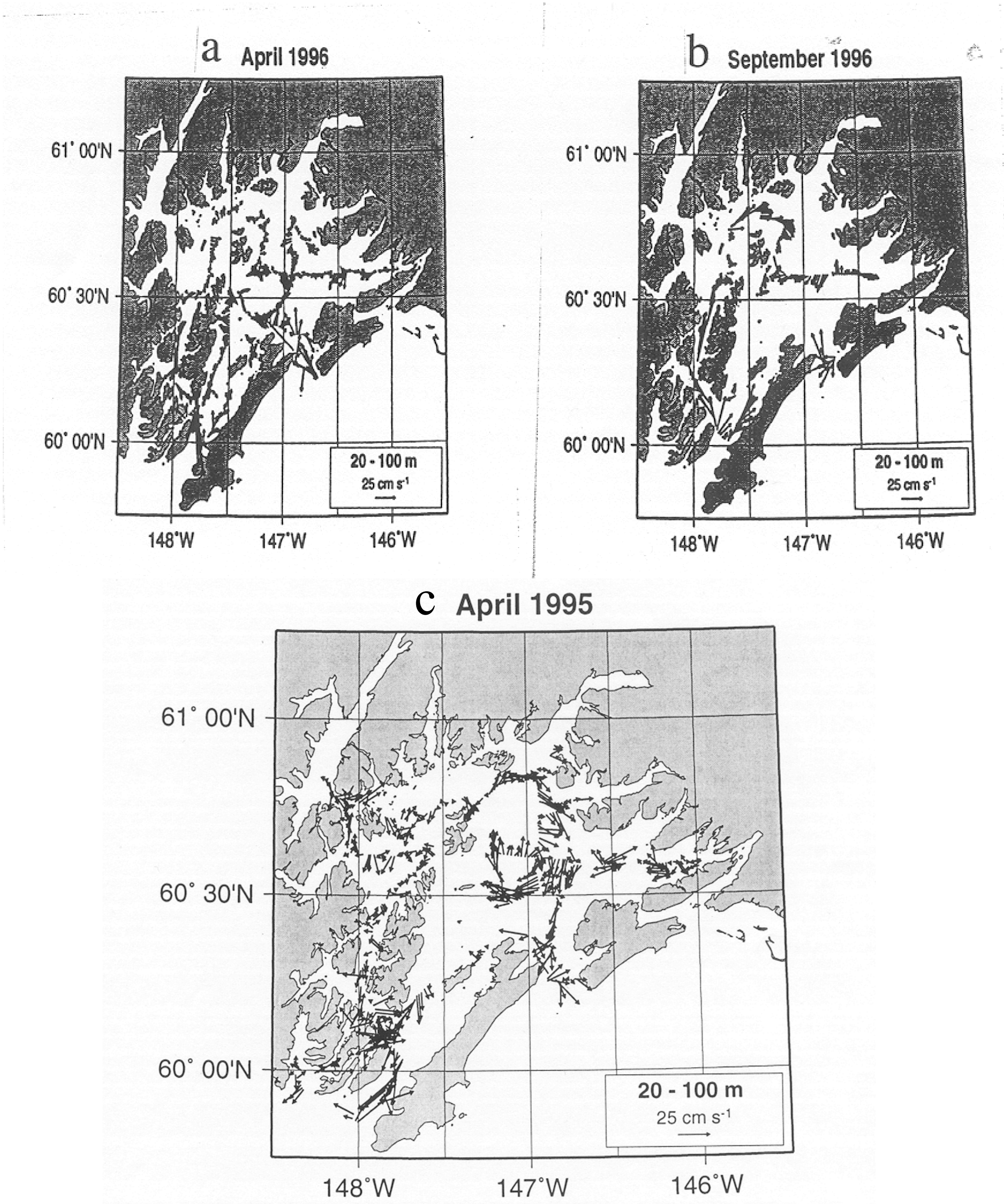


Fig. 6. Observed surface current of (a) April 1996, (b) September 1996, and (c) April 1995 (from Vaughan et al., 1997).

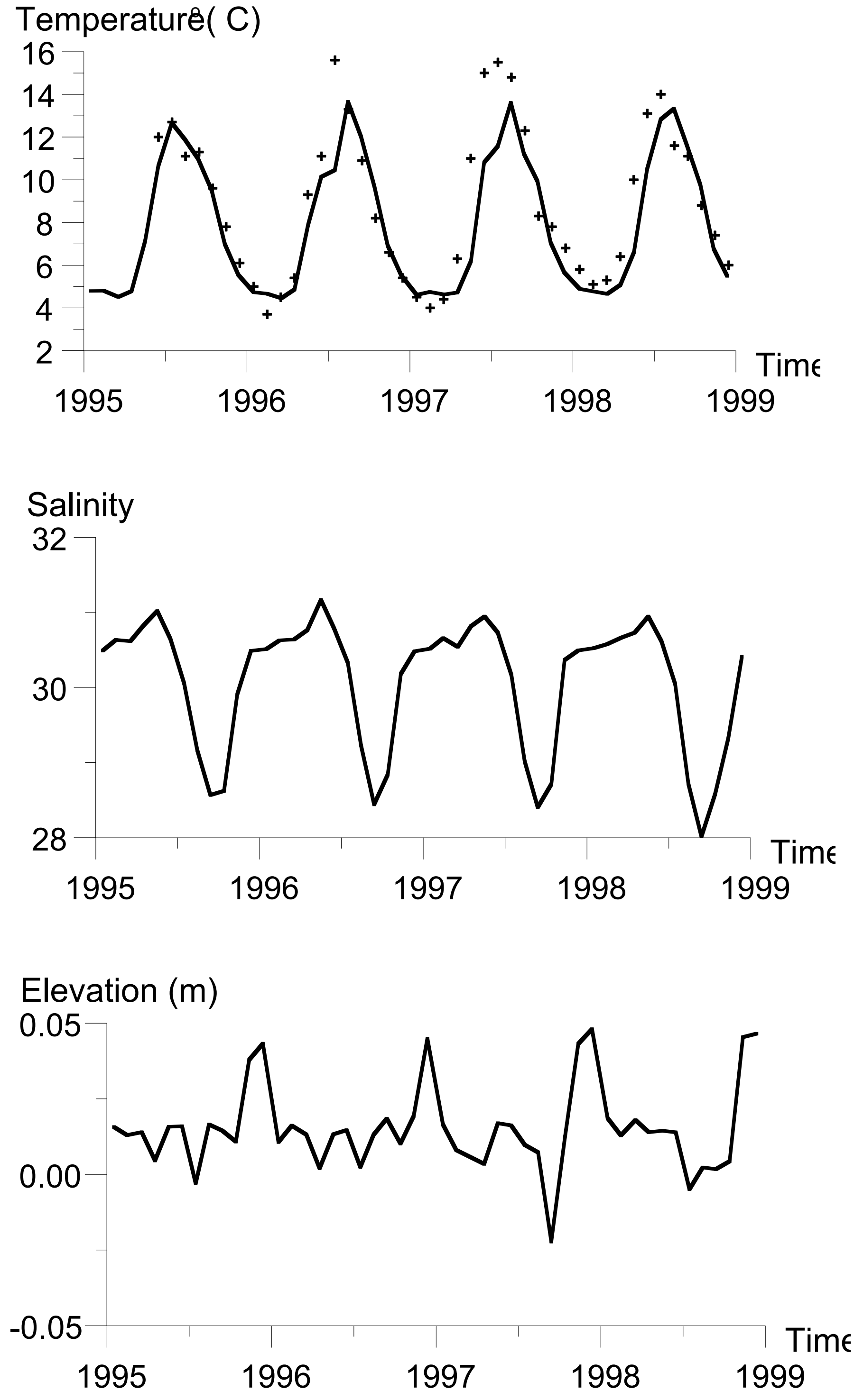


Fig. 7. Monthly mean sea surface temperature (top), salinity (middle) and elevation (bottom) at Station 46060. Solid-simulated, dotted-observed.

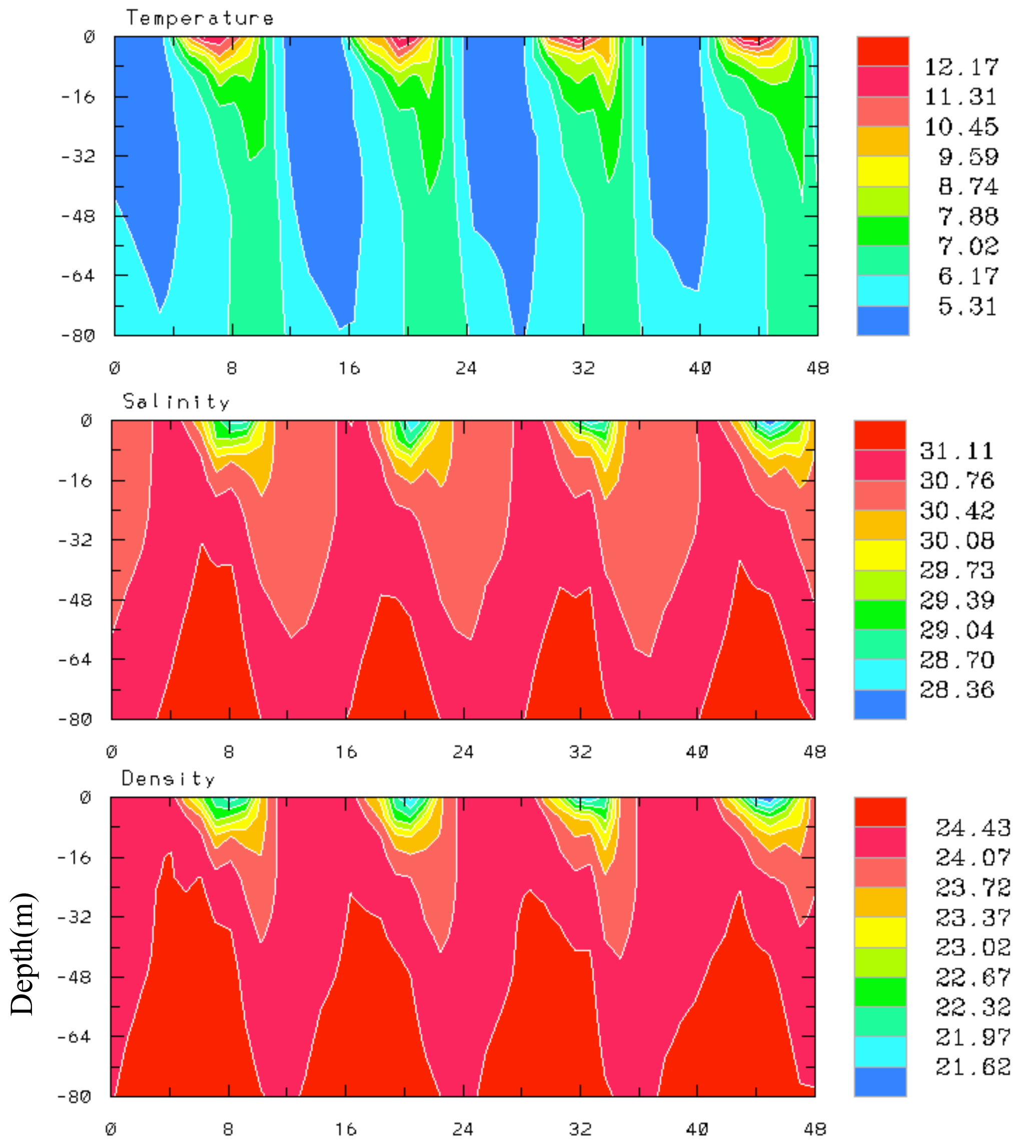


Fig. 8. Simulated temperature (top), salinity (middle) and sigma-t (bottom) time series vs. depth at Station 46060.

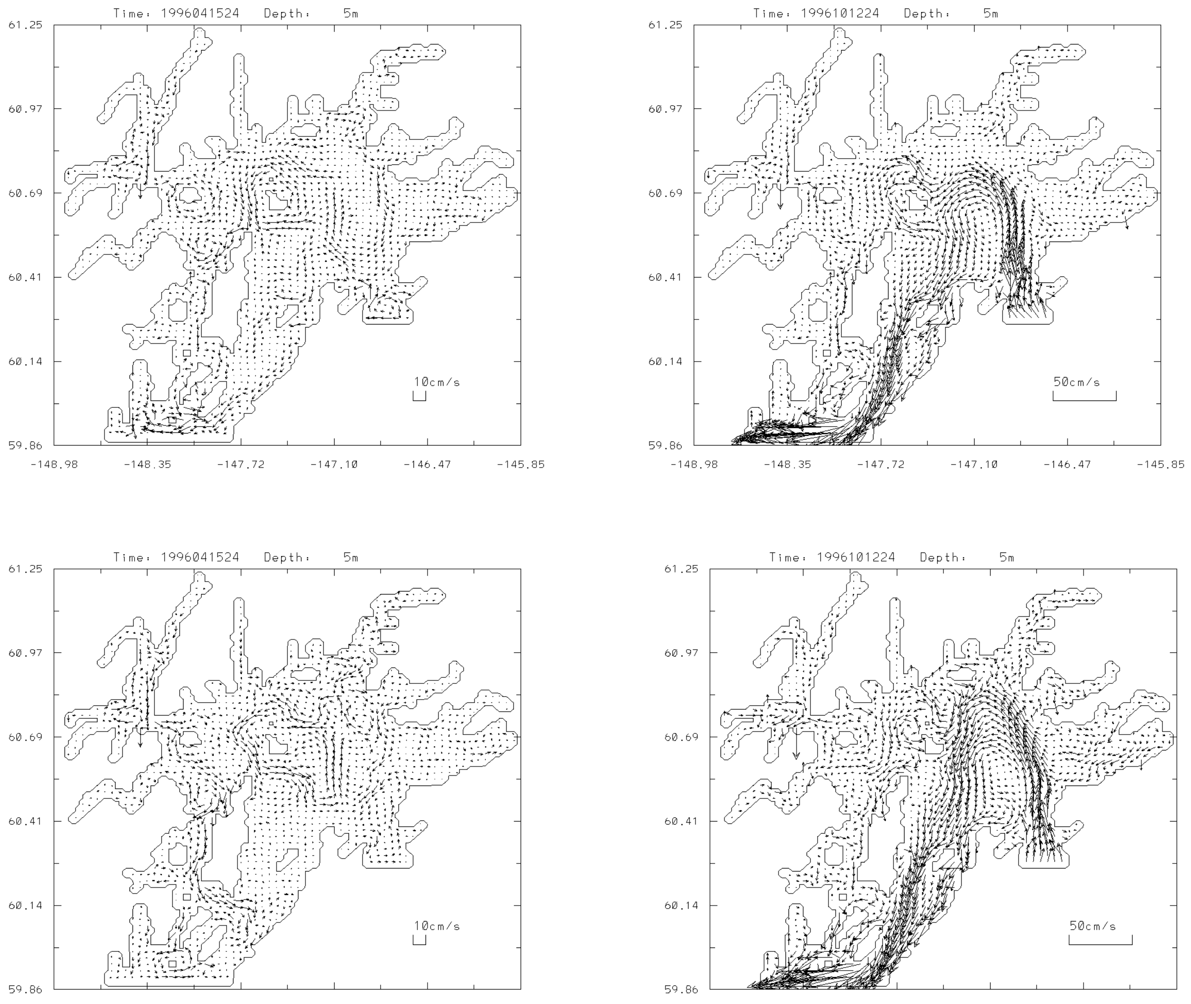


Fig. 9. Surface circulation in April (left panel) and October (right panel) of sensitivity study case 1(no wind, upper panel) and case 2 (no tide, lower panel)

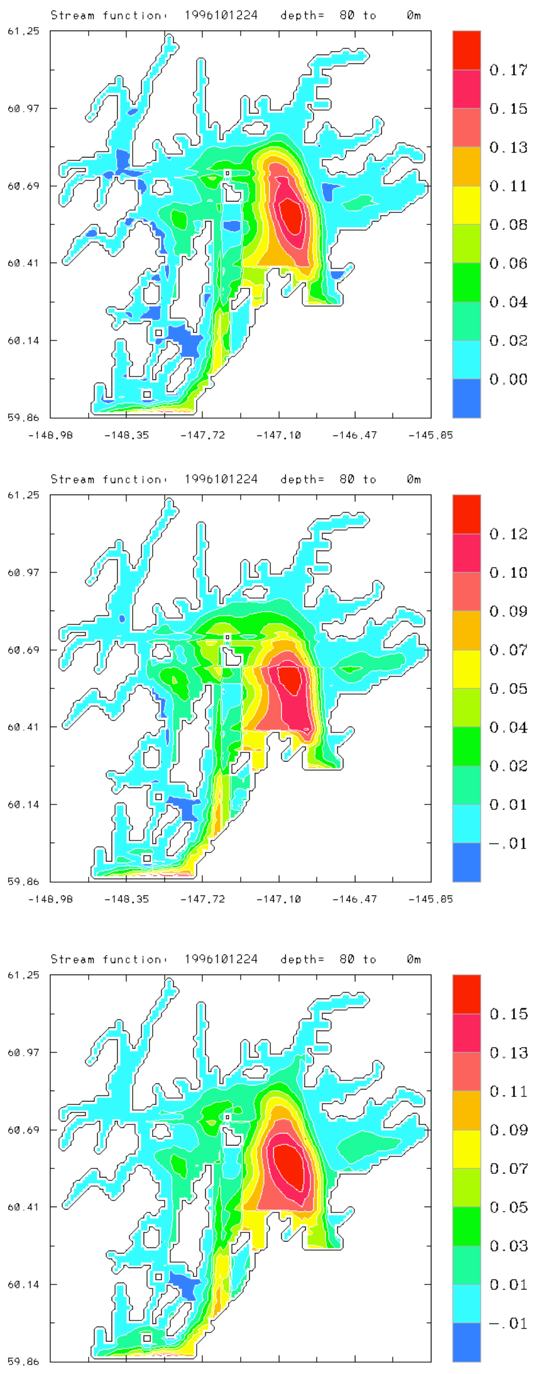


Fig. 10. Depth (0m – 80m)-averaged transport in October of control run (upper panel) and sensitivity study case 1 (no wind, middle) and 2 (no tide, lower panel).

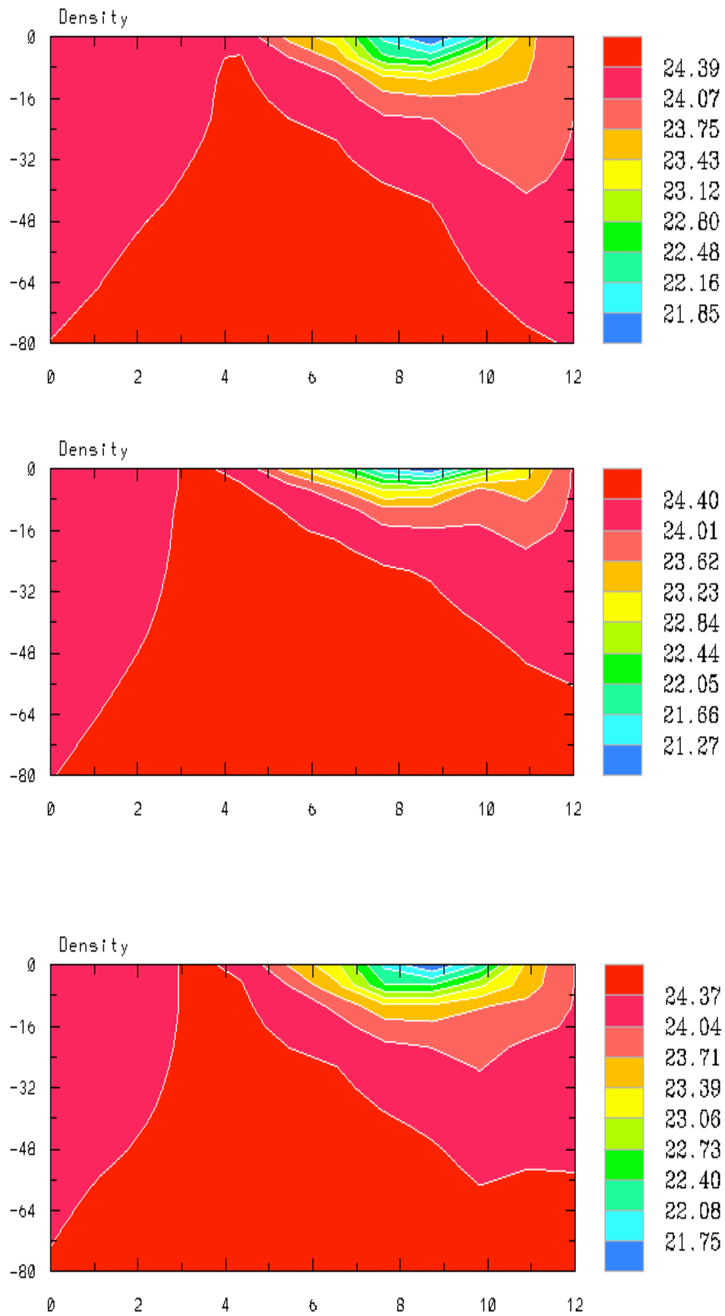
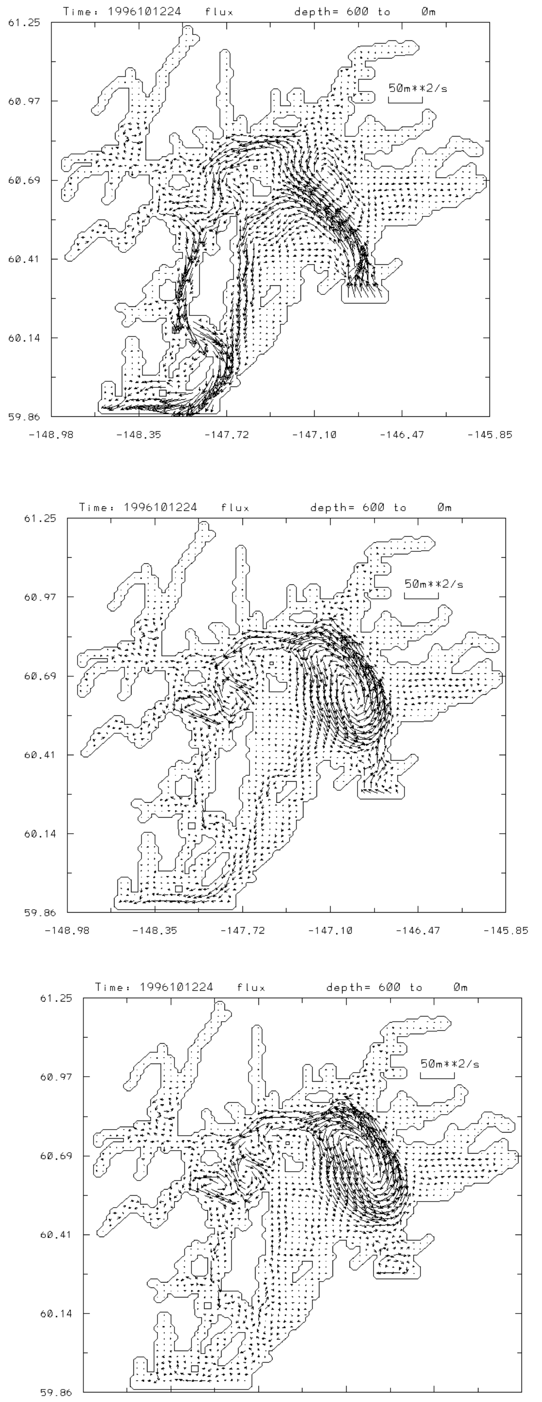


Fig. 11. Density time series of control run (upper) and sensitivity study case 1 (no wind, middle) and case 2 (no tide, lower) at Station 46060.



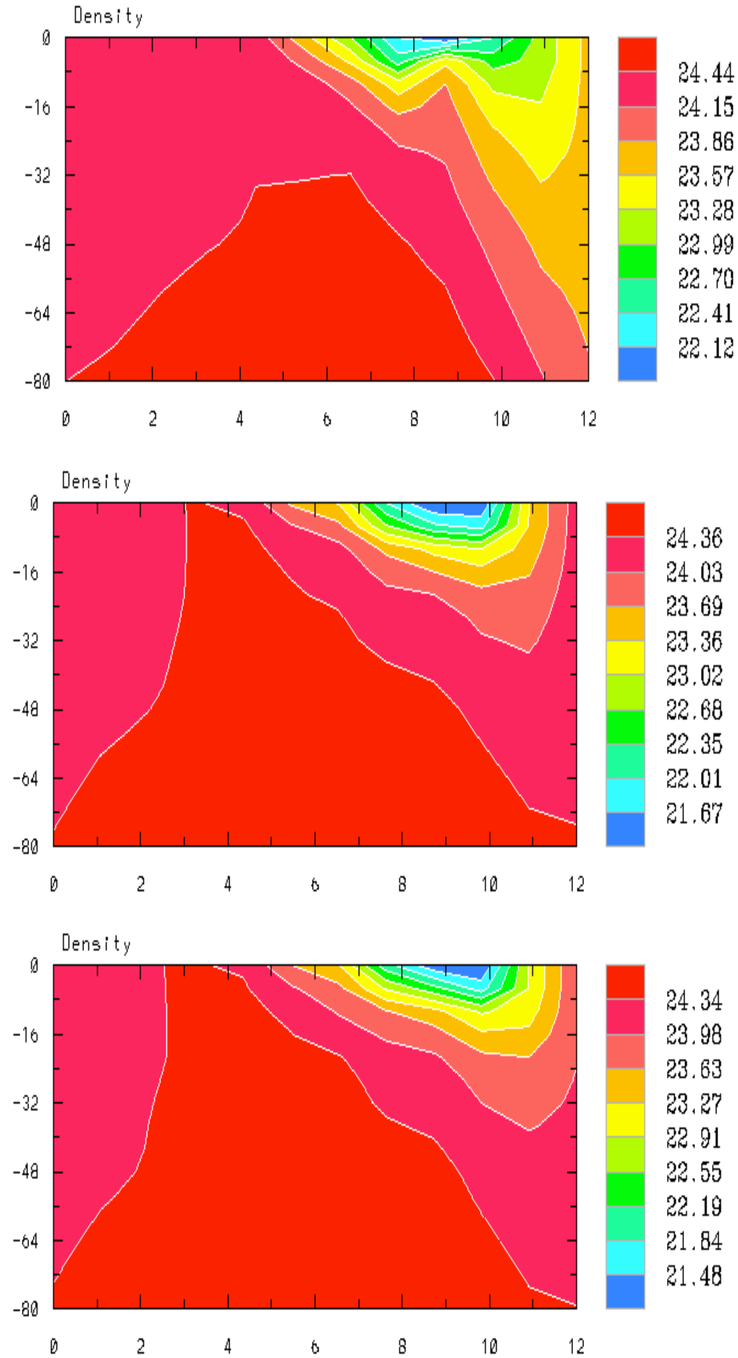


Fig. 12. Depth-integrated transport (m^2/s) of sensitivity study cases 3 (double ACC, upper), 4 (half ACC, middle), and 5 (no ACC, lower panel) in October.

Fig. 13. Vertical density time series of sensitivity study cases 3 (double ACC, upper), 4 (half ACC, middle), and 5 (no ACC, lower panel) at Station 46060.

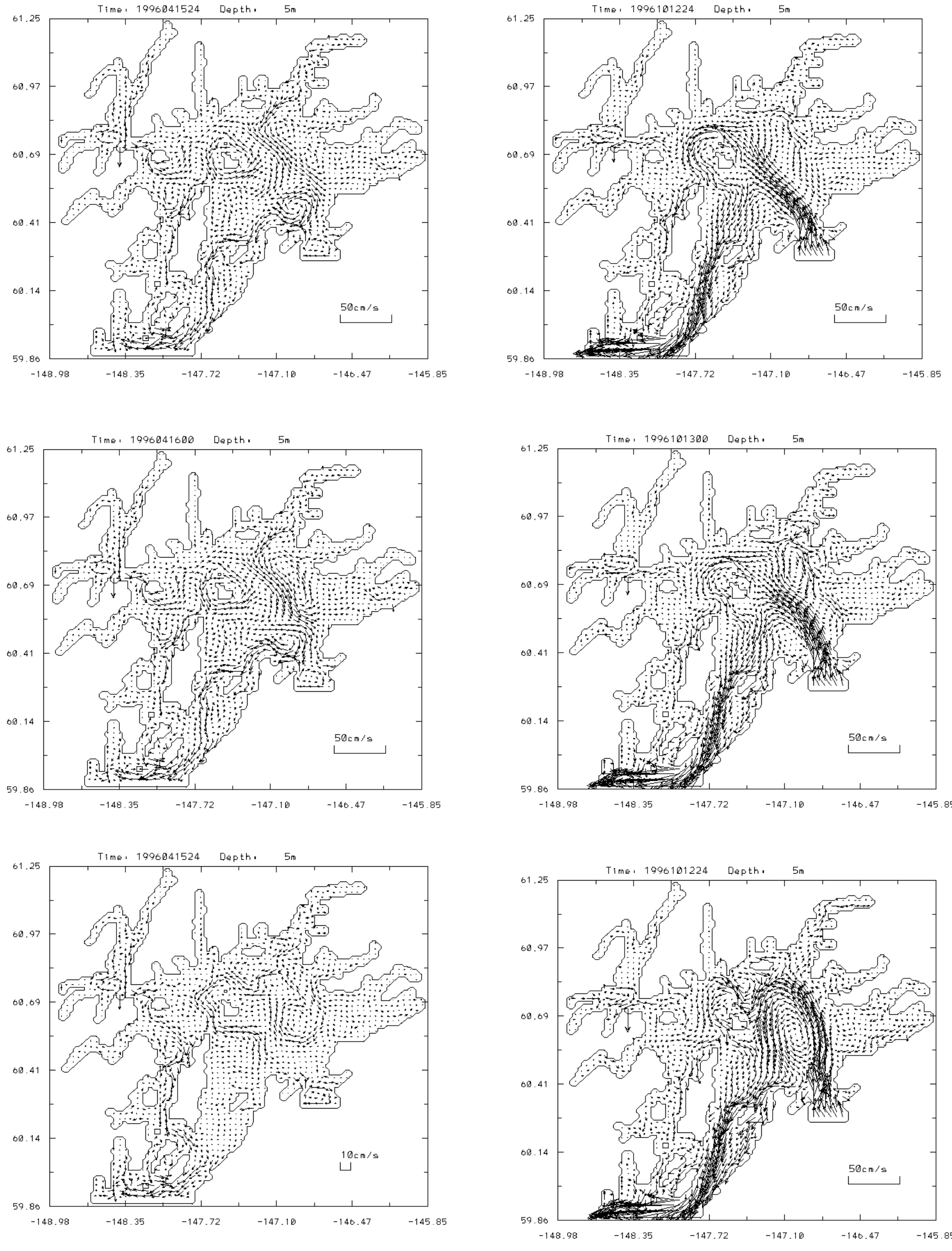


Figure 14. Simulated surface circulation of case 6 (no restoring), 7 (restoring T only) and 8 (restoring S only) in April (left column) and October (right column).

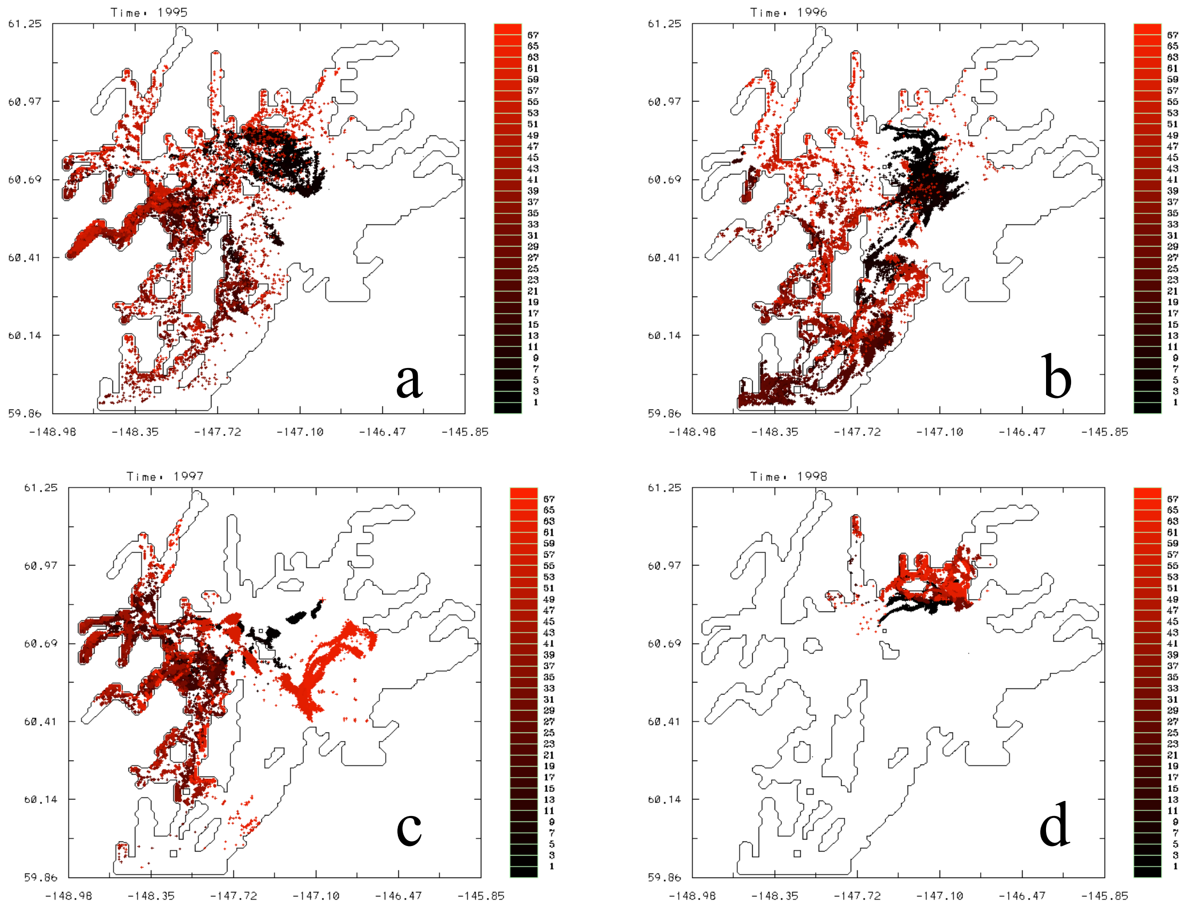


Fig. 15. Simulated oil spill tracks of a) 1995, b) 1996, c) 1997, and d) 1998. "+" is releasing position, color bar denotes the days from release.