Ship Drift Analysis for the Northwest Olympic Peninsula and the Strait of Juan de Fuca

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Hazardous Materials Response and Assessment Division
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Modeling and Simulation Studies Branch
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Contents

Figures

Figures continued

Abstract

The United States Coast Guard (USCG) is studying a Tug of Opportunity System (TOS) in the Strait of Juan de Fuca and the Olympic Coast National Marine Sanctuary (OCNMS) to formalize the practice of commercial vessels coming to the assistance of another vessel in distress. A critical part of such a system is determining what "response time" might be required to ensure that a vessel under distress does not drift aground while waiting for assistance. This report provides results from ship-drift analyses conducted to determine the probable threat distribution for disabled vessels inside the western Strait of Juan de Fuca and off the Northwest Olympic Peninsula. Using archived surface wind data from meteorological stations off Cape Elizabeth (Washington), La Perouse Bank and Race Rocks (British Columbia), 12-hour periods of winds were randomly sampled to represent the climatology during the fall, winter, spring and summer seasons. Hydrodynamic models were used to generate current patterns for the coastal currents off Vancouver Island and Washington as well as the flow within the Strait. Historical oceanographic data and predicted tidal currents were used to scale these patterns. Vessel drift factors were determined from surveys of actual drifts reported by ships. The ship drift analysis is summarized in maps showing 12-hour probability distributions.

Introduction

In response to a request by the USCG, the Hazardous Materials, Response and Assessment Division (HAZMAT) of the National Oceanic and Atmospheric Administration (NOAA) has completed an analysis for vessels adrift in the Strait of Juan de Fuca and off the Northwest Olympic Peninsula. The intent of this analysis is to provide probable ship-drift locations within 12 hours of a vessel becoming disabled. This analysis is based on climatology. It should also be pointed out that this analysis is for ship drift only and makes no presumptions about on-board mitigation using rudder controls, ballast re-distribution, anchor deployment, or TOS response times.

The trajectory model selected to simulate the movement of a disabled vessel, the On-Scene Spill Model (OSSM) (Torgrimson 1984), and the hydrodynamic models, Diagnostic Analysis of Currents (Galt 1980) and Wind-driven Analysis of Currents, were designed by NOAA. Since the initial field test during the IXTOC I well blowout in 1979, the models have been used extensively by NOAA to provide tactical support to the USCG and industry for accidental discharges of oil. In addition, the models have been used for search and rescue operations and tracking disabled vessels.

Section 1 discusses the procedure for identifying the initial sites for ship drift. A complete description of OSSM will not be provided here. However, the basic trajectory modeling procedure, including winds, currents, and ship-drift factors, are important for understanding the analysis. These aspects are discussed in Section 2. In Section 3, the output from the model simulations are analyzed and interpreted with the results summarized as 12-hour probability distributions for accidents occurring at each of the selected sites. Section 4 contains a summary of the analysis and a discussion of the likelihood that a vessel drifting from selected sites would come ashore within a 12-hour period.

1.0 Site Selection

The sites used for this study were not selected as a result of any formal risk analysis. Site locations were selected based on the competing criteria of minimizing, for computational purposes, the number of sites while still providing an adequate representation of the probability distribution for drifting vessels in the region. A total of five sites were selected for analysis; three sites within the vessel traffic lanes in the Strait of Juan de Fuca and two sites off the Northwest Olympic Peninsula. Figure 1 shows a map of the study area and the five sites identified for analysis.

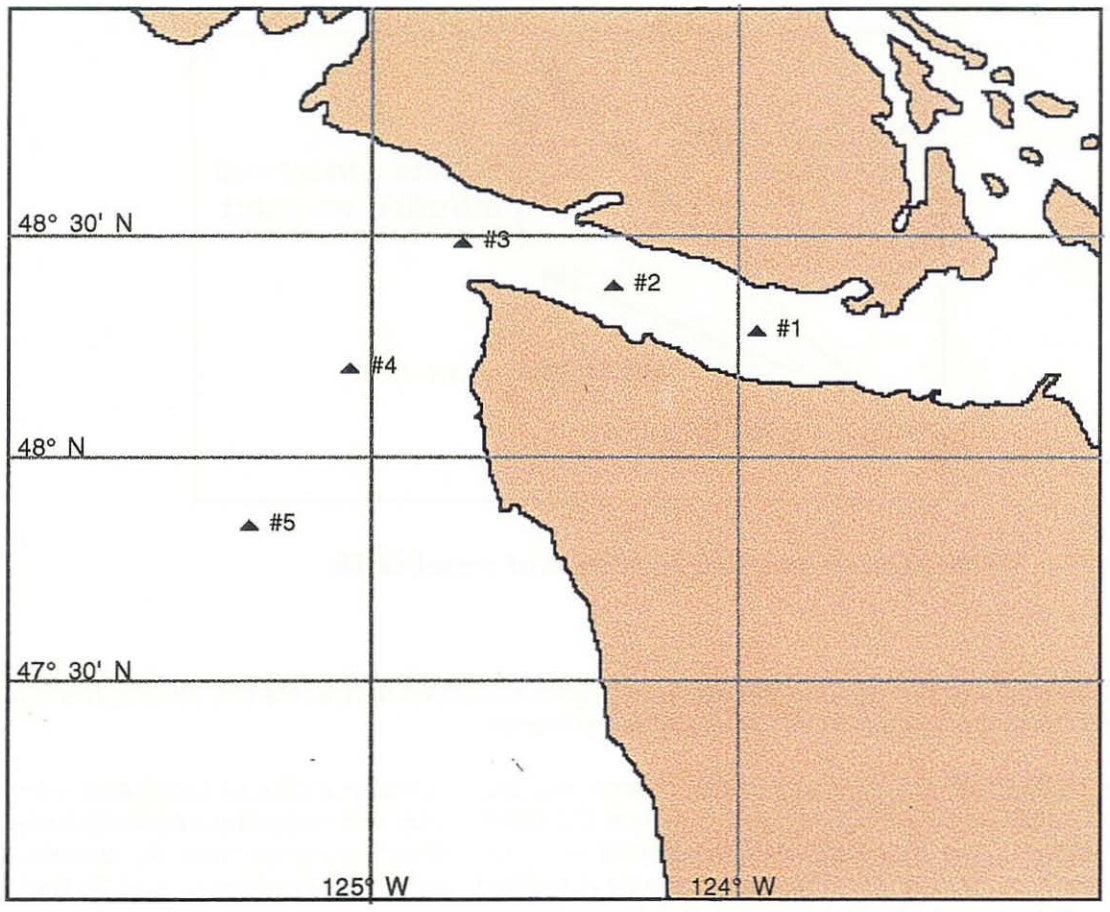

Figure 1. Map of study area and sites selected for ship drift analysis.

2.0 Modeling Procedure

OSSM and many other models, use a Lagrangian element (LE) method to simulate the movement of a drifting vessel. During the model simulations, a single instance of a drifting ship is represented by one particle or LE. Variations in ship characteristics such as size, shape, list, and orientation of the vessel are represented by varying the LE drift factors. In OSSM, the total movement of the particle is calculated as the sum of the wind (using ship-drift factors for windage and drift angle), surface current, and a turbulent diffusion parameter representing small-scale fluctuations in the currents (Figure 2).

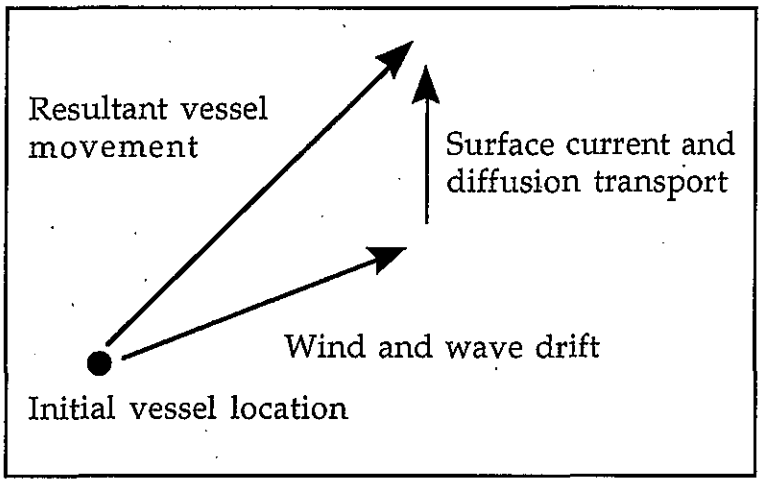

Figure 2. Vector diagram showing movement of vessel adrift.

The movement of the floating particles, or trajectories, then represents the general trend and variability in the winds, waves, and surface currents.

The intent of this analysis was to run trajectories that started at different times and were subject to different conditions and combine the results into a 95 percent probability zone for each season. This required that the trajectories span different seasonal weather, current, and windage conditions. This was done by running trajectories of independent LEs that had their own wind histories and surface current histories.

As shown in Figure 3, the development of this analysis required a number of different pieces. Literature searches were conducted to determine the suitable wind-drift factor ranges for disabled vessels and the seasonal mean surface currents for scaling the current patterns generated from the hydrodynamic models. Additionally, potential sources of surface-wind data were identified, acquired and translated into a format suitable for the trajectory model, OSSM. After the appropriate data were entered into OSSM, 120 model simulations (each of which included 2,000 statistically independent realizations) were run. Each of the simulations was then analyzed for the 95 percent probability contour using the Trajectory Analysis Tool (TAT).

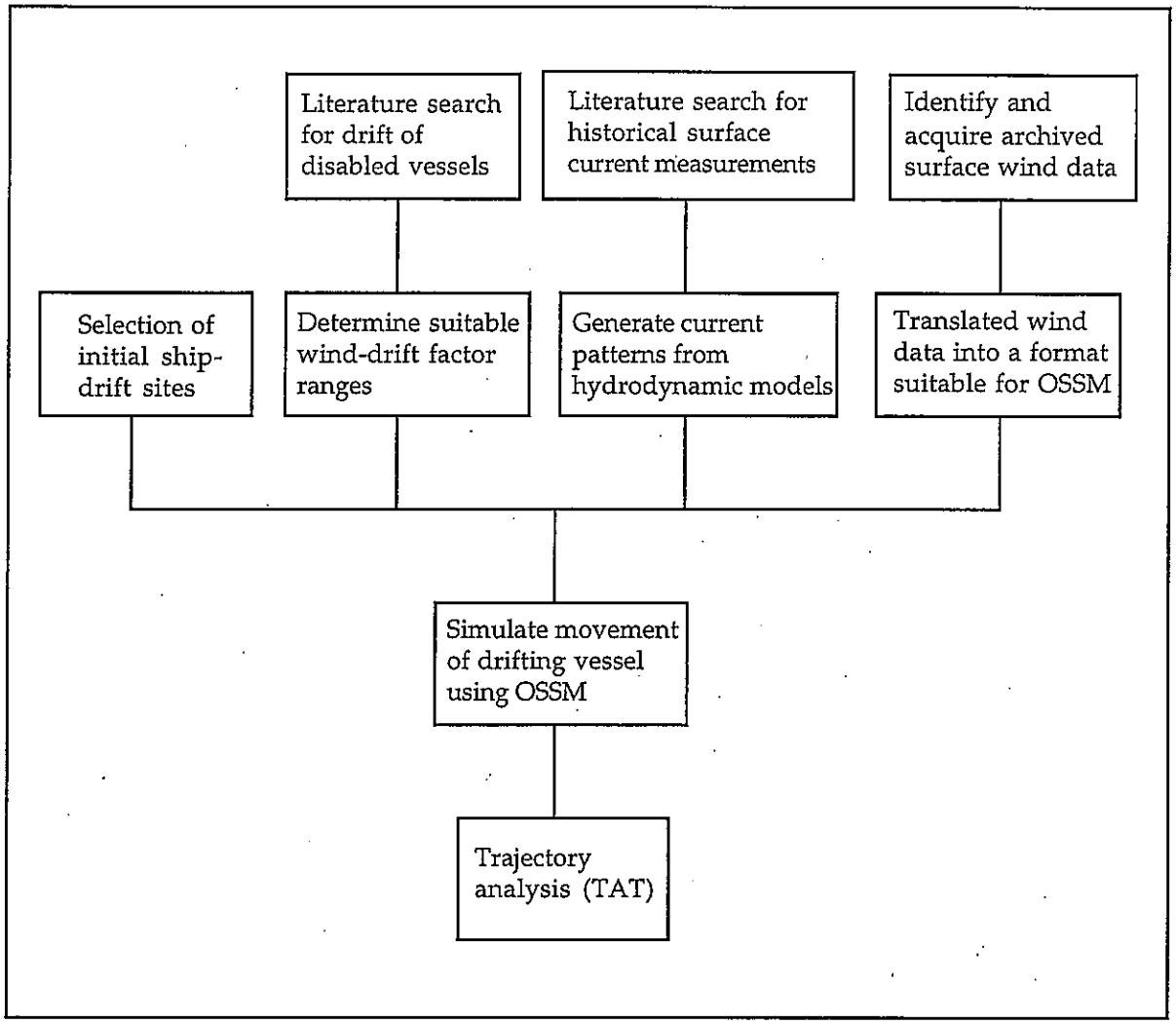

Figure 3. Flow chart for trajectory analysis.

2.1 Winds

Bourke and Glenne (1971), Hickey (1980), and Thomson (1981) analyzed the seasonal wind patterns for the Washington coast and indicated the patterns depended on the locations and strengths of two atmospheric pressure cells: the North Pacific high and the Aleutian low. Each summer, a high-pressure cell centered to the west of the northern California coast reaches its maximum intensity. Since the coastline is to the east of the high's center, winds off the Washington coast are predominantly from the northwest. During the winter season, the high-pressure cell weakens and moves southward. Southwest of the Aleutian Islands, a low-pressure cell intensifies and generates predominantly southwesterly winds off the coast. Spring and fall are transitional periods: the winds are typically weaker and variable during these seasons with changes in the local winds field occurring rather abruptly.

Archived data from the National Climatic Data Center and Environment Canada were reviewed for areas off the northwest Olympic Peninsula and the Strait of Juan de Fuca. To

ensure that the wind data contained a sufficient number of independent records, only stations with hourly archived data for at least 7 years were considered in the analysis. Because the winds have a sizable effect upon the movement of a drifting vessel, it is important that the archived wind data represent the wind field over the study area as closely as possible.

There have been 15 permanent meteorological stations deployed along the Strait of Juan de Fuca (NOAA 1976). However, many of the stations are located at the eastern end of the Strait and in northern Puget Sound, outside of the study area. In addition, our criteria for selecting stations with long records limited the sites within the Straits to Race Rocks Light and Tatoosh Island.

Initially, Tatoosh Island appeared ideally located for depicting the wind field over the study area. It is situated near the entrance of the Strait of Juan de Fuca just off Cape Flattery. However, Tatoosh Island is sheltered to the southeast by the higher mainland. As a result, the historical data collected from the site is questionable as an indicator of the surface winds inside the Strait (NOAA 1976). During the summer season, the winds from Tatoosh Island indicate southerly flow. Data from sites farther offshore indicate primarily northwest winds and sites farther inside the Strait, easterly. Because the summer winds from Tatoosh Island are not representative of either the flow offshore or inside the Strait, the data were not used in this analysis.

Race Rocks Light is located on a small island 1.5 nautical miles (NM) off the southeast portion of Vancouver Island. According to NOAA (1976), exposure to the wind sensor is excellent in all directions and is a useful indicator of the east-west flow through the Strait and winter northerlies. Because the island is located near the eastern end of the Strait, winds are likely to show a stronger northerly component than areas to the west.

The Race Rocks data set used in the analysis contains 8 years of data and extends from January 1988 to December 1995. Figures 4 and 5 show the speeds, directions and percent occurrence of winds observed for 8 years in January and July. A climatic summary of the winds from Race Rock Light for January show that the dominate wind direction is from the north-northeast and northeast with the respective frequencies of occurrence 22 percent and 18 percent. The strongest wind speeds, 41 to 47 knots, tend to occur when the winds are from the west-southwest and west. July data shows that westerly winds occur nearly 62 percent of the time. The strongest wind speeds, 34 to 40 knots, also occur when the winds are from the west and west-northwest.

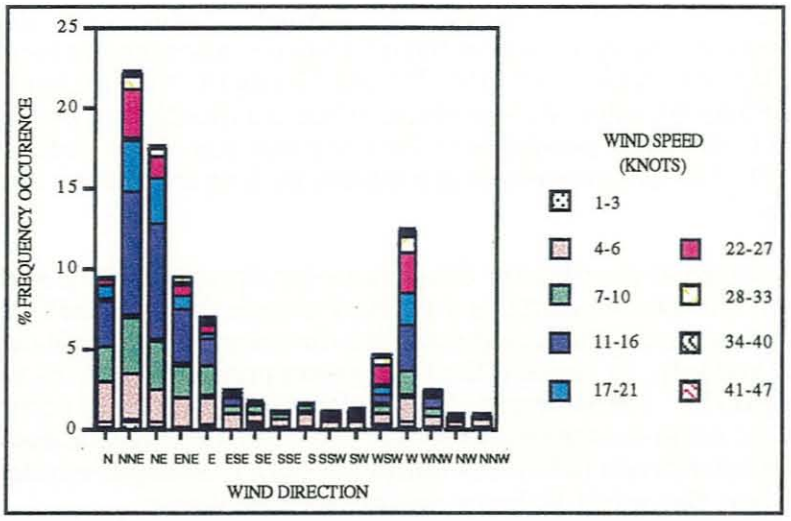

Figure 4. Percent frequency of occurrences of total observations from Race Rock Light in January.

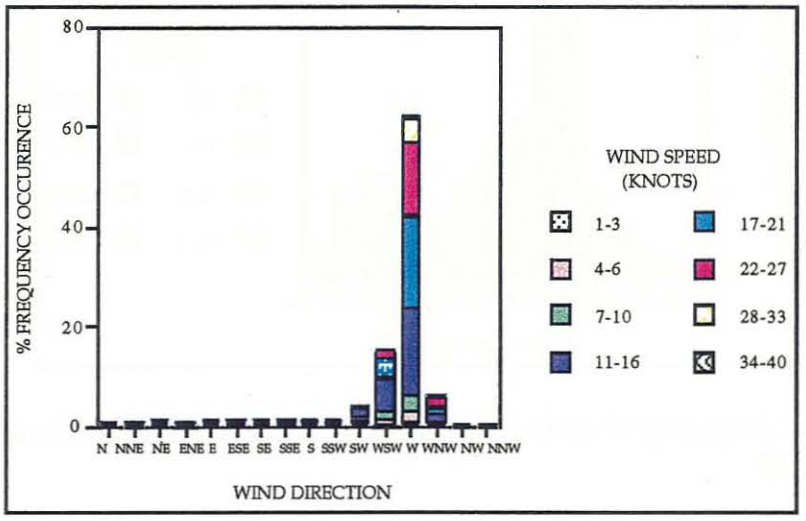

Figure 5. Percent frequency of occurrences of total observations from Race Rock Light in July.

For areas off the outer Washington coast, seven stations were identified as possible data sources: Tatoosh Island, Quillayute, Destruction Island, and Buoys 46010, 46029, and 46041. As previously discussed, the winds from Tatoosh Island are not representative of the summer offshore winds and, therefore, not used in the analysis. Bourke and Glenne (1971) have indicated that data from the Quillayute station is not indicative of winds farther offshore due to topographical influences. Buoys 46010 and 46029 were deployed off the Columbia River entrance and were considered outside the study area.

Comparison of winds from the Coastal Marine (C-Man) Station at Destruction Island and Buoy 46041 indicate that winds from both sites generally reflect the seasonal wind patterns.

Nonetheless, the winds are typically stronger at Destruction Island, particularly during the winter season. This is probably a result of the difference in anemometer heights. The moored buoy, 46041, was deployed 7 NM off Cape Elizabeth, Washington by NOAA with the Department of Interior, Minerals Management Service (MMS) support in 1987. Due to its location, the buoy is fairly representative of the wind patterns off the outer coast. In addition, the height of the anemometer is at 5 meters, making this station a good source for surface wind-data.

Buoy 46041 was selected as the primary data source for representing the winds off the outer Washington coast. The data set contains 9 years of records that extends from June 1987 to August 1996. Figures 6 and 7 indicate the speeds, directions and percent occurrence of winds for January and July. In January, the winds were primarily from the southeast (22%) and east-southeast (17%). The strongest winds, 34 to 40 knots, tend to occur when the winds were from the south-southeast and south. July data indicates the dominate winds were from the north-northwest (29%) and northwest (23%). Stronger winds, 22 to 27 knots, tend to occur when the wind is from the north-northwest.

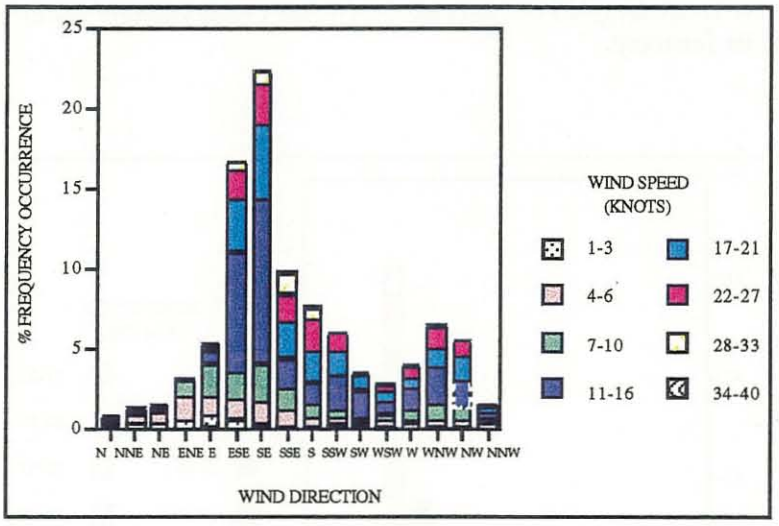

Figure 6. Percent frequency of occurrences of total observations from Buoy 46041 in January.

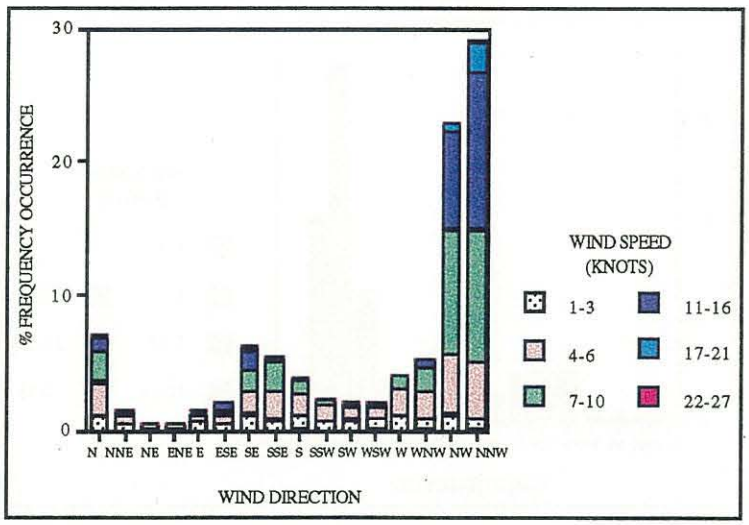

Figure 7. Percent frequency of occurrences of total observations from Buoy 46041 in July.

The study area for this analysis also included the coastal waters off Vancouver Island. A survey of offshore stations with long data records identified Buoy 46206 as the representative station for this area. The buoy is deployed approximately 35 NM west of Vancouver Island, British Columbia at La Perouse Bank. The data set contains 8 years of data extending from November 1988 to December 1995. Figures 8 and 9 indicate the frequency of occurrence for the wind directions and speed for January and July. In January, the dominate wind direction was from the east-southeast and east at 19 percent and 13 percent, respectively. The stronger speeds, 34 to 40 knots, occurred when the winds were from the south-southeast and east. For July, west-northwest winds tend to dominate with 35 percent of the occurrences. The stronger winds, 28 to 33 knots, also tend to occur when winds are from the west-northwest.

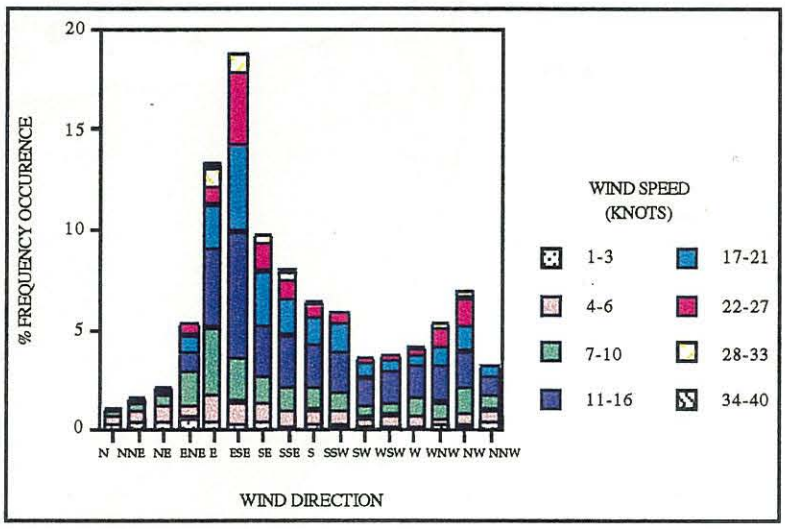

Figure 8. Percent frequency of occurrences of total observations from Buoy 46206 in January.

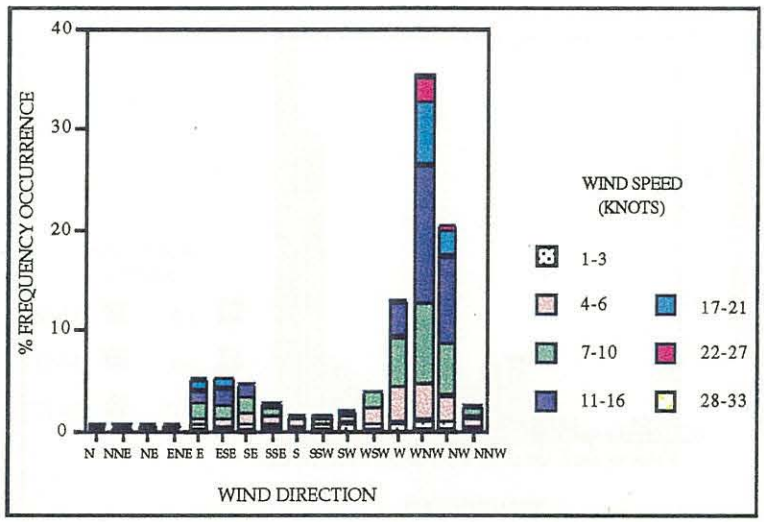

Figure 9. Percent frequency of occurrences of total observations from Buoy 46206 in July.

The locations of the three stations selected, Race Rocks Light, Buoys 46041, and 46206, are shown in Figure 10. These stations are intended to represent the winds over a very large area. Vagaries in topography can result in localized winds not represented by the offshore buoys.

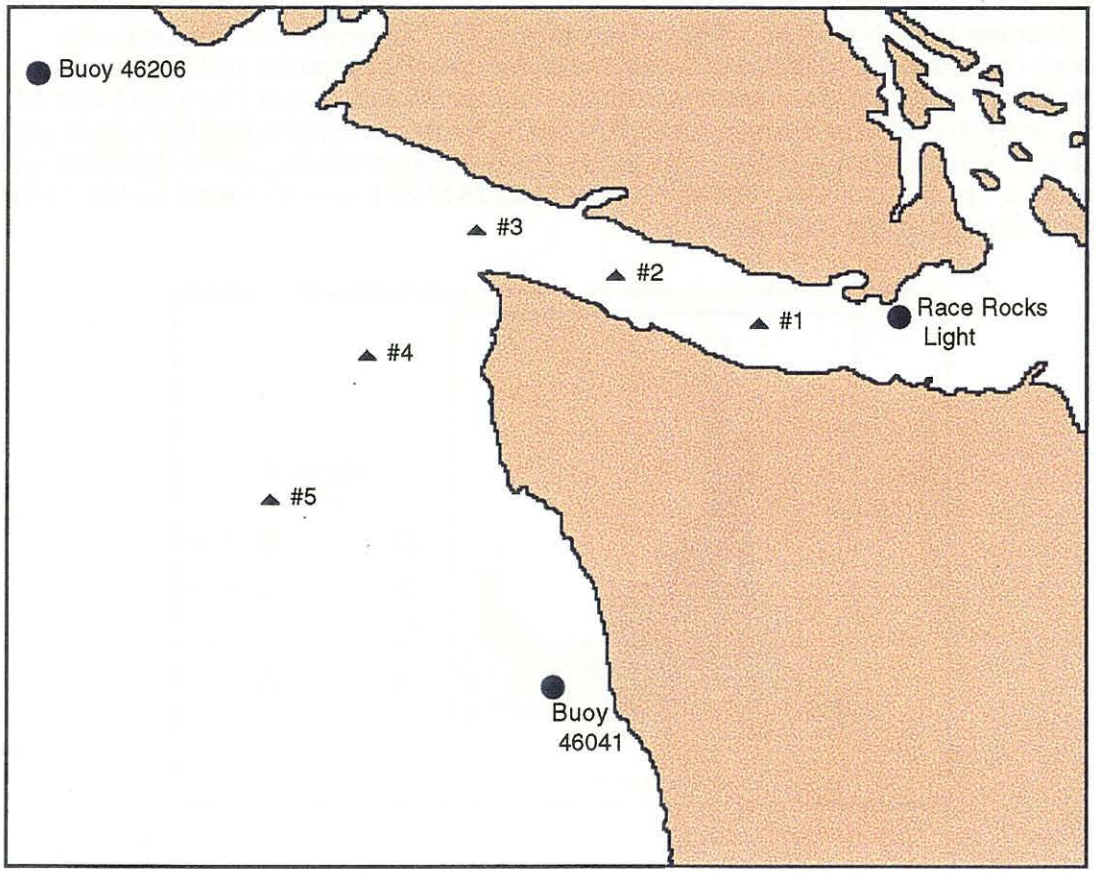

Figure 10. The location of the wind stations and ship drift sites.

The hourly archived wind data for each station were translated into a format suitable for OSSM. The long wind records were grouped by season: December, January, and February data represent winter season; March, April, and May, spring; June, July, and August, summer; and September, October, and November, fall. Within OSSM, each LE was assigned a random, seasonal start time within the wind records subject to the following criteria. The start times had to be within an assigned season (i.e. December, January, February for winter), at least one hour apart, and, for the duration of the model simulation, there could be no data gaps larger than 6 hours. All time interpolations were done using a cubic hermite fit. The spatial variances of the winds were handled by assigning influence zones for each wind station. Each element obtained its wind information from only one station at any time, depending upon what zone it was in. The zones are as follows; any element inside the Strait and east of longitude 124° 35' W was assigned winds from Race Rocks Light; any element north of latitude 48° 22'N and west of longitude 124° 35' W, Buoy 46206; and, elements south of 48° 22'N and west of longitude 124° 35' W, Buoy 46041.

2.2 *Surface Currents*

The coastal winds are also an important factor for determining residual circulation. In particular, the wind-induced currents for areas off Vancouver Island and the Washington coast show a definite seasonal variation with the dominant current patterns in the summer being southerly and, in the winter, northerly (Thomson 1981; Freeland et al. 1984; Hickey et al. 1991). Typical current velocities off the Washington Coast are approximately 10 to 20 centimeters per second (cm/s). During the spring and fall, the currents are less intense and in transition.

The tides within the Strait of Juan de Fuca are semi diurnal. During strong river flows, the ebb tides tend to be stronger than the flood with a net outflow through the Strait (Downing 1983). Stronger ebbs occur during the spring due to snow runoff from the Fraser River. Heavier runoff also occurs in the fall after the onset of seasonal rains and prior to freeze up in the mountains. This increases the outflow from the largest rivers into the Puget Sound in the late fall and early winter.

A brief description of the models is presented here; the reader is directed to Galt (1980) and Galt and Payton (1981) for more detailed information. The two-dimensional hydrodynamic models used in the ship-drift analysis provide a simple method for extrapolating one current measurement over a large area based on bathymetry and fluid conservation laws. Since the models are linear, the different current patterns can be linearly superimposed to describe the overall circulation.

Mean seasonal coastal currents were generated and used for the offshore areas of Washington and Vancouver Island. These currents were assumed to be constant for each season. To simulate the transition period in the spring and fall, the currents were reversed every 5 days in the trajectory runs. Spatial interpolation of the tide inside the Strait of Juan de Fuca was done by generating tidal current patterns and keying the patterns to the National Ocean Survey tide station at the Strait of Juan de Fuca Entrance (48° 27'N, 124° 35'W). The tidal current record was loaded into OSSM for each season (a 3- month record) and each element was randomly assigned a start time within the record.

The current patterns generated from the hydrodynamic solutions represent the mean seasonal currents based on climatological winds: the patterns do not represent short-term events. Coastal winds are a major contributor in determining residual circulation over the

continental shelf off the Washington-Oregon coast. Yet, changes in local wind field, such as weather systems passing through the area, can result in unpredictable current reversals. As discussed in Hickey (1980), a reversal of the coastal current can occur within a few hours or days of the wind change.

In addition, strong currents move through the entrance on the south side of the Strait as a result of specific wind events along the outer coast (Holbrook and Halpern 1982; Frisch et al. 1981). These episodic events typically generate currents that are along the shoreline not towards it. This may cause an offset where a ship comes ashore, but will have a minimal effect on when it does. In any case, they were not included in the current patterns generated for the model simulations.

2.3 *Drift Factors*

When its propulsion or steering device fails, a ship will drift due to the combined effects of the wind, waves, current, trim, and ballast. Tanker drift data has been studied with theory and models (Holder et al, 1981; Lewison et al, 1981; Smeaton, 1981). These models can be quite complicated with a large scatter in predictions based upon variations in ship size, shape, orientation, list, degree of loading, and other parameters. Ship drift factors are also important in USCG search and rescue operations (USCG, 1991), where tables relating drift speed and angles for different vessels and environmental conditions are tabulated.

In addition to theoretical and test tank studies, industry records and questionnaires provide solid empirical information for defining bounds to the problem. For example, Holder et al. (1981) summarized a Oil Companies International Marine Forum (OCIMF) study that sent a questionnaire to member companies and members of the International Chamber of Shipping. A total of 196 evaluation periods using 47 ships were used in the study. From the questionnaire returns, the direction and rate of the ship drift could be determined. Then, by subtracting current vectors, the drift due to wind and wave forces for up to 6 hours at a stretch could be estimated. The ships were divided into categories by size and load type. Smaller vessels were considered less than 200,000 tonnes summer dead weight (SDWT). Larger vessels or very large carrying capacity (VLCC) are greater than 200,000 SDWT. The vessels were considered fully loaded or carrying ballast.

Figures 11 and 12 show the results for a fully loaded and ballasted VLCC (> 200,000 SDWT). There is a loose linear relationship between ship drift speed and wind speed, with the ship drift generally bounded between 2 percent to 10 percent of the wind speed.

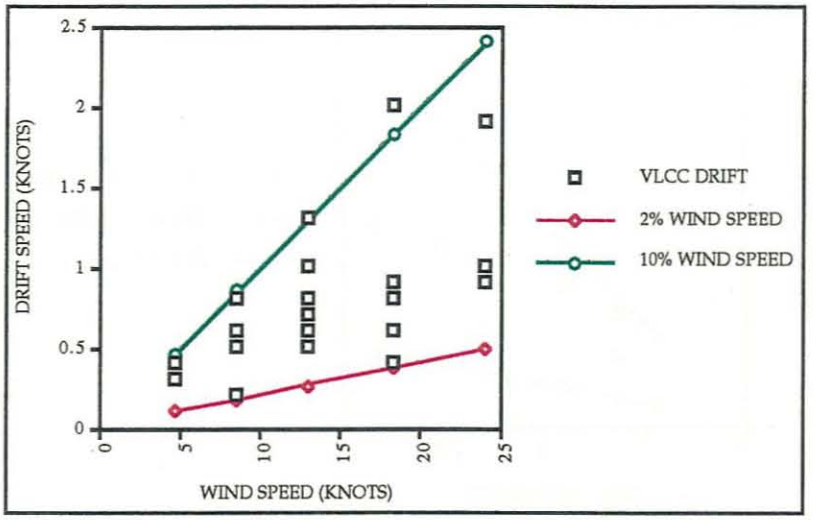

Figure 11. Plot of drift speed and wind speed for loaded VLCC.

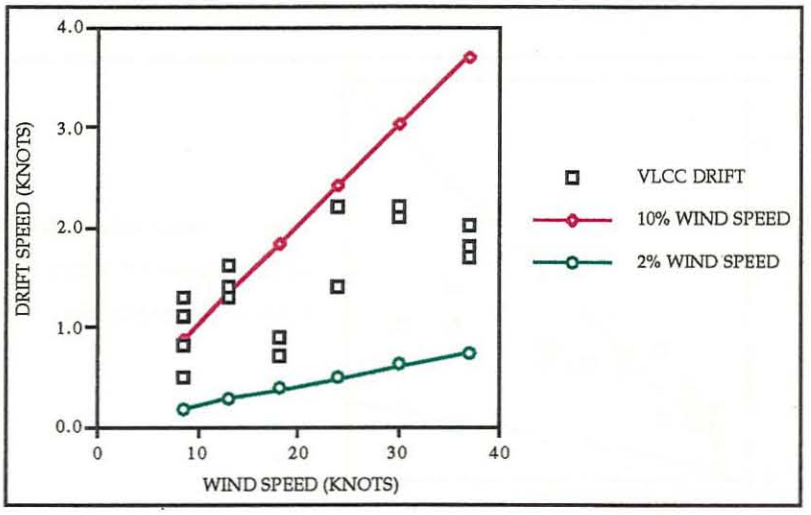

Figure 12. Plot of drift speed and wind speed for ballasted VLCC.

Figures 13 and 14 show the plot of the drift speed and wind speed for small vessels (< 200,00 SDWT). Again, the ship drift is generally bounded between 2 percent to 10 percent of the wind speed.

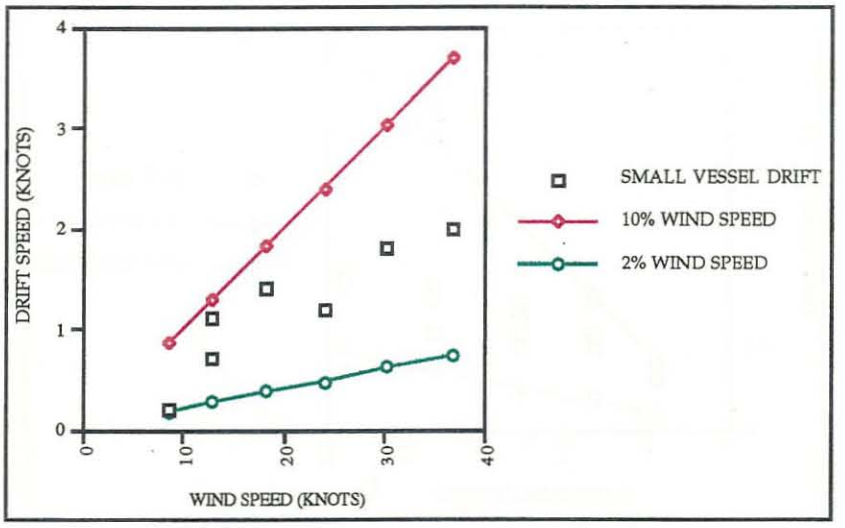

Figure 13. Plot of drift speed and wind speed for loaded small vessel.

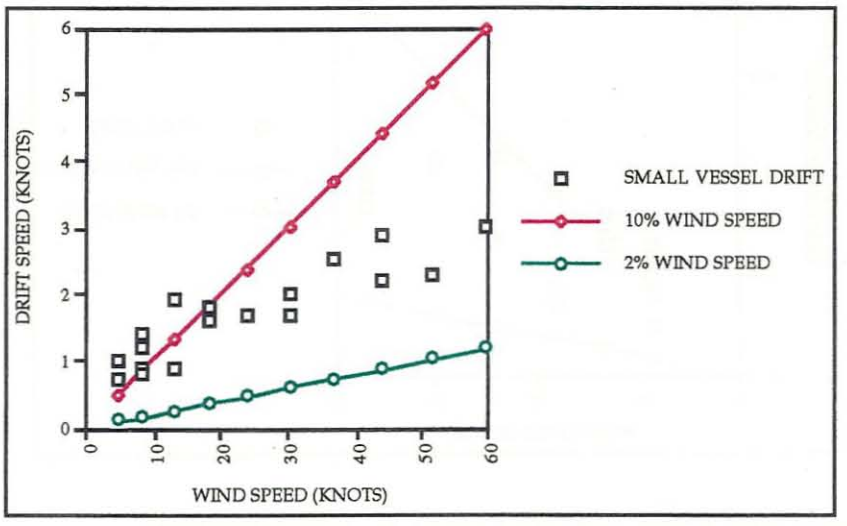

Figure 14. Plot of drift speed and wind speed for ballasted small vessel.

The ships do not generally drift straight downwind, but show a drift angle to the wind. This drift angle can vary 60 degrees or more to the right or left. A similar maximum drift angle is reported in USCG (1991). Based on data from Holder et al. (1981), there does not seem to be a clear relationship between the choice of drift angle and wind speed, ship size or degree of loading. Figures 15 and 16 show a plot of the absolute value of the drift angle and wind speeds for both large and small loaded vessels and ballasted vessels.

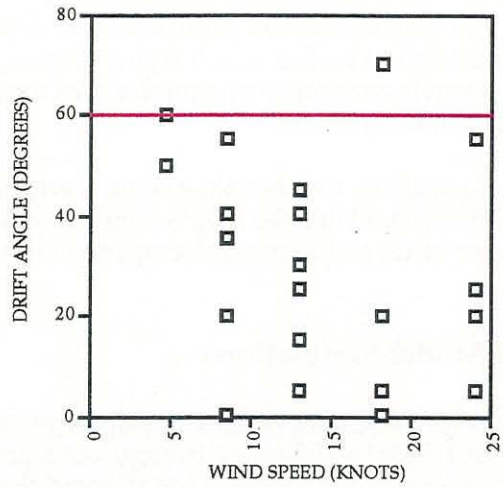

Figure 15. Plot of drift angle (absolute value) and wind speed for loaded vessel.

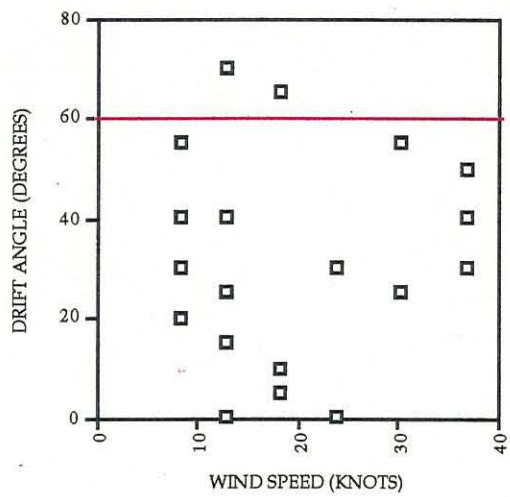

Figure 16. Plot of drift angle (absolute value) and wind speed for ballasted vessel.

Since this study is not designed for any particular ship or configuration, it seemed best to consider a range of choices for drift factors. Lacking specific knowledge of a particular ship configuration, the entire set of results can be used. Where the drift factors are known for a specific case, the appropriate subset can be selected.

Using the information from the questionaires, we developed the following model to simulate the variation in drift speeds and angles due to winds and waves. A set of LEs, with each element representing a potential drifting vessel, are released at the same point. Wind, waves[1], and currents are determined as specified elsewhere in this report. For a particular

[1]For this analysis, the waves are assumed fully developed and in the direction of the wind.

run, all the LEs are assigned the same drift factor, either 2, 4, 6, 8 or 10 percent of the wind speed. Each LE within that run is assigned the same constant drift speed factor as 2, 4, 6, 8 and 10 percent. This factor, multiplied by the time varying wind speed, gives the ship's speed. However each LE in a run is randomly assigned a drift angle from -60 to +60 degrees of the complementary wind direction.

It should be noted that such a model is, to a certain extent, a worst-case scenario since it does not take into account situations where the ship's crew, by adjusting ballast, list, residual steering capabilities, or other techniques, attempt to maintain their vessel on a safe trajectory.

3.0 Trajectory Analysis of Model Simulations

The positions of the Lagrangian particles, representing ship locations, were converted to Eulerian probability density functions by delauney triangulation and the use of Vornoi diagrams (also referred to as Thiessien polygons). This allowed the determination of a 95 percent confidence contour. This means that 95 percent of the final ship scenario locations lie within this contour for the specified hour, season, and drift factor (Figure 17).

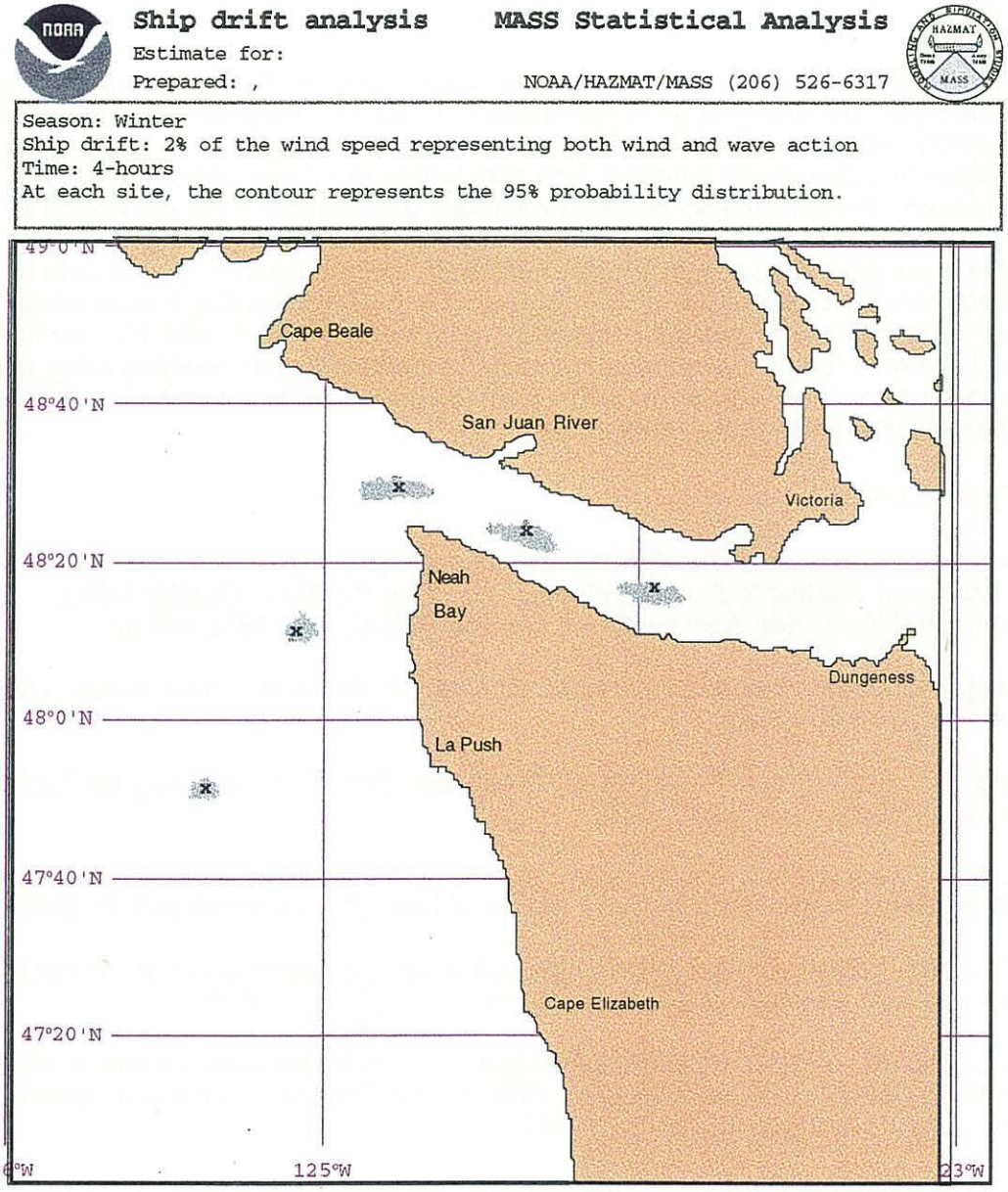

Figure 17. Example of 4-hour probability contour for five sites, winter at 2 percent drift.

The output maps are organized as follows: The 95 percent confidence contours are displayed. Results for the four seasons are plotted separately. Outputs are shown at four, eight, and twelve hours after the presumed loss of power or steering by the drifting vessel. For drift factors of 2, 4 and 6 percent, all five sites are shown on the same map. For drift factors 8 and 10 percent, two maps are used due to the larger areas covered by the confidence contours.

4.0 Conclusions

Mean seasonal surface current data off the northwest Olympic Peninsula, tidal currents inside the Strait, and archived wind data from three stations were used to simulate the drift of a disabled vessel from five sites. These sites were not selected as a result of any formal risk analysis but do indicate potential drift sites within the vessel traffic service area in the study domain. For each site, 95 percent probability distributions were developed for the four seasons and with vessel drift factors of 2, 4, 6, 8 and 10 percent. For each model run, 2,000 LEs were initialized and each had a randomly assigned start time into both the tide and wind records. The probability distributions are displayed on maps: each contour on the map represents the 95 percent probability distribution for 4-, 8-, and 12-hour intervals. It should be noted that in the event of an actual incident, trajectory analysis using real-time winds and current observations should be used to predict the movement of the vessel rather than the statistical presentation given in the maps.

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APPENDIX A

Ship Drift Simulations

Contents

Figures continued

Figures continued

Figures continued

Figures continued

Figures continued

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

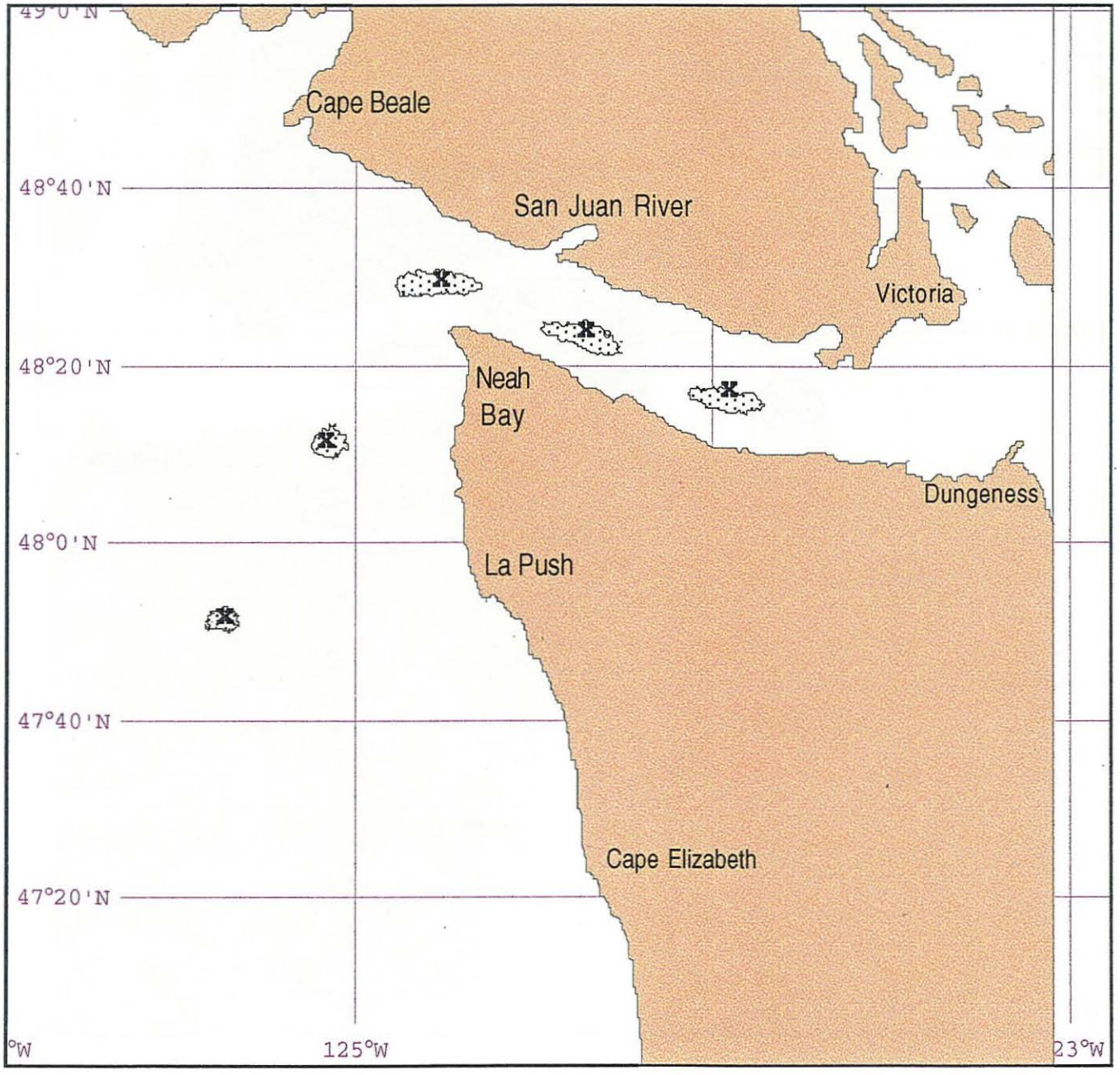

Figure A-1 Map of 4-hour probability contours, winter, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

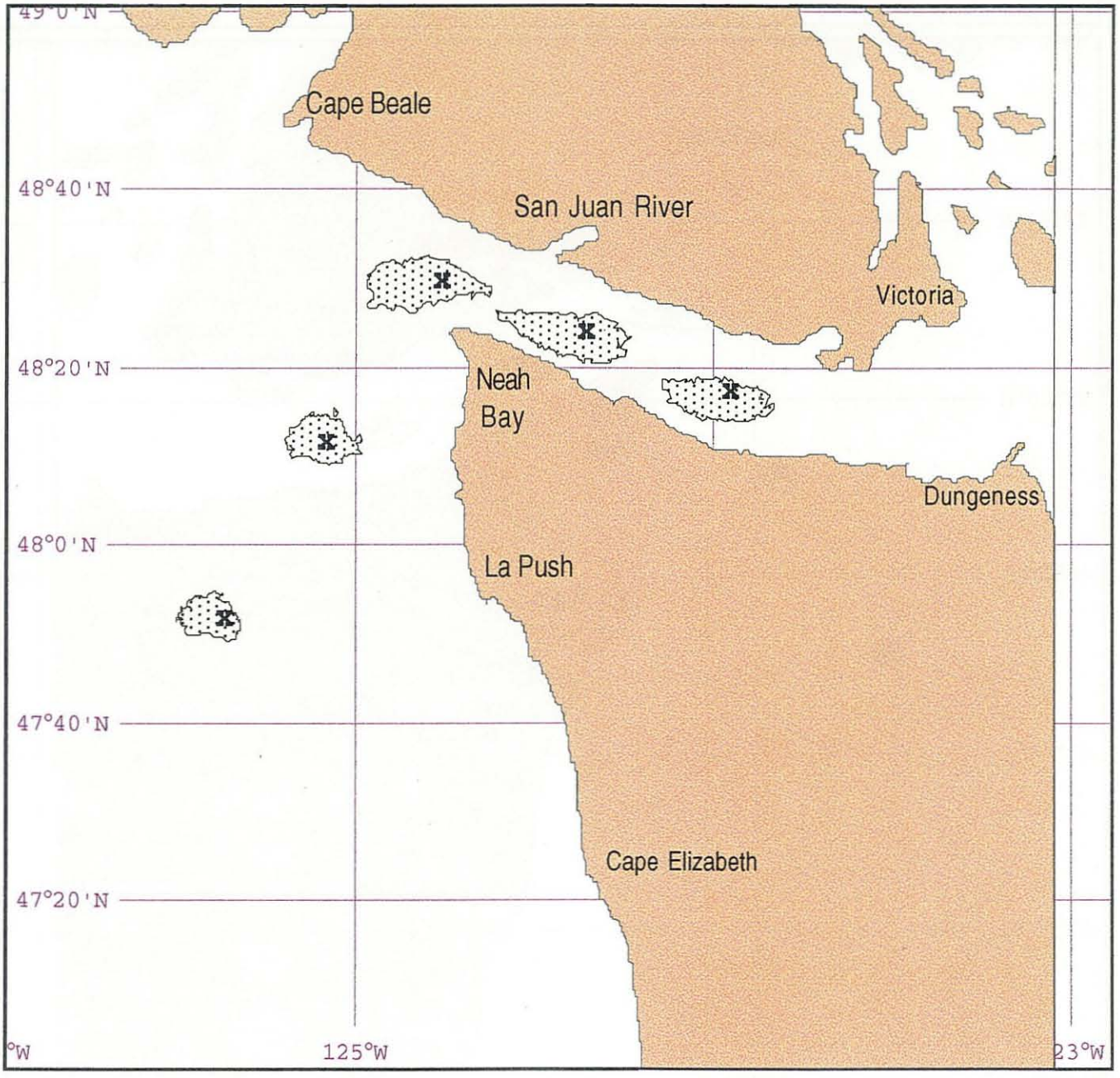

Figure A-2. Map of 8-hour probability contours, winter, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

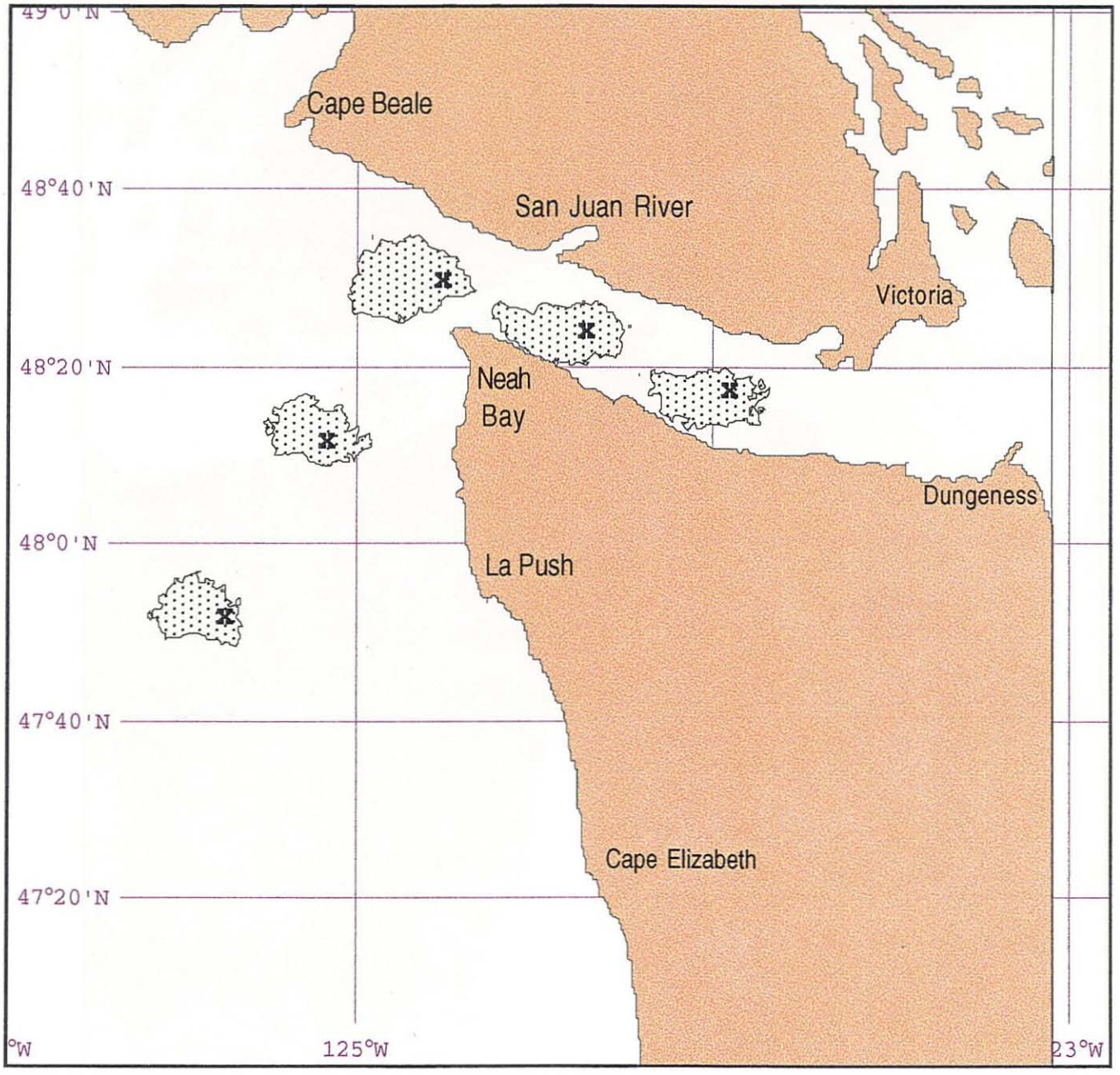

Figure A-3. Map of 12-hour probability contours, winter, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

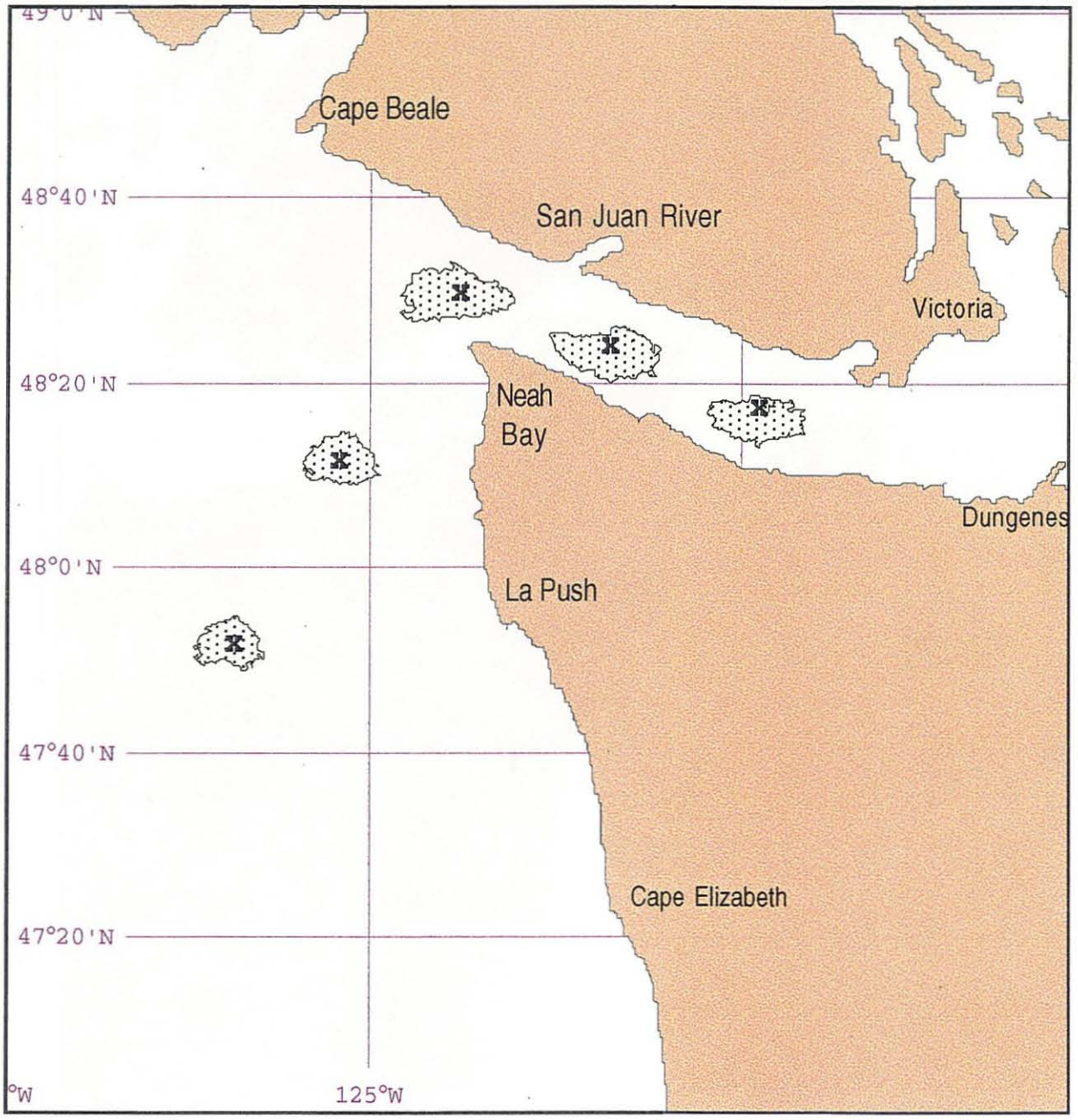

Figure A-4. Map of 4-hour probability contours, winter, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

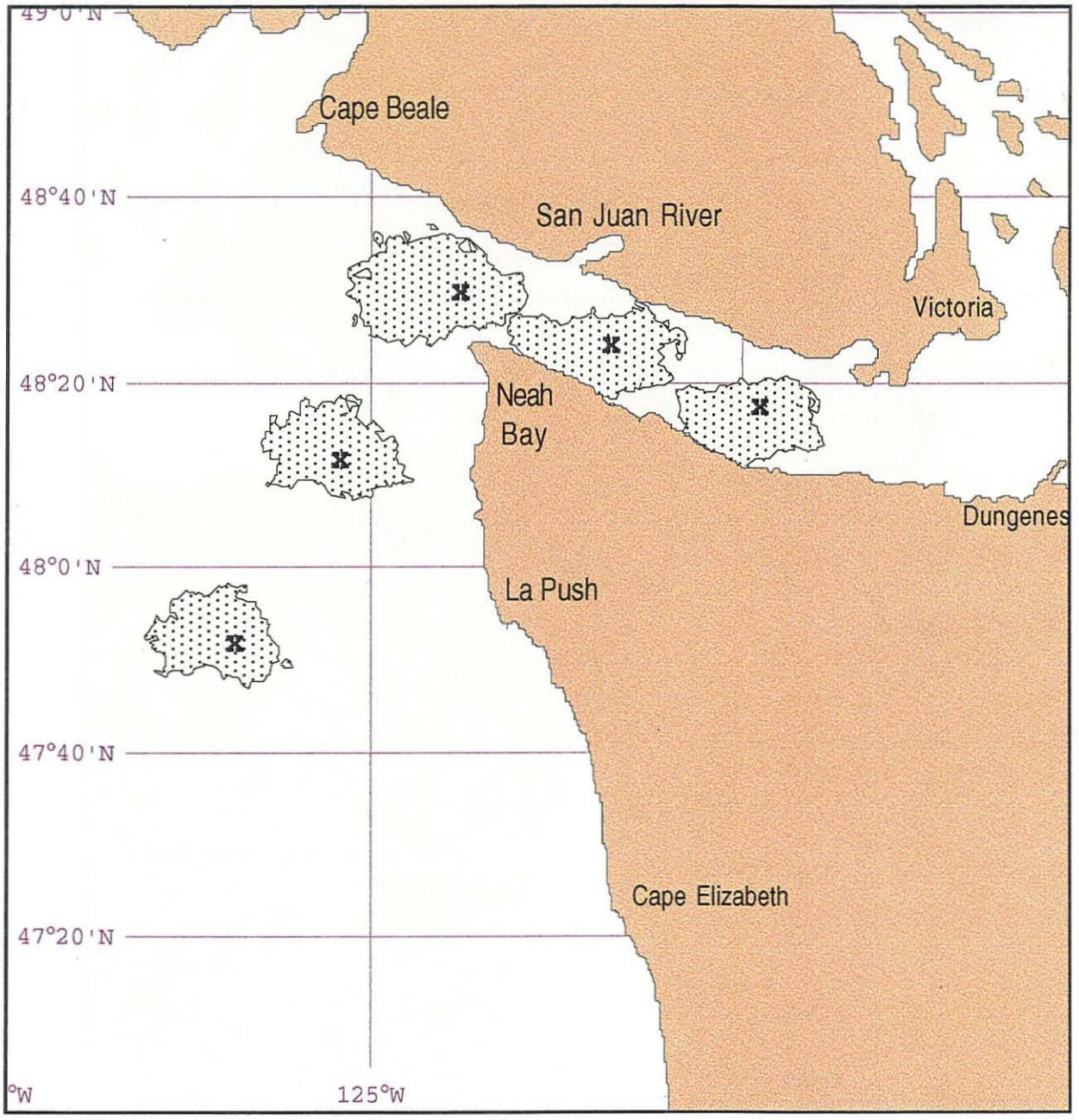

Figure A-5. Map of 8-hour probability contours, winter, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

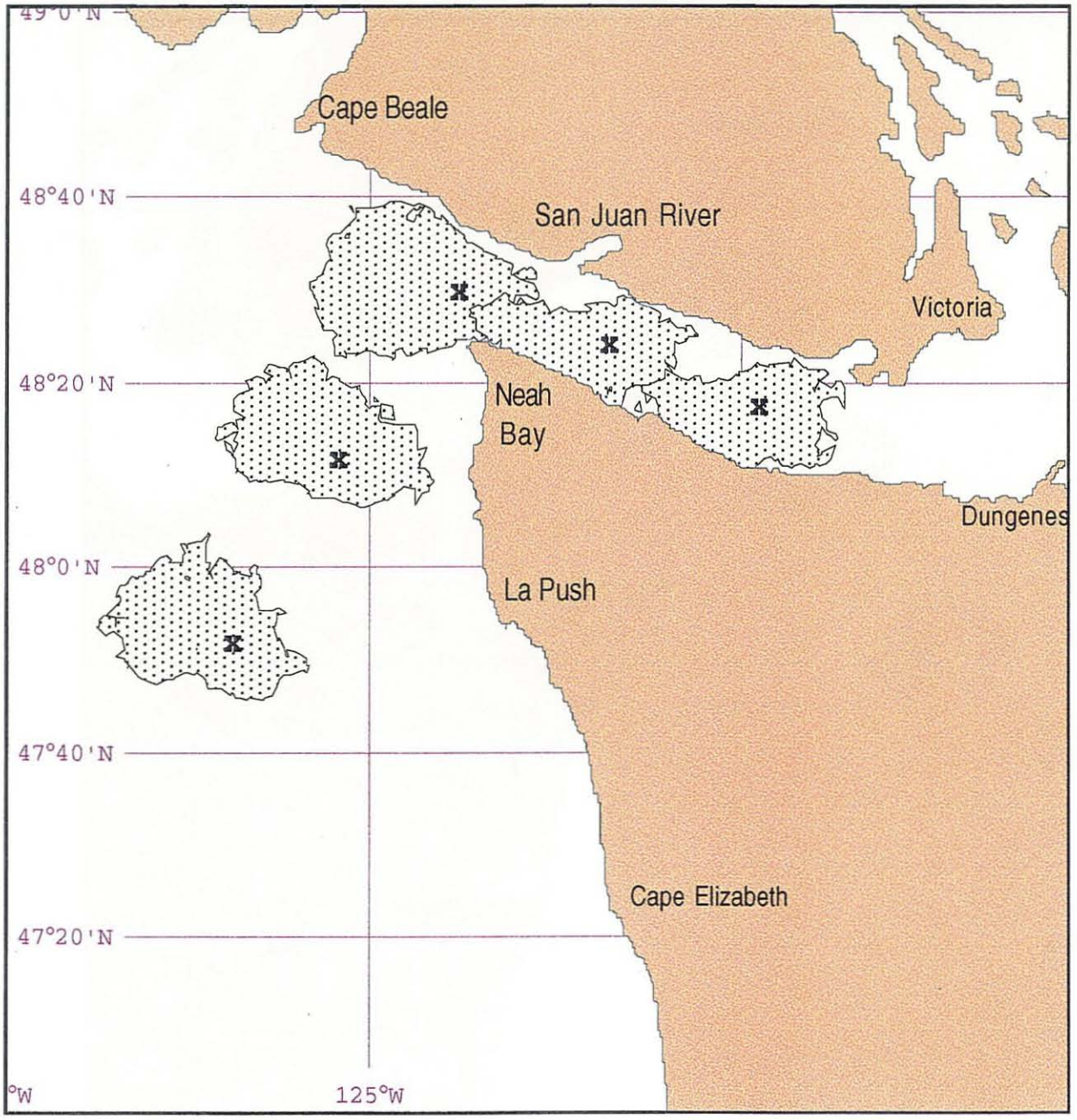

Figure A-6. Map of 12-hour probability contours, winter, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

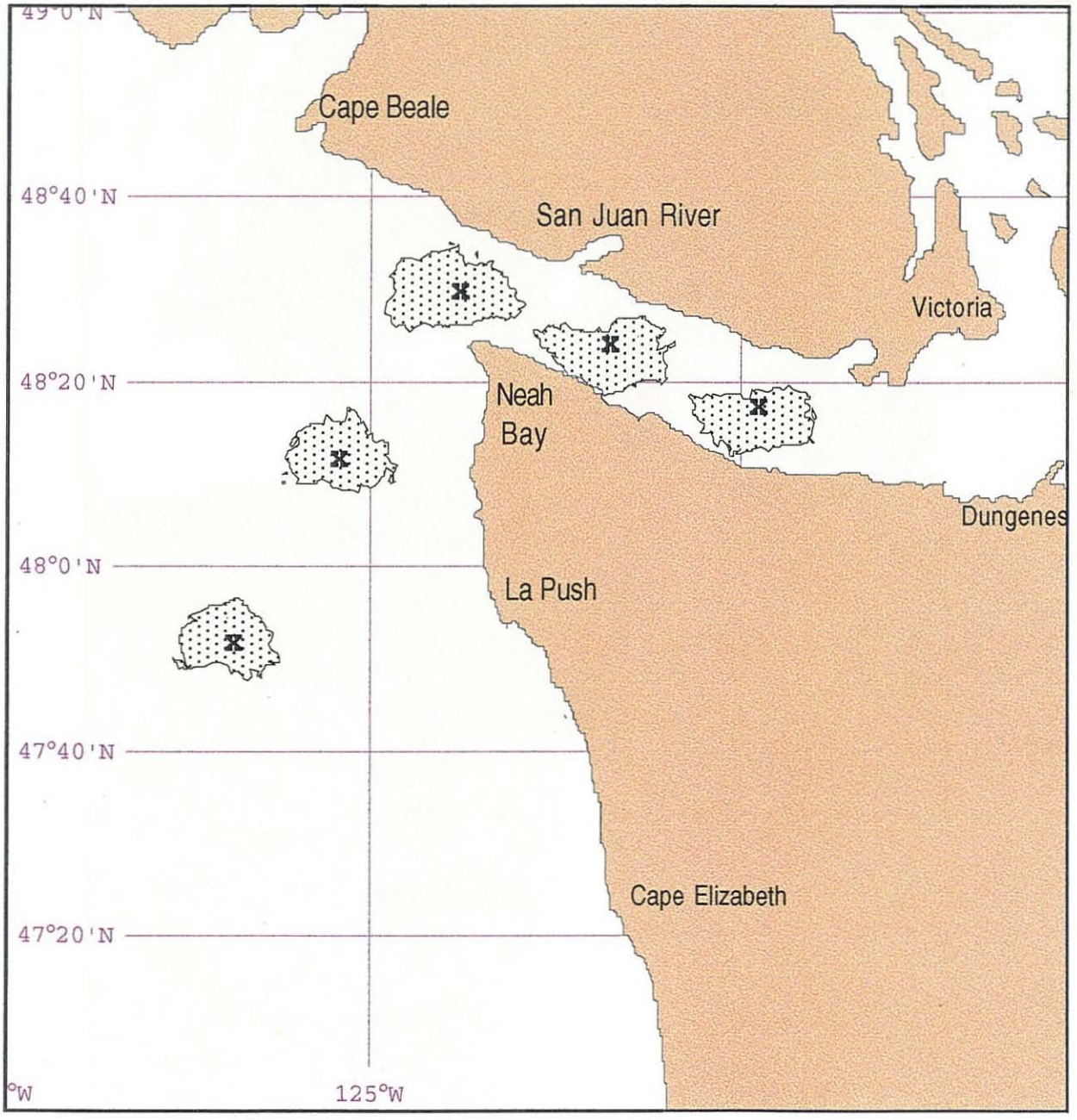

Figure A-7. Map of 4-hour probability contours, winter, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

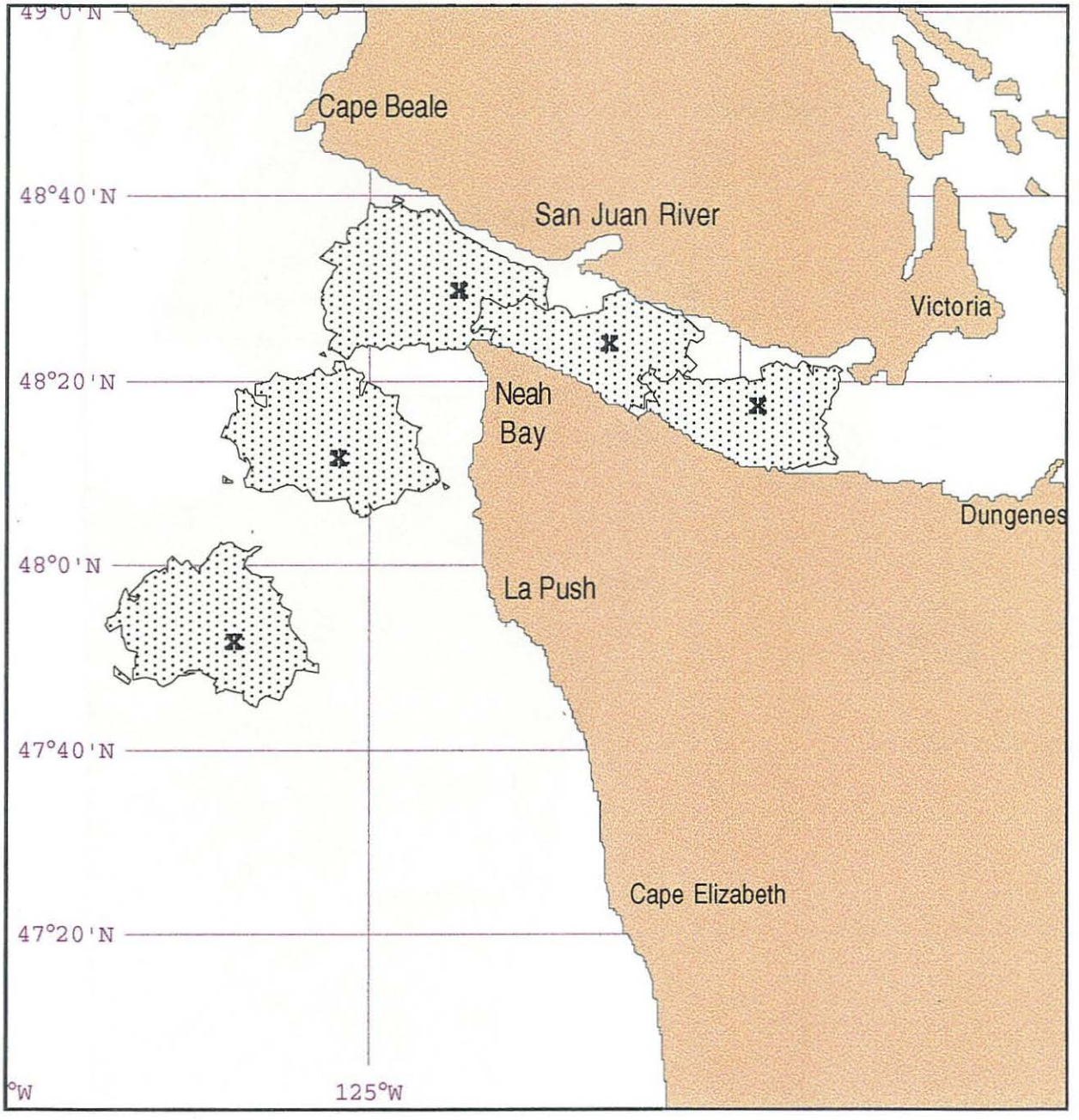

Figure A-8. Map of 8-hour probability contours, winter, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

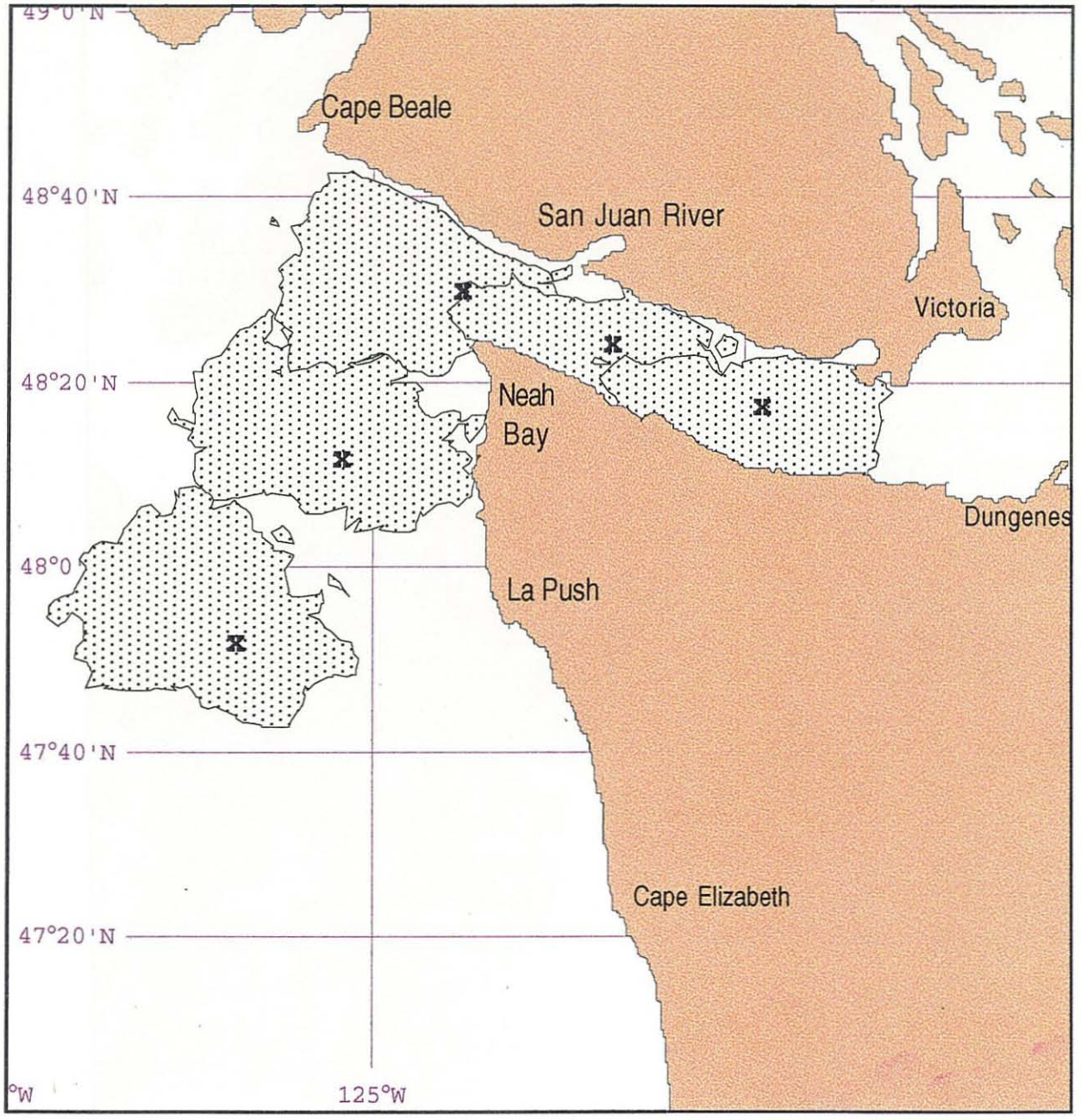

Figure A-9. Map of 12-hour probability contours, winter, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 8% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

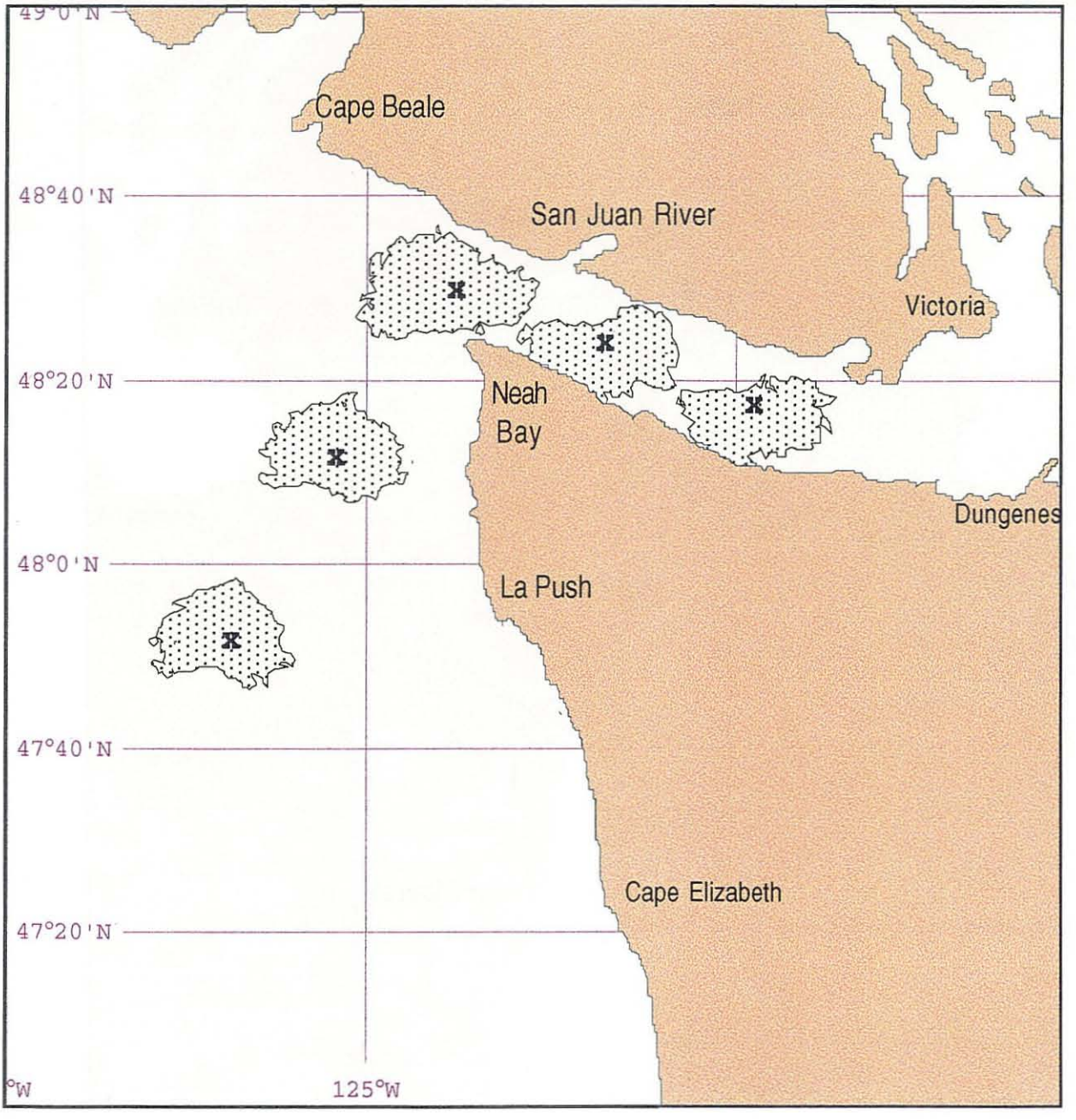

Figure A-10. Map of 4-hour probability contours, winter, 8 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

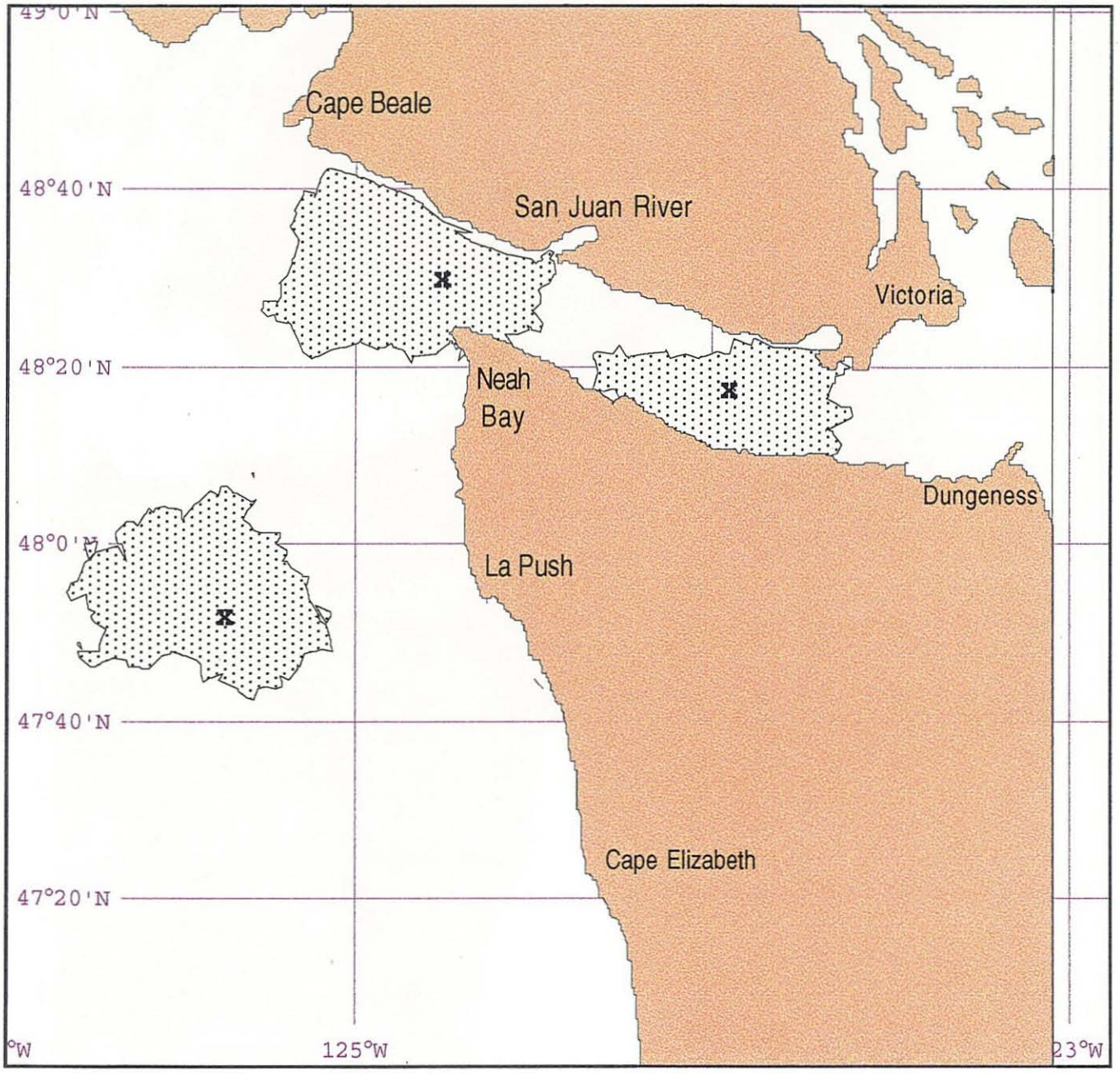

Figure A-11. Map of 8-hour probability contours, winter, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

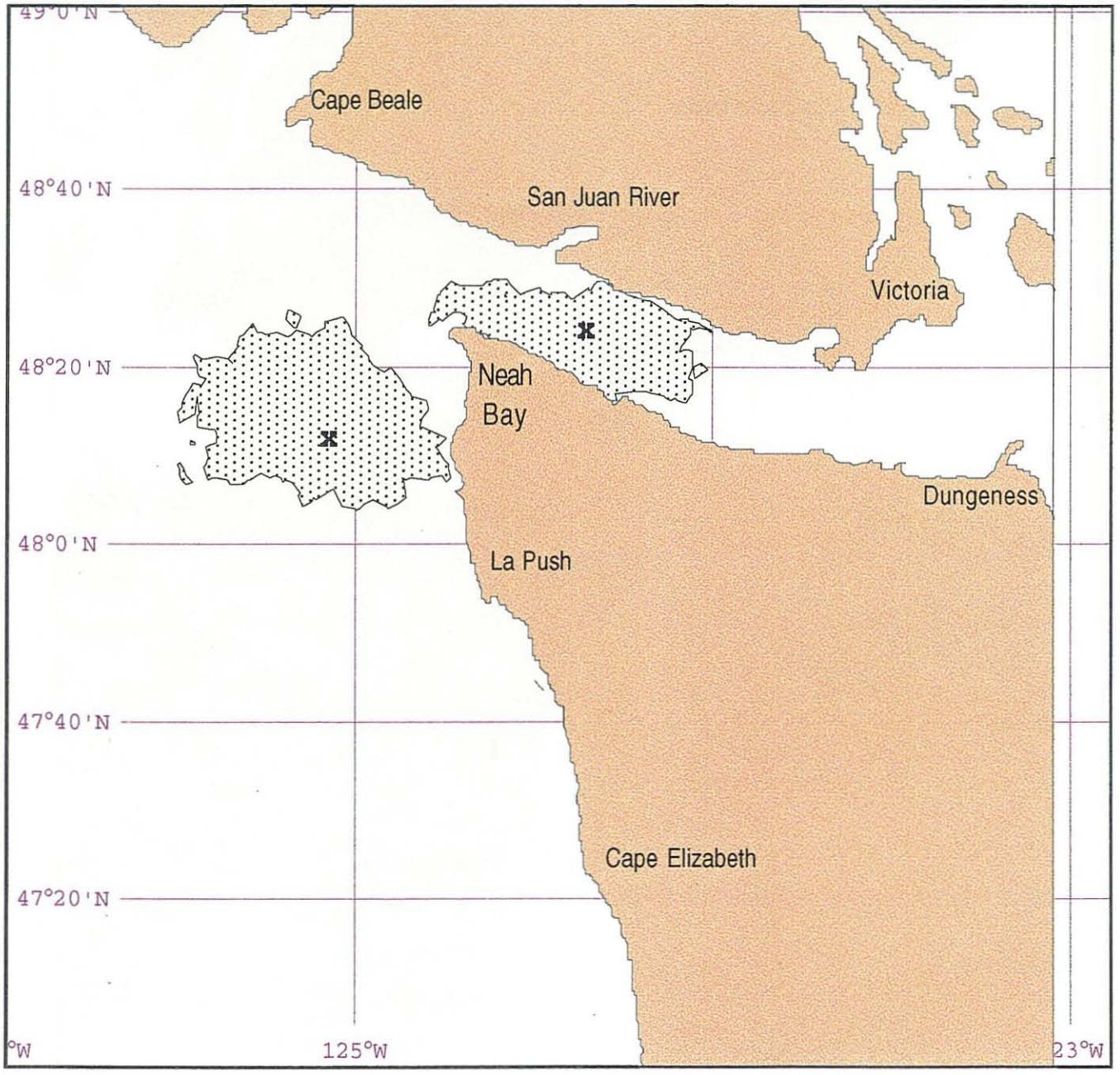

Figure A-12. Map of 8-hour probability contours, winter, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

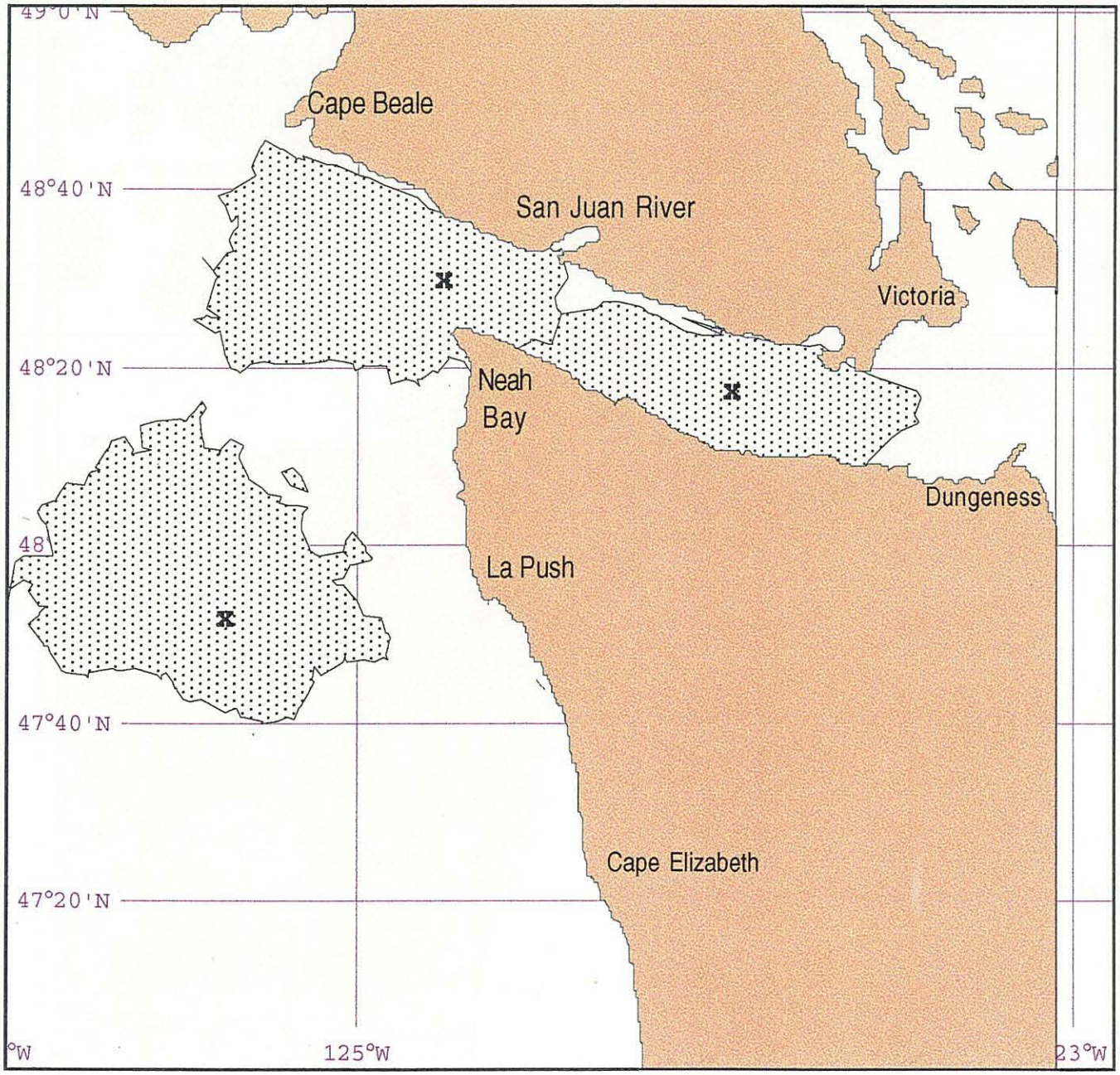

Figure A-13. Map of 12-hour probability contours, winter, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

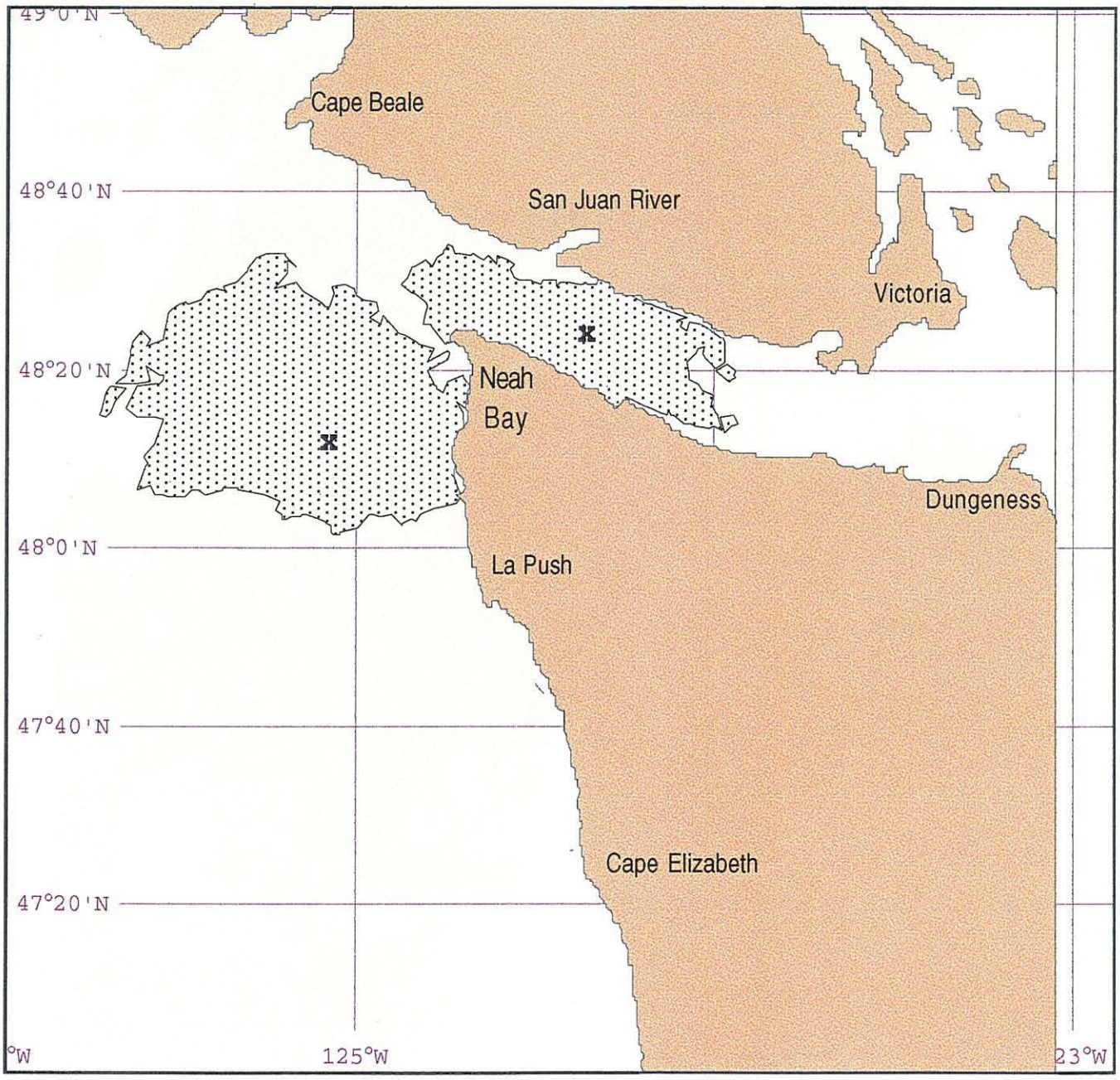

Figure A-14. Map of 12-hour probability contours, winter, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 10% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

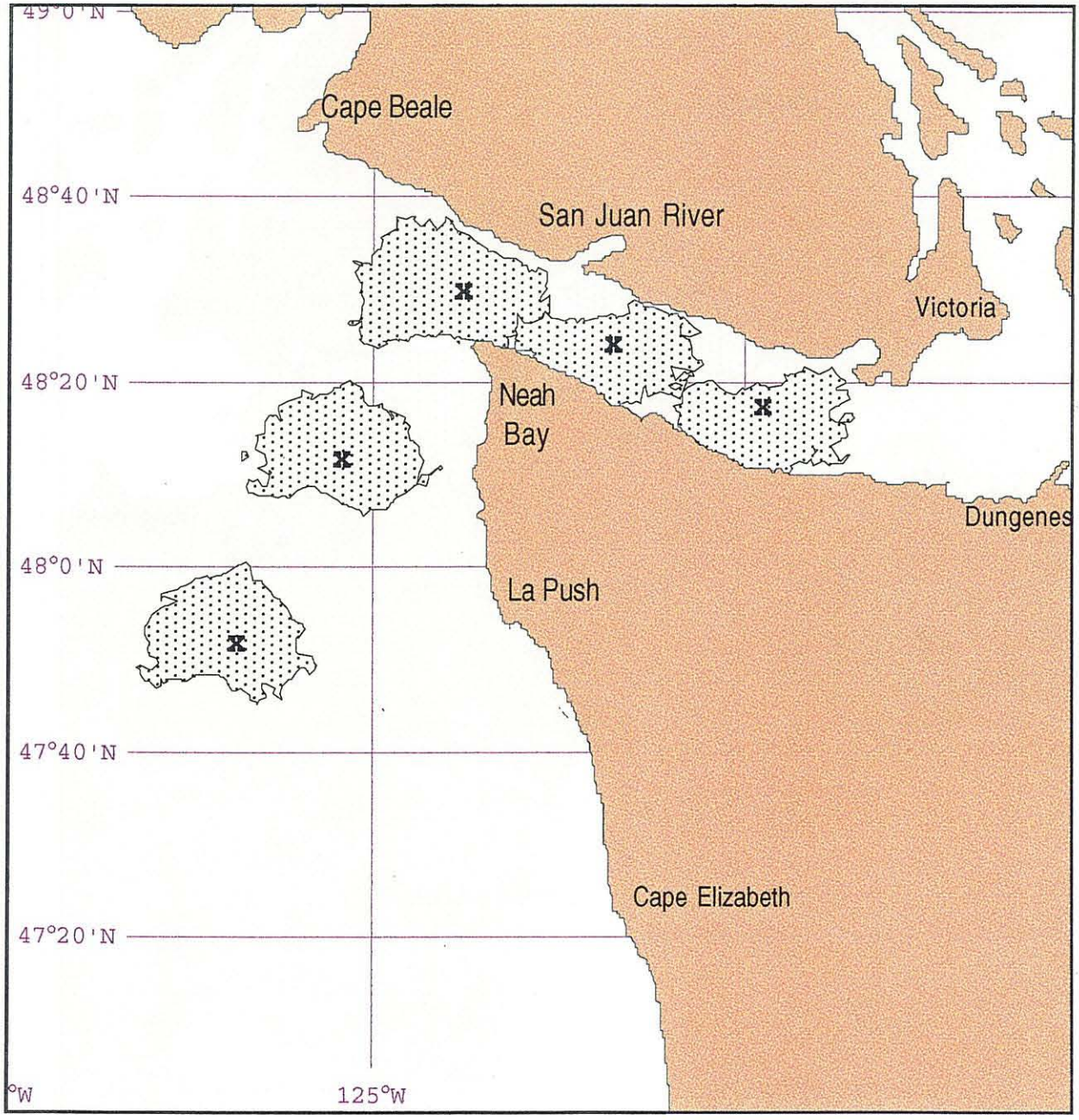

Figure A-15. Map of 4-hour probability contours, winter, 10 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

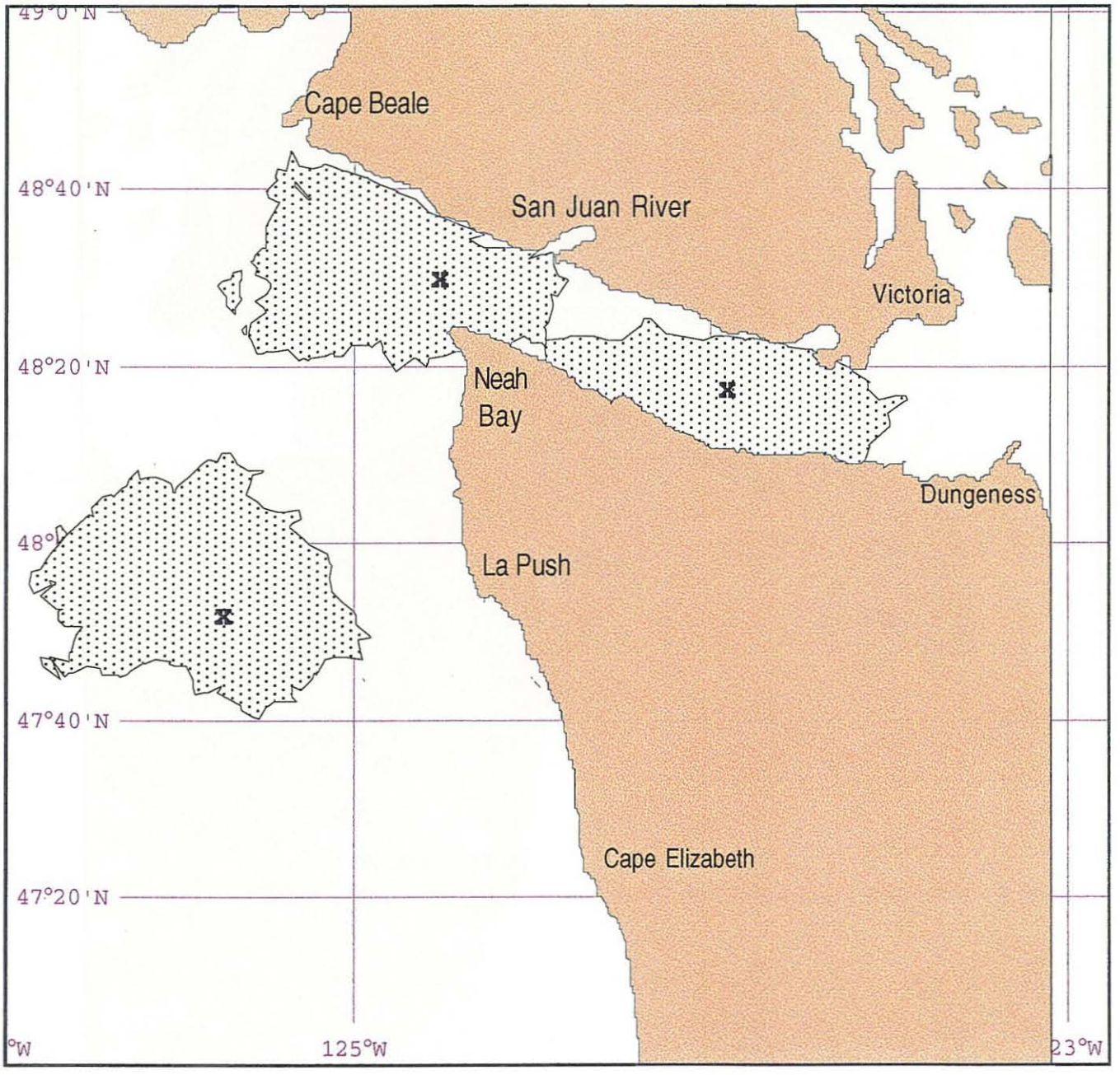

Figure A-16. Map of 8-hour probability contours, winter, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

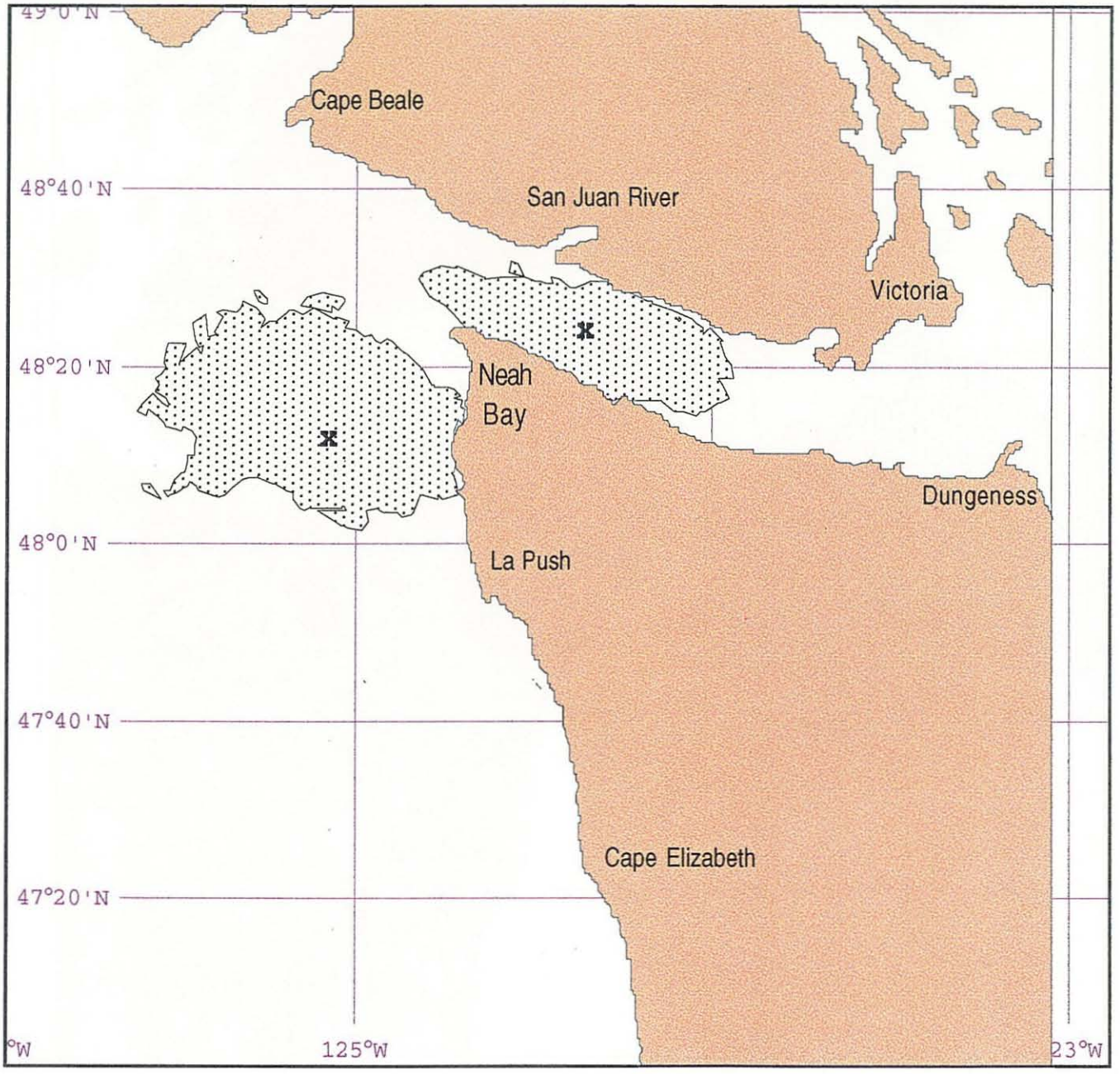

Figure A-17. Map of 8-hour probability contours, winter, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
Ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

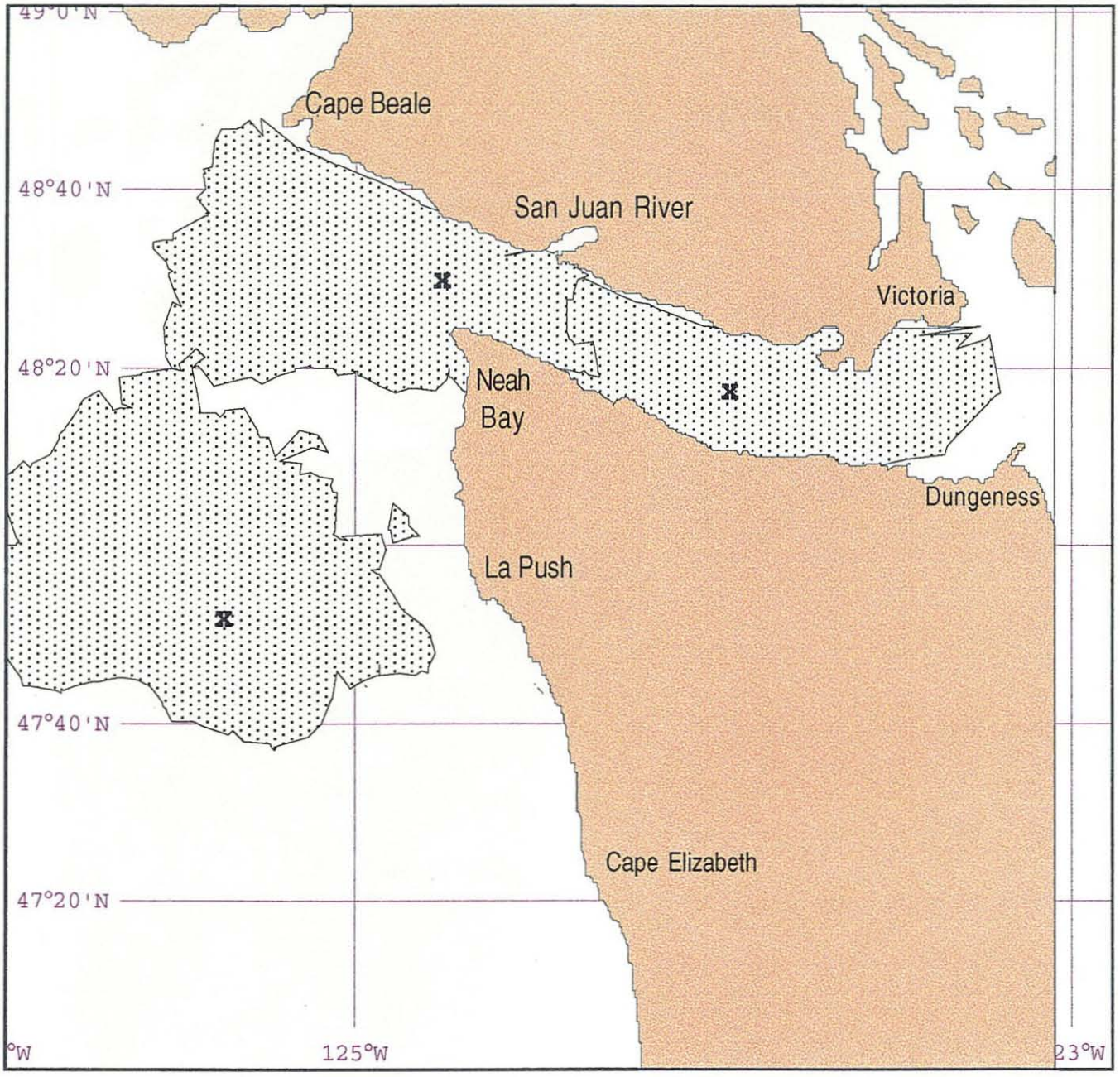

Figure A-18. Map of 12-hour probability contours, winter, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Winter
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

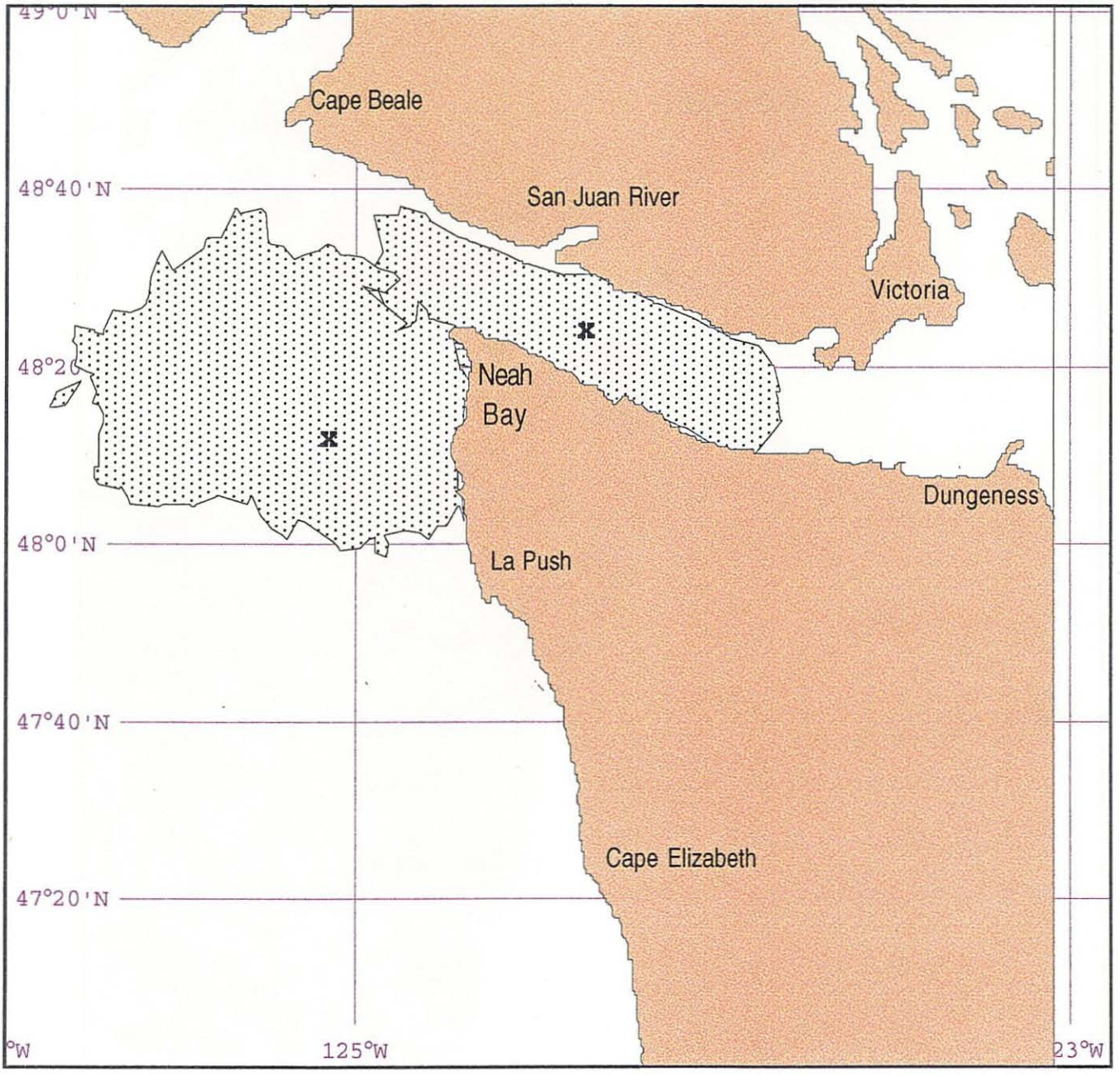

Figure A-19. Map of 12-hour probability contours, winter, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

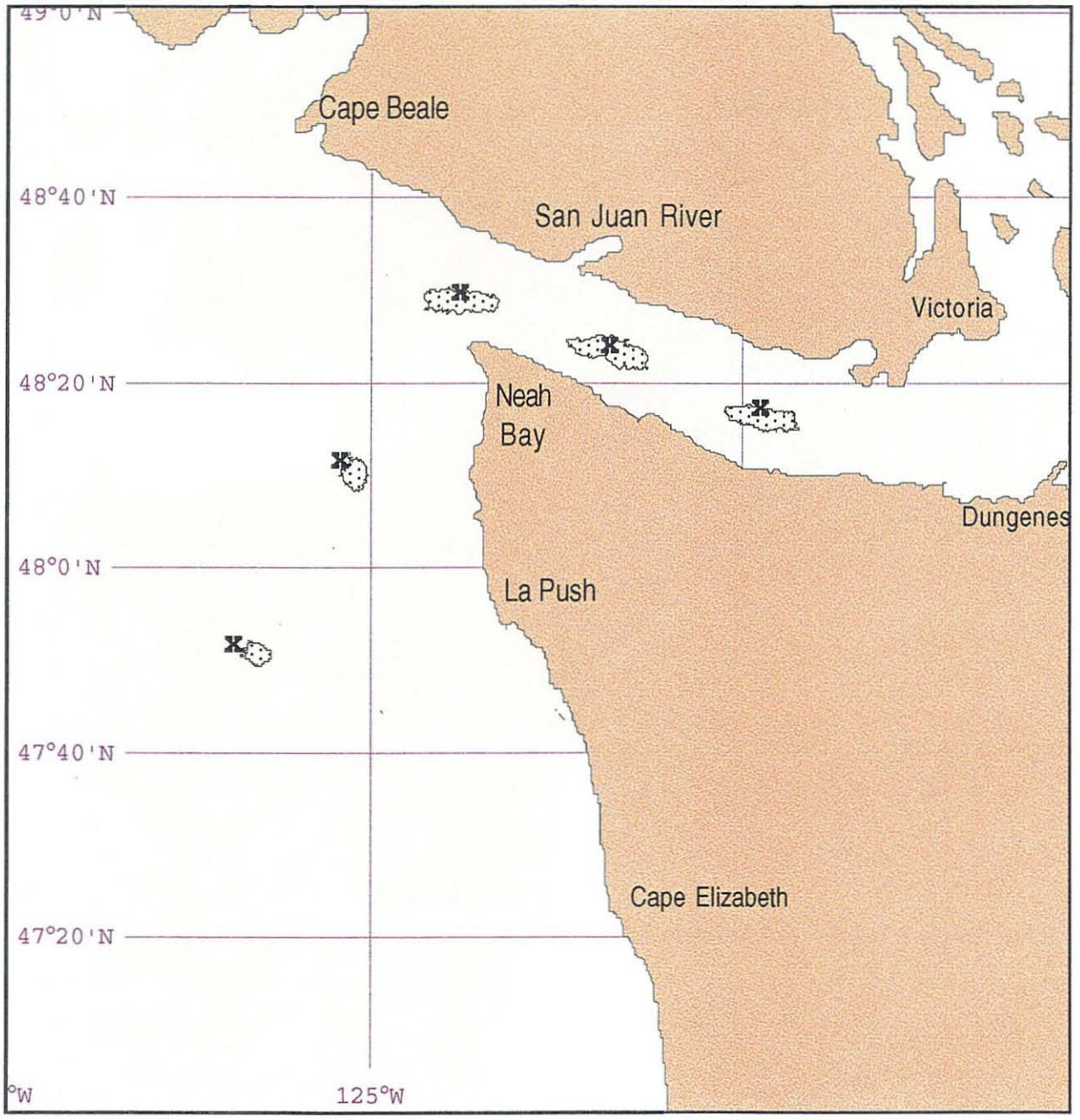

Figure A-20. Map of 4-hour probability contours, spring, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

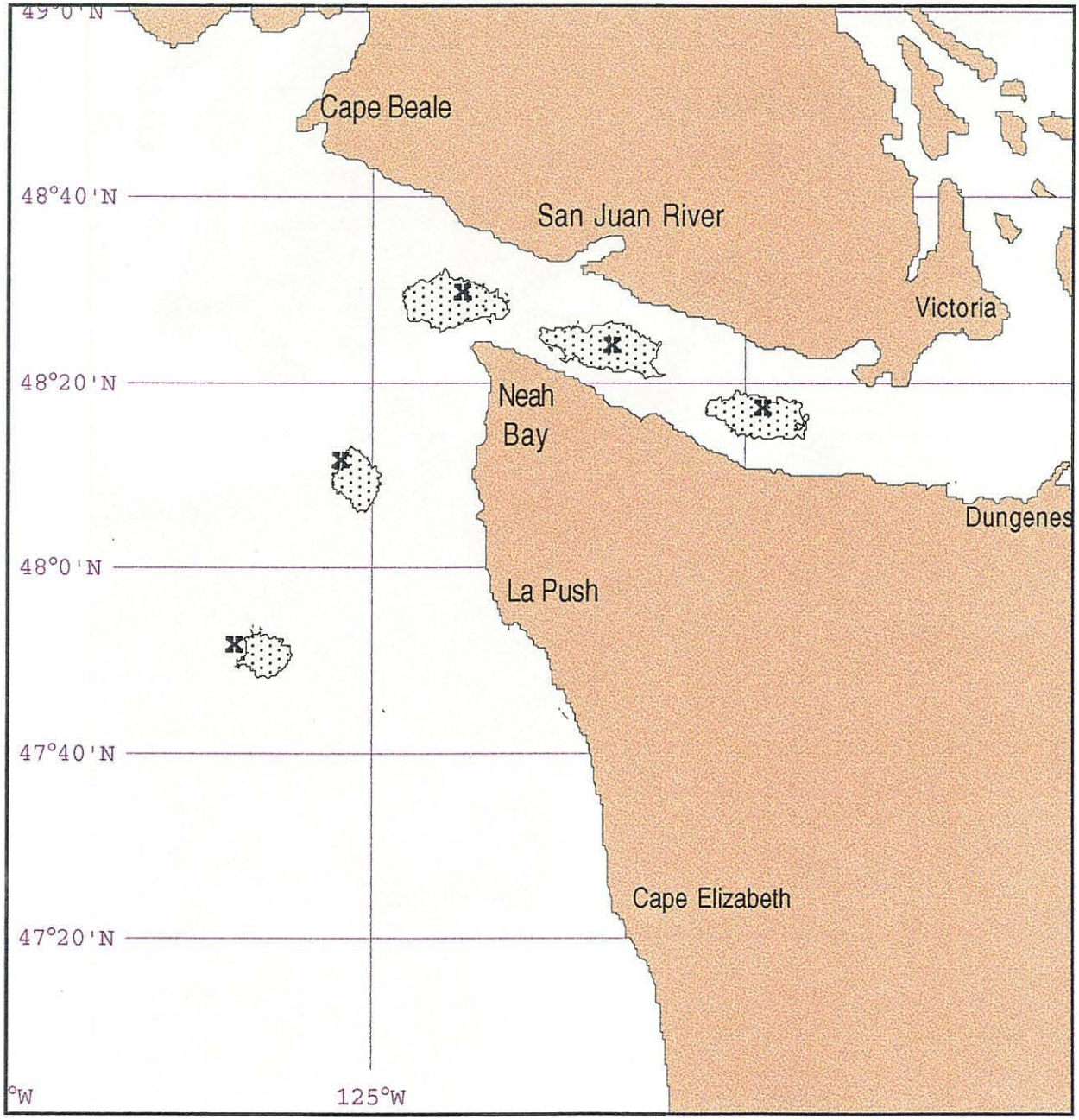

Figure A-21. Map of 8-hour probability contours, spring, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 2% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

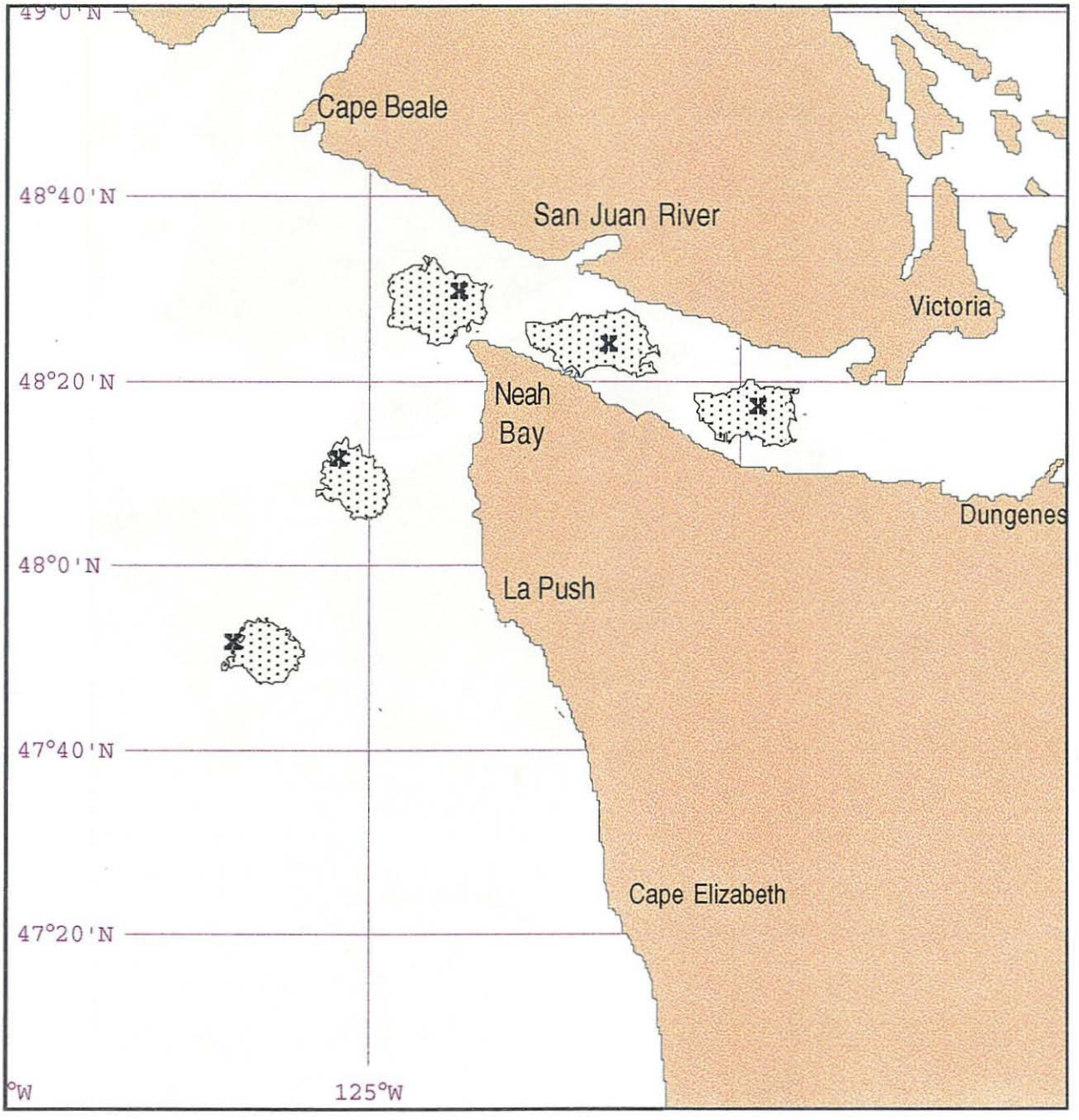

Figure A-22. Map of 12-hour probability contours, spring, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

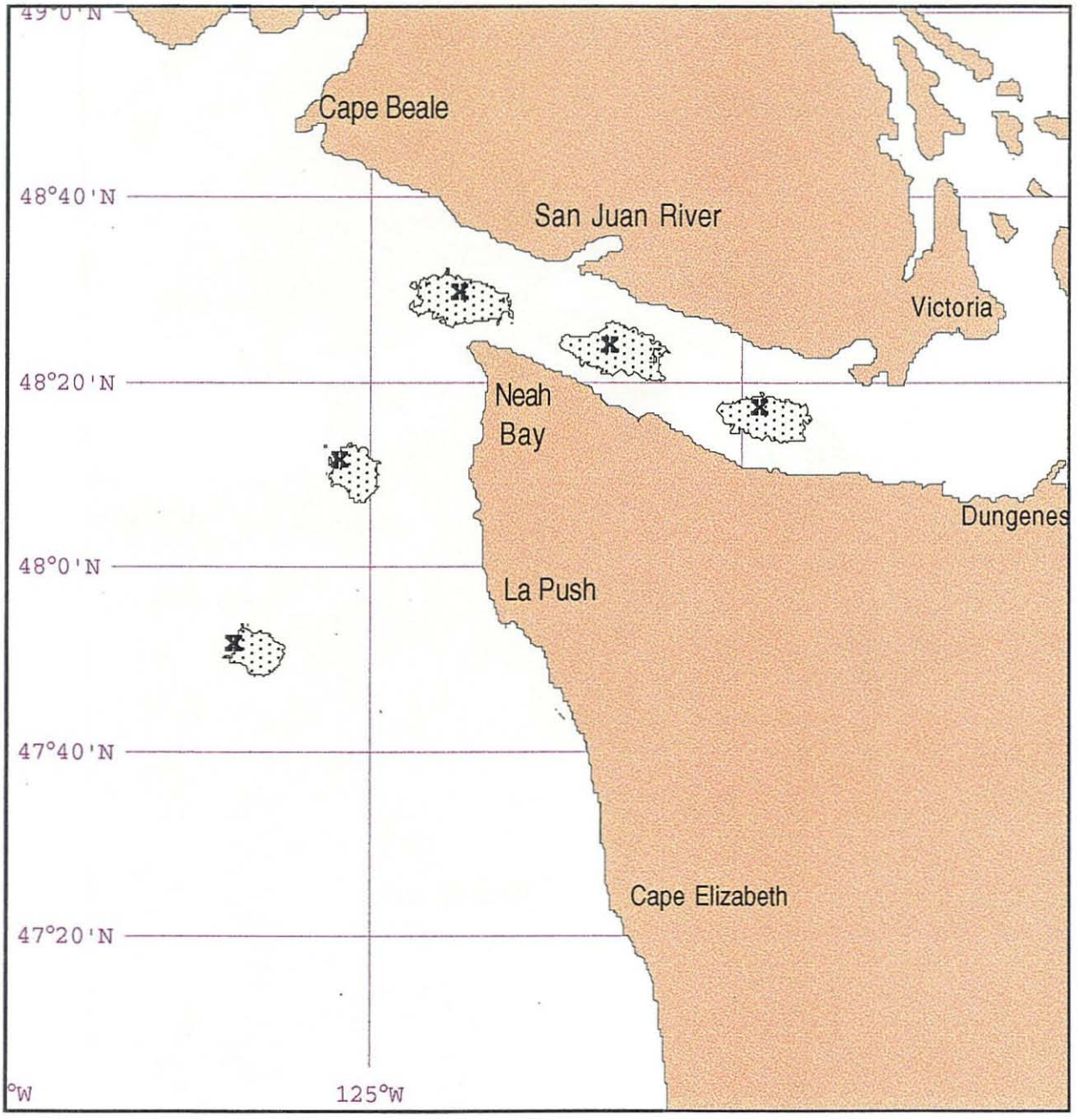

Figure A-23. Map of 4-hour probability contours, spring, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

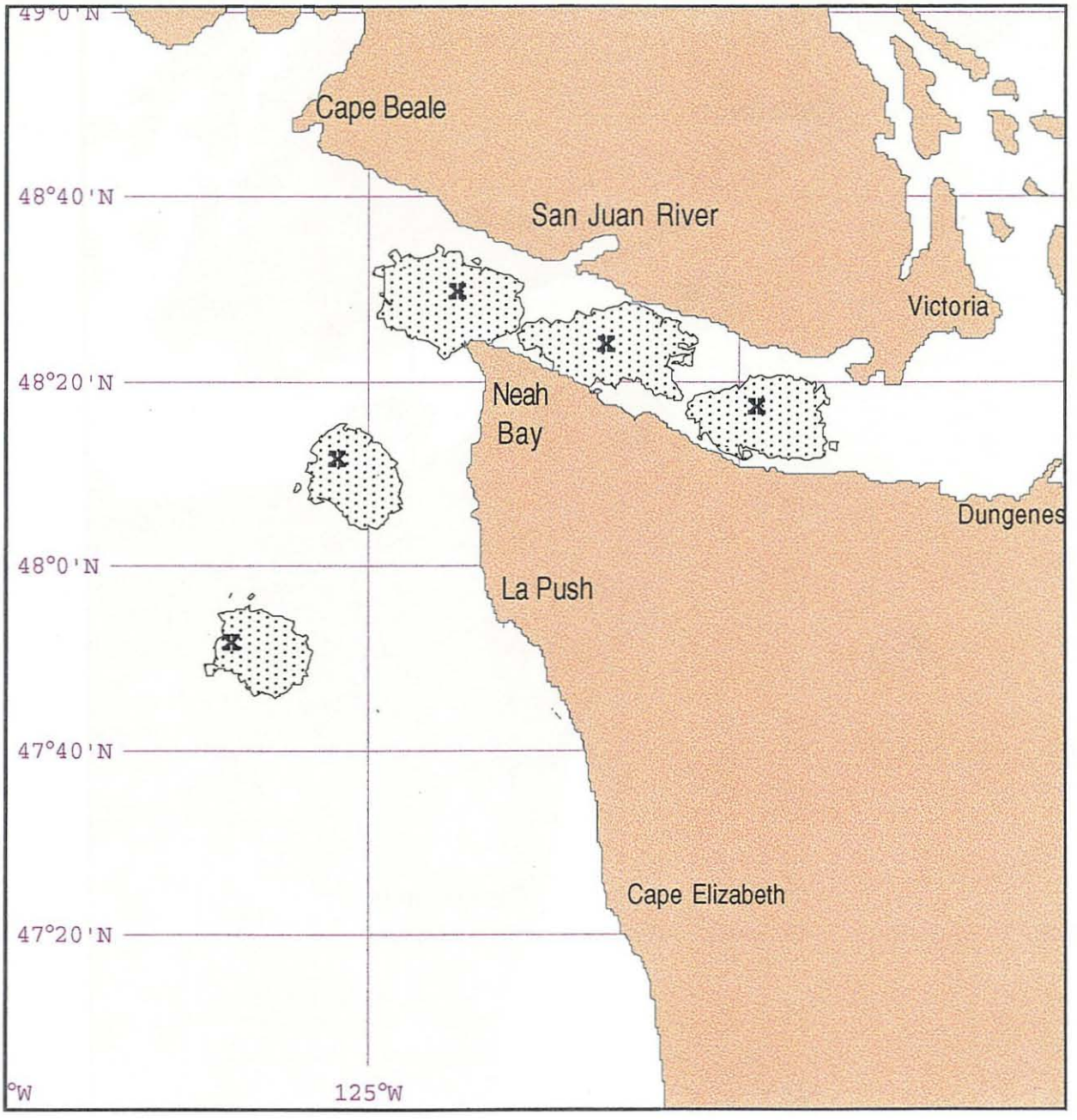

Figure A-24. Map of 8-hour probability contours, spring, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 4% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

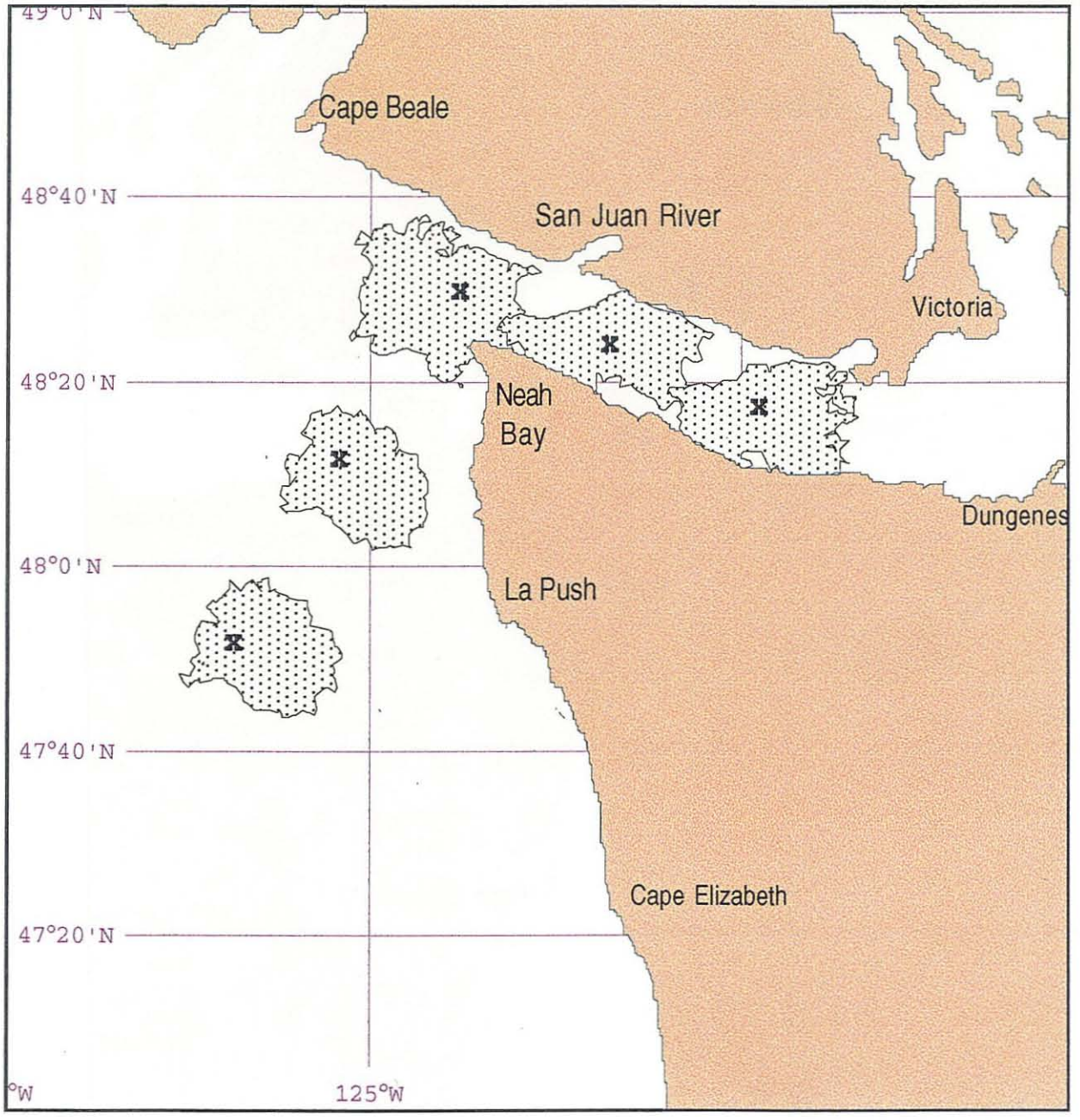

Figure A-25. Map of 12-hour probability contours, spring, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

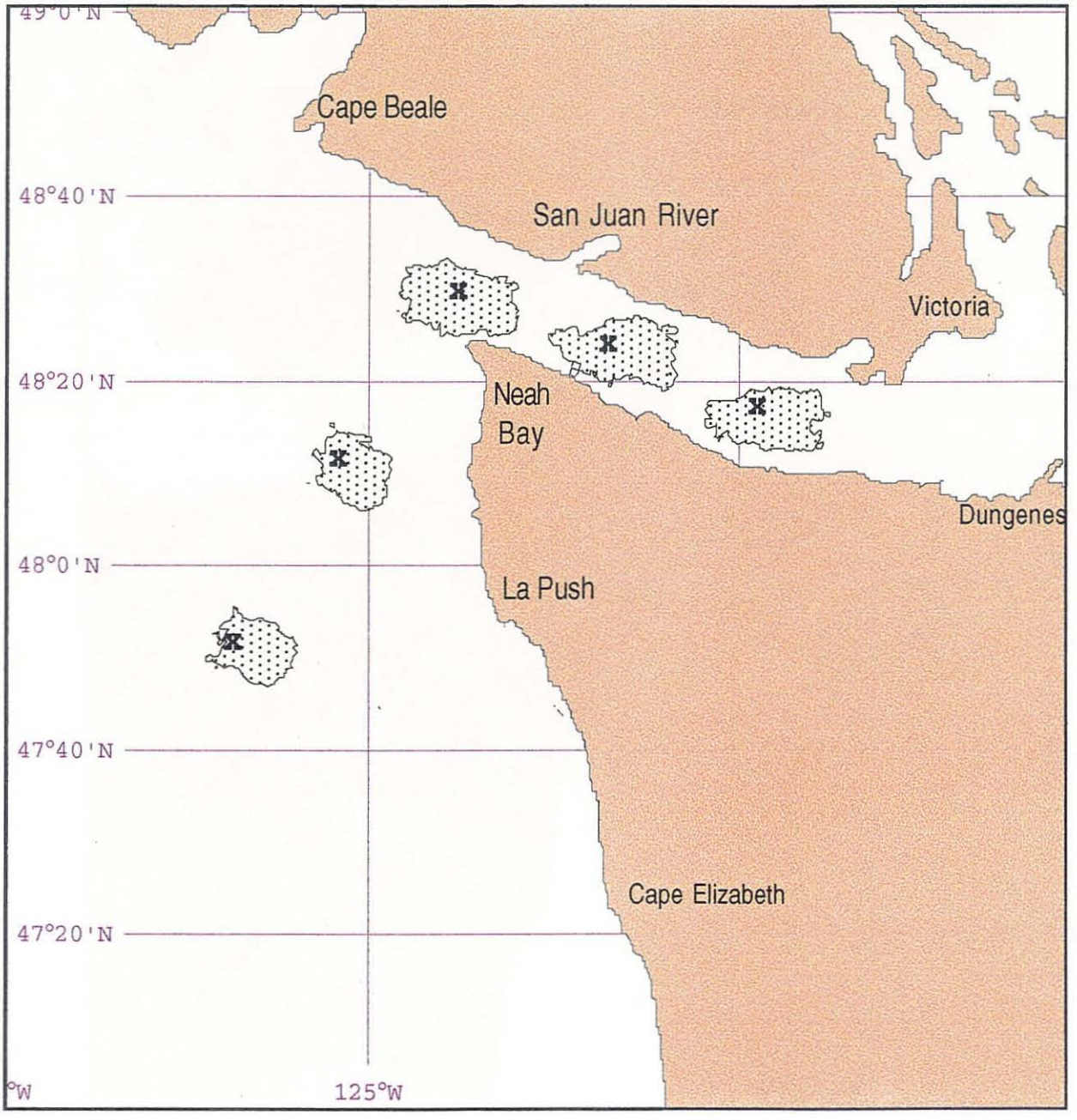

Figure A-26. Map of 4-hour probability contours, spring, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

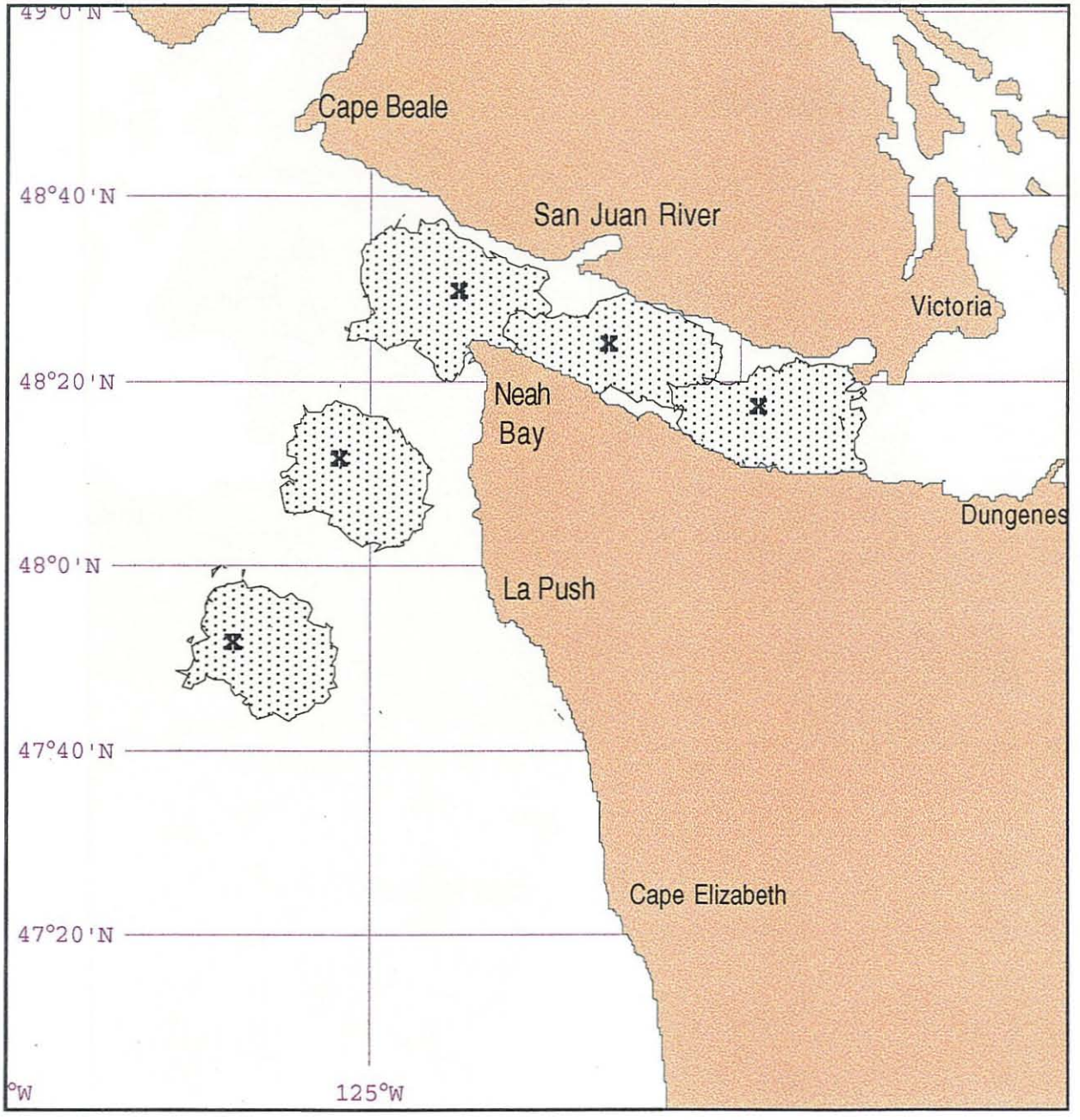

Figure A-27. Map of 8-hour probability contours, spring, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 6% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

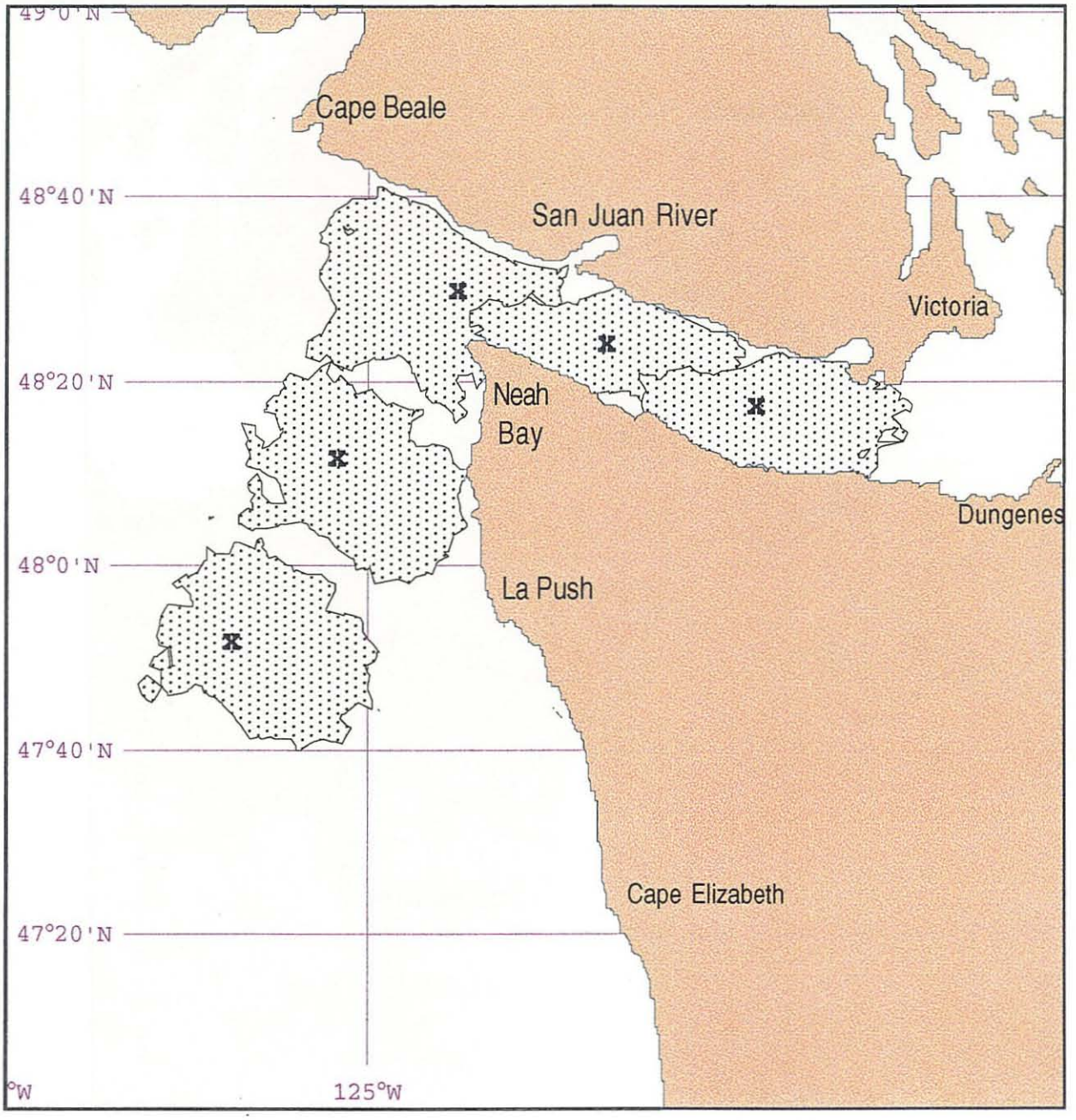

Figure A-28. Map of 12-hour probability contours, spring, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 8% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

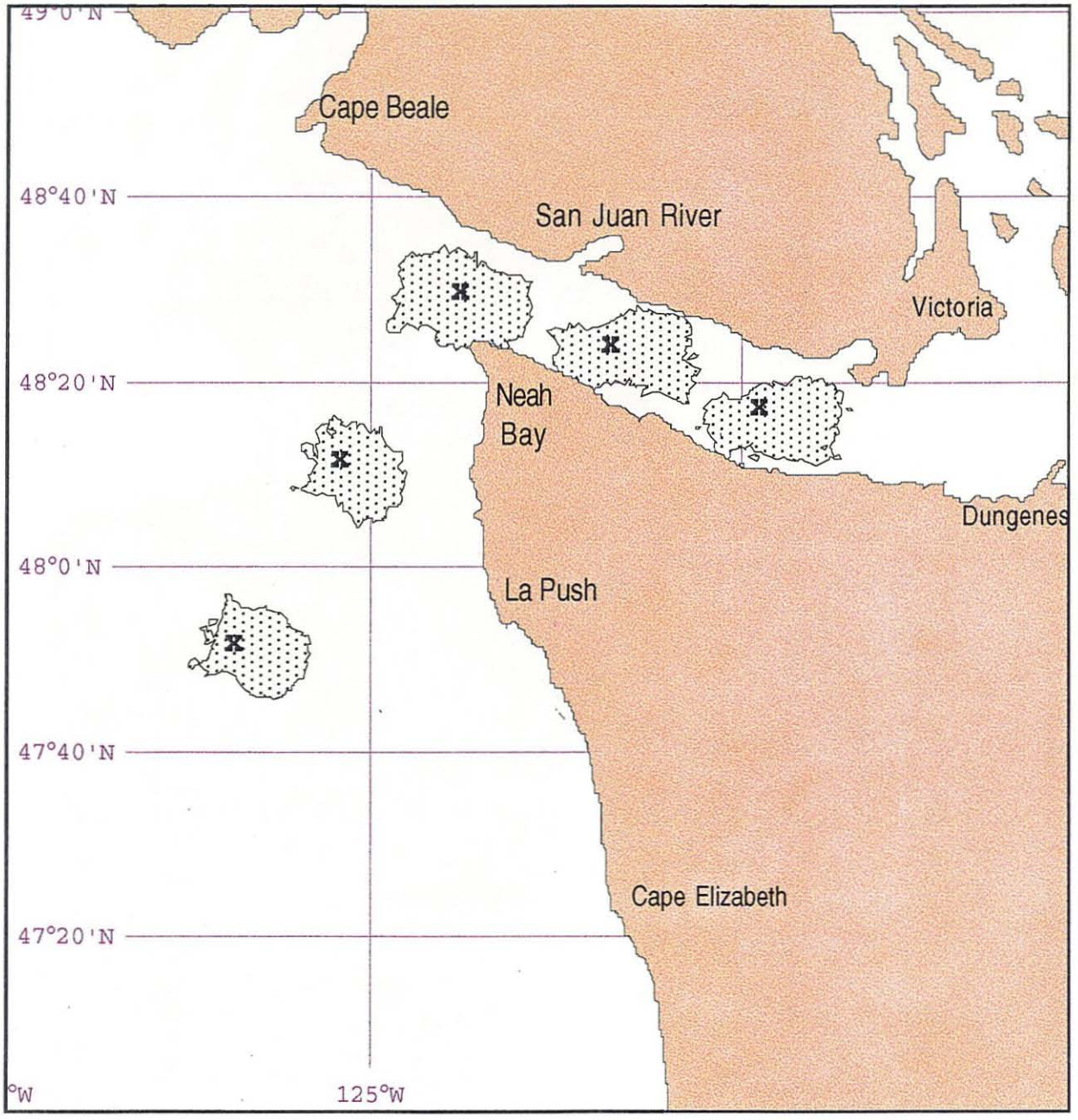

Figure A-29. Map of 4-hour probability contours, spring, 8 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

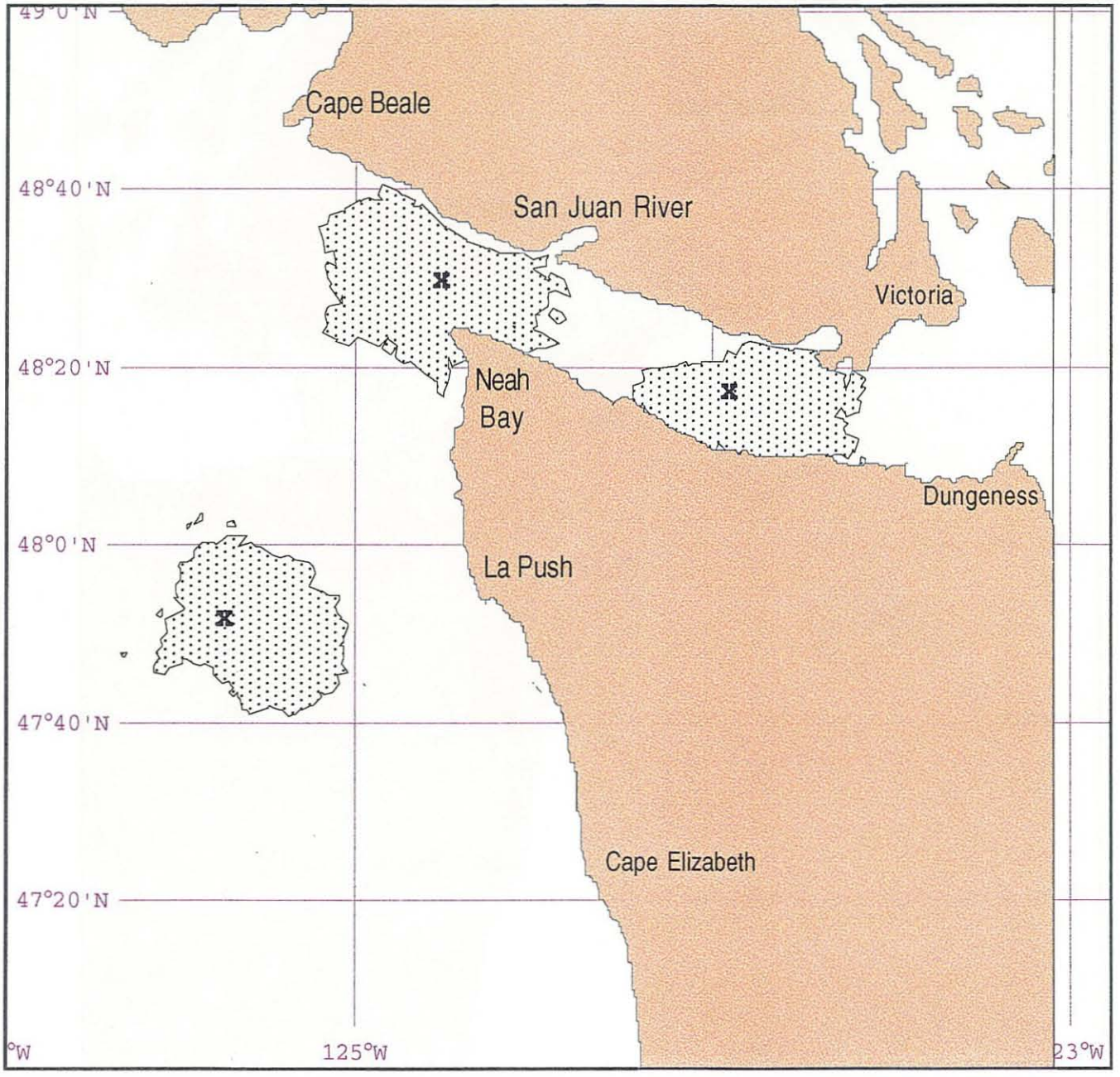

Figure A-30. Map of 8-hour probability contours, spring, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

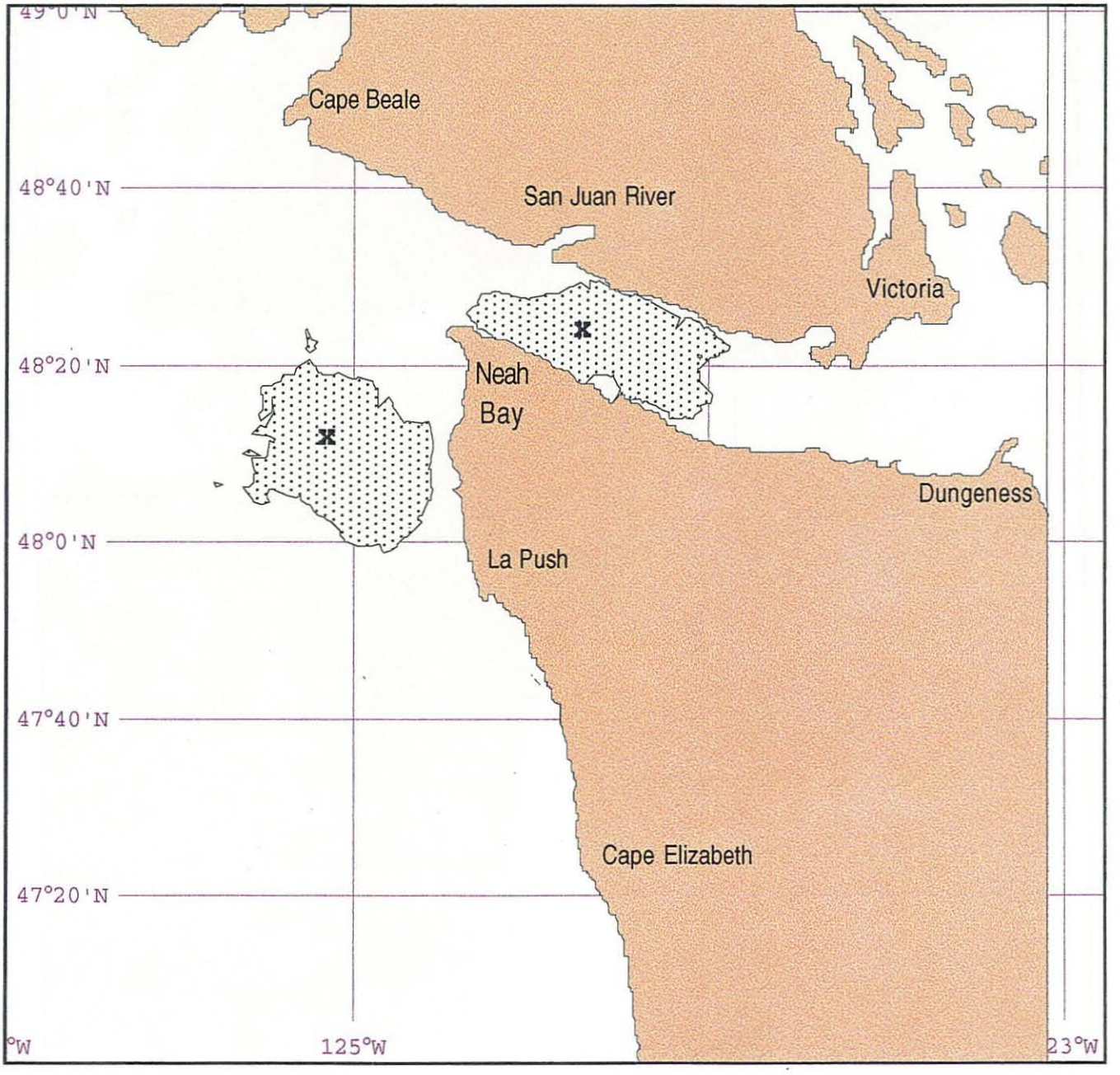

Figure A-31. Map of 8-hour probability contours, spring, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

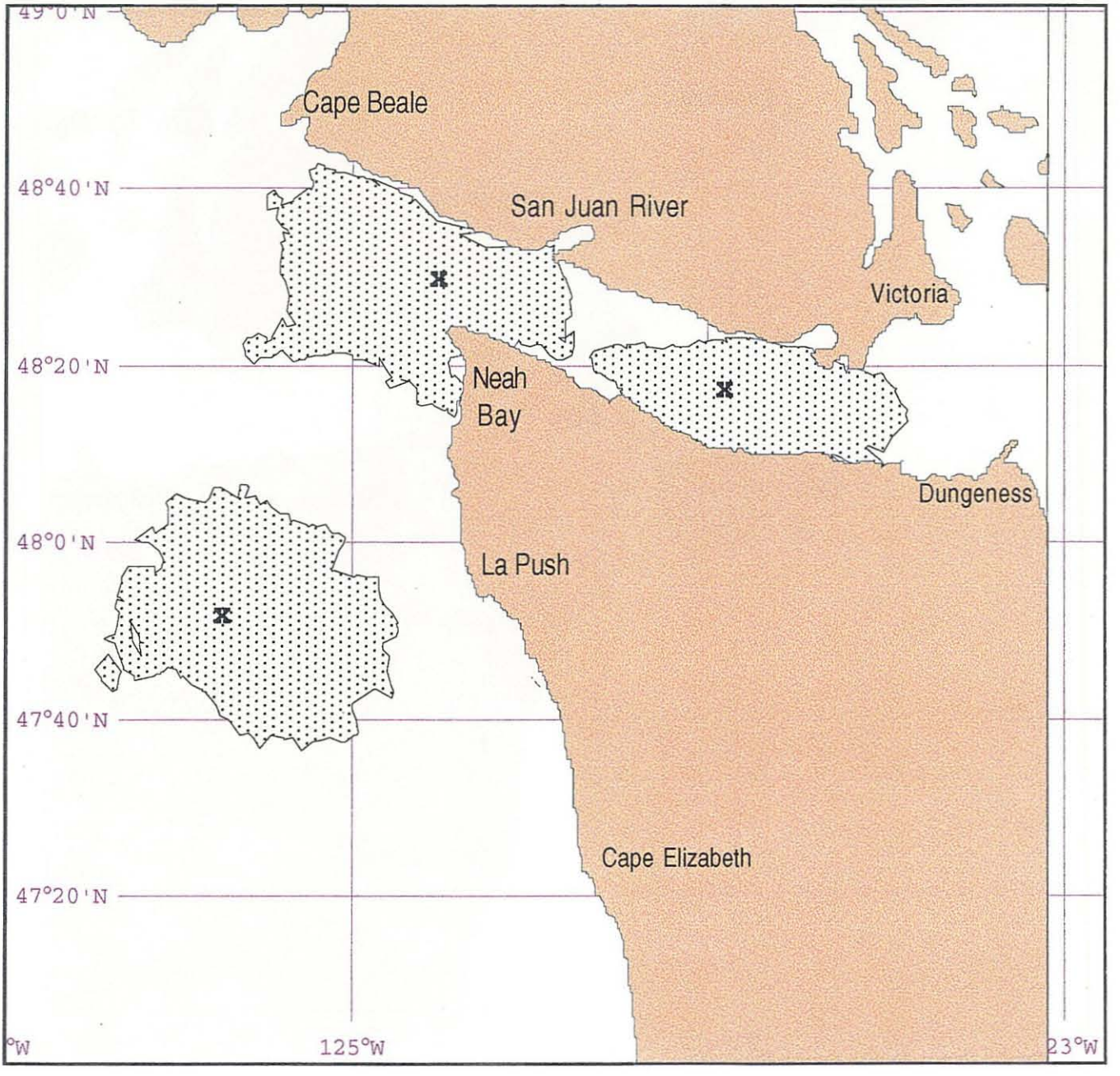

Figure A-32. Map of 12-hour probability contours, spring, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

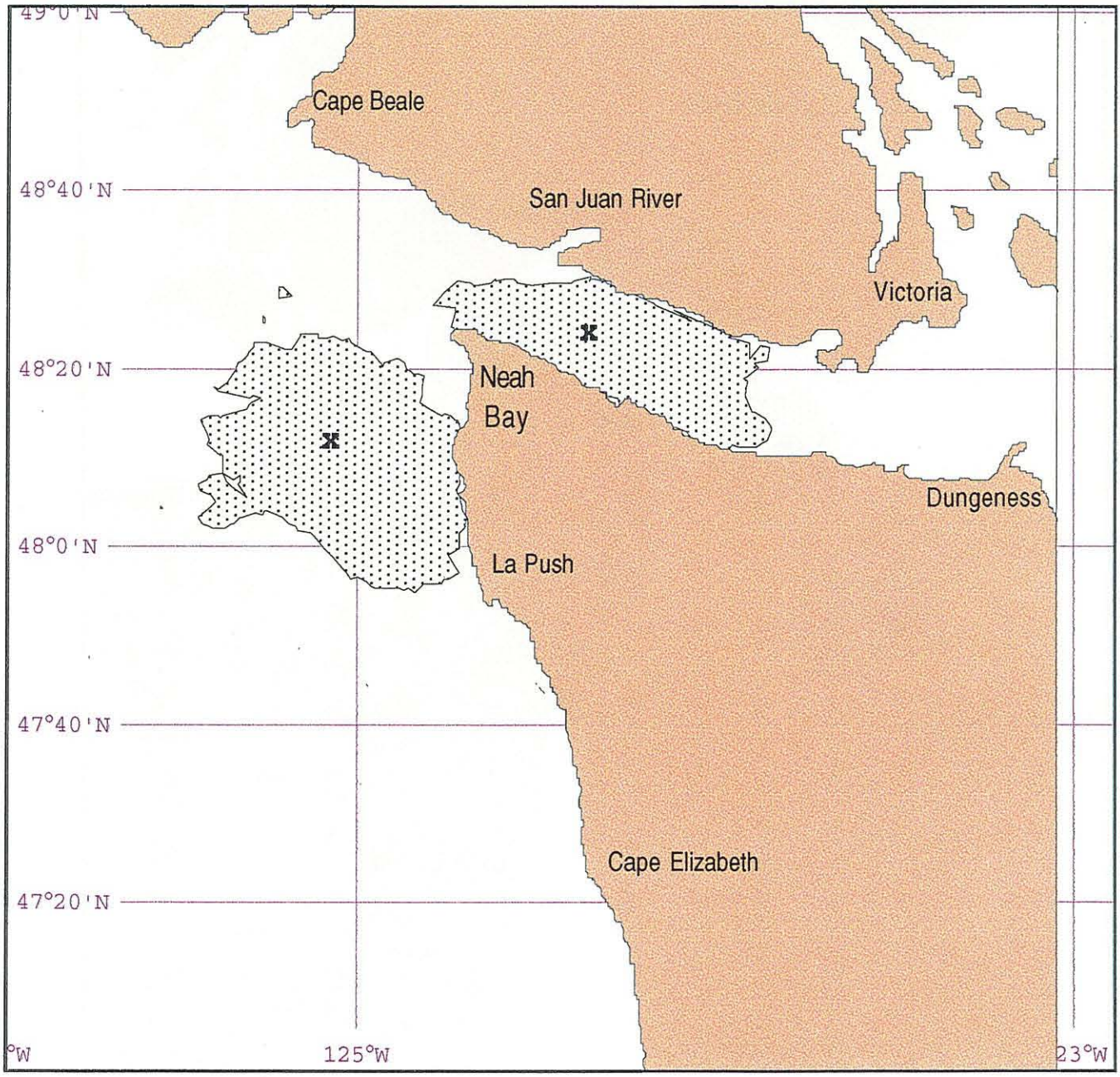

Figure A-33. Map of 12-hour probability contours, spring, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
Ship drift: 10% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

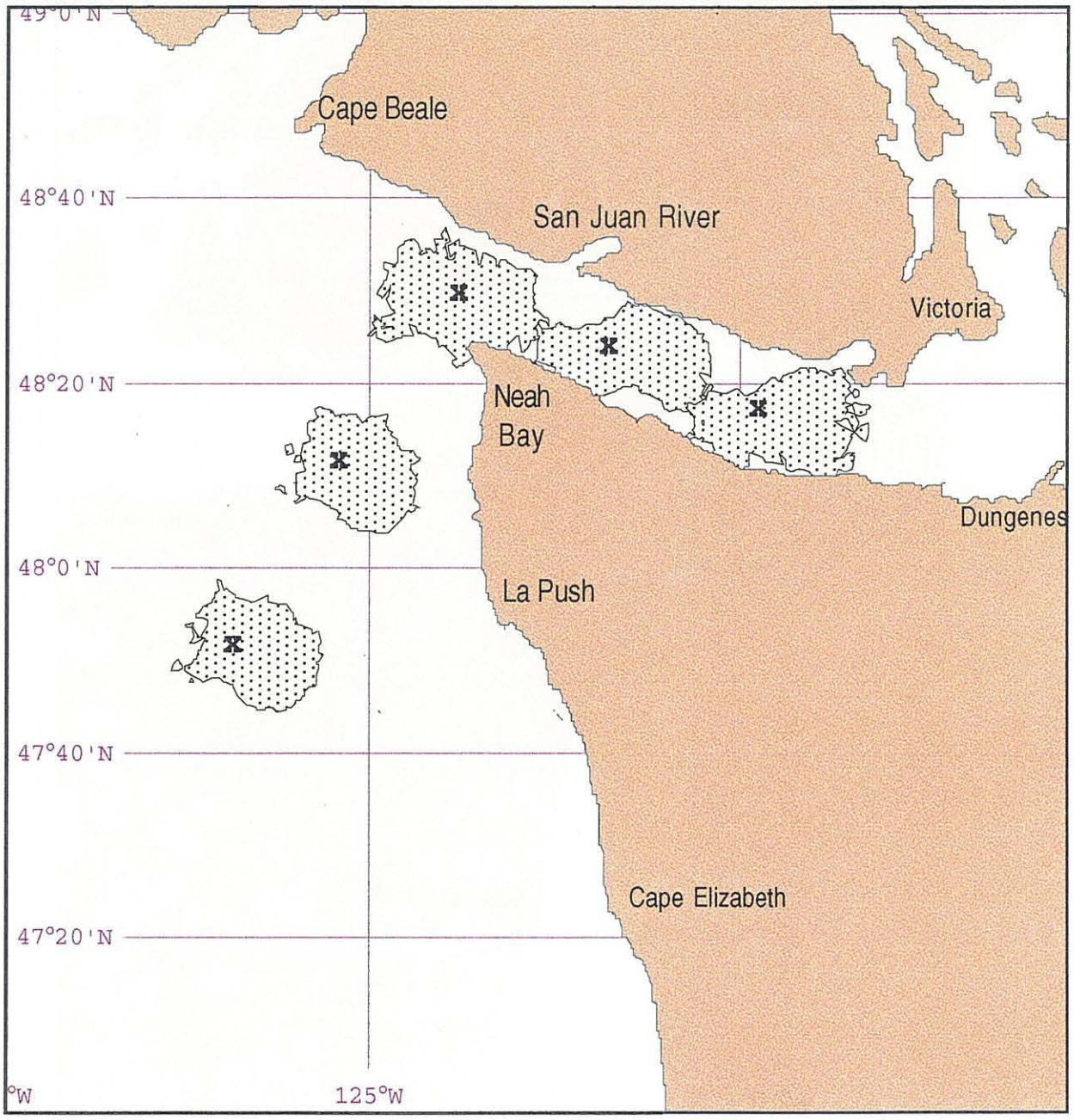

Figure A-34. Map of 4-hour probability contours, spring, 10 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

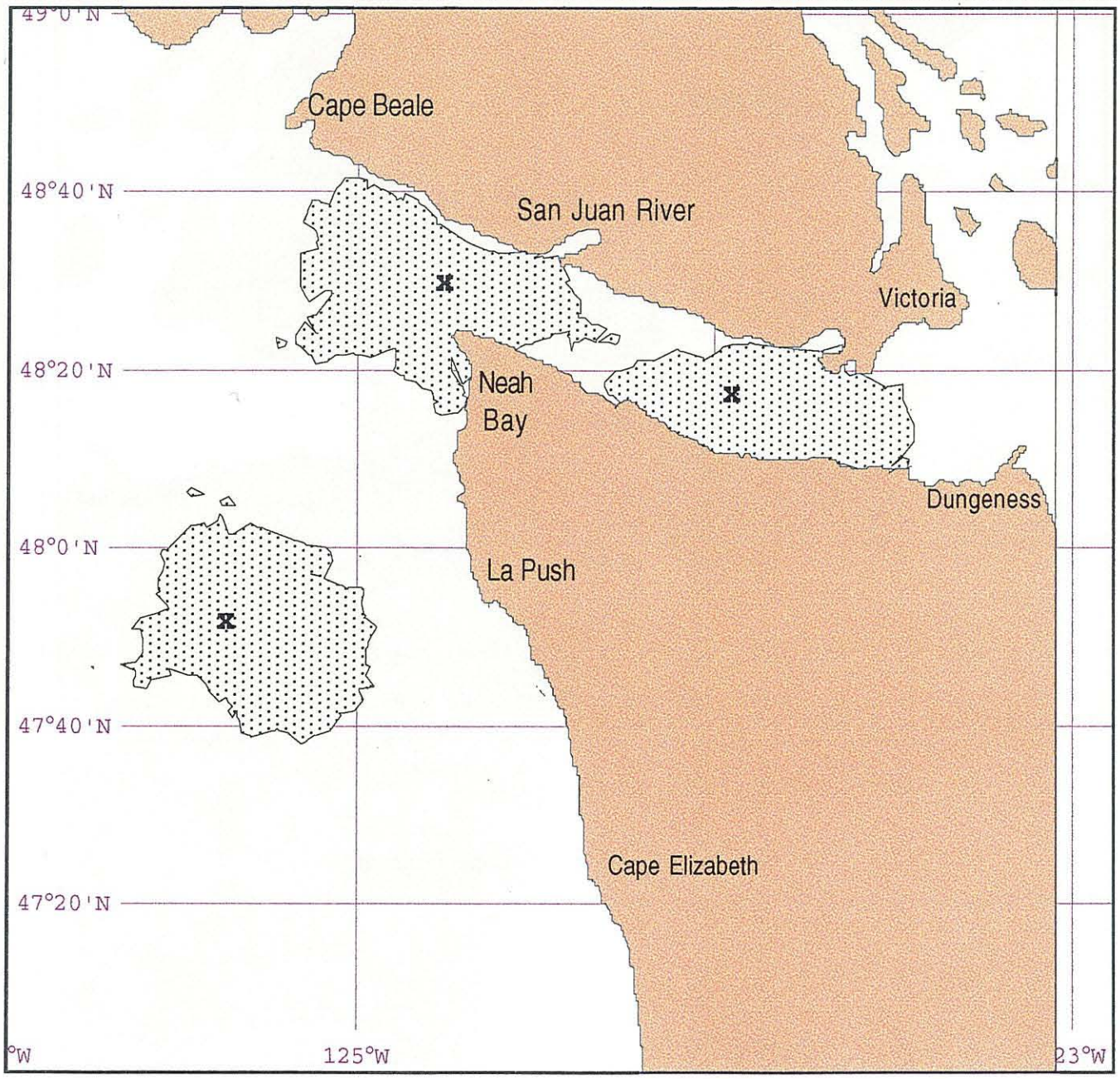

Figure A-35. Map of 8-hour probability contours, spring, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

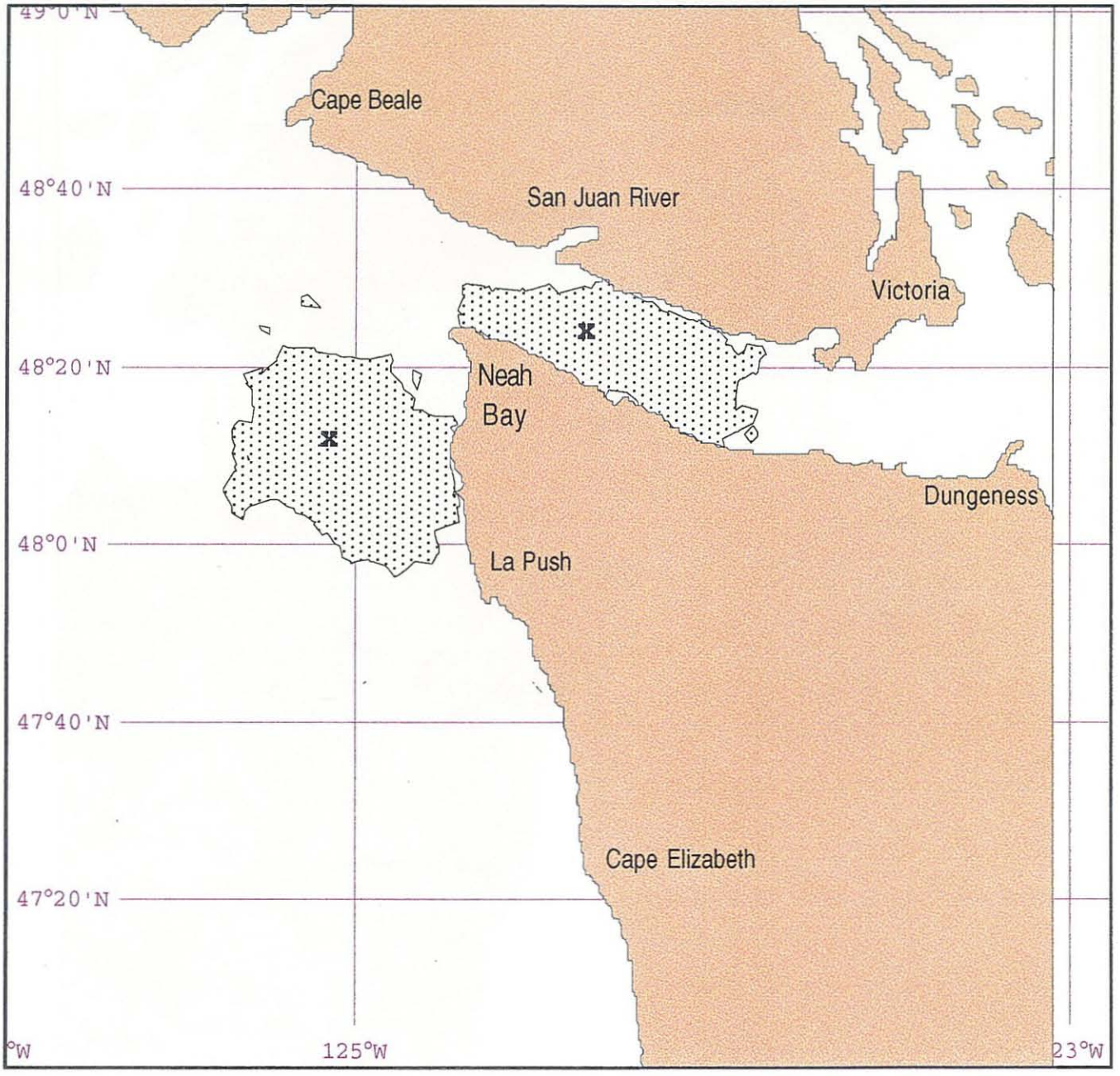

Figure A-36. Map of 8-hour probability contours, spring, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

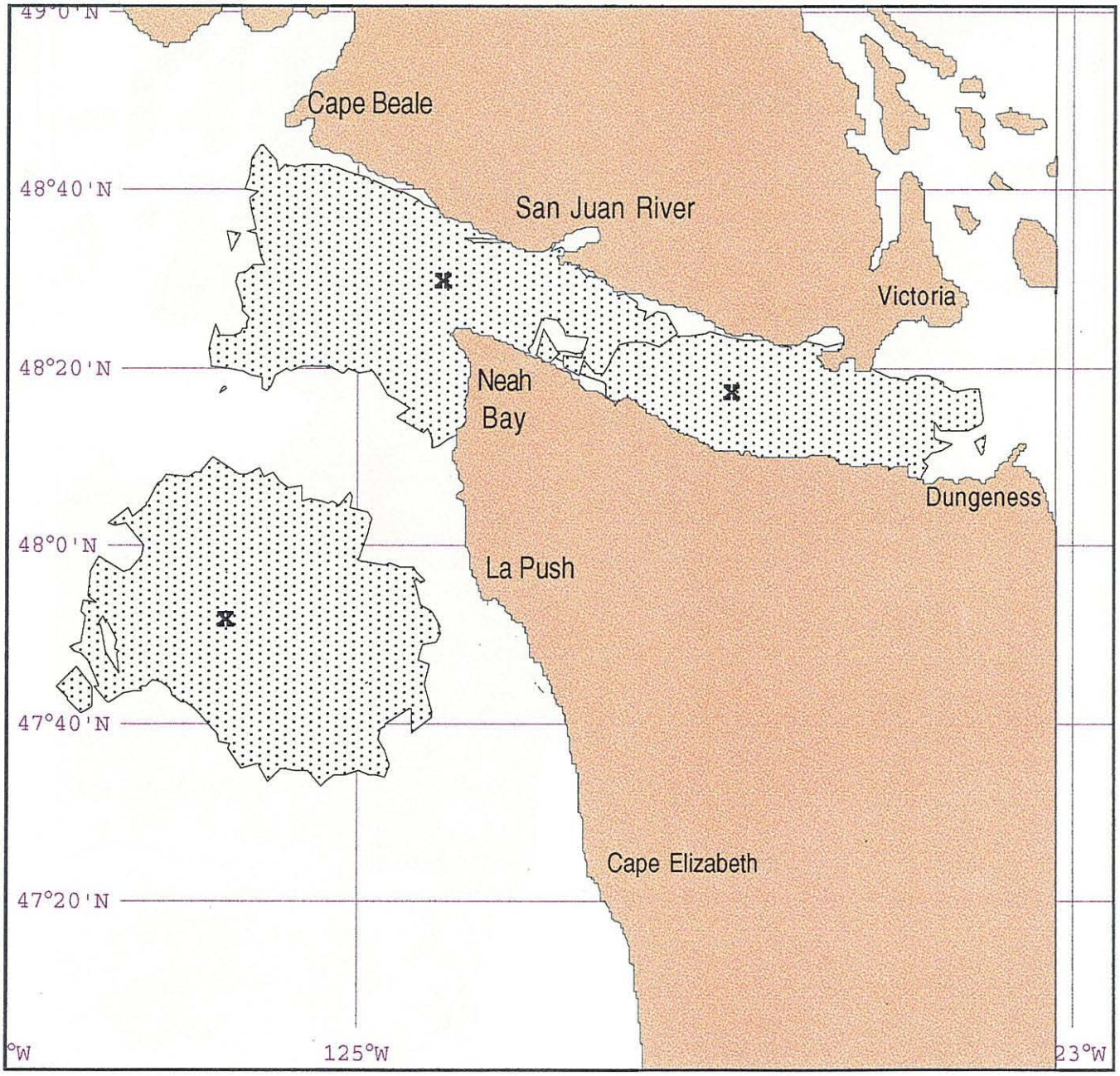

Figure A-37. Map of 12-hour probability contours, spring, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Spring
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

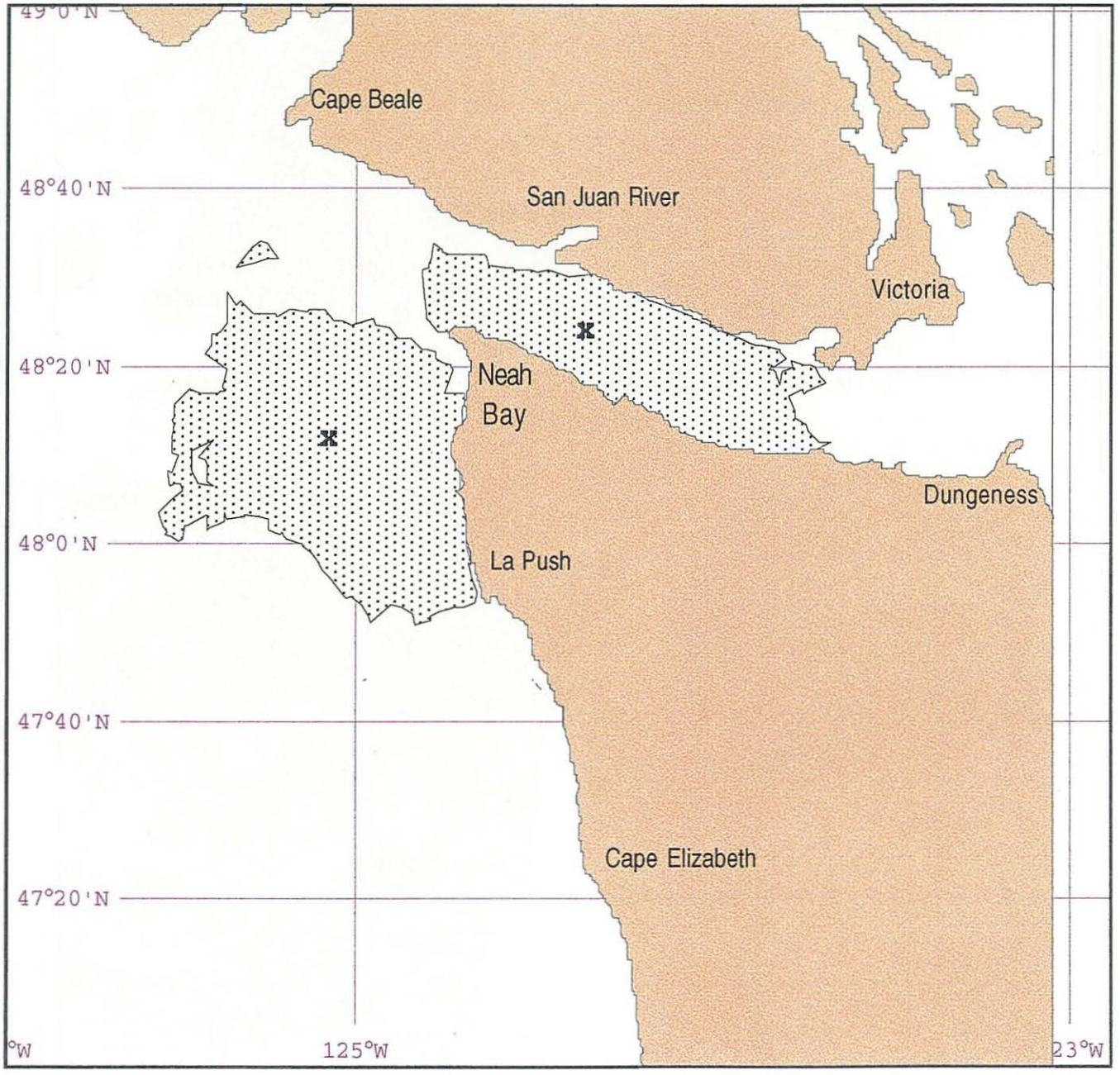

Figure A-38. Map of 12-hour probability contours, spring, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 2% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

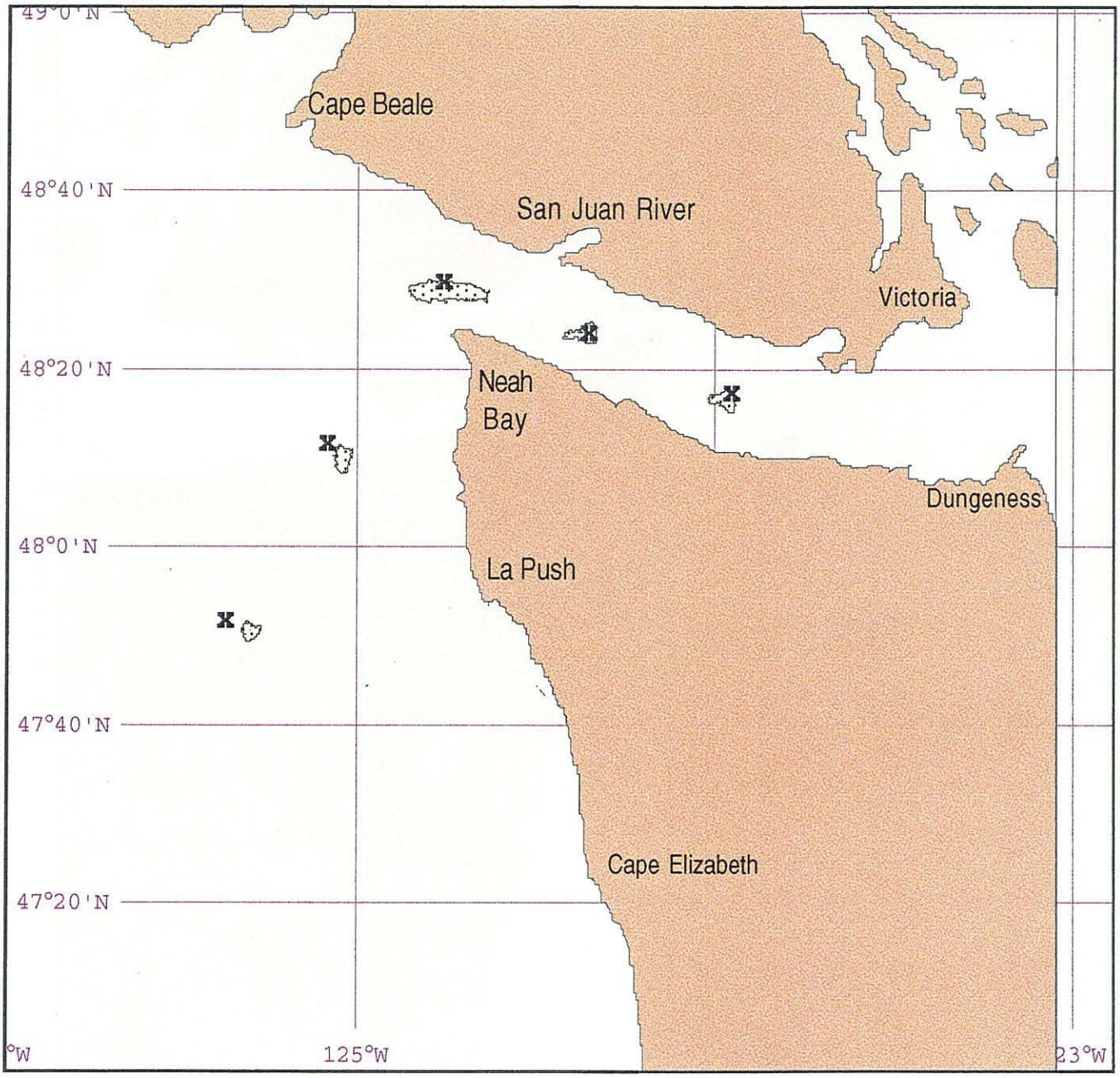

Figure A-39. Map of 4-hour probability contours, summer, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 2% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

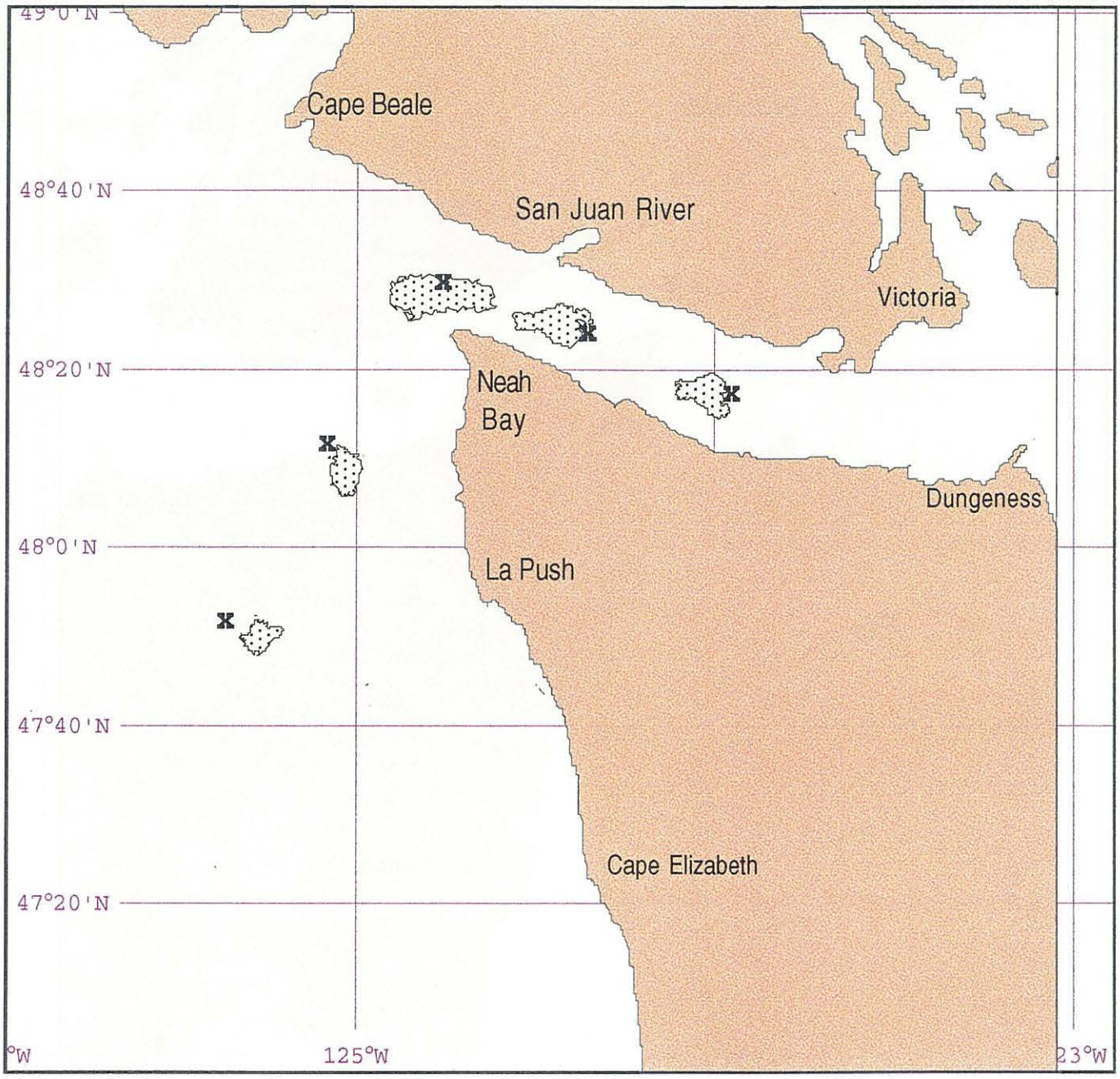

Figure A-40. Map of 8-hour probability contours, summer, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 2% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

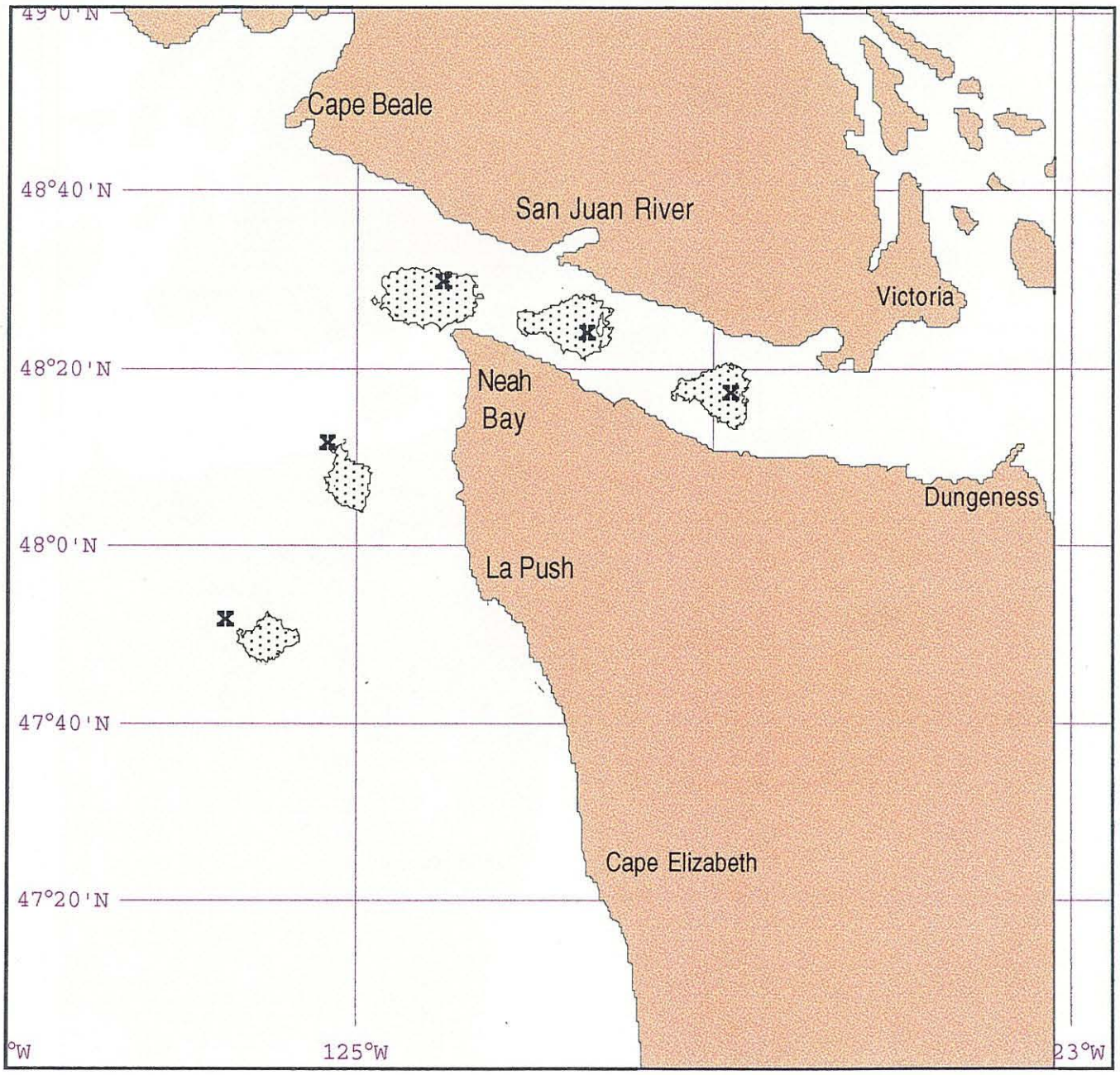

Figure A-41. Map of 12-hour probability contours, summer, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 4% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

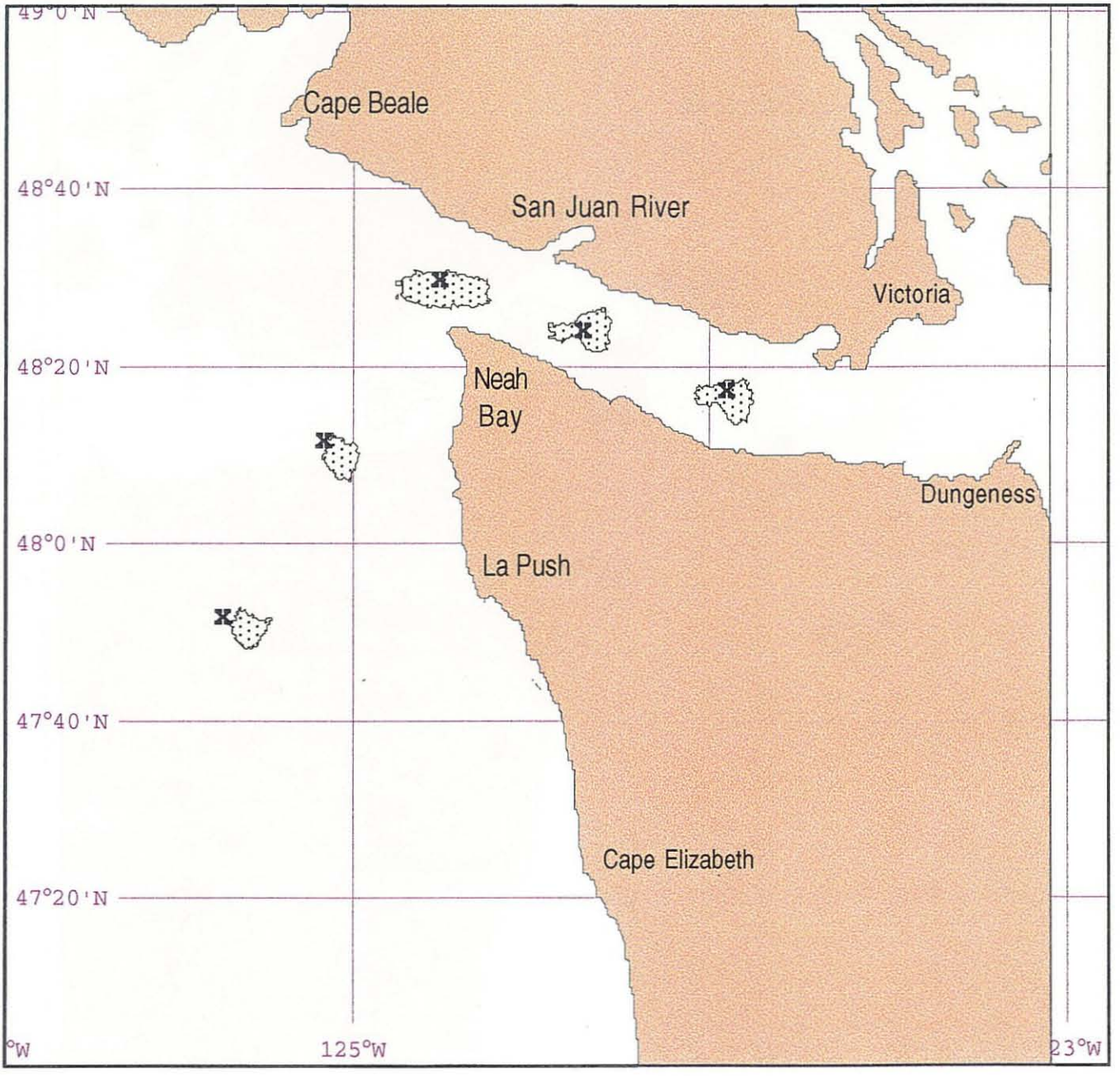

Figure A-42. Map of 4-hour probability contours, summer, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 4% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

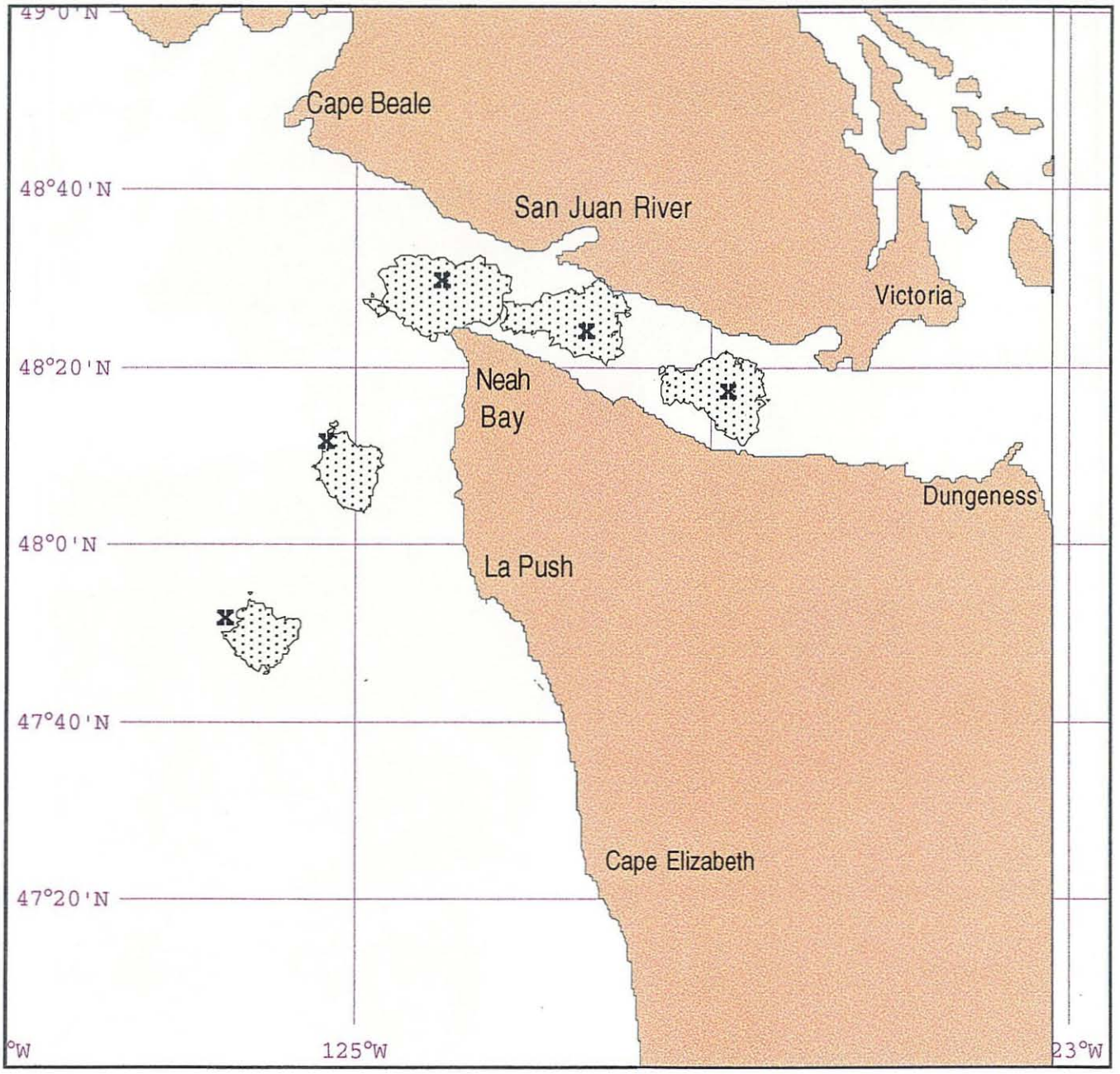

Figure A-43. Map of 8-hour probability contours, summer, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 4% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

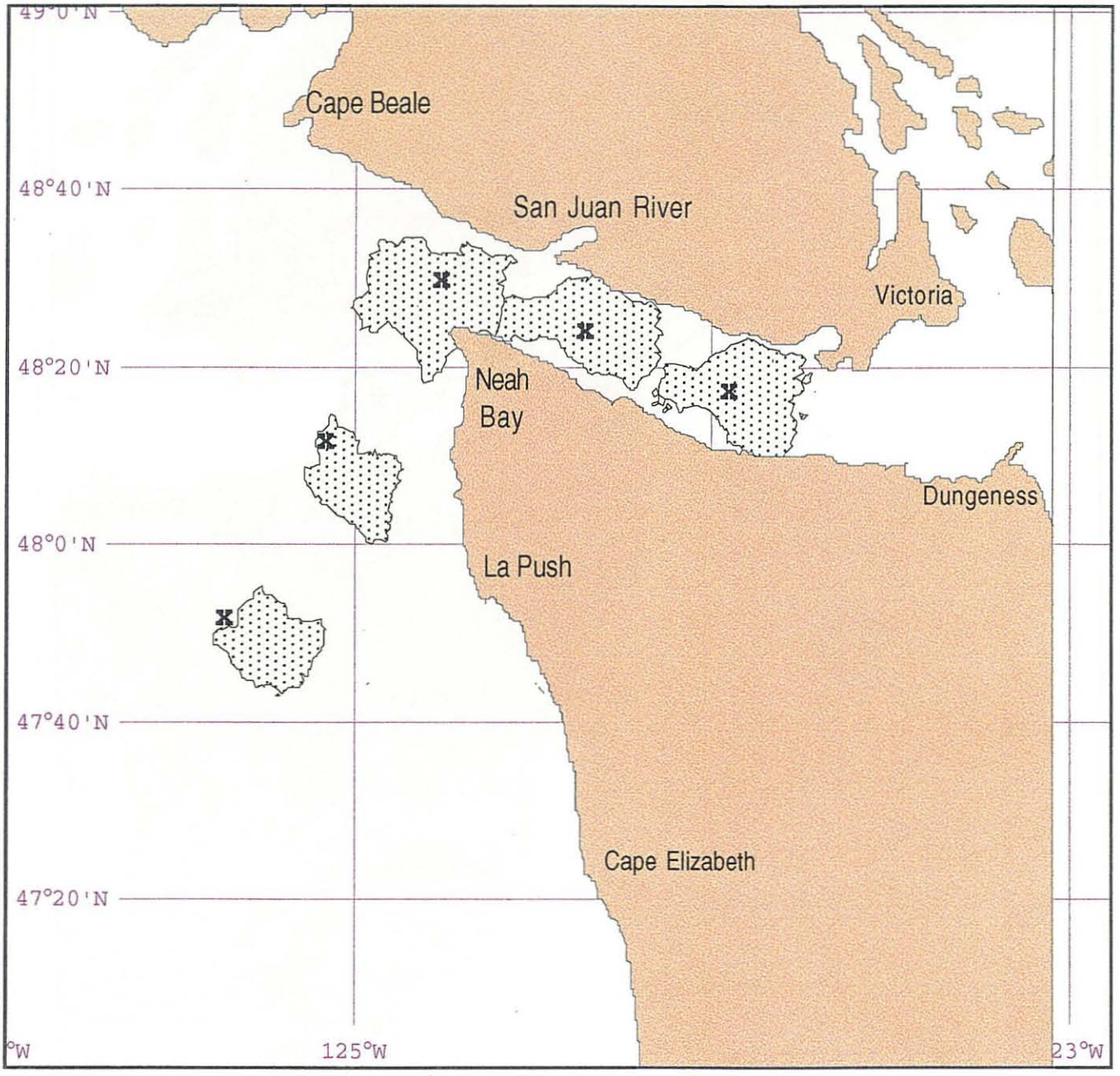

Figure A-44. Map of 12-hour probability contours, summer, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 6% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

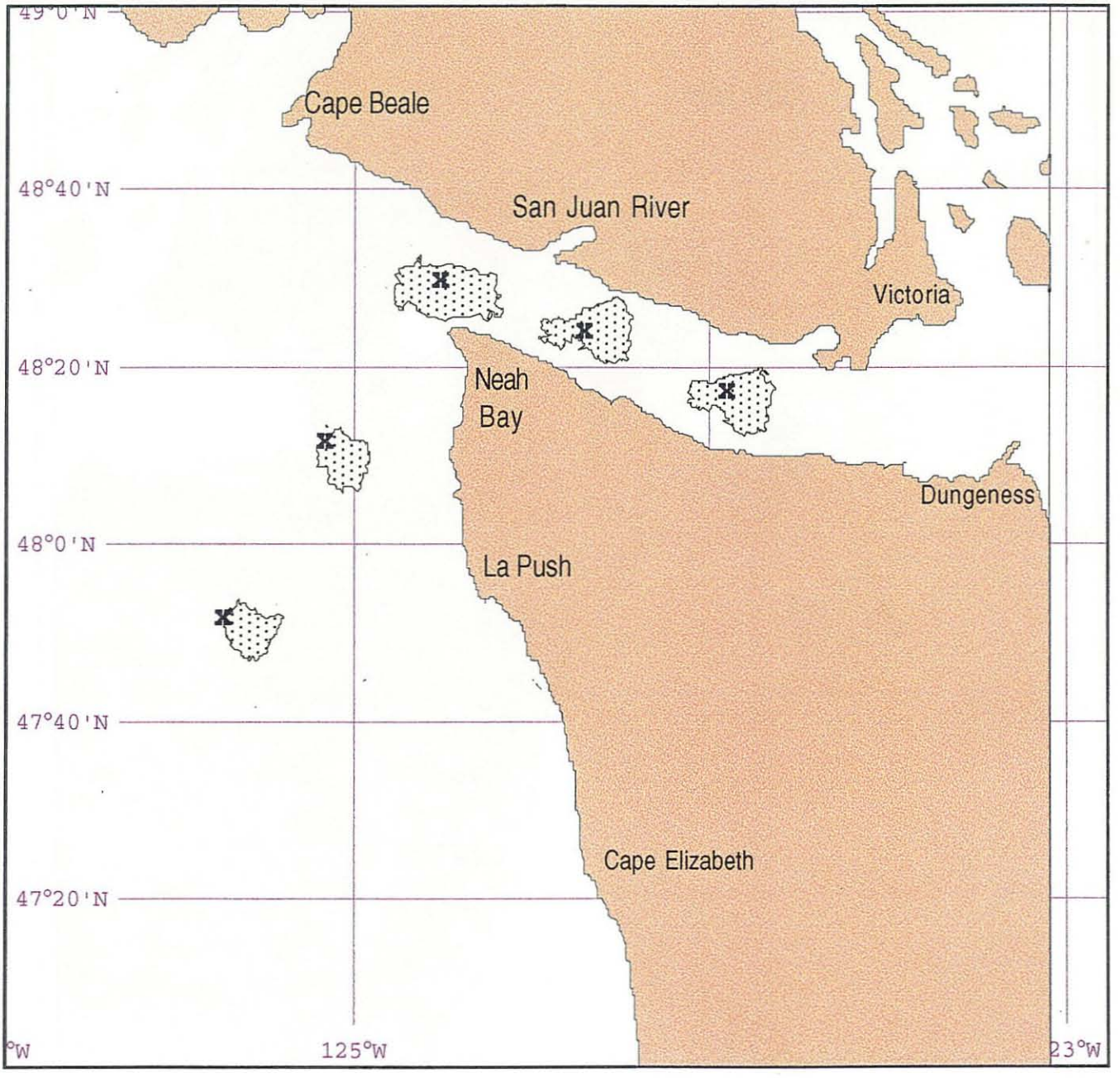

Figure A-45. Map of 4-hour probability contours, summer, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 6% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

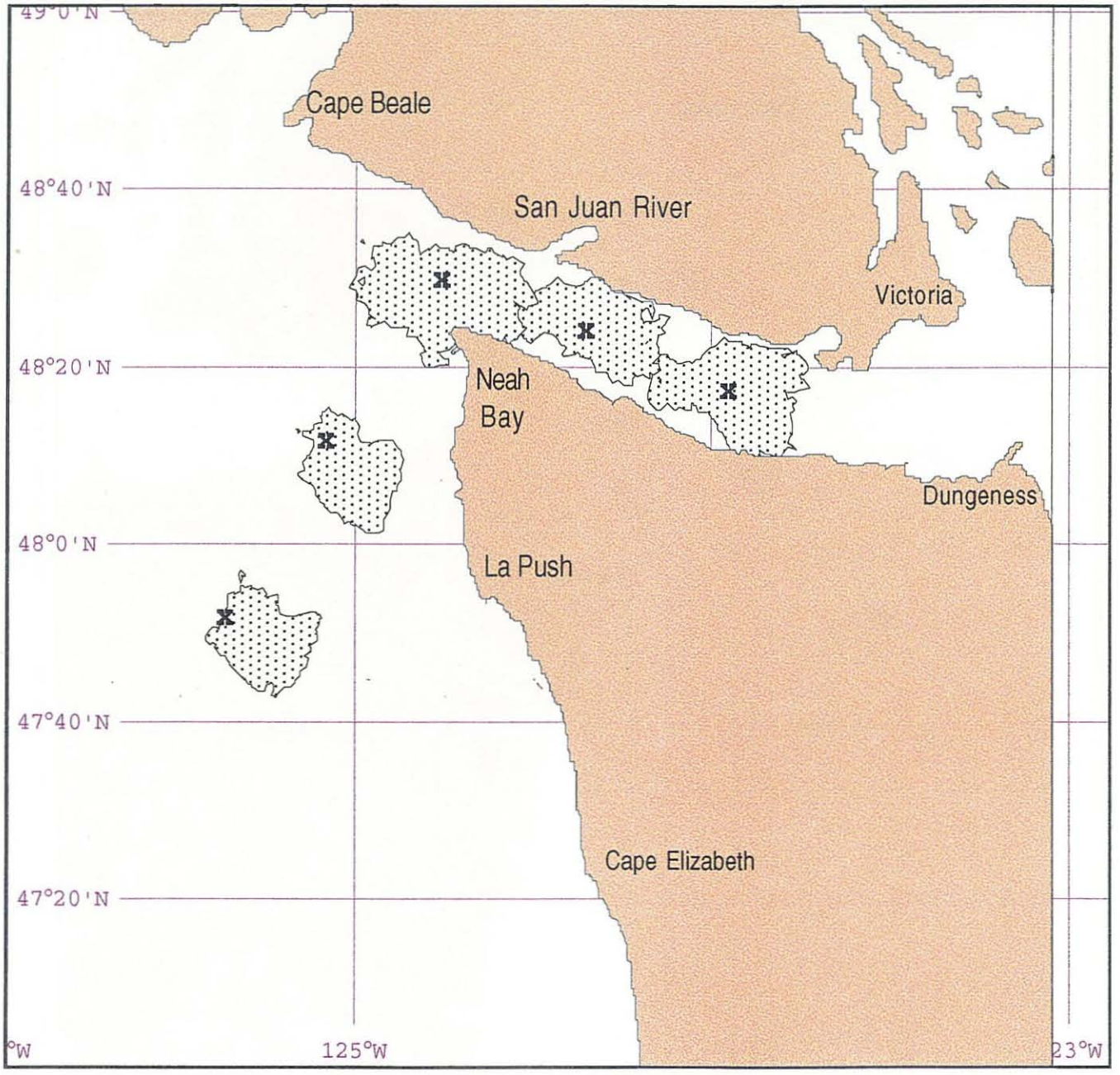

Figure A-46. Map of 8-hour probability contours, summer, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 6% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

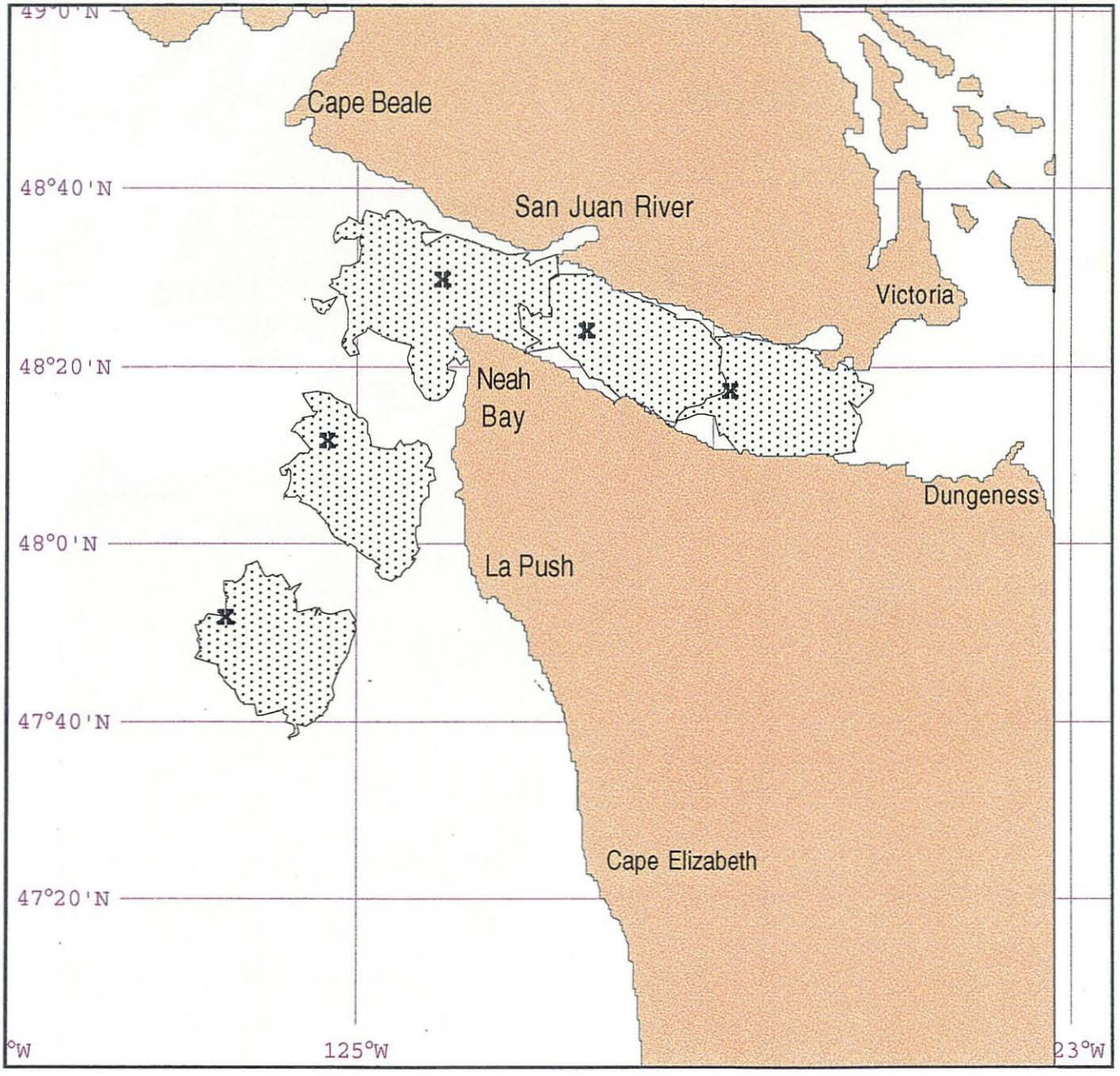

Figure A-47. Map of 12-hour probability contours, summer, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

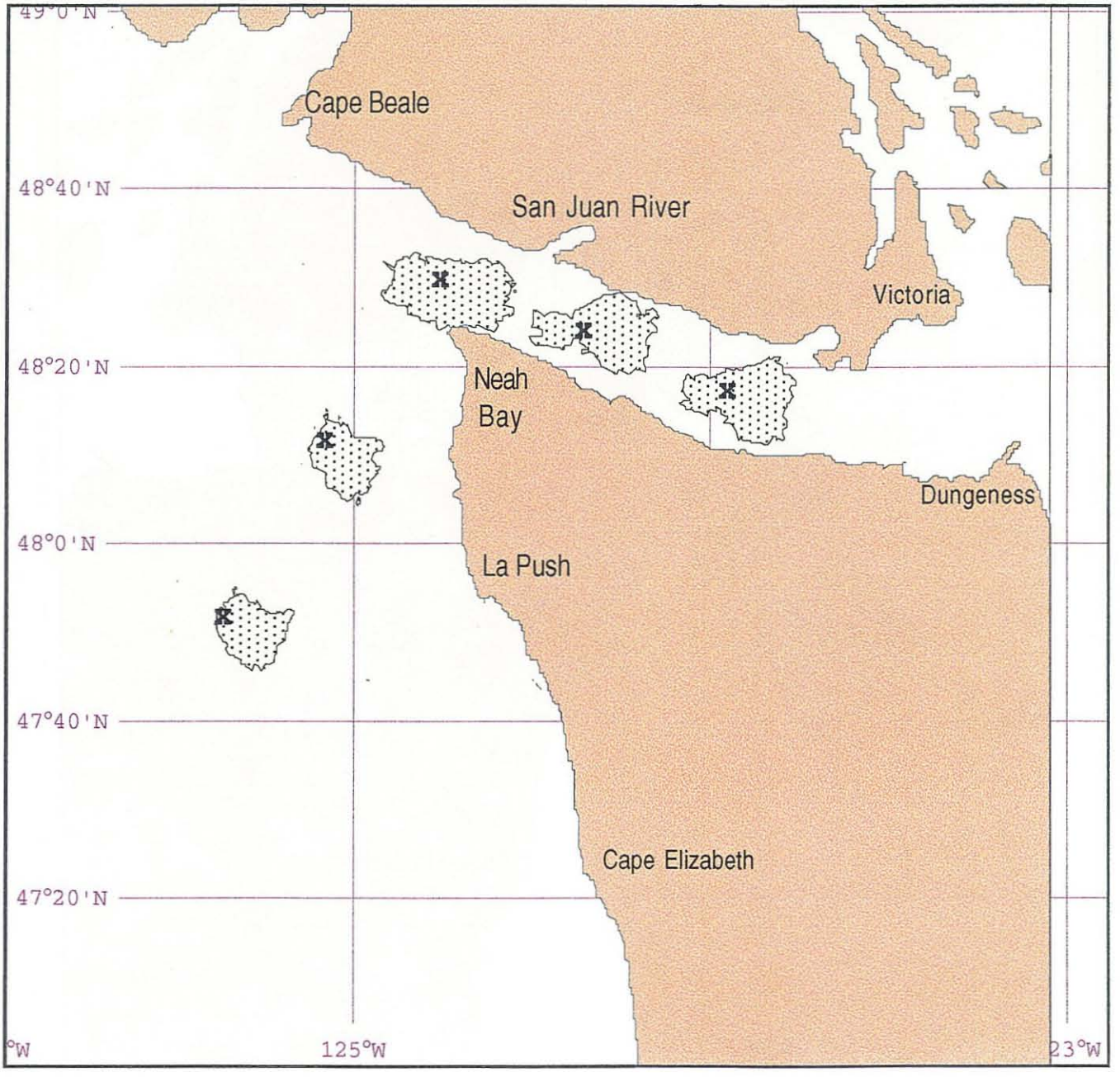

Figure A-48. Map of 4-hour probability contours, summer, 8 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

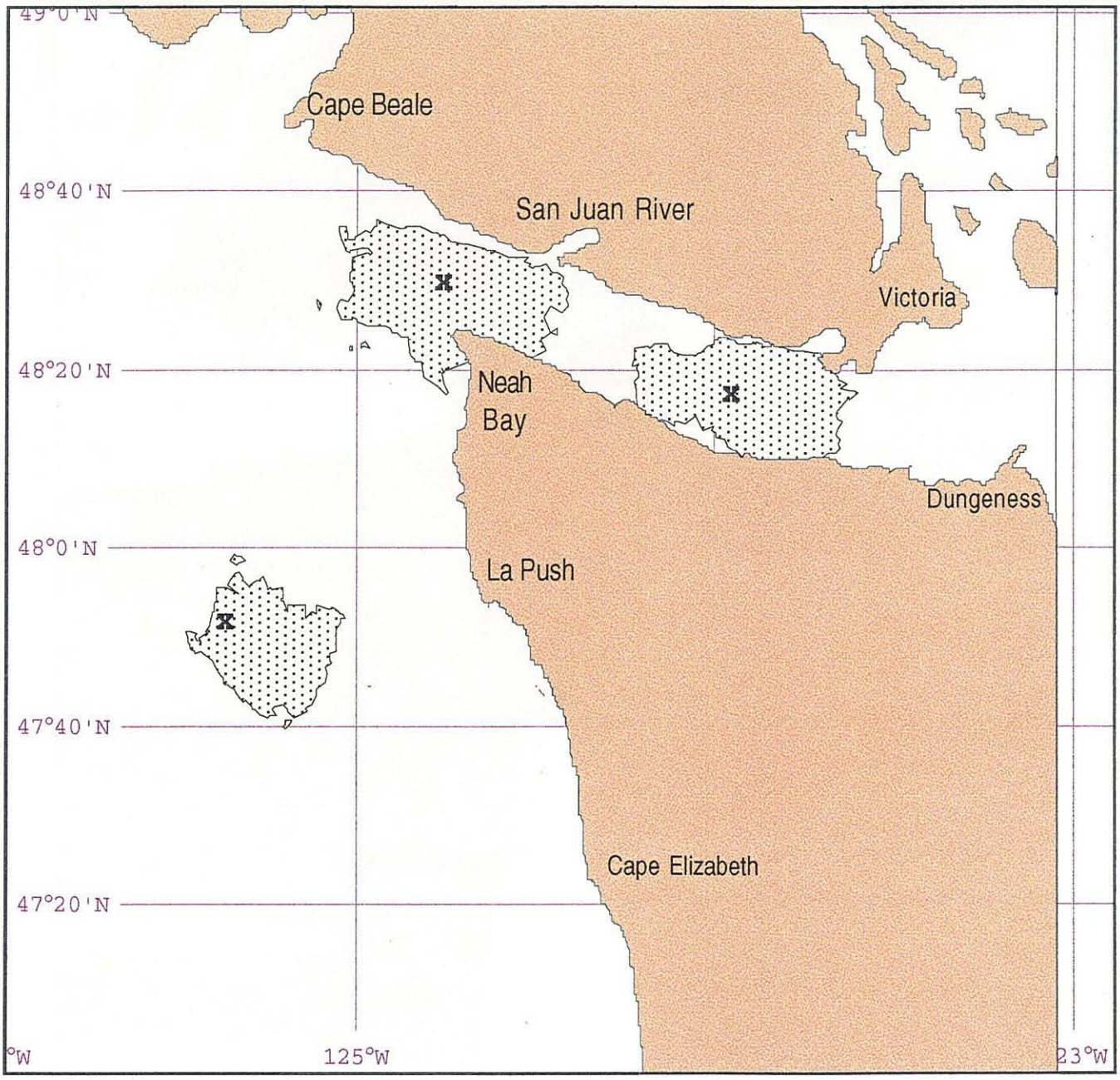

Figure A-49. Map of 8-hour probability contours, summer, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

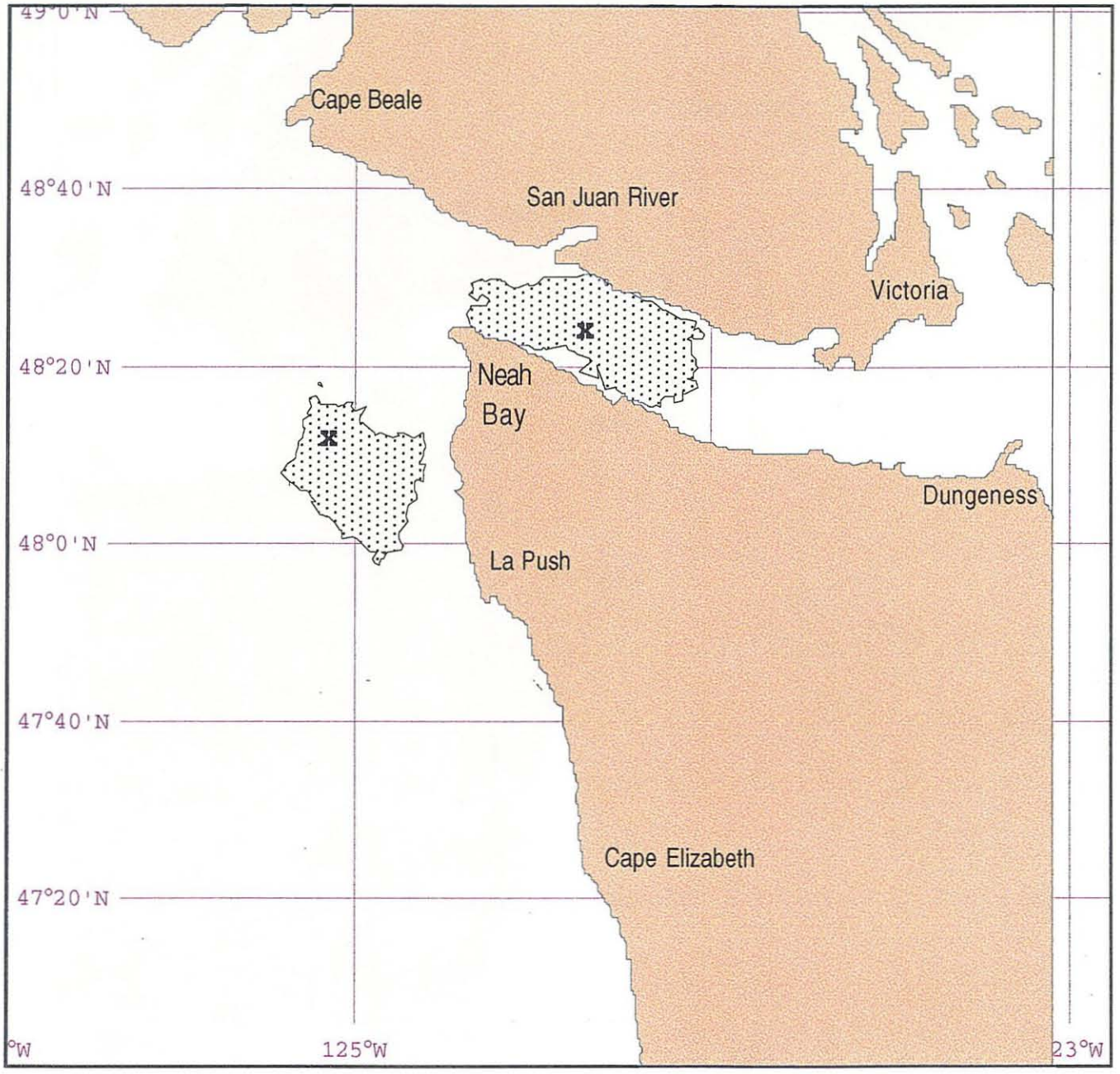

Figure A-50. Map of 8-hour probability contours, summer, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , 5/27/97 NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

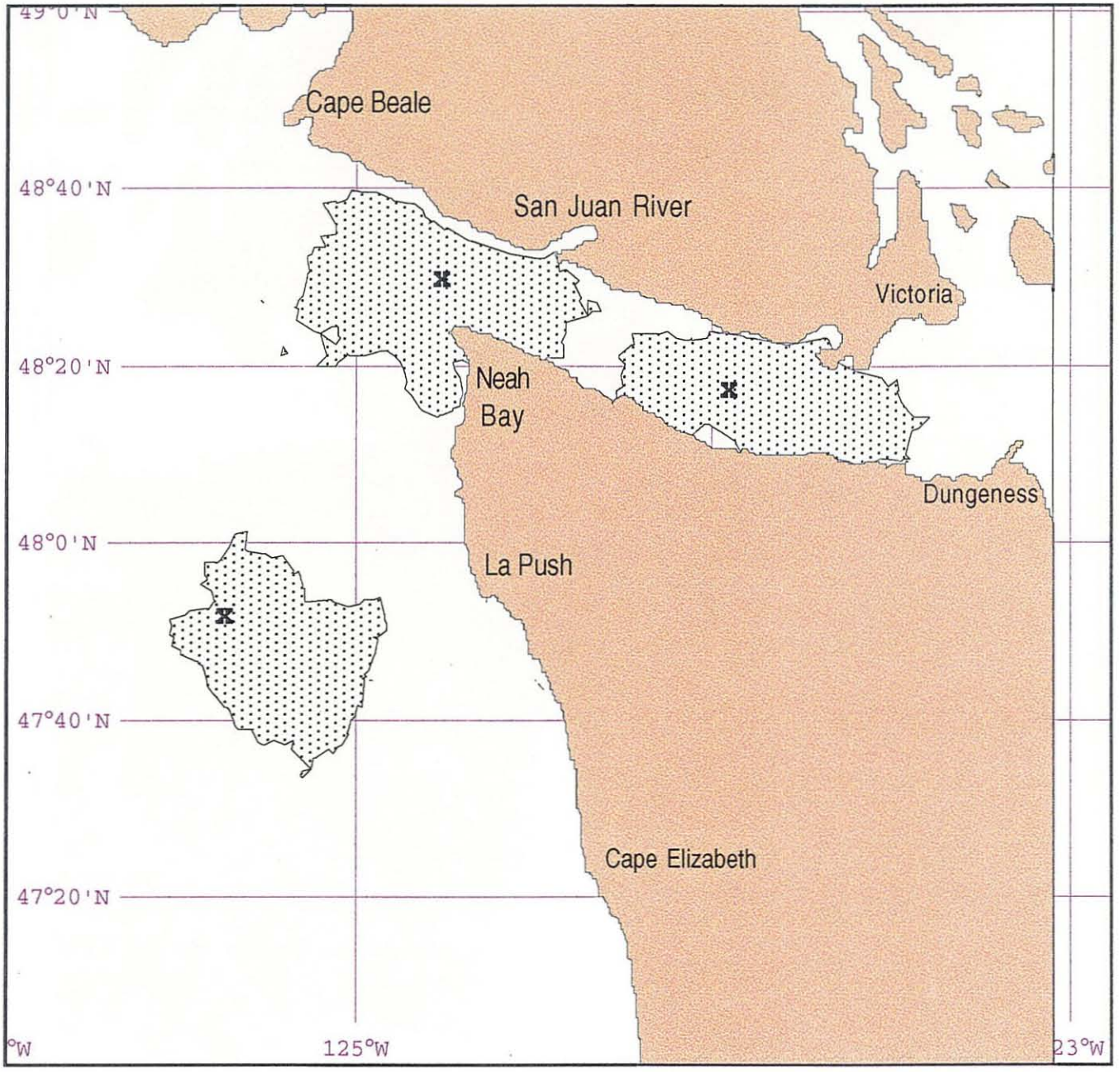

Figure A-51. Map of 12-hour probability contours, summer, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

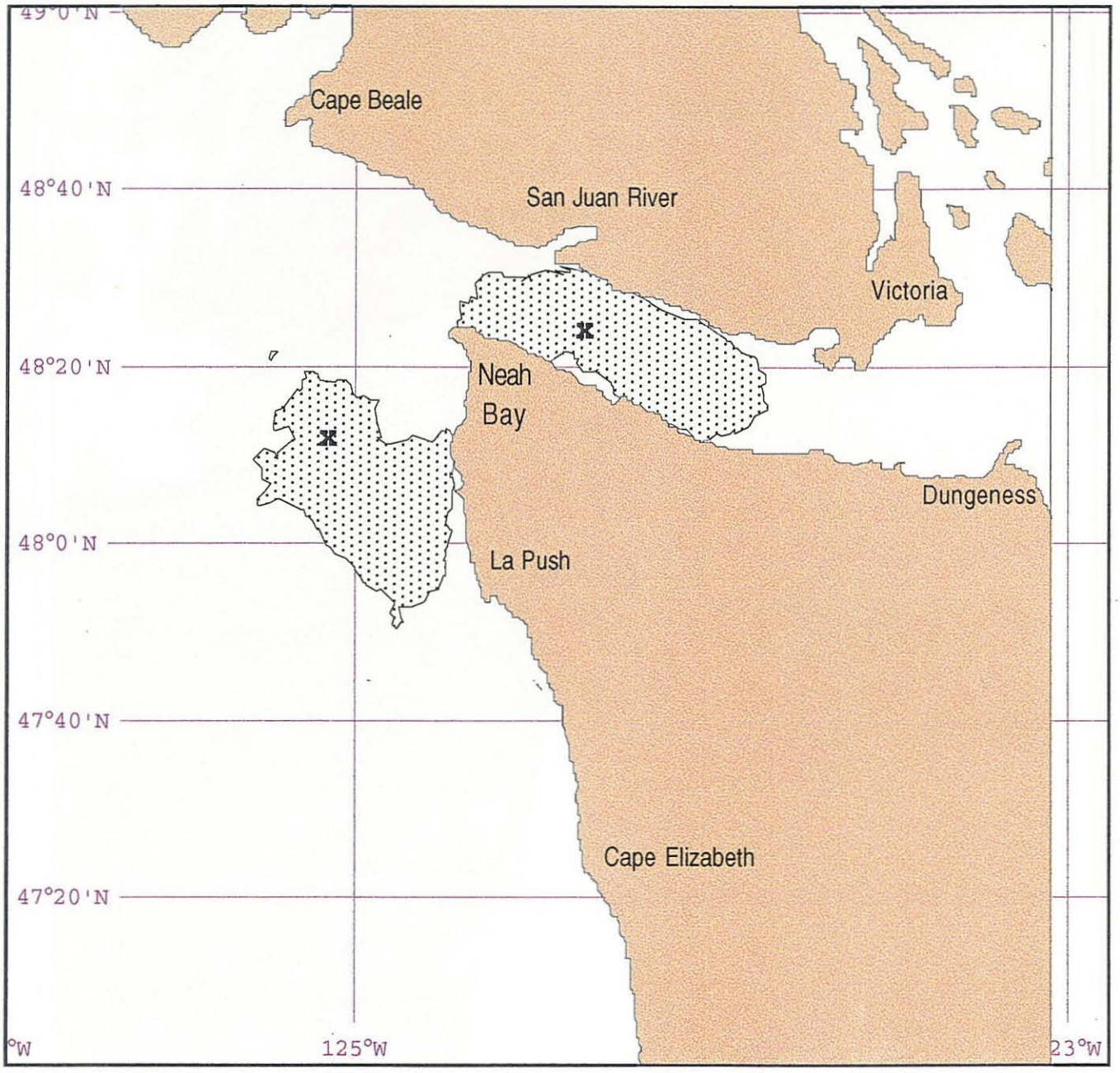

Figure A-52. Map of 12-hour probability contours, summer, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 10% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

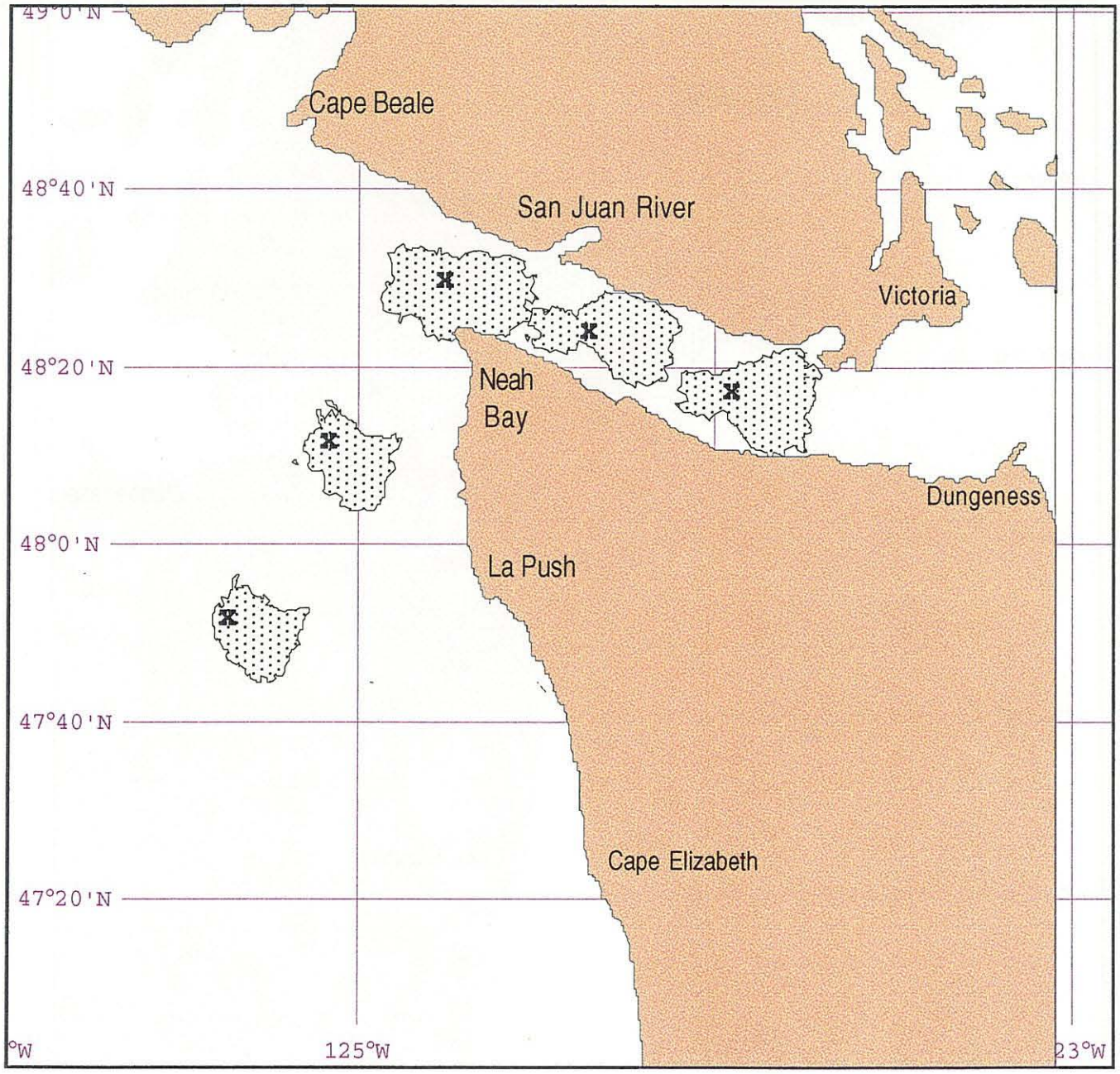

Figure A-53. Map of 4-hour probability contours, summer, 10 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

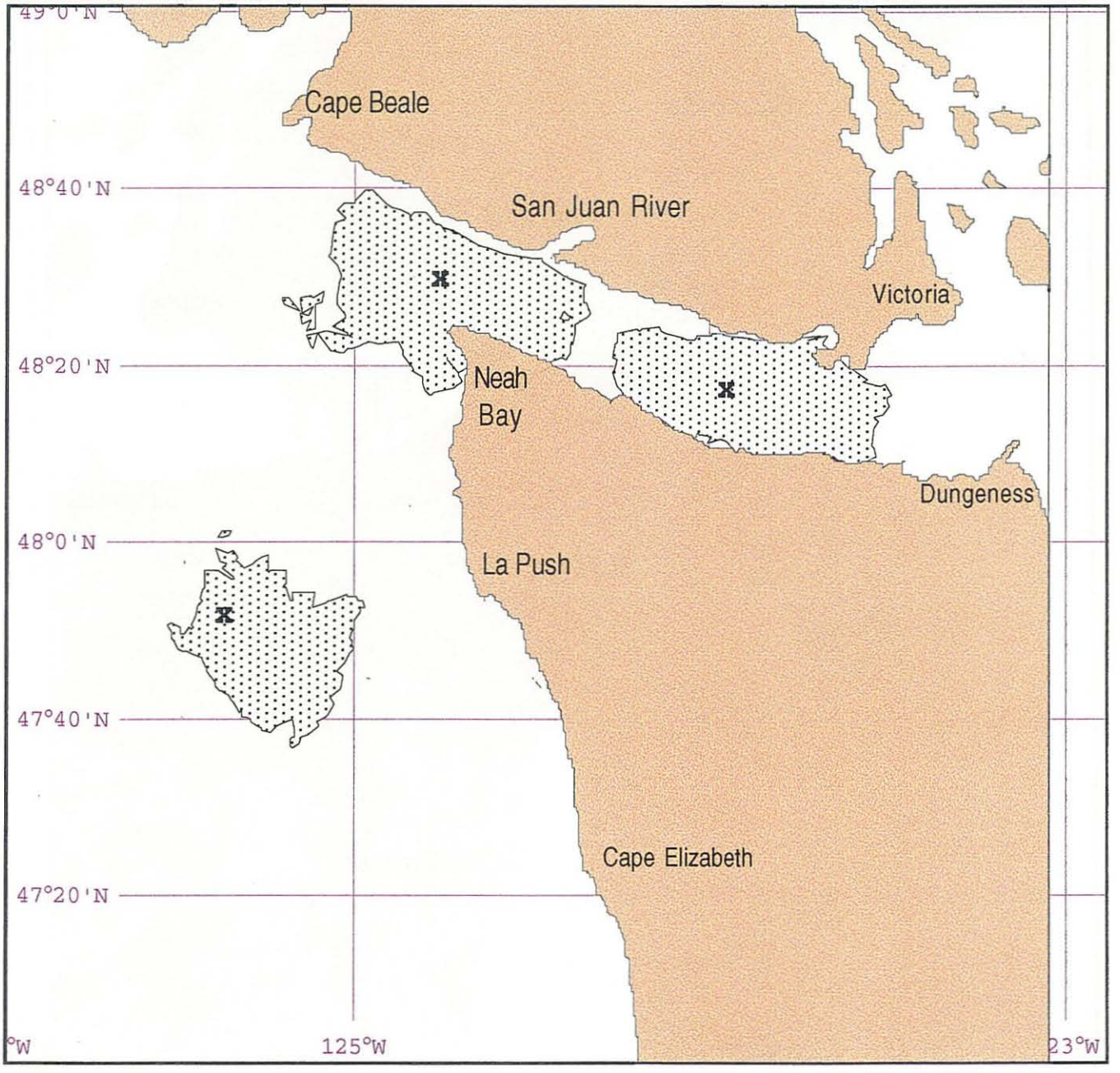

Figure A-54. Map of 8-hour probability contours, summer, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

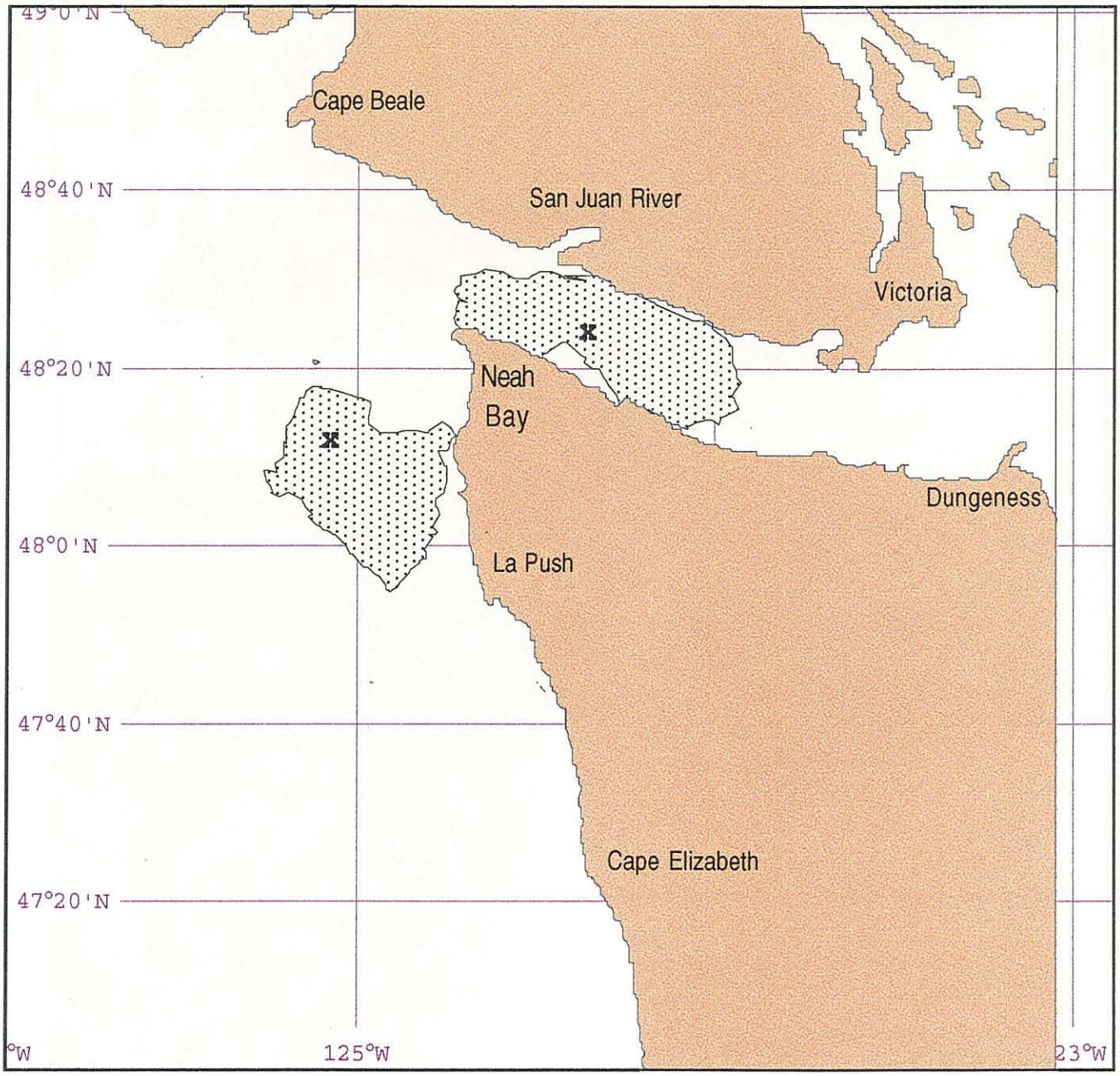

Figure A-55. Map of 8-hour probability contours, summer, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

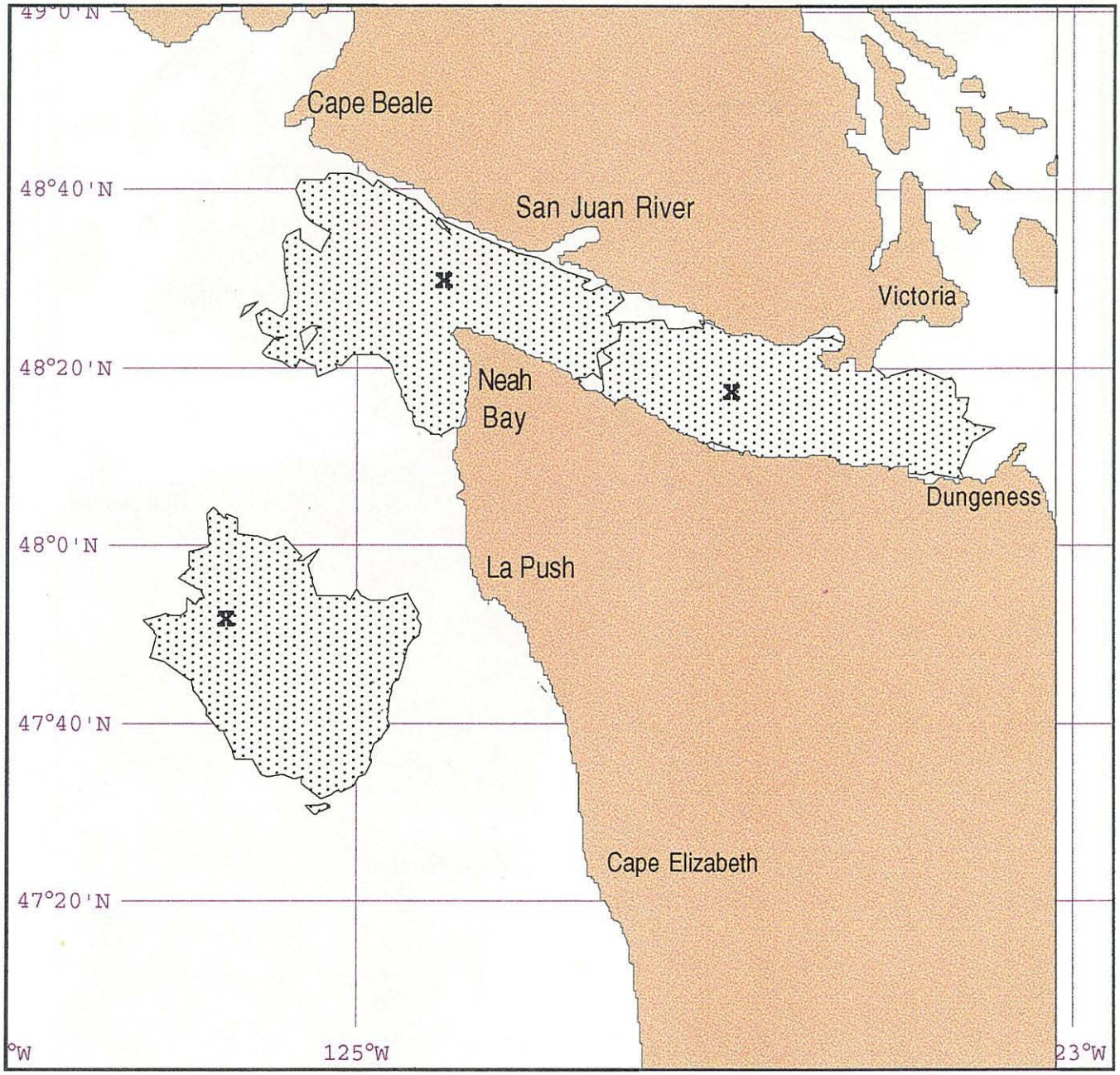

Figure A-56. Map of 12-hour probability contours, summer, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Summer
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

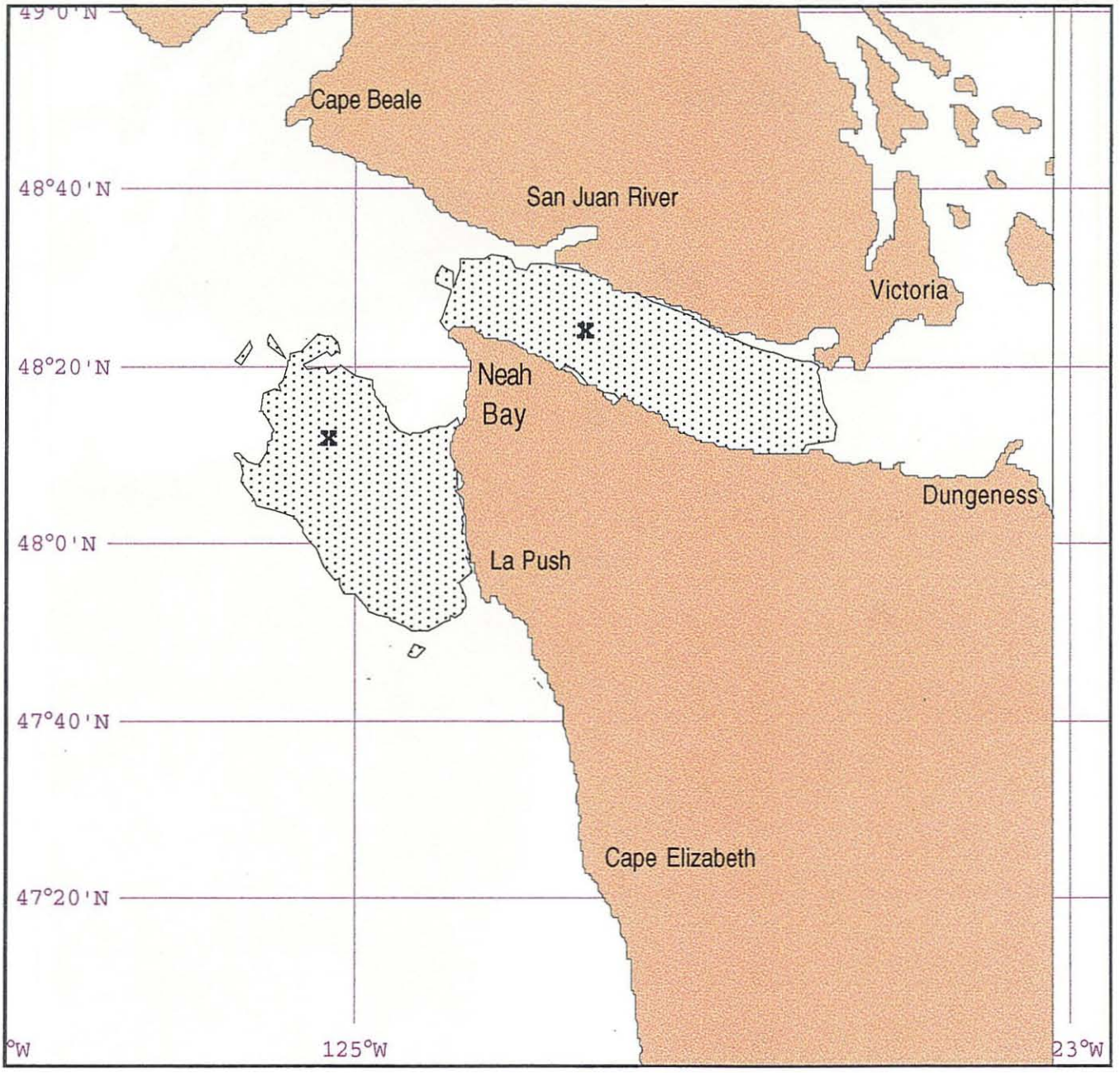

Figure A-57. Map of 12-hour probability contours, summer, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 2% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

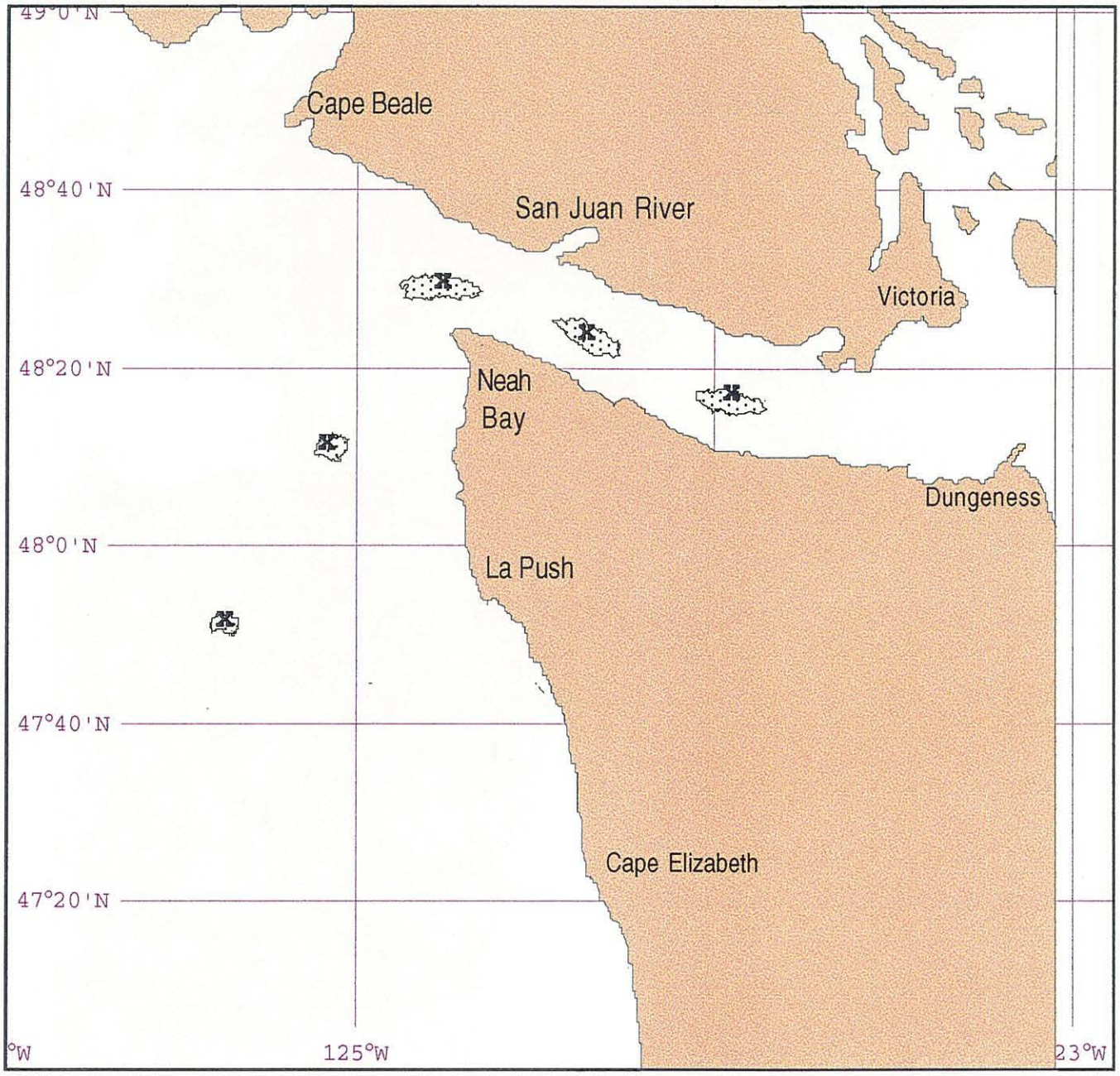

Figure A-58. Map of 4-hour probability contours, fall, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 2% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

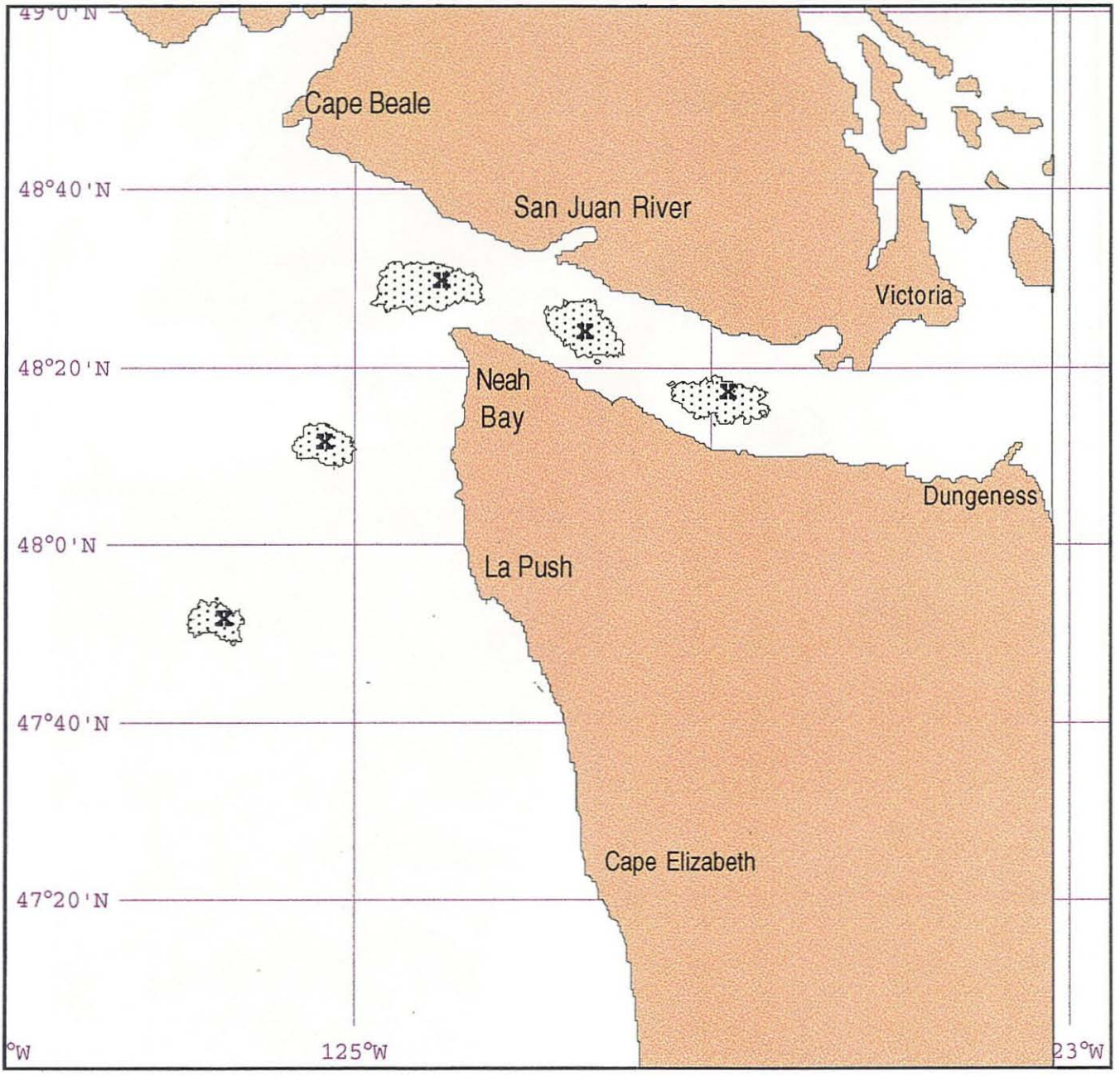

Figure A-59. Map of 8-hour probability contours, fall, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 2% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

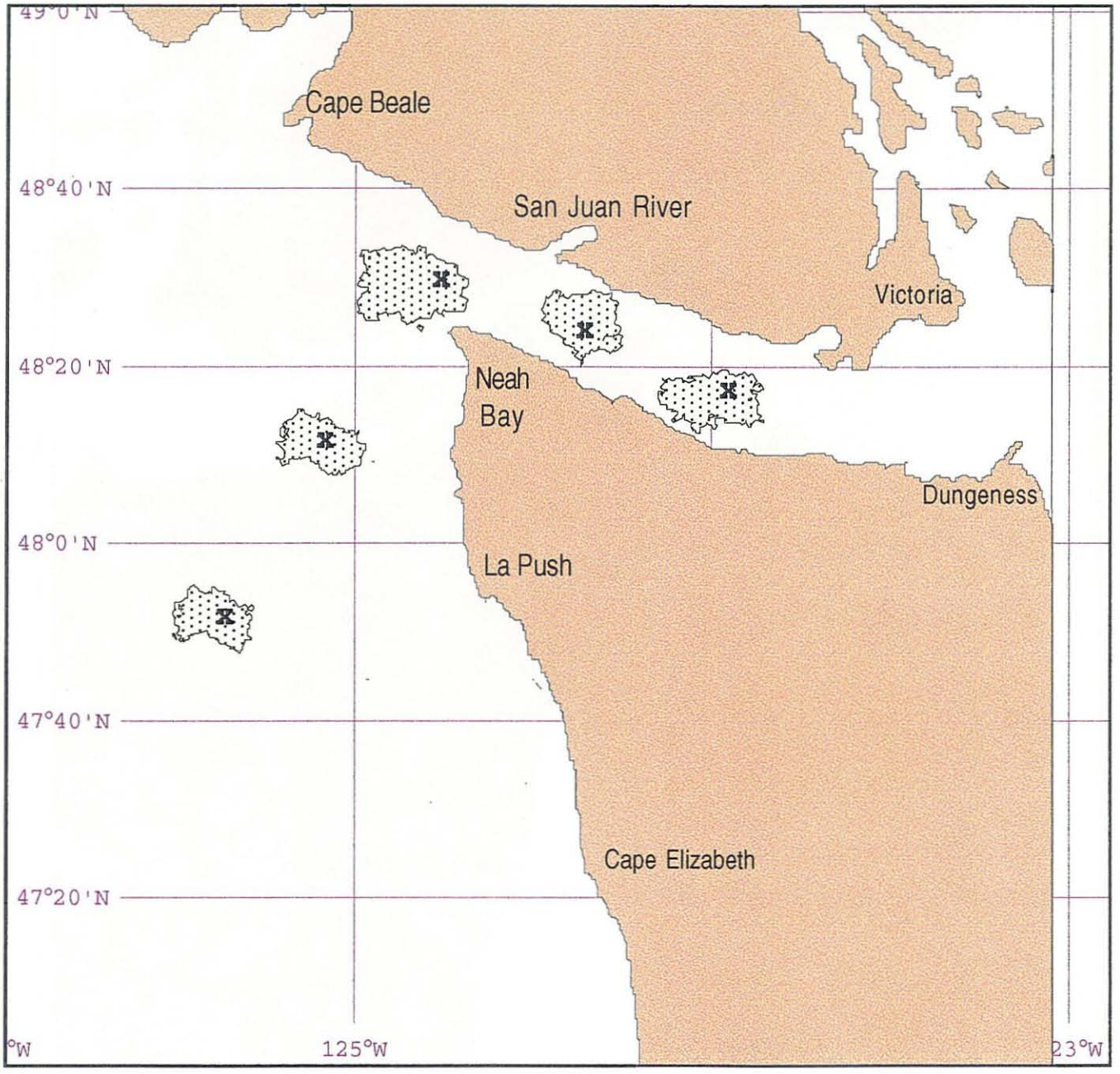

Figure A-60. Map of 12-hour probability contours, fall, 2 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 4% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

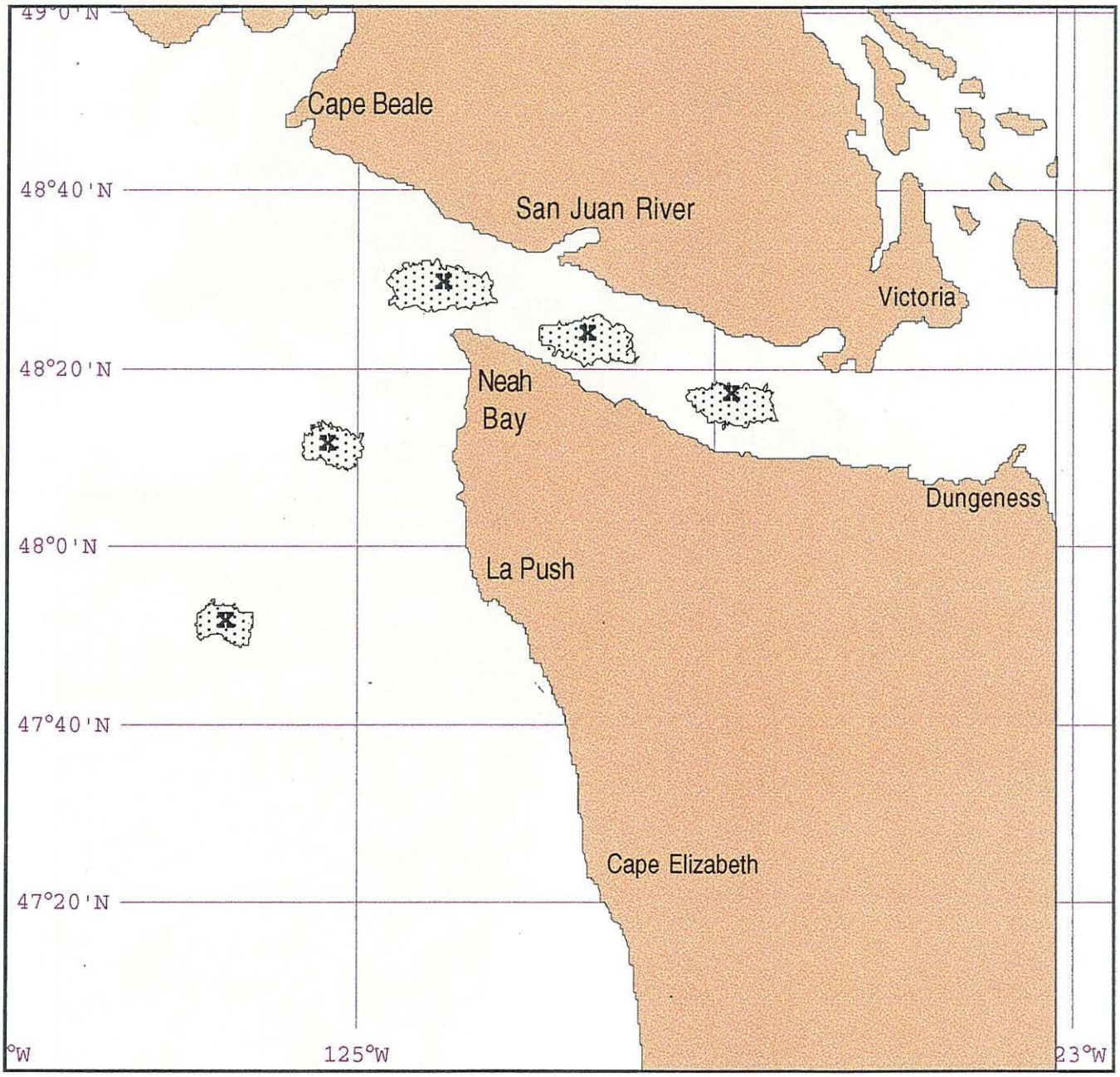

Figure A-61. Map of 4-hour probability contours, fall, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 4% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

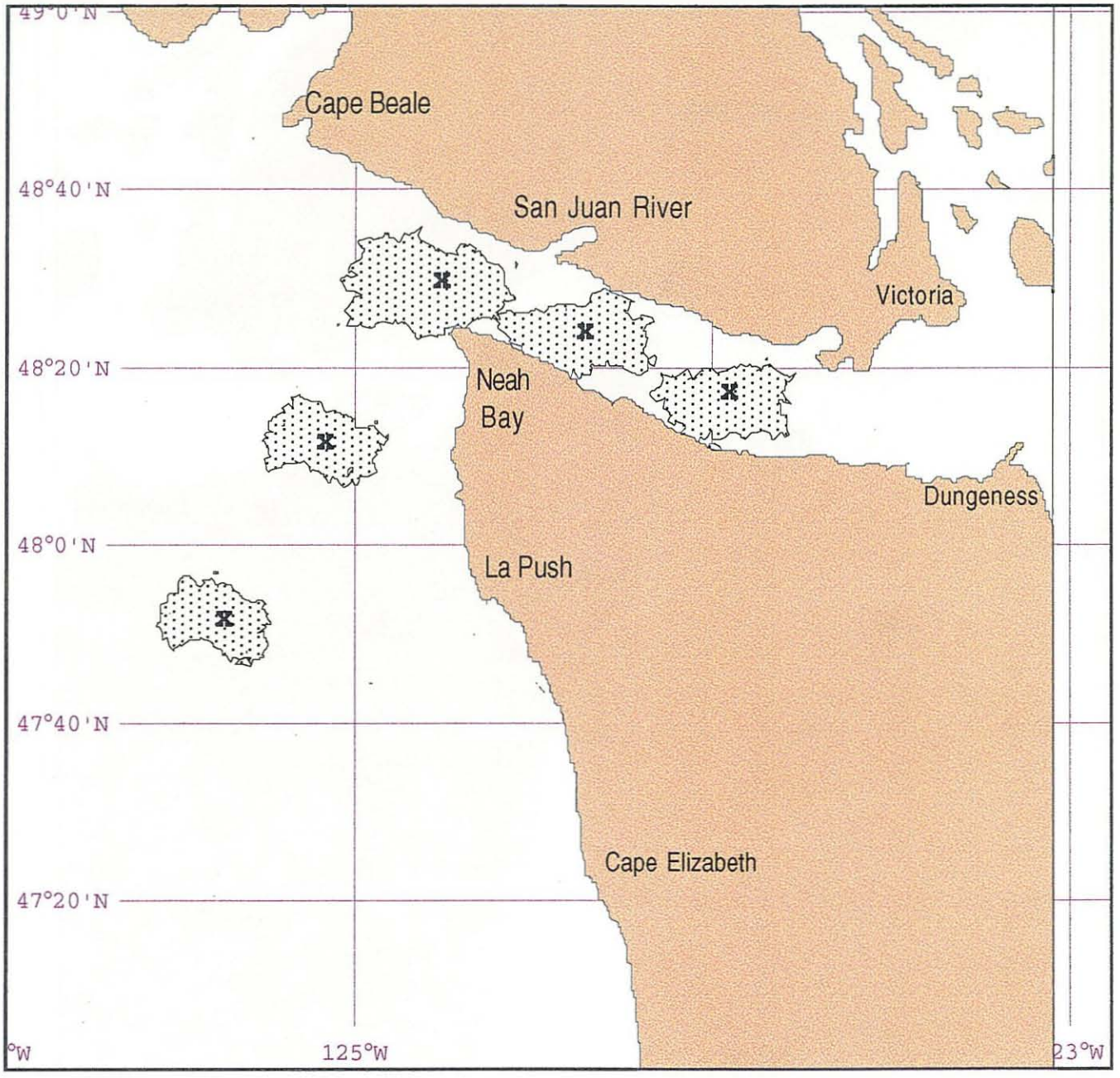

Figure A-62: Map of 8-hour probability contours, fall, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 4% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

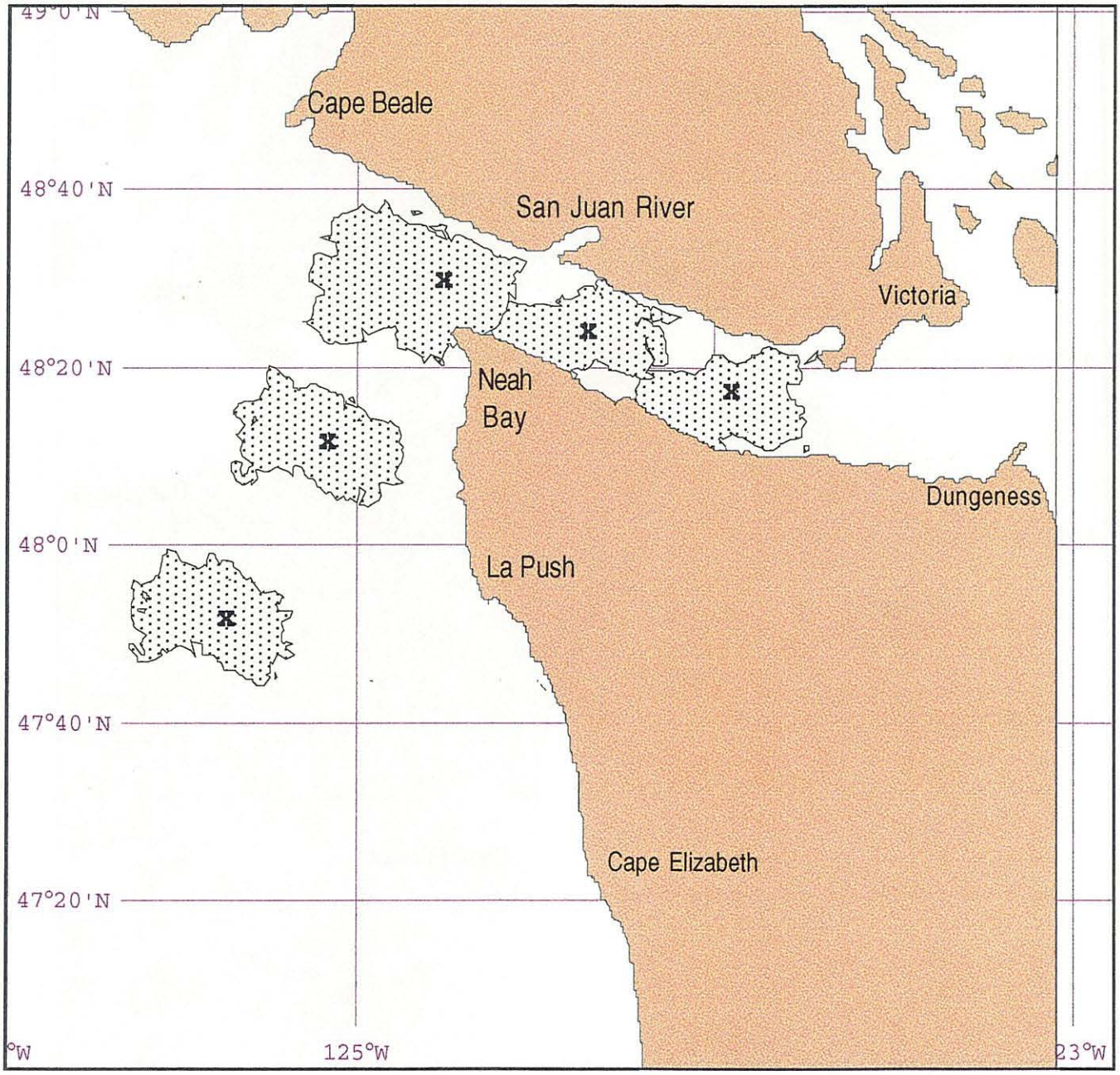

Figure A-63. Map of 12-hour probability contours, fall, 4 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 6% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

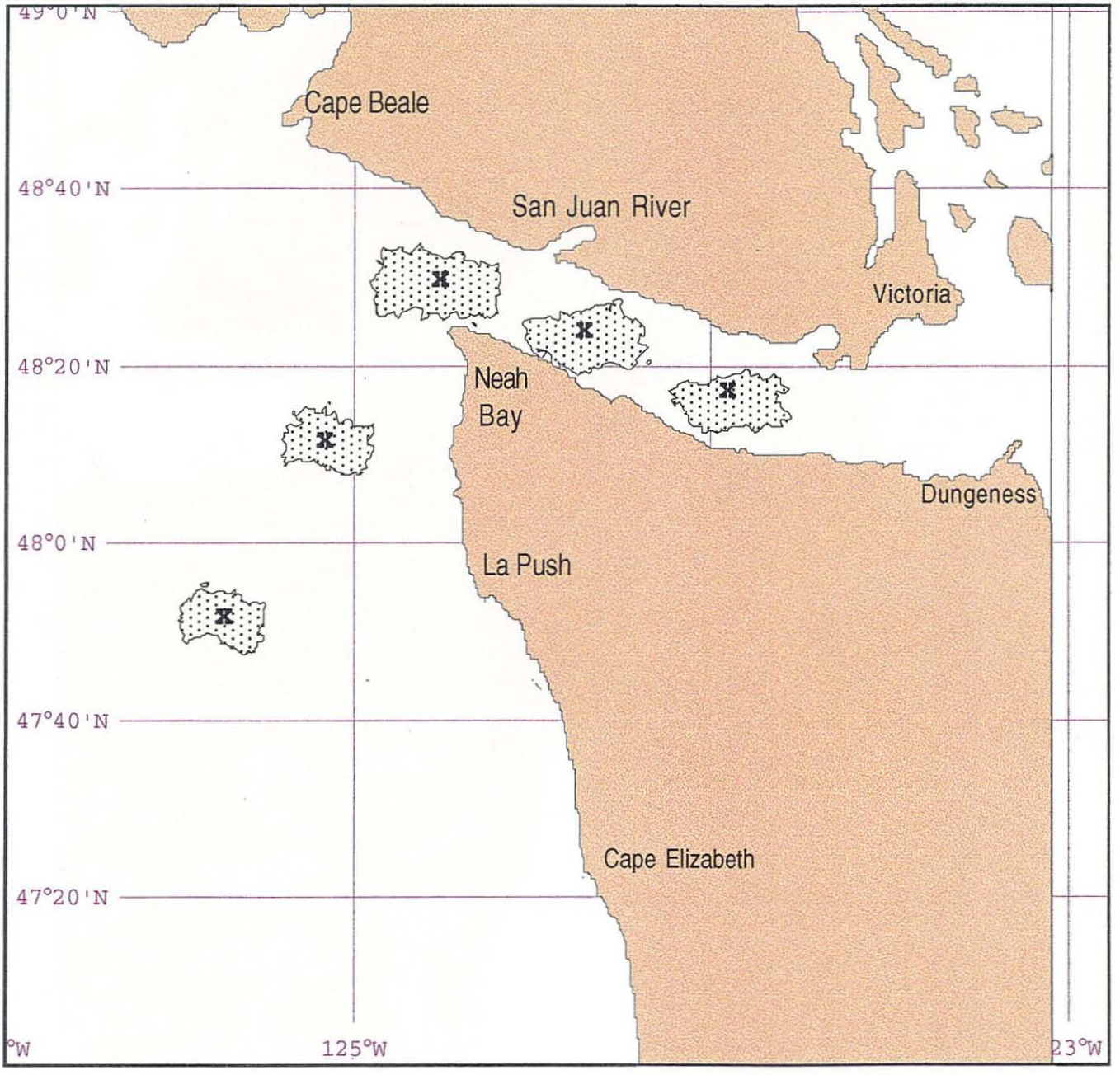

Figure A-64. Map of 4-hour probability contours, fall, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 6% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

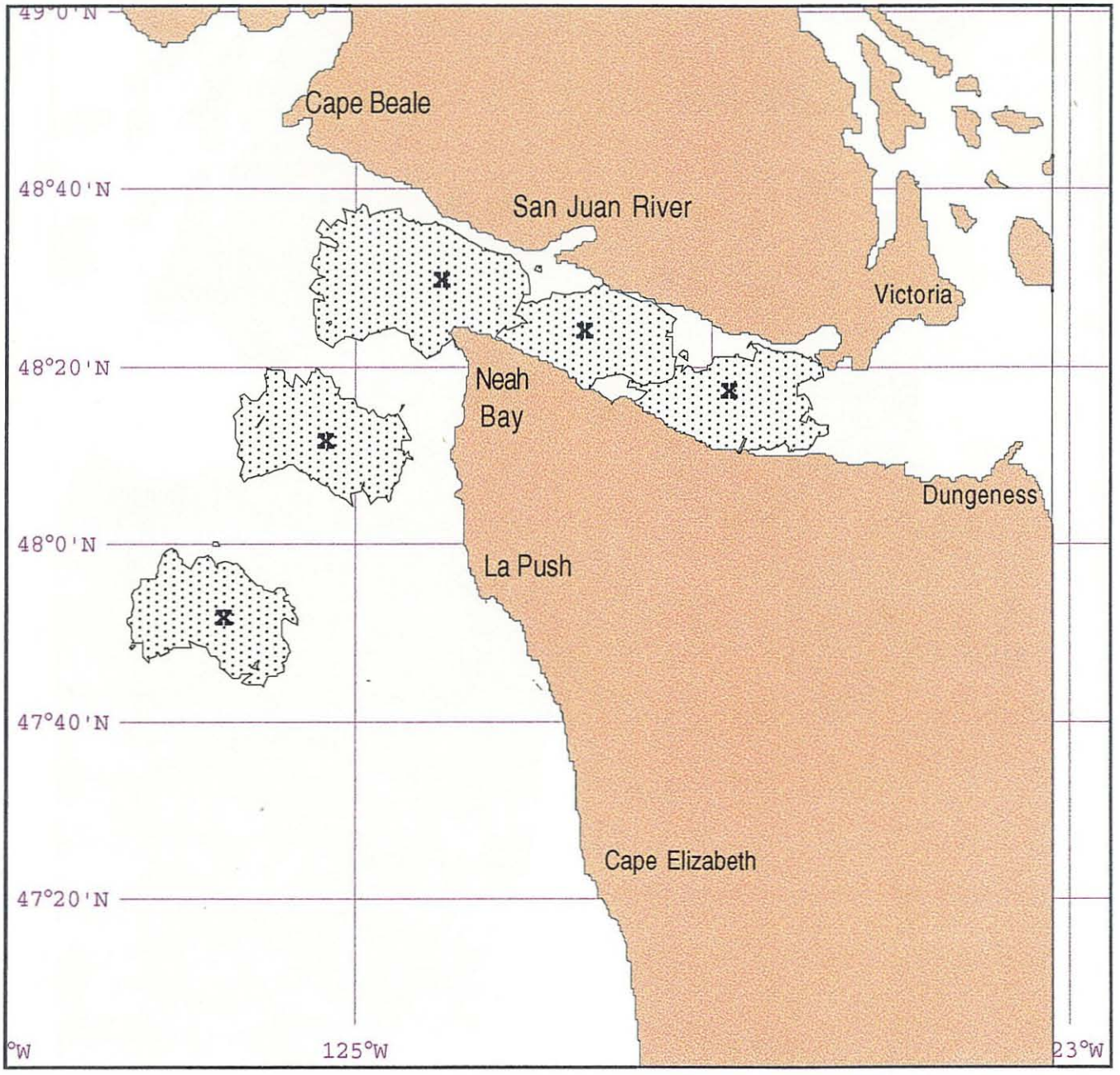

Figure A-65. Map of 8-hour probability contours, fall, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 6% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

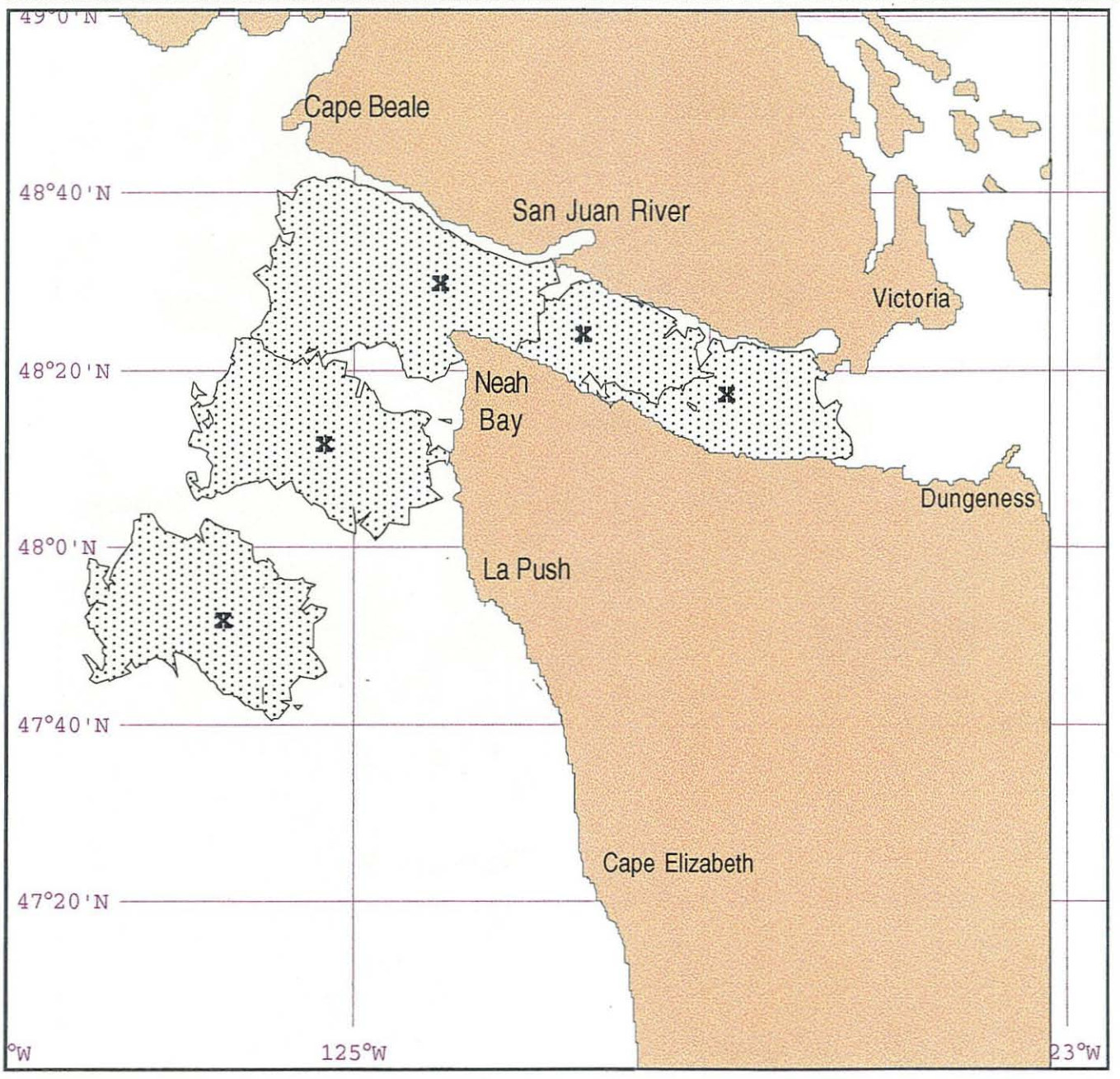

Figure A-66. Map of 12-hour probability contours, fall, 6 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 8% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

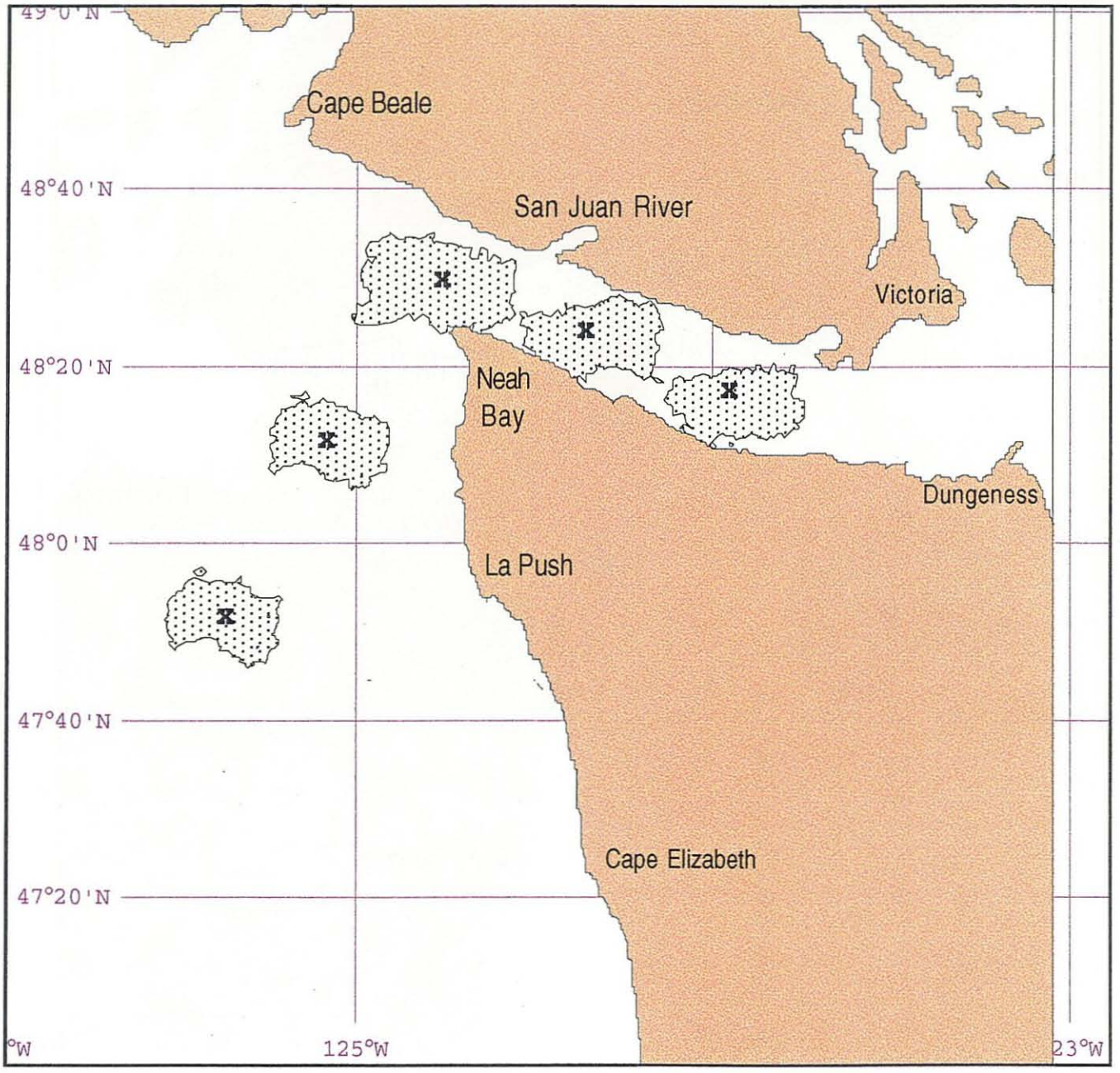

Figure A-67. Map of 4-hour probability contours, fall, 8 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

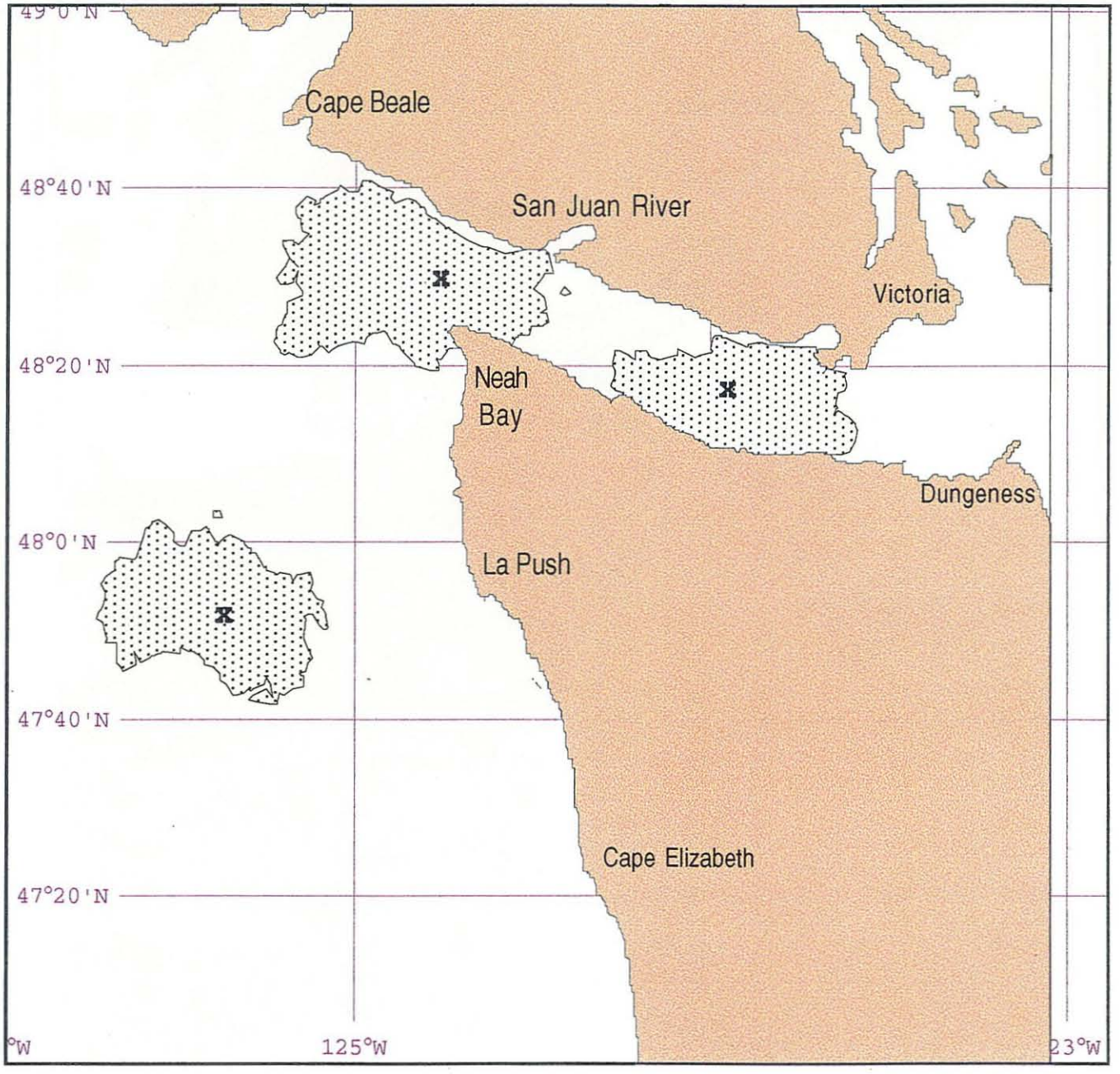

Figure A-68. Map of 8-hour probability contours, fall, 8 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: , NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 8% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

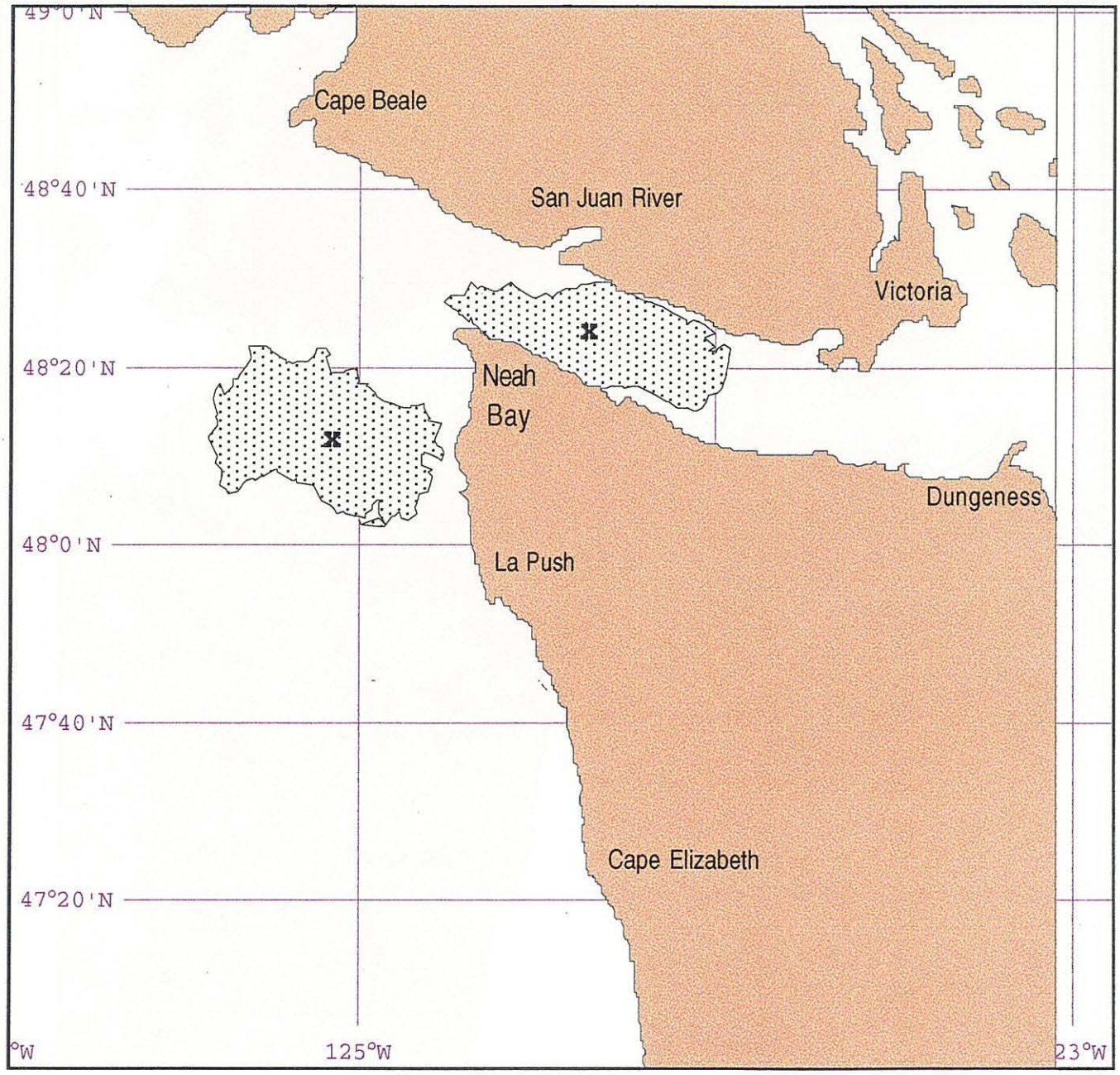

Figure A-69. Map of 8-hour probability contours, fall, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

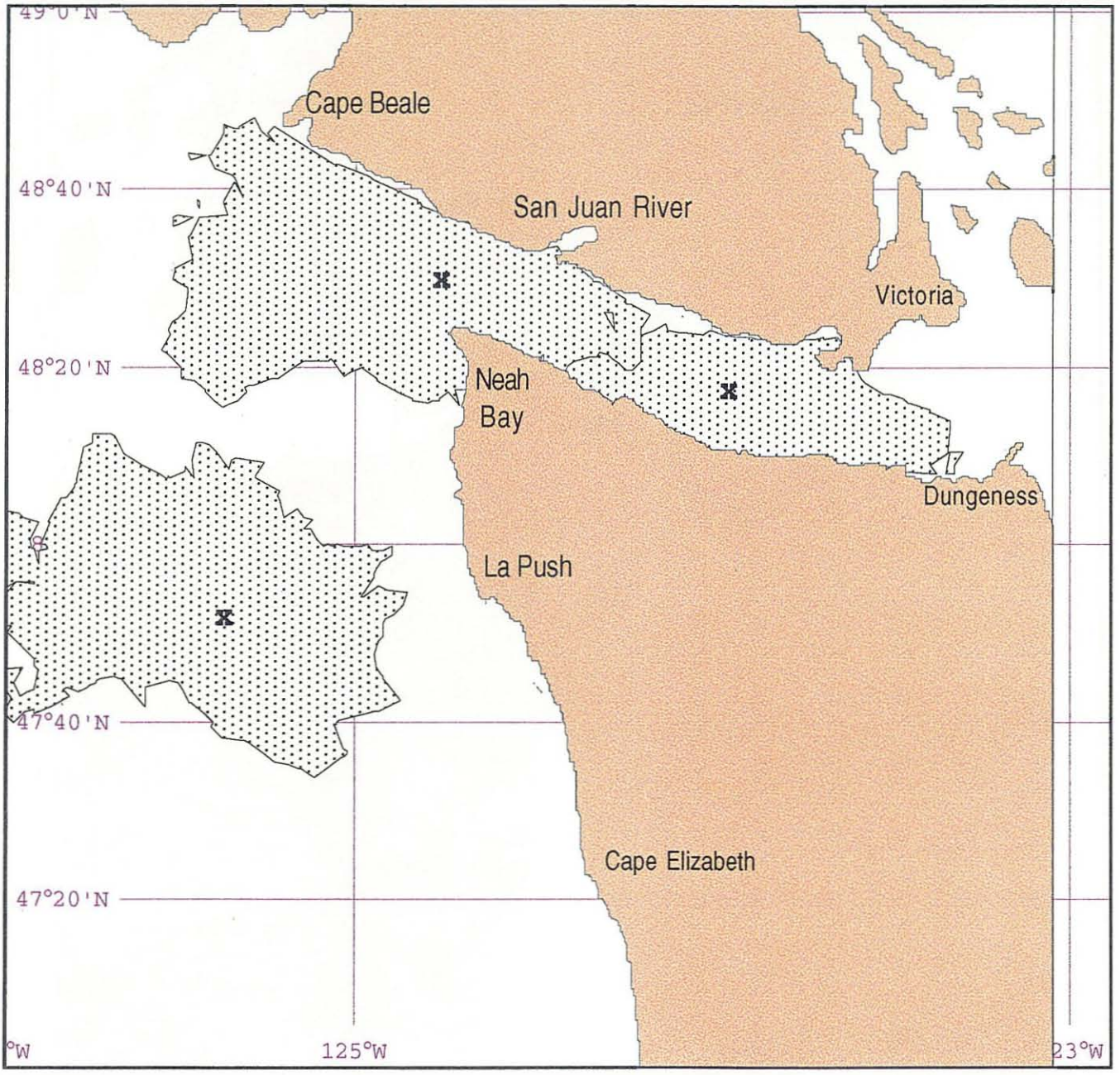

Figure A-70. Map of 12-hour probability contours, fall, 10 percent drift for sites 1, 3 and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 8% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

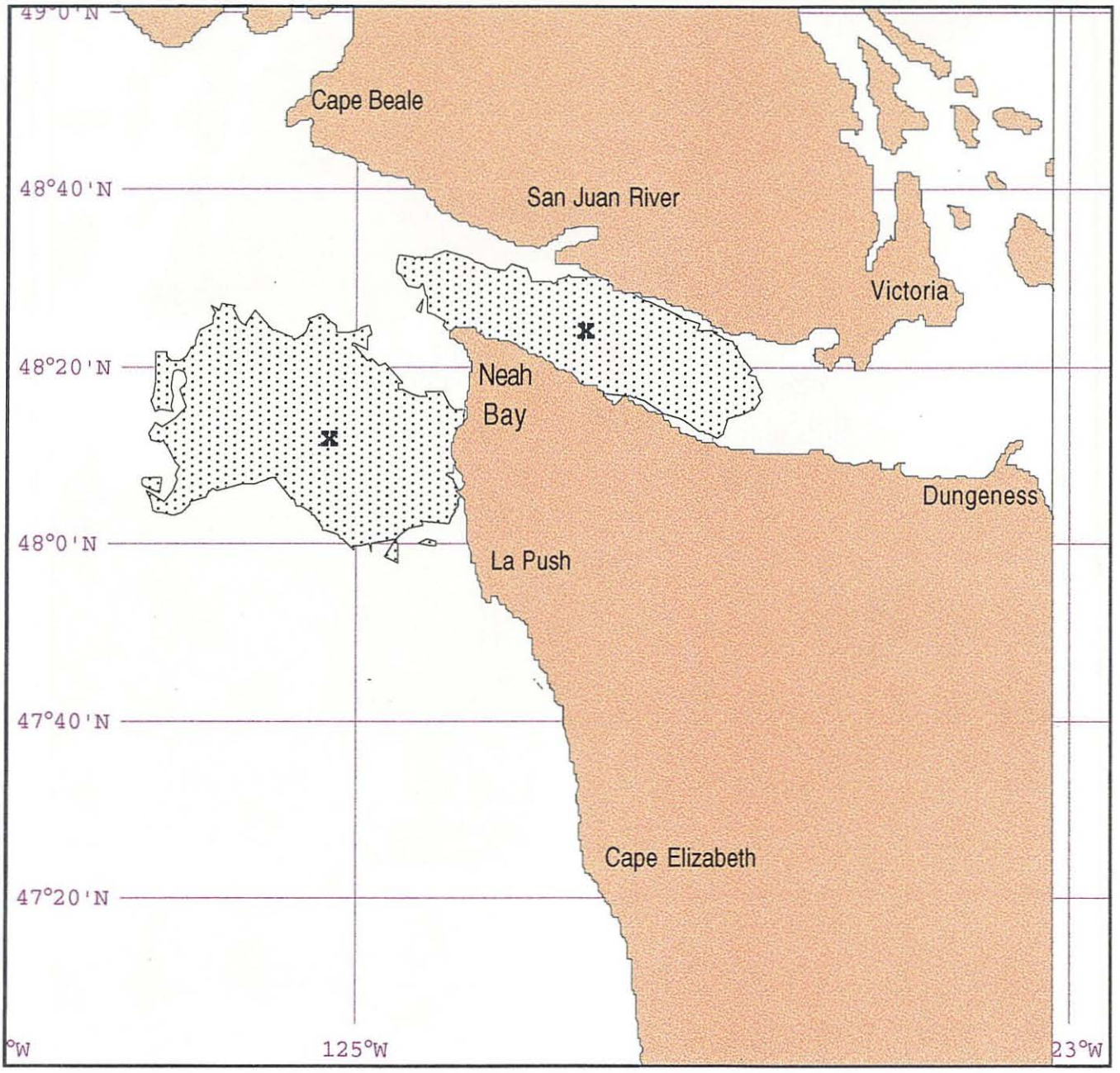

Figure A-71. Map of 12-hour probability contours, fall, 8 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 4-hours
At each site, the contour represents the 95% probability distribution.

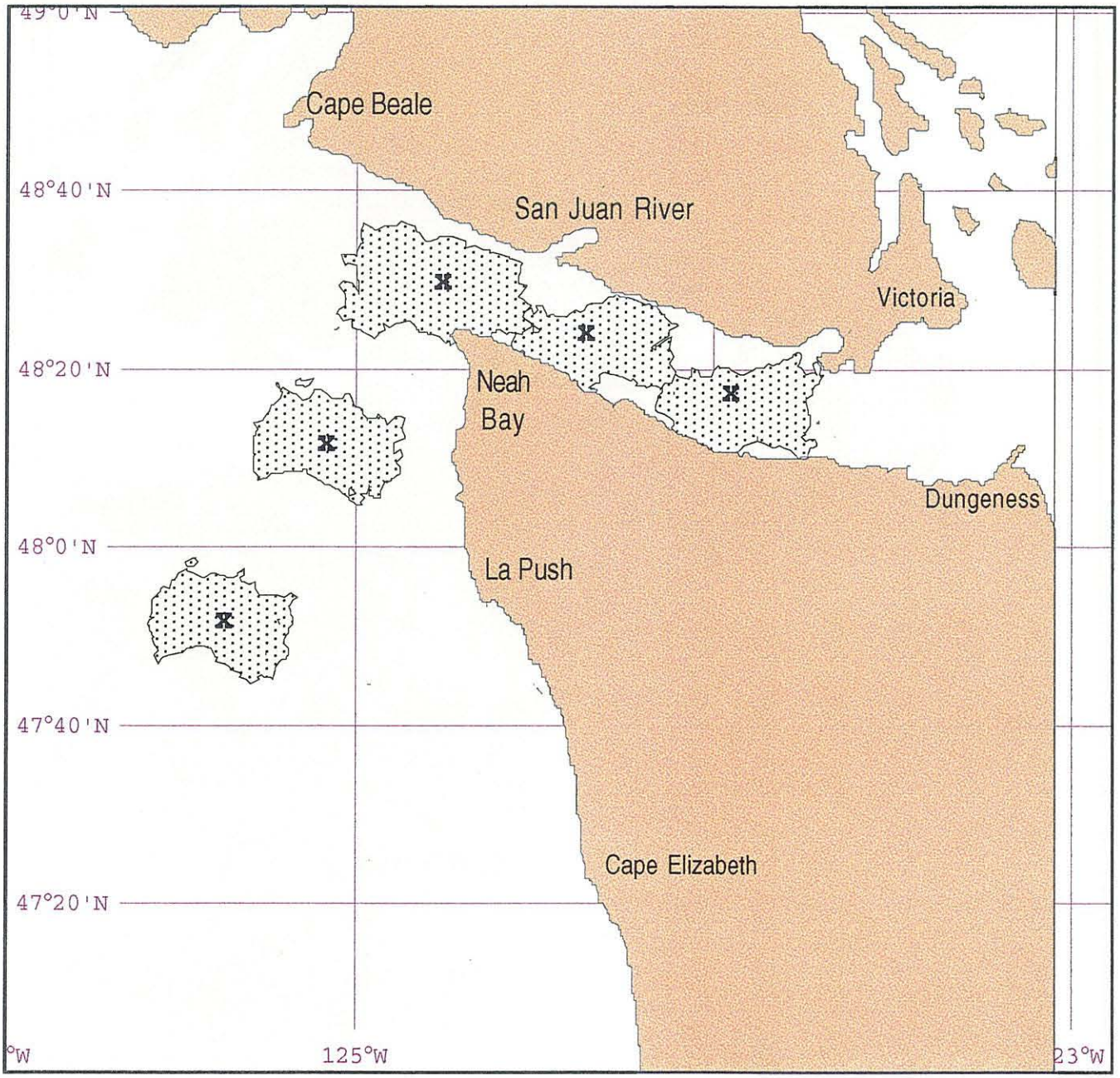

Figure A-72. Map of 4-hour probability contours, fall, 10 percent drift for five sites.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

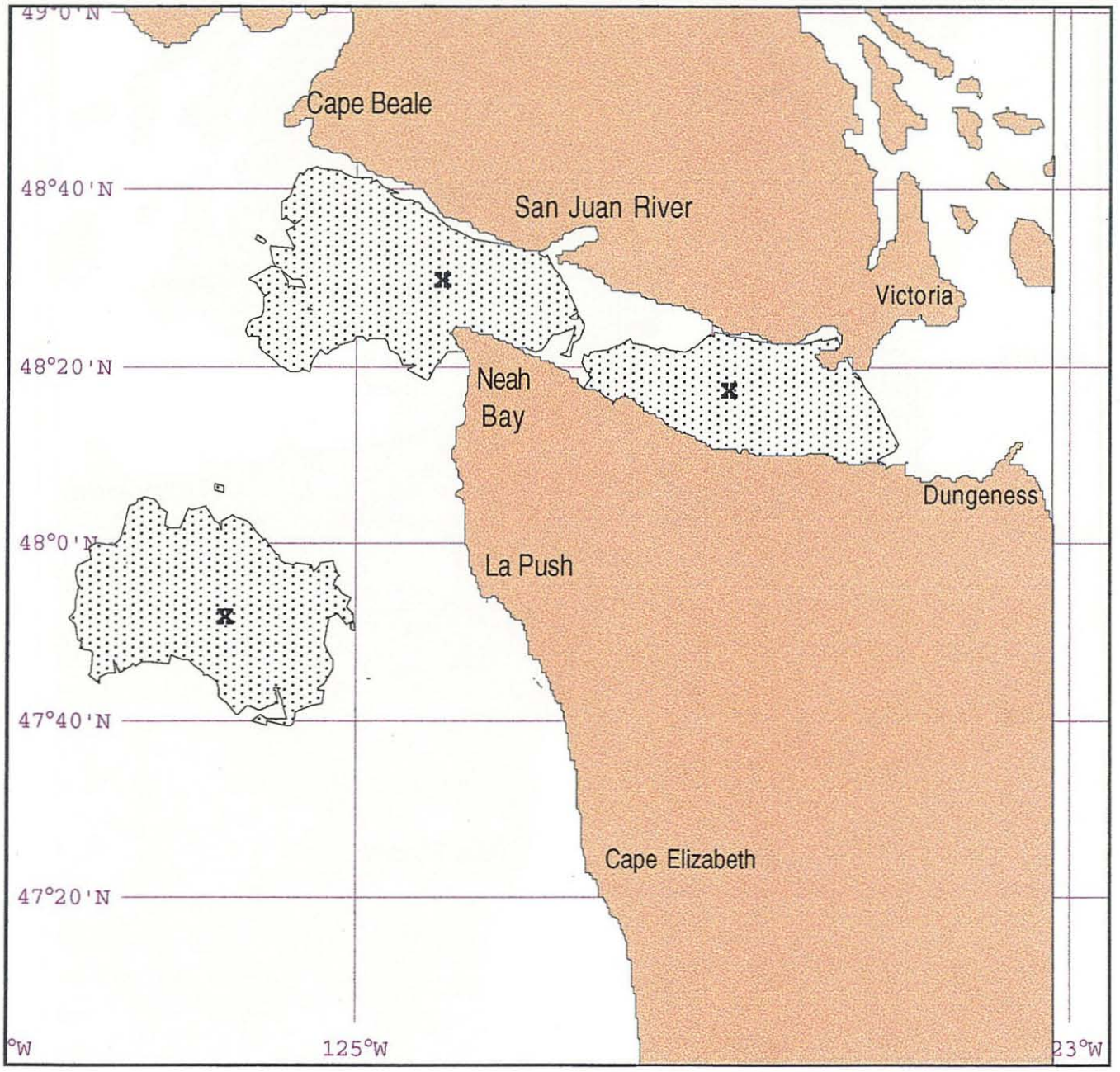

Figure A-73. Map of 8-hour probability contours, fall, 10 percent drift for sites 1, 3, and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 8-hours
At each site, the contour represents the 95% probability distribution.

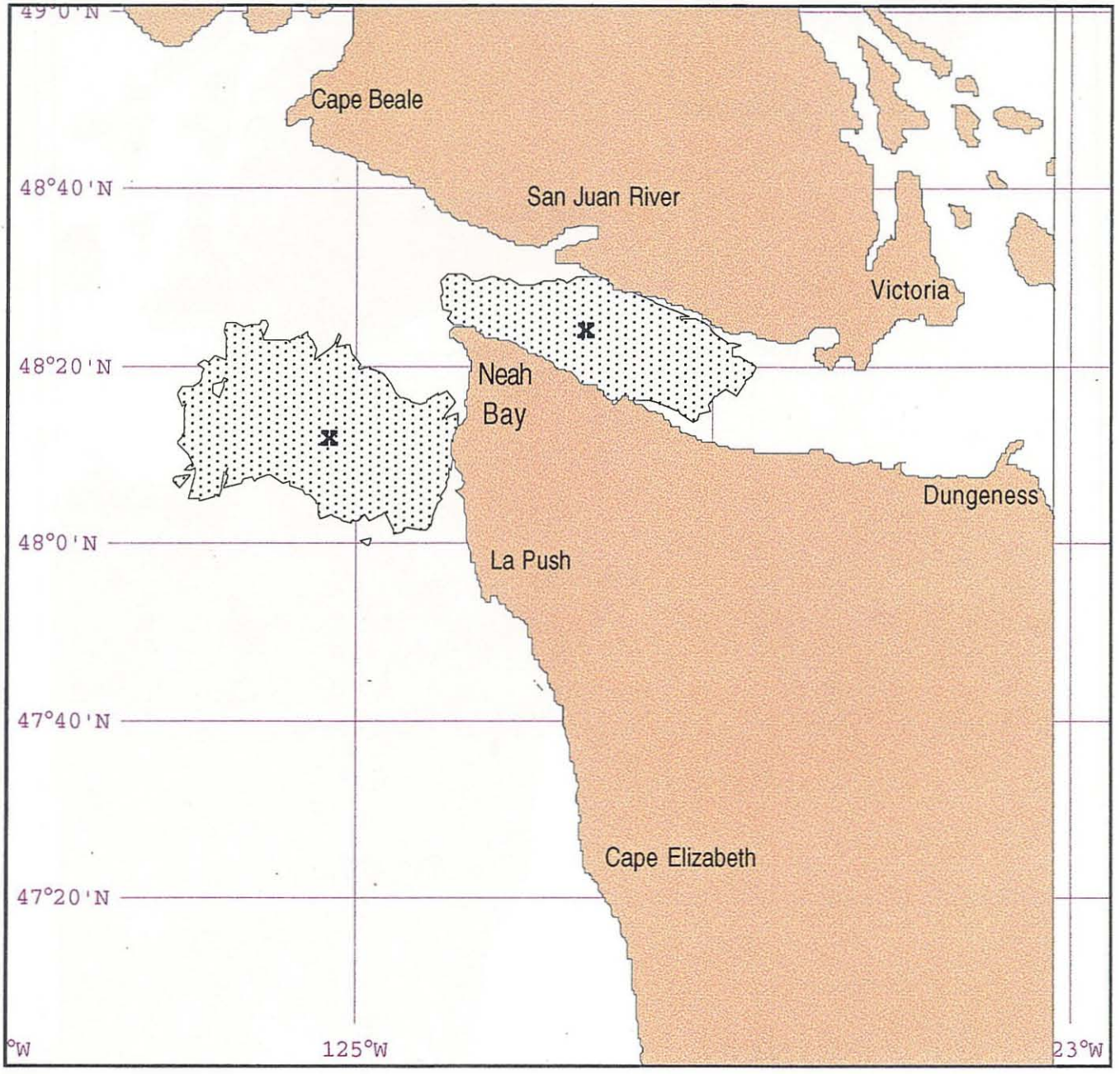

Figure A-74. Map of 8-hour probability contours, fall, 10 percent drift for sites 2 and 4.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

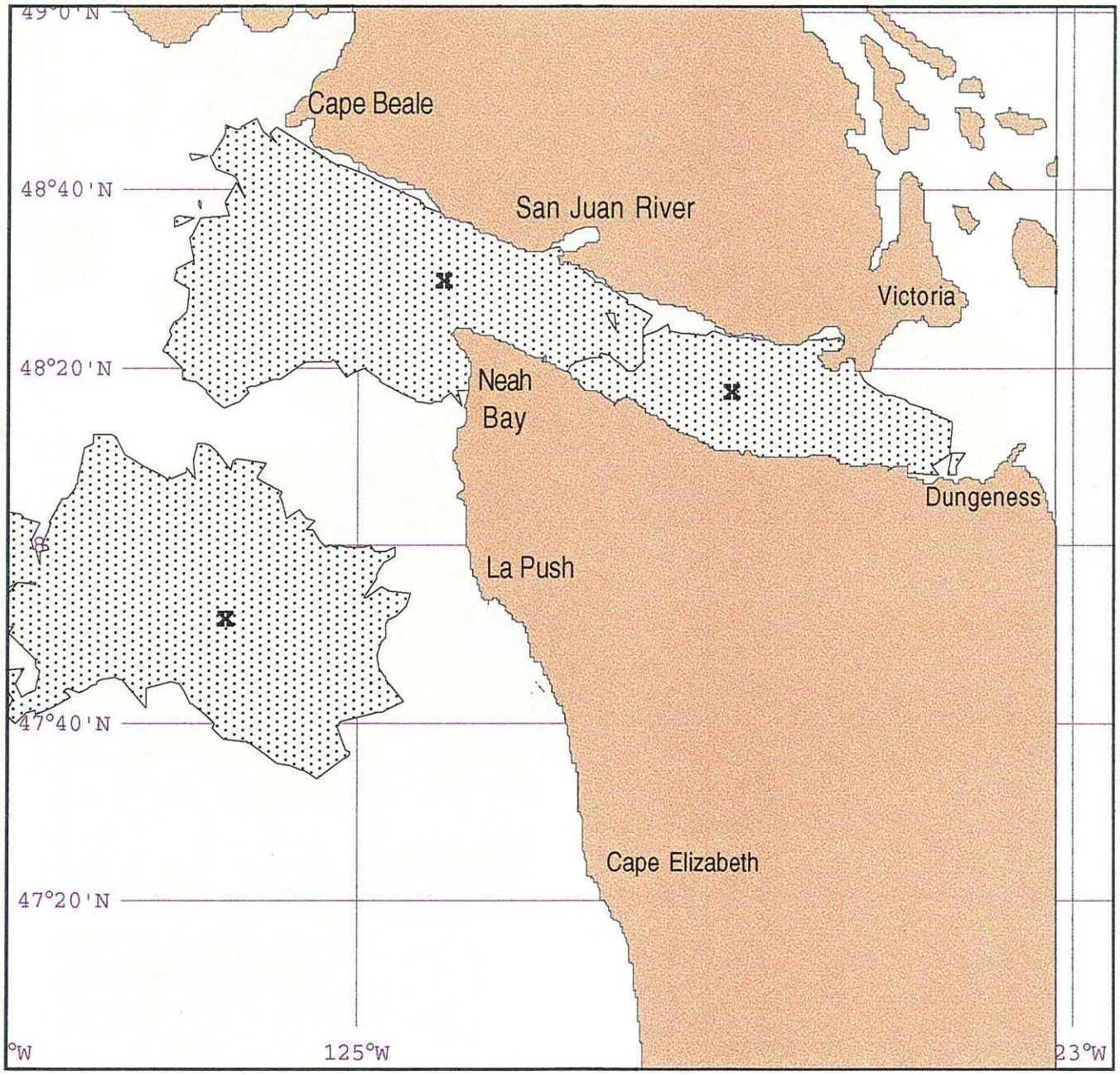

Figure A-75. Map of 12-hour probability contours, fall, 10 percent drift for sites 1, 3 and 5.

Ship drift analysis **MASS Statistical Analysis**

Estimate for:

Prepared: ,

NOAA/HAZMAT/MASS (206) 526-6317

Season: Fall
ship drift: 10% of the wind speed representing both wind and wave action
Time: 12-hours
At each site, the contour represents the 95% probability distribution.

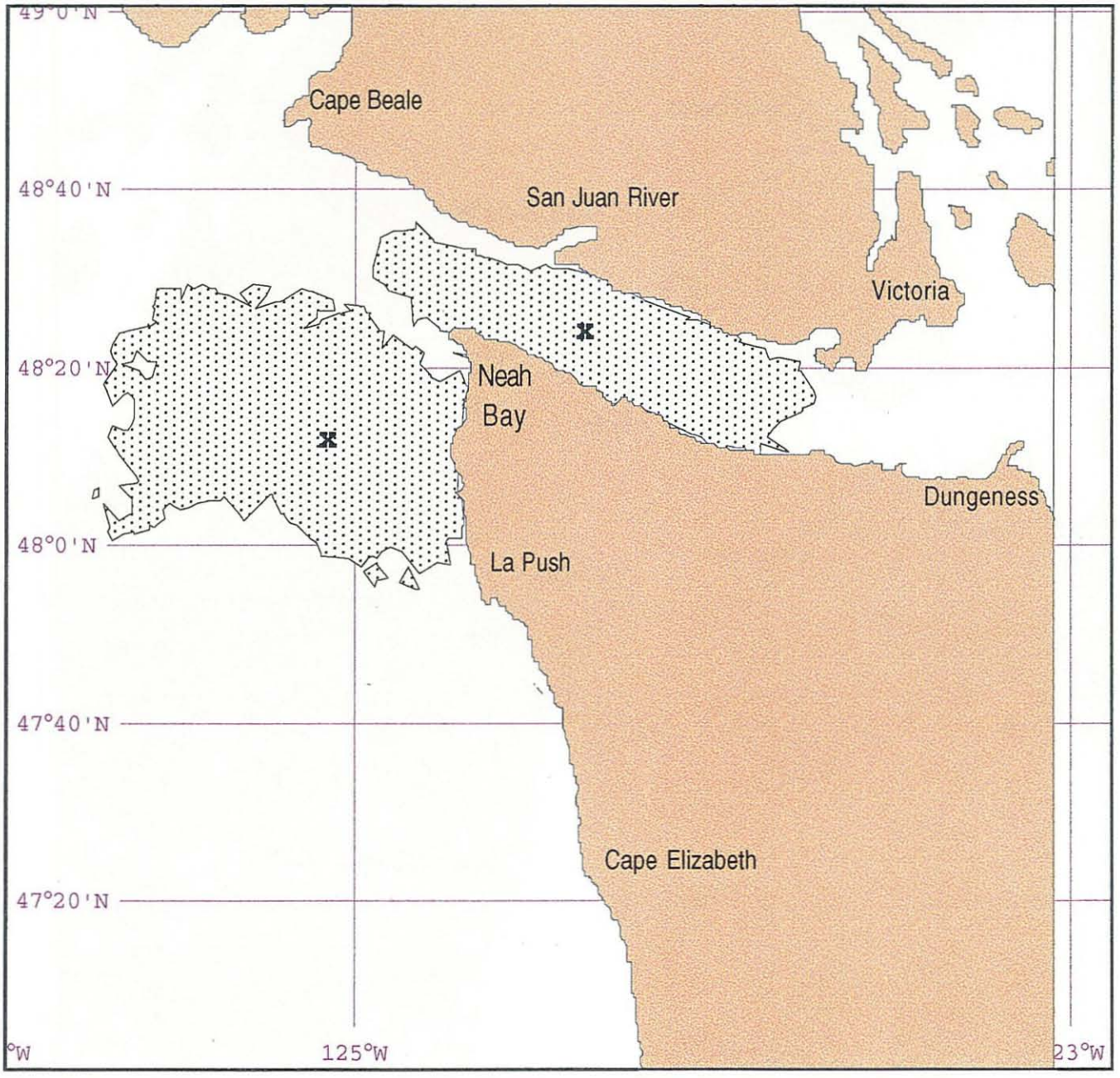

Figure A-76. Map of 12-hour probability contours, fall, 10 percent drift for sites 2 and 4.