THE CHARACTERISATION OF SYNOPTIC CIRCULATION PATTERNS IN SALDANHA BAY

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of the degree of Master of Science

ABSTRACT

Saldanha Bay, on the west coast of South Africa, is the only deep water port between Cape Town and Walvis Bay. It is separated into two smaller bays, Small Bay and Big Bay, by an iron-ore jetty built in 1975. With its sheltered environment it is an ideal site for the development of a mariculture industry, but a conflict of interest arises between the mussel farmers and the use of the iron-ore jetty and other sources of pollution. This thesis is a contribution to an effort to understand how the requirements of the mariculture industry in respect of food provision and clean water can be met.

Seven field trips were made to Saldanha Bay with the aim of studying the circulation characteristics in the various regions of the bay. It was found that drogues were an effective method of measuring currents in Saldanha Bay, with the best method of drogue tracking being with the use of a Differential Global Positioning System (DGPS).

The Saldanha Bay system was found to be predominantly wind driven with regions of strong tidal influence being at the mouth of Small Bay and at the entrance to Langebaan Lagoon. When the winds are strong (>10m/s), they will dominate the tides over the whole of Saldanha Bay. When they are intermediate (5-10m/s), they will dominate tides in all regions except for the mouth of Small Bay and the entrance to Langebaan Lagoon. When the winds are light (<5m/s), they will dominate tides only in Small Bay. Tides have been found to exert a greater influence during winter when the bay is well mixed and when they are at full spring.

It was found that we could consider Small Bay and Big Bay to be one system and that Saldanha Bay as a whole was part of the Benguela upwelling system. The semi-enclosed nature of the bay reduced the full influence of the upwelling. The implications for mariculture based on the results were that the best location for additional mussel rafts would be in Small Bay, but future research is needed to establish the viability of allowing various competing industries to operate and expand within the confines of Small Bay.

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CHAPTER 1

INTRODUCTION

Saldanha Bay is the only deep water port on the west coast between Cape Town and Walvis Bay. Prior to 1974 it was a single bay, but major harbour works completed in 1975 modified the physiography of the area to a large extent. Since 1975, when the loading jetty for iron ore and oil and the causeway linking Marcus Island to the mainland were completed, Saldanha Bay itself has been virtually subdivided into a northern "Small Bay" and a southern "Big Bay"(figures 1.1 and 1.2).

Saldanha Bay has many features which make it attractive to both the tourist and commercial sectors. Offering scenic splendour, unique wildlife and protected wetlands, Saldanha Bay has become a desirable vacation venue. The sheltered water environment of the bay, close to Cape Town, also makes it an ideal site for the development of a mariculture industry. There is an important fishing harbour located on the western side of Small Bay with the total fish catches being some 30 000 tons per annum. Mussel farming in the bay at the moment has a turnover of R20-30 million per annum with potential for growth and in addition to this, algae (from which agar is extracted) has an export value of roughly $450 000 per annum.

The mussel farmers, in both the north-east region of Big Bay and just north of the causeway on the western boundary of Small Bay, require sea water that meets certain water quality and nutrient criteria. The operation of the iron ore jetty results in general harbour filth with 2.1 million tons of iron ore being handled every year. Coupled with the pollutants from the fish factories and from the town of Saldanha pumped into the bay, this conflicts with the first of the mussel farming requirements, namely clean sea-water and can also have a detrimental effect on the attraction of the bay for tourists, many of whom come to sail and fish. As well as this, the pollutants deplete the oxygen levels in the water, conflicting with the mussel farmers second criterion, that is oxygen rich sea water. Thirdly, there is a food requirement by the mussels and this food productivity is driven by nutrient supply from the wind driven coastal upwelling.

This thesis is a contribution to an effort to understand how requirements of the mariculture industry in respect of food provision and clean water can be met. A precise knowledge of the circulation and current dynamics in the bay, as well as an idea of the residence times of water in the bay, is therefore needed.

The primary objective of this thesis is to determine the character of the circulation in the different sectors of Saldanha Bay, and to show how the various forcing mechanisms combine to affect these circulation patterns. This objective was addressed through a series of field trips to Saldanha Bay. Emphasis during the field trips was placed on Small Bay and Big Bay (figure 1.1), with neither Langebaan Lagoon nor the open coastal entrance to the Saldanha Bay system being studied. The aim of this study was to investigate the circulation with respect to current speeds and directions under all tidal and wind conditions. Of the numerous methods available to us to establish the currents, practicality and cost dictated that we use drogues to achieve our results. In total, seven visits were made to Saldanha Bay from February 1993 to June 1995 and a total of 107 drogues were successfully tracked. This enabled us to meet our required range of environmental variables and obtain sufficient data from which to draw reasonable conclusions. During this same period, environmental measurements including nutrient levels in the bay, water quality tests and temperature / salinity profiles were made by other groups, thereby complementing the drogue studies.

Variations in environmental factors in Saldanha Bay influenced the data gathering. The dates for the field trips were chosen to meet wind, tide and stratification criteria, and thus enabled us to make measurements under all varying environmental conditions. Nevertheless the wind placed a limit on conditions in which we could work.

Chapter 2 describes the Southern Benguela region with respect to sea level, wind processes and upwelling and coastal-trapped waves. It also deals with previous studies undertaken in Saldanha Bay and reviews their conclusions about the circulation. This is used as a baseline for comparison with the new results found during this study.

As the methodology in this drogue study has applications for other similar studies, Chapter 3 deals with the methods used for current determination in detail. Firstly, the drogues themselves are discussed with respect to comparable current measurement techniques and the individual drogue design specifications. Secondly, the three methods of drogue position fixing used are analysed and the merits and shortfalls of each method are discussed.

Chapter 4 provides details of the individual drogue study results. Firstly, a summary is made of drogue deployment conditions for each day of the study with respect to stratification, wind strength, tide state and position-fixing method used. Deployment diagrams for each day are also provided, with accompanying descriptions and details of the wind and tide. Estimates of current strengths at the various depths are made. Composite diagrams divided into summer and winter wind regimes, and ebb and flood tidal cycles have also been compiled. These are presented here to enable us to draw inferences concerning the relative strengths of the various forcing mechanisms.

The discussion in chapter 5 provides answers to key questions concerning the methodology of the drogue study and the Saldanha Bay system as a whole. It also compares physical characteristics such as mixed layer depth and longshore velocity shear as measured in Saldanha Bay, with the offshore study by Brown and Hutchings (1987) and the overview of four upwelling regions worldwide by Lentz (1992). From these answers we are able to characterise the nature of the circulation and describe the implications of this study for the mariculture industry. Recommendations in terms of methodology and future research are also given.

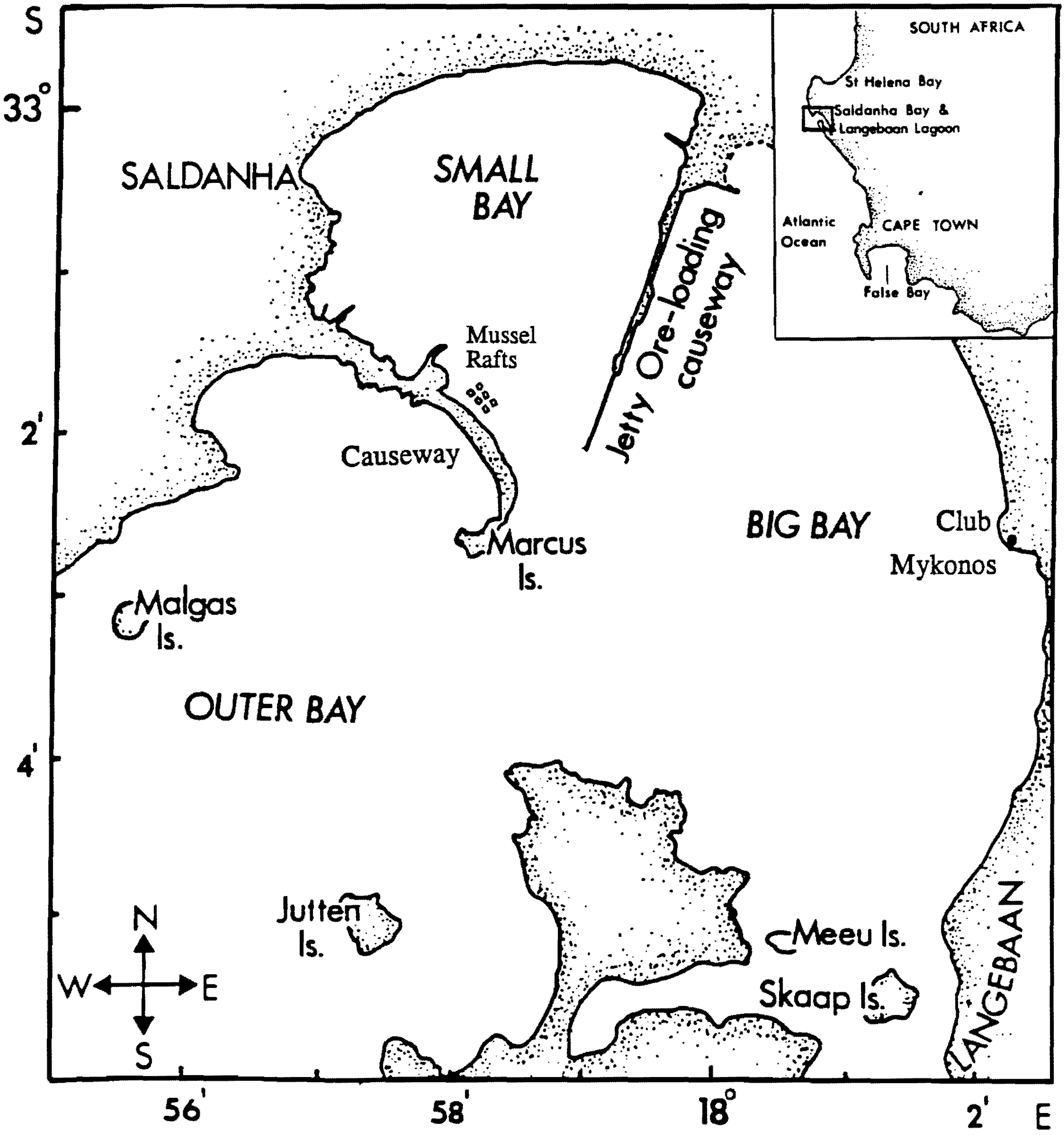


Figure 1.1: Map of Saldanha Bay illustrating important geographical features

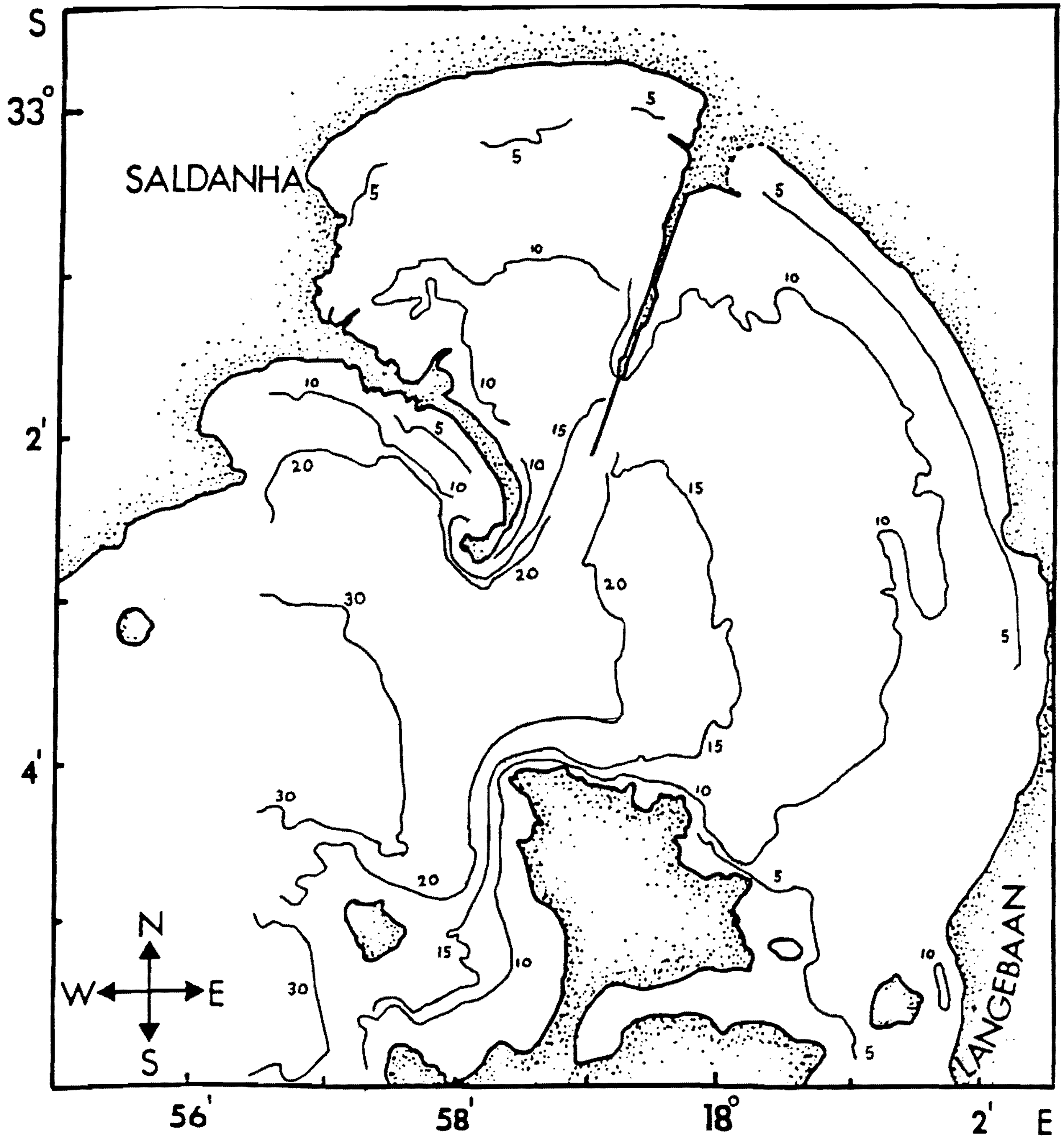


Figure 1.2: Map of Saldanha Bay illustrating general topography with contours measured in metres

CHAPTER 2

LITERATURE REVIEW

2.1 Background to the Southern Benguela

The Benguela is one of the four major eastern boundary current regions of the World ocean and the oceanography of the western coast of Africa south of about 15° S is dominated by a coastal upwelling system (Shannon, 1985). The Benguela itself is divided into a northern and a southern part with the division between the two occurring at the Luderitz region. The southern Benguela, therefore, can be thought of as the west coast of Southern Africa between Cape Point and Luderitz and is characterised by a uniformity of physical processes within that region. Saldanha Bay is part of the Southern Benguela and is the only deep water port on the west coast between Cape Town and Walvis Bay.

2.1.1 Sea Level

We can think of the recorded sea level height as a combination of an astronomical tide component and a weather determined component. The Form Factor (Defant, 1961) gives a measure of the astronomical tidal character by comparing the magnitude of the two main diurnal constituents to the two main semi-diurnal ones. The Form-Factor for Saldanha Bay predicted from the South African Tide Tables is 0.099, which falls between 0 and 0.25, indicating that the tides are strongly semi-diurnal. A semi-diurnal tide can be defined as a tide having two high waters and two low waters during a tidal day (Parker, 1994)

In the Southern Benguela, the tidal range between the highest astronomical tide and the lowest astronomical tide is typically 2 to 2.5 metres (Searson, 1994), while the astronomical tidal range for Saldanha Bay is 2.15 metres (SA Tide Table, 1995). Details of the tide for Saldanha Bay can be found in the South African Tide Tables. The weather component of the sea level is provided by the existence of coastal trapped waves, which will be discussed later in the section.

2.1.2 Wind Processes and Upwelling in the Southern Benguela

The seasonal wind cycle has a profound influence on the oceanography of the southern Benguela and there is a well-defined upwelling season which extends from late September to March (Andrews and Hutchings, 1980). During these months there is a predominance of strong, equatorward, longshore winds. In winter, a greater percentage of longshore, poleward winds with increased intensity occurs.

These longshore, equatorward winds are mostly prevalent during summer, when the local pressure gradient between the South Atlantic Anticyclone and a continental trough dominates the seasonal climatology (Jury et al, 1985). They drive surface water away from the coast and are the primary cause of upwelling along the west coast of southern Africa.

While the wind events in the southern Benguela are seasonal resulting in seasonal upwelling, further north constant winds result in the upwelling being perennial. As one moves northwards along the west coast of southern Africa to approximately 31° S, the first strong, perennial upwelling site we find is in the Luderitz region (Shannon, 1985). We thus define Luderitz as being the division between the southern and northern Benguela regions.

The prevailing winds over the Benguela region are determined by the South Atlantic high pressure system, the pressure field over the adjacent subcontinent and by eastward moving cyclones across the southern part produced by perturbations on the subtropical jet stream (Nelson and Hutchings, 1983). In this southern part an important modulation of upwelling with a period of about a week is provided by the wind relaxation or reversals associated with the passage of these cyclones south of the continent during the upwelling season (Shannon, 1985).

An illustration of a 5 day cyclic weather pattern over the Benguela system typical of summer conditions can be found in Shannon (1985) on page 120. On day 1, the South Atlantic high is established, there is a coastal low at Luderitz and Cape Town experiences southerly winds. On day 2, the South Atlantic high ridges, the coastal low moves south and there are gale force winds at Cape Town. The South Atlantic high weakens on day 3, and following the passage of the coastal low, Cape Town has northwest winds. On day 4 southerly winds blow along the west coast and the South Atlantic high strengthens leading to offshore berg wind conditions on day 5.

The southern Benguela has three distinct upwelling regions, these being the Hondeklip, the Cape Columbine and the Cape Peninsula upwelling cells. As far as Saldanha Bay is concerned, it can be thought of as part of the southern border of the Cape Columbine upwelling region. Aerial radiation thermometry has shown how, as the wind develops, typically in cycles of six days, cold water appears along the coast north of Cape Town and extends northwards into the Cape Columbine upwelling cell (Nelson and Hutchings, 1983). This cold, upwelled water has a temperature typically of around 10° C, compared with the offshore water which has a temperature of typically 16° C (Shannon, 1985).

2.1.3 Coastal-Trapped Waves

The existence of coastal-trapped waves with periods of a few days to weeks has been demonstrated along various coastlines around the world. Initial investigations used sea level measurements to identify their propagation, while later the associated current structures were also analysed (Schumann and Brink, 1990). It was found that the propagation of sea level disturbances occurred down the west coast and along the south coast (De Cuevas et al, 1986). Their activity was limited, though, perhaps due to the nature of the wind forcing and the topography (Schumann and Brink, 1990). Generally, coastal trapped waves travel with speeds of around 5m/s and have amplitudes ranging from 10-50cm on a time scale of 2-20 days. It is these waves which form an important part of the weather determined component of sea level. Due to seasonal changes in the prevailing synoptic weather conditions there are seasonal differences in shelf waves (Searson, 1994).

2.2 Previous Work in Saldanha Bay

Saldanha Bay was a single bay prior to 1974. From 1974 to 1975 the physiography of the area was modified into two bays by major harbour works with Small Bay being located to the north of the ore jetty and Big Bay to the south. The iron ore jetty thus separates the two bays from one another and the causeway linking Marcus Island to the mainland separates Small Bay from the open southern Benguela.

What follows is a review of previous studies in Saldanha Bay, Small Bay in particular, with respect to currents and circulation. The studies include those by the CSIR (1976), Shannon and Stander (1977), Monteiro and Brundrit (1990), and two by Weeks et al (1991a,b). The information provided will have applications for similar work, both with respect to current studies methodology and with respect to current and circulation dynamics in similar upwelling regions.

Drogue measurements and sampling techniques were used by Shannon and Stander (1977) to describe the nature of the hydrology and the currents in Saldanha Bay prior to the construction of the jetty and causeway. They showed that the currents in the bay were about 5-10 cm/s, but stronger at the mouth where the most tidal forcing was felt. They also predicted (as was confirmed by Weeks et al I, 1991) that changes would occur upon completion of harbour works.

A study was conducted by Monteiro and Brundrit (1990), the aim of which was to show how chlorophyll is affected by interannual variability in the characteristics of coastal water. The water samples used were collected between 1974 and 1979 and analysed for temperature, salinity, chlorophyll, oxygen and nutrient components.

Although no detailed data on vertical structure was obtained for the Saldanha Bay system, it was shown that the system exhibits thermal stratification in summer with a thermocline at 3 - 6m. The thermocline separates a surface layer which is sun-warmed (18-20°C) from a cool (11-13°C) bottom layer. In winter however, the water column is largely isothermal (13-14°C). This is important in so far as it will be shown that the tides and winds exert differing influences on the currents under stratified as opposed to well-mixed conditions.

The survey of Weeks et al I (1991) is comparable with the present study and is therefore presented first. The methodologies of this study were in fact adapted for use in the present study.

The boat used was fitted with a Decca Navigator, and station positions had an accuracy typically better than 100m. The wind speed and direction were taken by means of a hand-held anemometer, while current speed and direction were measured by tracking floats fitted with drogues.

Current measurements were taken at various depths, including 1m (referred to as the surface), 5m and 10m. Drogues were deployed simultaneously at these depths from an anchored boat and their movements tracked by means of a hand-held hand-bearing compass and range-finder. The influence of the windage on the floats was very low and so the drogue design was recommended for use in future research.

In total, 486 current measurements were taken , of which 276 (57%) were during summer, and 210 (43%) during winter. Because the small boat could not be used in high waves, the data collection was biased away from high wind speed conditions. Scatter plots were then used to analyse the relationship between current and wind directions. Percentage frequency distributions of current speeds at different depths and under various conditions were plotted to determine the relative impact of wind and tidal forcing on current speeds. Wind strengths were grouped into two categories, these being "low wind" and "high wind", representing winds of strengths less than 5m/s and between 5 and 12m/s respectively.

At the surface, more than 80% of current speeds were less than or equal to 12 cm/s, while the speeds at 5m and 10m were even lower, 75% being less than or equal to 6 cm/s. A tendency towards lower speeds with increasing depth was seen. The "high wind" data is not truly representative of the strong winds (12 to 25m/s) which occur during the summer months, and only 25% of the data were collected during winds of strengths in that category. The predominant wind direction was from the south south west.

The impact of the wind forcing on the direction of current flow was evident. Two dominant wind directions, south-westerly and north-westerly, gave rise to northerly and southerly currents respectively (Weeks et al I, 1991). This correlation between surface wind and current direction held true for many observations.

Current vectors at depths of 1m, 5m and 10m were plotted for various tidal and wind conditions, at different locations within Saldanha Bay, in order to examine the flow patterns (Weeks et al I, 1991). The direction of flow largely reflected a seasonal wind-driven pattern: The resultant current vectors for summer pointed in a northward direction, whereas the winter vectors were directed southerly. This confirmed wind dominance at the surface, even during very light winds. Some vectors were stronger than others, showing a possible synergism between wind and tidal forcing.

It was also shown that the water circulation in Small Bay appeared to be dominated by wind forcing. An aerial photograph taken during a SSW wind of 8 m/s showed the water being driven against the northern margin, and being deflected predominantly to the east, from where it flowed out as a narrow jet alongside the jetty, i.e. suggesting a clockwise circulation pattern in Small Bay. Looking at the vertical scale, Weeks et al I (1991) showed the wind/current direction correlation weakened with depth, this probably due to decreasing effect of wind forcing. The weakening of correlation with depth was attributed to tidal forcing, shear in the water column and bottom drag.

To investigate the tidal impact on the circulation, a study of the tidal flow patterns at different locations in Saldanha Bay was done by plotting current vectors under different tidal conditions. Data to the south of 33° 04' 20 was omitted from all analyses as these points lie within Langebaan Lagoon, which is shallow and almost completely tidally driven. The contributions of tidal and wind forcing on the circulation in Saldanha Bay were studied separately. Only low winds with all tidal conditions were selected and thus tidal forcing, if significant, should have been more important than wind forcing. The current to wind direction correlation, however, was maintained. This correlation was also still present during spring floods and ebbs (extreme tidal conditions) showing that, during summer and winter at least, wind forcing dominated tidal influence on current direction.

Weeks et al II (1991) showed that upper and lower layer movements in the Bay satisfy a mass balance. Wind forcing was shown to be an important factor in driving the surface circulation over most of Saldanha bay (Weeks, Boyd and Monteiro, 1990) and mixing in the surface layers should therefore be enhanced by the wind. This is supported by Shannon and Stander's horizontal temperature profile of the bay (1977) which indicates complete mixing at the surface and at 5m.

Wind influence, however, weakens with depth, especially under stratified conditions typical of summer (Weeks, Boyd and Monteiro, 1990) when the presence of a thermocline separates a wind-driven surface layer from a tidally-driven bottom layer. While both the surface and deeper layers are very mixed (by wind and bottom interference respectively), there is minimal mixing across the interface between the two layers.

Measurements were made by the CSIR in 1976, using tide gauges, dyes and drogues to determine the circulation in the bay. These measurements were included into a two-dimensional hydrodynamical model employed as a management tool which simulated only the tidal current circulation of Saldanha Bay. The current patterns computed during the trial runs of the model showed a certain similarity with the results of their field measurements and even though the data collected was not sufficient for meaningful or complete interpretation, certain trends in current circulation appeared repeatedly and allowed for a number of tentative conclusions to be made.

Firstly, propagation of the tide in the bay does not follow the simple inflow and outflow characteristics. Secondly, large eddies are caused by tides entering or leaving the bay and opposing currents are formed in some areas of the bay. Thirdly, current flow can be different in direction and speed to the extent that the current flow near the surface and in deeper waters is in completely opposite directions.

In addition, despite the fact that the majority of data was collected under little or no wind conditions, they conclude that wind appears to have a significant influence on the circulation in the bay and the direction and speed of the currents. Based on the observed current speeds, Shannon and Stander, (1977) estimated a residence time of water in the bay to be about 20 days. Knowledge of this residence time is fundamental to modelling the impact of natural and anthropogenic organic carbon and nitrogen inputs.

2.3 Summary of Previous Results

Bearing in mind the results of all the previous studies, an overall idea of the characteristics of forcing mechanisms and subsequent circulation patterns can be formed.

Two dominant wind directions, south westerly and north westerly, give rise to northerly and southerly currents respectively (Weeks et al I, 1991). Currents in the bay are generally sluggish, except at the mouth of Small Bay where the strongest tidal forcing is felt (Shannon and Stander, 1977). At the surface, current speeds are generally less than or equal to 12 cm/s, while at 5m and 10m depth, speeds are less than 6 cm/s (Weeks et al I, 1991).

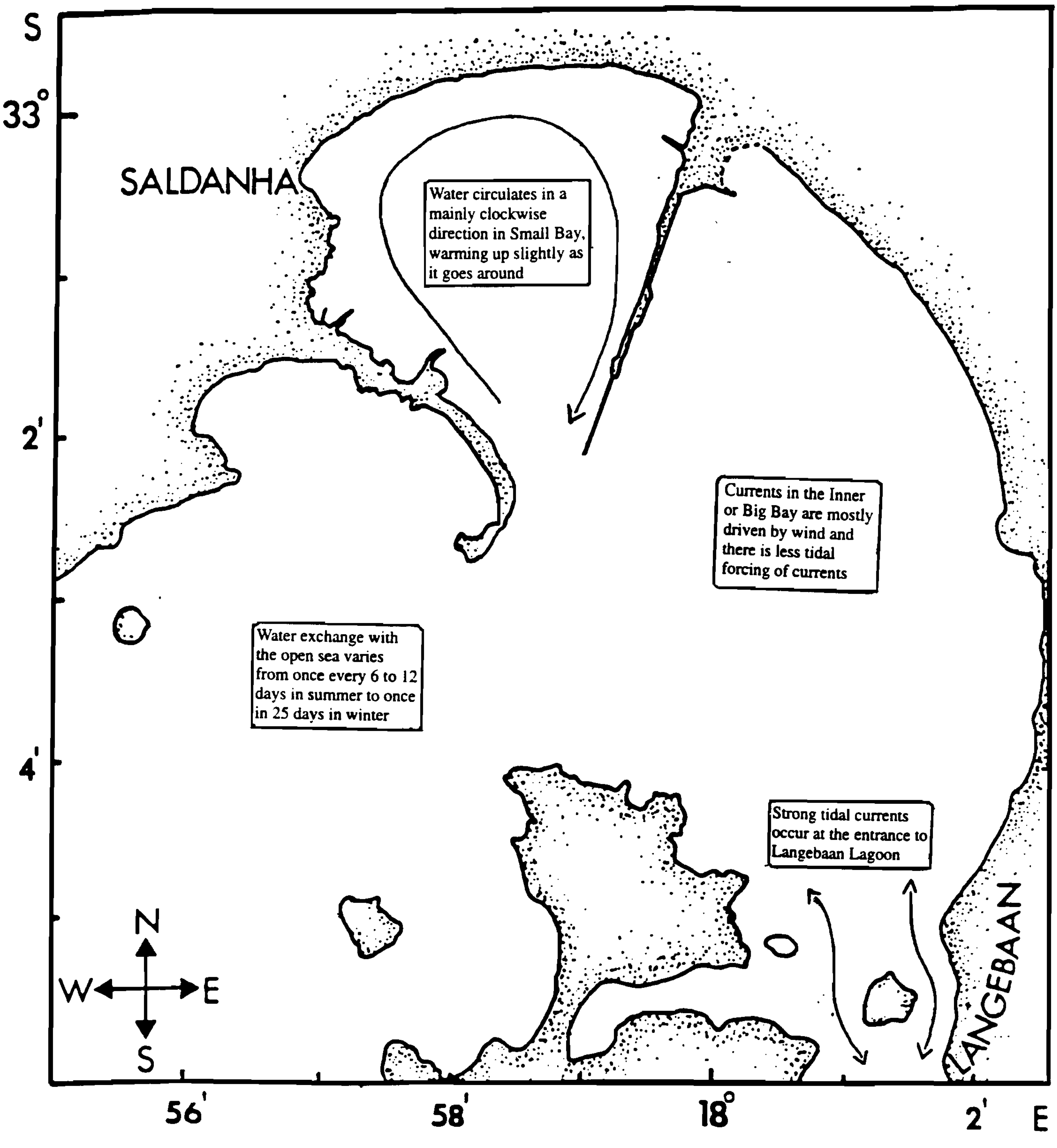
The system is thermally stratified in summer with a thermocline at 3-6m, separating a sun-warmed surface layer from a cool bottom layer. In winter the water column is largely isothermal (Monteiro and Brundrit, 1990). During summer and winter, wind forcing dominates tidal influence on current direction (Weeks et al I, 1991). Under stratified conditions, movement in the wind-driven surface layer is compensated for by movement in the tidally driven bottom layer in the opposite direction (Weeks et al II, 1991).

The wind/current direction correlation weakens with depth and aerial photographs show that the harbour construction has constrained the circulation in Small Bay, resulting in a clockwise circulation pattern with boundary enhancement (Weeks et al I, 1991).

The direction of flow reflects largely a seasonal wind-driven pattern (Weeks et al I, 1991).

Tidal propagation in the bay does not follow the simple inflow and outflow characteristics and the tides entering or leaving the bay cause large eddies and opposing currents to form in some areas of the bay (CSIR, 1976). The residence time of water in Saldanha Bay is about 20 days (Shannon and Stander, 1977).

A graphical summary of the circulation in Saldanha Bay according to the literature prior to the present study is provided in figure 2.1 (after CSIR, 1995).



Water circulates in a mainly clockwise direction in Small Bay, warming up slightly as it goes around

Currents in the Inner or Big Bay are mostly driven by wind and there is less tidal forcing of currents

Water exchange with the open sea varies from once every 6 to 12 days in summer to once in 25 days in winter

Strong tidal currents occur at the entrance to Langebaan Lagoon

Figure 2.1: Map of Saldanha Bay showing important features of the circulation according to literature prior to this study

CHAPTER 3

METHODOLOGY

3.1 Current Tracking Using Drogues

There are various methods available for tracking currents, including surface drifting buoys (some satellite-tracked), Acoustic Doppler Current Profiling (ADCP) where absolute water velocities are calculated by combining the east and north components of the ship's motion over the ground with the east and north components of the motion of the water relative to the ship (King and Cooper, 1993), current meters and drogues. Each of these methods has associated advantages and drawbacks and fall naturally into two categories. The first is Eulerian, where the currents moving past a fixed point are measured, for example in current meters. The second is Lagrangian, where a parcel of water is tracked. Lagrangian drift measurements are probably the oldest method of measuring ocean currents near the sea surface and drift data from ships represents the basis of the present charts of surface currents (Krauss, Dengg and Hinrichsen, 1989). What is needed for the Lagrangian approach is a relatively cheap, easily manageable method of following both surface and deep currents, and this is best done with the use of drogues. Surface drifting buoys by their nature only provide information about the surface currents, while satellite tracked buoys are expensive. Where ADCP is concerned, the only boats fitted with the system at present are too large to work in an enclosed bay.

Drogues work on the principle that they will move in the same direction and speed as the current at the particular depth at which they are deployed. Wind and waves are important considerations when designing drogues. Minimum structure should be presented above the surface and a uniform area should be presented to the pressure field (Lamberth and Nelson, 1987). The drogues themselves have various shapes and sizes, to suit the conditions in which they are deployed. The stronger the wind and the currents are, the more robust and bigger the drogues have to be. For our purposes, one design was used for all deployments.

The drogue consists of a biplanar tetrahedral PVC or canvas parachute of sides 1m tied to a float with nylon cord. It is weighted at the bottom and the position on the surface is marked by a marker flag and pole, attached to the float (figure 3.1). The decision to use drogues of this type was based on a number of criteria. Firstly, they need to be able to record near-surface currents under even high wind conditions.

Secondly, there needs to be a low windage (deflection of a projectile, namely the drogue, by the wind) of which an estimate can and will be made later. Thirdly, they need to have a suitably quick response to the currents. Fourthly, they need to be practical to deploy, locate and retrieve and lastly, because they are not always able to be retrieved, they need to be cost-effective. All drogue designs comply with the first criteria to a greater or lesser extent. As far as the windage is concerned, this can be measured with the following specifications in mind:

The float has a volume of 2 litres and is trimmed to minimal freeboard. The drag on the suspension line and the pole can be neglected (Murray, 1975). The pole is 0.03m in diameter and 1.5m long and it can be assumed that it has a tilt angle of 15° (maximum found due to observations). The wind speeds measured are typically 2-10m/s. Obviously the larger the drogue the smaller the error in speed due to wind effects on the drogue and for the drogues used in this study (length of the side of the drogue = 1m), the estimated maximum error in speed is just over 2 cm/s (Murray, 1975). We will see that this is negligible when compared with the observed drogue speeds of typically 5-30 cm/s.

The parachute design drogue has a suitably quick response to the currents and they are fairly easy to deploy and retrieve. Because they are designed with the weight at the bottom of the pole, the marker flag is kept upright during even high wind conditions, and in rough seas this makes the drogues easier to be tracked. The construction of drogues of this design costs about R200 per drogue, with the materials costing in the region of R50 and the labour making up the bulk of the cost. Canvas drogues are more durable than their PVC counterparts but are also more expensive. Because drogues are sometimes lost canvas drogues are preferred as they are the more environmentally friendly option due to their biodegradability.

The length of the nylon cord is varied, depending on the required depth of the drogue. The float is designed with a specific surface area and is weighted so that when in the water, it provides minimum wind resistance. Wind then only plays a role in the movement of the drogue in so far as it can govern the actual current speed and direction.

Seven visits were made to Saldanha Bay, three in 1993 (February, August and December), two in 1994 (August and September) and two in 1995 (March and June). Of these seven visits, three were under stratified conditions (February 1993, December 1993 and March 1995) and four under well-mixed conditions (August 1993, August 1994, September 1994 and June 1995). The principles of drogue tracking will be discussed and details of the three methods of position fixing will be given. Note that in all cases drogues were deployed from the boat and the boat pulled up alongside each in turn, for the position fix to be obtained.

Wind speeds were obtained either using a hand-held anemometer and compass, or a Thies Clima Model anemometer, capable of measuring the wind speed in metres per second. The Thies Clima Model has a claimed accuracy of ± 0.5m/s, but care was taken to hold this level of innacuracy to a minimum by always providing the anemometer with maximum exposure to the wind (this was done by taking the readings standing on the roof of the boat cabin when the boat was stationary). It was found that because the wind was fluctuating it was best to average the wind speed over ten seconds.

Wind directions were measured with a hand held compass and were recorded as compass points, for example south west. Wind measurements were taken concurrently with each drogue position fix.

Temperature/salinity profiles at various locations within the bay were measured daily using either a Kent EIL5005 Salinity Temperature Bridge Type MC5 with an attached probe, or a Seacat Salinity Temperature probe. The temperature profiles were used to determine the stratification within the water column and if stratified, to locate the position of the thermocline and hence the depth of the well mixed layer. This information assisted in determining at which depths to deploy the drogues, as well as contributing to calculations concerning Saldanha Bay as an upwelling area.

3.2 Drogue Position Fixing

The minimum current speeds measured by Weeks et al I were of the order of 5 cm/s. A current of 5 cm/s will travel 180m in an hour and based on this, we decided that the accuracy requirements necessary for current tracking was to be 10m, that is to say an error of ± 5%. This can be seen as an obvious improvement compared with the accuracy of about 100m obtained by Weeks et al. (1990) using a Decca Navigator. A more detailed description of the field accuracies required will be discussed later.

Three different methods of position fixing were used during the course of this project in an attempt to determine the most suitable method of drogue position fixing, namely surveying, stand-alone Global Positioning System (GPS) and differential GPS. At the beginning of 1993, when the first field trip to Saldanha Bay was undertaken, we were accompanied by surveyors, whose accuracy levels confidently met our requirements. Later on in the year, a stand-alone GPS system became available to us and based on the relatively low cost and ease of operation of the system, it was decided to use the GPS in place of the surveyors. However, the accuracy levels that could be achieved under the unique conditions in Saldanha Bay were not known and it was discovered that the accuracy was suitable under certain conditions and not under others. Fortunately, the differential GPS was made available to us and it was found, as will be seen later, to be both accurate, cost-effective and easy enough to operate to justify using it as the method of drogue tracking for future field trips.

3.2.1 Surveying

This position fixing technique was used only during the February 1993 field trip to Saldanha Bay. Three surveyors set up theodolites at various locations surrounding the bay. The boat was moved as close to the drogues marker flag as possible and an operator in the boat held up a prism with a flag. All three surveyors obtained a position fix on the prism relative to a fixed position on land with known co-ordinates. Radio contact was maintained between the surveyors and the boat and when the fix had been obtained, the boat moved on to the next drogue. The drogues positions were then calculated by triangulation.

In addition, one of the theodolites was fitted with an EDM (electromagnetic distance measuring) device which calculated the distance from the sensor to the prism via an infra-red signal beam and hence determined the position of the drogue independently of the other two theodolites. Both the survey triangulation method and EDM are able to theoretically calculate the position of the drogue with an accuracy of 1mm plus 1 ppm (Burnside, 1991). This translates to an ideal accuracy of 2mm over a distance of 1 km. Although this was impossible due to the movement of the boat, the boat's movements were relatively small and hence this method was clearly well within our accuracy requirements. The resultant latitudes and longitudes recorded by the surveyors, relative to the Clark reference ellipsoid, were then transformed into the Lo-19 surveying co-ordinate form (distance in metres relative to the 19 degree line of longitude). They were inserted into a Geographical Information System (GIS), designed for Saldanha Bay by Noel Gehren, a student in the Department of Surveying and Geodetic Engineering at the University of Cape Town. A GIS is basically a collection of hardware and software components designed to manage spatial databases. It was developed out of the need to retrieve and analyse spatial information more effectively with the help of a computer (Lee and Zhang, 1989). The results from the drogue study were displayed graphically in the form of a base map with the associated drogue tracks for each deployment. Hourly markers were plotted on the drogue tracks and this, together with a wind and tide diagram on each map, enables the viewer to absorb detailed information about each deployment at a glance. Because of the labour intensiveness of survey position fixing, an alternative method of position fixing, GPS, was investigated.

3.2.2 Stand-Alone GPS

The Global Positioning System is a satellite-based navigation system developed for use by the United States Department of Defence. It uses range as its basic measurement. In principle, ranges are measured simultaneously from at least 3 satellites to a single ground station. The satellite positions are known, and a three dimensional trilateration enables the ground station position to be determined. The ranges themselves are deduced from measuring the time taken for a particular code, superimposed upon a microwave carrier signal, to travel from the satellites to the ground receiver. In principle, this means that the clock at the receiver must be exactly synchronised with the clocks on board the satellites. In practice, the receiver clock has an arbitrary offset, and four, not three, satellites are observed simultaneously. The additional observation is used to solve for this clock offset (Merry, 1994).

This stand-alone GPS system was used during the August 1993 and December 1993 field trips. On each station the readings in latitude and longitude were recorded manually and electronically from a Magellan Nav 5000 Pro hand-held GPS as well as from a second GPS manufactured by Trimble.

Trimble claimed accuracy levels of 100m while the Magellan manual stated accuracies of the order of 15m averaging over 5 minutes. Ideally, we were hoping to take averaged readings over approximately 5 minutes using the Nav 5000 Pro, but due to the movement of the drogue and the difficulty of keeping the boat close to the drogue for 5 minutes, it was decided to average over 30 readings, taking roughly 1 minute.

As each of the 30 readings in a session were taken, a standard deviation of the position fix was calculated and displayed. This is an indication of the relative accuracy of the fix. Thus the absolute position fix may be incorrect, but during the 30 readings the individual fixes will be relatively close to each other. Bad standard deviations can be a result of either distorted satellite to GPS receiver information transmission or from excessive movement of the boat during the readings.

The Position Dilution Of Precision (PDOP) is an estimate of the geometric quality of the fix and thus gives an indication of the accuracy of the absolute position - the smaller the PDOP the better the fix is likely to be. This depends on the position and geometry of the satellites used to determine the position fix. If a bad PDOP was obtained, other satellites with better positional geometry were used, or we waited until the geometry of the satellites improved as they moved within their orbits. The accuracy requirement set for the project was that the standard deviation did not exceed 5m and that only a PDOP of less than 2.5 was accepted. Mostly, a PDOP of less than 1.6 was achieved. If the readings obtained did not meet the accuracy requirements set, another 30 readings were obtained and the mean of the two readings was used to calculate the position fix.

Both GPS receivers were used to calculate the position fix of a moored CSIR buoy in a known location on three occasions throughout the first day. The result was that the Trimble receiver gave us consistent position fixes on the buoy to within 50m of each other, whereas the Magellan's position fix on the buoy varied by as much as up to 150m. It was therefore decided to use only the former to calculate the drogue positions during the remainder of the field trip.

The drogue trajectories for deployment 1 (February 1993) based on the Trimble GPS co-ordinates show a disparity with the drogue tracks based on the surveyors' co-ordinates. The latter are therefore shown to be the more accurate way of tracking the drogues (figure 3.2). As an example, the positions of drogues B3 and D3, as seen in figure 3.2, differed by 200m and 90m respectively, when using the two different methods.

There are three main ways in which the satellite signals could be varied such that they become less usable to the receiving equipment. Firstly, the information contained in the data stream transmitted can be encrypted. Secondly, the information from which the system time is derived can be varied and thirdly, the information concerning the position of the satellite when the transmission is made can be corrupted. These latter two, taken together, can readily give a controlled degradation of the positional accuracy which can be gained from the system.

When such variations are applied to all of the satellites in view, then the controls of the degradation of accuracy covers wide areas. It is the method of time and orbital position data variation which has been chosen by the US Department of Defence to control available accuracy of the Navstar system which can be directly obtained by the user equipment. This system of control is termed Selective Availability (SA).

The effect of SA may be considerably reduced if two GPS receivers are used in a procedure called differential GPS (DGPS). This entails setting up one GPS receiver in a surveyed (known) position on land and having a roaming receiver on the boat. Because neither of the two stand-alone GPS receivers could match the accuracy levels achieved by the surveyors (as has been shown in the comparison of co-ordinates), and neither met our stringent accuracy requirements, it was decided to investigate the possibility of using the differential GPS system, details of which are described in section 3.2.3.

The GPS is also subject to certain manufacturing errors concerning the satellites and power source. Using a more accurate hand-held GPS and averaging over time (eliminating the "bad" readings) enables us to eliminate the need for surveyors. This, however, is not practical when tracking moving drogues. Magellan's claim that using averaged readings, the Nav 5000 Pro can obtain position fixes to within 15m is not appropriate in drogue tracking, since it is impossible to take a 5 minute averaged reading. Thus an accuracy level of 150m is more realistic.

3.2.3 Differential GPS

The concept of DGPS has grown from the fact that the US Department of Defence, for security reasons, declared a policy of spoiling the accuracy available to the general user of the Navstar GPS transmissions. Twenty-five metre accuracy, and certainly 100m accuracy are not acceptable. Most applications require better than 10m accuracy with 5m accuracy being vastly preferable and so the concept of differential GPS has been under study, test and refinement for about 10 years (Denaro and Kalafus, 1990). In Germany, DGPS surveying has been used as a common measuring tool since 1983 (Beckmann, Larisch, Schuster and Barwinski, 1989). Samples of transmissions have been characterized by the US Department of Transport and the application of differential techniques pointed to possible accuracies of 10 metres using transmissions modified by Selective Availability algorithms (Wheeler, Hendley and Fenner, 1994).

Inspection of the applications where there is a requirement for a high order of accuracy in position fixing shows that the requirements are, for the greater part, restricted to areas in which a clear signal path to the satellites is available, and in areas where the maximum number of satellites are in orbit. This leads to the investigation into the feasibility of providing a differential measuring service in these areas.

This is achieved by putting a monitor receiver at an accurately surveyed position and measuring the deviation in that position as calculated from the satellite transmissions. The differences are then encoded on to a datalink and generally disseminated within the area of interest for use by other suitably equipped receivers so as to substantially reduce the error in their own calculated position. By applying differential techniques, navigational accuracies of better than 10m can be achieved.

In addition to providing a highly accurate navigational signal, DGPS also provides a continuous integrity check on satellite health. With the design of the ground segment of GPS, a satellite can be transmitting an unhealthy signal for 2 - 6 hours before it can be detected and corrected. However, with the continuous, real-time messages generated by DGPS, unhealthy satellites can still be used, or the navigator's receiver can be directed not to use a particular satellite. This can eliminate the danger of the navigator relying on an erroneous signal.

The entire system is easy to operate and reliable. While the roaming receiver is being used in the field, the base station is switched on and acquires its position after only a few minutes each morning. During the day's operation, it requires no care or adjustment; it just records the appropriate data.

Once all the data has been stored, both the base station and roaming receiver data are downloaded and differential corrections made to the roaming receiver data. During testing, the DGPS never provided misleading information. There are instances in which DGPS can fail to provide adequate fix information. These instances are short in duration and can be attributed to changes in the satellite coverage or constellation.

The hand held receiver used was manufactured by Corvallis MicroTechnology (CMT). In stand-alone mode, CMT claimed an accuracy of typically better than 80m, with the accuracy being 5m after differential corrections are applied.

For the base station, a number of possibilities exist and these will be examined in turn. The easiest is for the base station to be set up in the Department of Surveying and Geodetic Engineering at the University of Cape Town and switched on and off according to a pre-arranged schedule. Once back from the field trip, the base station and hand-held receiver data is downloaded and the differential corrections made. Another option is to position the base station in Saldanha Bay itself. This was attempted on one field trip, but because the beacon on which the base station had to be placed was on the top of a remote hill and very exposed, this made its operation impractical. The accuracy levels are increasingly degraded with increasing distance between the roaming receiver and the base station, based on the fact that at greater distances apart, different satellites will be available to the base station and roaming receiver, making differential corrections more difficult.

Hence different satellites will be obstructed from the view of the ground components. At a separation distance of less than 300km, however, the manufacturers assume that the same satellites will be available and so it is only beyond 300km that the separation distance becomes important. Since Saldanha Bay is within 300km of Cape Town, the accuracy levels for the differential system are assumed to be 5m.

The final option is to use the base station data from an independent station, such as Hartebeeshoek which is 1500km north-east of Cape Town or Telkom at Van Rijnsdorp, 100km north of Cape Town. Problems arise, however, in that the data are not always compatible and this, coupled with the distance between the base station and the roaming receiver (greater than 300km), do not make using alternative base stations feasible.

From the investigations into drogue position fixing we can conclude the following:

For the accuracy levels required, the use of a stand-alone hand held GPS unit is not suitable. The results are not reliable enough and the levels of accuracy do not meet our requirements. As has been shown, the survey method's accuracy abilities are well within our requirements, but the process is labour intensive and therefore expensive. The other method available to us and suitable for our purposes is the use of differential GPS. This system also performs to well within our accuracy requirements, and at the same time is comparatively cheap, time efficient and easy to operate.

The Short Range Aids to Navigation Division of the US Coast Guard recognized the potential use of DGPS as a new aid for navigational positioning. The present manual positioning methods are tedious, time-consuming, and error-prone. The units must continually check and recheck their positions with electronic navigation aids, radar information, and horizontal sextant angles to place a buoy on station. Automation of this procedure with DGPS input allows units to obtain real-time positioning information for navigation and placement (Klinger, Wroblewski and Krammes, 1992).

The American Coast Guard Research and Development Centre developed an automated navigation aid positioning system - Laptop Automated Aid Positioning System, or LAAPS. Tests conducted on the system show it can find the position of aids to navigation with 2-3 metre accuracy. DGPS will provide accurate navigation information throughout the US coastal zone (Klinger et al, 1992) and will fulfill the 8-20m navigation accuracy requirement for harbour and harbour approach areas with an availability of up to 99.9% (Alsip, Butler and Radice, 1993).

It is anticipated that DGPS will be the navigational choice once the transmitters and receivers are widely available. GPS without the differential correction is already being used world-wide. The recent war in the Persian Gulf exemplified the usefulness of GPS positioning, with the United States using GPS-guided missiles to destroy Iraqi scud missile bases. Land, sea and air navigation, and terrestrial surveying and mapping operations all employ some form of GPS information. When DGPS improves GPS accuracy from 100m to 5m, there will be a significant accumulation in the use of the signal. Plans call for nation-wide coverage of DGPS in South Africa by 1996.

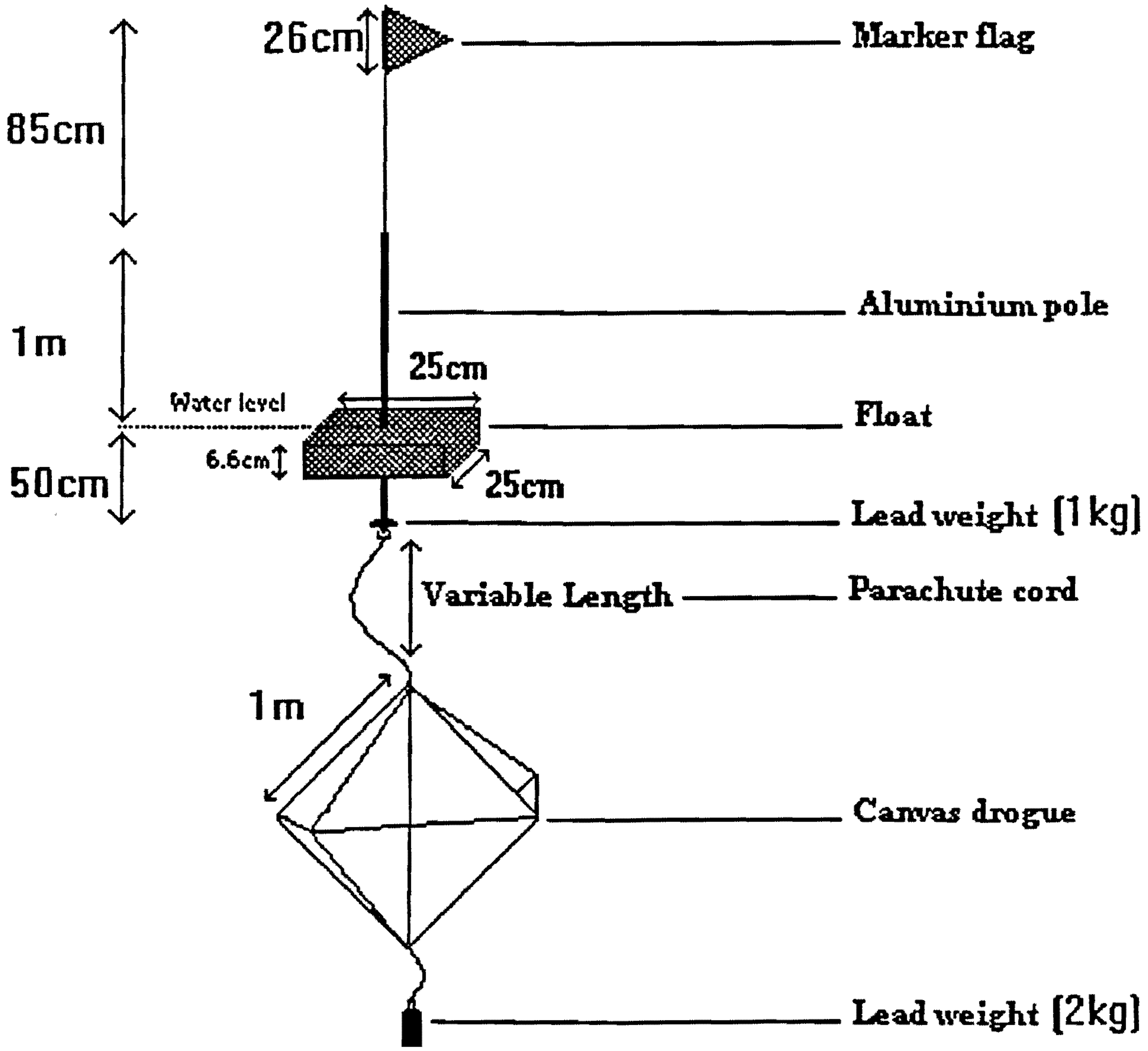


Figure 3.1: Schematic diagram of a typical fully assembled drogue for use in current tracking

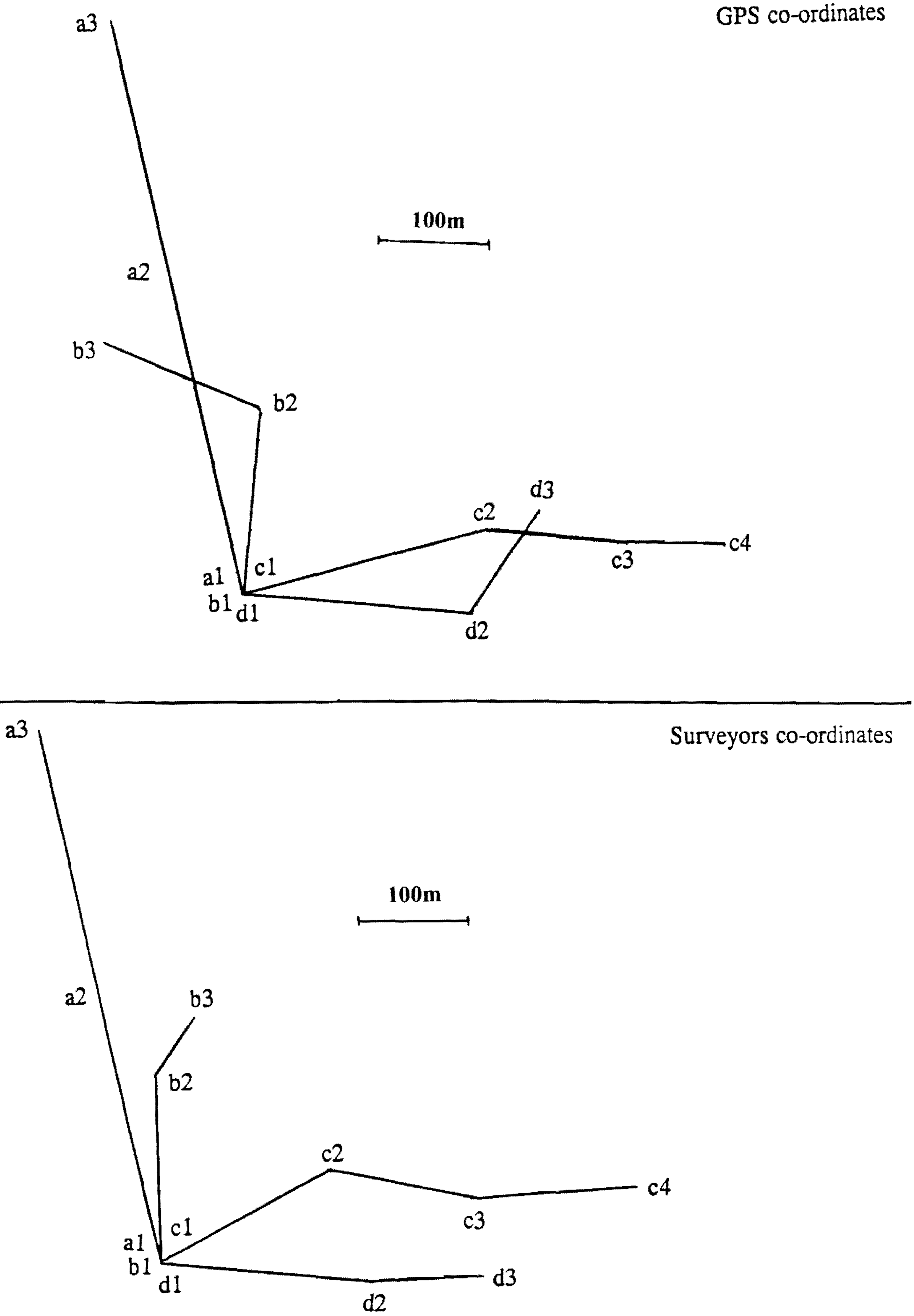


Figure 3.2: Comparison of surveyors and GPS drogue tracks for 15 February 1993 showing variations between the two methods

CHAPTER 4

RESULTS

4.1 Drogue Deployment Conditions

Drogues were deployed under the complete range of tidal conditions (full and partial flood neaps, full and partial ebb neaps, full and partial flood springs and partial ebb springs) to enable us to observe the wind effects on the currents. Full refers to the tidal cycle from low water to high water or vice versa, and partial refers to part thereof.

Winds were categorized into three main classes, these being light (below 5m/s), moderate (between 5 and 10m/s) and strong force (greater than 10m/s). Tides were also grouped into three main categories, neap (between 50 and 100cm tidal range), intermediate (tidal range between 100 and 150cm) and spring (tidal range > 150cm). Note that here tidal range is measured as the range of the tide on the days of the deployments.

Deployments were divided into summer and winter, depending on the stratification of the water column, and not on the actual season. When there was a definite thermocline, it was deemed to be a summer visit, and when no obvious thermocline was present (less than 1°C difference between the bottom and surface temperature) it was assumed to be winter. In effect, the months June to September were found to be winter.

Most observations were made when the wind was 5 - 10m/s, with very few during wind speeds exceeding 10m/s. This was as a result of the fact that the boat could not be held alongside the drogues for sufficient time for position-fixing under high wind conditions. Apart from the lack of results from strong wind conditions, a reasonable spread of conditions has been obtained.

Table 4.1 describes the deployments with respect to stratification (hence summer or winter, as defined earlier), mean wind strength, the tide state and the position-fixing methods. Figure 4.0 displays graphically the percentage of drogues deployed with respect to depth, season, tidal range, forcing mechanism and wind strength.

Table 4.1

Date	Stratified	Wind strength	Tide state	Position-fixing
15/02/93	Yes	Moderate	Neap	Surveying
16/02/93	Yes	Light-strong	Neap	Surveying
17/02/93	Yes	Light-moderate	Neap	Surveying
18/02/93	Yes	Light-moderate	Intermediate	Surveying
18/02/93	Yes	Light	Intermediate	Surveying
02/08/93.	No	Moderate-strong	Intermediate	GPS
03/08/93	No	Light-moderate	Intermediate	GPS
04/08/93	No	Light	Intermediate	GPS
12/12/93	Yes	Light-moderate	Spring	GPS
13/12/93	Yes	Light-moderate	Spring	GPS
14/12/93	Yes	Moderate	Spring	GPS
08/08/94	No	None	Spring	DGPS
09/08/94	No	Light	Spring	DGPS
10/08/94	No	Light	Spring	DGPS
11/08/94	No	None	Spring	DGPS
27/09/94	No	Moderate	Neap	DGPS
28/09/94	No	Light	Neap	DGPS
07/03/95	Yes	Light	Neap	DGPS
08/03/95	Yes	Moderate	Neap	DGPS
27/06/95	No	Light	Intermediate	DGPS
28/06/95	No	Light	Intermediate	DGPS

4.2 Drogue Deployment Results

What follows is a day-by-day description of the drogue deployments. Different information about the deployments is given in the text and on the diagrams. The text provides a description of the position of deployment of the drogues, their movements, the duration for which they were deployed and gives an indication of their mean velocities. The diagram shows the actual drogue tracks plotted onto a portion of the base map of Saldanha (this portion varies according to their deployment position) and a detailed description of the winds and predicted tides for the duration of the deployment is provided in the form of a graph. The tide graphs show tide height in metres taken from the South African tide tables and the wind graphs indicate only wind speed (m/s). The hourly wind direction is given by the arrows at the bottom of each graph, with the top of the graphs pointing true north. Hourly markers are interpolated on the drogue tracks to enable a cursory examination of the drogue speeds. Dotted lines on drogue tracks indicate a redeployment where a drogue was grounded, that is to say the drogue did not move along the path of the dotted line but was rather moved in the boat. The individual deployment diagrams need to be viewed in conjunction with table 4.1, which provides details about the stratification, wind strength, tide state and position-fixing method for each deployment date.

15 February 1993 (figure 4.1)

Drogues at four depths (2m, 5m, 10m and 15m) were deployed in the middle of Small Bay from 14h00 to 18h00. The wind was over 5m/s and the tide falling. The 2m and 5m drogues moved with consistency in the direction of the wind, the 10m drogue perpendicular to the wind, and the 15m drogue in the direction of the falling tide. The surface drogue moved with a mean current speed of 15 cm/s, considerably faster than the deeper ones at 3 cm/s.

16 February 1993 (figure 4.2)

Drogues were deployed from 08h00 to 16h00 at 2m and 10m near the mouth of the bay during rising and falling tides, with the wind south-west to south increasing from below 5 to above 15m/s. All drogues moved into the bay following the wind and rising tide, and against the falling tide. The 2m drogues had a mean velocity 16 cm/s, again faster than the 10m ones at 8 cm/s.

17 February 1993 (figure 4.3)

Drogues were deployed at 2m and 8m near the mouth of the bay from 08h00 to 19h00. The tide was rising and falling, the wind south to south-west at 2 - 10m/s. Three out of the four 2m drogues moved with the wind, while the one next to the ore jetty moving initially with the wind, then against the wind and in the same direction as the falling tide. Three out of the four 8m drogues moved with the wind and rising tide, and against the falling tide. The other 8m drogue's direction was tidally controlled, moving into the bay with the rising tide, and out of the bay on the outgoing tide. The surface drogues moved marginally faster (7 cm/s) than the deeper ones (5 cm/s), with the exception of the pair closest to the mouth of the bay, where the 8m drogue moved at 20 cm/s.

18 February 1993 (figure 4.4)

Drogues were deployed from 08h00 to 14h00 at 2m and 5m inside the causeway, with the wind south to south-west rising from between 2 cm/s to 7 cm/s. The tide was also rising. All the drogues moved with the tide and the wind, except for a 2m drogue which moved against the wind and the tide. This could possibly be explained by an oscillation within the curve of the causeway. All drogues had similar mean velocities of 4 cm/s).

18 February 1993 (figure 4.5)

Drogues were deployed from 15h00 to 19h00 at 2m and 15m at the mouth of the bay, during a falling tide with the wind south to south-west at <5m/s. All the drogues moved against the wind, with the falling tide, and the surface drogues moved at 10 cm/s, faster than the deeper ones at 4.5 cm/s. This is expected at the mouth of the bay in the case of low winds and spring tidal conditions.

2 August 1993 (figure 4.6)

Surface and deep drogues were deployed just outside the mouth of the bay from 14h00 to 17h00, with wind approximately 10m/s from the south-east and the tide rising and falling. All drogues moved out of the bay, against the wind and rising tide, then with the falling tide. The 2m drogues moved faster at ± 27 cm/s than deeper ones at ± 16 cm/s.

3 August 1993 (figure 4.7)

Drogues were deployed from 11h00 to 17h00 at 2m and 10m inside the mouth of the bay, with the tide rising and the wind from the south-west at 2 - 10m/s. All drogues moved into the bay, with the wind and rising tide, and once again, the surface ones had higher mean velocity (10 cm/s) than the deeper ones (7 cm/s).

4 August 1993 (figure 4.8)

Drogues were deployed from 0800 to 15h00 at 2m, 5m and 8m in the bay and at 2m and 10m ones outside the mouth of the bay. The wind was from easterly to south-westerly at < 5m/s and the tide rising. All the drogues moved into the bay, with the surface ones having velocities of 8 cm/s and the deeper ones 3.5 cm/s.

12 December 1993 (figure 4.9)

Drogues were deployed from 10h00 to 16h00 at 2m and 10m outside the mouth of the bay, with the tide rising and the wind from just below to just above 5m/s south to south-easterly. The 10m drogues all moved with the tide and wind into the bay while the 2m ones moved against the wind and the tide. All drogues had mean velocities of 11 cm/s.

13 December 1993 (figure 4.10)

A mussel raft was the deployment position for 2m and 10m drogues from 10h00 to 18h00 with the tide rising and falling and the wind between 2 and 10m/s, direction variable. All except one pair moved into the bay with the tide, the pair in question moving against both the tide and the wind. All drogues had mean velocities of 6 cm/s.

14 December 1993 (figure 4.11)

Only 10m drogues were deployed from 10h00 to 14h00 in Big Bay, with the tide rising and the wind 5 - 10m/s north-west. All drogues moved with the tide and against the wind with mean velocities of 11 cm/s.

8 August 1994 (figure 4.12)

Drogues were deployed at 2m and 8m just inside the causeway from 17h00 to 19h00, with the tide falling and no wind. All moved with the tide, the average velocity being 6 cm/s.

9 August 1994 (figure 4.13)

Drogues were deployed at 2m and 8m from 10h00 to 16h00 on the Big Bay side of the iron ore jetty, with the wind approximately 5m/s north to north-easterly and the tide rising. The surface drogues moved at 10 cm/s, considerably faster than the deeper ones at 2 cm/s.

10 August 1994 (figure 4.14)

Drogues were deployed at 2m and 8m on either side of the iron ore jetty, between 10h00 and 16h00. The wind was ± 5m/s south to south-westerly, and the tide rising. All moved with the rising tide and wind. Average surface velocities were 8 cm/s, with velocities in deeper water being 4 cm/s.

11 August 1994 (figure 4.15)

Only 2m drogues were deployed in the middle of the bay between 0900 and 14h00, with the tide falling then rising, and no wind. The drogues moved with the falling tide out of the bay, and then into the bay with the rising tide. Mean velocities were 1.4 cm/s.

27 September 1994 (figure 4.16)

Drogues were deployed at various depths (2m, 5m, 10m and 13m) on the Big Bay side of the iron ore jetty from 10h00 to 16h00. The tide was weakly falling and then rising, with the wind between 5 and 10m/s north to north-westerly. Even though no evidence of stratification was evident surface drogues moved to the left of the wind, deeper ones with the wind and slower than the surface ones. All had similar mean velocities of 9 cm/s.

28 September 1994 (figure 4.17)

Drogues were deployed at 2m and 5m off the outermost mussel raft from 10h00 to 15h00. The tide was falling and the wind < 5m/s from the south-west. It appears that the drogues were initially in the lee of the causeway and then moved slowly out into the entrance of Small Bay, where they came under the influence of the wind and their speeds increased. Surface drogues had mean velocities of 9 cm/s and deeper ones 4 cm/s.

7 March 1995 (figure 4.18)

Drogues were deployed at 2m and 8m outside the channel on the Langebaan side of Big Bay between 09h00 and 16h00. The tide was falling and then rising, with the wind < 5m/s ranging from south-westerly to westerly. All the drogues moved out with the falling tide and then came in with the rising tide. The 2m drogues moved considerably faster (25 cm/s) than the deeper ones (6 cm/s), and one of the surface drogues seemed to follow the bathymetry.

8 March 1995 (figure 4.19)

The same drogues as for 7 March were deployed, this time considerably further into Big Bay. The wind had strengthened to between 5 and 10m/s from the south-west, and the tide was falling and then rising. The surface drogues moved almost parallel (following the 5m contour) to each other out of the bay, with the wind and falling tide, and then against the rising tide. The deeper drogues moved to the right of the wind. Mean surface velocities were 17 cm/s and deeper ones 4 cm/s.

27 June 1995 (figure 4.20)

Drogues were deployed at 2m and 8m between 13h00 and 18h00 on the Club Mykonos side of Big Bay. With the wind less than 5m/s from the south-west, the drogues moved into the bay. The tide was again at slackwater high and mean velocities were comparable between surface and deeper waters (12.5 cm/s).

28 June 1995 (figure 4.21)

The same drogues as 27 June were deployed towards the centre of Big Bay from 10h00 to 19h00. The wind was again less than 5m/s from the south-west and the tide was rising. The 2m drogues moved at a rapid rate into the bay (8 cm/s), while the 8m ones moved to the right of the wind (3 cm/s).

A summary of the individual drogue statistics (107 drogues deployed) is provided in table 4.2. This table shows how many drogues at each depth were deployed under stiff and steady, light and steady, and light and variable wind conditions. This analysis was used to determine how many drogues at each depth were influenced mainly by tide, by wind or as a combination of both.

For analytical purposes, the drogues are classified as being either wind driven, tidally driven or driven as a result of a combination of wind and tide. It is important to define the parameters that enable us to deduce the predominant forcing mechanism. In this regard we examine the individual drogues in each deployment.

If the drogues move consistently with the wind, without fluctuations in direction, we assume that they are being driven predominantly by the wind. If the drogues exhibit a change in direction coinciding with a change in direction of the tide, or if they are moving in direct opposition to the wind, we say that they are predominantly tidally driven.

Table 4.2

	Wind			Forcing Mechanism		
	Stiff/Steady	Light/Steady	Light/Variable	Wind	Tide	Both
Depth						
2m (52)	12	21	19	15	23	14
5m (8)	2	5	1	3	1	4
8m (24)	5	12	7	5	16	3
10m (18)	10	0	8	4	10	4
15m (5)	2	3	0	0	4	1
Total (107)	31	41	35	27	54	26

4.3 Inferences

If we look at the Saldanha Bay system as a whole we see that two dominant forcing mechanisms influence the circulation in the bay, namely wind and tide, and these drive the currents to varying degrees. Their effects vary both geographically within the bay and within the water column (i.e. on a spatial scale) as well as on a temporal scale.

The drogue track results have been synthesised into composite diagrams and explained in terms of wind and tide forcing as well as factors which modify this forcing. Examples of these include topographical influences and Ekman veering. We are then able to draw inferences from these syntheses.

4.3.1 Tidal Forcing

The tidally driven drogues based on previously described criteria, both surface and deep, have been extracted from the individual deployment diagrams and divided into flood and ebb tide composite diagrams. The aim is to get an understanding of the strength and geographical influence of the tide on the current flow, as well as a sense of the direction of tidal circulation within Small Bay and Big Bay.

Examining the tidally driven drogues on the flood (figure 4.22) tide we can see that the largest tidal excursions are at the mouth of Small Bay and at the entrance to Langebaan Lagoon. Within Small Bay the tidal movement is not large and does not suggest the clockwise circulation originally proposed by Weeks et al (1991). Within Big Bay itself, there appears to be a division to the north-east of 33° 04' S and 18° 00' E in the direction of the tidal flow separating the flow towards the mouth of Langebaan Lagoon from the flow into the rest of Big Bay. During spring tides one would expect this division to be found further away from the mouth of the lagoon as the tidal influence extends further into Big Bay. The tracks in the middle of Big Bay suggest tidally driven water movement directly into the bay, their tendency to move northwards perhaps being caused by topographical influences. The deeper drogues are marked with a filled circle and there seems to be no distinct difference in current velocities and directions between surface and deeper drogues.

Looking at the tidally driven flow on the ebb tide (figure 4.23), similar aspects of the circulation are seen. Again, movement within Small Bay is minimal, and no evidence of clockwise circulation is seen. At the mouth of Small Bay and at the entrance to Langebaan Lagoon strong tidal currents are seen, with a marked difference in current velocity between surface and deeper drogues found at the entrance to the lagoon. The unexpected direction of tidal flow out of Big Bay on the ebb tide could be as a result of the strong southerly flow from the mouth of Small Bay.

From these two composite diagrams of tidally driven drogues, two features are apparent. Firstly, two regions of strong tidal influence exist, these being at the mouth of Small Bay and at the entrance to Langebaan Lagoon. Secondly, when comparing the speeds and directions between surface and deeper currents for the tidally driven drogues, we see that they have comparable speeds and directions, except for the region in the mouth of Langebaan Lagoon and inside the entrance of Small Bay. Here the deeper drogues are distinctly slower than the surface ones.
The shallow water depth of less than 5m and the increased bottom turbulence is the likely explanation for this phenomenon.

4.3.2 Wind Forcing

Wind driven surface drogues were extracted from the individual deployment diagrams and have been divided into summer and winter regimes. Where drogue tracks overlap, only one set is displayed.

During summer stratification (figure 4.24) it is evident that the surface wind driven flow is reacting to the predominantly south-westerly wind. The surface drogues moving at a slower rate in a north-easterly direction away from the coast are in the lee of the breakwater, and so will initially have low velocities. Evidence of bottom topography influencing the direction of drogue movement can be seen in Big Bay in the composite diagram and in the 8 March and 28 June 1995 individual deployment diagrams. Here the drogues closely follow the 5m contour (figure 1.1).

In winter (figure 4.25), the surface currents are influenced by both the south-westerly and northerly winds. Currents influenced by the south-westerly wind are marked with a filled square. It is important to remember that "winter" is not characterised by the wind regime but by the lack of stratification.

It is therefore obviously possible for the surface currents to fall under the influence of both dominant wind regimes. At the mouth of Small Bay we can see that the currents are initially moving eastwards, but then move northwards as they tend towards the iron ore jetty. This suggests tidal influence, but looking at the deployment diagram for 28 September 1994, we can see that this is not the case. The tide is an outgoing neap, and we can see that the currents are initially in the lee of the breakwater, but then as they tend towards the iron ore jetty, come under the influence of the south-westerly wind.

When we compare the direction of the surface and deeper drogues for the wind driven situation, the observations of 15 February 1993 (figure 4.1) and 27 September 1994 (figure 4.16) are particularly instructive. We see that the deeper drogues move increasingly to the right of the surface drogues.

In the presence of frictional interaction between the ocean circulation and the sea bottom, there is a turning and lessening of current with depth in the form of a spiral (Ekman, 1905). The effect of wind on a model barotropic ocean is to produce two Ekman spirals. The surface Ekman layer begins at the free surface and is associated with wind stress, and the bottom boundary layer is associated with bottom friction. The thickness of the bottom Ekman layer is estimated to be about 60m off Northwest Africa and 12m off Oregon. For the case of Northwest Africa the flow appears to be simply two Ekman layers superimposed on each other (Kundu, 1977). It is possible that this same description applies to the situation in Saldanha Bay.

In the surface friction layer the transport is to the left of the driving force of the wind in the southern hemisphere (offshore), and in the frictionally inhibited bottom layer the flow turns inshore as it approaches the bottom. The observation of 27 September 1994 is consistent with the Ekman theory of a frictionally inhibited bottom boundary layer as we see an inshore movement from 10m downwards, the boundary between the two layers being between 4m and 10m.

4.3.3 Comparisons Between Wind and Tidal Forcing

To investigate which forcing mechanism is dominant we will divide Saldanha Bay into three regions and examine the surface and deeper drogues individually. The first of these areas is the mouth of Small Bay, the second the entrance to Langebaan Lagoon and the third is the areas not included in the first two.

a) Surface Drogues

We have divided the wind strengths into light, moderate and strong. We can make various statements as to when the wind dominates the tide influence on surface drogues. When the winds are strong, they will dominate the tide in all three regions of Saldanha Bay. When they are intermediate, they will dominate tides in all regions of the bay except for at the mouth of Small Bay and the entrance to Langebaan Lagoon. When the winds are light they will dominate tides only in Small Bay.

b) Deep Drogues

At the mouth of Small Bay tidal forcing dominates deeper currents under light to moderate wind conditions. Tidal forcing is also seen to be the dominant forcing mechanism on deep drogues at the mouth of Langebaan Lagoon. Seasonally, tides exert a greater influence during winter when the bay is well mixed and when they are at full spring.

4.3.4 Influence on the Thermocline

Figure 4.26 shows the two lines of a CTD survey through Small Bay and Big Bay during stratified conditions, intersecting at the mouth of Saldanha Bay. At stations S5 (figure 4.27) and S15 (figure 4.28) a strong thermocline is present at around 8m. Looking at station X3 on either of figures 4.27 or 4.28, we see that although the bay is still stratified with a 10°C temperature difference between the bottom and surface water, there is no strong interface giving the thermocline a definite depth. This is also true for station S9 at the entrance to Small Bay. When we look at station S11 at the entrance to Big Bay, however, we see that the fairly sharp interface (of the order of a meter) over which the thermocline occurs is still present.

This means that the turbulence causing the thermocline smearing at stations X3 and S9 has not extended into Big Bay at station S11. Because the stations were done on the same day, the wind could not have caused the turbulence in one region and not the other, and so it can be deduced that the turbulence is as a result of tidal forcing. This supports the previously suggested idea that tidal forcing is dominant in the mouth of Small Bay, but does not extend a large influence into the mouth of Big Bay.

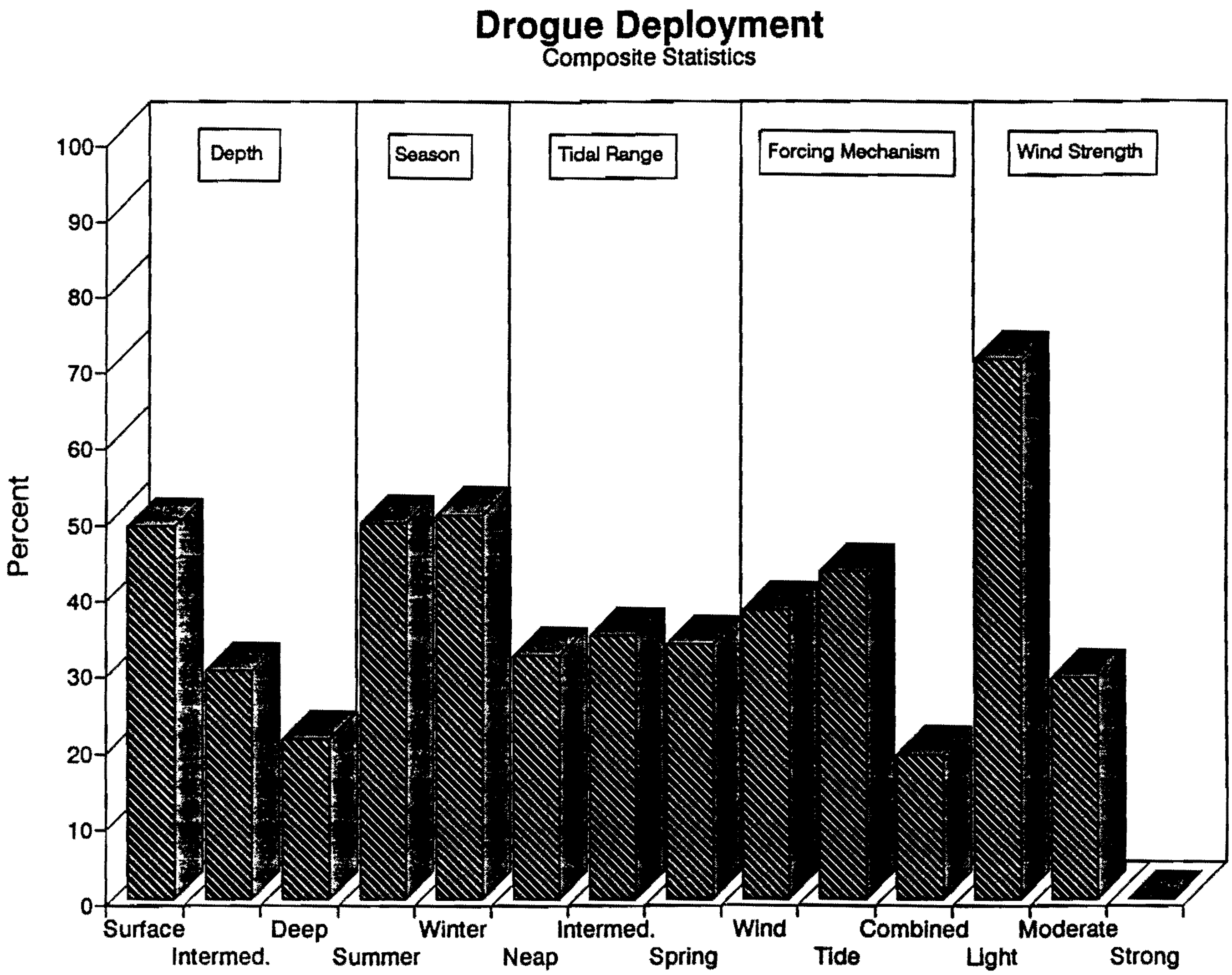


Figure 4.0: Drogue deployment conditions with respect to depth, season, tidal range, forcing mechanism and wind strength

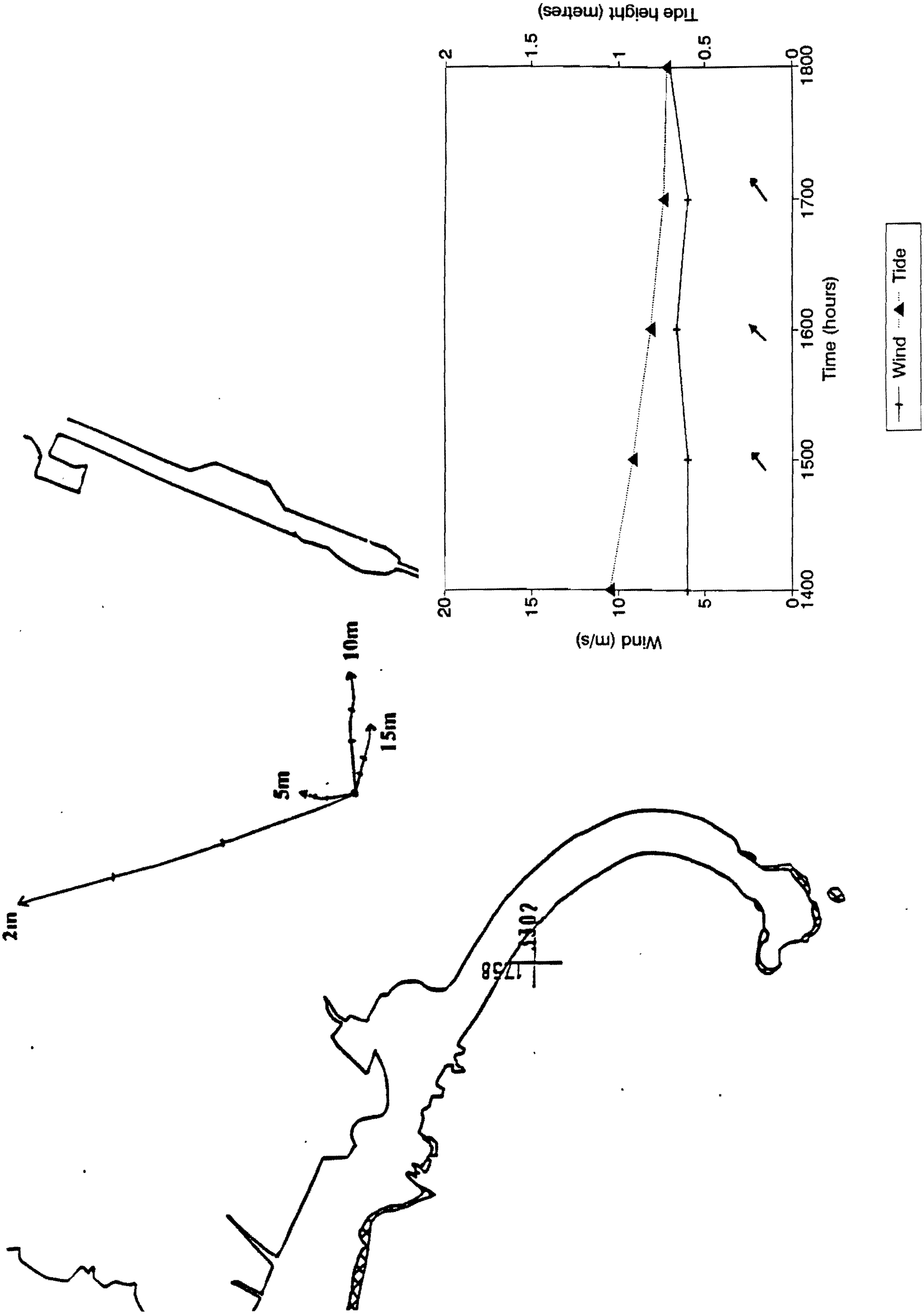


Figure 4.1: 1:25000 map of 2m, 5m, 10m and 15m drogue tracks for 15 February 1993

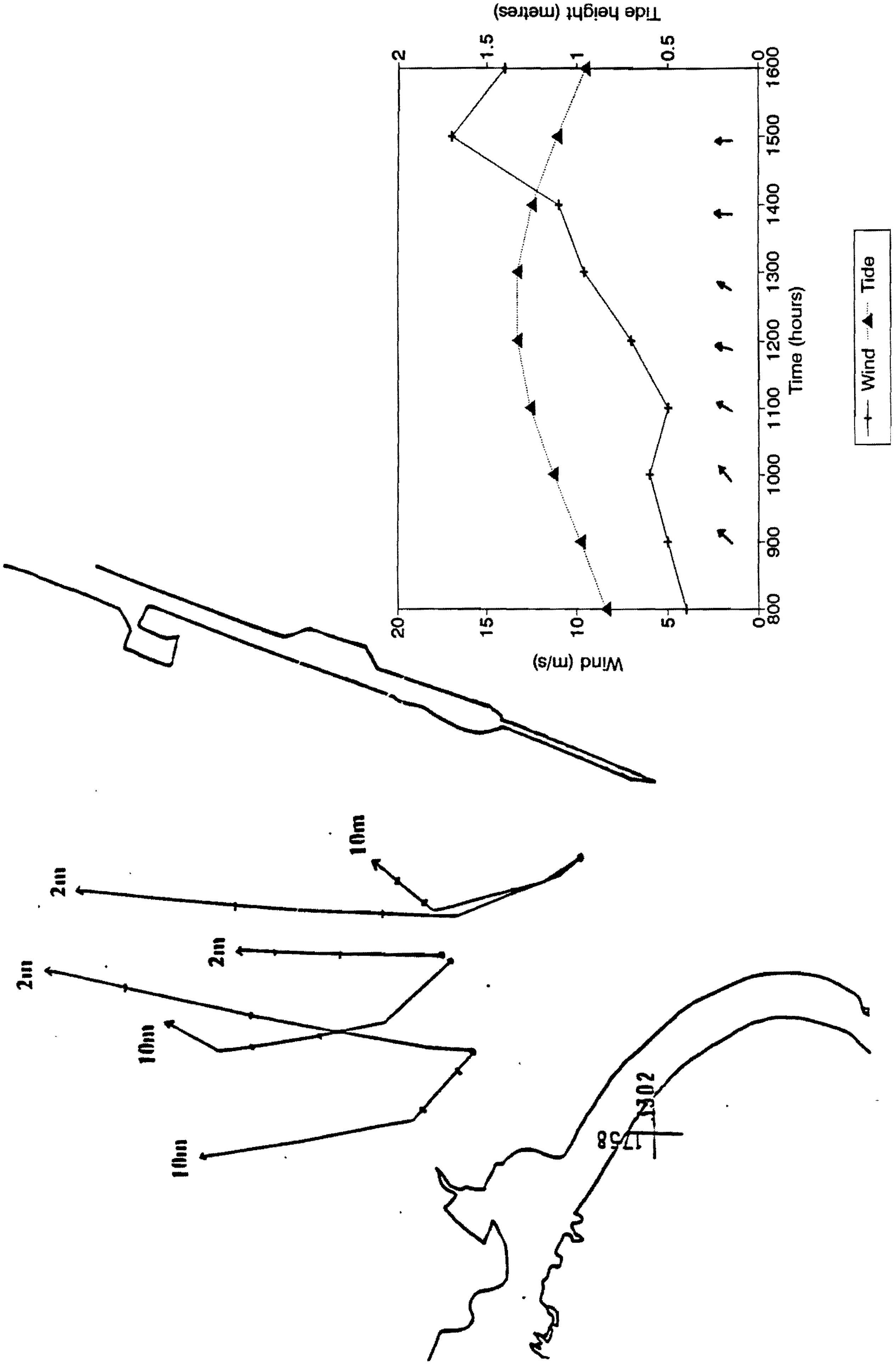


Figure 4.2: 1:25000 map of 2m and 10m drogue tracks for 16 February 1993

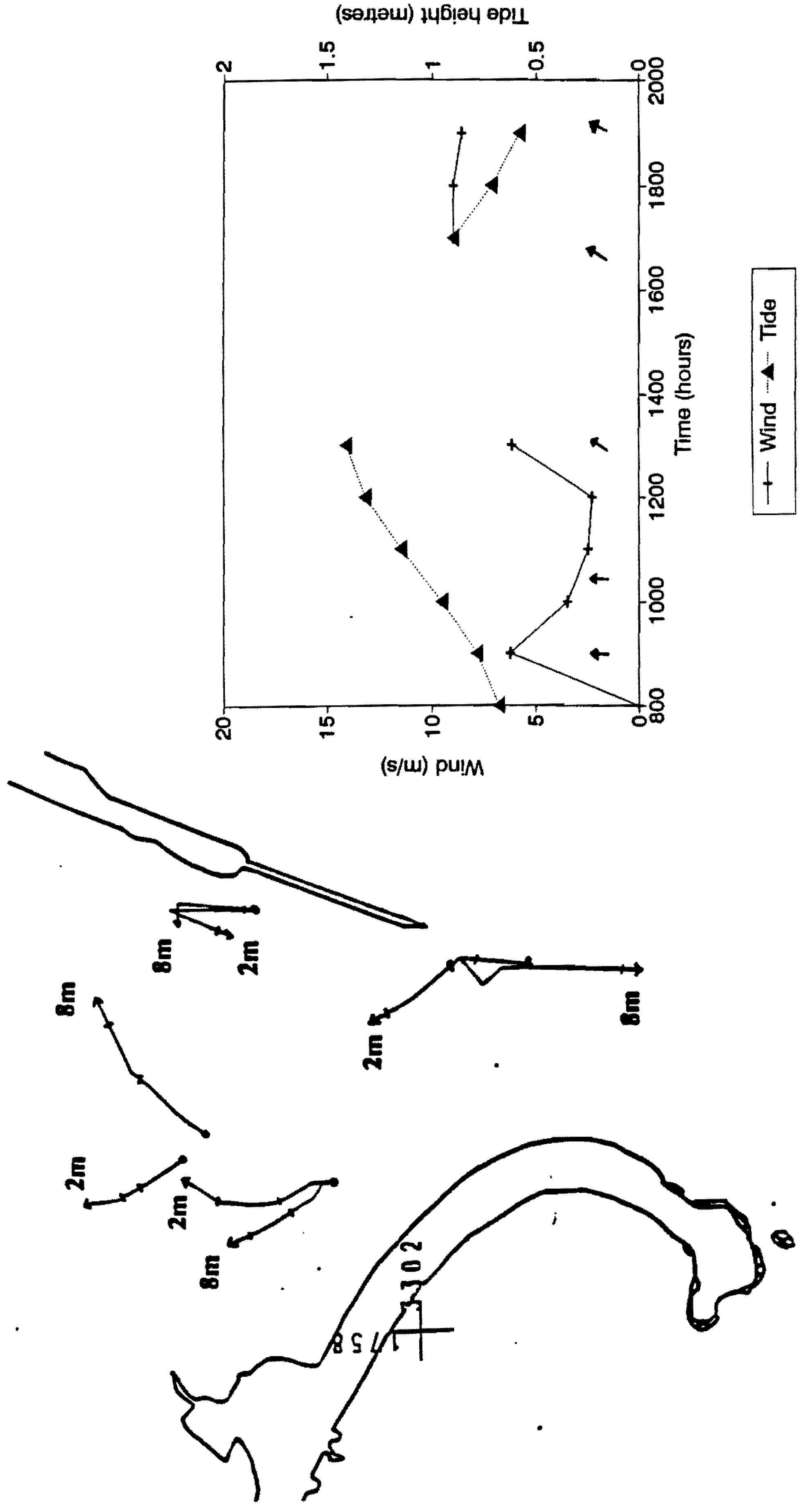
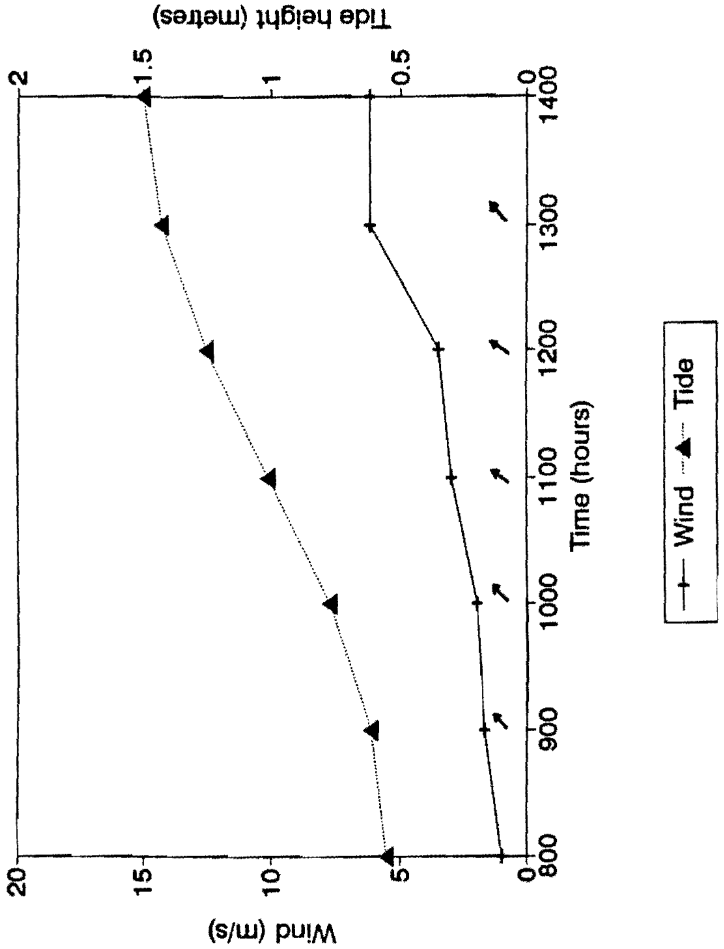


Figure 4.3: 1:25000 map of 2m and 8m drogue tracks for 17 February 1993



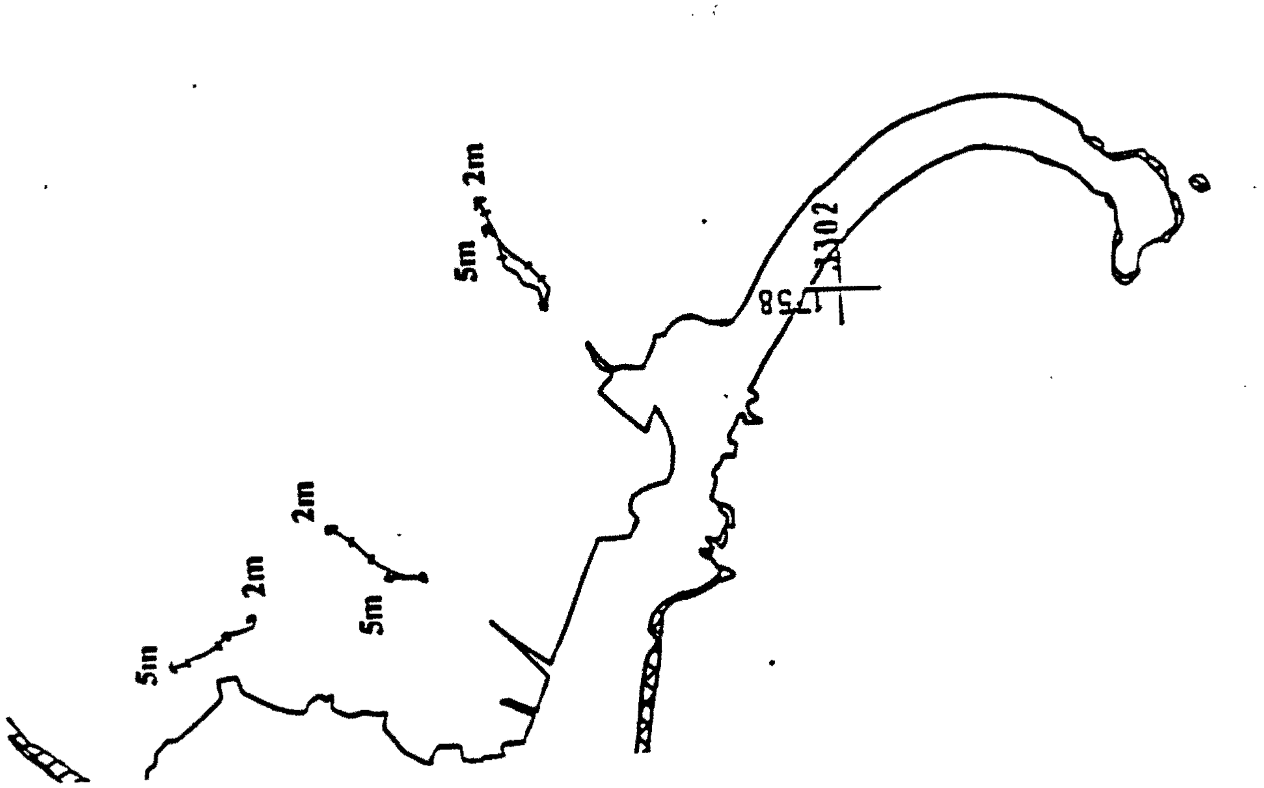


Figure 4.4: 1:30000 map of 2m and 5m drogue tracks for 18 February 1993

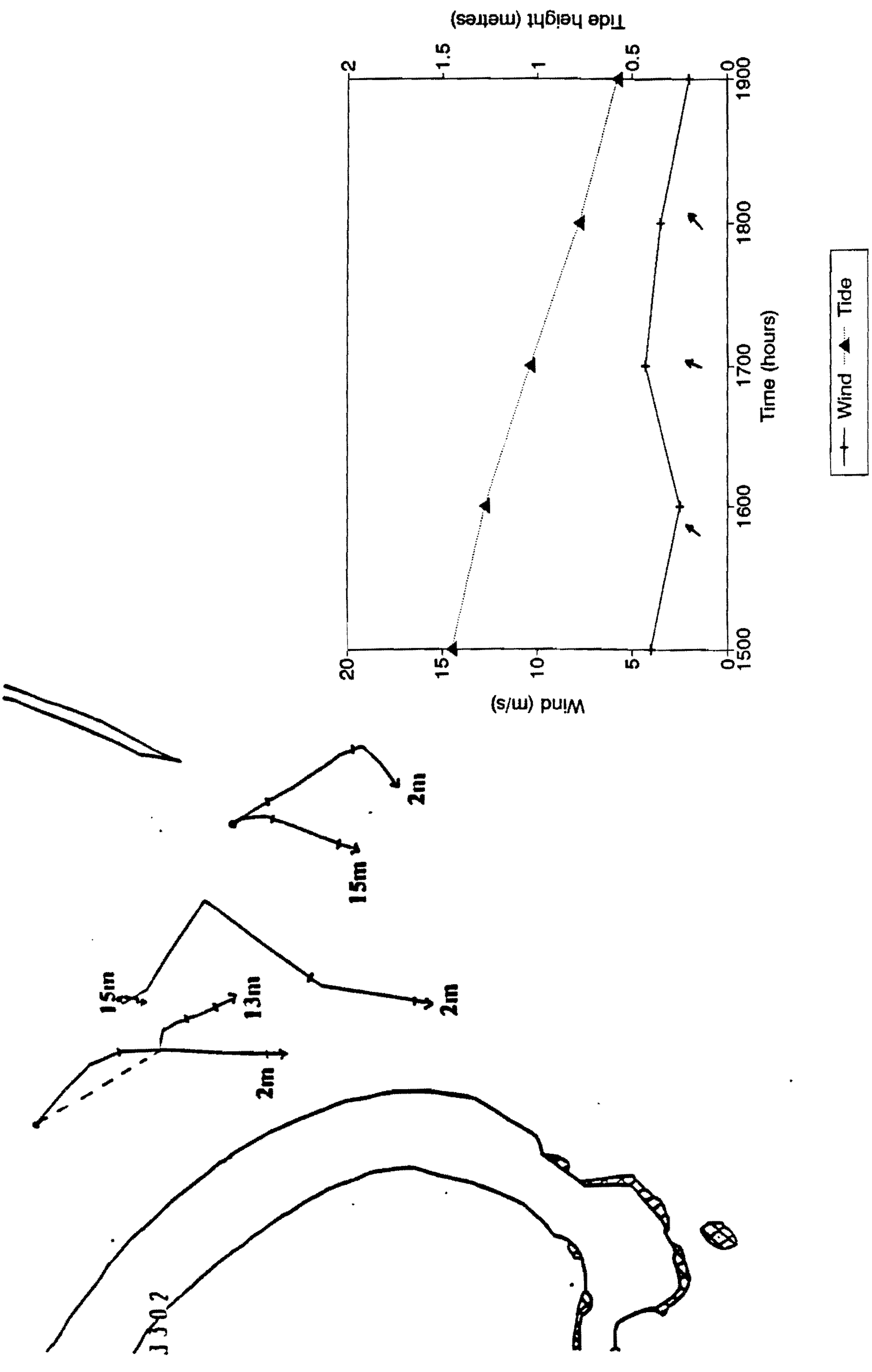
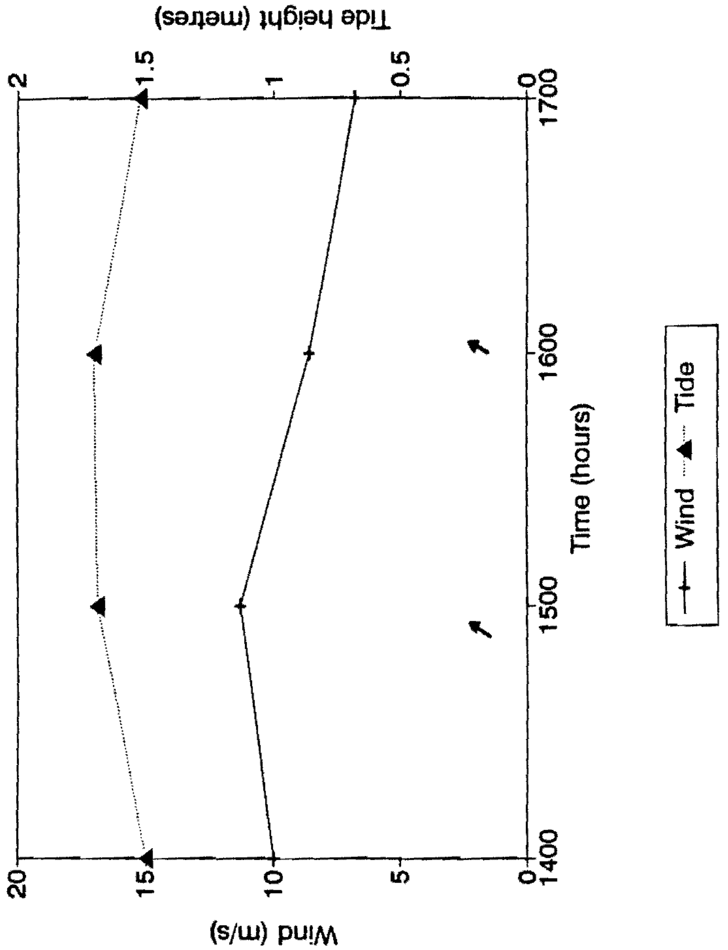


Figure 4.5: 1:15000 map of 2m and 15m drogue tracks for 18 February 1993



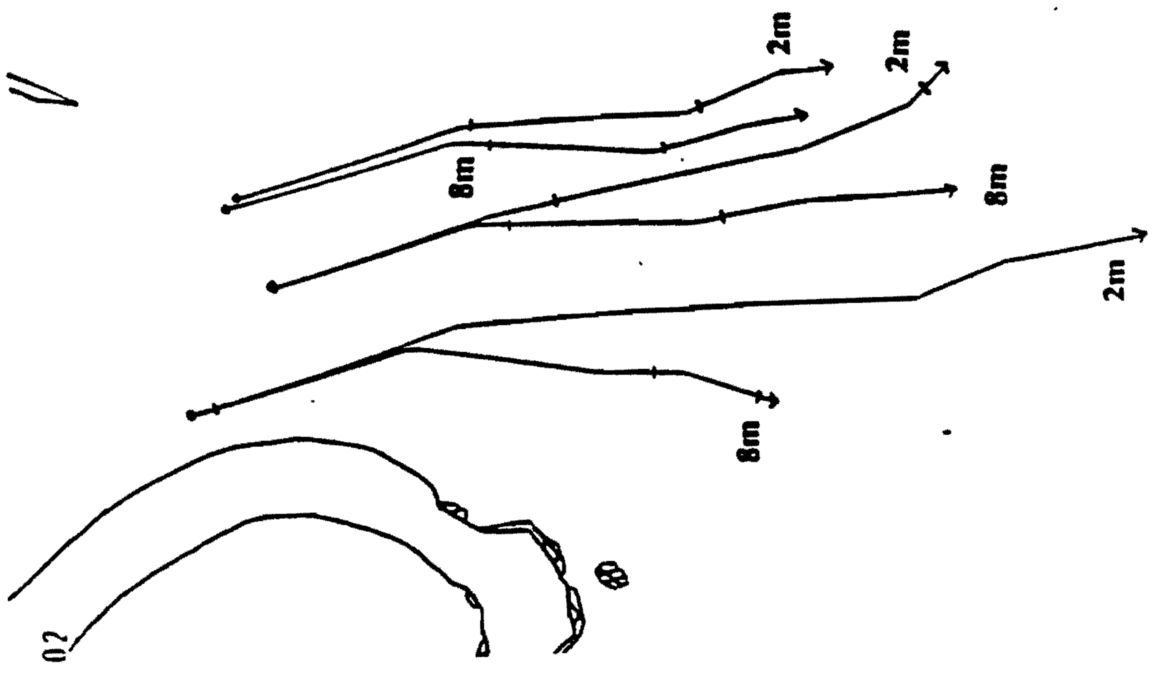


Figure 4.6: 1:20000 map of 2m and 8m drogue tracks for 2 August 1993

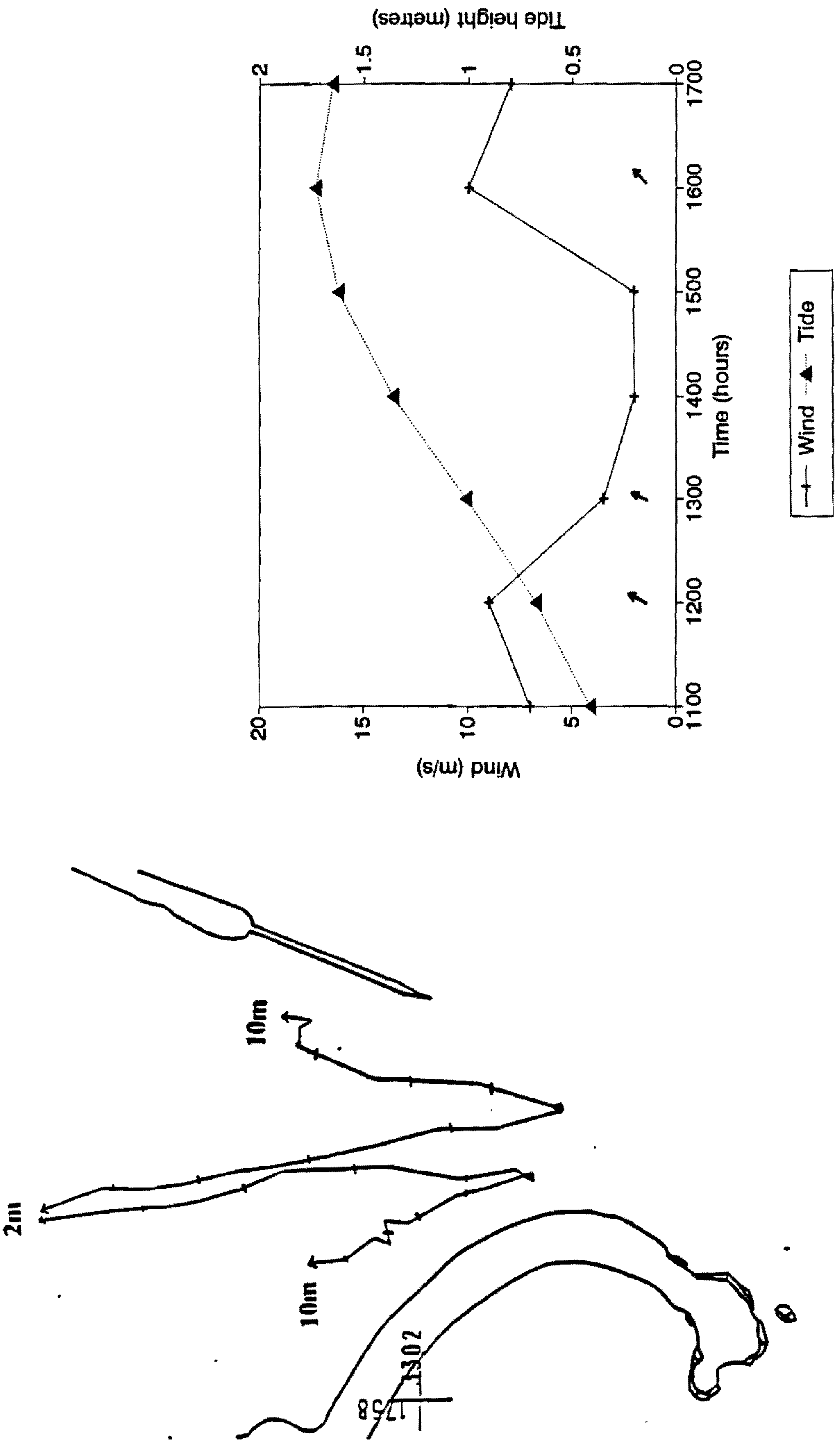


Figure 4.7: 1:25000 map of 2m and 10m drogue tracks for 3 August 1993

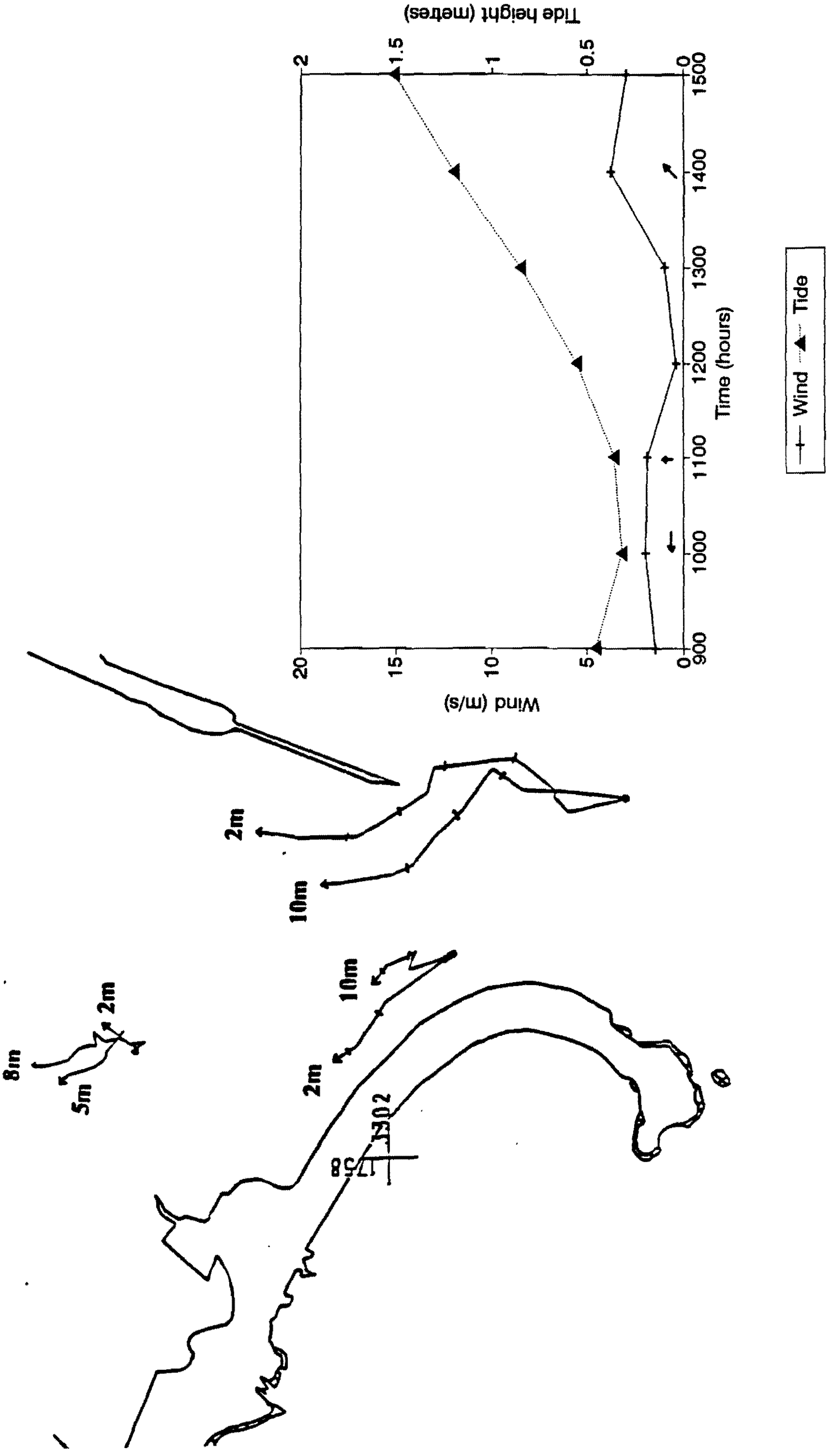


Figure 4.8: 1:25000 map of 2m, 5m, 8m and 10m drogue tracks for 4 August 1993

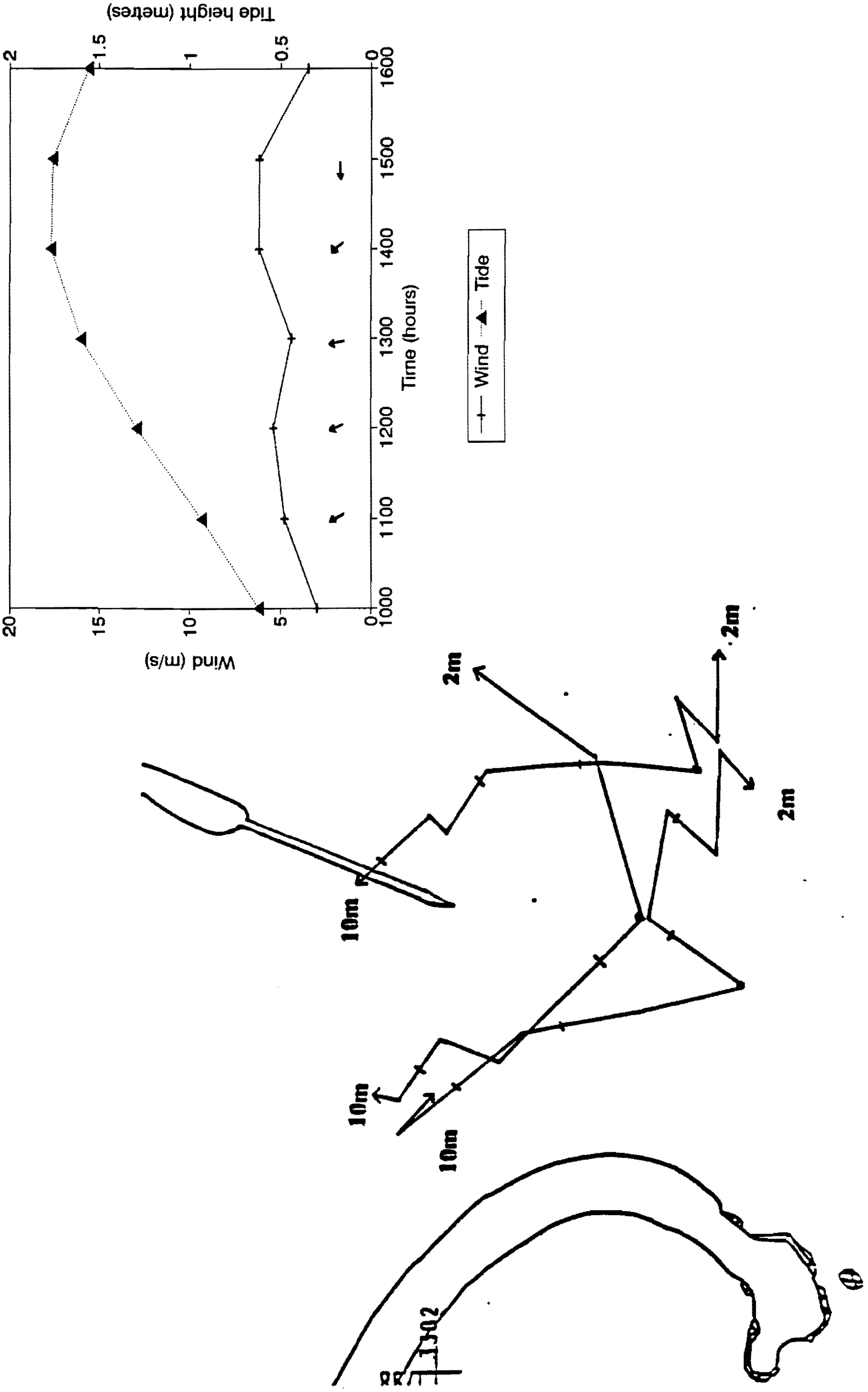


Figure 4.9: 1:20000 map of 2m and 10m drogue tracks for 12 December 1993

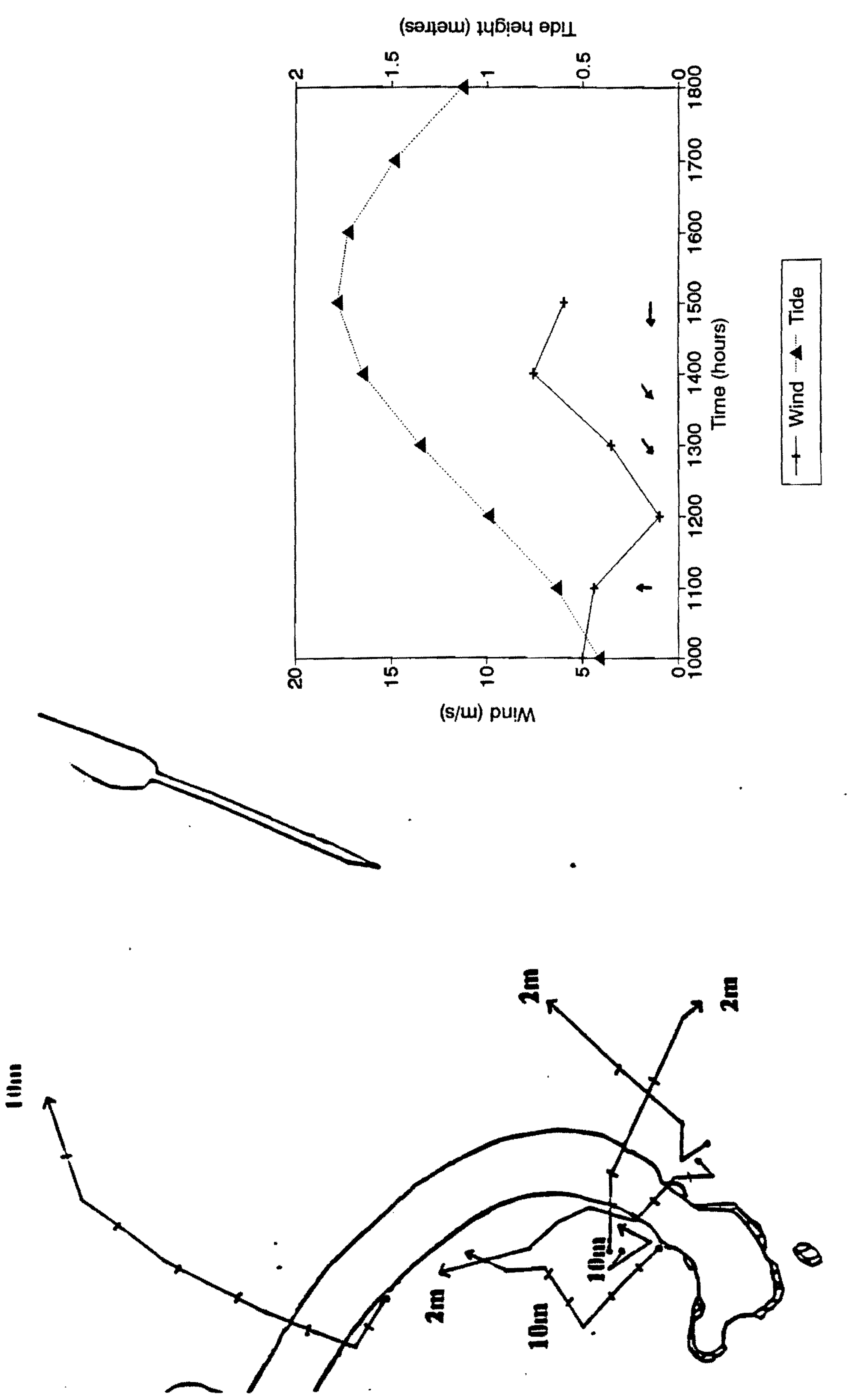


Figure 4.10: 1:20000 map of 2m and 10m drogue tracks for 13 December 1993

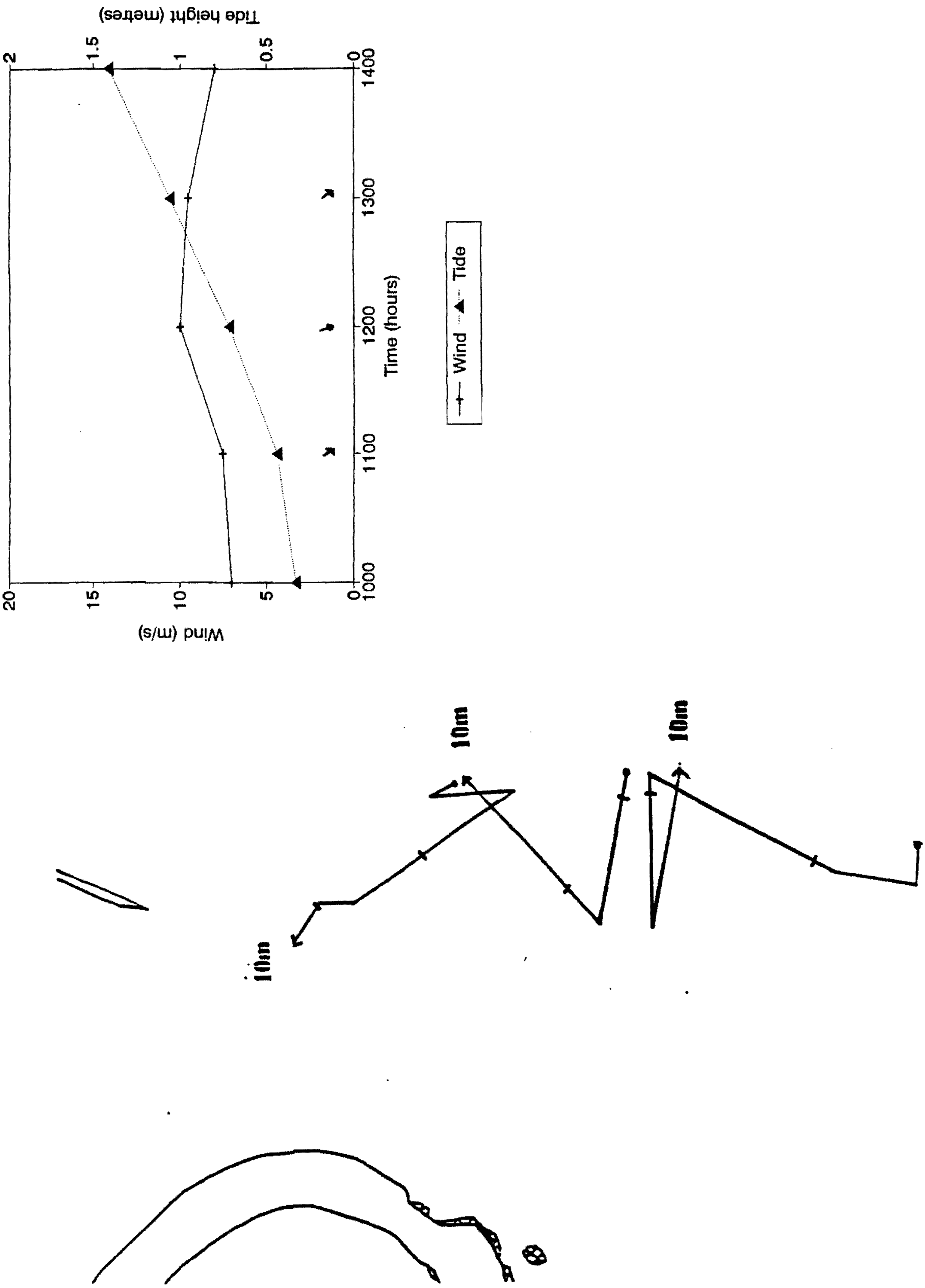


Figure 4.11: 1:20000 map of 10m drogue tracks for 14 December 1993

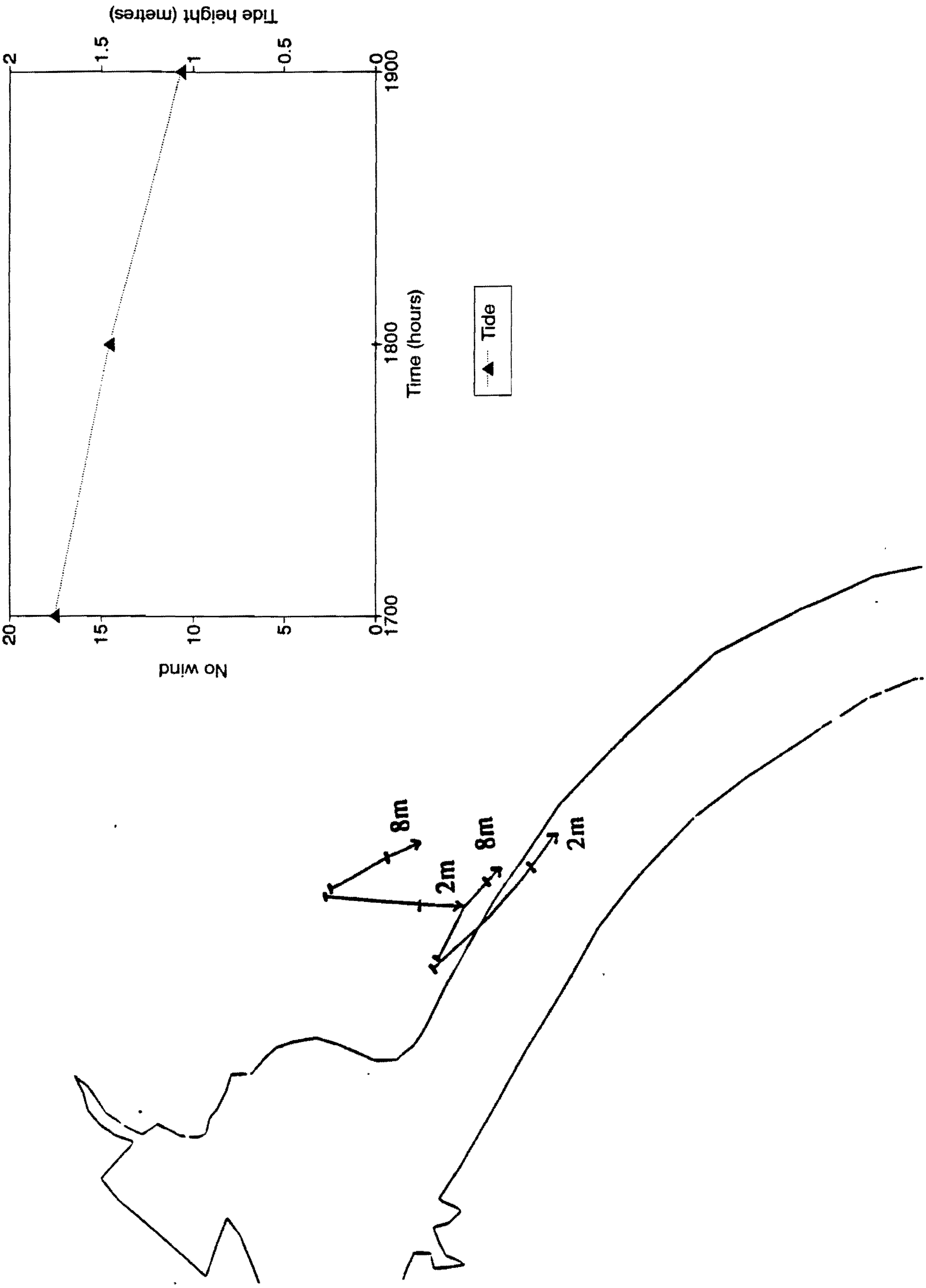


Figure 4.12: 1:10000 map of 2m and 8m drogue tracks for 8 August 1994

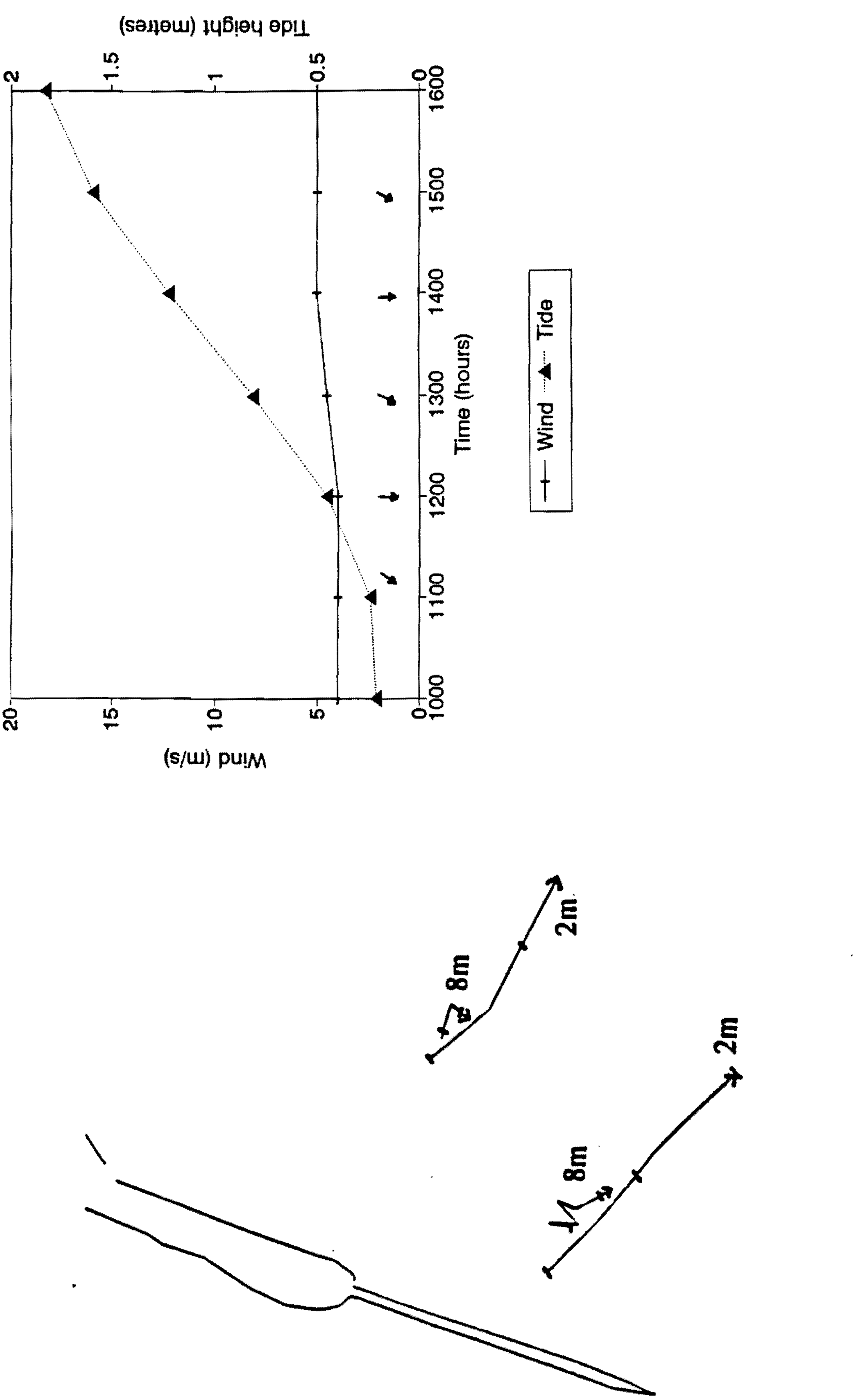
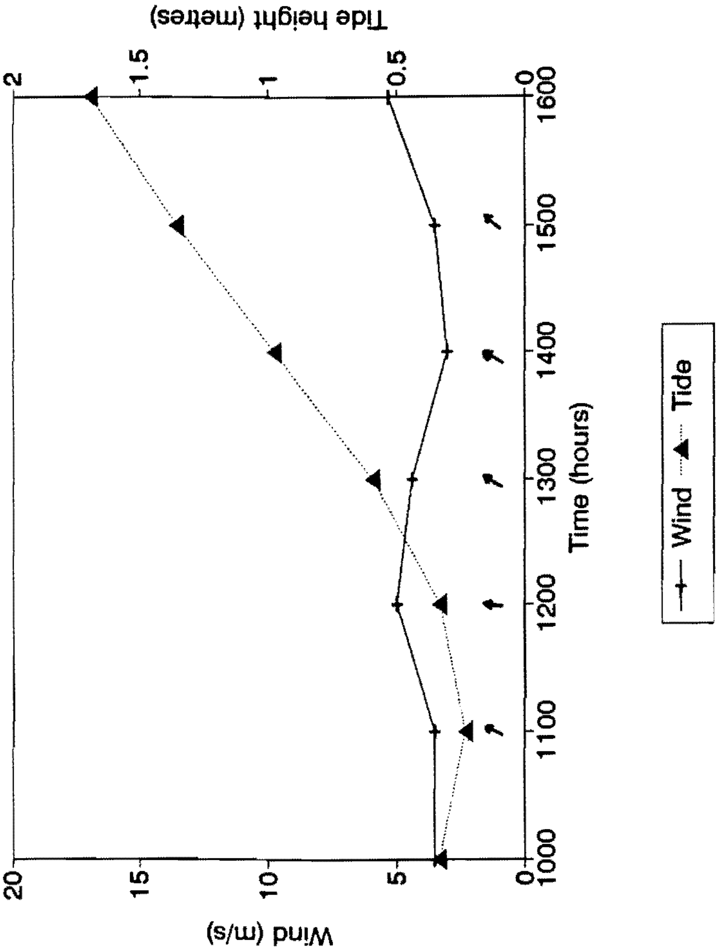


Figure 4.13: 1:15000 map of 2m and 8m drogue tracks for 9 August 1994



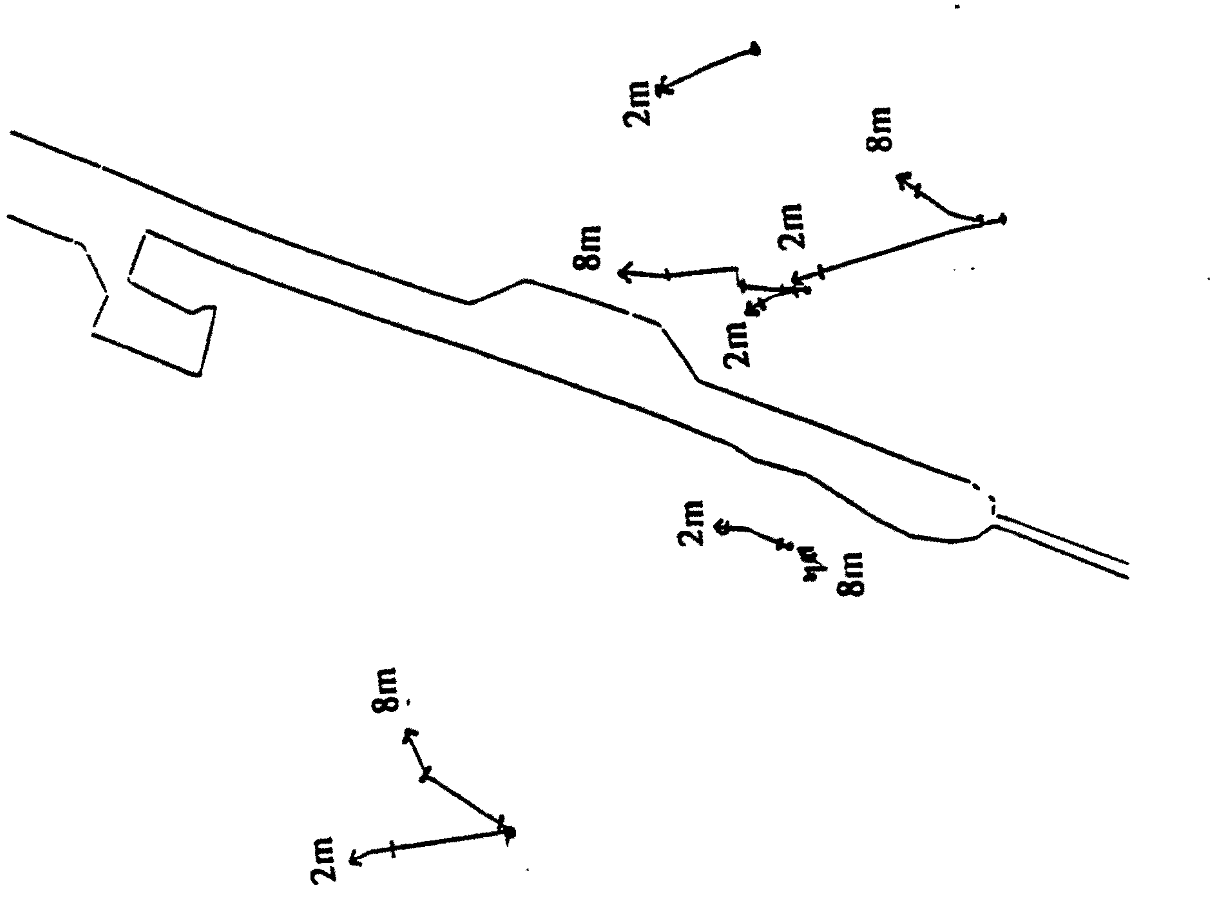
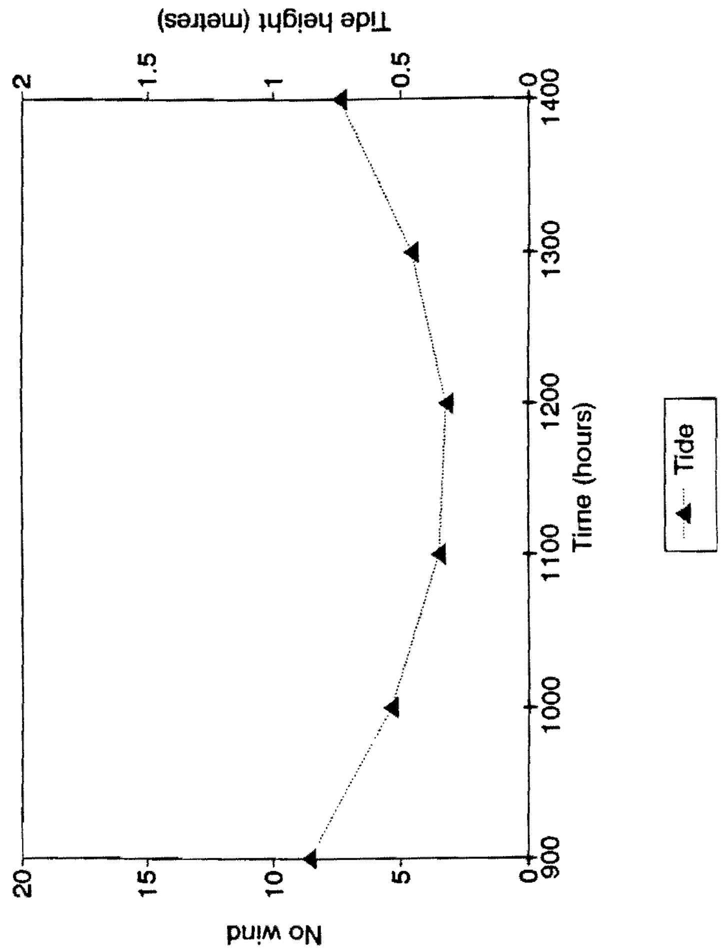


Figure 4.14: 1:15000 map of 2m and 8m drogue tracks for 10 August 1994



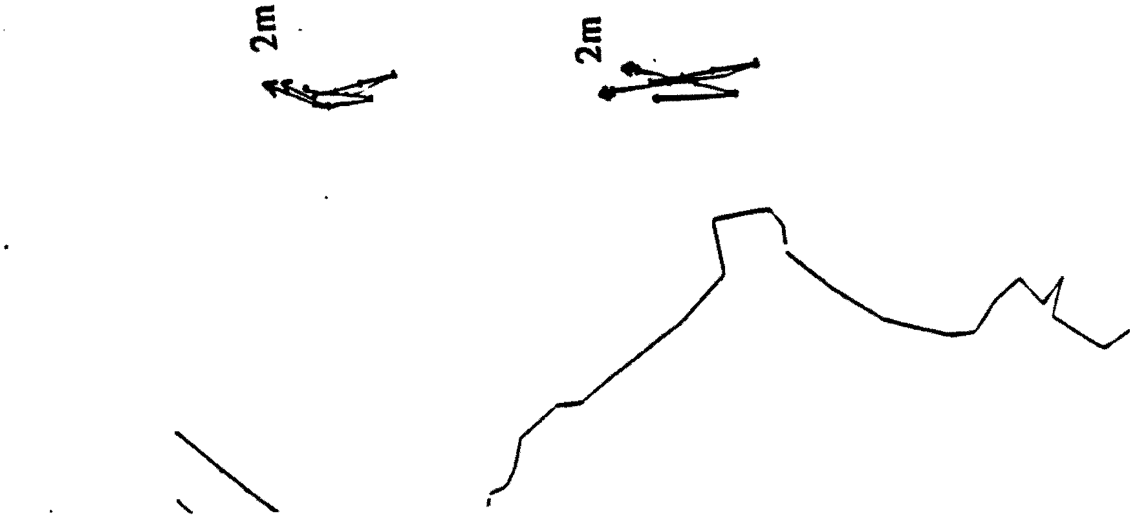


Figure 4.15: 1:10000 map of 2m drogue tracks for 11 August 1994

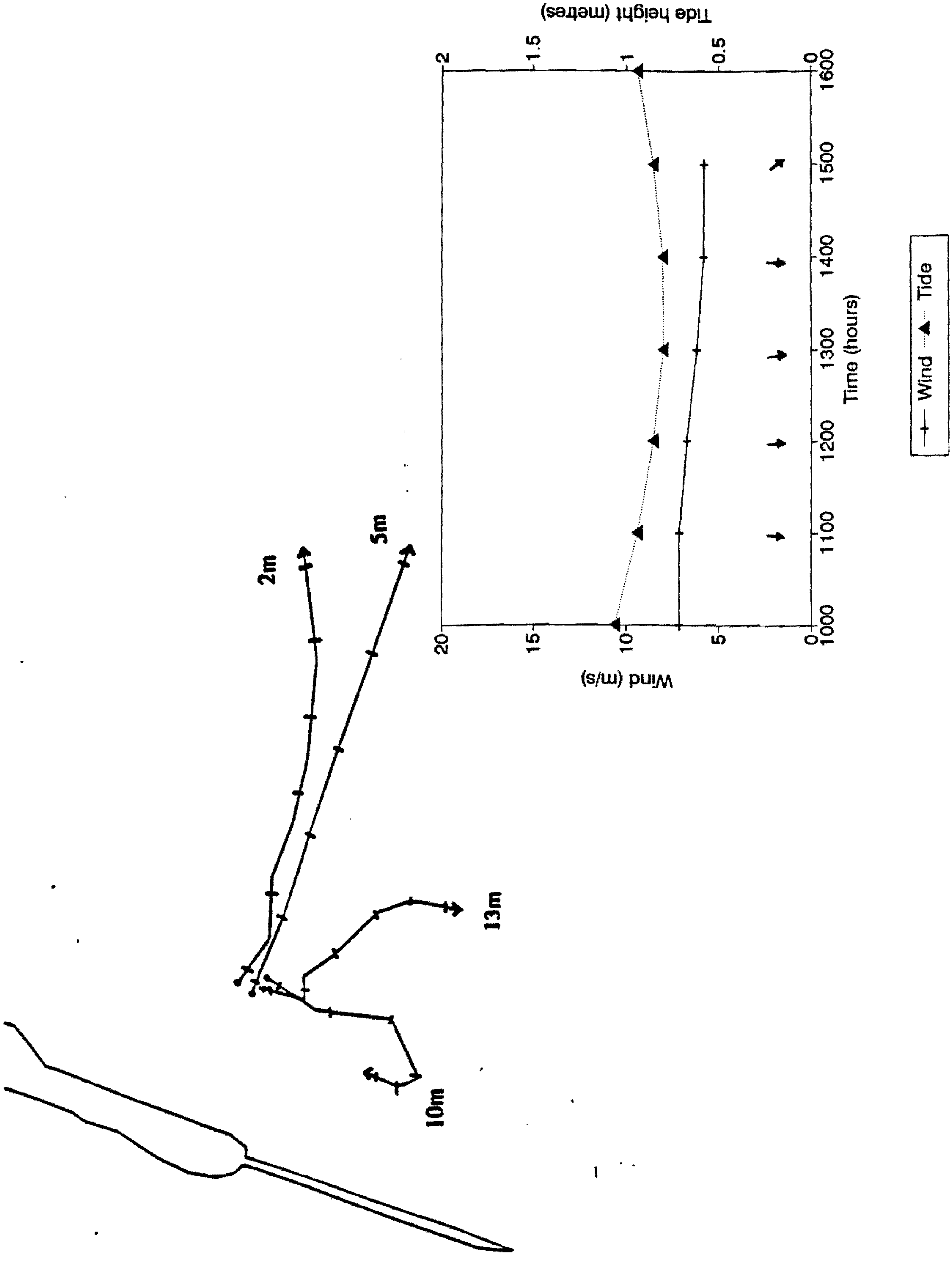


Figure 4.16: 1:15000 map of 2m, 5m, 10m and 13m drogue tracks for 27 September 1994

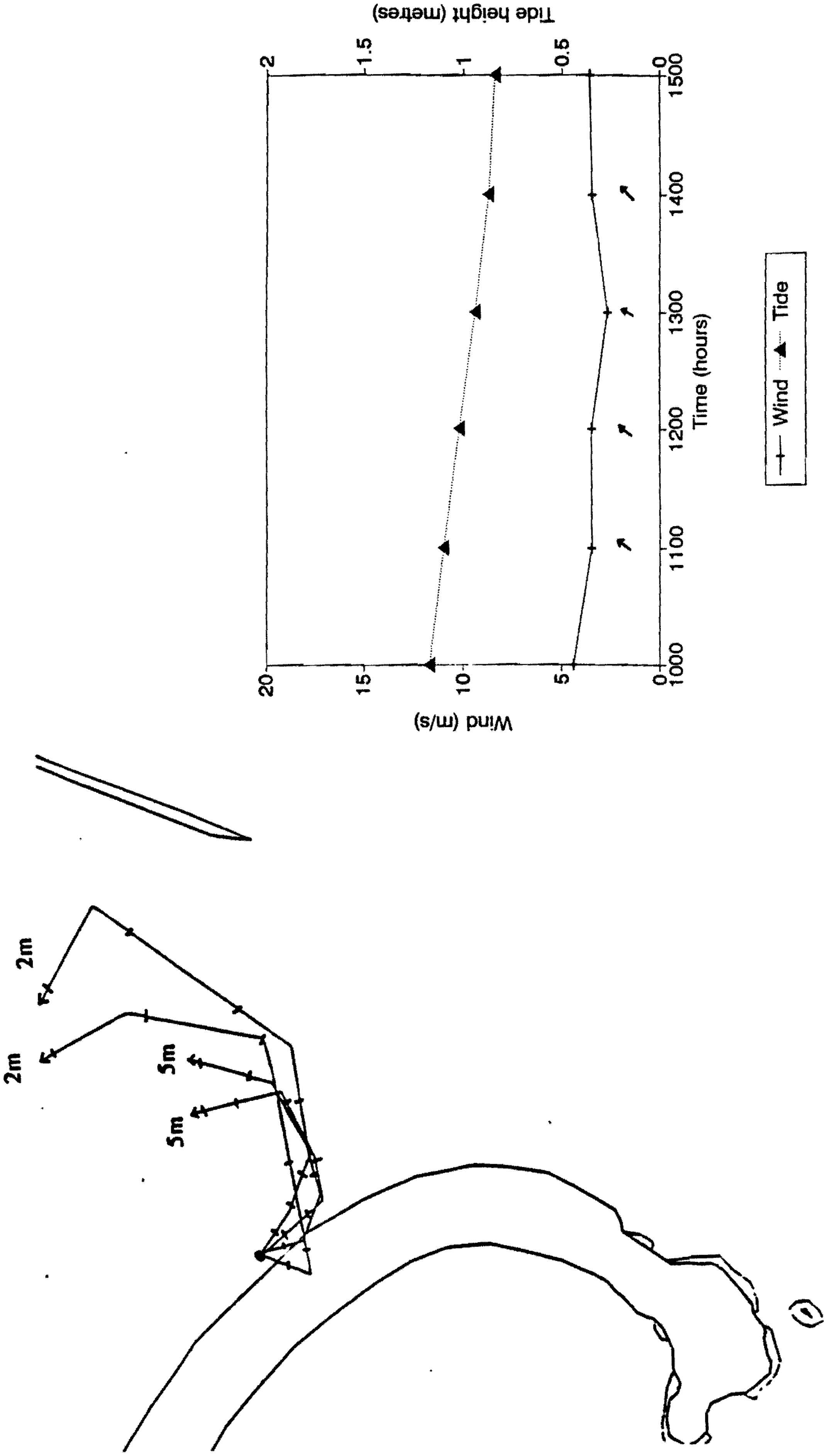
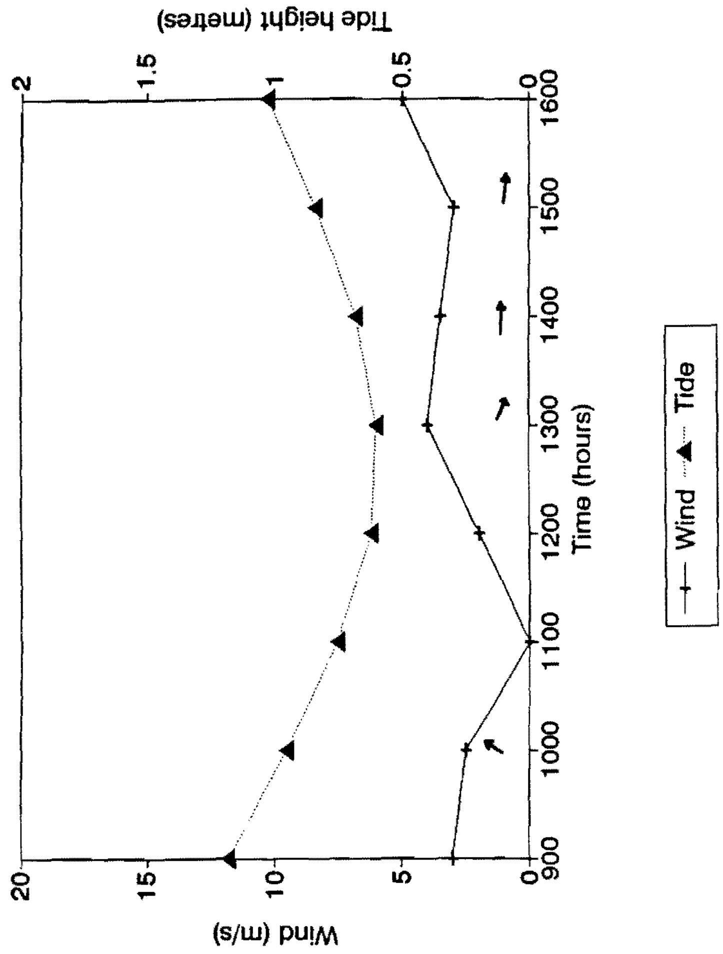


Figure 4.17: 1:15000 map of 2m and 5m drogue tracks for 28 September 1994



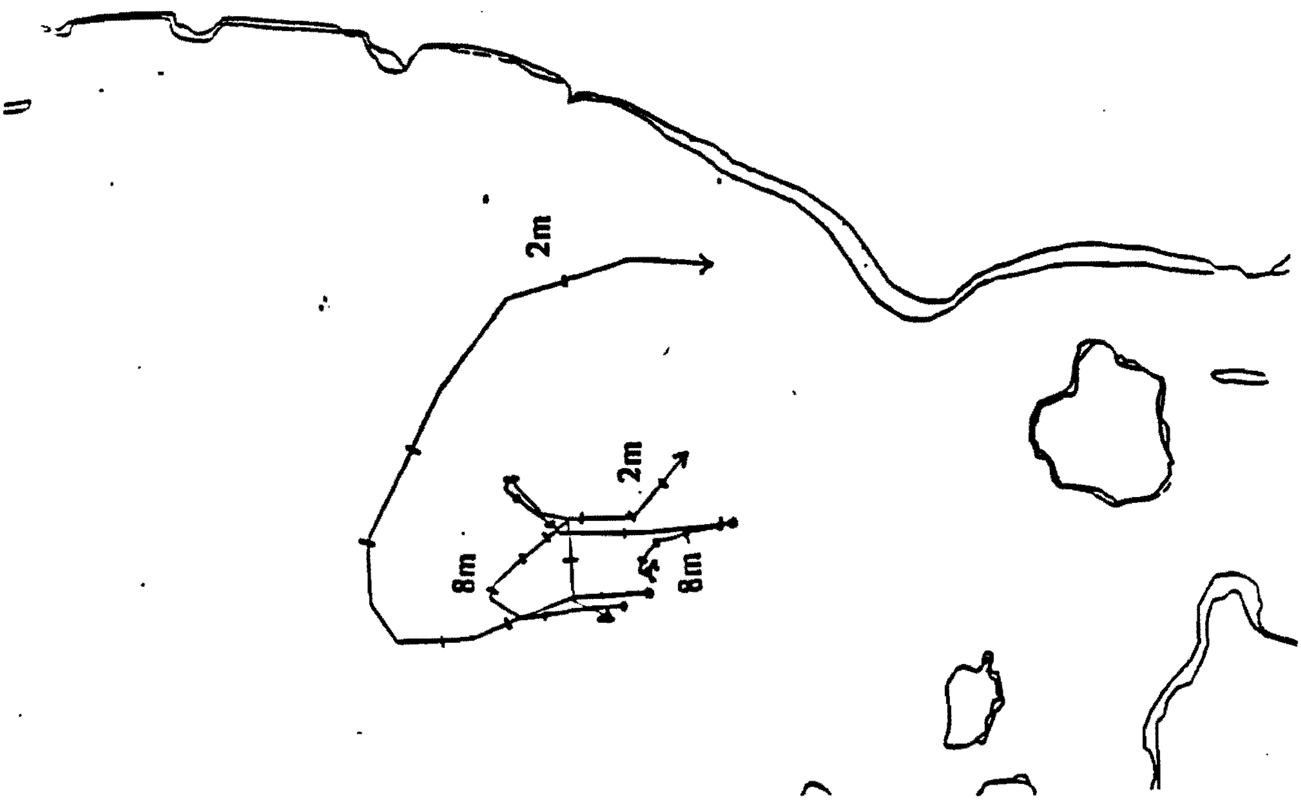


Figure 4.18: 1:35000 map of 2m and 8m drogue tracks for 7 March 1995

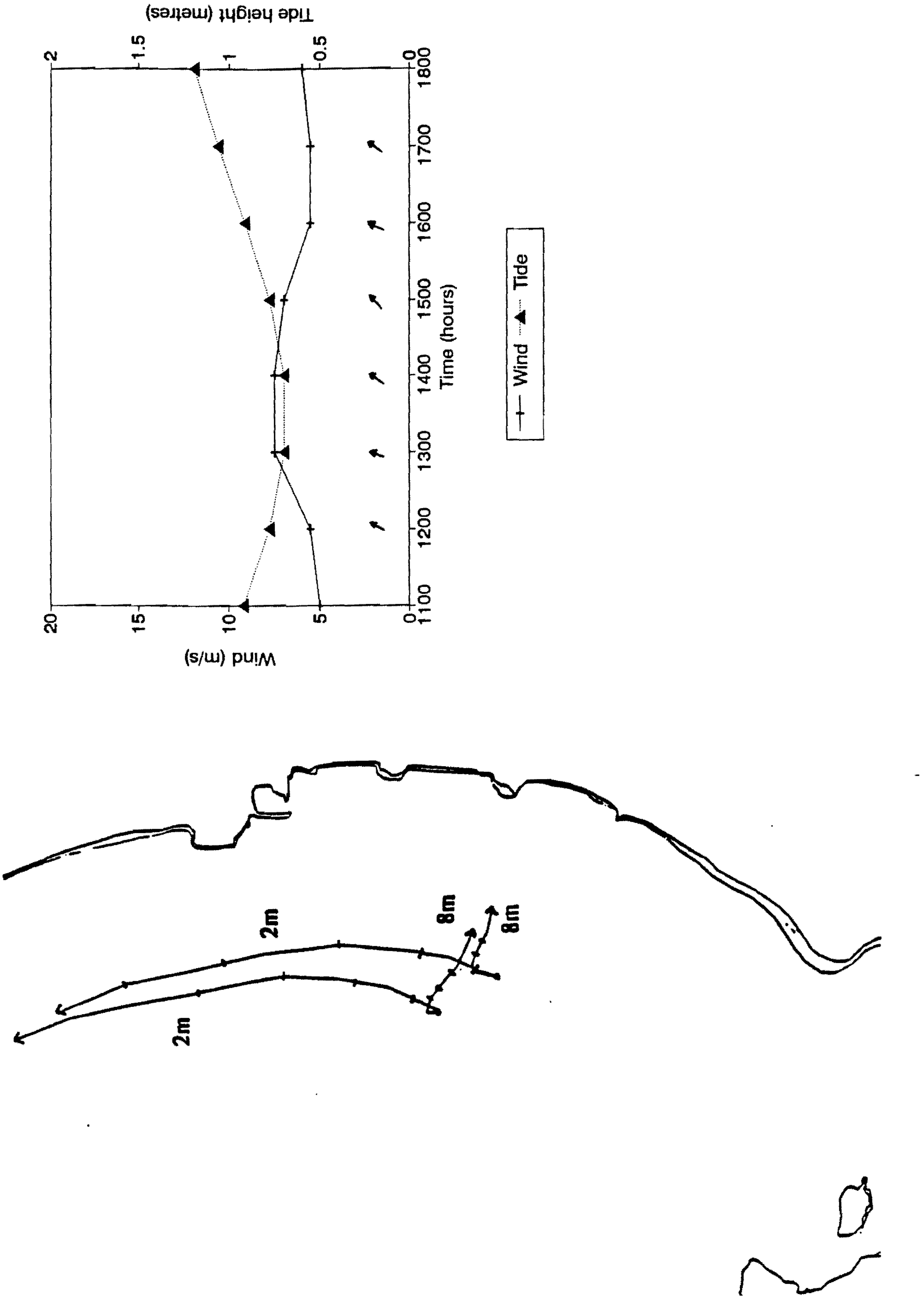


Figure 4.19: 1:40000 map of 2m and 8m drogue tracks for 8 March 1995

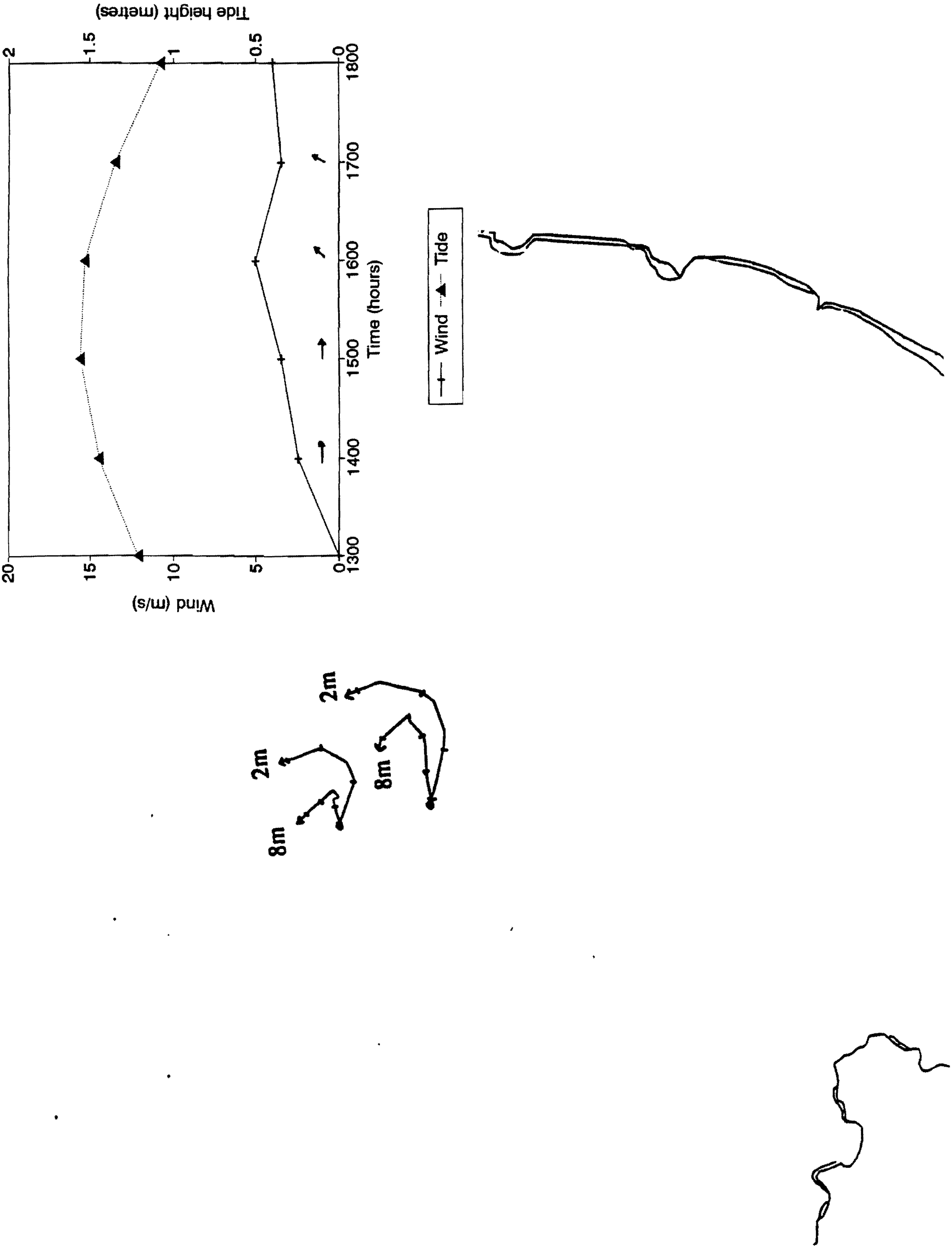


Figure 4.20: 1:30000 map of 2m and 8m drogue tracks for 27 June 1995

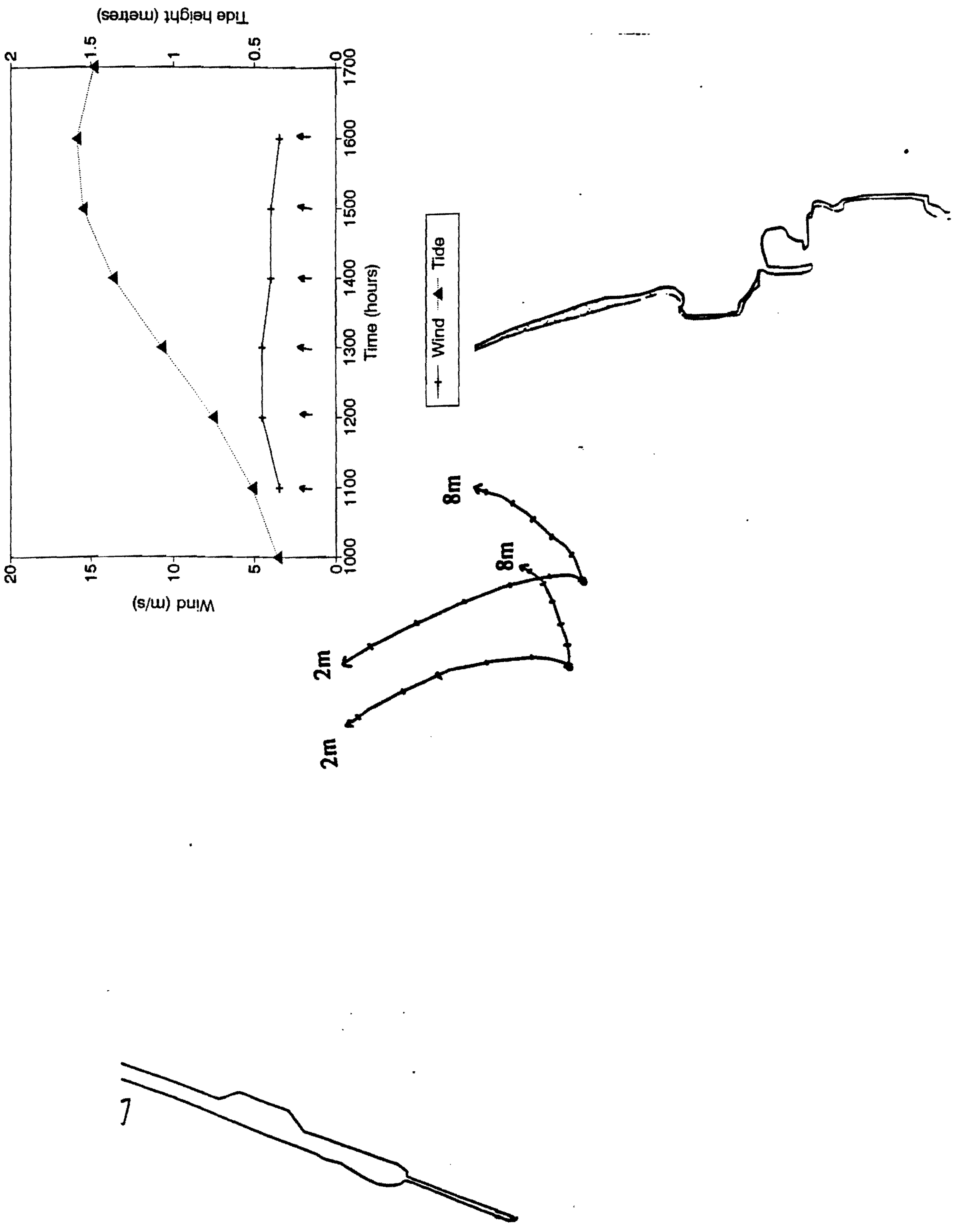


Figure 4.21: 1:30000 map of 2m and 8m drogue tracks for 28 June 1995

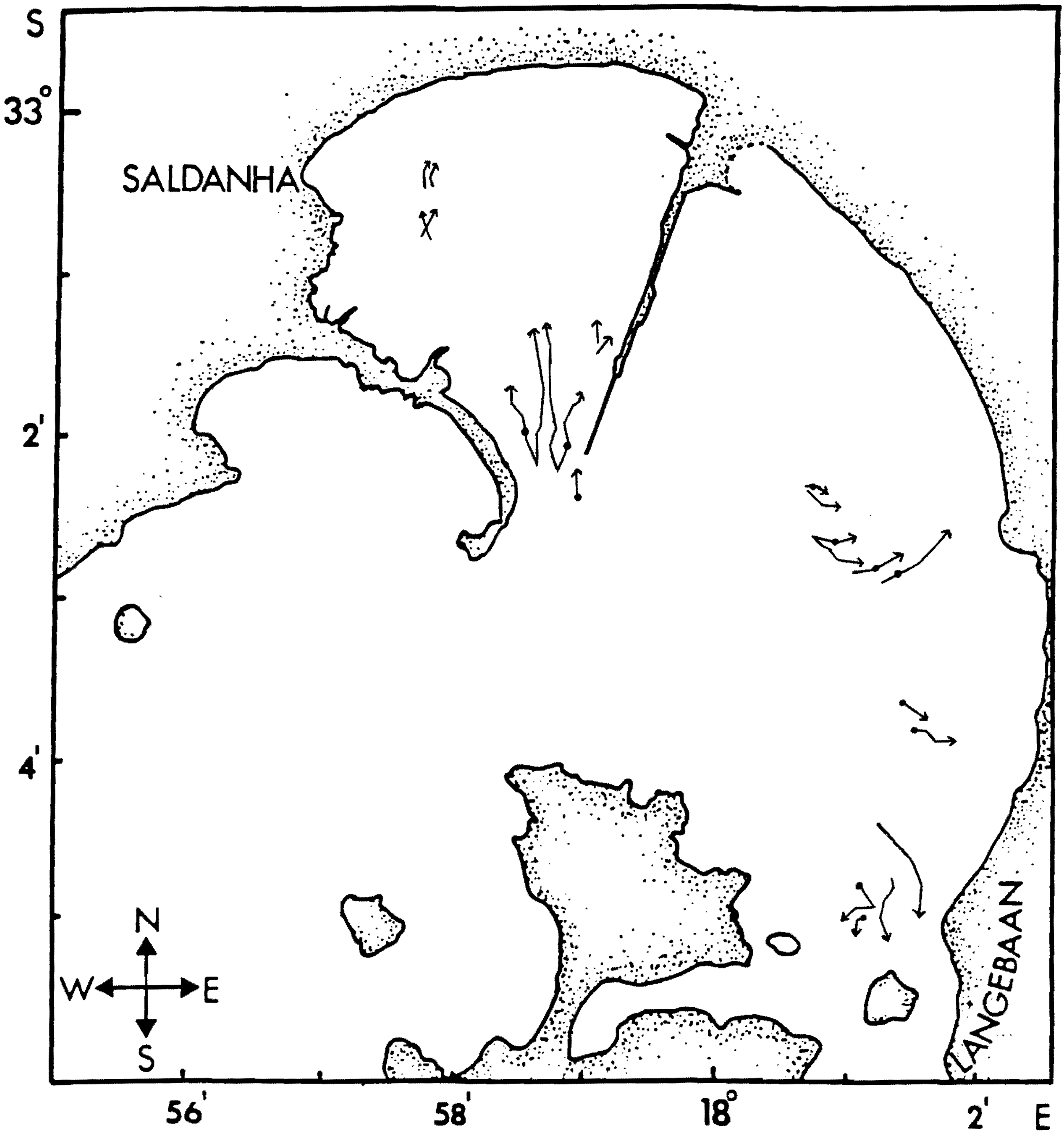


Figure 4.22: Composite diagram of surface and deep (annotated with a filled circle) tidally driven drogues on the flood tide

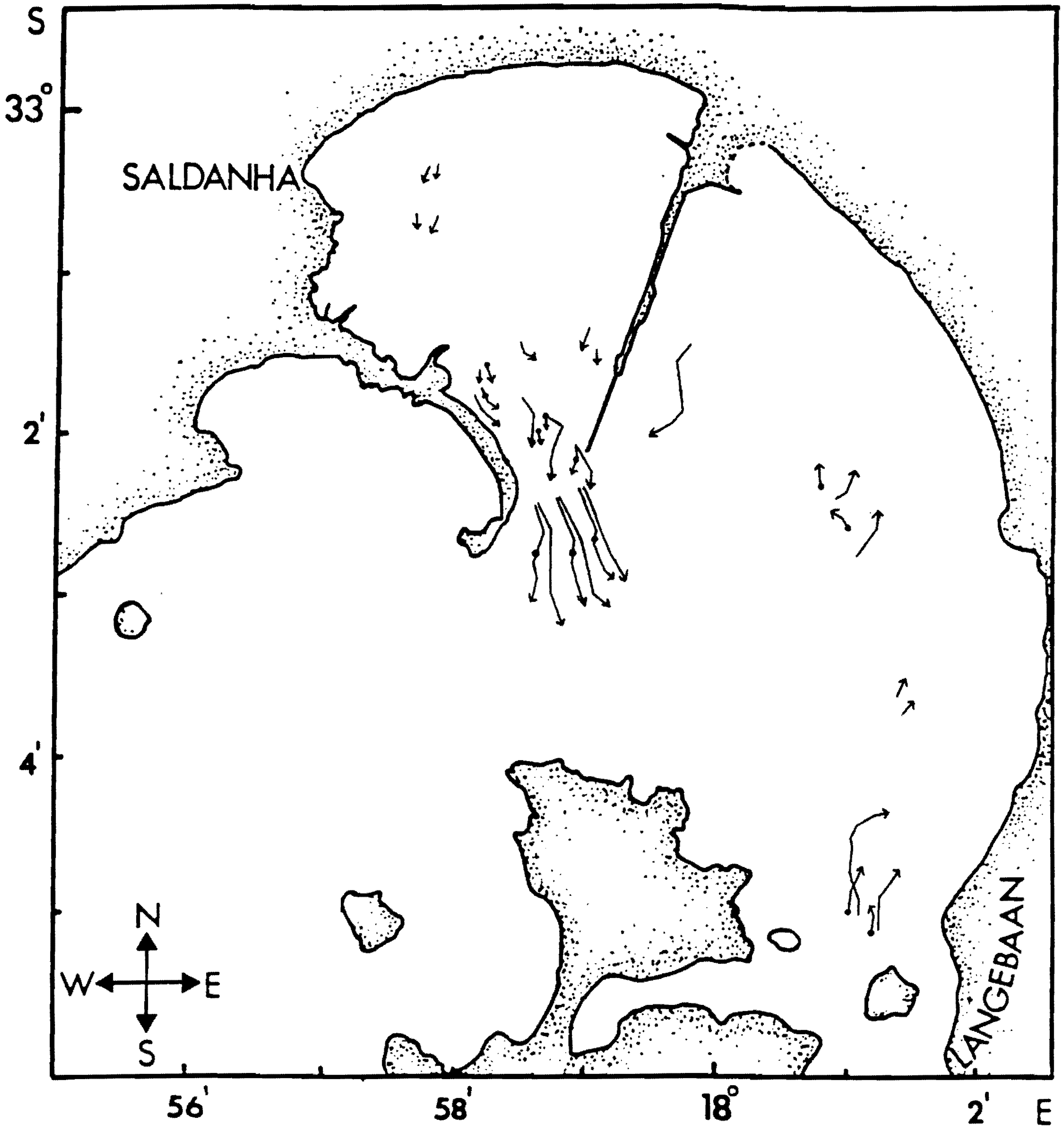


Figure 4.23: Composite diagram of surface and deep (annotated with a filled circle) tidally driven drogues on the ebb tide

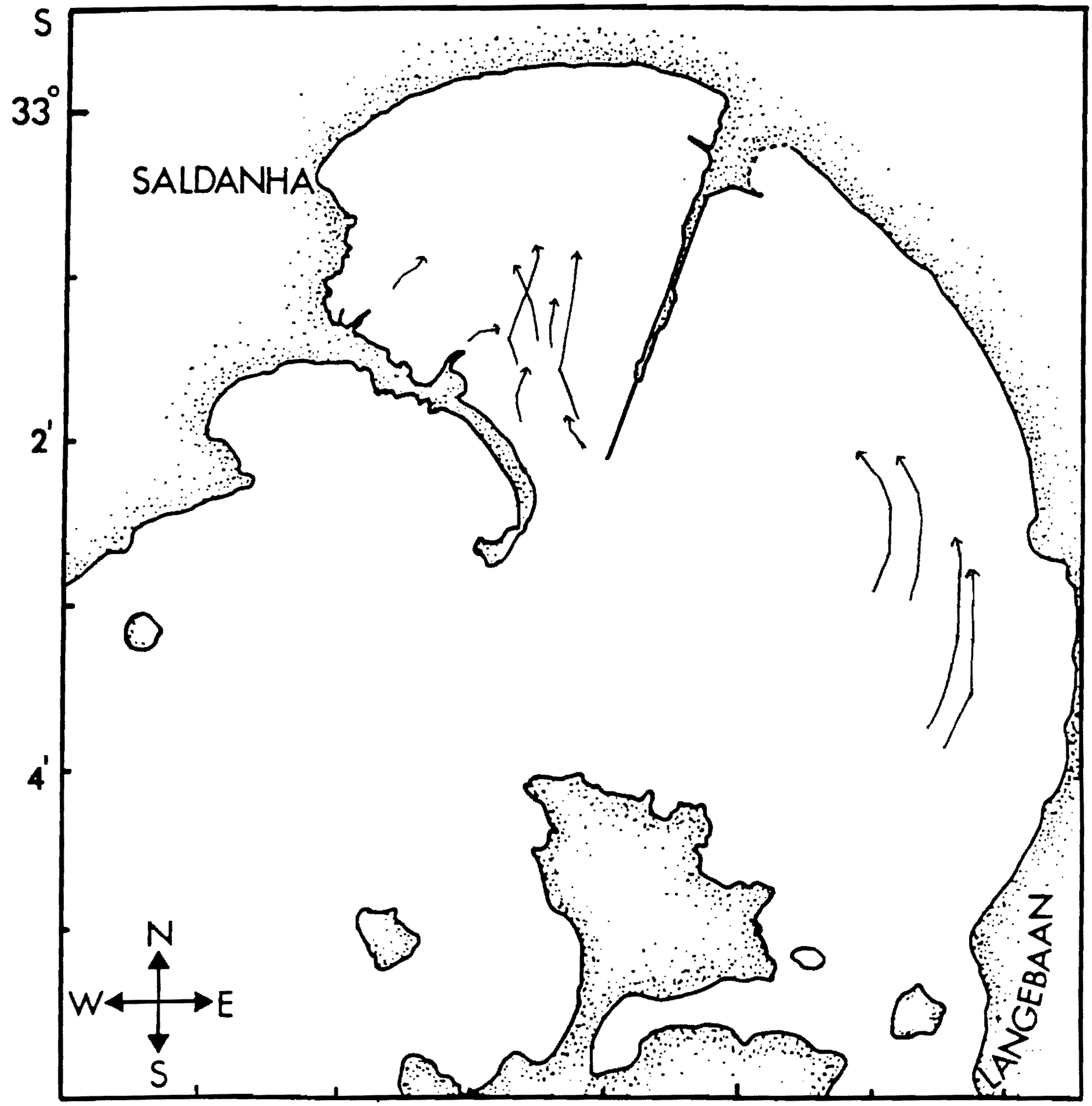


Figure 4.24: Composite diagram of wind driven surface drogues in the summer situation

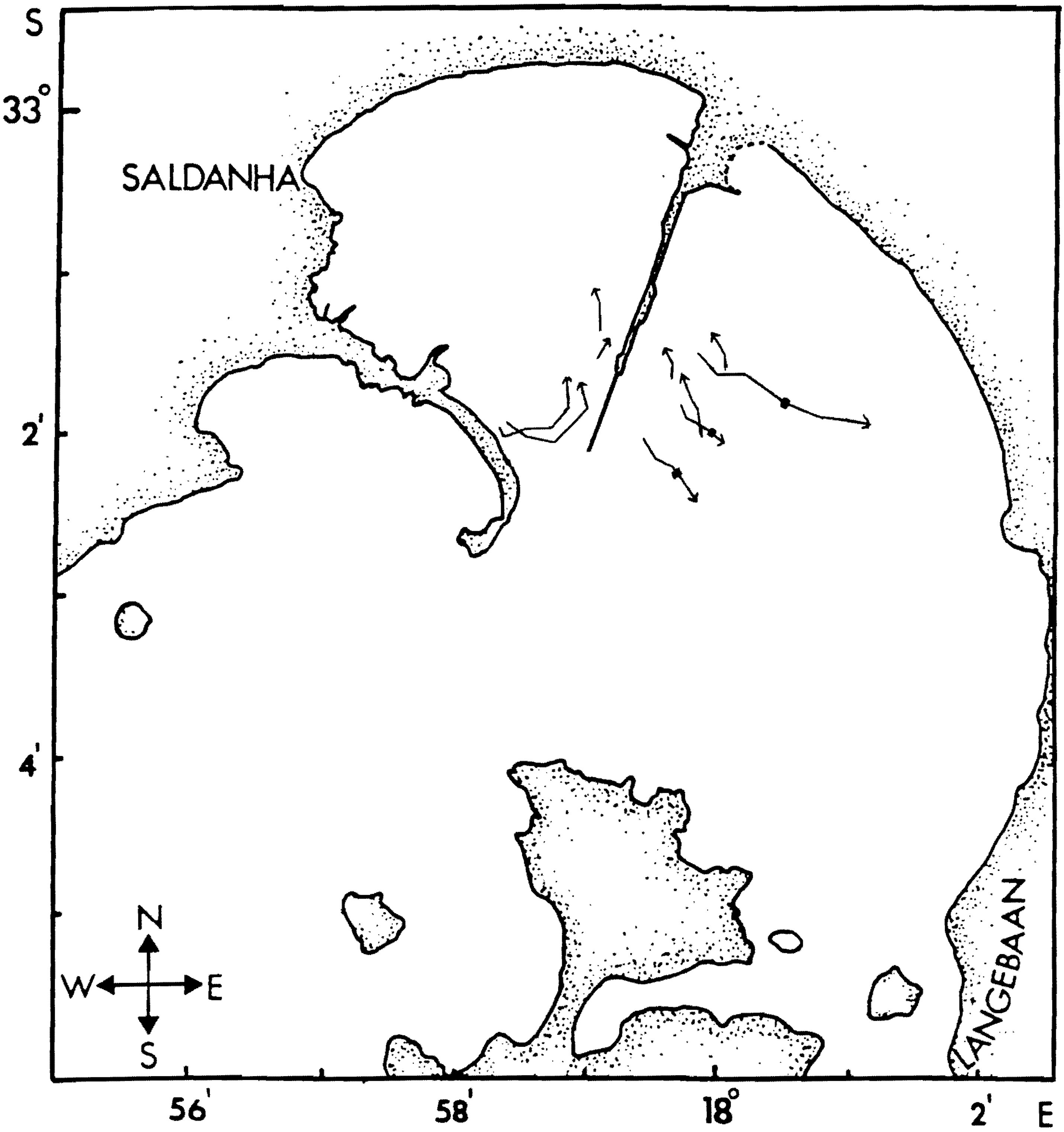


Figure 4.25: Composite diagram of wind driven surface drogues in the winter situation

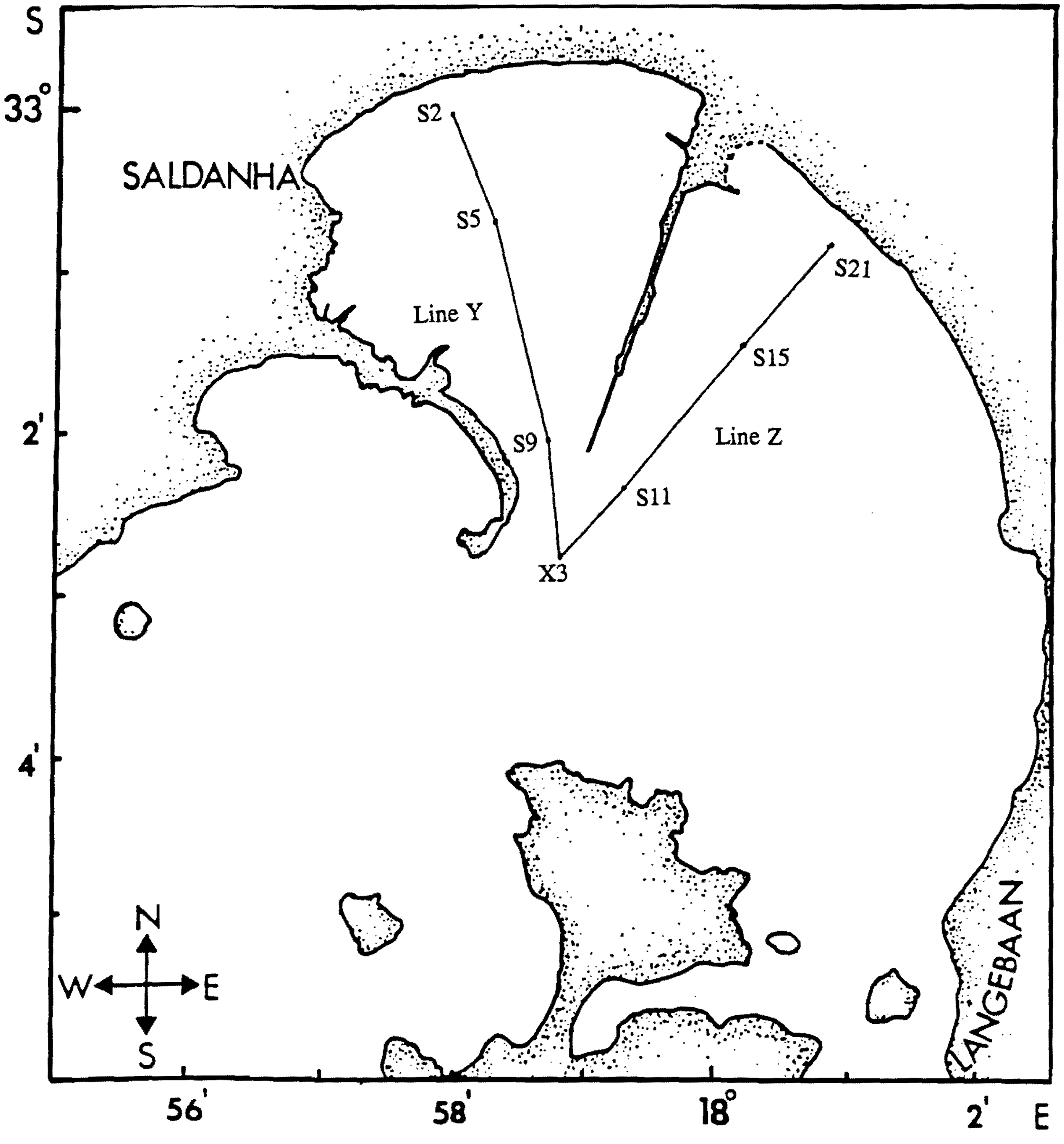


Figure 4.26: CTD lines through Small Bay and Big Bay showing station names and intersecting at station X3

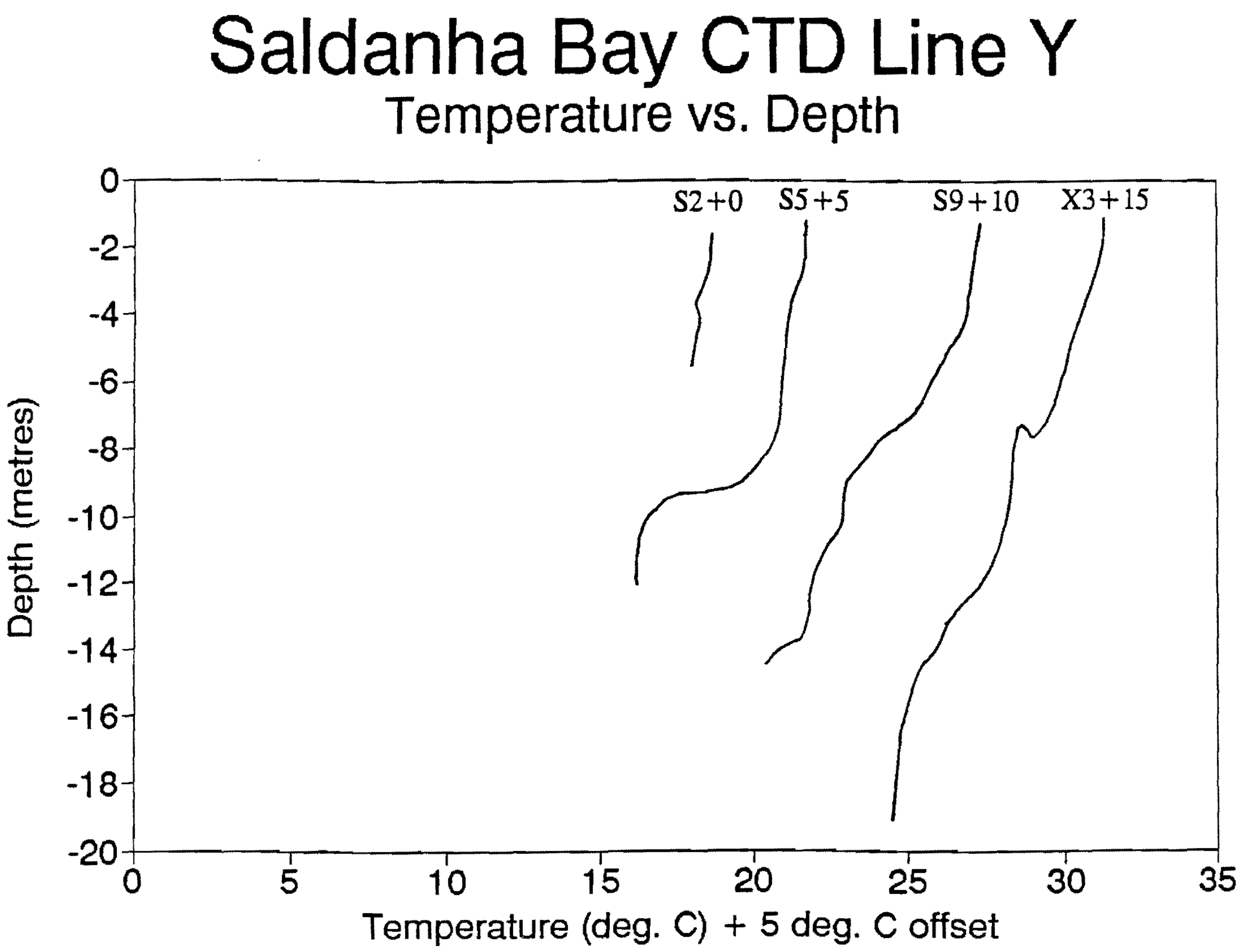


Figure 4.27: Sections of temperature versus depth for CTD line Y with 5°C offset (24/11/94), showing the structure of the thermocline with increasing distance offshore

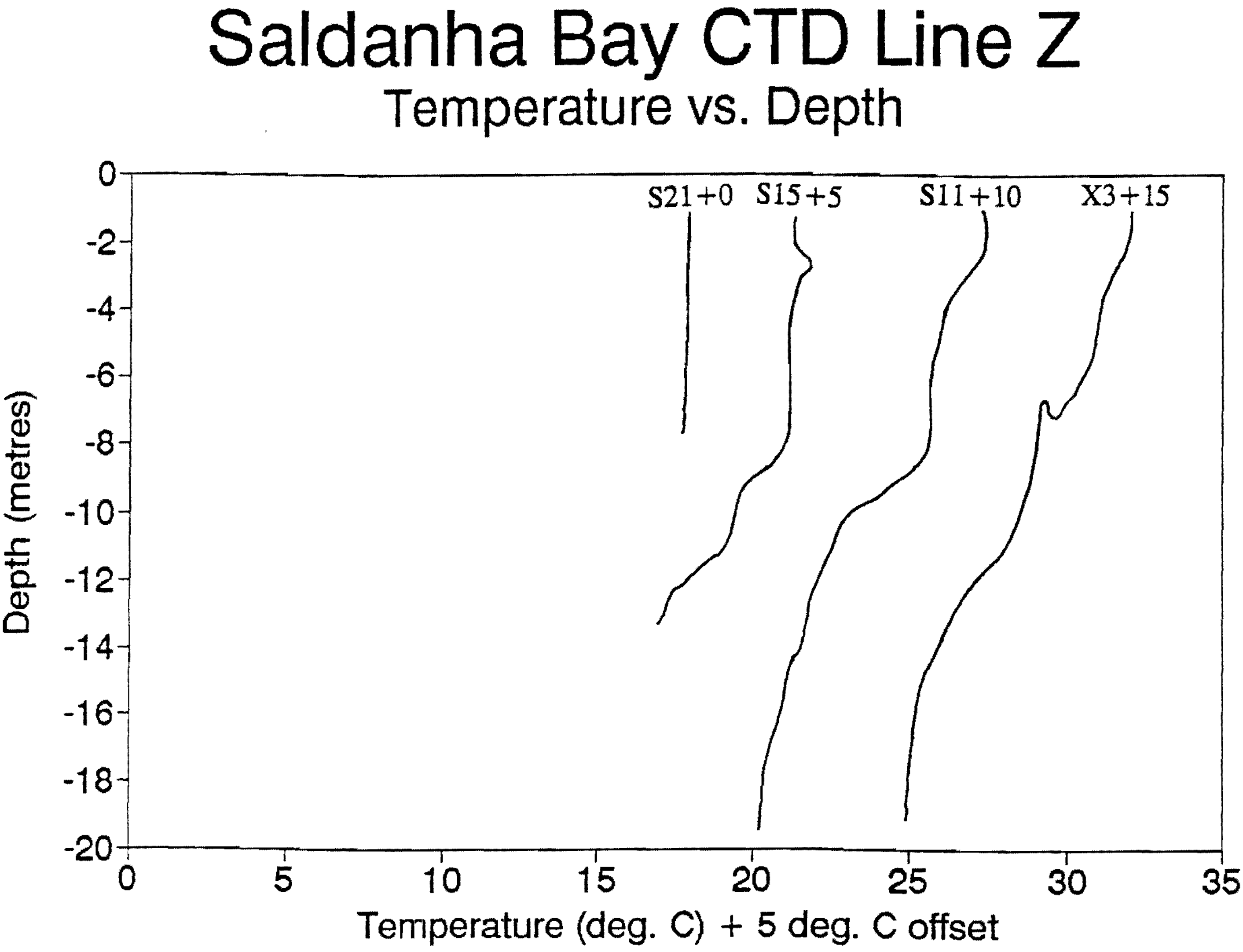


Figure 4.28: Sections of temperature versus depth for CTD line Z with 5°C offset (24/11/94), showing the structure of the thermocline with increasing distance offshore

CHAPTER 5

DISCUSSION

The primary objective of this thesis is to characterise the synoptic circulation patterns in Saldanha Bay and to establish the implications for the mariculture industry.

In the first section the use of drogues as an effective method of current tracking will be discussed. As well as this, the use of GPS for position fixing will also be mentioned. The effectivity of GPS is evaluated by taking into account the conditions under which the greatest positional accuracy is required and whether the GPS system can achieve these levels of accuracy. In the second section the new results are compared with those of previous studies. In the third section, it will be investigated whether Small Bay and Big Bay can be considered to operate as one system, and in the fourth section we will compare oceanographic variables to see whether or not Saldanha Bay is typical of the Benguela upwelling region and other upwelling regions worldwide. Section five deals with the very important implications of these results for the mariculture industry and section six discusses future research regarding Saldanha Bay and similar semi-enclosed upwelling areas.

5.1 Methodology

Discussion with respect to the methodology of drogue tracking and position fixing can be divided into two parts, the first being concerned with the actual drogues themselves, and the second with the means of position fixing.

As far as the drogues are concerned, the drogues of sides 1m and tetrahedral shape used are quite suitable for bay surveys. The size of the surface float and pole with marker flag result in windage which has been shown to be negligible. Using bigger drogues decreases the surface windage effect, but also makes the deployment and retrieval of the drogues impractical. Depending on the boat used for the study and the manpower available, it might be feasible to use bigger drogues. We used both PVC and canvas drogues and found that the canvas ones were the preferred choice.

In order to conclude whether differential GPS is indeed an effective tool in drogue position fixing, we need to compare the accuracy levels achieved with the system to the accuracy levels required under the most stringent conditions. The main factor affecting the accuracy requirements in Saldanha Bay is in fact the current velocities. The greater the velocities, the less the necessity for a high level of accuracy. This can be illustrated by the following example:

A current with velocity 20 cm/s will travel 720 m/hour. An accuracy of 50 metres over 720 metres is acceptable. If, however, we are tracking currents with velocities of the order of 2 cm/s, 50 metres accuracy over 72 metres is clearly not acceptable. The velocities measured ranged from 2000 m/hour for surface drogues during spring tides and under high wind conditions, down to 100 m/hour for deeper drogues under neap tides and no wind conditions. Clearly, the accuracy required depends on the lowest velocities i.e. in the region of 2 cm/s. For this we would need an accuracy of better than 10m and ideally better than 5m.

Standard GPS, which provides accuracy in the order of 50m to 100m is therefore only adequate during strong current conditions, whereas the setting up of a differential GPS system in Cape Town applicable in Saldanha Bay provides us with levels of accuracy typically less than 5m, and therefore useful under all conditions. The increased accuracy that could be obtained by positioning the base station in Saldanha Bay rather than in Cape Town does not justify the effort required to do so.

It can therefore be concluded that differential GPS is an effective means of position fixing under conditions requiring the highest levels of accuracy. As well as providing consistent and reliable results, it is inexpensive and can be operated single-handedly.

There are other methods of drogue tracking which are feasible, and all have unique advantages and disadvantages. Using surveying techniques to triangulate the drogues position results in accuracy level errors of < 1m in Saldanha Bay, but requires extra manpower. Using a theodolite with electronic distance measuring is also equally accurate but still requires an additional person. Tracking the drogues using radar requires the addition of radar reflectors to the drogues, thereby increasing windage. In addition, a radar system is required and the use of radar for tracking is not appropriate in foul weather as it becomes difficult to locate the drogues in high swell and distinguish them from the white water.

The most practical method of tracking drogues is with the use of radio transmitters fitted to the drogues, with the radio signals emitted from the transmitter monitored by at least two base stations. Because there is no need for continuous tracking by boat the drogues can be tracked through the night. They need only be deployed at the start of the survey and retrieved at the end. The main disadvantage of this system is the cost, but if used regularly it can prove cost-effective. Since a boat is only required for the deployment and retrieval of the drogues, the cost of boat hire is minimised. Until more funding is received, however, the differential GPS system seems to be the most appropriate means of position fixing.

5.2 Comparison of Previous and New Results

After having completed this project, we are now in a position to investigate the various conclusions drawn during the previous studies and if necessary criticise them. This will be done by looking at the various statements made in the summary of results in Chapter 2.

With respect to winds our findings concur with those of Weeks et al (1991a) in that during our field trips, two main wind regimes were dominant. They were the south to south-westerly giving rise to northward currents and the north to north-westerly giving rise to southward currents. Our drogue tracking indicated current speed at the surface ranging between 6 and 30 cm/s, and at the deeper levels from 2 to 17 cm/s. The strongest deeper currents were observed in the region of the mouth of Small Bay. These findings are spatially similar to those of Shannon and Stander (1977) who say that the currents are generally stronger in the mouth of Small Bay. They are also comparable in velocity to those found by Weeks et al (1991a) who give surface currents of the order of 12 cm/s and deeper currents generally less than 6 cm/s.

As regards stratification in the bay, we found that the thermocline was generally found between 3 and 6m, as found by Monteiro and Brundrit (1990). However, Weeks et al (1991a) states that wind forcing dominates tidal influence on current direction, although tidal forcing is felt at depths beneath the thermocline. Our findings show that tidal forcing can be felt at the surface as well as at depth in the mouth of Small Bay and at the entrance to Langebaan Lagoon in Big Bay. We found that the association between wind and current direction does weaken with depth, supporting Weeks et al (1991a), but found no evidence to support the clockwise circulation pattern in Small Bay proposed in the same report.

We found no evidence of large eddies being formed by tidal flow into and out of Big Bay as suggested by the CSIR (1976), but did find that the tidal propagation does not follow the simple inflow and outflow characteristics. Shannon and Stander (1977) estimate the residence time of water in the bay to be the order of 20 days. Figure 5.2 shows results from a thermistor chain placed at the entrance to Saldanha Bay by the Sea Fisheries Research Institute as part of an associated mariculture environment project. From this diagram it can be seen that the exchange of the upper layer is of the order of 6 days, a fact which has implications for mariculture as will be discussed later.

In addition to these comparisons, we have identified the regions of maximum tidal influence to be the mouth of Small Bay and the entrance to Langebaan Lagoon. We have also suggested the possibility of Ekman turning in the bottom boundary layer, a feature not investigated through previous research.

5.3 Small Bay and Big Bay as One System

For us to consider Small Bay and Big Bay as one system we need to understand the physical forcing mechanisms in the two bays. Both Small Bay and Big Bay are semi-enclosed and both are subject to wind and tidal influences. The predominantly south-west wind in summer causes a northward current flow in both bays, while in winter, the opposite is true with the winds being predominantly from the north, and the currents southwards. This indicates that they are both under the influence of the same wind-regime.

The observed and calculated mixed layer depths for both Small Bay and Big Bay indicate that the mixed layer depth in Small Bay and Big Bay shares the same physical characteristics. CTD lines through Small Bay and Big Bay (figure 4.26) show the depth of the well mixed layer decreasing as the distance offshore increases (figures 4.27 and 4.28). The mixed layer depth in both bays is also virtually non-existent onshore and well-defined in the middle of both bays (at between 7 and 9m). Both bays are predominantly stratified during the summer months and predominantly well mixed during the winter ones. In addition to this, the mixed layer depth change on a synoptic scale applies to both Small Bay and Big Bay.

Both Small Bay and Big Bay have regions of enhanced tidal flow and there is evidence of bottom topography influencing the direction of current movement. These results, coupled with the previous ones, lead us to conclude that we can consider Small Bay and Big Bay as one system, namely Saldanha Bay.

5.4 Saldanha Bay as Part of the Benguela Upwelling System

To discuss whether Saldanha Bay is part of the Benguela upwelling system, results from the present survey of Saldanha Bay are compared with those from a drogue study by Brown and Hutchings (1987) in the Southern Benguela. In that survey, a drogue was placed in a patch of newly upwelled water on five different occasions (Cruises A to E) between 1979 and 1981 in order to follow the temporal sequence of events after upwelling. Deployment was just south-west of Cape Town and the drogue was tracked as far north as St. Helena Bay. The drogue used was after Boyd (1983), the same design used in the Saldanha Bay study, but with modifications to enable the drogue to be tracked by ship's radar. Positional accuracy was 250 - 600 metres, compared with the accuracy of 5 - 100 metres for the present survey. Because the drogue in the earlier study was fitted with a radar reflector, it was tracked through the night for periods from 102 - 168 hours, compared with the deployment periods of 3 - 6 hours for Saldanha Bay. Mean drogue speeds ranged from 20 - 39 cm/s, consistently higher than the measured speeds of 3 - 27 cm/s for the present survey. This indicates that the circulation in Saldanha Bay could be constrained by the boundaries of the bay.

The wind conditions for both surveys was similar, with the wind speed range 0 - 20 m/s for Brown and Hutchings and 0 - 17 m/s for the Saldanha Bay study. Because Brown and Hutchings were tracking recently upwelled water, the deployments were timed to coincide with winds ranging from SSE - SSW. Our survey, on the other hand, was conducted throughout the year and two dominant wind directions prevailed, these being NW and SSW. For the offshore survey, the drogue was deployed at 10m, considered to be in the well mixed surface layer. For the Saldanha Bay survey, drogues were placed at various depths in the water column, both in the surface and bottom layers. For both surveys, windage on the drogue was measured and found to be negligible.

As far as results are concerned, there are similarities between the two surveys and these need to be highlighted. Firstly, Brown and Hutchings conclude that in the Southern Benguela, the upper 10 metres is influenced mainly by the prevailing southerly winds. This concurs with our findings in Saldanha Bay that the surface is predominantly wind driven by prevailing winds. Tidal forcing influences the circulation within the Bay due to the constrictions at the mouth of Small Bay and Langebaan Lagoon.

Figure 5.1 compares the wind speed with the drogue speed for the Brown and Hutchings offshore survey as well as for the 2m and 10m drogues in the present survey. All three graphs show similar trends, that is an increase in drogue speed with an increase in wind speed. It can also be seen that for the 10m drogues for Saldanha Bay, some drogue speeds of less than 10 cm/s were found for high wind speeds. This may be due to some 10m drogues being in the bottom mixed layer, and hence not under the direct influence of the wind.

For the individual deployments, measurements of temperature, salinity and various nutrients were made through the water column at stations along the drogue track. During the low winds prevalent on the first cruise (Cruise A), the upper mixed layer was found to range from 0 to 15 metres with a mean depth of 6 metres. Cruises B through E experienced stronger winds and the mixed layer depth deepened to average 9.5 metres for Cruise B, 32 metres for Cruise C, 30 meters for Cruise D and 6.3 for cruise E where once again low wind conditions prevailed. These results led Brown and Hutchings to conclude that mixed layer depth is proportional to the wind speed. The average mixed layer depth for Saldanha Bay was ± 6 metres, under similar wind conditions as Cruises A and E, and therefore comparable.

Lentz (1992) uses a dynamical model to compare the characteristics of the surface boundary layer in four coastal upwelling regions viz. Oregon, Northwest Africa, Peru and Northern California. The parameters studied are calculated and observed mixed layer depths, calculated and observed longshore velocity shears and water residence times.

Two main features of his study are apparent. The first is that a model exists which is effective in describing wind driven upwelling processes. The second is that there are distinct similarities between these processes worldwide. We will compare the results found by Lentz with those from Saldanha Bay and from the offshore study by Brown and Hutchings (1987) to see what similarities are present between the three studies.

The input variables for the model are wind stress, the Coriolis parameter and a stratification parameter, namely the temperature gradient across the mixed layer. The wind stress is responsible for generating turbulence and for forcing the upwelling. The Coriolis parameter varies with latitude and hence will vary with each location to which the model is applied. The stratification inhibits turbulence at the interface of a two layer system.
These parameters enable the output of a predicted mixed layer depth and a predicted longshore velocity shear.

5.4.1 Mixed layer depth

Lentz (1992) compared the observed mixed layer depth with that calculated by the model (figure 5.2). What is evident from the figure is that there is a direct correlation between the observed and calculated mixed layer depths which holds true for all four of the examined areas. In the study of Saldanha Bay in summer and in that of Brown and Hutchings (1987) the calculated depth corresponds well with the observed mixed layer depth on the seven occasions that the mixed layer depth was measured, as can be seen in figure 5.3. These results are therefore comparable to those established by Lentz as far as the mixed layer depth is concerned. In winter, the winds are stronger, the mixed layer extends to the bottom and thus it is of no use to compare the calculated mixed layer thickness with the observed.

5.4.2 Longshore velocity shear

Lentz showed that for typical upwelling areas, the observed longshore velocity shear is much greater than the calculated shear. This result is illustrated in figure 5.4 where the observed shear is on the x-axis and the calculated on the y-axis. In Saldanha Bay the same equation holds true for deployments where the wind was the dominant shear-inducing influence (figure 5.5) and can therefore also be compared with Lentz. Complete agreement is unlikely given that Saldanha Bay is an enclosed bay. The results do not hold true for deployments where the shear is dominated by a tidal influence. Where the currents and winds move in the same direction, the water moves as a block and shear is at a minimum. Nevertheless, a tendency is demonstrated and further study might provide more definitive results. We cannot compare these results with those of Brown and Hutchings because in that study the drogues were only deployed at one depth and hence no shear can be calculated.

The depth of the well mixed layer in Saldanha Bay compares favourably with those found by Brown and Hutchings in the Southern Benguela and by Lentz in established upwelling areas, while the longshore velocity shear in Saldanha Bay also compares with that measured by Lentz. These comparable parameters aid in suggesting that Saldanha Bay is part of the Benguela upwelling system.

5.5 Implications for Mariculture

From the results a number of important implications for mariculture arise. Small Bay and Big Bay can be considered to respond to external forcing mechanisms in a similar manner and their circulation characteristics are similar, facts that can influence decisions regarding the spatial distribution of mussel rafts.

With this in mind, we need to remind ourselves of the water criteria required by the mussels, that is clean water with a continuous supply of nutrients. The supply of nutrients to the bay will be affected by the residence time of water in the bay.

The water moving into and out of Saldanha Bay is in response to synoptic forcing. If the forcing is strong enough, all the surface water will be flushed from the bay and new cold water introduced. The residence time of water in the bay must be related to synoptic time scale events. Figure 5.6 shows the temperature profile with time taken from a thermistor chain in Northern California, indicating the influx of cold, upwelled water in response to synoptic scale wind events. This same movement of water can be seen in Saldanha Bay and the data is obtained from a monitoring station positioned just inside Small Bay. Figure 5.7 shows the change in temperature temporally at the bottom and at one metre below the surface. One can see an influx of cold water into the bay, driven by the south-easter, a relaxation of the wind and a subsequent influx of cold water as the south-easter starts blowing again. This gives the residence time of water in the bay at roughly 150 hours, or just over six days.

Thus we have established that the flushing of the bay is controlled by synoptic scale processes, namely wind-induced upwelling events of the order of six days. This is a somewhat reduced estimate from previously published figures and is the optimal rate at which the phytoplankton that the mussels feed on take to utilise the available nutrients and thus the constant supply of nutrients result in continuous phytoplankton blooms, which in turn are very favourable for mariculture (Brown and Hutchings, 1987). At the same time, the constant and rapid flushing of the water in the bay prevents the build up of pollutants toxic to the mussels.

Nutrients are injected into the upper layer through shear induced entrainment of lower layer water. The shear is present in wind driven areas of the bay, and in tidally driven areas where there is a difference in current velocities between the upper and lower layers. Likewise, in areas of little or no shear, this entrainment will not occur. There are areas of sluggish currents where the exchange of water between the layers is not effective. These include tidally driven backwaters where there is little difference in current velocities between the surface and bottom flow, and therefore no shear. This means that it would not be feasible to place mussel rafts in these areas of the bay.

The shaded areas on figure 5.8 show under what wind conditions the various areas of Small and Big Bay are wind driven. Where the tides are driving the currents, there is very little shear between the top and bottom of the water column and thus it excludes the possibility of placing mussel rafts in these areas. It is possible that even under the lightest wind conditions shear will be induced into the water column and since the only region of Saldanha Bay where the currents are wind driven under even very light winds is Small Bay, this would probably be the preferred place for the location of new mussel rafts.

5.6 Future Research

From a local research point of view there are a number of aspects which need to be looked at in more detail. The circulation in Big Bay needs to be examined more closely, as well as the circulation patterns under high wind conditions. Additional research also needs to be done regarding the effects of local forcing mechanisms on the circulation patterns.

We have described Small Bay and Big Bay to operate as one system. From a modelling point of view, there may be specific similarities and differences which are important, and these need to be identified and examined in more detail. Having determined that Saldanha Bay is an example of an upwelling area, similar studies can be done in other upwelling areas, to determine if these same results hold true.

The bulk of future research in Saldanha Bay will be with respect to the conflict between the various users. On the one hand, the mariculture industry is valuable and has potential for growth based on the fact that we have shown a reliable supply of food and clean water is available in other parts of the bay. On the other hand, the possibility exists for Saldanha Bay to become a storage deposit for oil from Iran, as well as the site for a proposed steel mill and other associated industries. As the oil spill from the Hawaiian King in Saldanha Bay on 9 September 1995 has illustrated, there exists a large conflict of interest between the mariculture and mineral industries. Much work is needed to establish the viability of allowing the various competing industries to operate and expand within the confines of Saldanha Bay.

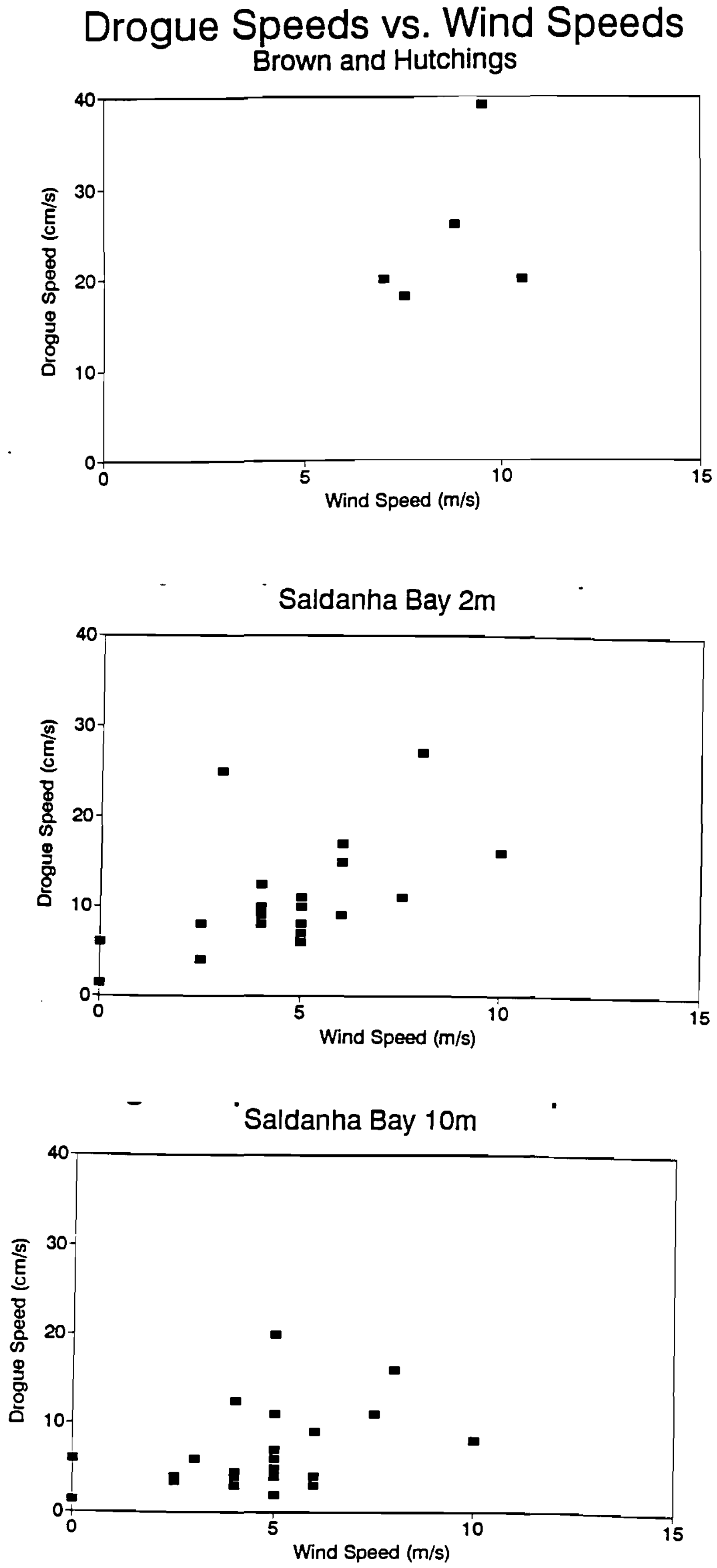


Figure 5.1: Comparison of drouge and wind speeds for Brown and Hutchings (1987) and Saldanha Bay showing how drogue speed increases proportionally with an increase in wind speed.

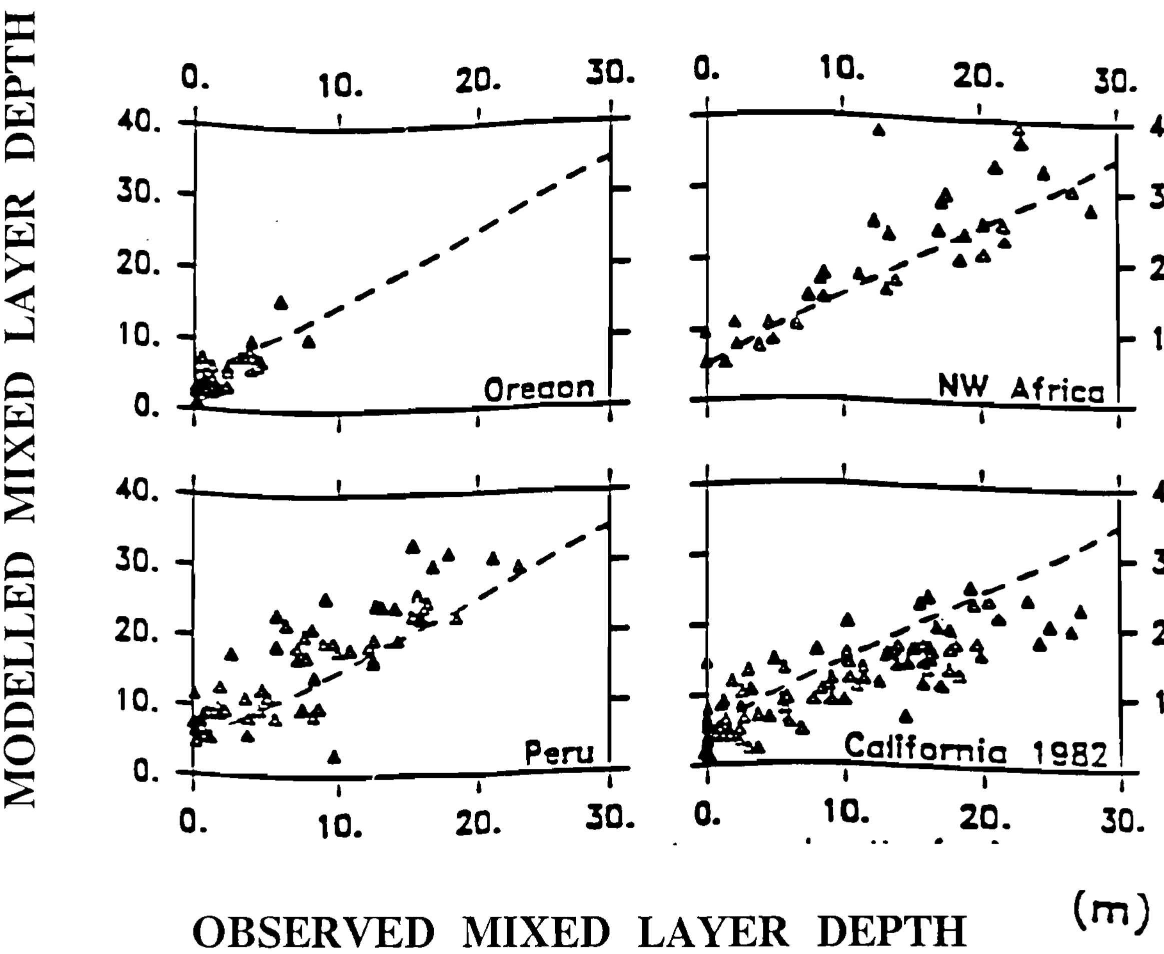


Figure 5.2: Comparison of calculated and observed mixed layer depths for four upwelling regions showing their direct association, after Lentz (1992)

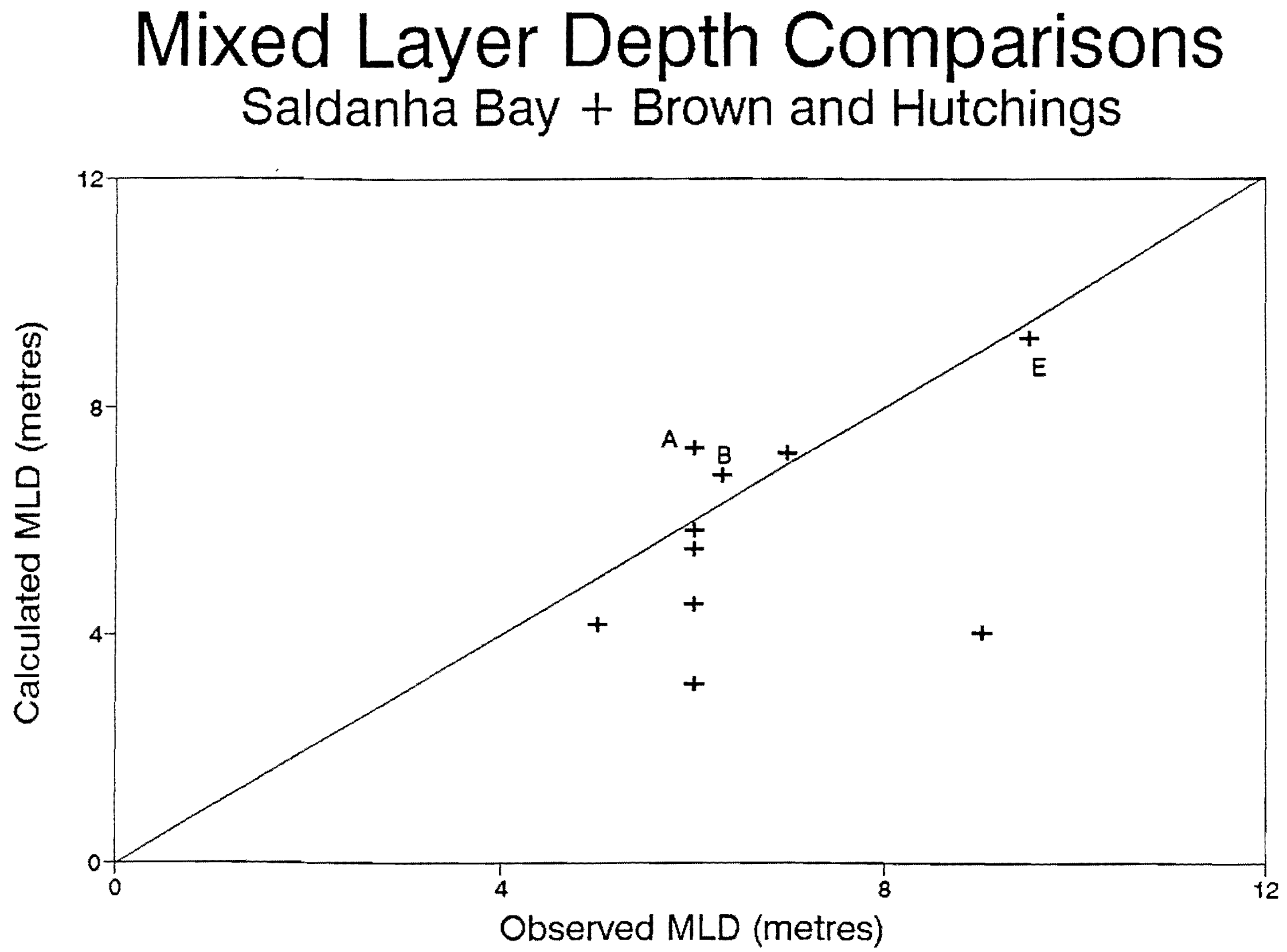


Figure 5.3: Comparison of calculated and observed mixed layer depths for Saldanha Bay and Brown and Hutchings (data points A, B and E) in the Southern Benguela showing their direct association.

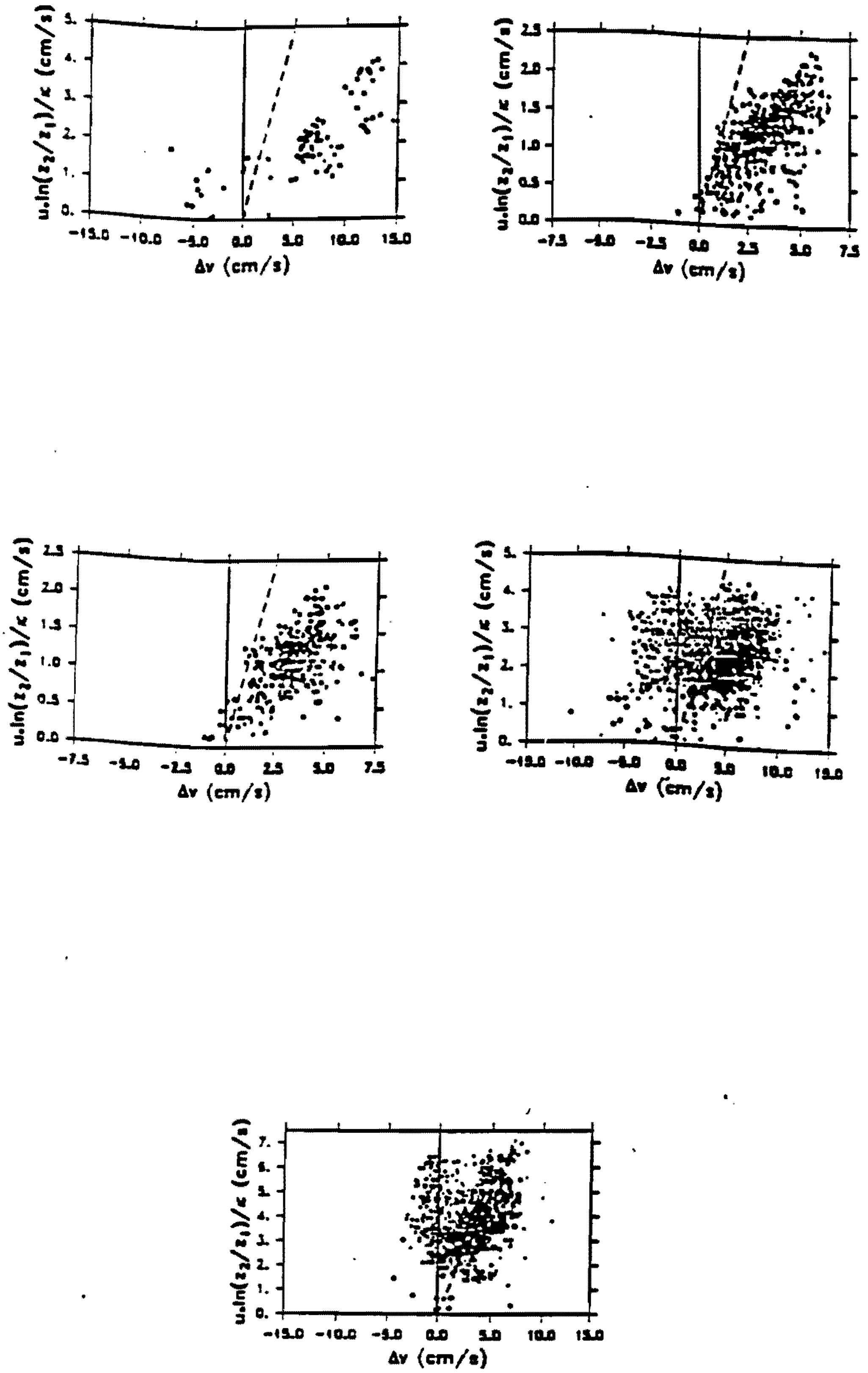


Figure 5.4: Comparison of calculated and observed longshore velocity shear for four upwelling regions showing their association, after Lentz (1992)

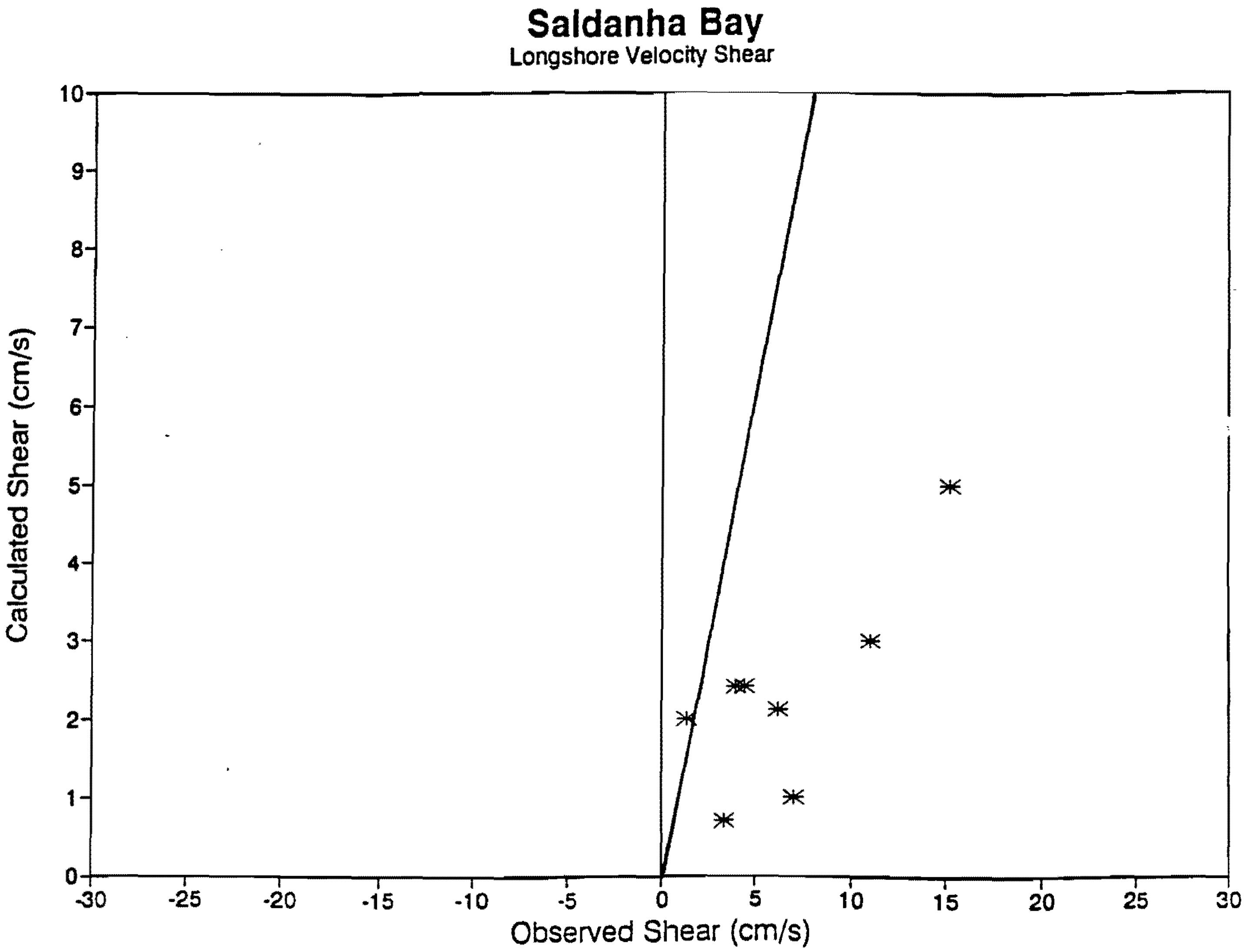


Figure 5.5: Comparison of calculated and observed longshore velocity shear for Saldanha Bay showing their association

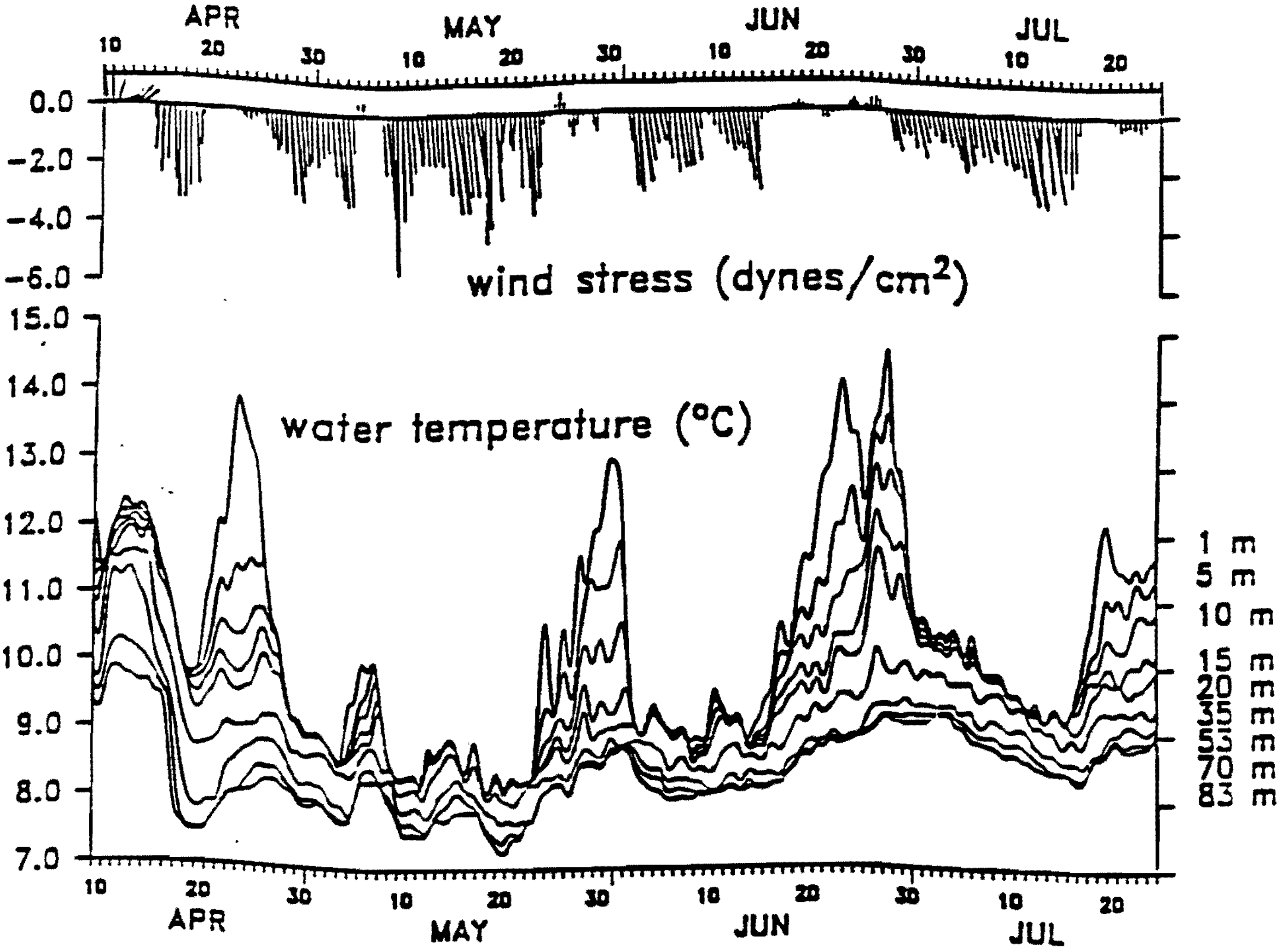


Figure 5.6: Time series of water temperature at various depths from the northern California shelf showing the stratification change in response to the wind stress, after Lentz (1992)

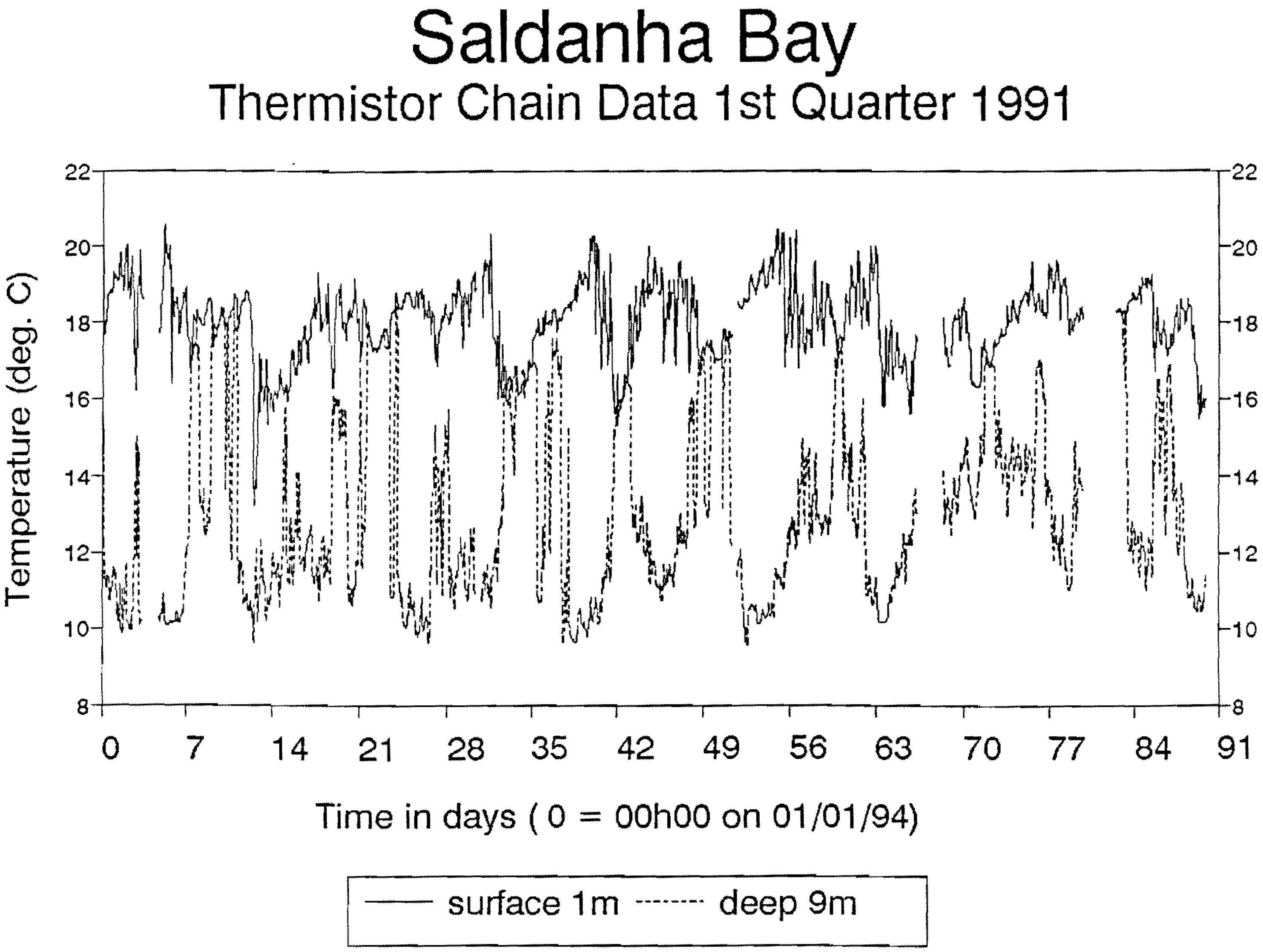


Figure 5.7: Time series of water temperature at two depths obtained from a thermistor chain (by the Sea Fisheries Research Institute) inside Small Bay showing the change in stratification

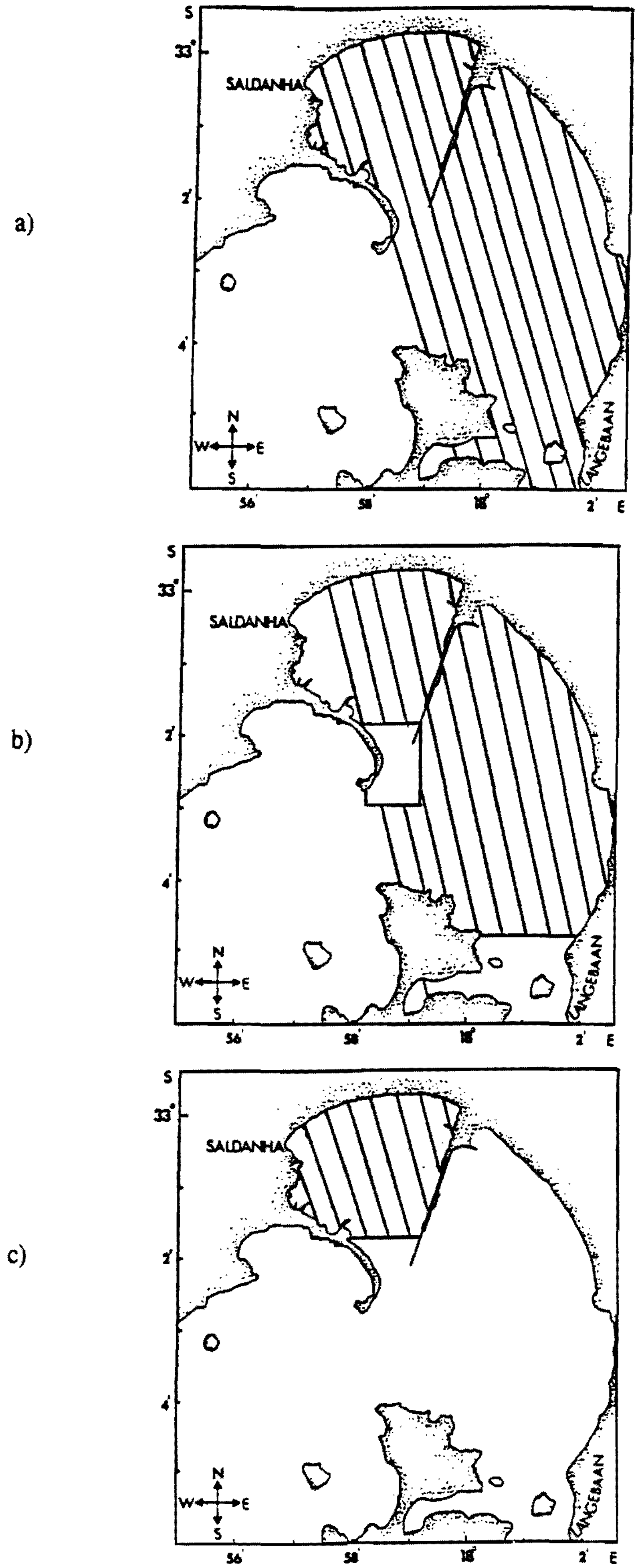


Figure 5.8: Diagrams showing current dominance by wind under (a strong winds, b) moderate winds, c) light winds

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