RRS CHARLES DARWIN CRUISE 68
08/05/1992 – 08/06/1992

THE NORTH ATLANTIC TRACER RELEASE EXPERIMENT (NATRE): FIRST SAMPLING LEG

Principal Scientist: A. J. Watson
Co-Principal Investigator: J. R. Ledwell

Report prepared by: C. S. Law, J. R. Ledwell, A. J. Watson, M. Beney, S. Becker, T. Donaghue, C. Fernandez, B. J. Guest, C. Kinkade, M. I. Liddicoat, K. Lubcke, P. Nightingale, C. Marquette, R. Oxburgh, D. A. Phillips and S. Watts

Acknowledgement: We thank the personnel of the RRS Charles Darwin under Captain P. Macdermott. Their hard work and skilful seamanship helped to make this a successful and enjoyable cruise.

Funding for NATRE is provided by the Natural Environment Research Council in the UK and the National Science Foundation in the USA.

For a complete set of figures, tables and appendices see:

RRS Charles Darwin Cruise 68 08/05/1992 – 08/06/1992, The North Atlantic Tracer Release Experiment (NATRE): First Sampling Leg, Internal report, Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth. Date 1992.

1 INTRODUCTION AND CRUISE OBJECTIVES

The North Atlantic Tracer Release Experiment (NATRE) is a study of vertical and horizontal mixing processes in the thermocline region of the subtropical gyre of the North Atlantic, with the aim of characterising rates of diapycnal and isopycnal mixing and the processes which give rise to them. The experiment was initiated by the WHOI vessel R/V Oceanus on a cruise concurrent with CD68; between 0100 on 05/05/1992 and 0700 on 13/05/1992, Oceanus released a total of 945 moles of sulphur hexafluoride (SF_6) in a series of 9 streaks on an isopycnal surface at approximately 300m. The streaks were 5-10km long, and were injected into a region of order 20 x 20km centred at 25° 38'N, 28° 15'W. Along with the tracer, ten SOFAR "bobber" neutrally buoyant floats were released and ten RAFOS floats.

The plan for the experiment as a whole is to follow the dispersal of this tracer over a period of a year following release. The spread of the tracer in the vertical will give a direct measurement of diapycnal mixing, while the horizontal dispersion of the floats and tracer will enable the quantification of the isopycnal mixing. The floats serve the additional purpose of enabling the location of the tracer. In order to study the processes driving vertical mixing, measurements of fine structure have been and will be made during cruises by R/V Oceanus and the Canadian vessel CSS Hudson in the area of the tracer patch. The overall cruise plan for the experiment is:

April 1992 – site survey	R/V Oceanus
May 1992 – injection	R/V Oceanus
May 1992 – first sampling	RRS Charles Darwin (this cruise)
October 1992 – 2nd sampling	R/V Oceanus
March 1993 – microstructure	CSS Hudson
April 1993 – final sampling	RRS Charles Darwin

In this context, the objectives of CD68 were therefore:

a) To document the "background" concentrations of SF_6 in the region of the experiment. Industrial use of SF_6 has led to a significant global atmospheric background concentration, presently of order 2 x 10^{-12} v/v, and this has in turn generated a concentration in ocean water which decreases with increasing depth. It will be important in the later stages of the experiment to know what background this atmospheric source has generated at the depth of the release, since as the tracer spreads and dilutes, the concentrations will decline sufficiently that the background will begin to become significant in the total after a year.

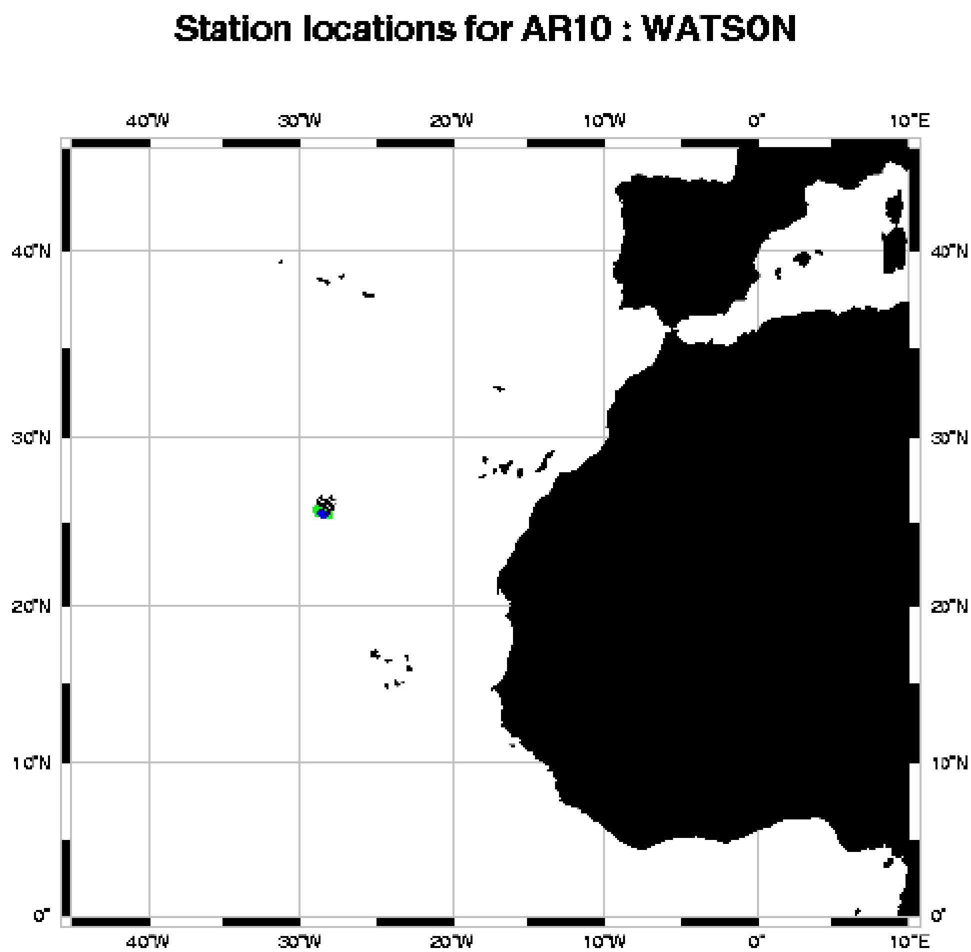
b) To document the initial distribution of the tracer as soon as practicable after release. The "quality" of the release needed to be verified by obtaining measurements of its initial vertical and horizontal spread, since it is from these values that any future spreading due to mixing processes within the ocean will be measured. An initial vertical spread as narrow as possible was therefore desirable. In practice we hoped ideally to confine the initial vertical spread to within ±5m, with ±10m considered acceptable.

c) To show that the entire tracer patch has been documented, we wished to attempt a "budget" of the patch, that is, a reconstruction to sufficient accuracy to estimate the total amount of SF_6 in it and show that this agrees with the amount injected.

To achieve these objectives, two main scientific areas were set up on the ship. These were a gas chromatography analysis area in the main lab, and a sample handling area in the wet lab.

2 ITINERARY

Figure 1 shows the cruise track:



2145 8 May 1992: The vessel departed from Las Palmas, Gran Canaria and set course for the working area. At Las Palmas we had been delayed about 12 hours awaiting a package emergency-shipped from Woods Hole containing parts for an experimental Richardson Number float to be launched from Oceanus. It was agreed that the time lost from our schedule was worthwhile in order to save this project. During the passage we made frequent stops to test equipment and techniques, described in Section 3 below.

0600 12 May to 1600 14th May: Arriving near 25°N 28°W we documented the background concentrations of SF6 in the working region, in 8 casts. These are described in Section 4 below.

1600 14 May to 1130 31st May: We documented the tracer and float initial distributions resulting from the releases by Oceanus. This was the main part of the work and is described in Section 5.

1130 31 May to 0000 8th June: Passage to Barry, UK.

3 EQUIPMENT TESTS (8th – 11th May)

9 May – Casts 1 and 2: The CTD sled to be used for tracer "tows" (see below) was modified and tested in the water towing at speeds up to 1kt close to the surface. Its behaviour was monitored and we verified that it showed no tendency to rotate or fishtail. We monitored the load on the wire (which did not exceed 400kg) and then tested various switches which would form part of the main sampling array (see Section 5).

10 May – Casts 3 and 4: We tested the automated winch control system designed and built by R. Powell of RVS, by hanging a heavy (650kg) weight on the wire, paying out wire and verifying that the winch responded correctly when artificial CTD input was fed into the system. We then tested the system for real by putting the CTD sled on the wire, lowering to 150m and transferring to automatic control. The system showed some tendency to "hunt" but did respond basically correctly.

We also stopped to deploy a hydrophone (cast 5) to listen for the "bobber" SOFAR floats deployed by Oceanus from 1630 to 1930, but could not hear any of them.

11 May – Cast 6: Intercalibration of CTD and autonomous "SEACAT" CTDs. The SEACATs were mounted on the CTD cage and lowered to 600m, stopping every 100m for 5 minutes to allow time for equilibrium of all sensors.

Cast 7: (nearly) full casts of samplers and flying cage at 300m. We were pleased with the automatic winch driving system which on quiet sections was able to maintain density surface with a standard deviation of about 0.0012-0.0015 units of sigma. However, it also hit noisy sections where it was many times worse. This cast flew for 4 3/4 hours.

4 BACKGROUND SAMPLING (12th – 14th May)

These casts were made in an octagonal pattern around the central region where the tracer had been laid, but at about a distance of 40 nautical miles to ensure that the injection did not affect the background values. Initially the samples were collected using the canister samplers designed for obtaining integrated samples of a streaky tracer. As the analysis proceeded it became apparent that the canister samplers were not well suited for very low levels of SF_6, and we therefore reverted to standard Niskin bottle sampling. Figure 2 shows the positions of the stations, details of which are given in Table 1.

The cross-pattern was chosen to make sure that we bracketed the central position, and also to allow close approach and VHF contact with the Oceanus in the centre.

4.1 Hydrographic Data

We used the SEACAT autonomous CTDs rather than the Neil Brown CTD as this avoided having to dismount the CTD or the pylon from the cage. The station list gives details of the positions of the SEACATs on the wire. A description of the SEACATs is given in Appendix III. The SEACATs are not well configured for measuring salinity because of the slow response of the conductivity cell, and especially for vertical profiles because the cells are oriented horizontally. Therefore, we used temperature as a surrogate for potential density for the casts performed only with the SEACATs, the mean relationship between temperature and potential density having been determined later in the cruise with the EG&G MkIII CTD.

The SEACATs were calibrated for the upper 600m of the water column during cast 6, when they were deployed together with the MkIII CTD on the sampling sled. A multiplier and addend were established for each SEACAT for temperature and conductivity, and for pressure for the two SEACATs with strain gauges, namely 884 and 885 (Table 2).

4.2 SF_6 Data

Casts 8-12 showed some obvious contamination and considerable scatter, though the precision of duplicates taken from the same sampler were generally good. This confirmed a trend seen earlier in the samples analysed from Cast 7, the first flying of the winch, in which two bags gave high results. Several samples had bubbles in, so for instance a total of 5 samples out of cast 9 had to be discarded.

Because of the contamination problem, all interpretation of the background concentrations was made with the last four casts only, for which Niskin samples were taken. Figure 3 show SF6 concentrations from these casts plotted as a function of depth. Three of the profiles agree closely but the last (cast 15) is consistently high – it is just possible that this is due to generalised contamination picked up during the transfer of personnel from the Oceanus which took place a few hours before this cast was performed. However, in the absence of firm evidence of contamination this cast was treated in the same way as the other three.

For each sample from casts 12-15, a potential density was assigned using the observed temperature and the cruise-mean temperature vs potential density relationship. The four profiles were then linearly interpolated to standard densities and averaged. Figure 4 shows the results of this exercise and also tabulates the basic cast data. At the “target” isopycnal of 28.05, the men background value is 4.23×10^{-16} moles/l.

5 TRACER SAMPLING (14^{th} – 31^{st} May)

5.1 Method

The difficulties in sampling a tracer when the distribution is streaky are well known and have been described in the literature. Grab samples, as obtained with Niskin bottles, cannot be relied on to give an accurate estimate of the vertical profile because there is no way of knowing whether the sample was taken in a streak or out of it, and even small-scale vertical shear in the water column will distort the apparent profile. The method we employed to circumvent the “streakiness problem” was to use a vertical array of custom-designed water samplers which fill with water at a slow and reasonably constant rate, interspersed with SEACAT CTDs. The array was towed through the water for a period of several hours, with its centre kept homed in on the isopycnal surface on which the tracer was released. During this time the array may cross one or more streaks of tracer, and subsequent analysis revealed a vertical cross-section averaged over the tow track. Figure 5 shows the position of samplers, SEACATs and central CTD in the array used for casts 16 – 28. From cast 29 onwards, extra samplers were added at +30m and –30m from the centre.

The purpose of the SEACATs was to provide information on the variation in density and density gradient over the region from 30m above to 30m below the centre of the array. Without such information it would be necessary to assume that these properties remained constant over each sampling tow, whereas examination of the data shows that this is frequently far from the truth. Use of the SEACATs is described in more detail in Appendix III and Figures 30-34 show examples of the kind of data obtained from them.

In order to measure the true tracer distribution with respect to density, it was necessary to keep the centre of the array “flying” along a constant-density surface. Since these surfaces are not at constant depth, a CTD sensor at the centre of the array was required which measured the density there, along with a method of altering the amount of wire out in response to this signal to continuously adjust the sensor to the correct depth. In addition to the CTD, samplers, calibration equipment and an experimental “multichamber sampler” system were mounted at the centre of the array. To carry this equipment, a custom “sled” was built at WHOI. The upper half of the array was attached to the CTD wire itself, while the lower part was attached to an auxiliary wire hung from the bottom of the sled. Upper and lower arrays were triggered by messengers.

The sled, a frame, approx. 1m x 1m x 2m, held the following:

(a) The CTD (Neil Brown MkIII).
(b) Two or more integrating samplers.
(c) A multisampler holding a carousel of 18 sampling syringes filled sequentially during the tow.
(d) A rosette pylon which fired to perform several tasks, in the following sequence:

    (1) Release a messenger which tripped the samplers below the sled.
    (2) Start the samplers on the sled.
    (3) Start the multisampler.
    (4) Collect up to seven salinity samples and turn four reversing thermometers during the course of the tow, for purposes of calibrating the CTD.

The procedure for the tracer tows was to head due north, that is with the wind on the starboard bow, while towing the sample array at 0.5 – 1kt from the starboard “A” frame and CTD winch. In order to counteract the westerly drift and wind effect, the ship actually headed at about 30° to starboard to do this. Deployment of the sled and all the associated samplers took a time of order 2 hours initially, but decreased to one hour after a little practice. The sled was then lowered to 500m in order to get CTD data through the depth of interest. It was then returned to 300m and transferred to automatic winch control, and the messenger dropped to start the samplers filling. After a time of 3.5 hours all the samplers should be filled, but to be sure they were left down for an extra 0.5 hours. Finally another drop to 500m was performed followed by recovery to deck, which took about 45min. Turn-around of the apparatus was performed during steaming to the next site. The total time of the cycle was generally of order 8 hours.

5.2 Float Location

Hydrophone listening stations were occupied as detailed in the station list on 3 occasions. The vessel steamed a good distance to the NE or SW of the tracer patch (typically 20nm) in order to obtain a favourable geometry with respect to a Drifting SOFAR receiver deployed by Oceanus, which was about the same distance to the NE of the patch. The hydrophone was lowered to listen during the period 0630-0930 or 1830-2130 when the SOFAR floats deployed by Oceanus were programmed to transmit. We heard respectively 4, 8, and 5 floats out of 10 released on casts 31A, 37A and 44A.

On three occasions we were able to obtain good fixes on some of the floats by using the Simrad PES to listen for the 10kHz pings emitted by them. We used a box-search technique whereby as the point of closest approach is passed (indicated by a flattening out and then decrease in the pattern of pings on the Simrad) a 90 turn to port or starboard is made. We used this technique between 2340 on 22 May and 0440 on 23

May to obtain fixes on four floats. The Simrad proved an excellent instrument for listening to the signal from the floats, with a range of about 3nm.

5.3 Hydrographic Data

Additional calibrations of the SEACATs against the MkIII CTD were made at intervals. It was found that, because of a software imperfection, a correction must be applied to the time record from the SEACATs. The time since Startup of the SEACATs must be multiplied by the drift correction in Table 2 to determine the correct time.

The SEACATs were calibrated again at the target density of the sampler tows by towing them for 1 hour on the sled during Cast 28 (Table 3). They were checked once more in this way during Cast 49 (Table 4), and found to have drifted very little.

The MkIII CTD was calibrated for temperature and pressure on shore prior to departure. The temperature calibration was checked throughout the cruise with four digital reversing thermometers mounted on the Sampling Sled (Appendix II). These were the same thermometers used during the injection cruise on Oceanus. However, for both cruises the strong temperature gradients and the mismatch in time and space between the reversing thermometers and the CTD probes resulted in rms noise of around 0.090°C. Therefore the shore-based calibrations, which should stand to better than 0.004°C will be relied upon for temperature.

Salinity calibrations were also performed throughout the cruise, with samples from the 5-litre Niskin bottles during the background casts and from 1.2-litre Niskin bottles mounted horizontally on the Sampling Sled during the tows (Appendix II). They showed a consistent salinity error of –0.022psu for the MkIII system for the part of the water column sampled. This correction was applied in processing the CTD data. The processed CTD data are considered as accurate as possible; no post-cruise adjustment of the data is anticipated.

Each sampler tow was preceeded by a downcast to 500m at about 25m/min, and was followed by an upcast from 500m at roughly the same speed. Since the ship was generally moving at about 1kt (30m/min) the descent and ascent angles are about 45° from the vertical. Also the CTD probes, while located in an open area just a few cms from the leading edge of the sled, may see thermal contamination from the sled. For these two reasons the finestructure at scales of 1m or so are not to be taken as representing the vertical hydrographic structure. Averages of the data over many casts and the individual profiles over scales of 10m or more should be accurate, however.

Table 1 lists the times and positions at the start and end of the tows, and the tow tracks are plotted in Figure 6. These can be taken as applying to the downcasts and upcasts, respectively. The data stream from the MkIII Deck Unit to the SUN-based processing system was not always turned on at the start of the cast and was sometimes turned off early. Also, although the wire out was always brought to 500m or more at the bottom of each cast, the pressure did not always reach 500db. Tables 5 to 8 list the properties caught at the top and bottom of each descent and ascent to show what data are available from the processed CTD files.

Representative profiles from the MkIII are shown in Figures 7 to 11. These are the raw data, with only the spikes near the rosette trips removed. There are still obvious spikes of noise in the data. These also appear in the plots of potential temperature versus salinity shown in Figures 12 to 16. These spikes are not severe enough to seriously affect the means discussed next.

The data from the CTD descents and ascents were interpolated to standard levels every metre from 10m to 500m, where data are available. These were then averaged at the 1m intervals to produce the mean profiles of Figures 17 and 18, and the plots of mean potential temperature versus salinity in Figures 19 and 20. Profiles are allowed to drop out of these averages where there are no data. This can lead to discontinuities in the mean profiles, but does not in this case because the number of profiles remaining is so large. A listing of the mean of the descent data every 10m is given in Table 9.

Considerable CTD data near the target density surface of σ_p = 28.05 were also obtained with the MkIII and SEACAT CTDs. Figures 21 to 29 show samples of data from the MkIII for several selected casts, including the ones where problems following the target density were encountered. These figures show about 4 hours of data, and sometimes include the approach and leaving of the target surface at the ends of the records. However, if the winch control system is operating properly, σ_p should remain close to a constant value for the remainder of the record. Figures 27 to 29 show the CTD data for the tows for which this was not the case.

The winch control system failed during Casts 35, 49, and 54. Fortunately, no SF_6 was found during Cast 35, Cast 49 was a calibration tow without samplers, and only small amounts of SF_6 were found from Cast 54. It is possible that the anomalous shape of the SF_6 profile from Cast 54 is due to the poor flight control shown in Figure 29.

The 4 SEACAT CTDs were hung on the wire above and below the MkIII on the sampling sled to give data on the vertical temperature distribution along the sampling track. The SEACATs were hung just below the integrating samplers nominally at 16m, 6m, -9m, and -20m above the CTD. The SEACAT probes were located between 40 and 60cm below the inlet of the sampler above. The positions of these inlets are listed in Table 10. The approximate heights of the SEACAT probes are then: 15.5m, 5.1m, -9.8m, and -20.8m. The heights for SEACATs 885 and 884, at 15.5m and -20.8m, inferred from the pressure records average 15.8m and -20.2m, in fair agreement. The differences are not understood completely but may be due in part to the 0.3db digital resolution of the SEACAT sensors and a slight hysteresis in the MkIII gauge.

The discrepancies cannot be explained by wire angle. The angle at the sheave was typically less than 10°, and the 500lb weight at the bottom of the array will reduce this angle to nearly 0° in the vicinity of the array. Furthermore, the pressure offset at 15.5m is in the wrong sense to be explained by wire angle. Therefore, no corrections need be attempted for wire angle in the sampler heights.

Examples of the temperature records from the 4 SEACAT CTDs and the MkIII are shown in Figures 30 to 34. It is clear from these figures how variable the spacing of isothermal and isopycnal surfaces is. A correction for the effect of this finestructure on the vertical distribution of the tracer as it is used to infer the diapycnal distribution will be made in post-cruise analysis.

The data from the 5 CTDs obtained during the 43 tows of the sampling sled give an excellent record of the hydrographic properties in the vicinity of the target density surface. Table 11 summarises the mean and rms temperature, salinity and density at the tow level of the sled. The target density was not always 28.05 because of errors made in correcting for the calibrated offsets earlier in the cruise. A history of nominal target densities is given in Table 12, along with the actual target density, accounting for the errors made, and the actual mean density of the tow as measured by the MkIII CTD.

The mean and rms potential temperature, salinity, and σ_p at the MkIII are listed for the tows in Table 11. This table also includes an estimate of the gradient $dT/d\sigma_p$ from the SEACAT and MkIII data and the ratio of rms temperature to this gradient. This last ratio gives an estimate of the rms σ_p which is generally lower than that made directly from σ_p, presumably because the latter is strongly affected by noise in the salinity record.

The array of SEACATs and MkIII CTDs has been used to estimate pressure, potential temperature, and salinity at the σ_p = 28.05 surface by interpolation between the MkIII and the appropriate neighbouring SEACAT, usually SEACAT 882, located 9.8m below the MkIII. Estimates of the gradients dT/dz, dS/dz, and $d\sigma_p/dz$, as well as the Density Ratio (R_) and the Buoyancy Frequency (N) are listed in Table 13. These gradients are estimated using the differences between the mean temperature, conductivity and pressure at the two extreme SEACATs, 885 and 884, separated by 36.3m. Many of these quantities are shown in contour maps below.

The gradients calculated from the MkIII and the neighbouring SEACAT have also been used to estimate the mean height of the MkIII above the σ_p = 28.05 surface for the tows. These are listed in Table 14, and have been used to estimate the heights of the sampler inlets above the 28.05 surface in reducing the concentration data.

5.4 Lateral Motion of the Patch

The data from the “bobber” floats are described in detail in Appendix III. These data have been used to infer the motion of the tracer patch during the sampling survey. These estimates have been used in choosing locations for the survey, and are used here for plotting and reducing the data. Two estimated for the motion of the patch have been made. The first is based on the positions of 5 of the floats, namely, 55, 56, 57, 58, and 59.

The positions of the floats on the days between actual fixes were estimated by linear interpolation. The longitudes for the days from the last fix to the end of the survey on 31 May were estimated by linear interpolation, while the latitudes, being more variable, were held at the last known position. The velocities of the floats for each day were estimated from simple differences of the positions. The velocity of a water parcel at any position and day was estimated from a weighted mean of the float velocities, the weighting function taken as inversely proportional to the distance from the float. Displacements of water parcels over a period of several days were then estimated using a day by day stepping procedure of position and velocity. Thus, the sampling tracks could be transformed from their original positions to positions on 23 May, the approximate central time of the survey (see Figure 35).

The translation inferred in this way from the 5 floats mentioned above is considered conservative, in that 3 of the floats, 55, 57, and 58 are relatively stationary and remain close to one another. Thus they are redundant, and their low velocities are weighted too heavily.

A more liberal estimate of the translation was made by using only data from floats 56, 59, and 64, the last representing the slow velocities in the eastern area of the patch (see Figure 36). Some data have been reduced using 3 sets of positions, namely the original positions of the tracks, those translated with the conservative estimate, and those translated to 23 May with the liberal estimate. Most of the data, however, is presented using the conservatively translated positions.

5.5 Lateral Hydrographic Patterns at σ_p = 28.05

Contour maps of some of the hydrographic properties listed for the sampler tows in Table 1 are shown in the contour maps. The map of pressure, Map 1, simply illustrates the mean and variation of the pressure on the surface. The pattern is probably a badly aliased picture of internal wave displacements. The potential temperature map (Map 2) shows that there are systematic variations of potential temperature and salinity at constant σ_p, even over the small area of our survey. The salinity map (Map 3) reflects the potential temperature map, and confirms this conclusion.

Density ratio has proven to serve well as a water mass tracer. It is contoured in Map 4. It appears that its value in the western part of the patch, where the tracer was found, is about 1.80, which is characteristic of the region at this level on the larger scale. Since density ratio is the best water mass tracer, it is also mapped using the original positions (Map 5) and in the liberally translated positions (Map 6). The unrealistically fine structure seen in the original positions suggests that the translation was justified, while there is little basis in these figures to choose between the liberal and the conservative translation.

Map 7 contours the density gradient, which is proportional to the local absolute potential vorticity. Like the pressure, this is mostly useful for evaluating the mean and the variance, since the dominant features are probably aliased internal tides and waves.

5.6 Distribution of SF_6 within the Patch

Forty two tows were made to document the distribution of the released tracer. Of these, 13 had no measurable SF_6 (these were casts 19-21, 35, 38-42, 45, 56, 57, and 59). Each of the remainder is summarised in figures and tables 15 to 43. In these summaries the concentrations are plotted at the nominal heights of the samplers above or below the sled, except for casts 16-18 and 23 for which the sled was flying substantially off the true target density surface and the profiles have accordingly been offset.

Figure 37 summarises the contribution of the individual profiles to the mean profile. The profiles are arranged in chronological order. The largest contribution comes from profile number 31, with profiles 16, 17, and 18 close behind. Figure 38 shows the same data with the vertical scale percentage contribution of each cast at the given distance from the target surface. It is notable from this diagram that the earlier profiles tend to be more narrow and higher in the water column than the later profiles. A few profiles (i.e. casts 30, 37, and 55) tend to dominate in the wings of the distribution.

Heights from the target isopycnal were subject to two further minor adjustments: these take account of changes in the positions of the samplers on the wire as detailed in Table 44, and a further adjustment based on the observed mean density at which the sled was flying during each cast and the temperature gradient between the MkIII and the SEACAT which bracketed the true target surface. These adjustments are small, typically <<1m. The observed profiles (except for cast 51 which was discarded for subsequent analysis because the samplers below the sled did not trigger) were then linearly interpolated to an evenly spaced grid. The results of this interpolation are shown in Table 45. Finally, a mean profile was obtained by averaging the interpolated profiles together. The mean profile is shown in Table 46 along with the summary statistics. The mean profile has a nearly symmetric shape, an rms width of 6.8m and a displacement below the target surface of 0.84m. Such a profile is very satisfactory for the start of the mixing experiment, and should enable accurate measurements of vertical mixing as even if the K_z is as low as 0.01-0.02cm^2/s.

The profiles from each cast can be column-integrated to obtain an amount of SF_6 in moles per unit area for each tow track, as well as a displacement from the target surface, rms width and second moment about the target surface. The spatial distribution of these data around the patch area are contoured in Maps 8 – 13. The data for column integrated amounts are the best, being constrained not only by the profiles which did have SF_6 in them, but also by those which did not.

Map 8 shows the column-integrated SF6 in the float-guided, conservatively-translated co-ordinates – those which we believe are the closest to a lagrangian co-ordinate system. According to this and the other maps, the tracer has strained out mostly in an east-west direction as might be expected from the observed direction of drift. It remains however relatively simple in shape, and contours well. In absolute co-ordinates (Map 9) the distribution is much more difficult to contour. In “liberally translated” co-ordinates

(Map 10), the patch shows a more nearly circular shape. Integration of the distributions over the maps yields our best estimates of the total amount of tracer in the measured patch. These values are:

1128 moles (conservative co-ordinates)
1111 moles (liberal co-ordinates)
1586 moles (absolute co-ordinates)

Of these, the "absolute" value is clearly suspect because we have plenty of evidence that the patch did move substantially during the course of the cruise. Of the three, we favour the "conservative" figure. The number is about 20% greater than the best estimate of the amount actually released, but this represents a much closer agreement than we had expected to be able to achieve and clearly shows that no major areas of the patch were undocumented. The distribution of zero and near-zero values also indicates that we succeeded in closing off the patch on all sides.

The first moment of the vertical distribution, i.e. the displacement of the centre of mass from the target surface, is mapped in conservative co-ordinates in Map 11. There is a clear indication of high values on the north-west edge and low values to the south. Quite substantial offsets are shown in an area to the east, but comparison with Map 8 shows that there are only very low concentrations of tracer here. The gradient in height across the patch can be interpreted as evidence for shear, tending to move the upper portion of the distribution more rapidly to the north-west than the lower part. The second moment of the patch, that is the rms widths relative to the centre of mass and to the target surface, are shown in Maps 12 and 13. Once again, the centre of the patch shows widths of 6-8m, with more extreme values on the edges of the distribution where the concentrations are low.

TABLE 1: STATION LIST

Cast no. 1
09/05/1992, 1530: 27°17.9'N, 18°19.7'W.
Test CTD sled at surface.

Cast no. 2
09/05/1992, 1830: 27°15.0'N, 18°43.7'W.
Test CTD sled and samplers at 100m.

Cast no. 3
10/05/1992, 1330: 26°32.7'N, 22°42.7'W.
Test CTD wire with 1350lb weight using automatic winch controller.

Cast no. 4
10/05/1992, 1600: 26°32.3'N, 22°49.7'W.
Test CTD sled with weight on lower wire. Test fire samplers. Test automatic winch controller.

Cast no. 5
10/05/1992, 1745: 26°35.1'N, 22°50.0'W.
Hydrophone cast to listen for SOFAR floats.

Cast no. 6
11/05/1992, 1100: 26°15.0'N, 26°42.8'W.
Intercalibration of RVS CTD and SEACAT autonomous CTDs.

Cast no. 7
11/05/1992, 1700: 26°14.7'N, 26°43.3'W.
Test complete sampler array and automatic control system for CTD winch.

Casts 8-15: 600m casts to determine background SF_6 concentrations, using CTD wire, SEACAT CTDs and 14 water samplers. The arrangement of samplers and SEACATs on the wire was as follows:

Depth	
10m	sampler
50m	sampler
100m	sampler, SEACAT
150m	sampler
200m	sampler
250m	sampler, pressure SEACAT
300m	2 samplers
350m	sampler
400m	sampler, SEACAT
450m	sampler
500m	sampler
550m	sampler
600m	sampler, pressure SEACAT, pinger, weight.

Times and positions of the casts were:

Cast 80600, 12/05/1992 Position A: 26°08.0'N, 27°38.0'W.
Cast 91530, 12/05/1992 Position B: 25°11.0'N, 28°42.0'W.
(Done in two hoists, Messenger dropped too soon).
Cast 10 2300, 12/05/1992 Position C: 25°11'N, 27°38'W.
Cast 11 0830, 13/05/1992 Position D: 26°08'N, 28°42'W.
Cast 12 1300, 13/05/1992 Position E: 25°39'N, 28°55'W.
Cast 13 2000, 13/05/1992 Position F: 24°58'N, 28°10'W.
Cast 14 0300, 14/05/1992 Position G: 25°39'N, 27°24.5'W.
Cast 15 1450, 14/05/1992 Station H: 26°22'N, 28°10'W.

Casts 16-59: Tracer sampling tows and hydrophone casts. See text for descriptions of these. The following table gives times and positions of deployment, triggering of the sampler array and end of the sampling tow.

Cast no.	Date / Time begun	Posn begun	Time triggered	Posn triggered	Time ended	Posn ended
16	14/5, 2035	24 35.0N, 28 18.0W	2240	24 37.0N, 28 18.0W	0342	25 42.0N, 28 18.0W
17	15/5, 0915	25 40.1N, 28 18.0W	1110	25 41.5N, 28 18.7W	1521	25 45.9N, 28 18.0W
18	16/5, 1915	25 34.8N, 28 23.5W	2113	25 36.7N, 23.5W	0142	25 41.4N, 28 23.3W
19	15/5, 0443	25 29.5N, 28 23.5W	0620	25 06.0N, 28 23.5W	1100	25 36.7N, 28 23.5W
20	16/5, 1521	25 28.1N, 28 18.1W	1652	25 28.8N, 28 18.2W	2130	25 32.9N, 28 18.0W
21	16/5, 2324	25 28.1N, 28 12.3W	0050	25 21.1N, 28 12.3W	0442	25 33.0N, 28 12.3W
22	17/5, 0638	25 36.5N, 28 12.5W	0753	25 37.4N, 28 12.5W	1200	25 41.8N, 28 12.9W
23	17/5, 1510	25 40.0N, 28 23.7W	1630	25 41.1N, 28 23.4W	2050	25 45.6N, 28 23.7W
24	17/5, 2316	25 44.7N, 28 23.4W	0040	25 44.6N, 28 23.3W	0415	25 49.0N, 23.5W
25	18/5, 0705	25 47.9N, 28 23.5W	0828	25 48.9N, 28 23.4W	1236	25 53.2N, 28 23.6W
26	18/5, 1532	25 44.1N, 28 32.9W	1701	25 45.2N, 28 33.1W	2112	25 49.1N, 28 32.9W
27	18/5, 2354	25 42.0N, 28 29.1W	0145	25 43.5N, 28 30.2W	0548	25 47.4N, 28 30.1W
28	19/5, 0841	25 43.7N, 28 30.6W	SEACAT CALIB.		1102	25 45.4N, 28 30.0W
29	19/5, 1244	25 46.7N, 28 30.2W	1442	25 47.6N, 28 30.0W	1843	25 51.4N, 28 30.0W

Cast no.	Date / Time begun	Posn begun	Time triggered	Posn triggered	Time ended	Posn ended
30	19/5, 2335	25 38.5N, 28 30.0W	0109	25 40.0N, 28 30.1W	0519	25 44.5N, 28 30.0W
31	20/5, 0815	25 38.9N, 28 26.7W	0912	25 39.7N, 28 26.5W	1344	25 43.7N, 28 26.7W
31A	20/5, 1740	26 05.7N, 28 41.1W	H'PHONE CAST		2152	26 05.4N, 28 41.3W
32	21/5, 0051	25 34.8N, 28 26.6W	0220	25 35.9N, 28 26.4W	0620	25 40.1N, 28 26.5W
33	21/5, 0836	25 36.0N, 28 20.7W	0946	25 36.8N, 28 20.7W	1354	25 40.9N, 28 20.7W
34	21/5, 1650	25 32.2N, 28 20.6W	1810	25 32.8N, 28 20.8W	2216	25 36.3N, 28 20.7W
35	22/5, 0106	25 31.3N, 28 27.3W	0215	25 31.9N, 28 27.3W	0620	25 36.0N, 28 27.2W
36	22/5, 0900	25 38.9N, 28 24.1W	1008	25 39.7N, 28 24.0W	1410	25 44.3N, 28 24.0W
37	22/5, 1612	25 37.8N, 28 28.6W	1736	25 38.5N, 28 28.4W	2136	25 41.0N, 28 28.6W
37A	23/5, 0615	28 55.8N, 28 30.7W	H'PHONE CAST		1000	25 54.6N, 28 31.1W
38	23/5, 1150	25 40.3N, 28 21.0W	1303	25 41.5N, 28 21.0W	1722	25 46.7N, 28 21.2W
39	23/5, 1913	25 40.5N, 28 17.9W	2025	25 41.5N, 28 18.0W	0045	25 46.0N, 28 18.0W
40	24/5, 0230	25 37.8N, 28 13.1W	0400	25 38.8N, 28 13.0W	0824	25 43.5N, 28 13.1W
41	24/5, 1039	25 36.2N, 28 17.0W	1148	25 37.2N, 28 18.0W	1552	25 42.6N, 28 17.9W
42	24/5, 1837	25 30.8N, 28 17.4W	1955	25 32.2N, 28 18.0W	0000	25 37.2N, 28 18.0W
43	25/5, 0226	25 43.3N, 28 26.8W	0342	25 43.9N, 28 26.6W	0707	25 47.2N, 28 26.7W
44	25/5, 1024	25 40.0N, 28 33.0W	1128	25 40.8N, 28 33.0W	1453	25 43.6N, 28 33.0W
44A	25/5, 1754	25 52.1N, 28 49.3W	H'PHONE CAST		2154	25 50.5N, 38 50.3W
45	26/5, 0146	25 50.0N, 28 58.0W	0302	25 50.6N, 28 52.0W	0627	25 53.4N, 28 52.1W
46	26/5, 0915	25 46.3N, 28 47.9W	1037	25 47.0N, 28 48.0W	1402	25 49.7N, 28 48.1W
47	26/5, 1700	25 43.3N, 28 43.4W	1823	25 44.0N, 28 43.3W	2148	25 46.8N, 28 43.3W
48	27/5, 0043	25 41.5N, 28 38.2W	0202	25 42.5N, 28 38.1W	0527	25 46.4N, 28 38.2W
49 SAMP. TEST	27/5, 0850	25 41.9N, 28 38.1W	0948	25 42.3N, 28 38.3W	1313	25 44.5N, 28 38.2W

Cast no.	Date / Time begun	Posn begun	Time triggered	Posn triggered	Time ended	Posn ended
50	27/5, 1631	25 38.3N, 28 43.6W	1823	25 39.5N, 28 43.5W	2148	25 42.9N, 28 43.6W
51	28/5, 0124	25 47.8N, 28 45.8W	0232	25 48.2N, 28 43.5W	0557	25 52.4N, 28 43.5W
52	28/5, 1906	25 50.0N, 28 33.0W	2040	25 50.7N, 28 33.0W	0115	25 53.7N, 28 33.0W
53	29/5, 0447	25 48.6N, 28 38.3W	0603	25 49.9N, 28 38.2W	1015	25 55.1N, 28 38.2W
54	29/5, 1306	25 38.6N, 28 49.9W	1419	25 39.4N, 28 49.8W	1826	25 43.2N, 28 49.2W
55	29/5, 2032	25 38.4N, 28 39.6W	2139	25 39.5N, 28 39.6W	0215	25 44.3N, 28 39.7W
56	30/5, 0421	25 34.3N, 28 39.7W	0527	25 35.0N, 28 39.6W	0939	25 38.9N, 28 39.6W
57	30/5, 1115	25 34.9N, 28 45.5W	1222	25 35.7N, 28 45.5W	1650	25 39.8N, 28 45.5W
58	30/5, 1945	25 44.2N, 28 26.0W	2056	25 45.1N, 28 25.9W	0120	25 48.3N, 28 26.0W
59	31/5, 0248	25 48.6N, 28 26.5W	0458	25 53.6N, 28 31.5W	0910	25 57.0N, 28 31.5W

APPENDIX 1: SCIENTIFIC PERSONNEL

Embarked at Las Palmas:

Dr Andrew Watson	(Plymouth Marine Laboratory)	Principal Scientist
Ms Susan Becker	(Woods Hole Oceanographic Institution)	
Mr Terry Donaghue	(Woods Hole Oceanographic Institution)	
Ms Cecelia Fernandez	(Woods Hole Oceanographic Institution)	
Dr Clifford Law	(Plymouth Marine Laboratory)	
Mr Malcolm Liddicoat	(Plymouth Marine Laboratory)	
Mr Kay Lubcke	(Plymouth Marine Laboratory)	
Mr Craig Marquette	(Woods Hole Oceanographic Institution))	
Dr Phillip Nightingale	(University of East Anglia)	
Ms Rachel Oxburgh	(Lamont-Doherty Geological Observatory)	
Mr Martin Beney	(RVS)	
Mr Darrell Phillips	(RVS)	
Mr Simon Watts	(RVS)	
Mr Chris Rymer	(RVS)	
Mr David Dunster	(RVS)	

Transferred at sea from R/V Oceanus:

Dr James Ledwell	(Woods Hole Oceanographic Institution)
Dr Brian Guest	(Woods Hole Oceanographic Institution)
Mr Chris Kinkade	(Woods Hole Oceanographic Institution)

APPENDIX 2: CTD CALIBRATION

Temperature and pressure channels of the RVS Neil Brown MkIII instrument (s/n 01-1195) were both calibrated at RVS against known standards. However, the conductivity (salinity) channel had to be calibrated at sea using samples drawn from Niskin bottles on the sled.

In total 168 samples were taken from 59 casts and then analysed on a Guildline autosal (s/n 52395) which was calibrated against Standard Seawater ampoules from batch P118 (see Table A2.1). The results from the comparison of (autosal-CTD) data showed an average offset of +0.022ppm with a standard deviation of 0.006 (see Table A2.2).

Also to ensure that there was no offset between the salinity measurements taken on Oceanus and Charles Darwin an inter-calibration exercise was carried out. This involved measuring 28 duplicate samples from Oceanus.