DIRECT OBSERVATIONS AND MODELLING OF THE SECONDARY CIRCULATION ASSOCIATED WITH A TIDAL MIXING FRONT

L. Fernand[1], J. Brown[1], J. Read[1], M. Pizzamei[2], K. Horsburgh[2], E. Tinton[1], S. R. Dye[1], E. R. Parker[1] and D. Mills[1]

Introduction

Observations in stratified shelf seas consistently reveal thin layers of phytoplankton associated with the base of the thermocline (e.g. Figure 2). Contemporaneous observations of nutrients (e.g. Total Oxidised Nitrogen (TOXN); Figure 3) suggest that the 'fuel' for this may arise via a number of mechanisms: (1) transfer of nutrients across the base of the thermocline from the deep isolated pool; (2) input by lateral advection from far field sources; (3) injection of bottom waters along the thermocline as a results of transverse cross-frontal density driven circulation; (4) breakdown of decaying plankton and subsequent recycling as nutrient within the water column. An understanding of the processes requires knowledge of the ambient flow fields. While strong along frontal flows associated with bottom fronts are easily resolved (Hill *et al*., 1997; Brown *et al*., 1999), direct observations of the weak cross frontal flow (mechanism 3) are not possible by conventional means.

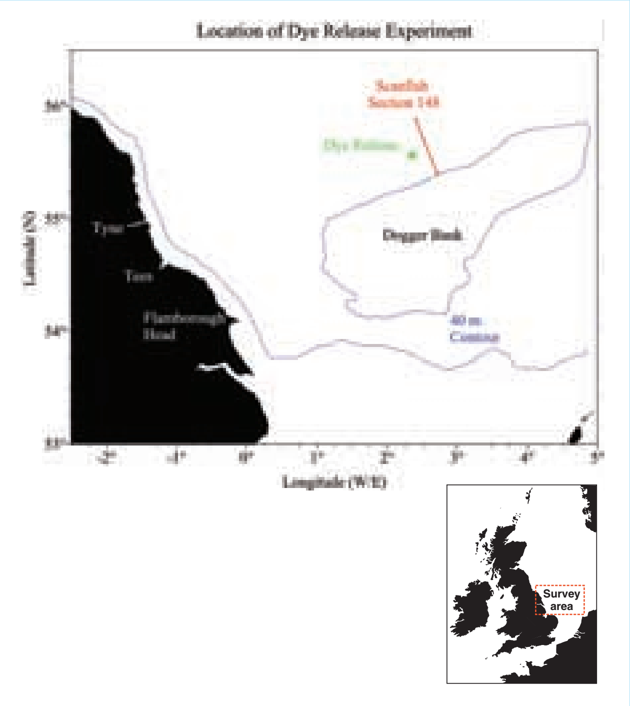


Figure 1: Location of Survey Area

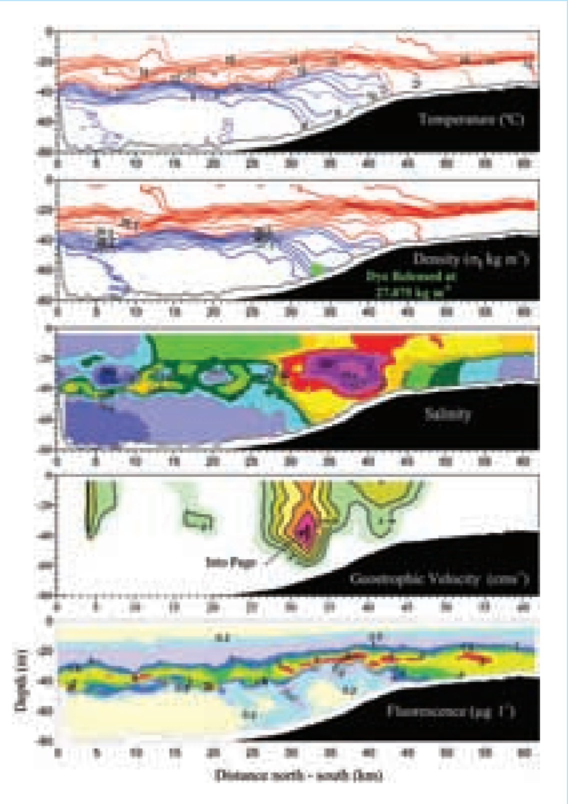


Figure 2: Water column structure along section 148

Here, we describe an experiment to measure such flows by observing the spread of rhodamine dye released near the seabed at the base of a bottom front in the central North Sea (Figure 1). The typical temperature, salinity, density and associated along frontal velocity structure of the region is shown in Figure 2.

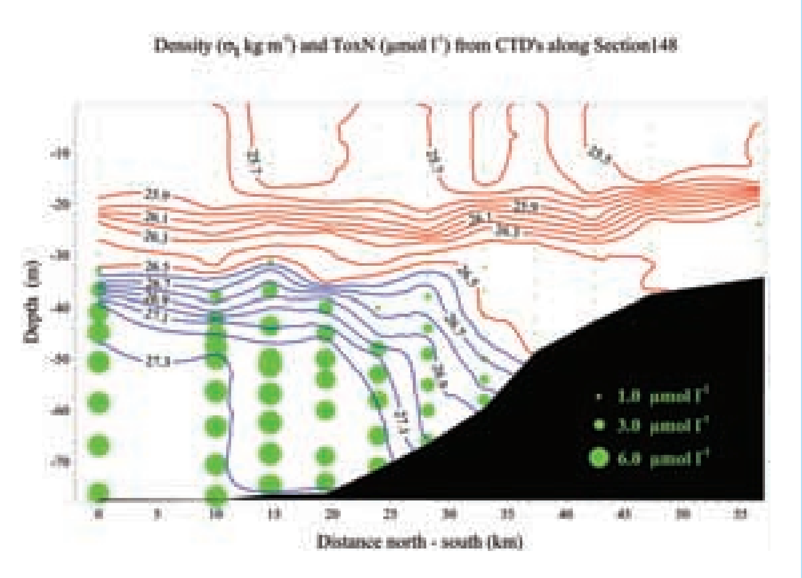


Figure 3: Nutrient structure in relation to section 148

Dynamics

Whilst along-frontal geostrophic jet-like flows are readily observed (e.g. Figure 2), weak cellular velocity fields perpendicular to the front, as predicted by diagnostic models (e.g. Garrett and Loder, 1981), are not. Figure 4 shows the circulation derived from a version of the Princeton Ocean Model (Blumberg and Mellor, 1987), on an idealised rectangular grid (x = 150, y = 180, Z = 35 cells) with invariant bathymetry in the along-front direction.

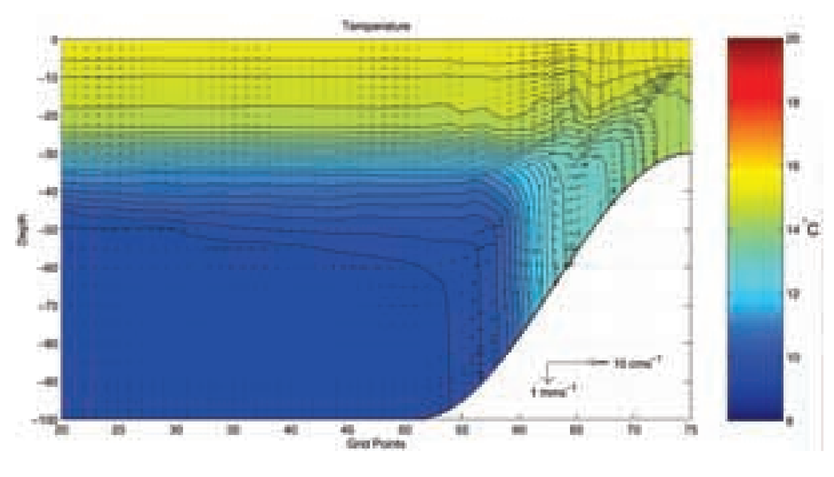


Figure 4: Modelled flow field

The temperature field (shown at day 12) was initialised as a sharp front with three distinct water masses. The model is forced at the western boundary with a single tidal constituent. There is a weak divergence at the foot of the near bed front (< 1 cm s^{-1}).

Results of Dye Tracing Experiment

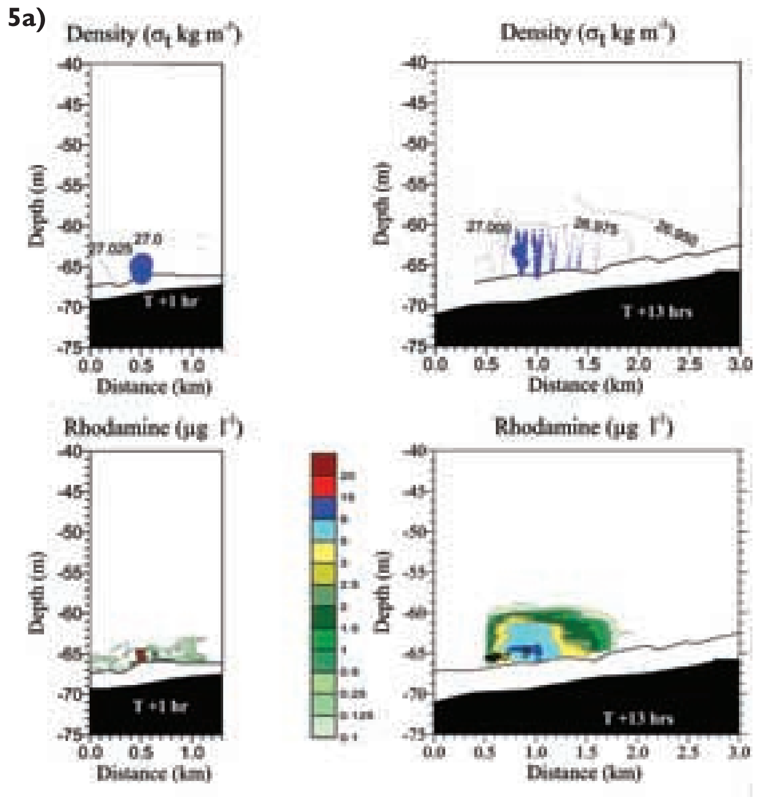
50 kg of rhodamine WT solution mixed with ethanol (33 litres) and water (50 litres) to the appropriate density was released at the seabed over ~30 minutes at a density of 27.075 kg m^{-3}. Tidal advection created a patch of approximate length 300 m. This was tracked for 74 hours using a Haart fluorometer fitted to a Scanfish undulating CTD, until it became difficult to determine concentrations above instrumental noise levels.

A subset of the sections illustrating the evolving rhodamine concentration, corresponding density profiles and Scanfish trajectories are presented in Figure 5. There is evidence of movement of the dye upslope across isopycnals (Figures 5 & 6b). The near bed upslope edge became less dense and changed more than the downslope edge, indicating that there were advective processes present as well as random diffusive ones. The velocity of this near bed transport was 0.25 - 0.5 cm s^{-1} upslope. However, the Centre of Mass (C of M) of the patch remained at a constant density and was advected downslope, away from the bed, along the isopycnal at 0.2 cm s^{-1} (Figure 6a). The maximum excursion of the rhodamine from the release point as a combination of advective and diffusive processes equates to velocities of 0.7 cm s^{-1} in the horizontal and 0.1 mm s^{-1} vertically.

Some parts of the patch appeared to be detached from the bed (e.g. Figure 5d 69 hrs), being advected by the strong along front jet-like flow.

The standard deviation of the dye with respect to the centre of mass (Figure 6c) indicates that the dye expanded along the isopycnal for the first forty hours. Diffusivity during this period was 4.5 m^2 s^{-1} in horizontal and 4x10^{-4} m^2 s^{-1} in the vertical. Where the density gradients strengthened the standard deviation remained constant, indicating inhibition of diffusive processes.

5a)



5b)

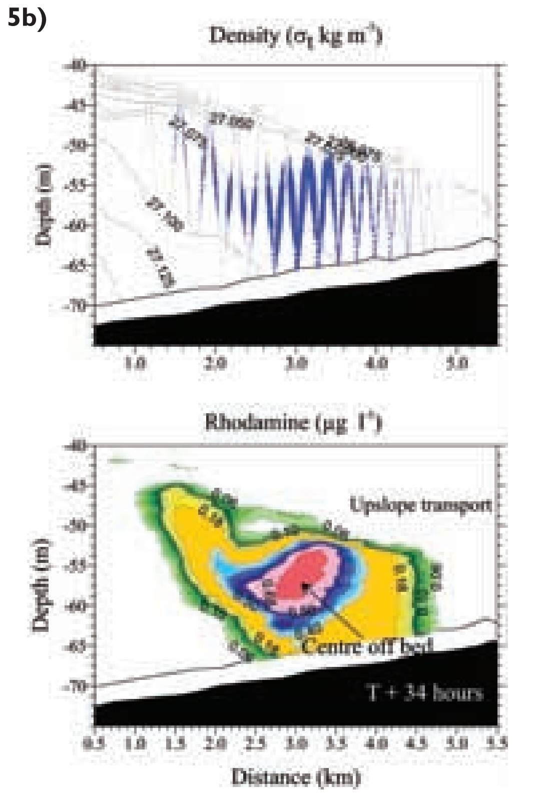
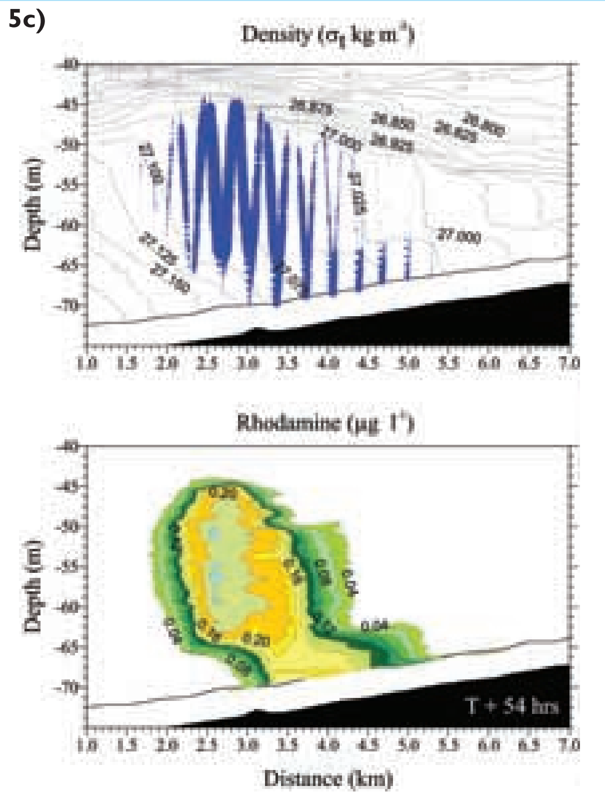
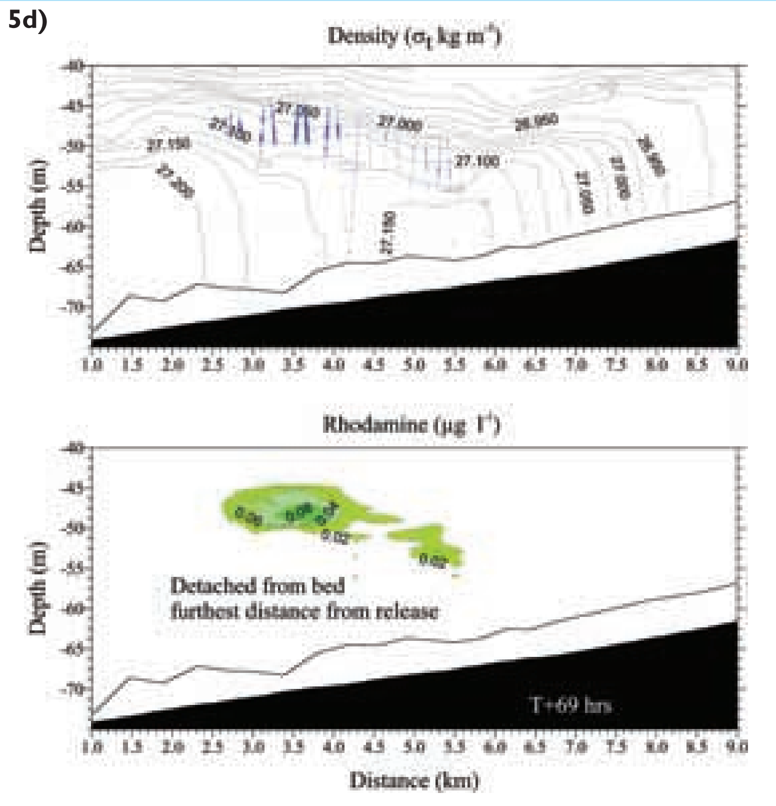


Figure 5a-e: Track of dye release

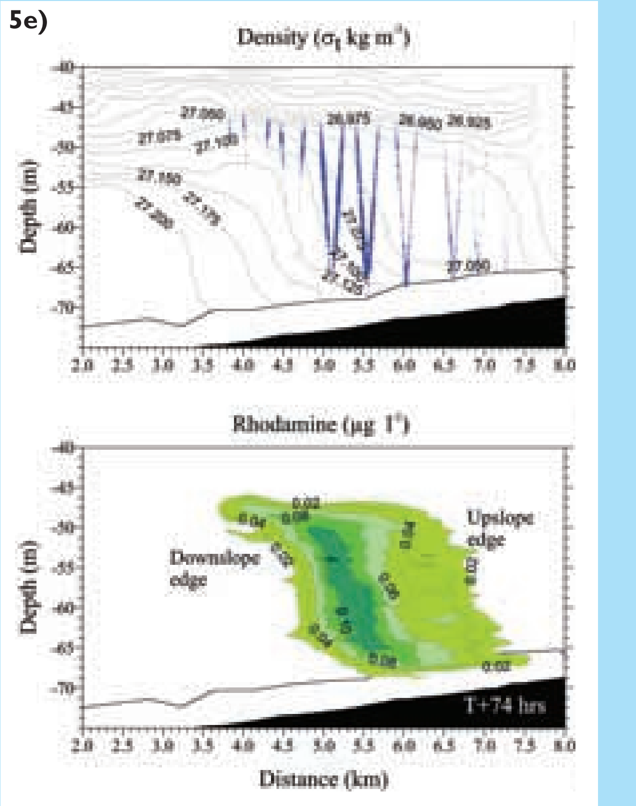
5c)



5d)



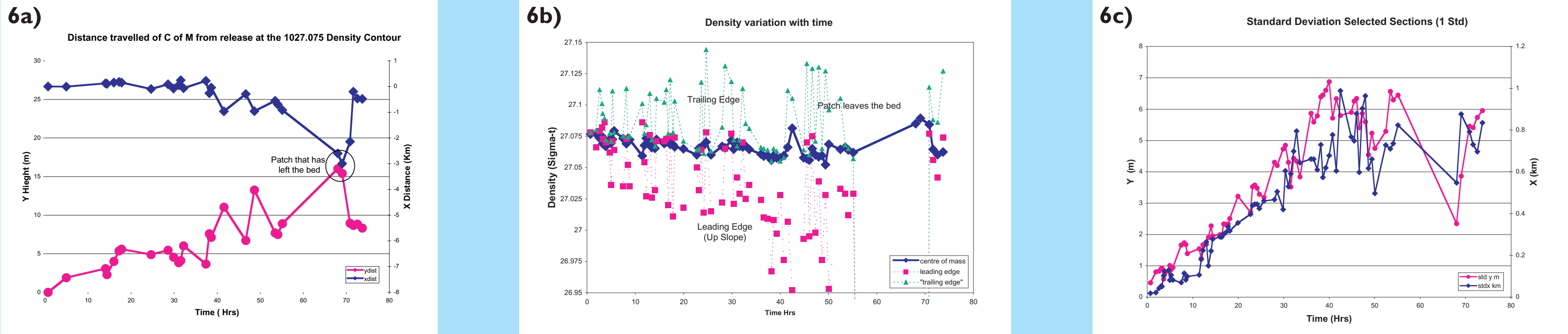
5e)



Dyeframe

Scanfish

Figure 6a-c: Advection or diffusion?



Summary

The experiment has demonstrated directly the secondary circulation associated with a shallow shelf seas tidal front. Advective velocities are weak (order 0.2 cm s^{-1}), with the downslope edge of the dye moving along isopycnals at ~ 0.7 cm s^{-1} through advective and diffusive processes. The dynamic nature of the tidal front makes direct comparison with models difficult, but there is a qualitative agreement with diagnostic models.

Estimated horizontal diffusivity was of order 4.5 m^2 s^{-1}, comparable with other studies (Sundermeyer and Ledwell 2001). In the local vicinity of the front the secondary circulation has the potential to supply nutrients from deep water to the level of the photic zone. However, in the stratified region away from the front, the work of Sharples *et al*. (2001) suggests that it is vertical diffusive processes that supply the nutrient flux to sustain phytoplankton growth close to the base of the thermocline.

References

Blumberg, A.F. and Mellor, G.L., 1987. A description of a three dimensional coastal ocean circulation model. In N. S > Heaps, *Three dimensional coastal ocean models. Coastal and Estuarine sciences,* **4** Washington: American Geophysical Union (208pp).

Brown, J., Hill, A.E., Fernand, L. and Horsburgh, K.J., 1999. Observations of a seasonal jet-like circulation at the central North Sea cold pool margin. *Estuarine Coastal and Shelf Sciences*, **44**, 343-355.

Garret, C.J.R. and Loder, J.W., 1981. Dynamical aspects of shallow sea fronts. *Philosophical Transactions of the Royal Society of London*, **A 302**, 563-581.

Hill, A.E., Brown, J. and Fernand, L., 1997. The summer gyre in the western Irish Sea: shelf sea paradigms and management implications. *Estuarine Coastal and Shelf Sciences*, **44** (Supplement A), 83 - 95.

Sharples, J., Moore, C.M., Rippeth, T.P., Holligan, P.M., Hydes, D.J., Fisher, N.R., Simpson, J.H., 2001. Phytoplankton distribution and survival in the thermoclines. *Limnology and Oceanography*, **46**, 486-496

Sundermeyer, M.A. and Ledwell, J.R., 2001. Lateral dispersion over the continental shelf: Analysis of dye release experiments. *Journal of Geophysical Research*, **106**, 9603-9621

[1] The Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK http://www.cefas.co.uk
[2] School of Ocean Science, University Wales, Bangor, Menai Bridge, Anglesey LL59 5EY