SUBSURFACE FLOWS IN THE SEASONALLY STRATIFIED CENTRAL NORTH SEA: ANALYSIS OF DRIFTER TRACKS THROUGH OBSERVATIONS AND MODELLING

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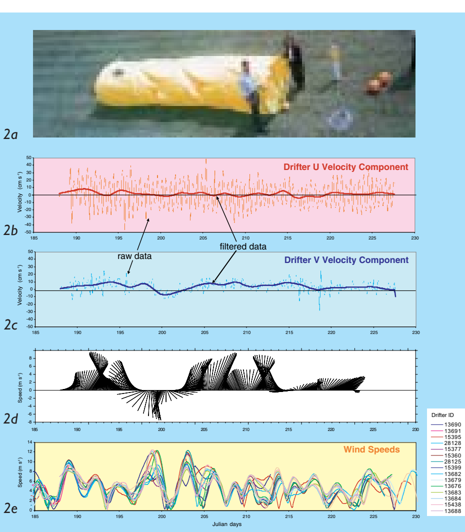

Figure 2: *Drifter and wind data*

Drifter Data

16 ARGOS satellite tracked drifters were deployed in the Oyster Grounds during summer 2002 (Figure 1). Holey sock drogues of length 5.5m and diameter 1.5m were centred at depth 25m whilst attached to surface buoys (Figure 2a). They were tracked at a spatial resolution of up to 1.1km every 1.5 hours on average though a few intervals extended to 46 hours due to satellite factors or rough seas. Drifter positions were interpolated to give 3 hourly drifter locations; their associated u and v velocity components calculated; and then filtered (Horsburgh, 2000). Figures 2b and 2c show typical velocity profiles for drifter 13688.

Wind Correlation

Method

U and v components of wind were extracted from the UK Meteorological Office Unified Model output at the 3 hourly drifter locations and filtered as for the drifters (Figure 2d, example). The drifters were correlated to the wind using a method (Gmitrowicz and Brown, 1993) that implements a conceptual model of wind driving a coastal flow. By rotating the wind at 5 degree intervals to the drifter velocities and lagging the drifters from 0 to 6 hours, the peak correlation was deduced. The significance of this value was determined from auto-correlation of the drifters' motion in each component.

Temporal division of the paths was carried out to capture dominant flow regimes that are significantly shorter than the drifter track. Figure 2e shows that every 10 days, 3-5 wind events passed over each drifter (i.e., 3-5 peaks and troughs in wind speed). This level of variation was considered a minimum threshold for wind correlation. Since the shortest period is preferable in order to capture short duration flow regimes, 10 days were chosen for temporal segmentation of trajectories. Winds over the study area are generally similar except for passing depressions. By starting each 10 day segment at Julian days 185, 190, 195, 200, etc to day 230, temporal comparisons could clearly be made. Each segment overlaps the previous by 5 days (i.e., sliding 10 day segments) to ensure coverage of events that would otherwise straddle two individual segments.

Results

Several of the drifters in this study were significantly correlated to the wind in only one of the u or v components. When a drifter moves in one dominant direction, small fluctuations normal to this axis can often show poor correlation with the wind but these represent a minor proportion of the trajectory. Drifters significantly correlated in only one of the u or v components have therefore been classed as significant overall.

13 of the 16 whole tracks were found to correlate with the wind, with the 6 hour lag dominant. Subset in Figure 4 are 1) zero correlation tracks and 2) wind driven tracks shown by percentage of variance caused by wind (i.e., by the coefficient of determination, R2). Non-wind driven flows are prominent along the Dogger Bank and Dutch coast whilst those in the deeper Oyster Grounds have a stronger wind driven component. The 10 day results of wind correlation (main part of Figure 4) have been translated into langrangian flows in Figure 10.

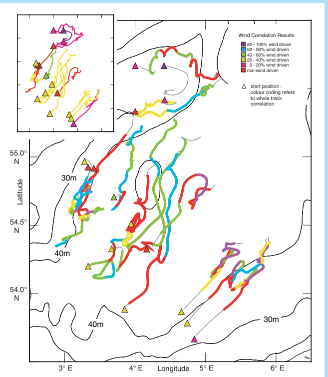

Figure 4: *Wind correlation for whole tracks (subset) and 10 day tracks (main)*

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INTRODUCTION

From May to November thermal stratification dominates large areas of the central North Sea. Trapped beneath the thermocline, cold pools of isolated water remain throughout the summer in relatively deep (50-150 m) basins where tidal amplitudes are weak. With surface to bottom temperature differences of ~7 °C (Harding and Nichols (1987); Brown *et al.*, (1999)), the cold pools are known to drive persistent and narrow (10-15 km) baroclinic jets at speeds of > 10 cm s^{-1}. These circulate in a cyclonic sense with the cold water to the left (Brown *et al.*, 1999).

Whilst flows influenced by the cold pool north of the Dogger Bank have been quantified (Brown *et al.*, 1999), those associated with the Oyster Grounds basin to the south have not. This work aims to establish spatial and temporal importance in the Oyster Grounds of each of the different forcing mechanisms: tidal, baroclinic and wind driven (local and far field wind events). The dominant flow regimes are determined from a combination of drifter and CTD observations; a modified wind correlation technique; and use of a fully advective 3D model. The observations were collected during June-July and August 2002 surveys.

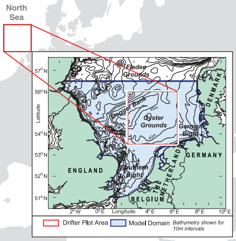

Figure 1: *Location map*

Observed and Modelled Trajectories

The observed drifter trajectories (thick lines, Figure 3) indicate a cyclonic path around the Oyster Grounds. Most simulated tracks (thin lines) show a reasonable agreement and runs at all depths show similar behaviour with the model under-predicting observed flow speeds. This is likely to result from the undr-prediction of horizontal density gradients, as illustrated in Figure 5. The shallower sensitivity runs show faster flow speeds in wind-dominated areas, as would be expected, but these runs still under predict velocities when compared to the observations. Dispersion of the 10 simulated particles (per drifter) was less than 8 km though marked diversion is seen in the centre of the basin (drifters 13679 and 21228, up to 25 km).

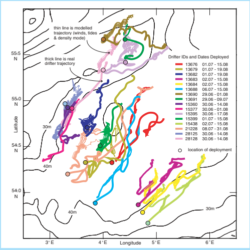

Figure 3: *Observed and simulated drifter trajectories*

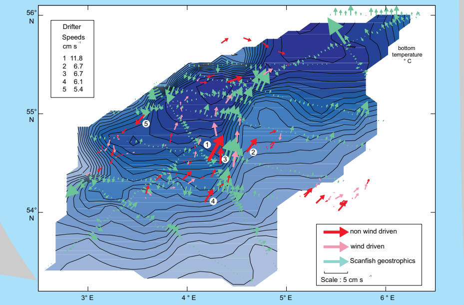

Figure 10: *Lagrangian drifter derived flows with calculated geostrophic velocities and bottom temperature from Scanfish sections*

Real Drifter Lagrangian Flows

The average velocity vectors of each drifter segment are plotted in figure 10 at their mean locations. Wind driven flows are defined here when R^2 (for either u or v, highest taken) >50% (pink arrows) and non-wind driven flows when R^2 <50% (red arrows). The underlain Scanfish (towed undulating CTD - Brown *et al.*, 1996; Fernand, 1999) derived geostrophic velocities agree well with non-wind driven flows. This is evident north and south of the cold pool with fast drifter speeds of up to 5.4 cm s^{-1} (no.5 in Figure 10) and <11.8 cm s^{-1} (no.1). In contrast, wind driven drifter flows oppose the geostrophic velocities, e.g., drifter 13682 crossing the cold pool northwards and drifter 13676 as it heads southwards away from the cold pool (cross-comparison with Figure 3). These results support success in the wind correlation method.

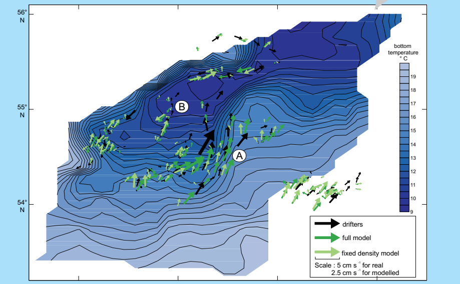

Figure 11: *Lagrangian model and drifter derived flows with bottom temperature*

Simulated Drifter Lagrangian Flows

The predicted particle tracks are plotted in Figure 11 as outlined above. Along the southern edge of the cold pool (A) there are large differences in magnitude and direction between the full (dark green arrows) and fixed density (light green arrows) modes. This area also shows the greatest underprediction of model speeds, likely to result from underrepresentation of density forcing in the current model design. Both these factors reinforce that region A has strong baroclinic forcing. This supports the technique used and the results deducing that real drifters here are strongly non-wind driven (Figure 10).

In contrast in the centre of the cold pool region (B) there is little difference in magnitude or direction when density effects are removed from the simulations, indicating that flows are predominantly wind driven. This is also confirmed by the wind driven characteristics obtained for real drifters.

3D Modelling

A three-dimensional model based on the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) has been developed at CEFAS for the central and southern North Sea regions. POM is a primitive equation, σ co-ordinate, free surface model that has been used successfully to simulate tidal and density driven circulations for a wide range of applications (e.g. Galperin and Mellor, 1990). It includes the essential physics required to model the seasonal evolution of baroclinic flows in the European shelf seas.

The model domain is shown in Figure 1. The grid has 270 columns and 165 rows with cell dimensions of 1/20° of longitude and 1/30° of latitude. Fifteen sigma levels are arranged vertically with irregular spacing to provide enhanced resolution of the high-shear surface and near-bed layers. Currently the model has fully implemented temperature but runs with spatially and temporally constant salinity. Meteorological forcing is generated from the UK Meterological Office Unified Model output on 0.11° resolution.

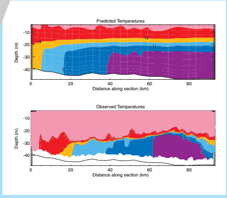

Figure 5: *Observed (top) and predicted (bottom) temperatures across the Oyster Grounds cold pool*

Model Validation

Cross-sections of predicted and observed (Scanfish derived) temperatures through the Oyster Grounds cold pool are shown in Figure 5. Whilst surface and bottom temperatures are generally well predicted, the rapid vertical changes in temperature at the thermocline are not. This is due to the model's restricted vertical resolution, particularly mid water column. Horizontal temperature gradients are also under predicted as a result of the model's horizontal resolution of ~ 3.5km.

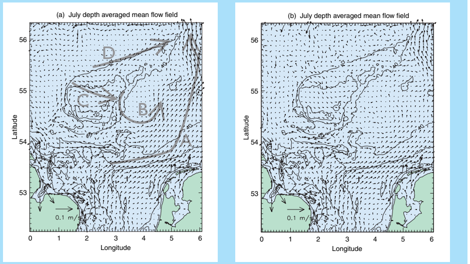

Figure 6: *Modelled depth averaged flow fields for July 2002 in full (a) and fixed density (b) modes (flow vector arrows plotted every ~ 10km; model resolution is ~ 3.5km).*

Simulated Flow Fields

Some broad features of the modelled summer circulation of the central North Sea are highlighted in Figure 6a. These are outlined below with the changes visible after removal of density effects (italics) as seen in Figure 6b.

A. Strong north-eastward to northward flow in the eastern side of the region - *Weakens along eastern side of Oyster Grounds.*
B. Cyclonic flow around a quiescent region between the Oyster Grounds and Dogger Bank - *No longer evident.*
C. Eastward flow on the south-west end of the Dogger Bank and diversion at the Oyster Grounds - *Now more southward.*
D. A narrow jet flowing northeastwards along the northern edge of the Dogger Bank - *No longer evident.*

Particle Tracking Model

An offline, particle tracking model was used to calculate drifter trajectories. Each drifter was simulated with 10 particles, arranged around the deployment position (Figure 7). Particles were advected by horizontal flow fields from a depth of 25m, as extracted from the 3D model. Additional runs were carried out using flow fields from depths of 21m, 23m and 27m to examine depth sensitivity. Simulations were made for the original drifter deployments and for the 10 day start positions, both in the full POM mode (winds, tides and density) and fixed density mode. Simulations using the full POM mode are shown in Figure 3 (whole trajectories) and Figure 8 (10 day).

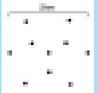

Figure 7: *Starting positions for 10 particles per drifter*

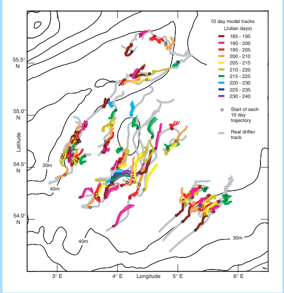

Figure 8: *Simulated 10 day particle tracks*

Simulation of Drifter 13688

An example track series for drifter 13688 is shown in Figure 9 for the real and modelled tracks. The grey arrows represent the density flow as deduced from the difference between the two simulations (full run and fixed density run). They indicate a baroclinic flow towards the northeast along the southern edge of the cold pool. These data are translated into Figure 11 for all 10 day track simulations.

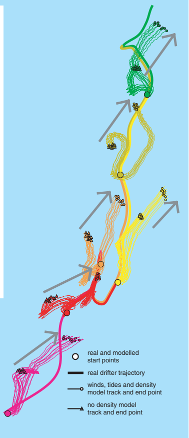

Figure 9: *Observed and simulated trajectories for drifter 13688*

Conclusions

The drifter analysis has successfully demonstrated that baroclinic flows are forced southwest along the southern Dogger Bank and northeast on the southern side of the Oyster Grounds cold pool. These results confirm and account for previous observations within the basin (e.g., van Aken *et al.*, 1987). Crucial to our method is the use of a 10 day period which allows spatial and temporal variations of wind induced, tidal residual and baroclinic flows to be separated. Robustness of the wind correlation method is confirmed by comparison with geostrophic velocities and simulated trajectories. The model has replicated individual tracks well and allows suitable scenario testing for examination of the forcing mechanisms. These models are vital to the continued understanding of the varied driving forces associated with complex shelf sea systems.

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