National Oceanography Centre

Internal Document No. 08

POLCOMS sensitivity analysis to river temperature proxies, surface salinity flux and river salinity in the Irish Sea

D L Norman, J M Brown,
L O Amoudry & A J Souza

2014

National Oceanography Centre, Liverpool
6 Brownlow Street
Liverpool
L3 5DA
UK

Author contact details
Email: danon@noc.ac.uk
Jebro@noc.ac.uk

DOCUMENT DATA SHEET

AUTHOR	*PUBLICATION*
NORMAN, D L, BROWN, J M, AMOUDRY, L O & SOUZA, A J	*DATE* 2014

TITLE

POLCOMS sensitivity analysis to river temperature proxies, surface salinity flux and river salinity in the Irish Sea.

REFERENCE

Southampton, UK: National Oceanography Centre, Southampton, 22pp.
(National Oceanography Centre Internal Document, No. 08)
(Unpublished manuscript)

ABSTRACT

This report contains an investigation into the best setup for the 1.8km POLCOMS model of the Irish Sea. It begins with an introduction into the existing POLCOMS model and what I hope to achieve. I will be adding both atmospheric temperature as a proxy for river temperature into the model, and precipitation data together with surface salinity flux calculations, validating the output and performing model-model comparisons to evaluate under which configuration the model is optimum. I will also investigate the effect of river source salinity on the model simulation by running the model four times, each with a different initial saline concentration, namely, 0, 15, 20 and 25psu. Again I will validate the model and measure the effect on performance. Finally, I will take the best of these model setups and re-run without waves checking the run time is reduced and validating again. This final run will be used to provide boundary conditions for a study of the tidal mixing front in Liverpool Bay using a high resolution (180m) model.

KEYWORDS

ISSUING ORGANISATION

National Oceanography Centre
University of Southampton Waterfront Campus
European Way
Southampton SO14 3ZH
UK

Not generally distributed - please refer to author

Page intentionally left blank

1. INTRODUCTION

I will be applying the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) model, with 1.8km horizontal resolution and 34 sigma levels in the vertical, to the Irish Sea (Fig.1) and comparing annual model simulations. (For full details of POLCOMS, refer to Holt and James, 2001.) The aim is to identify the best model setup for the Irish Sea to provide boundary forcing for the higher resolution Liverpool Bay model. I will therefore be validating the model simulations against data recorded in Liverpool Bay. Liverpool Bay is a shallow, hypertidal region (where spring tides have a range in excess of 6m, see Archer, 2013) of freshwater influence (Polton et al, 2013). That is, the dynamics of the region are strongly influenced by estuarine outflow and thus stratification is dominated by salinity, though river temperature does have a seasonal effect (Polton et al, 2011). Souza (2013) clearly shows the occurring fronts in the region: the Irish Sea front west of the Isle of Man, the Celtic Sea front and a thermal front in Liverpool Bay.

The study focuses on the year 2008, using December 2007 as the spin-up month. The temperature and salinity conditions are warm-started off the pre-operational NOC Liverpool Bay Coastal Observatory (COBS) model. COBS was a 10-year campaign of observations which provides data with which POLCOMS can be validated against (Howarth and Palmer, 2011). It has been shown that POLCOMS performs well in predicting surface temperature and salinity, though more accurately temperature (O'Neill et al, 2012).

Six different executables were compiled and their run times for January 2008 noted for model-model running time comparisons (Table 1). The configuration elements in bold highlight the test parameter for each model run. The last row in the table refers to a simulation that used the mobius_PWG_salfx executable, but with waves turned off through the "nowam" coupling run option.

Table 1: Model configuration, identification name and run time when applied on 128 processors for each simulation. The three investigations are colour coded as follows, red: the effect of river temperature; blue: the effect of surface salinity flux; green: the effect of river source salinity.

Run name	Executable name	Configuration	Run time for Jan 08 (hrs)
CONTROL	mobius_PWG_control	▪ **river temperature on** ▪ **surface salinity flux off** ▪ 20psu salinity	2.8118
NORIVTMP	mobius_PWG_norivtmp	▪ **river temperature off** ▪ surface salinity flux off ▪ 20psu salinity	2.8088
SALFX	mobius_PWG_salfx	▪ river temperature on ▪ **surface salinity flux on** ▪ **20psu salinity**	2.6586
0SAL	mobius_PWG_0SAL	▪ river temperature on ▪ surface salinity flux on ▪ **0psu salinity**	2.8011
15SAL	mobius_PWG_15SAL	▪ river temperature on ▪ surface salinity flux on ▪ **15psu salinity**	2.8354
25SAL	mobius_PWG_25SAL	▪ river temperature on ▪ surface salinity flux on ▪ **25psu salinity**	**2.6333**
NOWAM	mobius_PWG_salfx	▪ As for SALFX ▪ WAM turned off	0.6554

In creating the executables, in order to switch on/off river temperatures and the surface salinity flux, I used the following compile options:

- NORIVTMP – do not read in river temperatures;
- SALFLUX – include salinity flux calculations (evaporation minus precipitation); and
- SALTFLUX – read in surface precipitation data.

To identify the 73 river locations I used read_POLCOMS_bath_rivtmp_DN.m to mark land points as close to the river mouths as possible (Fig. 1). The atmospheric temperature at these points was then extracted using river_tmp_DN.m to be used as a proxy for the river temperature. In the absence of recorded river temperatures, we use the atmospheric temperature as a proxy as the land responds to the atmospheric temperature and river flows over the land catchment. It can therefore be assumed that they will be similar. The temperature of the Mersey Estuary, in particular, has been shown to closely match the air temperature as the network of shallow streams that feed into it are efficiently heated and cooled by the atmosphere (Polton et al, 2011). Both matlab files are found at /projectsa/iCoast/Mersey_CEFAS/IRS2008/IRS_tests/Riv_tmp/scripts.

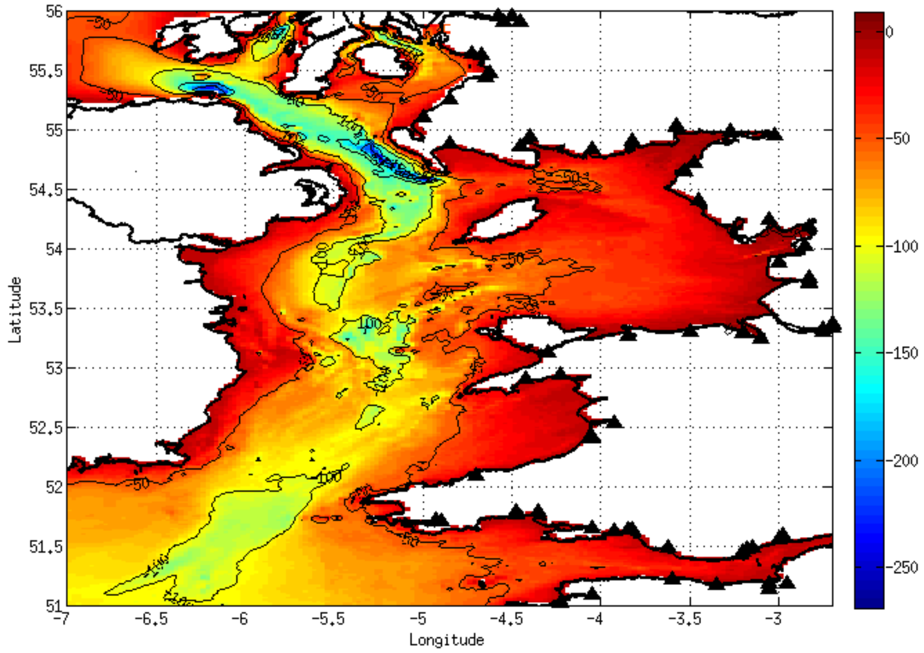

FIGURE 1: Bathymetry map of the Irish Sea domain displaying triangular markers for each river source location.

Each model run was validated using matlab scripts SAL_MAPS_DN.m, TMP_MAPS_DN.m and WAVE_MAPS_DN.m. These scripts read in the model data and plot maps displaying surface or bottom salinity, temperature and wave properties respectively. They also extract a month-long time series at Sites A and B, fixed moorings in Liverpool Bay (Fig. 2) used for validation, and plot a vertical time-varying profile for each site. Sites A and B are detailed in Howarth and Palmer (2011), but, briefly, they were established as part of COBS, with Site A being located close to where the outflow from the river Mersey enters Liverpool Bay and Site B being installed to enable calculation of horizontal gradients between the two locations.

FIGURE 2: Location of Site A and Site B in Liverpool Bay (http://cobs.noc.ac.uk/cobs/fixed/).

I am analysing each model run at Site A and Site B using validation_siteA.m and validation_siteB.m respectively. These read in both the simulated model data and observed data into arrays, compute error metrics such as root mean squared error and bias of the mean, and extract and plot annual time series for temperature, salinity, density and density difference. More details are given in Section 2.

2. METHODS

Following completion of each simulation, on 128 processors, surface and bottom temperature and salinity maps, and a month-long vertical profile at both Site A and Site B, were produced for January and July (Figs. 3-4). This enables a visible comparison to check that a change in output has occurred consistent with the configuration of the executable file, i.e. with river temperature switched off compared with it being switched on.

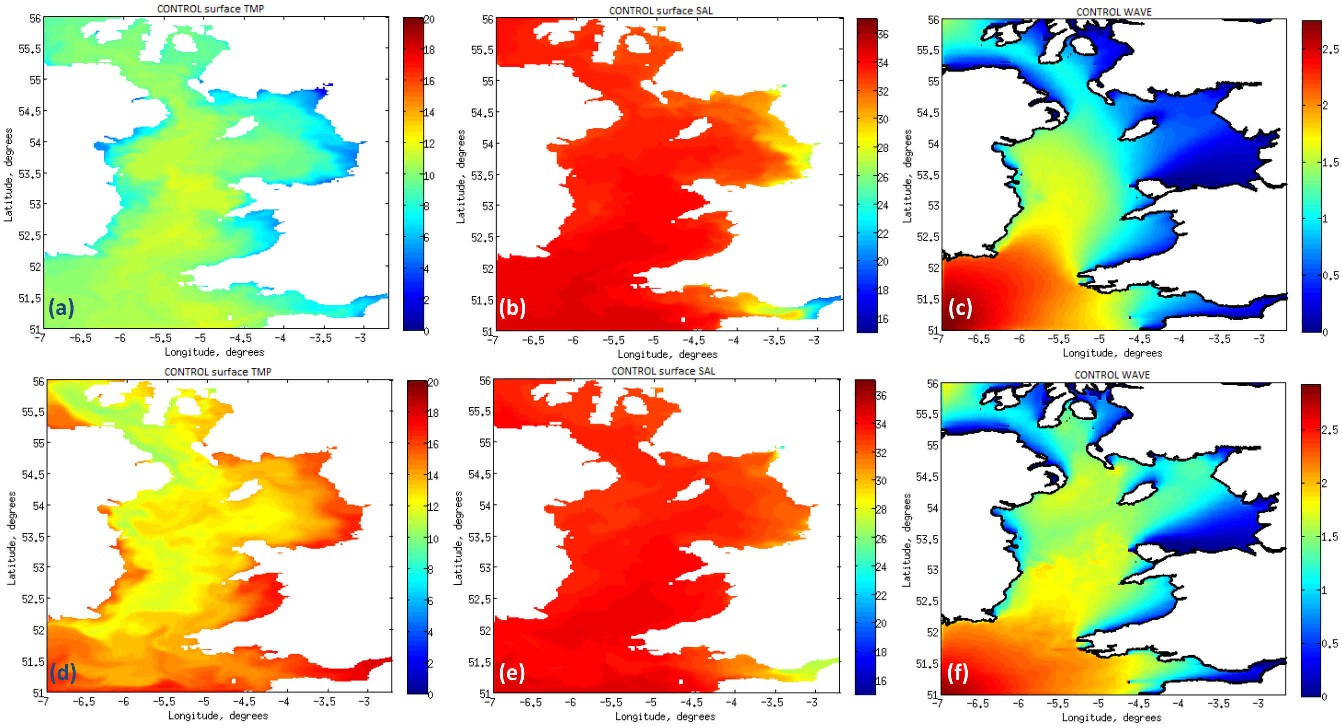

FIGURE 3: Temperature, salinity and wave maps of the Irish Sea: CONTROL simulation, 4th day of month. January 2008: (a) Temperature; (b) Salinity; (c) Wave height; and July 2008: (d) Temperature; (e) Salinity; (f) Wave height.

Fig. 3 shows the land-ocean interaction influencing coastal water temperature; the near-land sea surface is cooler than the internal ocean sea surface due to the different heat capacities of land and sea. The sea surface is also cooler overall in January (a) than in July (d). Fig. 3(b) and (e) show an overall increase in salinity around the northwest English/north Welsh coast and also particularly in the Bristol Channel from January to July, due to a higher river discharge in January (Table 2) creating a fresher sea surface. This is consistent with the surface temperature increase shown in Fig. 4(a) and (c), and the decrease in surface salinity shown in Fig. 4(b) and (d), at both sites A and B situated in Liverpool Bay. Fig. 4 is used to identify times of stratification (large difference between surface and bottom values) and mixing (small or no difference) at the selected time. Fig. 3(c) and (e) both show low wave activity in the Irish Sea and greater activity towards the Celtic Sea, due to shallow water effects. The maximum wave height observed over these periods was 5.8m (Table 2). Previous studies (Brown et al, 2011) have shown that waves can reach up to 5.6m in the Irish Sea during storms.

TABLE 2: Minimum and maximum variable values for the CONTROL simulation In January and July 2008.

		Jan	July
TMP	min	0.967	9.12
	max	12.527	20.877
River discharge	Dee: min	40.46	10.2221
	Dee: max	279.65	33.32
	Mersey: min	16.677	7.8183
	Mersey: max	400.86	52.02
Wave height: max		5.8151	3.186

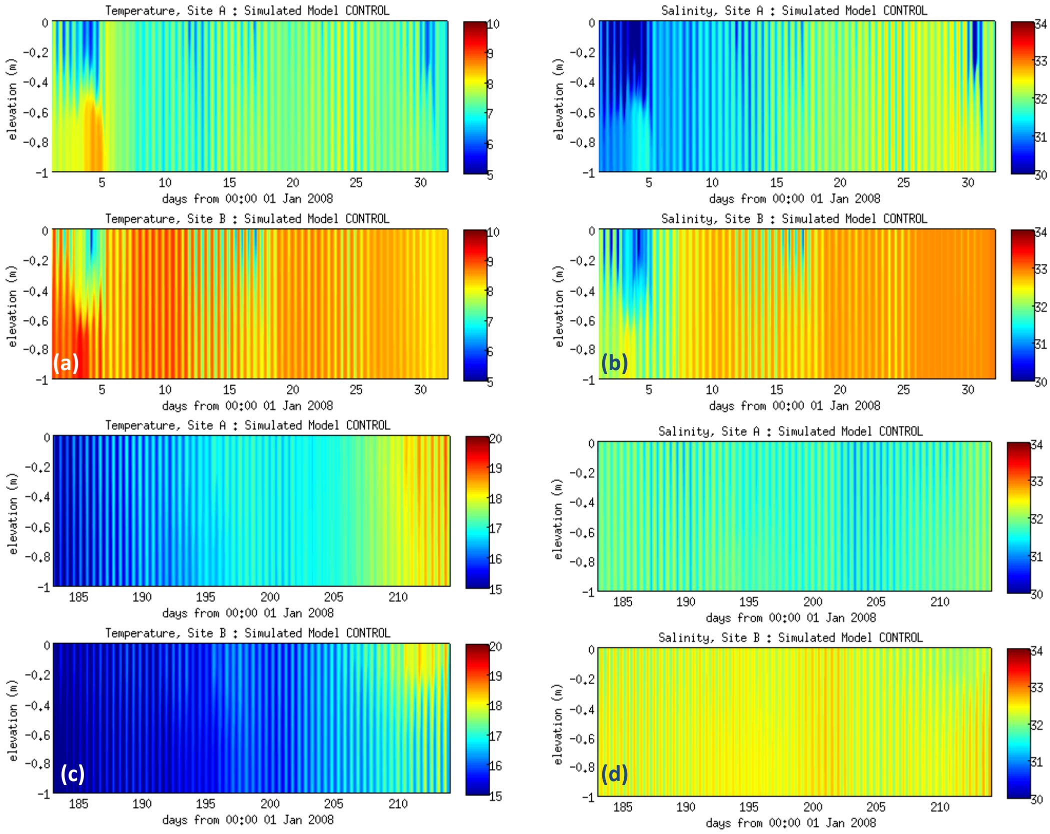

FIGURE 4: Vertical temperature and salinity profiles for Sites A and B: CONTROL simulation.
January: (a) temperature; (b) salinity; and July: (c) temperature; (d) salinity.
NB Scale for the two temperature plots are the same size range only with 10°C difference owing to the seasons.

In January, the water at Site A was colder and less saline than that at Site B as Site A is closer to river influence from the Mersey. Stratification at both sites occurs around days 3 to 5 and 15 to 17, where the water near the surface is cooler due to the fresh river water inflow, but less saline and salinity is having a stronger influence on the density structure. We see further stratification at Site A around days 28 to 31. In July, temperatures have increased from 5-10°C (in January) to 15-20°C, increasing throughout the month. Now, Site A is warmer than Site B due to the heating effect of the land and still less saline, due to its closer proximity to the freshwater influence of the rivers. In the salinity profile for Site A, there is slight stratification towards the end of the month at days 207 to 211, whereas at Site B there is slight stratification around day 195 and clear stratification after day 210. The stripes in the figures are due to the tide interacting with the horizontal density gradient, more specifically SIPS (strain-induced periodic stratification), and the resulting time-varying mixing at the front (Simpson et al, 1990).

The validation scripts then read in the observed velocity, salinity, temperature and density measurements taken at 5m below the surface, 10m below the surface and 0.5m above the bottom. Density is a function of both temperature and salinity and the model density is calculated using the Fofonoff and Millard (1983) equation then, along with salinity and temperature, extracted from the model data at the three elevations using scalar_at_Zelev.m. Five plots are produced for each site (Figs. 5 and 6) displaying the time series extracted from the model against the observed time series for salinity, temperature and density at the three elevations. There are also two plots showing the calculated difference in density between 5m below the surface and 0.5m above the bottom for both the model and observed data.

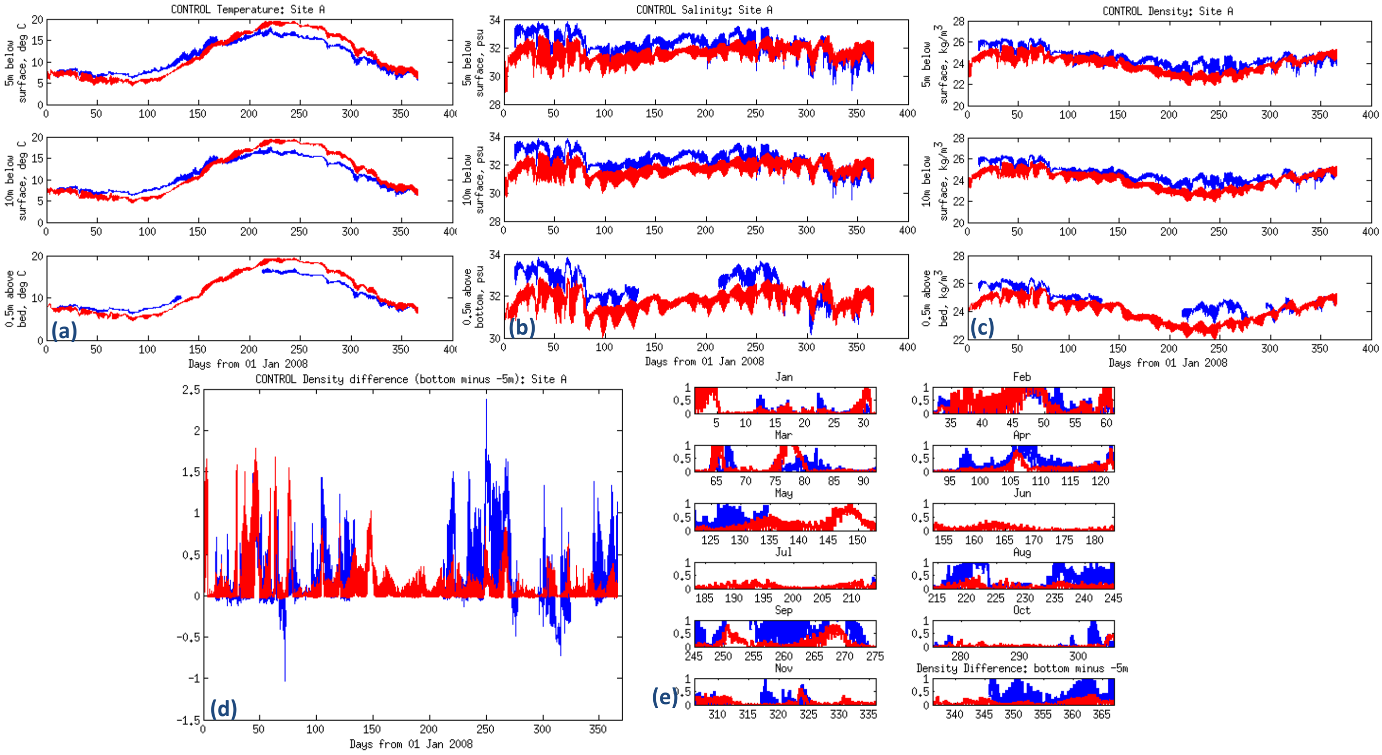

FIGURE 5: Site A annual model (red) and observed (blue) time series for 2008: CONTROL simulation.
(a) Temperature at -5m, -10m and 0.5m; (b) Salinity; (c) Density; (d) Annual density difference between 0.5m and -5m; (e) Monthly density difference

In general, the model is under-predicting salinity and density with over-prediction in the last two months (Figs. 5 and 6, (b) and (c)). The model begins by under-predicting temperature too, but over-predicts for the second half of the year (Figs. 5 and 6, (a)). Overall, the seasonal model trends do coincide with the observations and the difference between the two is small (see Bias in Table 3). However, temperature does show greater seasonal variability than salinity. The low seasonal variation in density is therefore consistent with salinity being dominant, but there is a need to identify the processes controlling stratification here. Salinity itself is more variable in winter than in the warmer months, due to more variable precipitation events. Over the summer, there is a slight increasing trend as a result of less precipitation, more evaporation and reduced river discharge. At these particular locations, there is not much variation with depth.

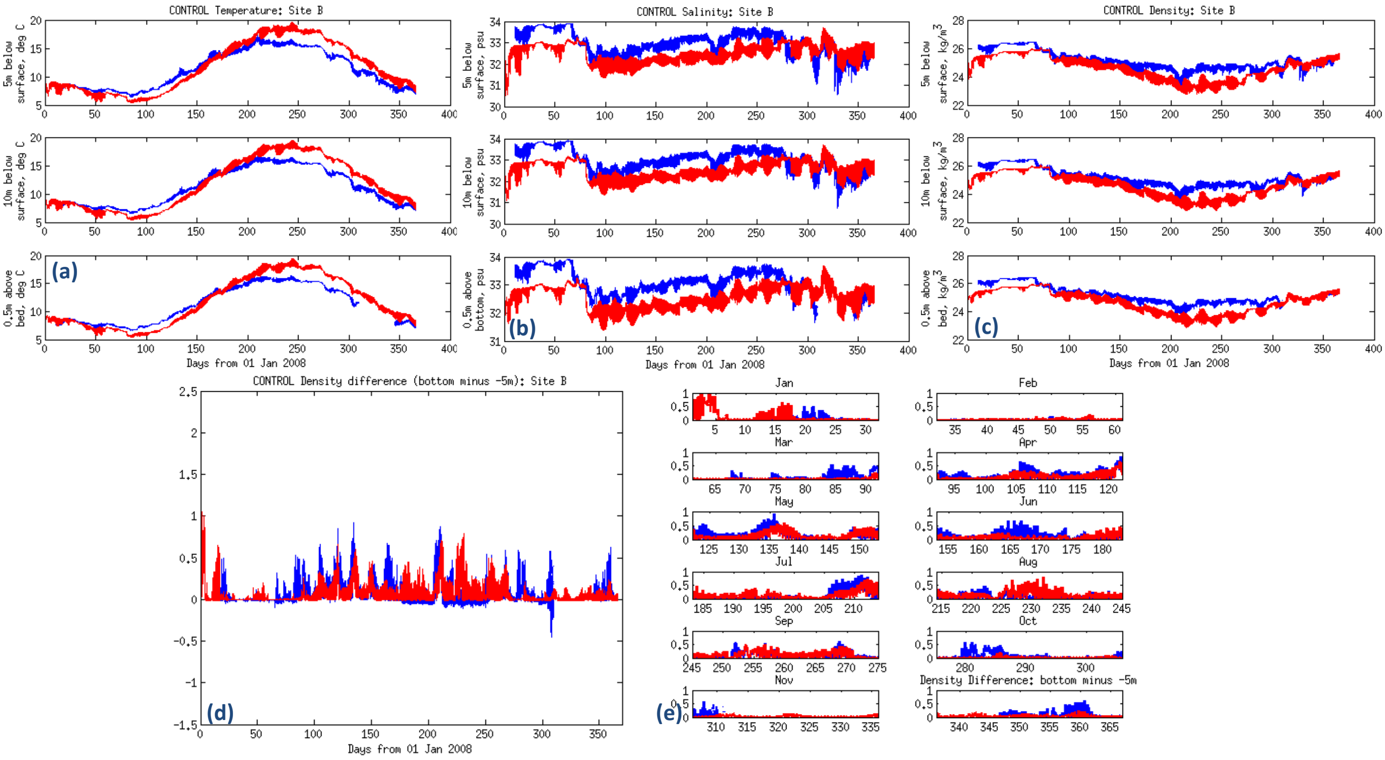

FIGURE 6: Site B annual model (red) and observed (blue) time series for 2008: CONTROL simulation.
(As per Figure 5.)

In Figs. 5(d) and 6(d) the model density difference does not drop below zero so the density at 5m below the surface is always less than that at 0.5m above the bottom, as we might expect. However, negative differences are observed in the recorded data. This is probably due to errors in the (near-bed) observations occurring when the water is well mixed. In this instance, it does not matter too much, but when progressing onto the Liverpool Bay model, I will set these negative differences to zero. The magnitude of the density differences is smaller at Site B (-0.5 to 1psu) than at Site A (-1 to 2.5psu) due to Site B being positioned further offshore so the surface water is less affected by incoming river flow.

The bias of the mean, RMSE and model skill following Willmott (1981) for model hindcasts were calculated (Table 3) using get_bias_array.m, get_rmse_array.m and Model_Skill_array.m respectively. These enable numerical analysis of the model runs to contribute to the visual analysis using the plots.

The Bias is defined as

$$Bias = \bar{M} - \bar{O}$$

where M represents the model values, O the observed values and $\bar{X} = \frac{1}{n}\sum_{k=1}^{n} X_k$. A value of 0 corresponds to an unbiased estimator; a positive value implies positive bias, that is, the model is over-predicting and a negative value implies negative bias or under-predicting.

The RMSE is defined as

$$RMSE = \sqrt{\overline{(M - O)^2}}$$

where a smaller value indicates better model performance, and the model skill is defined as:

$$D = 1 - \frac{\overline{(M - O)^2}}{\overline{(|M - \bar{M}| + |O - \bar{O}|)^2}}$$

D takes values between 0 and 1, where 0 implies no agreement and 1 implies total agreement.

TABLE 3: Error metrics for Site A and Site B: CONTROL run.

		Site A			Site B		
		Model Skill	Bias	RMSE	Model Skill	Bias	RMSE
	u	0.96	0.02	0.15	0.98	0.02	0.11
	v	0.81	0.01	0.07	0.87	0.00	0.06
S	-5m	0.63	-0.58	0.65	0.63	-0.45	0.49
	-10m	0.62	-0.63	0.56	0.63	-0.47	0.44
	Bottom	0.60	-0.73	0.61	0.60	-0.53	0.36
T	-5m	0.96	0.23	1.70	0.96	0.50	1.47
	-10m	0.96	0.31	1.65	0.96	0.50	1.44
	Bottom	0.95	1.09	1.84	0.96	0.38	1.44
ρ	-5m	0.82	-0.55	0.47	0.82	-0.48	0.41
	-10m	0.81	-0.60	0.44	0.82	-0.49	0.39
	Bottom	0.77	-0.83	0.54	0.82	-0.52	0.35

The model skill in all instances is near to 1 (>0.6) suggesting good capability (Table 3). Bias and the RMSE are also low compared to the maximum values suggesting the model is highly accurate. These metrics therefore imply acceptable model performance.

3. RESULTS

3.1 TEMPERATURE

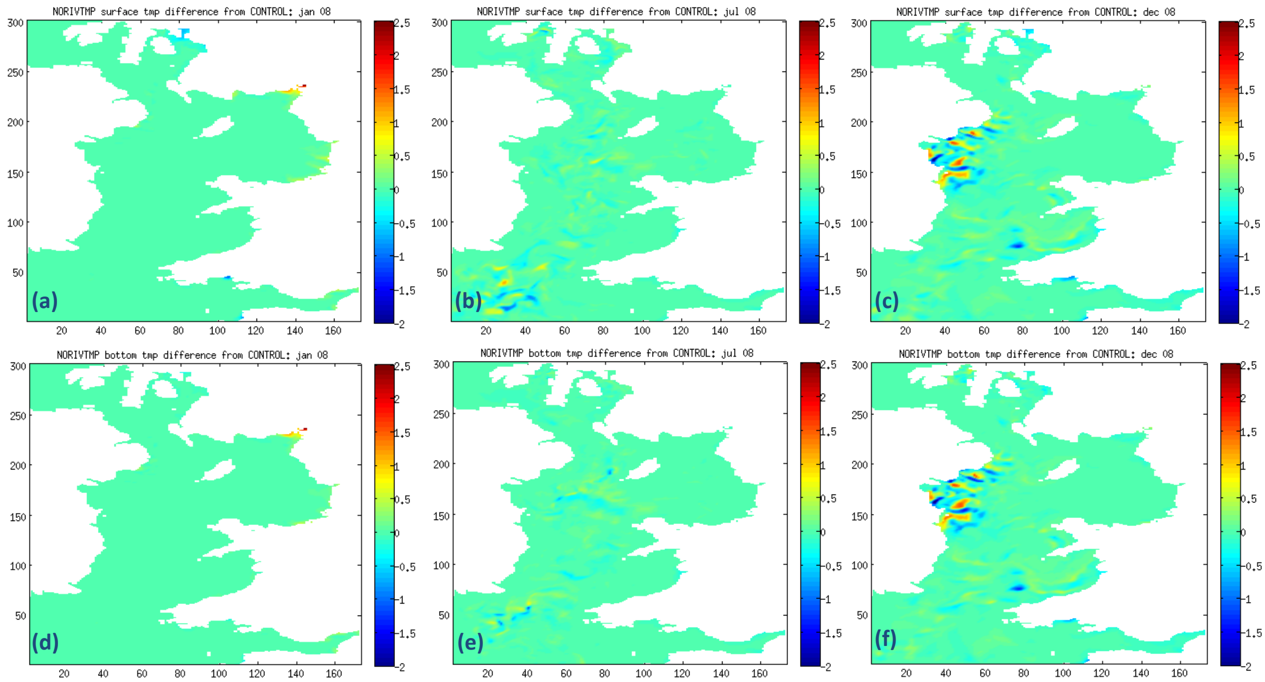

FIGURE 7: Difference in temperature: CONTROL minus NORIVTMP.
Surface: (a) Jan; (b) July; (c) Dec; and Bottom: (d) Jan; (e) July; (f) Dec.

The above plots were produced by extracting a horizontal temperature profile at the 385th time point (hour) of January, July and December 2008 from the CONTROL and NORIVTMP simulations' outputs, subtracting the NORIVTMP temperatures from those of CONTROL and plotting the difference. In January, the effect of switching the river temperatures off has only caused a variation of between -0.5 and +2.5°C to predominantly the North-west English coast. By July, the rivers have had enough time to propagate into the interior causing variations of between -1 and 2°C. These small variations in the coastal interior are seen as a result of different physics to those at the coastal point sources of river inflow, which are relatively unaffected by river temperature at this model resolution. To confirm this delay in propagation I ran December through the script and it shows the rivers have now had a mixed heating/cooling effect on the water around the northern Irish coast too.

TABLE 4: Error metrics: temperature for CONTROL and NORIVTMP. NB higher accuracy values are in bold.

TMP	Run	Model Skill			Bias			RMSE		
		-5m	-10m	Bottom	-5m	-10m	Bottom	-5m	-10m	Bottom
Site A	CONTROL	0.96	0.96	0.95	0.23	0.31	1.09	**1.70**	**1.65**	**1.84**
	NORIVTMP	0.96	0.96	0.95	**0.22**	**0.30**	1.09	1.72	1.66	1.85
Site B	CONTROL	0.96	0.96	0.96	0.50	0.50	0.38	1.47	1.44	1.44
	NORIVTMP	0.96	0.96	0.96	0.50	**0.49**	**0.37**	1.47	1.44	1.44

Figure 8 confirms that over an annual cycle, switching off the river temperatures has had little effect on the overall accuracy of the model temperature predictions. Table 4 also shows the error metrics calculated; there is a maximum difference between the two simulations' error metrics of 0.02 in the root mean squared error at 5m below the surface. Again, this contributes to the evidence that switching off the river temperatures does not have a significant effect on the model accuracy.

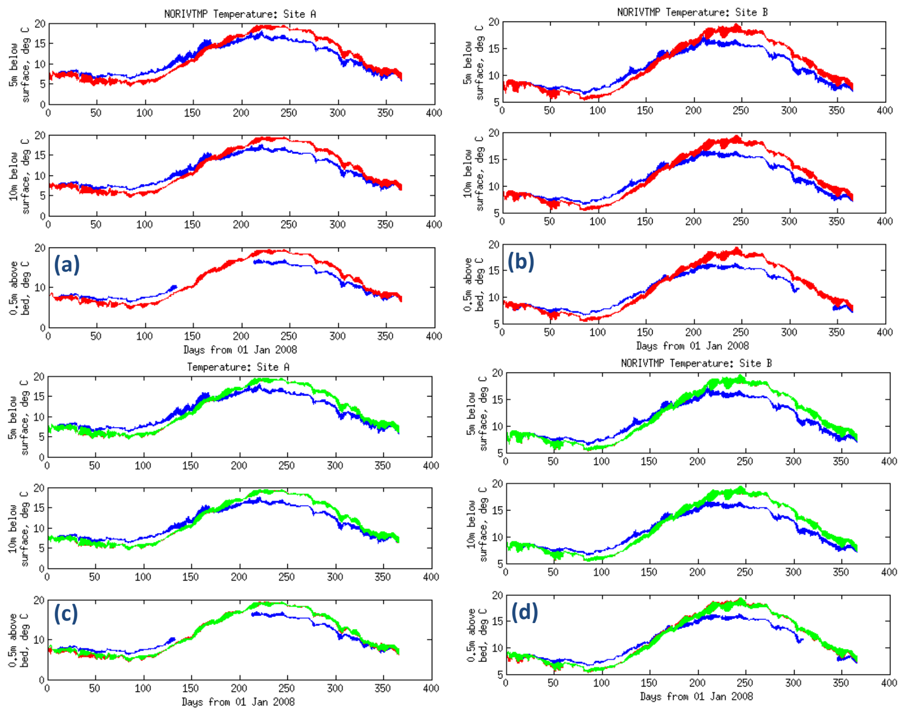

FIGURE 8: Annual temperature time series: NORIVTMP.
NORIVTMP (red) and observed (blue) time series: (a) Site A; (b) Site B; and with CONTROL (green) time series added: (c) Site A; (d) Site B.

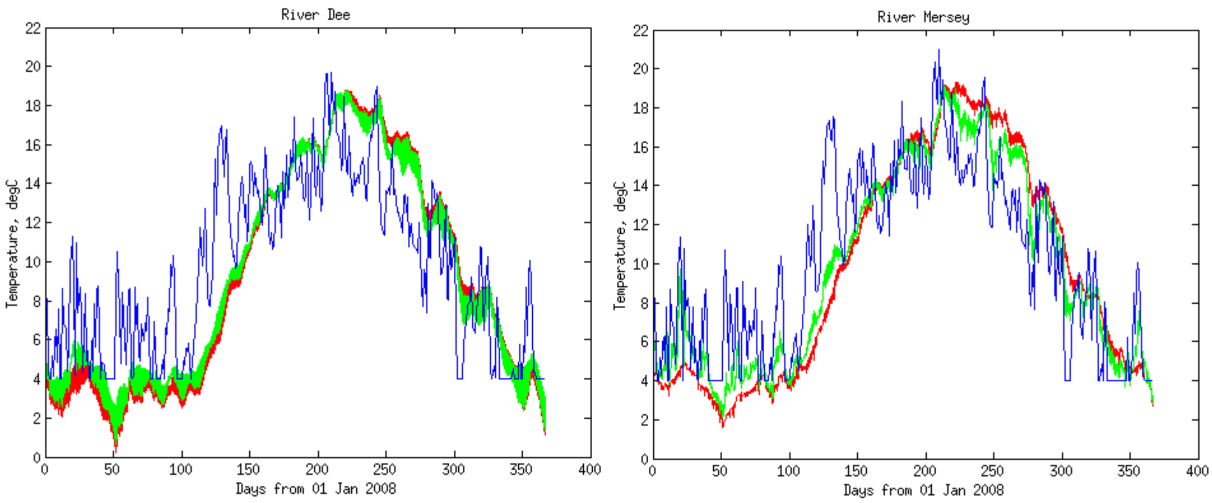

FIGURE 9: Atmospheric temperature (blue) over land used as a proxy for rivers Dee (left) and Mersey (right) temperature compared with the sea surface temperature near to the river source from NORIVTMP (red) and CONTROL (green).

Fig. 8(c) and (d) show that river temperature appears to have most impact on the bottom water temperature as NORIVTMP is cooler than CONTROL through winter at the beginning of the year and also slightly warmer at the peak of the summer. Fig. 9 and Table 5 show that CONTROL follows the atmospheric temperature proxy for both the Dee and Mersey more accurately than NORIVTMP, with river temperature having a warming effect on sea surface temperature through January and into the spring and a cooling effect in summer and autumn. Particularly, at the start of the year, the river inflow in NORIVTMP is cooler than in CONTROL. It may therefore sink down and cool the bottom water with greater effect. The model sea surface temperature curves lag the atmospheric curve showing the slower response of the ocean to seasonal heating than the land.

TABLE 5: Maximum and minimum differences: Atmospheric temperature as a proxy for river temperature minus CONTROL and NORIVTMP temperature: Rivers Dee and Mersey. NB higher accuracy values are in bold

	River Dee		River Mersey	
	Atmos-CONTROL	Atmos-NORIVTMP	Atmos-CONTROL	Atmos-NORIVTMP
Max temp. difference	**8.9818**	9.3718	**7.7486**	9.5727
Min temp. difference	**-6.2428**	-6.6960	**-5.2327**	-6.9570

3.2 SURFACE SALINITY

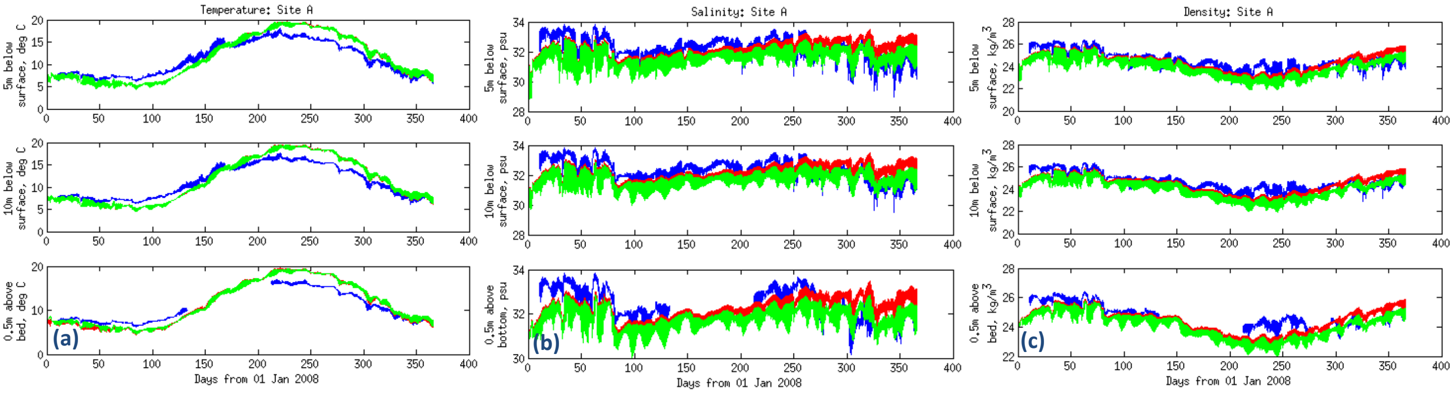

FIGURE 10: Site A Annual SALFX (red), CONTROL (green) and observed (blue) time series for (a) Temperature at -5m, -10m and 0.5m; (b) Salinity; (c) Density.

Including the surface salinity flux calculations in the model had no significant effect on the predicted temperatures; Figs. 10(a) and 11(a) show almost no deviation from the CONTROL time series and the values in Table 6 confirm this with a maximum difference of 0.05 for the RMSE at the bottom.

The added surface salinity flux does, however, affect the salinity hindcasts, resulting in slightly higher predictions than those of CONTROL overall (Figs. 10(b) and 11(b)). This is due to the "SALTFLUX" switch in POLCOMS accounting for evaporation, as well as precipitation. Evaporation is having a greater effect as salinity is increasing, which implies that there is a net loss of freshwater from the sea surface temperature to the atmosphere. As a result, SALFX is closer to the observed values for much of the year, thus the bias is reduced. (The observed time series is consistently under-predicted until approximately the final two months where the observed values drop below the modelled.) The model skill at all three elevations is slightly reduced and the RMSE increased.

In terms of density, the two model runs follow a similar line for much of the year, diverging most during the last two months of the year when they switch from under-predicting to over-predicting the observed values (Figs. 10(c) and 11(c)). Both simulations show a dip in density at both sites and at all three elevations, which does not replicate the observed time series. This is due to summer heating and the over-prediction of temperature during this time. Again, the inclusion of the surface salinity flux has raised the density predictions overall. It has also increased the model skill over all three elevations and reduced the bias, but increased the RMSE.

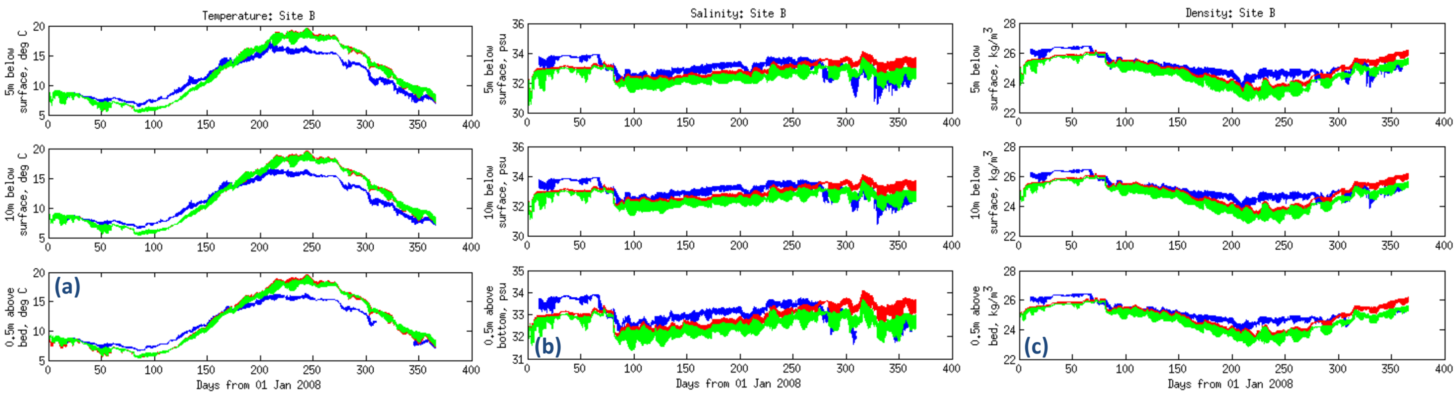

FIGURE 11: Site B annual SALFX (red), CONTROL (green) and observed (blue) time series for (a) Temperature at -5m, -10m and 0.5m; (b) Salinity; (c) Density.

The error metrics (Table 6) support the visual evidence that the two configurations perform very similarly in temperature hindcasting. In terms of salinity, the error metrics show a mixed result, but visually we can see that SALFX is closer to the observed time series for the majority of the year. For density, SALFX is favoured in having a higher model skill and less bias, and again, being closer to the observed time series overall.

We will use the model to look at seasonal longer-term circulation and density fields. The model's ability to predict the mean conditions and variability are therefore important, rather than the accuracy of the hourly values.

TABLE 6: Error metrics: CONTROL and SALFX. NB higher accuracy values are in bold.

		Run	Model Skill			Bias			RMSE		
			-5m	-10m	Bottom	-5m	-10m	Bottom	-5m	-10m	Bottom
SAL	Site A	CONTROL	**0.63**	**0.62**	**0.60**	-0.58	-0.63	-0.73	**0.65**	**0.56**	**0.61**
		SALFX	0.52	0.53	0.54	**-0.21**	**-0.27**	**-0.38**	0.86	0.76	0.80
	Site B	CONTROL	**0.63**	**0.63**	**0.60**	-0.45	-0.47	-0.53	**0.49**	**0.44**	**0.36**
		SALFX	0.54	0.54	0.59	**-0.13**	**-0.15**	**-0.23**	0.66	0.62	0.50
TMP	Site A	CONTROL	0.96	0.96	0.95	**0.23**	0.31	1.09	**1.70**	**1.65**	**1.84**
		SALFX	0.96	0.96	0.95	0.24	0.31	1.09	1.72	1.67	1.86
	Site B	CONTROL	0.96	0.96	0.96	**0.50**	**0.50**	**0.38**	**1.47**	**1.44**	**1.44**
		SALFX	0.95	0.96	0.96	0.53	0.52	0.40	1.51	1.48	1.49
ρ	Site A	CONTROL	0.82	0.81	0.77	-0.55	-0.60	-0.83	**0.47**	**0.44**	**0.54**
		SALFX	**0.84**	**0.84**	**0.79**	**-0.27**	**-0.32**	**-0.56**	0.58	0.53	0.62
	Site B	CONTROL	0.82	0.82	0.82	-0.48	-0.49	-0.52	**0.41**	**0.39**	**0.35**
		SALFX	**0.85**	**0.85**	**0.87**	**-0.24**	**-0.26**	**-0.29**	0.49	0.47	0.41

3.3 RIVER SALINITY

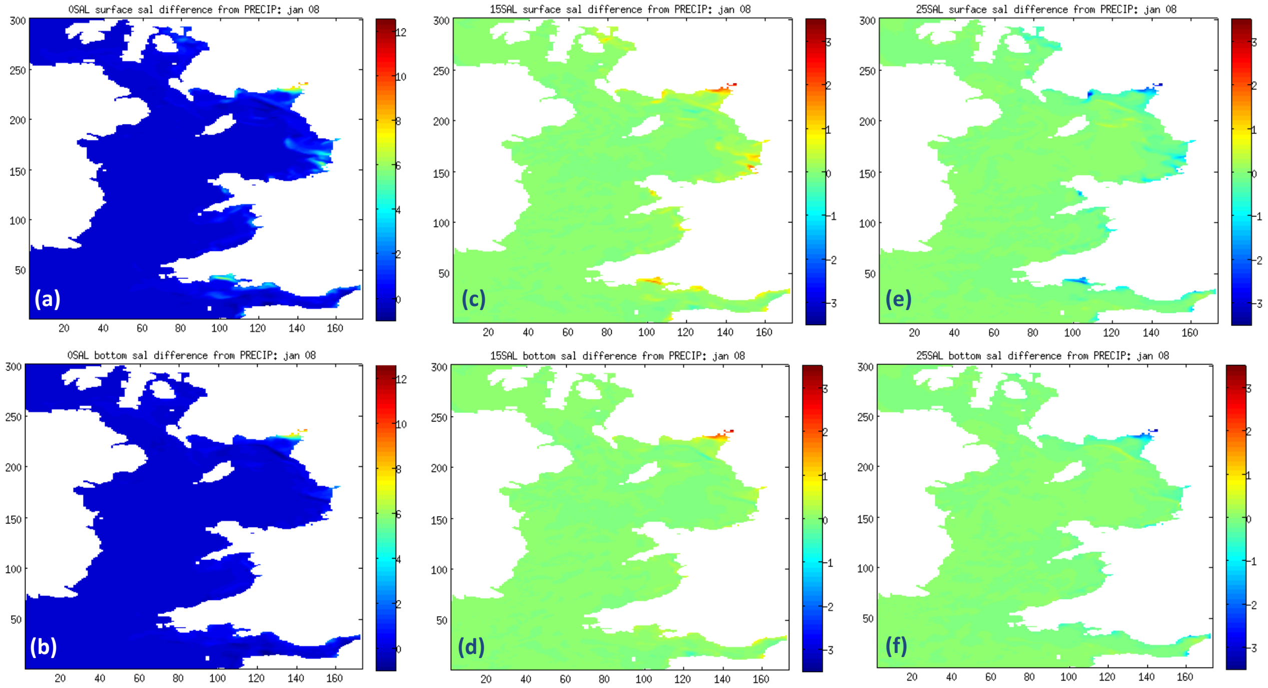

FIGURE 12: Difference in salinity: January.
Between SALFX (20psu freshwater) and 0SAL (0psu freshwater): (a) surface; (b) bottom; between SALFX and 15SAL (15psu freshwater): (c) surface; (d) bottom; and between SALFX and 25SAL: (25psu freshwater): (e) surface; (f) bottom.
NB Note the different scale for the 0SAL plot as the difference was much greater.

To measure the effect of freshwater salinity in the model, the SALFX run with 20psu salinity is used as the control. Surface and bottom salinity profiles were extracted at the 385th time point (hour) in January and July for the SALFX, 0SAL, 15SAL and 25SAL model runs. Salinity values from each model simulation were subtracted from SALFX in turn and the differences plotted (Figs. 12 and 13). All show that the surface water was more affected by the salinity changes than the bottom and that the visible differences occur around the English and Welsh coast, particularly in January due to a higher river discharge (Table 2). The maps show a positive difference for 15SAL, as expected, as the control run freshwater was more saline, a larger positive difference for 0SAL and a negative difference for 25SAL.

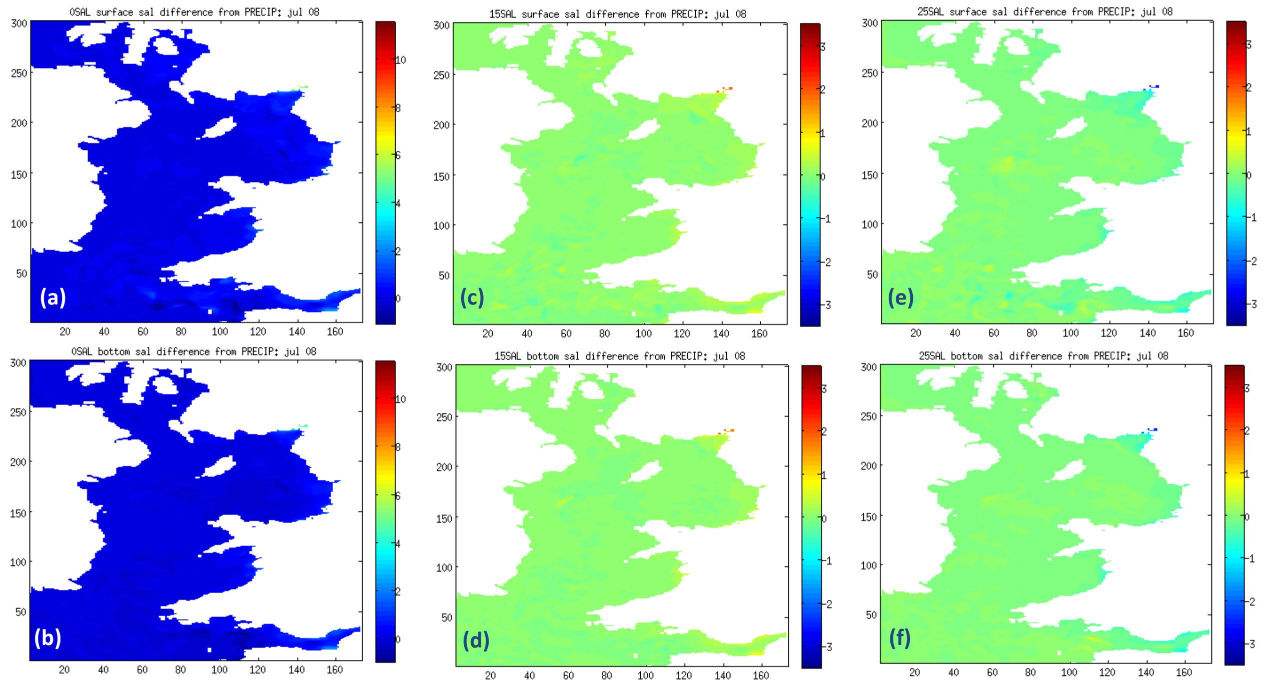

FIGURE 13: Difference in salinity: July. (As per Figure 12.)

TABLE 7: Error metrics: salinity for 0SAL, 15SAL, 25SAL and SALFX. NB The values that represent the greatest accuracy are shown in bold green and those that represent the least are shown in red.

SAL	Run	Model Skill			Bias			RMSE		
		-5m	-10m	Bottom	-5m	-10m	Bottom	-5m	-10m	Bottom
Site A	0SAL	**0.57**	**0.56**	0.54	-0.65	-0.63	-0.68	**0.82**	**0.72**	0.78
	15SAL	0.56	**0.56**	**0.56**	-0.34	-0.38	-0.48	0.83	0.73	**0.77**
	SALFX	0.52	0.53	0.54	-0.21	-0.27	-0.38	0.86	0.76	0.80
	25SAL	0.45	0.47	0.51	**-0.06**	**-0.14**	**-0.27**	0.92	0.82	0.84
Site B	0SAL	**0.65**	**0.65**	**0.63**	-0.32	-0.33	-0.38	**0.56**	**0.51**	**0.43**
	15SAL	0.57	0.58	0.61	-0.19	-0.21	-0.28	0.63	0.58	0.48
	SALFX	0.54	0.54	0.59	-0.13	-0.15	-0.23	0.66	0.62	0.50
	25SAL	0.49	0.50	0.58	**-0.08**	**-0.10**	**-0.18**	0.70	0.65	0.52

Reducing the freshwater salinity increases the model skill at both sites by a maximum of just 0.05 at Site A and 0.11 at Site B, and reduces the RMSE by as much or less, but increases the bias by up to 0.44 at Site A and 0.19 at Site B. Increasing the freshwater salinity has the opposite effect, reducing model skill (by a max. of 0.07) and increasing the RMSE (by a max. of 0.06), but reducing bias (by a max. of 0.15 at Site A; 0.05 at Site B). It can be observed that the model performance is consistently better at Site B than Site A (Table 7). Also, Site A is more affected by changes in the freshwater salinity as it is in closer proximity to the river mouths (Fig. 14) and particularly influenced by the Mersey outer channel.

Overall, the SALFX run with 20psu freshwater salinity and the 15SAL setup with 15psu freshwater salinity appear to be most consistent. Hopkins and Polton (2011) have previously shown that 20psu is an acceptable salinity level for river inflow.

TABLE 8: Difference between 15SAL metrics and SALFX metrics: salinity. NB The values that favour 15SAL are shown in green while those that favour SALFX are shown in red.

		Model Skill			Bias			RMSE		
15SAL-SALFX	Site A	0.04	0.03	0.01	-0.13	-0.11	-0.09	-0.03	-0.03	-0.02
	Site B	0.04	0.04	0.01	-0.06	-0.06	-0.05	-0.03	-0.03	-0.02

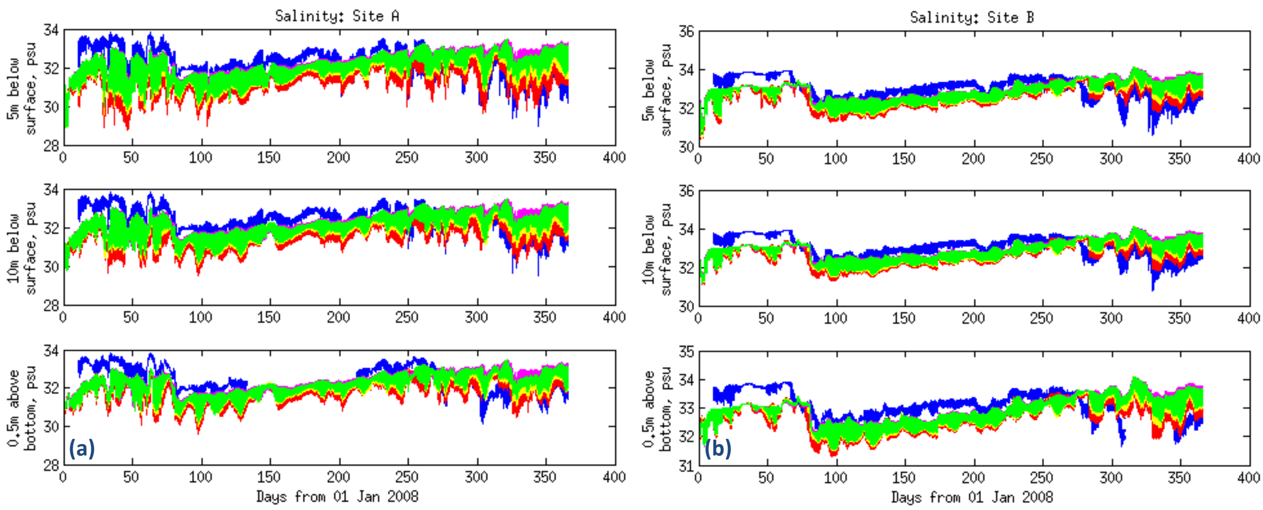

FIGURE 14: Annual 0SAL (red), 15SAL (yellow), 25SAL (magenta), SALFX (green) and observed (blue) time series at Sites A and B: salinity.

3.4 Density

In the analysis so far, the CONTROL, SALFX and 15SAL simulations have perfomed best so when comparing density predictions, just these three setups will be investigated.

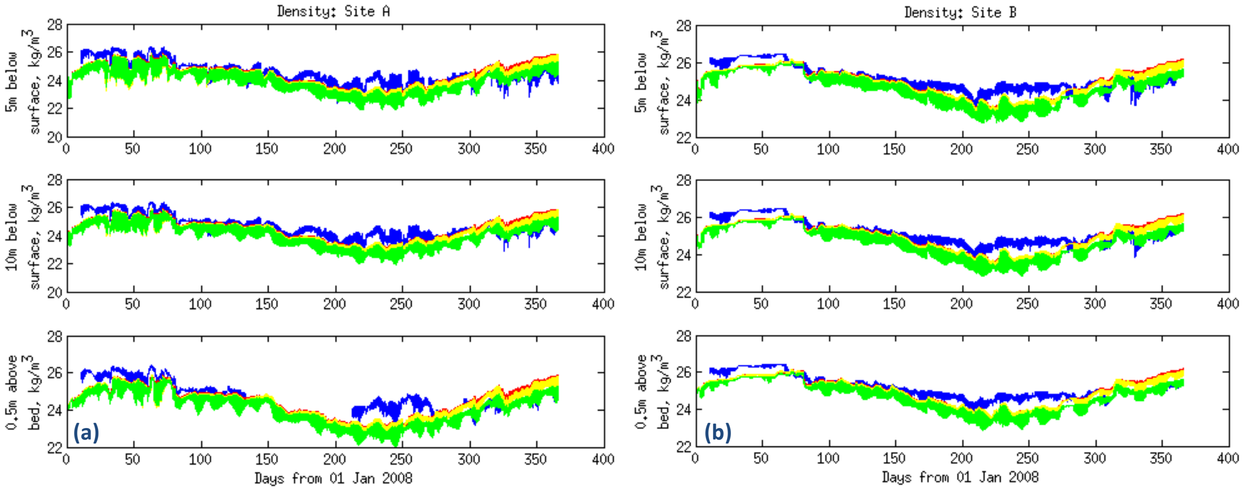

FIGURE 15: Annual SALFX (red), 15SAL (yellow), CONTROL (green) and observed (blue) time series at Sites A and B: density.

The three model runs follow a very similar line for much of the year, diverging most during the last two months of the year when they switch from under-predicting to over-predicting the observed values (Fig. 15). All of the simulations show a dip in density at both sites and at all three elevations, which does not replicate the observed time series. This is due to summer heating and the over-prediction of temperature during this time.

Overall, the error metrics (Table 9) favour SALFX; it has the highest model skill for all three elevations at both sites, and although both configurations are consistently negatively biased in terms of density, SALFX is the least biased across both sites. This demonstrates that increased physics improves the model validity at low computational cost, in this case. Whereas the CONTROL setup is most biased, it has the least RMSE across both sites. We choose CONTROL to be the best model setup despite SALFX having the overall high skill and low bias as we feel there are spin-up errors in SALFX, as discussed in Section 4.

TABLE 9: Error metrics: density. NB higher accuracy values are in bold.

DENSITY	**Run**	Model Skill			Bias			RMSE		
		-5m	-10m	Bottom	-5m	-10m	Bottom	-5m	-10m	Bottom
Site A	CONTROL	0.82	0.81	0.77	-0.55	-0.60	-0.83	**0.47**	**0.44**	**0.54**
	15SAL	0.83	0.83	**0.79**	-0.37	-0.40	-0.63	0.55	0.50	0.59
	SALFX	**0.84**	**0.84**	**0.79**	**-0.27**	**-0.32**	**-0.56**	0.58	0.53	0.62
Site B	CONTROL	0.82	0.82	0.82	-0.48	-0.49	-0.52	**0.41**	**0.39**	**0.35**
	15SAL	0.83	0.83	**0.79**	-0.37	-0.40	-0.63	0.55	0.50	0.59
	SALFX	**0.85**	**0.85**	**0.87**	**-0.24**	**-0.26**	**-0.29**	0.49	0.47	0.41

3.5 NOWAM

This run has the same configuration as SALFX, but with waves turned off. No wave output was generated and the run time for January was reduced by two hours, which confirms that the waves had been turned off. Otherwise, this model setup was validated in the same way as the other runs, ensuring the salinity and temperature maps produced were very similar to those for SALFX. Then the validation scripts were used to produce plots (Figs. 16-18) and error metrics (Table 10) for Site A and Site B.

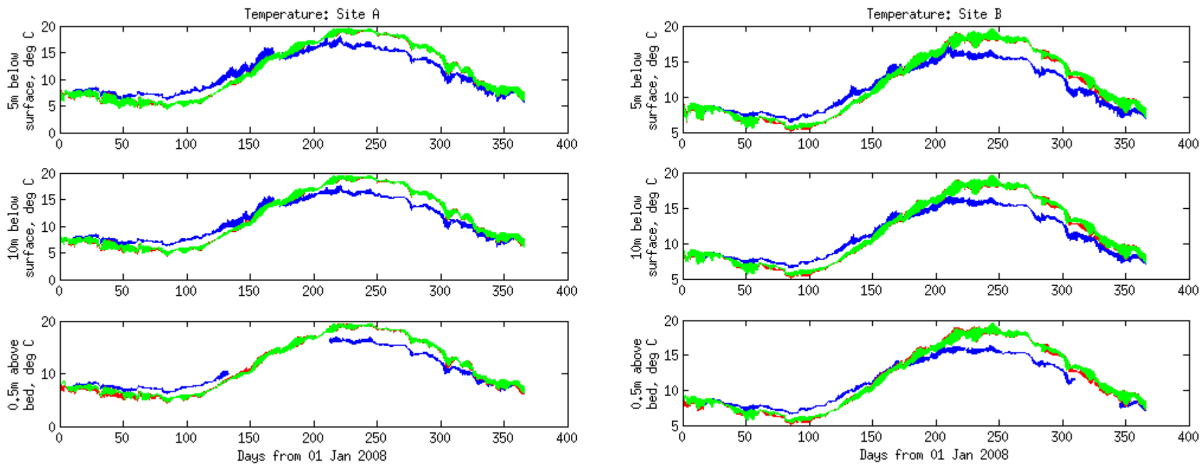

FIGURE 16: Annual NOWAM (red), SALFX (green) and observed (blue) time series at Sites A and B: temperature.

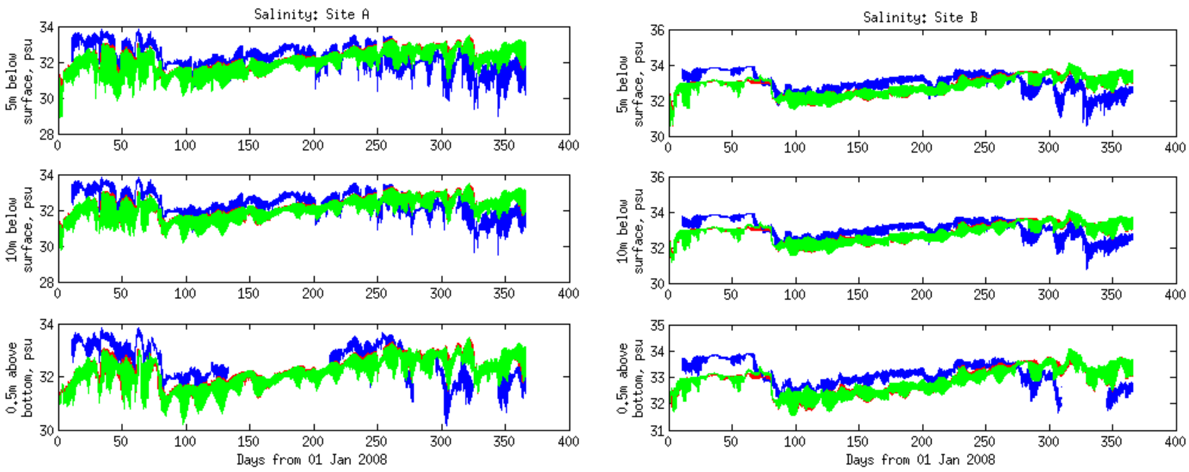

FIGURE 17: Annual NOWAM (red), SALFX (green) and observed (blue) time series at Sites A and B: salinity.

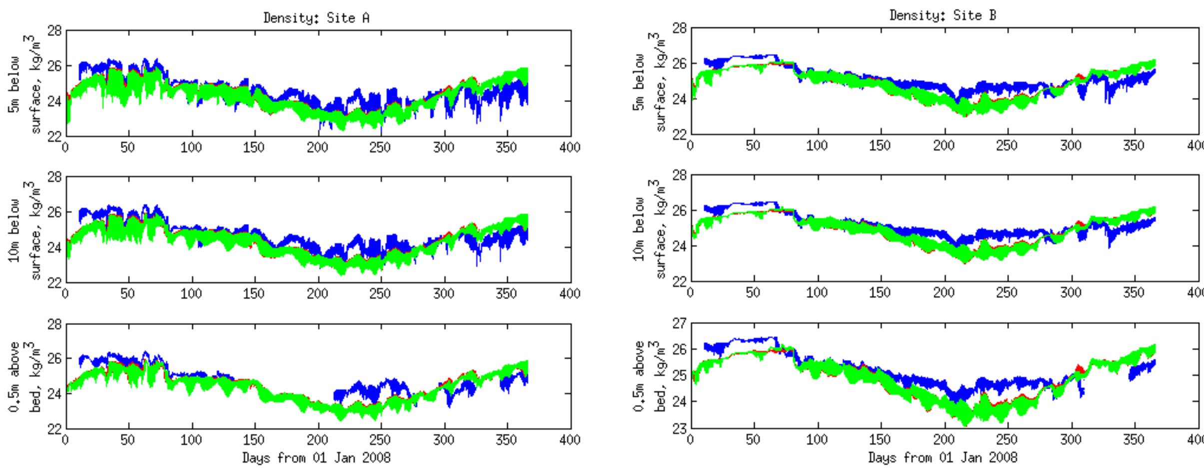

FIGURE 18: Annual NOWAM (red), SALFX (green) and observed (blue) time series at Sites A and B: density.

There is slight deviation from the SALFX time series in the plots, but nothing too great. This is due to reduced turbulent mixing as a result of wave activity; in POLCOMS-WAM, waves enhance both the surface and bottom stress. The error metrics (Table 10) also show very little variation between the two simulations' performance.

TABLE 10: Error metrics: SALFX and NOWAM. NB higher accuracy values are in bold.

		Run	Model Skill			Bias			RMSE		
			-5m	-10m	Bottom	-5m	-10m	Bottom	-5m	-10m	Bottom
SAL	Site A	SALFX	0.52	0.53	0.54	-0.21	-0.27	-0.38	0.86	0.76	0.80
		NOWAM	**0.55**	**0.57**	**0.57**	**-0.12**	**-0.20**	**-0.33**	**0.82**	**0.72**	**0.78**
	Site B	SALFX	0.54	0.54	0.59	-0.13	-0.15	-0.23	0.66	0.62	**0.50**
		NOWAM	0.54	**0.55**	0.59	**-0.12**	-0.15	-0.23	0.66	**0.61**	0.51
TMP	Site A	SALFX	0.96	0.96	0.95	0.24	0.31	1.09	1.72	1.67	**1.86**
		NOWAM	0.96	0.96	0.95	**0.21**	**0.27**	**1.05**	**1.71**	**1.66**	1.87
	Site B	SALFX	0.95	0.96	0.96	0.53	0.52	0.40	1.51	1.48	**1.49**
		NOWAM	0.96	0.96	0.96	**0.47**	**0.46**	**0.34**	1.51	1.48	1.51
ρ	Site A	SALFX	0.84	0.84	0.79	-0.27	-0.32	-0.56	0.58	0.53	0.62
		NOWAM	**0.87**	**0.87**	**0.81**	**-0.19**	**-0.26**	**-0.51**	**0.55**	**0.50**	**0.61**
	Site B	SALFX	0.85	0.85	0.87	-0.24	-0.26	-0.29	0.49	0.47	0.41
		NOWAM	**0.86**	**0.86**	0.87	**-0.22**	**-0.24**	**-0.28**	0.49	**0.46**	**0.40**

4. DISCUSSION AND CONCLUDING REMARKS

- The model performs well, but more accurately hindcasts some stratification events than others. Next, I will correlate atmospheric and river conditions with the density difference to identify which processes are controlling stratification.

- In nearshore density, temperature has a seasonal influence, but salinity is dominant.

- River temperature should be included as there is a seasonal influence up estuary, although the nearshore impact is small in response to slight changes in temperature input. Sea surface temperature is a good approximation for river temperature in the absence of real observations, as there is little difference between the sea surface temperature near the river source when atmospheric temperature is considered as a proxy for river temperature and when no temperature is implemented.

- Setting the river salinity as 20psu is acceptable as increasing salinity improves bias, but reducing salinity improves the model skill and reduces error.

- The divergence between CONTROL and SALFX salinity levels over the annual period indicates that the model could still be spinning-up as the operational model used for the warm-start conditions does not include surface salt flux. These results suggest that it takes at least a year to spin-up baroclinic fields.

- The model hindcasts for salinity, and therefore density, show a negative bias, which could be related to the operational model's use of a climatological river flow with 0psu underpredicting the coastal salinity field. This sensitivity analysis shows that using different river salinities causes changes of a few psu in coastal waters and as salinity is dominant in the density field, this small difference could have a large impact. The bias in the model run may therefore be due to the limitations of the operational setup used to warm-start this annual simulation.

- The modelled temperature seems to be accurate as the seasonal trend is correctly simulated with underprediction initially and overprediction in the latter half of the year.

- The reducing bias between the model simulations and the observed salinity (and therefore density) over the year again suggests that the model is still spinning-up over this time from underpredicted initial conditions.

- Waves have little influence on the model accuracy, but considerable influence on runtime. As there is a slight improvement without waves, we will not consider waves to investigate the mixing front and will use the CONTROL setup with "nowam" to simulate the boundary conditions for further high resolution investigations. The CONTROL setup (with waves) will be the standard for comparison to the coupled FVCOM-SWAVE Irish Sea model.

- For each simulation, the phys- and surfseries (the outputted model temperature, salinity, etc.) for a grid of points off Anglesey (the Skerries) have been saved in addition to those at sites A and B. These will be used to investigate turbulence for a renewable energy project.

- A further investigation would be to compare error metrics for each season (or over a running monthly interval) where convergence during the annual period would indicate the required spin-up time.

- The matlab scripts used and the model data, which is stored under each run name, can be found at /projectsa/iCoast/Mersey_CEFAS/IRS2008/IRS_tests/ .

References

Archer, A.W., 2013. World's highest tides: Hypertidal coastal systems in North America, South America and Europe. Sedimentary Geology 284-285, 1-25.

Brown, J.M., Bolaños, R., Wolf, J., 2011. Impact assessment of advanced coupling features in a tide–surge–wave model, POLCOMS-WAM, in a shallow water application. Journal of Marine Systems 87, 13-24.

Fofonoff, N.P., Millard Jr, R.C., 1983. Algorithms for computation of fundamental properties of seawater. Unesco technical papers in marine science 44.

Holt, J.T., James, I.D., 2001. An s coordinate density evolving model of the northwest European continental shelf: 1. Model description and density structure. Journal of Geophysical Research, 106(C7), 14015-14034.

Hopkins, J., Polton, J.A., 2011. Scales and structure of frontal adjustment and freshwater export in a region of freshwater influence. Ocean Dynamics 62, 45-62.

Howarth, M.J., Palmer, M.R., 2011. The Liverpool Bay coastal observatory. Ocean Dynamics 61, 1917-1926.

O'Neill, C.K., Polton, J.A., Holt, J.T., O'Dea, E.J., 2012. Modelling temperature and salinity in Liverpool Bay and the Irish Sea: sensitivity to model type and surface forcing. Ocean Science 8, 903–913.

Polton, J.A., Palmer, M.R., Howarth, M.J., 2011. Physical and dynamical oceanography of Liverpool bay. Ocean Dynamics 61, 1421-1439.

Polton, J.A., Palmer, M.R., Howarth, M.J., 2013. The vertical structure of time-mean estuarine circulation in a shallow, rotating, semi-enclosed coastal bay: A Liverpool Bay case study with application for monitoring. Continental Shelf research 59, 115-126.

Simpson, J.H., Brown, J., Matthews, J., Allen, G., 1990. Tidal Straining, Density Currents, and Stirring in the Control of Estuarine Stratification. Estuaries 13, 125-132.

Souza, A.J., 2013. On the use of the Stokes number to explain frictional tidal dynamics and water column structure in shelf seas. Ocean Science 9, 391–398.

Willmott, C.J., 1981. On the validation of models. Physical Geography, 2(2), 184-194.