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Processes controlling stratification in Liverpool Bay

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ABSTRACT

Liverpool Bay in the NW of the UK is a shallow, hypertidal region (with range >10m) of freshwater influence, that is, in addition to the fast tidal currents (>1m/s), the dynamics of the region are strongly influenced by estuarine outflow from the Dee, Mersey and Ribble estuaries (Simpson et al., 1990). Stratification is found to be dominated by salinity, although river temperature does have a seasonal effect (Polton et al., 2011). Instances of stratification within Liverpool Bay during 2008 are identified at mooring sites A and B, which form part of the National Oceanography Centre's Coastal Observatory (COBS), as a positive difference between bottom and surface density, in this study. These periods are then correlated to atmospheric forcing, waves, tides and river outflow with the aim of identifying the processes controlling stratification at those times. Previous analysis of distribution histograms over 2008 (Norman et al., 2014b) showed that it is a typical year in atmospheric, riverine and coastal conditions so is suitable for this study.

KEYWORDS

ISSUING ORGANISATION

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1. Introduction

Liverpool Bay in the NW of the UK is a shallow, hypertidal region of freshwater influence, that is, in addition to the fast tidal currents, the dynamics of the region are strongly influenced by estuarine outflow (Simpson et al., 1990). Stratification is found to be dominated by salinity, although river temperature does have a seasonal effect (Polton et al., 2011). Figure 1 illustrates the tidal straining of the mixing front within Liverpool Bay by an increased area of stratification at low water. Mooring sites A and B are also highlighted, which form part of the National Oceanography Centre's Coastal Observatory (COBS) and are the locations at which instances of stratification within Liverpool Bay are identified, as a difference between surface and bottom density, in this study.

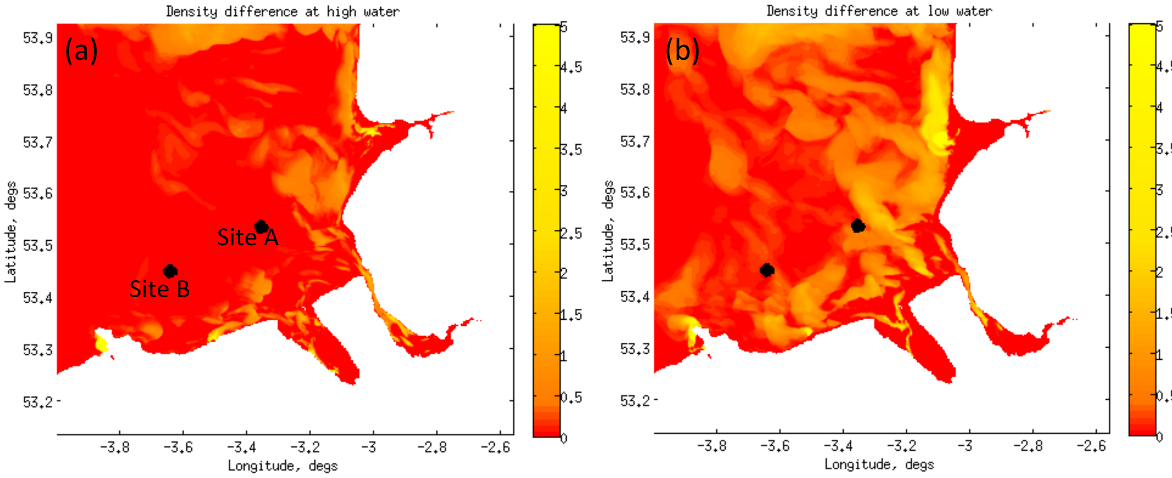

Figure 1: Difference between bottom density and surface density at (a) high water and (b) low water. Mooring sites A and B are identified by black dots.

Previous analysis of distribution histograms over 2008 (Norman et al., 2014b) showed that it is a typical year in atmospheric, riverine and coastal conditions so is suitable for this study. Periods of stratification during 2008 are identified at sites A and B then correlated to atmospheric forcing, waves, tides and river outflow with the aim of identifying the processes controlling stratification. The metocean parameters (Table 1) are available from the Hilbre met station (Fig. 2b), Gladstone Dock tide gauge (Fig. 2b) and the National River Flow Archive gauging stations (Fig. 2c).

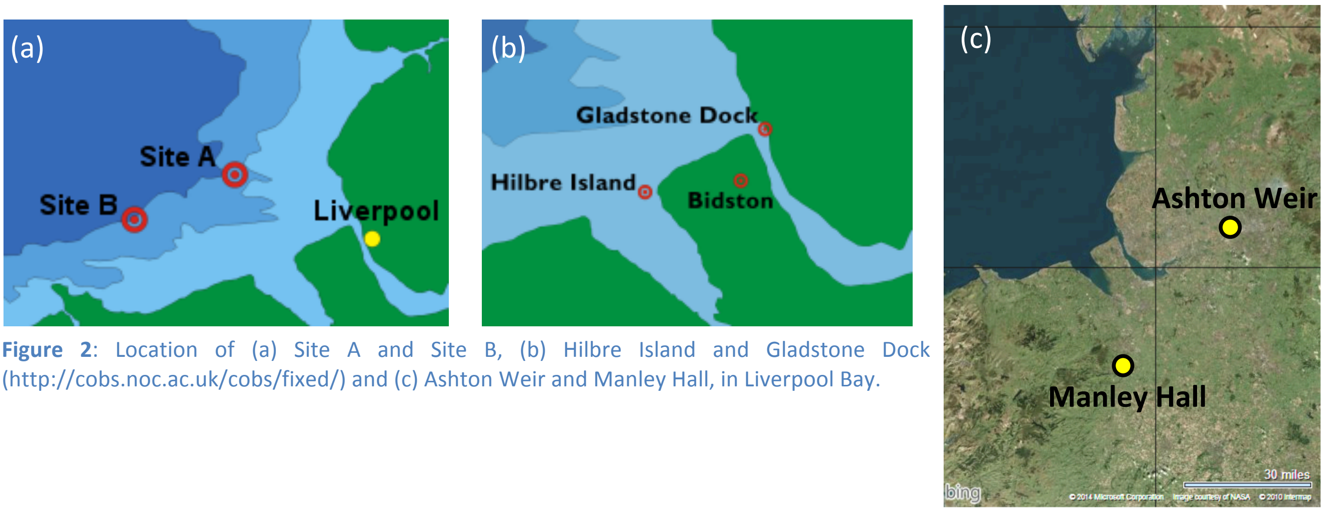

Figure 2: Location of (a) Site A and Site B, (b) Hilbre Island and Gladstone Dock (http://cobs.noc.ac.uk/cobs/fixed/) and (c) Ashton Weir and Manley Hall, in Liverpool Bay.

Table 1: The variables used in the correlations, along with their data source and the matlab script used to extract their time series.

Matlab script	Data source	Variable
Hilbre_dist.m	Hilbre Island weather station	Barometric pressure (mb)
		Precipitation (mm/10 mins)
		Atmospheric temperature (°C)
wind_dist.m		Wind speed (m/s)
		Wind direction (deg)
wave_dist.m	WaveNet: offshore wave buoy	Wave height (m)
		Wave peak period (s)
		Wave direction (°)
river_dist.m	CEH NRFA: Manley Hall and Ashton Weir stations	River Dee discharge (m^3/s)
		River Mersey discharge (m^3/s)
tide_dist.m	NTSLF: Liverpool (Gladstone Dock) tide gauge	Meteorological surge (m)
		Total (tidal + surge) elevation (m)

2. Methods

Each of the variables is correlated to observed density differences at the two mooring sites, A and B, in approximately 20-25m depth. data_diffs.m reads in the observed density data at available levels of 5m below the sea surface and 0.5m above the bed, and calculates the difference between them (the fresher near surface water is subtracted from the denser bottom water). Where negative differences are observed, which are probably due to errors in the (near-bed) observations occurring when the water is well mixed, these values are set to zero to represent a well-mixed water column. tocorrelate.m reads in the 2008 time series for each variable and the density difference at the two sites and uses the "corr" function in matlab to calculate Pearson's linear correlation coefficient using only the instances where there were numerical values for both; at times where no measurement could be taken, due to instrument failure, a "NaN" (Not a Number) is recorded to prevent erroneous data skewing the results in the correlation calculation. The correlation was computed over the whole annual period and also per month to identify any seasonal influences.

Pearson's linear correlation coefficient is defined[1] as:

$$r = \frac{covariance\ of\ X\ and\ Y}{variance\ of\ X \times variance\ of\ Y} = \frac{S_{XY}}{\sqrt{S_{XX}S_{YY}}},$$

where $S_{XY} = \sum(x-\overline{x})(y-\overline{y})$ and $\overline{x} = \frac{\sum_1^n x_n}{n}$.

r takes values between -1 and 1, where -1 represents perfect negative correlation, that is, a change in the X variable corresponds to an opposite change in the Y variable; 1 represents perfect positive correlation and an r value of 0 signifies that there is no linear relationship between X and Y.

[1] http://forrest.psych.unc.edu/research/vista-rames/help/lecturenotes/lecture11/pearson.html

3. Initial Results

Table 2 shows that over an annual cycle there is poor correlation between all of the variables considered and the density differences at the two sites, highlighted by the best correlation values being -0.28 (surge) for site A and -0.29 (tidal elevation) for site B. This is due to the fact that there is no one process controlling stratification, especially throughout a complete annual cycle; it is much more complicated. The majority of the correlations are negative, showing that the processes act to weaken stratification. In the case of the tide, the flood promotes mixing and the movement of the front towards the coast, while the ebb promotes stratification and the flow of brackish coastal water further offshore.

Table 2: r values for each variable at both sites A and B, calculated over the whole annual cycle. The values representing the best correlation to the time-varying surface and bottom density difference for each site are denoted in bold.

Variable	r value	
	site A	site B
barometric pressure (mb)	0.21	0.03
precipitation (mm/10mins)	-0.01	0.02
atmospheric temperature (°C)	0.16	0.17
wind speed (m/s)	-0.22	-0.23
wind direction (from) (°)	-0.13	-0.12
Dee discharge (m^3/s)	-0.11	-0.11
Mersey discharge (m^3/s)	-0.08	-0.05
meteorological surge (m)	**-0.28**	-0.11
tidal elevation (m)	-0.20	**-0.29**
wave height (m)	-0.24	-0.27
wave peak period (s)	-0.16	-0.16
wave direction (from) (°)	-0.09	-0.14

The highest annual correlation seen at site A is for surge, which suggests that storms, enabling turbulent mixing and reduced stratification, may have more impact here than at site B.

Table 3 shows that, when examining the best correlations over a monthly period, the river discharges dominate; in fact, they provide the best correlation value for six of the ten months for which we have data, and the greatest overall: -0.69 for the river Dee discharge in May. Figure 7, however, shows that there is only density difference data available for the first half of May, so this value will have been calculated on limited data; the next best value seen for river discharge, -0.50, occurs for the river Mersey during a full month of data, March. These negative correlations suggest that stratification is out of phase with the river discharge, with strong stratification in periods of low river outflow, which could be due to a lag in capturing the true estuarine river inflow, as the gauges are in the catchment area upstream (Fig. 2c) and the coastal moorings are offshore from the estuary mouth. Half of the best correlation values for the rivers are, conversely, positive and represent the corresponding increases in density difference with an increase in river discharge as there is a higher inflow of freshwater intensifying stratification that the tide cannot break down. This clearly shows river flow alone does not determine the occurrence of coastal stratification.

Site A is located between the two rivers studied here so both have an influence. It was suggested by Polton et al. (2011) that site A is more influenced by the Mersey than the Dee, but these results suggest otherwise, with the Dee being dominant (Table 3). It should again be noted that the river gauges are located within the catchment and do not represent the complete flow entering the estuary (Fig. 2c). The gauge locations relative to the estuaries will influence how well the discharge represents the total river inflow and therefore may bias the dominance in correlation with the offshore moorings.

At site A, eight of the variables show their best correlation values in the same month, February (Table 3), which also represents a full month of variable stratification strength. This suggests many processes are influencing stratification at this time.

Table 3: Monthly r values for each variable at site A. The value representing the best correlation overall is shown in bold. The green boxes represent the month of best correlation for each variable and blue represent the best correlated variable for each month. A striped box indicates that the best value occurs more than once.

	SITE A											
VARIABLE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
barometric pressure (mb)	-0.05	0.49	0.36	0.14	0.04	NaN	NaN	0.27	0.06	0.21	0.25	0.08
precipitation (mm/10mins)	0.07	-0.04	0.01	-0.02	-0.04	NaN	NaN	0.04	-0.07	0.01	-0.04	-0.06
atmospheric temperature (°C)	-0.32	-0.50	0.01	-0.26	0.11	NaN	NaN	0.10	0.21	-0.36	-0.04	-0.29
wind speed (m/s)	-0.22	-0.36	-0.15	0.01	-0.08	NaN	NaN	-0.12	0.00	-0.31	-0.01	-0.21
wind direction (from) (°)	-0.04	-0.46	-0.01	-0.04	-0.10	NaN	NaN	0.06	-0.14	-0.13	0.04	-0.21
Dee discharge (m^3/s)	-0.01	-0.49	-0.37	0.32	**-0.69**	NaN	NaN	-0.38	0.46	0.44	-0.07	-0.32
Mersey discharge (m^3/s)	-0.12	-0.46	-0.50	0.23	-0.65	NaN	NaN	-0.36	0.28	-0.31	0.17	-0.52
surge (m)	-0.28	-0.47	-0.22	-0.29	-0.22	NaN	NaN	-0.26	-0.18	-0.32	-0.29	-0.21
tidal elevation (m)	-0.49	-0.15	0.12	-0.26	-0.31	NaN	NaN	-0.19	-0.17	-0.22	-0.28	-0.67
wave height (m)	-0.24	-0.36	-0.18	0.04	-0.06	NaN	NaN	-0.09	0.05	-0.28	-0.03	-0.27
wave peak period (s)	-0.04	-0.46	-0.18	-0.02	0.15	NaN	NaN	0.12	0.10	-0.17	0.02	-0.22
wave direction (from) (°)	0.14	-0.53	0.06	-0.08	0.01	NaN	NaN	0.25	-0.04	0.17	0.13	-0.12

In contrast to site A, where rivers are dominant due to its closer proximity to the coast and estuaries (Fig. 1), tidal elevation is the dominant variable at site B, with the best correlation values for seven months of 2008, reaching -0.51 in June (Table 4), which suggests fairly strong negative correlation due to tidal mixing. (Tidal elevation does show a greater correlation of -0.63, in November, but is out-performed by the Mersey discharge during this month.) This indicates that the tide is dominant in driving stratification at site B due to straining of the stratified system. This is the consequence of the ability of the fast tidal currents to mix the water column at certain stages of the tide and for the east-west aligned flood and ebb currents to act with or against the river discharge within the system. Straining causes the frontal position to therefore move to and fro from the coast as shown by Prandle et al. (2011). There is a clear semi-diurnal cycle in the density difference in response to the daily tidal straining (dominated by M_2), but not a clear fortnightly (spring-neap) cycle. Hopkins and Polton (2012) suggest there is a spring-neap movement of the front of between 5 and 35km, and a further movement of 5–10 km driven by semi-diurnal tidal straining.

The rivers are of secondary importance at site B, in that collectively the river discharges studied account for three of the five months in which the tides are not dominant and also share the best correlation in June with tidal elevation. Furthermore, the best monthly values seen in Table 4 are 0.81 and 0.76 for the river Dee and Mersey discharges, respectively, both occurring in January. These coincide with the highest flow rates seen in 2008 for both rivers (Fig. 5a and b) and show a strong positive correlation. Site B is closer to the influence of rivers Colwyn and Clywd, but for the rivers analysed here (the Dee and the Mersey) it is closest to the mouth of the river Dee hence it is predictably most affected by the Dee.

The other three best correlation values for the rivers at site B are negative and occur at times of low flow rate (February and June: Dee; and November: Mersey). Greater differences in the surface and bottom density are seen during the summer months due to the seasonal solar heating of the sea surface also contributing to enhance stratification; July shows atmospheric temperature to be the most correlated variable (Table 4). So the stratification seen in June could be a result of solar heating of the sea surface. Later, Figure 5 shows that the early peak in density difference in November does follow a peak in river outflow, but there is not data for the whole month so the correlation value is only representative of these first few days. In the case of February, Figure 5 suggests the water column was well mixed and remained at zero throughout the month, despite the peak river outflows seen in January. The fact this month shows strong stratification at site A and is the only month at site B that is nearly continually mixed suggests the measurement could be erroneous. However, model investigation (see Fig. 6e in Norman et al., 2014a) confirms that the majority of February and long periods within March are well mixed. Whereas February proved to be the most highly correlated month at site A for many of the variables considered, there is no one month at site B where this is also true.

Table 4: Monthly r values for each variable at site B. The value representing the best correlation overall is shown in bold. The green boxes represent the month of best correlation for each variable and blue represent the best correlated variable for each month. A striped box indicates that the best value occurs more than once.

	SITE B											
VARIABLE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
barometric pressure (mb)	-0.16	0.04	-0.07	0.11	-0.08	0.09	0.10	-0.02	0.16	0.22	0.20	0.12
precipitation (mm/10mins)	0.15	-0.01	0.08	0.08	-0.01	-0.06	0.07	0.05	-0.06	0.04	-0.06	-0.02
atmospheric temperature (°C)	-0.06	-0.05	-0.15	0.19	-0.03	-0.21	0.52	-0.03	0.23	0.26	0.13	0.22
wind speed (m/s)	-0.29	0.00	-0.29	-0.11	-0.19	-0.02	-0.28	-0.15	-0.19	-0.25	-0.11	-0.19
wind direction (from) (°)	-0.16	-0.04	-0.03	-0.06	-0.02	0.12	-0.29	0.03	-0.08	-0.26	0.07	-0.01
Dee discharge (m^3/s)	**0.81**	-0.46	0.26	0.16	-0.03	-0.51	0.06	-0.05	0.06	0.25	-0.56	0.25
Mersey discharge (m^3/s)	0.76	-0.44	0.00	0.18	0.10	-0.36	-0.25	-0.13	-0.14	0.08	-0.65	0.20
surge (m)	-0.08	-0.05	-0.09	0.04	0.11	-0.18	-0.15	-0.03	-0.20	-0.15	-0.05	-0.16
tidal elevation (m)	-0.41	-0.23	-0.31	-0.44	-0.25	-0.51	-0.17	-0.43	-0.27	-0.19	-0.63	-0.47
wave height (m)	-0.35	-0.08	-0.27	-0.12	-0.10	-0.05	-0.34	-0.21	-0.23	-0.41	-0.12	-0.17
wave peak period (s)	-0.08	-0.05	-0.15	-0.02	-0.09	-0.05	-0.15	-0.08	-0.06	-0.39	-0.19	0.05
wave direction (from) (°)	0.02	-0.04	0.01	-0.07	-0.10	0.16	-0.39	-0.02	-0.09	-0.14	0.15	0.19

Collectively, the river discharges and tidal parameters provide the highest correlation values for nine out of ten months at site A (two months have no reliable data, represented by "NaN" values) and ten of the twelve months at site B. Besides rivers and tides, there is a case of wave direction having the best correlation value at site A in February and also of wave height having the best correlation at site B in October. In February, it has been shown that there was a period of cool, calm atmospheric conditions with low river flow (Norman et al., 2014b), so in the absence of other dominant parameters, wave direction has the strongest correlation closer to the coast at site A. Under fetch-limited conditions in the eastern Irish Sea, wave direction will be representative of certain wind and wave conditions (wave heights and periods, wind direction and speed), so captures the overall (combination of) wind-wave parameters. October, on the other hand, shows possible storm conditions resulting in big waves and surge, which have greater influence than the tides during this month. In July, atmospheric temperature sees the best correlation at site B, which could be due to seasonal heating of the surface water enhancing stratification; we have no data for June and July at site A to compare this with. Unlike at site B, tides seem to have minimal influence on the monthly stratification patterns at site A, relative to the other processes.

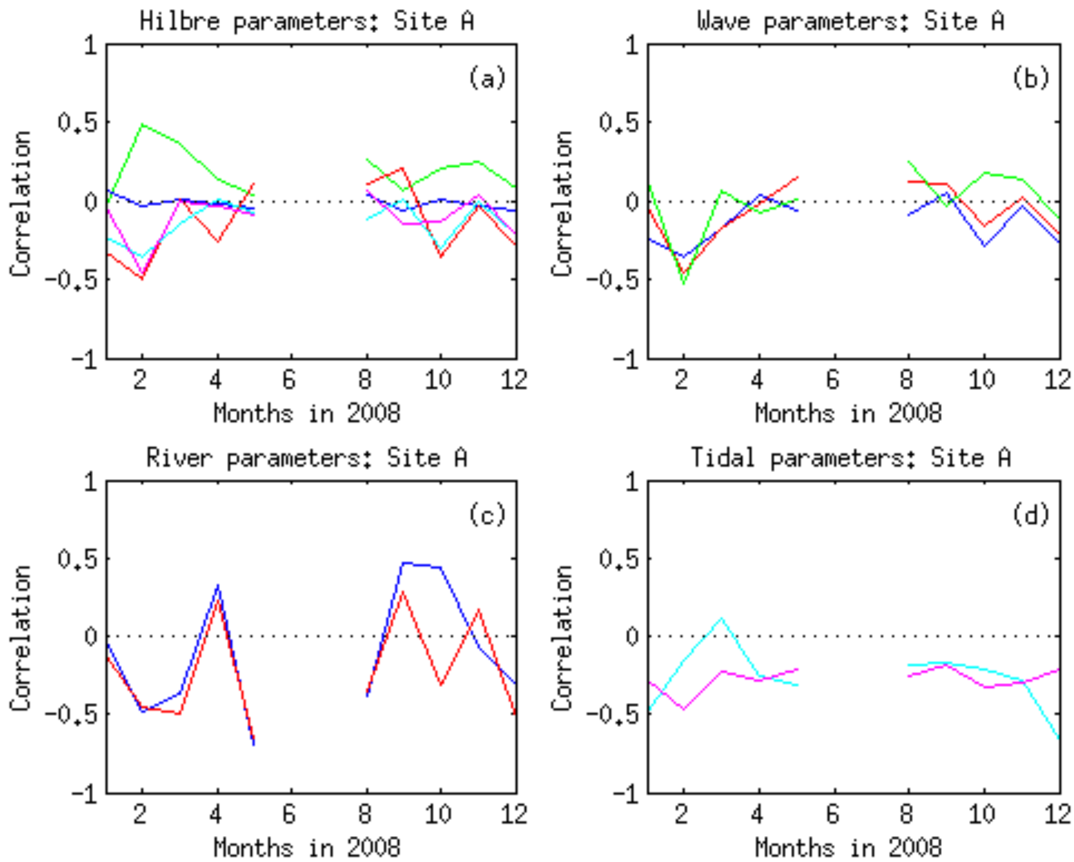

Figure 3: Monthly correlation values at site A plotted for (a) barometric pressure (green), precipitation (blue), atmospheric temperature (red), wind speed (cyan) and wind direction (magenta); (b) wave height (blue), peak period (red) and wave direction (green); (c) Dee (blue) and Mersey (red) river discharges; and (d) meteorological surge (magenta) and total high water (cyan).

Figures 3 and 4 show the monthly correlation values plotted as a time series for each parameter at sites A and B, respectively. Overall, the Hilbre parameters tend to remain near to zero with the exception of the peak in temperature in July at site B (Fig. 4a). The values at site A appear more variable to those at site B; Liverpool Bay has been shown previously to be a complex and highly dynamic region, which makes it difficult to model, especially at site A with its proximity to the estuary (O'Neill et al., 2012). Again at site B, the wave parameters stay just below zero for much of the year, diverging slightly in the last five months, whereas at site A a fairly strong negative correlation in all three wave parameters can be seen in February, the month in which many parameters experienced their best correlation values (Figs. 3b and 4b).

The tidal parameters show consistently negative correlation with one exception at each site (Figs. 3d and 4d). The river discharges visibly show the greatest variation at both sites (Figs. 3c and 4c). There is no obvious seasonal pattern in the correlation values.

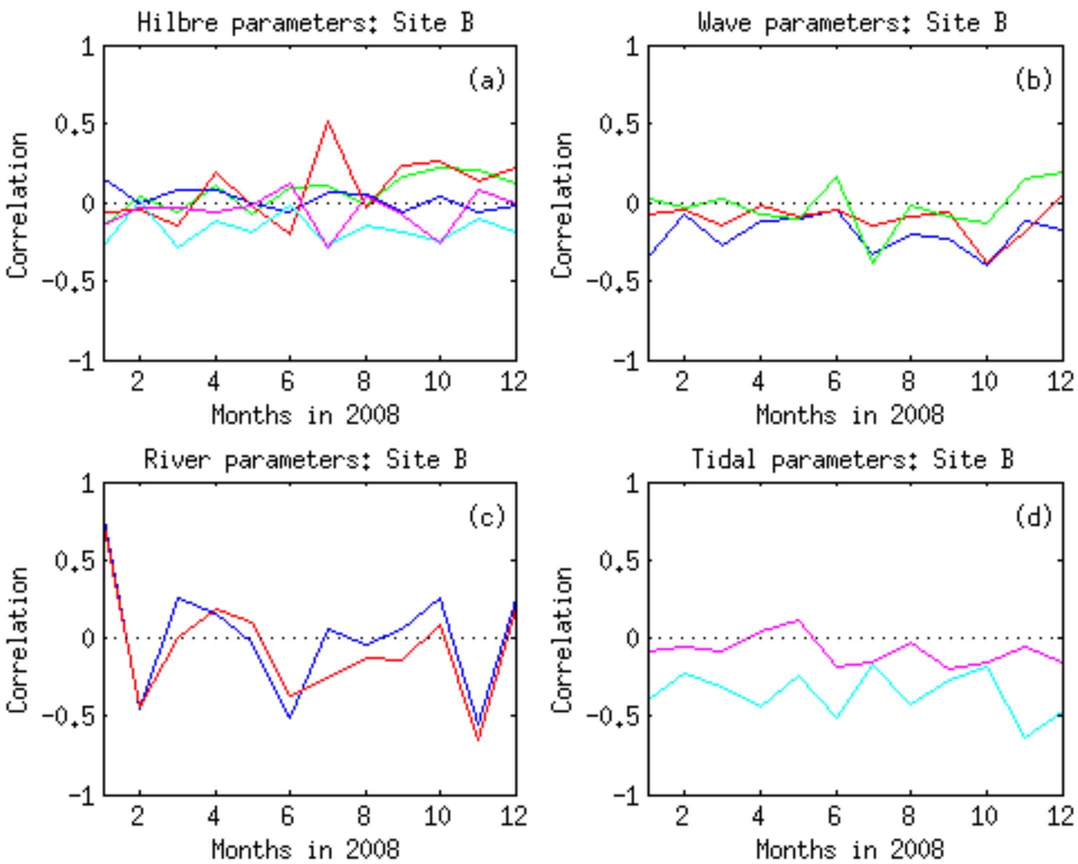

Figure 4: Monthly correlation values at site B plotted for (a) barometric pressure (green), precipitation (blue), atmospheric temperature (red), wind speed (cyan) and wind direction (magenta); (b) wave height (blue), peak period (red) and wave direction (green); (c) Dee (blue) and Mersey (red) river discharges; and (d) meteorological surge (magenta) and total high water (cyan).

4. Further Investigation

4.1 Influence of rivers and tidal straining

As the tidal and river parameters frequently show the best correlation, their time series are plotted against the density difference time series at both sites (Fig. 5). We can see that site A experiences greater differences between surface and bottom density – it is more stratified as it is closer to the freshwater influence of the estuaries – and that peaks did occur in the autumn coincidentally with higher river flows and also at the beginning of the year when the peak stratification appears to lag the high river flows seen. This is not so true at site B where the peak density differences occur in late spring and mid-summer with smaller peaks between and in mid-autumn. The period of zero density difference, indicating well-mixed water, during Feb/early March at site B does coincide with very low Mersey discharge and a drop (following a peak) in Dee discharge.

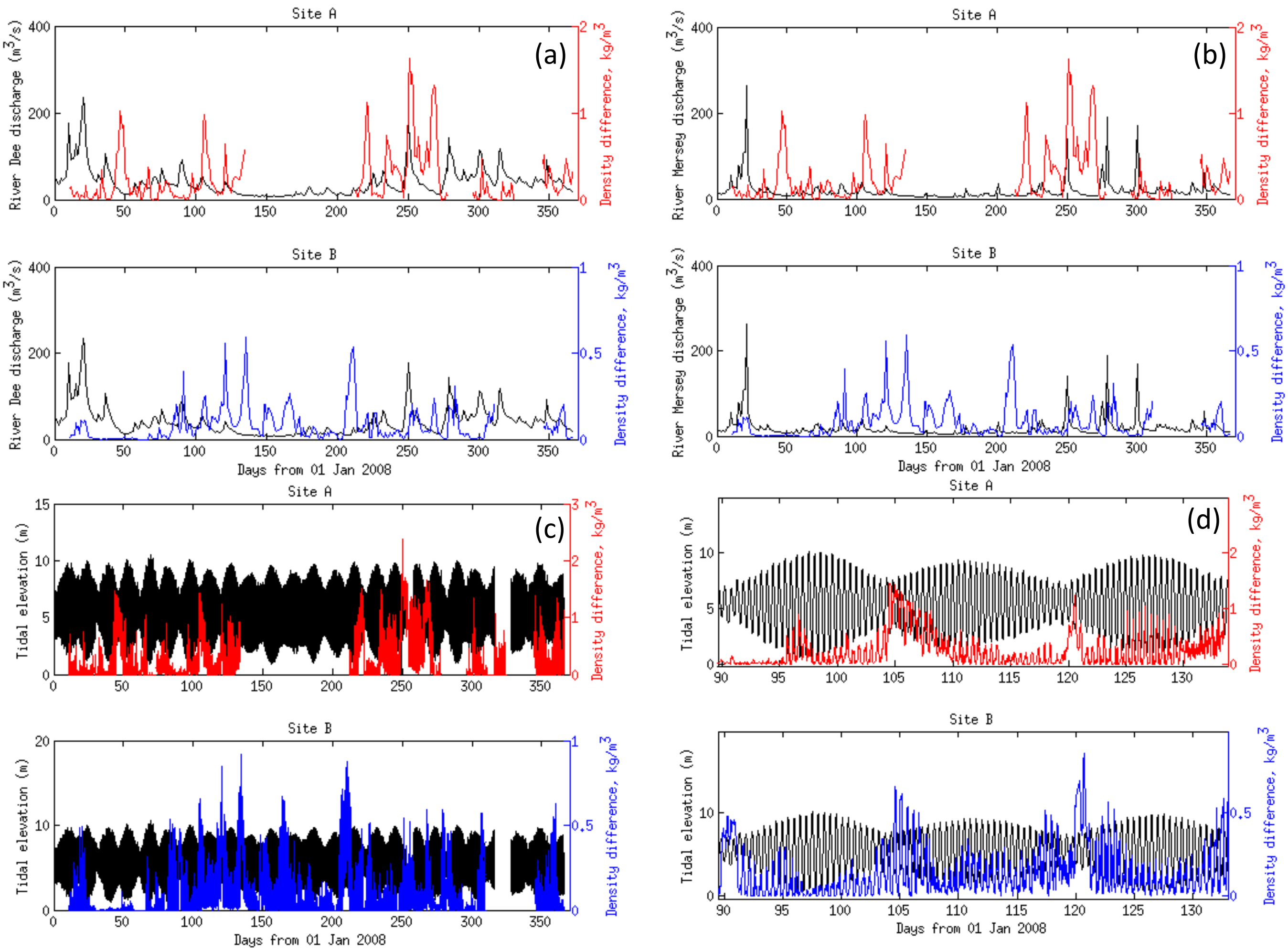

Figure 5: Density difference time series at site A (red) and site B (blue) plotted against metocean parameter time series (black) for (a) annual river Dee discharge, (b) annual river Mersey discharge, (c) annual tidal elevation, and (d) tidal elevation between days 90 and 135 of 2008. NB The density difference data is daily-averaged in plots (a) and (b) to correlate with the daily river flow data. Note the different axis scales for the two sites.

We have seen previously that tidal elevation correlates best with the density differences for half of the year at site B and Figures 5c and 5d clearly show peaks in density difference occurring at neap tide, and troughs occurring at spring tide, hence negative correlation. This represents strain induced periodic stratification (SIPS) further to the daily straining: during an ebb tide, the freshwater can advect over the more saline seawater away from the coast creating stratification. Whereas, during a flood tide the freshwater is prevented from extending and the water column is mixed (Simpson et al., 1990). Here, it is shown the less energetic tides enable stratification to occur, which is then slowly broken down as the tidal range increases towards spring tides. This suggests the spring-neap cycle is important in controlling where the frontal position is relative to the coast. Figure 5d clearly shows the semi-diurnal SIPS influencing the frontal position at daily time scales within the fortnightly cycle.

4.2 Combined river discharge

As the discharge from the rivers Dee and Mersey have a significant effect on stratification, their outputs were combined and these values correlated with the density differences at sites A and B (Tables 5 and 6).

Table 5: Annual correlation values for the combined river Dee and Mersey discharges at sites A and B.

Variable	r value	
	site A	site B
combined river discharge (m^3/s)	-0.10	-0.09

Table 6: Monthly r values for combined river Dee and Mersey discharges (m^3/s). The blue coloured boxes represent a correlation value better than the previous best at sites A and B recorded in Tables 3 and 4 respectively. The green colouring represents the month with the best correlation value overall including the data presented in Tables 3 and 4.

Combined river discharge	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Site A	-0.07	-0.48	-0.44	0.31	-0.69	NaN	NaN	-0.39	0.40	-0.05	-0.03	-0.42
Site B	**0.83**	-0.46	0.19	0.18	0.01	-0.57	-0.14	-0.08	-0.02	0.16	-0.59	0.24

Table 5 and Figure 6 show that combining the river discharges has no significant improvement on the correlation with the density differences at either site over the annual period. In Table 6, however, we can see that it now provides the best correlation overall out of all the parameters. The previous highest values were all attributed to the river Dee.

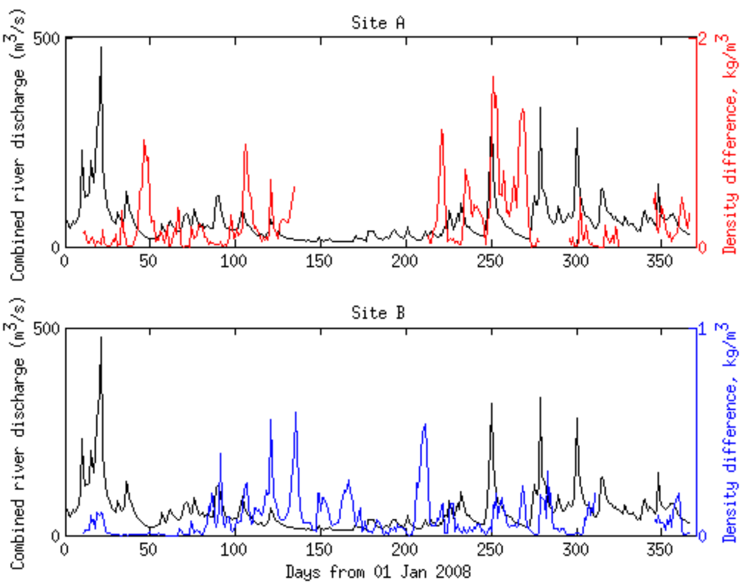

Figure 6: Density difference time series at site A (red) and site B (blue) plotted against the combined rivers Dee and Mersey discharge time series (black).

4.3 Effects of seasonality

Table 3 showed that eight of the twelve parameters studied experienced their highest correlation with the density differences at site A during February. As this seemed quite extraordinary, the time series of density difference at site A has been plotted for each month of 2008 (Fig. 7).

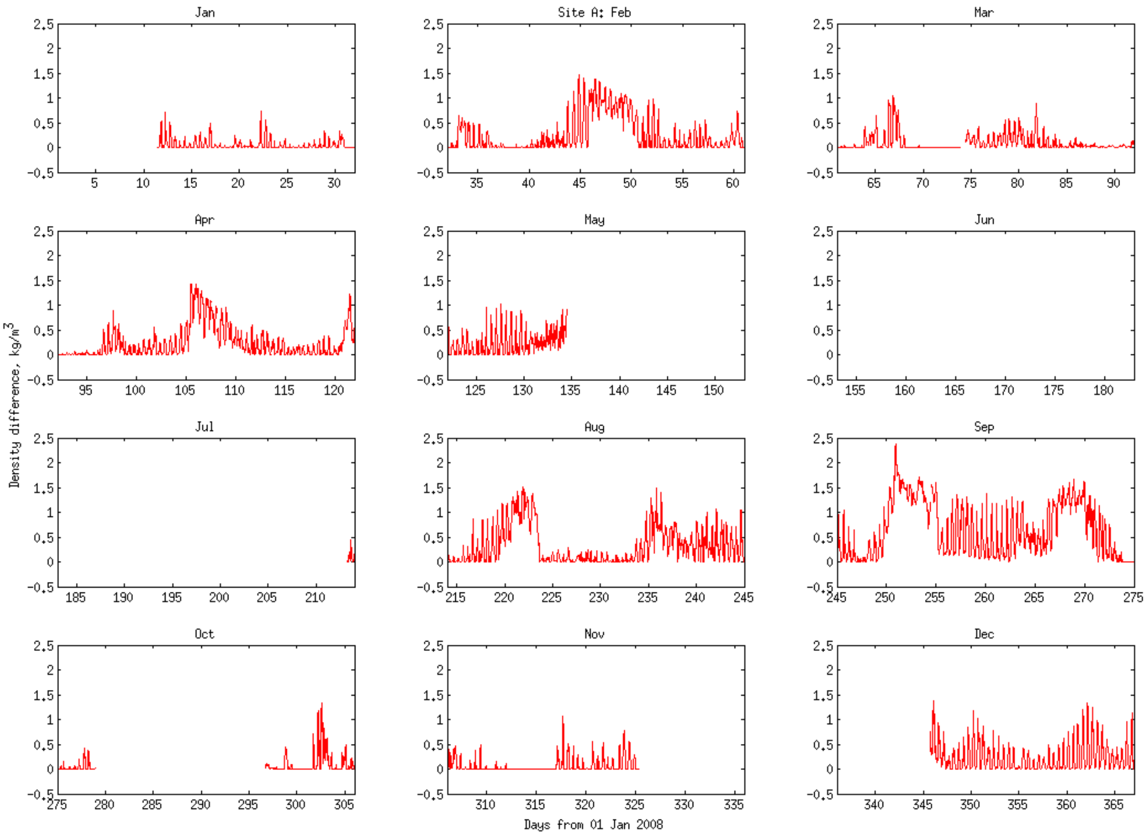

Figure 7: The density difference (kg/m^3) at site A plotted per month.

In Figure 7, we can see the lack of data for June and July, hence the NaNs for the correlations for these months. Also, there is a full month of data for February, which provides more data points to use for the correlation evaluation so could be improving the result, but this is also true of April, August and September. It is worth noting that in these four months of full data, the river Dee discharge shows the best correlation for three of the months at site A so the trend in dominance seen over the whole year is supported by these months. Equivalently, Figure 8 shows that there is a complete record of density difference data at site B for all months except January, November and December; of these nine months, tidal elevation provides the best correlation for six of them, supporting the overall annual trend seen of tidal dominance.

We can see that there is a peak in density difference in mid-February at site A. This particular period is highlighted in "Was 2008 a typical year in Liverpool Bay?" (Norman et al., 2014b) as being a time of the highest pressures seen in 2008, with the lowest temperatures, slow winds, low meteorological surge, small waves and low river flow. Hence, in the absence of strong tides or waves, the conditions are calm and stratification can occur without a particularly high river outflow, but with many parameters having an influence on the strength of stratification.

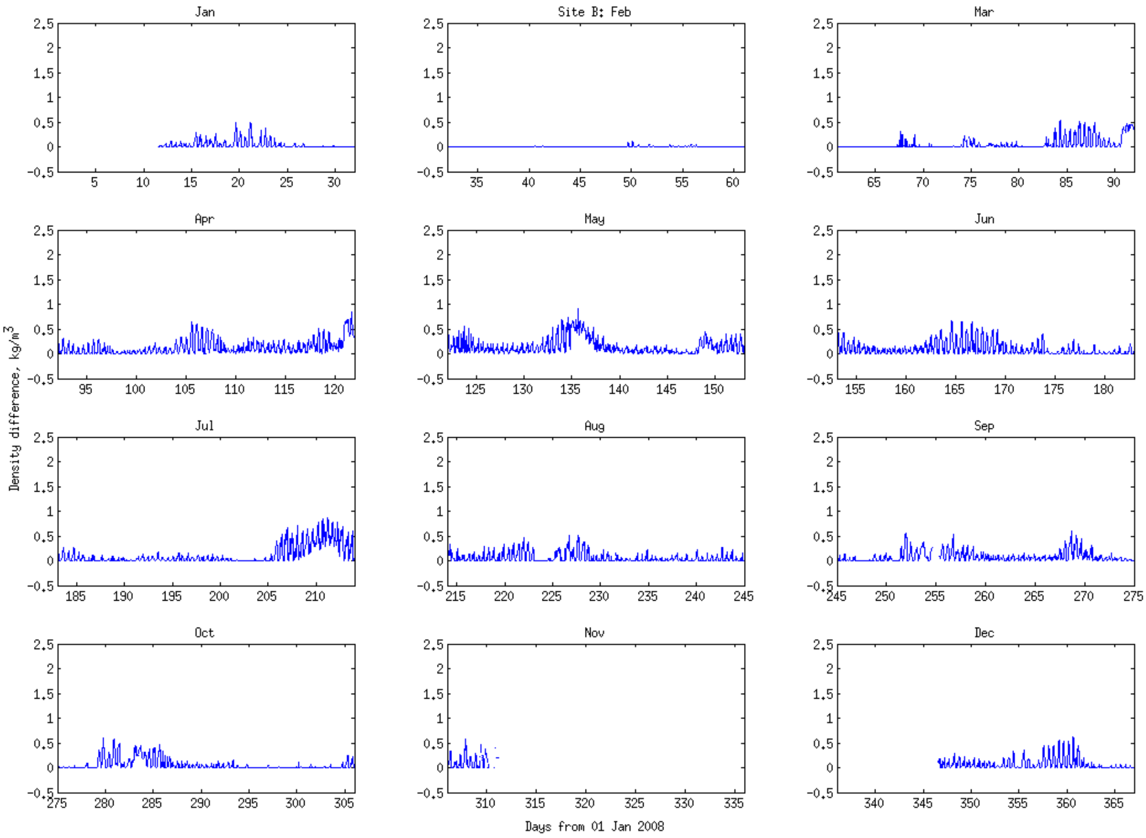

Figure 8: The density difference (kg/m^3) at site B plotted per month.

Site B shows weaker stratification at all times of the year and is more often well mixed. This is due to its greater distance from the three large estuary systems within Liverpool Bay, namely, the Dee, Mersey and Ribble. The continually well-mixed conditions during February are unexpected since site A shows periods of strong stratification. However, the observations in this month are not to be treated with caution due to suspected instrument failure, since model simulation confirms such conditions (Norman et al., 2014a). Both sites show a strong semi-diurnal oscillation in the time series data showing the importance of the tide in these hypertidal conditions.

4.4 Model capability

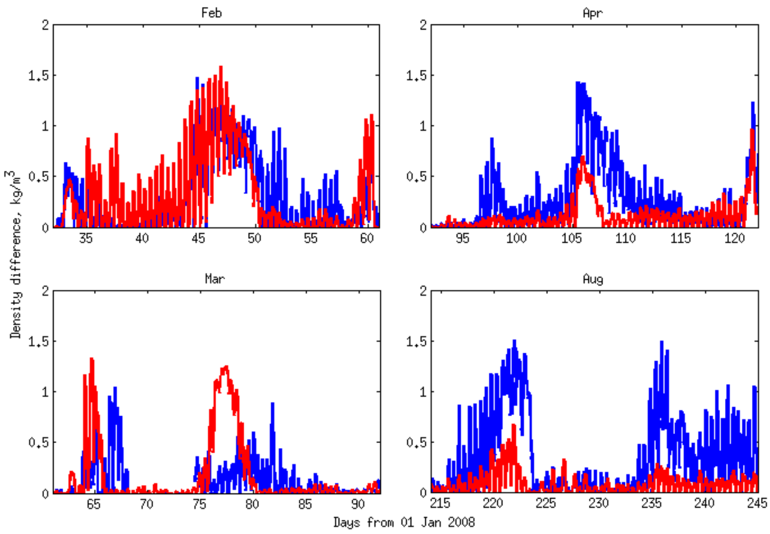

Figure 9: Examples of model performance (red) at mooring site A against observations (blue). Model shown is the POLCOMS model applied to the Irish Sea.

Figure 9 provides monthly examples of model performance at site A using POLCOMS with 1.8 km horizontal resolution and 32 sigma levels within the water column applied to the Irish Sea. The model performs well in February, which is the month in which many parameters have an effect, although there is a peak at the beginning of the month not seen in the observed data. In April, the model again performs well, replicating the trend but with slight under-prediction. The dominant parameter in driving stratification in April at site A was the river Dee discharge, with a positive correlation. This suggests better representation of the freshwater inflow is required within the estuary systems to improve the model simulation. In March, conversely, the model is over-predicting, and in October, the trend is captured, but is significantly under-predicted. The dominant drivers for these months were the rivers Mersey and Dee, respectively, but with negative correlations again suggesting improved riverine inflow is required within the model.

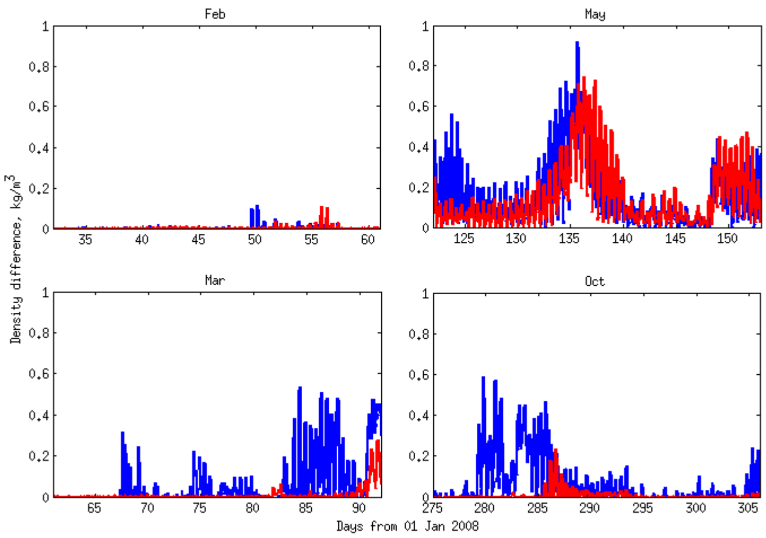

Figure 10: Examples of model performance (red) at mooring site B against observations (blue). Model shown is the POLCOMS model applied to the Irish Sea.

In Figure 10, we see examples of model performance at site B. February illustrates that the observed well-mixed conditions throughout the month were correctly simulated by the model. Again, in May, the trend is well replicated. In March, however, the model erroneously shows a month of mostly well-mixed water, which is not seen in the observed data. In October also, the model fails to simulate periods of stratification. Tidal elevation is the dominant driver in both May and March, and wave height in October, which suggests no correlation between the dominant driver and model performance.

5. Discussion and conclusions

- No parameter stands out as being singularly dominant in driving stratification over the whole annual cycle.
- The correlations are typically negative over the annual period showing the destructive influence of the processes investigated on the stratification. This was unexpected for river discharge showing the complexity of the interactive system.
- The flow rate from the river Dee shows the highest correlation with density differences at site A for much of the year, indicating stratification at site A is most influenced by riverine waters.
- Tidal elevation provides the best correlation values with the density differences at site B for much of the year, suggesting stratification at site B is mostly tidally influenced.
- The semi-diurnal oscillation within the density difference shows strong tidal straining. Filtering the data to remove energy at tidal frequencies may have improved the process correlations. A correlation between the tidal elevation and the signal removed by filtering may also have improved the tidal correlations.
- Site A shows greater differences in density between the surface and the bottom than site B. This is due to its closer proximity to the coast and the freshwater inflow.
- Waves occasionally provide the dominant influence at both sites, that is, when there is low river flow and calm atmospheric conditions, or equally under storm influence.
- Atmospheric temperature is best correlated with the density differences at site B in July, suggesting a seasonal influence on stratification here.
- Combining the two river flows had little impact on the correlations, but a possible further study could be to correlate the density differences to a variety of combinations of processes to investigate which interactive processes are dominant. This would require an in-depth modelling study.
- The atypical long period of well-mixed water at site B during February has shown the importance of using numerical simulation with observational data to give confidence in findings.
- There is not a clear driver for stratification that results in accurate or poor, under- or over-predicted model simulation.

6. References

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