3. Tide-Stratification Interaction in the Rhine ROFI Coastal Zone

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Abstract

The interaction between the semi-diurnal tide and the stratification field under the influence of the rotation of the Earth is investigated in the Dutch coastal zone. Our objective is achieved by adding powerful concepts to the Rhine region of freshwater influence (ROFI) body of literature.

First, upwelling, induced by tidal straining, was identified as a new key mechanism operating in the Rhine ROFI. The upwelling mechanism is detected using a 6-day unclouded series of KNMI NOAA-SST-imagery in May 1990 with about 2 images per tide. The ROFI is much warmer than the surrounding water, exhibits a distinct diurnal solar heating response and is clearly delineated by large spatial temperature gradients at the edges. This indicates that the whole ROFI area is stratified, an essential requirement for upwelling to occur. On three consecutive midday's a marked 5-10 km wide and 100 km alongshore band of cold upwelling water is visible along the coastline, while in the morning and afternoon this upwelling band is not present. The timing of this upwelling indicates that it is caused by tidal straining.

The existence of the upwelling mechanism was supported by simulations with the 3D numerical model of the idealized river plume. After adding temperature effects, the numerical model shows the same semi-diurnal band of cold upwelling water. We believe the presence of the 100 km long band shows for the first time the large spatial scale involved with the tidal straining mechanism of Simpson and Souza (1995) which was hitherto only observed in point observations.

In addition to the cross-shore tidal straining mechanism and the associated upwelling, the SST images also display a bulge of warmer water moving alongshore, independent of the cross shore straining. The movement of this bulge of warm water does not fit the cross-shore tidal straining paradigm. Therefore, a framework was subsequently developed that combines the observed tidal straining paradigm with the observed alongshore movements.

The well-known potential energy anomaly concept was for the first time applied with all terms. This forms the second simple, yet powerful contribution to meet our objectives.

i. Introduction

Artificial islands, harbor extensions and deepening of navigation channels, offshore sand mining, windmill parks, offshore gas extraction, disposal of dredged materials, illegal hull cleaning, marine nature reserves, fish quota and biodiversity. An almost endless list that shows that the seemingly wide and open North Sea is in fact a very versatile place. And fine sediments are right in the middle of it. Both physically – particles suspended by turbulence - and in terms of politics – by suspending laws. Sand extraction hoppers release small fractions fine sediments into the water causing unknown increases in turbidity levels. This potentially alters the light climate, impedes filter feeders, thereby possibly affecting the entire food chain. Furthermore, various pollutants are keen to attach to fine sediments, being released as harmful toxics into the water only decades later. The many unknowns concerning fine sediments made the Dutch Council of State delayed the mega-extension of the port of Rotterdam until more research was carried out.

Despite the large importance of fine sediments for the marine policy of the Dutch shelf and coast, there are still many unknowns. Even an essential figure as the net flux of fine sediments along the Dutch coast into the Wadden Sea is largely unknown today. The current estimates range from 1 to as much as 20 Megatons per year, with 1 Megaton being about a football stadium filled with mud.

The objective of this study is to gain a further understanding of the complex interactions governed by both tidal mixing and tidal straining on suspended particulate matter in the Dutch coastal zone.

Europe's largest river is in the coast

Unknown to many, Western Europe has a river carrying more water than the Mississippi. Official figures report the Rhine (2,500 $m^3.s^{-1}$) to be the biggest riverine flux of Western Europe. But, as soon as it debouches into the North Sea, it dilutes with 90 % seawater, yielding an increased volume flux of order 25,000 $m^3.s^{-1}$, ten times the Rhine flux and more then the Mississippi flux. This coastal river, river plume or Region Of Freshwater Influence (ROFI) in jargon, turns right after leaving the Dutch estuaries due to Earth rotation (Coriolis force) (Fig. B-3.1). The fresh water from the river is lighter than ambient North Sea water. This fresh water spreads pancake-like over the more salty ambient water, whereby all radial outward velocities are directed to the right and form half a cyclone structure. Where the cyclone hits the coast, the water is forced northwards, constituting a 10 to 30 km wide causeway for fine sediments northward. This flows along the European continent towards the tip of Denmark and beyond. The prevailing southwesterly winds and tidal asymmetry only add bit to this coastal river flux.

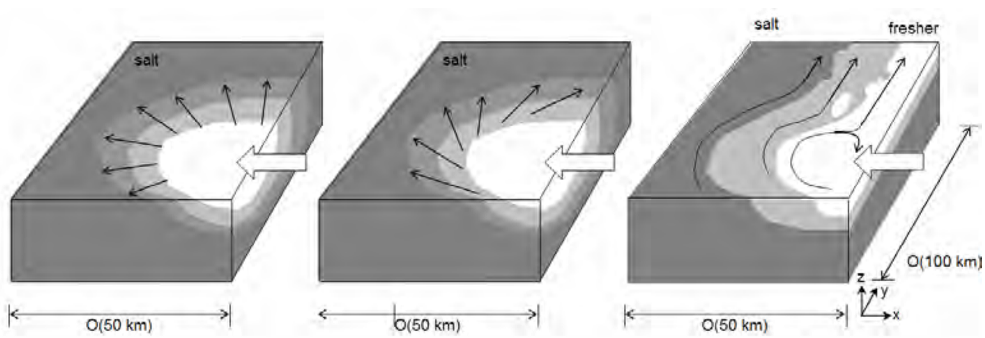

***Fig. B-3.1:** Schematic of how a river flow (the Rhine) generates a large coastal river with the coast 'at its right hand' under the influence of Earth rotation. This coastal flow is the dominant mechanism for the transport of fine sediments, pollutants, algae, nutrients etc.*

The area between Hook of Holland and Texel was examined using an idealized numerical model, remote sensing images and theoretical models. Assessing fine sediment fluxes in this area requires knowledge of supply of sediments, of upstream sources, of availability on the bed, and of transport capacity of the flow. This study focused on investigating the coastal river, a main source of uncertainty.

The Rhine ROFI exhibits a bi-model state

Previous studies in the early nineties by by Simpson and co-workers in the EU projects PROFILE (http://www.pol.ac.uk/coin/profile1.html) and PROVESS http://www.pol.ac.uk/provess/) identified that the Rhine ROFI is governed by two time scales in the stratification signal. First, the dominant cross shore density gradients in the Rhine ROFI compete with tidal/wind mixing to establish stratification. During spring tide and/or storms the whole area is well-mixed, i.e. there are only horizontal differences in salinity and no vertical differences. In contrast, during neap tide and in absence of storms a 30 x 100 km^2 area is stratified, i.e. there are strong vertical differences in salinity. During the well-mixed conditions the tidal currents are rectilinear alongshore, whereas under the stratified conditions the tidal currents exhibit ellipses that rotate anti-cyclonically at the surface and cyclonically at the bottom, resulting in strong cross shore exchange flows. These interact with the dominant cross-shore density gradients through differential advection, a process referred to as tidal straining by Simpson et al. (1990), to generate a semi-diurnal cycle of stratification. This is the second time scale.

Stratification has a profound effect on vertical distribution of fines, algae, nutrients, temperature and velocity structure. Nevertheless, the onset of stratification at neap, as well as the behavior of the ROFI during such a neap tide is very complex and is not fully understood yet today, despite neap tides occurring nearly half the time.

ii. New: tidal up and downwelling during neap tide

The dominant physics during neap tides was discovered by Visser et al. (1994) and Simpson & Souza (1995) as a special case of Prandle's (1984) classic theory on the vertical profile of tidal flows. During periods of stratification the surface layer is physically decoupled from the bottom layer, allowing different velocity patterns in the surface and bottom. You can image them as two layers with slippery green soap between. During normal Kelvin wave conditions (spring tide) the tidal velocities are alongshore southward during the ebb, alongshore northward during flood and zero during the two slack tides (Kelvin wave). These patterns hold for the entire depth. However, during periods of stratification the velocities in the surface layer behave differently showing pronounced differences over depth. The surface layers starts to rotate clockwise under the effect of Earth rotation, unimpeded by friction with the bottom layer from which it is detached. This causes a counterclockwise rotation in the bottom layer (Fig. B-3.2). Due to the opposed surface and bottom velocities the cross-shore velocity differences (shear) arise over depth up to 50 $cm.s^{-1}$. These shears deform the salinity field in a process known as tidal straining (Fig. B-3.3). These cross shore velocity differences alternatingly advect the fresher surface layer offshore and onshore. This process, known as tidal straining, is the dominant process during neap tides.

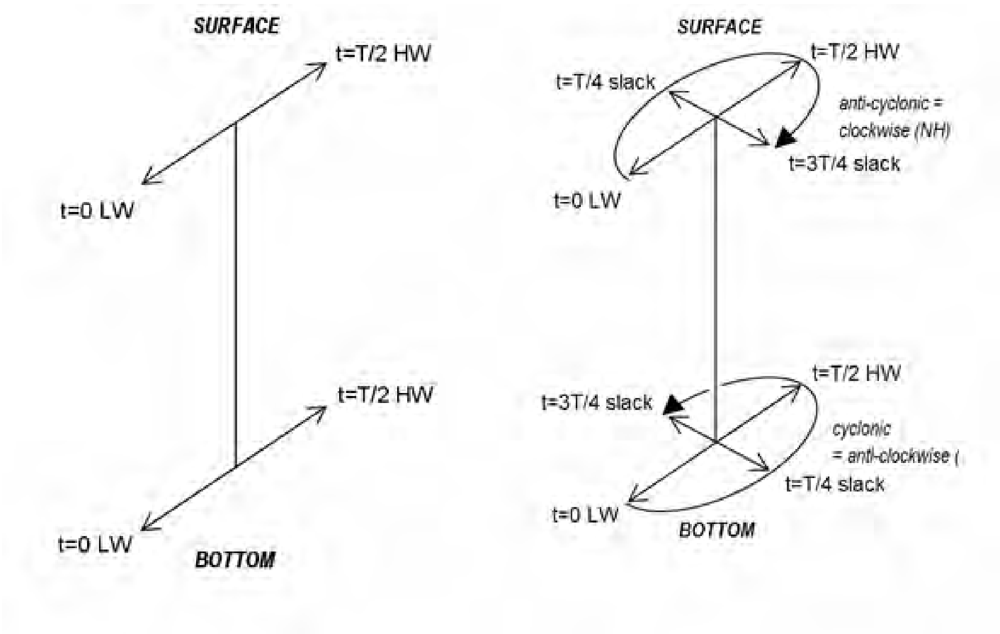

Fig. B-3.2: *Sketch of velocity profiles during normal cases (left) and stratified neap cases (right) in the Dutch coastal zone.*

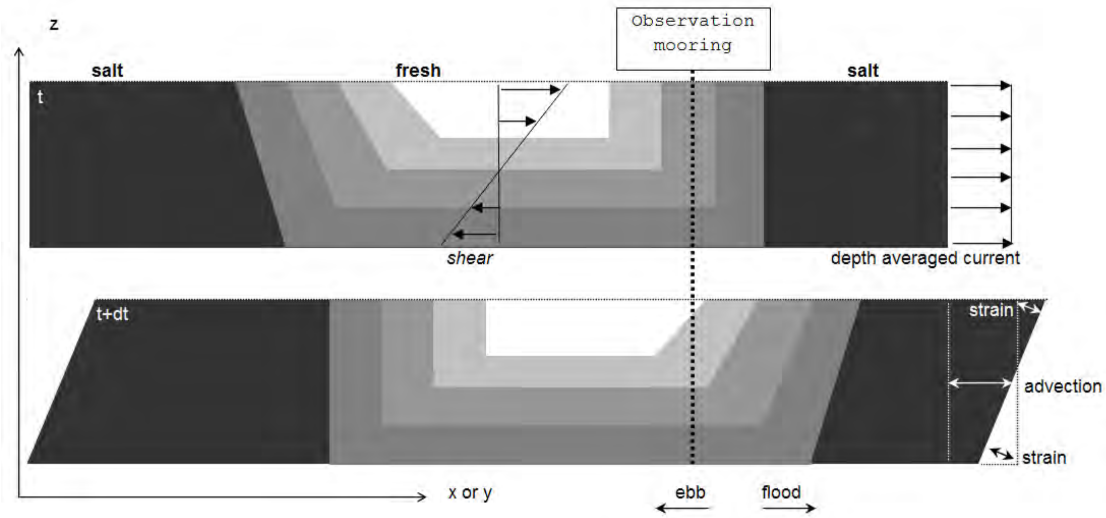

Fig. B-3.3: *A sketch of the combined effects of tidal straining and advection. Tidal straining causes the deformation of a depth averaged horizontal density gradient by a velocity shear, whereas advection describes the displacement of a low salinity structure (implying a vertical variation of the horizontal density gradient) by the depth averaged current without deformation. At a fixed mooring an observed increase in stratification can thus be caused by both advection and straining, in either x or y direction. The two processes have opposite effects on the opposite sides of the Rhine ROFI.*

In this study it was hypothesized that the known cross shore tidal straining process should theoretically lead to alternating up and downwelling near the coast. This cyclic upwelling pattern due to the tide was hitherto unknown. We corroborated its theoretical finding with remote sensing imagery and an idealized numerical model.

Remote sensing images could be used to detect the effects of tidal straining because the stratified areas in which this phenomenon occurs respond differently to solar heating than well-mixed waters. Solar radiation is adsorbed mostly in the surface layer, and is only subsequently mixed down into deeper layers. However, stratification inhibits mixing of warmer water into the bottom layer, leaving the heat in the surface layer. Therefore a stratified area shows a stronger increase in surface temperature than ambient well-mixed waters (Fig. B-3.4).

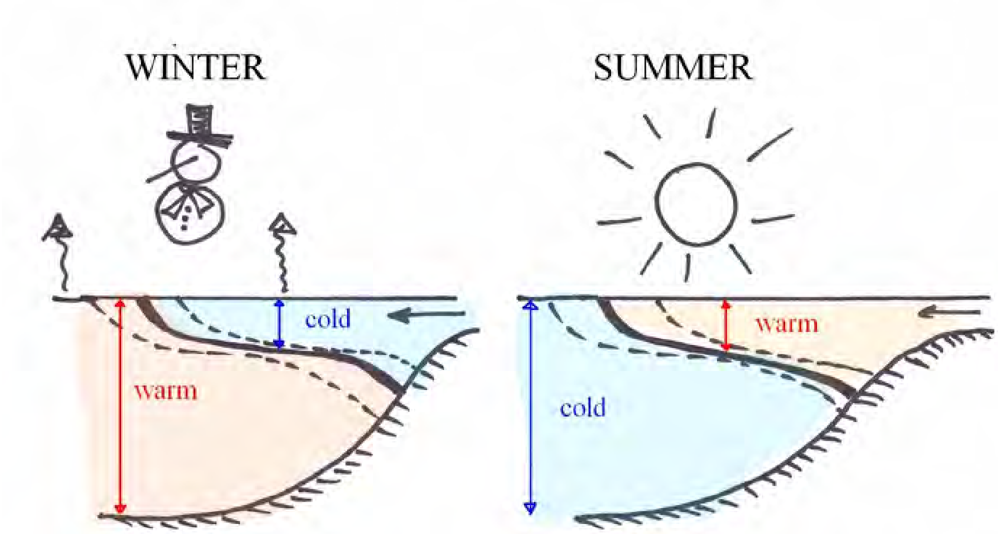

Fig. B-3.4: *Stratification by vertical gradients in salinity yields in summer a surface signature on the response to solar heating, and in winter time cooling.*

In May 1990 an excellent long series of Sea Surface Temperature images from NOAA-KNMI was available (Fig. B-3.5). Usually SST imagery have too low a temporal resolution to be able to detect tidal effects. But due the large number of unclouded images this series is a nice exception. The series of images shows the characteristic highlighting of the stratified area due to midday and afternoon solar heating, and cooling overnight. Remarkably, a 5 to 10 km wide band of cold water, with cold being the ambient temperature, appeared every high water, whereas at low water the band was very absent. The timing of the reappearing narrow band indicates this is due to the newly found tidal upwelling mechanism.

Next, a simple hydrodynamic model of a stratified Rhine plume was used to asses this assumption. In the model alternating up and downwelling was visible in the 3D velocity pattern, not possible with field measurements. After switching on atmospheric heat fluxes, the numerical plume shows the same characteristic SST response as observed in the remote sensing images. The presence of the narrow upwelling band in the model of the same area confirmed the presence of upwelling induced by tidal straining.

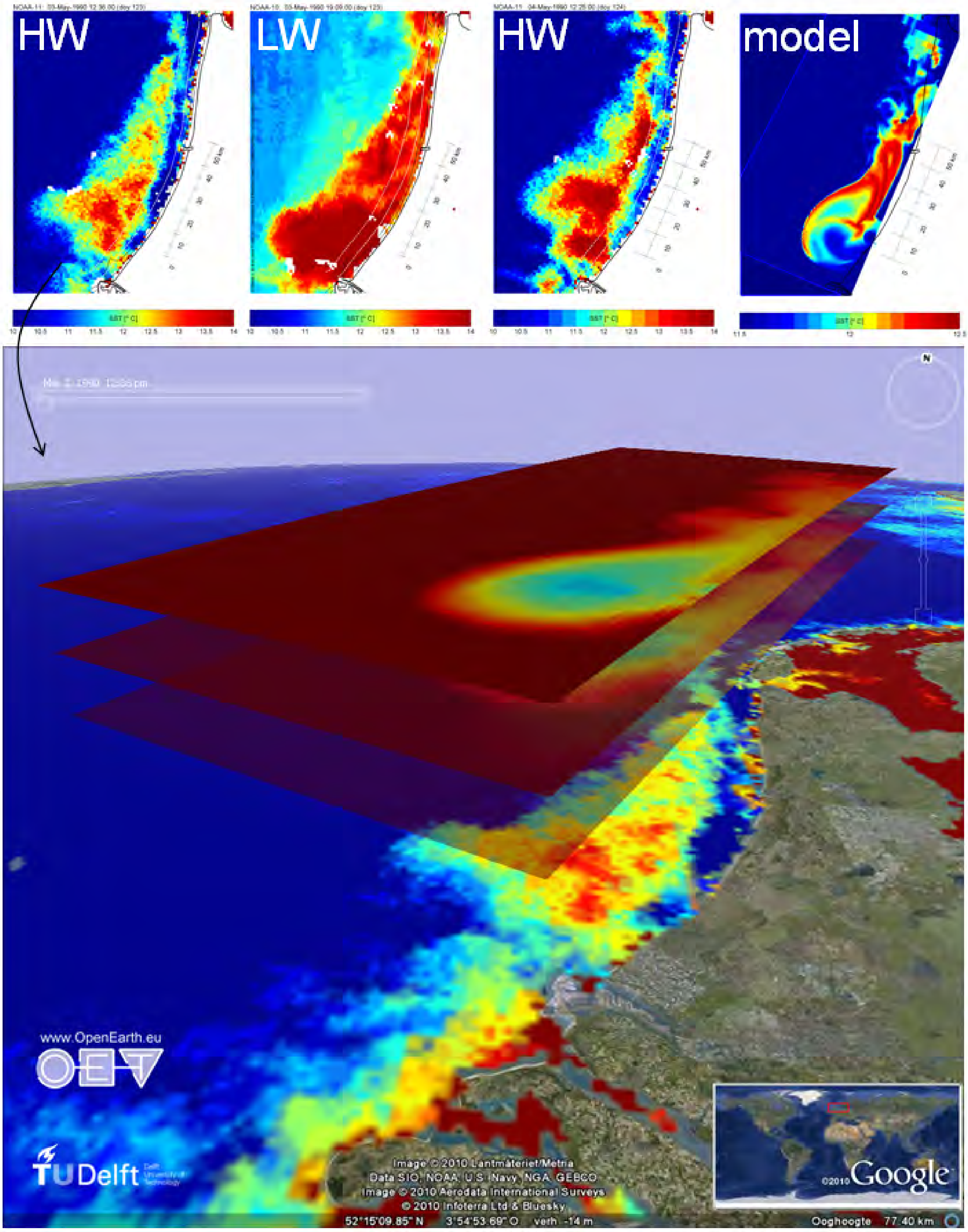

Fig. B-3.5: *Three subsequent KNMI NOAA SST satellites image of water surface temperature on May 3rd 1990 (blue=10°C, red=14°C). The 1st is high water, the 2nd is low water and the 3rd is the next high water, the 4th panel is the temperature calculated with an idealized numerical model at high water. The 1st satellite image is shown again in the Google Earth^{TM} mapping service panel. The blue cold band along the Dutch coast is caused by upwelling induced by tidal straining. Overlaid in the Google Earth panel are results of the 3D salinity structure from an idealized numerical model of the water movement in this area (blue fresher, red ambient salinity). The newly discovered upwelling induced by tidal straining is caused by the dominant stratification during neap tides as represented by the blue shades in the 1st and 3rd panel.*

iii. New: capturing the essence of 4D data

In addition to the cross-shore tidal straining mechanism and the associated upwelling, the SST images also display a bulge of warmer water moving alongshore, independent of the cross shore straining. The movement of this bulge does not fit the cross-shore tidal straining paradigm. Therefore, a framework was subsequently developed that combines the observed tidal straining paradigm with the observed alongshore movements. This forms the second simple, yet powerful contribution to meet our objectives.

For this framework the full potential energy anomaly equation suitable for the analysis of 3D numerical models is first derived. The ten terms that dominate the evolution of stratification in the Rhine ROFI are selected. These principal terms are the cross-shore and alongshore straining and cross-shore and along shore advection of horizontal density gradients. In addition, non-linear shear dispersion terms representing correlations between density and velocity perturbations over the vertical control horizontal exchange in the cross-shore and alongshore directions. Moreover, in the vertical direction one term describes the effect of vertical mixing on the density profile, while the other term is related to vertical advection, which we refer to elsewhere as upwelling and downwelling.

These ten terms are examined using the neap tide simulation of the Rhine ROFI that was used to analyze tidal upwelling before. Analysis of the model results using the potential energy anomaly equation allows us to present a detailed overview of the spatial distribution of the terms affecting the evolution of stratification. The results corroborate the important role that cross-shore tidal straining is known to play in the downstream coastal current region of the plume. In addition, the roles of alongshore advection, as well as alongshore and cross-shore straining are also of importance in the Rhine ROFI, in particular in the region of the bulge near the river mouth (Fig. B-3.6). The term ASIPS (advection and strain induced periodic stratification) is introduced in order to identify the joint action of these terms. ASIPS is shown to be a natural extension of the SIPS concept introduced by Simpson et al. (1990), but also forms the key subset of the terms in the potential energy anomaly approach. Near the edges of the river plume shear dispersion and upwelling and downwelling terms also play a significant role, indicating that a different physical balance is dominant than in the ROFI interior. Additionally, near the river mouth advection of fresh water lenses plays an important role. The results for the Rhine ROFI show that the potential energy anomaly equation and ASIPS constitute powerful tools to analyse the mechanisms contributing to mixing and stratification in coastal seas and estuaries.

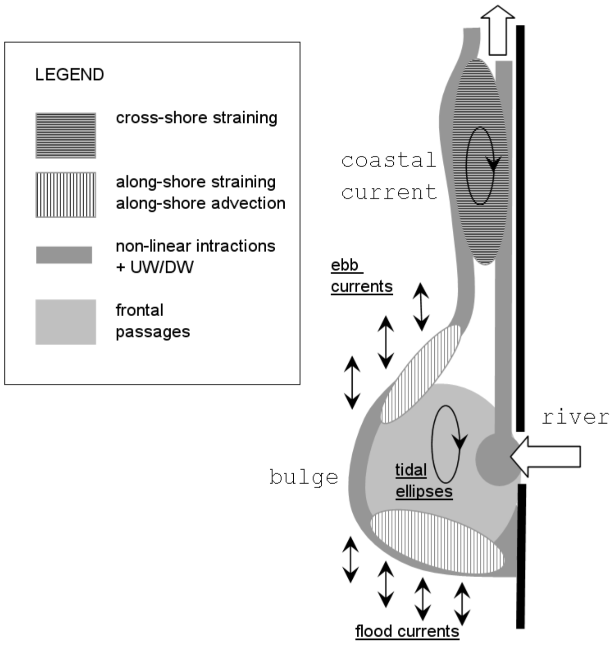

Fig. B-3.6: *A sketch summarising the dominant terms controlling stratification and mixing within the Rhine ROFI.*

In combination with temporal correlation analysis, the full potential energy anomaly equation allows for powerful aggregation of the plethora of 4D (x,y,z,t) data into manageable a 2D (x,y) bulk parameter fields. As the numerical models gain finer resolution nowadays in both space and time, the PEA method to obtain data reduction proved a very useful tool.

iv. Conclusions

In this LOICZ study two new concepts were found. First, upwelling induced by tidal straining was discovered to play a major role in the dynamic distribution of fresh water masses in the Rhine ROFI. Second, the full potential energy anomaly analysis was elaborated upon and proved an essential tool to aggregate 4D model outputs. Both new concepts led to a better understanding of the complex hydrodynamics required to assess suspended fine sediment transport into the Wadden Sea.

The main limitations for proper and further assessment of the fine sediment flux is the scarcity of in situ data in our opinion. Our main recommendation is therefore to aim for and organize an operational coastal observatory of the Dutch coastal zone, after the successful launch of similar coastal observatories in for instance Liverpool bay (UK) and the German Bight.

References

Borsje, B.W., De Vries, M.B., Hulscher, S.J.M.H. & De Boer, G.J. (2008). Modeling large scale cohesive sediment transport affected by small scale biological activity. Estuarine, Coastal and Shelf Science 78(3):468-480.

De Boer, G.J. (2009). On the interaction between tides and stratification in the Rhine Region of Freshwater Influence, PhD thesis, TU Delft, Delft, The Netherlands (http://resolver.tudelft.nl/uuid:c5c07865-be69-4db2-91e6-f675411a4136).

De Boer, G.J., Pietrzak, J. D. & Winterwerp, J.C. (2006). On the vertical structure of the Rhine region of freshwater influence. Ocean Dynamics 56(3-4), 198-216.

De Boer, G.J., Pietrzak, J.D. and Winterwerp, J.C. (2007). SST observations of upwelling induced by tidal straining in the Rhine ROFI. Continental Shelf Research 29(1):263-277.

De Boer, G.J., Pietrzak, J. D. & Winterwerp, J.C. (2008). Using the potential energy anomaly equation to investigate tidal straining & advection of stratification in a rofi. Ocean Modelling 22(1-2):1-11.

Pietrzak, J.D., G.J. de Boer, M.A. Eleveld (2011). Mechanisms controlling the intra-annual mesoscale variability of SST and SPM in the southern North Sea, accepted Continental Shelf Research, doi:10.1016/j.csr.2010.12.014.

Vinzon, S.B., Winterwerp, H., De Boer, G.J. & Nogueira (2008). Mud deposit formation on the open coast of the larger Patos Lagoon-Cassino Beach system. Continental Shelf Research 29(3):572-588.