MODELLING THE IMPACT OF THE RIVERS SCHELDT AND RHINE/MEUSE ON THE SALINITY DISTRIBUTION IN BELGIAN WATERS (SOUTHERN NORTH SEA)

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Abstract

In order to manage effectively eutrophication problems in the Belgian Exclusive Economic Zone (EEZ), it is necessary to establish a scientific understanding of cause-effect relationships between changing human activities and ecosystem response. In particular, it is crucial to know the relative contribution of each river (in terms of both magnitude and spatial distribution) on the nutrient stock in order to design and legislate appropriate measures for nutrient reduction in this area. One preliminary approach to such a sustainable development preoccupation consists in answering to the question "where does Belgian water come from?" To answer this question a 3D hydrodynamical model has been set up to describing the distribution and variability of the salinity of Belgian coastal waters. Particular attention was paid to determining the relative impact of the Scheldt and Rhine/Meuse freshwater plumes and testing the hypothesis that the salinity of Belgian waters is primarily a mix between salty offshore water and freshwater from the Scheldt Estuary. Attention was also paid to determining whether the Seine has significant impact on the Belgian zone. The 3D hydrodynamical model has been applied to the Channel and the Southern Bight of the North Sea for the period 1993-2002. Real river runoffs have been taken into account for the main rivers within the domain: the Scheldt, the Rhine/Meuse, the Seine and the Thames. Model tracers were used to characterise the signature of water masses in terms of Atlantic and riverine waters. Results indicate that the salinity of Belgian waters is dominated by inflow of the Channel water mass which mixes with freshwater originating mainly from the Rhine/Meuse with a much smaller contribution from the Scheldt Estuary. Thus, the "generally accepted" hypothesis of a “continental coastal river” with fresher coastal water flowing North-eastward up the French-Belgian-Dutch coast and picking up freshwater from successive outflows seems inappropriate for Belgian waters. This new view of the water masses considers not just the North-eastward residual current, which would advect Rhine water away from the Belgian EEZ, but also the horizontal diffusion of freshwater induced by tidal advection, which acts both north-eastward and south-westward and over a considerable distance.

Introduction

For most coastal regions, there is little transfer of salinity across the air-sea and sea-bottom interfaces and negligible change in salinity from biological or chemical interactions. Salinity is, thus, referred to as a conservative quantity, which is merely transported by advection and diffusion processes and hence provides a good tracer of water masses. In particular, since rainfall has effectively zero salinity in contrast to typical oceanic waters, which usually have salinity of about 35, the salinity of coastal water allows determination of the fraction of water originating from river discharge and thus an appreciation of the extent of freshwater influence. This is crucial in interpreting ecosystem functioning and salinity is recorded as a routine auxiliary measurement for nearly all biological or chemical data sets. If further conserved quantities or tracers can be identified then the salt/fresh water fraction of seawater can be further decomposed and the different origins of the water in terms of fractions of water from distinct water masses can be more precisely determined. Typical tracers include temperature (for regions where air-sea heat flux can be neglected), dissolved silicates (for periods when biological uptake can be neglected), and radioactive elements. However, for Belgian coastal waters there is presently no valid second tracer. Therefore it is possible from field observations to determine only to what extent oceanic water has been mixed with freshwater but not the specific riverine origin of freshwater. This problem can lead to incorrect or uncertain interpretation of the relative importance of different rivers, for example by mistaking the impact of the Rhine/Meuse plume for the Scheldt plume. In the present study a 3D model is used to simulate the salinity distribution allowing the influence of different rivers to be clearly distinguished by adding tracer state variables. The object and domain of interest of the present study is the salinity distribution in Belgian waters, as defined by the Belgian EEZ, and the adjacent waters of the Channel and the Southern Bight of the North Sea insofar as they impact the Belgian EEZ.

Based on salinity and temperature measurements recorded for nearly a century, the hydrographic regime of the Southern Bight of the North Sea has been classified according to three distinct water masses (Dietrich, 1950; Laevastu, 1963; Lee, 1980) as illustrated in Figure 1: (a) Channel water, which penetrates northward through the Dover Straits into the central region, (b) English Coastal water, along the coast of Southeast England, and (c) Continental Coastal water, a band of fresher water which extends from somewhere East of Calais along the Belgian-Dutch-German coast. The latter represents a mixture of Channel water with the continental coastal rivers such as the Western Scheldt and the Rhine/Meuse. The origin of freshwater within this band of Continental Coastal water is clearly the discharge from continental rivers. However, there remains some uncertainty about the relative geographical impact of each individual river. One popular conceptual picture is that of a “coastal river”(Salomon, 1992) flowing along the Northeast coast of France north-eastward along the Belgian, Dutch and German coasts into the German Bight, picking up freshwater and associated nutrients successively from the rivers Seine, Scheldt, Rhine/Meuse, Elbe and Weser and smaller rivers. The importance of such conceptual hydrological models is justified by their use to explain and interpret biological and chemical distributions. For example, maps showing the north-eastward residual transport are frequently reproduced in biological (Lancelot *et al.*, 1987; Lancelot *et al.*, 1997; Nihoul and Hecq, 1984; Schaub and Gieskes, 1991) and chemical (Baeyens *et al.*, 1998; Borges and Frankignoulle, 1999) studies often implying a one-way impact of “upstream” waters on waters further to the North-east.

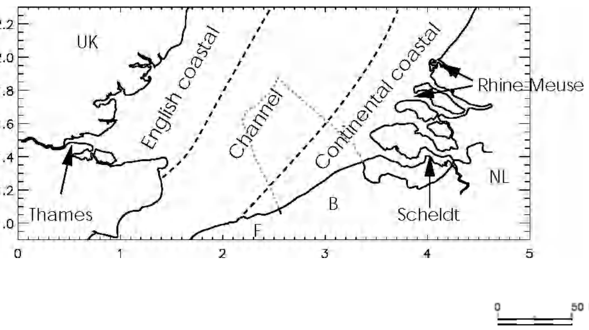

Fig. 1. The Southern Bight of the North Sea showing the classification of water types suggested by (Laevastu, 1963) and many subsequent studies (Hill, 1973; Lee, 1980; Otto et al., 1990), demarcated here by the dashed lines. The coastal states of the United Kingdom, France, Belgium and the Netherlands are denoted by capital letters and the main river estuaries are located by arrows. The Belgian EEZ is delimited by the dotted line

Proximity to the Scheldt Estuary mouth has also been cited (Warnock *et al.*, 1999) as a reason for supposing that freshwater influence on coastal waters is dominated by the Scheldt discharge. With one notable exception (Van Bennekom and Wetstijn, 1990), it is generally assumed that the salinity of Belgian waters is influenced primarily by Channel water from the South-west and by the Scheldt "plume" presumably on the basis of the appeal of the "coastal river" conceptual model and on the proximity of the region to the Scheldt discharge. In the present study, this hypothesis is tested directly by numerical model simulations. These simulations allow a clearer distinction between freshwater originating from different rivers than has been possible before by analysis of salinity measurements alone.

Model description

The salinity in the Southern Bight of the North Sea (SNS) and the Channel is modelled here using a 3D hydrodynamic model based on the COHERENS model (Luyten *et al.*, 1999). The model has been set up for the region between 48.5°N and 52.5°N using a 109x97 horizontal grid with resolution 5′ longitude (approx. 5.6 km) by 2.5′ latitude (approx. 4.6 km) and with 5 vertical sigma coordinate layers. A simulation is carried out for the period 1993-2002. All details concerning implementation, forcing, initial and boundary conditions can be found in Lacroix *et al.*(2004). For the four main rivers, the Rhine/Meuse (two different sources: Maassluis and Haringvlietsluis), the Scheldt, the Seine and the Thames the transport is imposed by temporal interpolation of daily measurements of flow rate for the Rhine/Meuse, Seine and Thames and 10-day measurements of flow rate for the Scheldt. To ensure salt conservation the incoming salinity at the river boundaries is set to zero. In addition to salinity and temperature, further transport equations are solved for 7 passive tracers, corresponding to water initially within the domain and water from the open boundaries as follows: Channel, Central North Sea boundary, and the Scheldt, Rhine/Meuse, Seine and Thames river boundaries. Each tracer is governed by an advection-diffusion equation identical to that for salinity except that for inflow open boundaries the tracer corresponding to that boundary is set to 1.0, while all other tracers are set to zero. Thus, for example, a Channel tracer concentration of 0.5 corresponds to 50% Channel water. Within the domain, and throughout the duration of the simulations, the sum of all tracers present at any point is equal to 1.0 to within the truncation error of the numerical method.

Results

Results are presented for the salinity field averaged over the period 1993-2002 and for corresponding tracers showing the contribution of freshwater from the Scheldt, the Rhine, the Seine and the Thames to this salinity distribution.

Figure 2 shows the modelled surface salinity averaged over the years 1993-2002. The band of lower salinity water along the Belgian and Dutch coasts identified by previous investigators (Lee, 1980) is clearly reproduced here. However, as with previous studies, such information alone does not allow a clear determination of the origin of this freshwater. Conceptually one could hypothesise that this salinity field results from two plumes, one from the Scheldt and one from the Rhine, of comparable extent with a slight overlap of the two plumes somewhere between the two estuary mouths. This hypothesis would imply that the freshwater in the Belgian EEZ originates primarily from the Scheldt Estuary. Similarly on the basis of Figure 2 alone the saltier origin of offshore water might originate from the Channel or the Central North Sea. *In situ* surface salinity measurements averaged over the period 1993-2002 from the BMDC[1] and the RIKZ[2] and averaged over the period 06/98-10/99 from MAREL[3] are also shown in Figure 2 for comparison with the model results. The observed inshore-offshore salinity gradient and salinity increase going South-west along the coast from the Scheldt Estuary mouth are clearly reproduced by the model. Globally, model results are in good agreement with data except close to the Rhine mouth and further North where predicted salinity is lower than observations. Small differences are not unusual for modelled salinity distributions in coastal waters, where simulations are sensitive to both the parameterisation of mixing processes and to the salinity boundary data which is generally not well-known. In the results shown here, the main discrepancies are restricted to the area close to the northeast boundary (Figure 2). A more detailed time series validation of model results, not shown here, can be found in Lacroix *et al.* (2004).

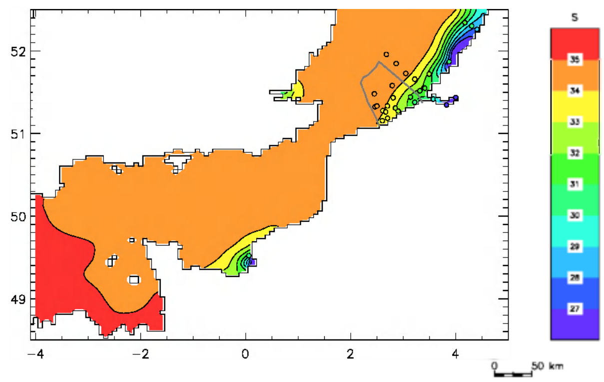

Fig. 2. Surface salinity (psu) averaged over the duration of the 1993-2002 simulation for model results (background colouring) together with in situ measurements averaged over the period 1993-2002 (BMDC1 and RIKZ2 data) and over the period 06/98-10/99 (MAREL3 data) superimposed as coloured circles. The Belgian EEZ is delimited by the solid line.

[1] Belgian Marine Data Centre, http://www.mumm.ac.be/datacentre/

[2] Rijks Instituut voor Kust en Zee, http://www.waterbase.nl

[3] MAREL-NORMANDIE, http://www.ifremer.fr/lern/Pages/Programme/marel.htm

Figure 3 shows the 1993-2002 averaged seasonal variation of the water masses at station 330 of the Belgian water quality monitoring network (51° 26.00' N, 2° 48.50' E, shown on Figure 4) as computed from simulated tracer fractions for water originating from the Channel, the Central North Sea and the Rhine, Scheldt and Seine Estuaries. Clearly Channel water dominates (0.955 in average ±0.024) with negligible contribution (0.002 in average ±0.003) of Central North Sea water. In this simulation the contribution of Thames water fraction, typically of order 10^{-4} is negligible compared to the Seine fraction (0.008 in average ±0.003) and the Scheldt fraction (0.013 in average ±0.008), and is not shown here. Comparing the river water fractions indicates that the freshwater influence at station 330 is mainly due to the Rhine estuary (0.019 in average ±0.016) with the fraction arising from the Scheldt generally smaller (except during February-March) with a ratio Rhine:Scheldt which varies between about 0.5 and 2.5 (1.5 in average) depending on wind strength and direction. The Rhine, Scheldt and Central water contributions at station 330 vary seasonally and reach a minimum during the winter period when south-westerly winds are stronger. In contrast, the Seine water fraction is relatively constant. Because of the greater distance from the Seine to the Belgian EEZ, horizontal mixing causes lower horizontal gradients of Seine water fraction in the far-field of this plume and consequently less temporal fluctuation from horizontal advection.

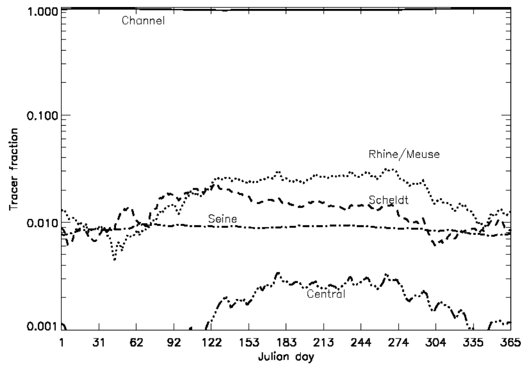

Fig. 3. Time series of the daily-averaged tracers for Channel water (solid line), Central North Sea water (dash-dot-dot-dot line), Rhine/Meuse water (dotted line), Scheldt water (dashed line) and Seine water (dash-dot line) presented here as an average over the period 1993-2002 at station 330 of the Belgian water quality monitoring network (51° 26.00' N, 2° 48.50' E, shown on Figure 4).

Figure 4 shows the 1993-2002 average horizontal distributions of the Channel, the Central North Sea, the Rhine, Scheldt, Seine and Thames water fractions. Clearly (Figure 4, upper panel) the Channel water spreads well into the Southern Bight of the North Sea, as found by Jones and Howarth (1995), with only a slight reduction of the Channel water fraction along the Belgian and Dutch coasts because of river water but a more significant reduction at the North boundary of the model domain due to the inflow of Central North Sea water. In this respect it is noted that the impact of Central North Sea water may well be under- or overestimated in this model particularly close to the Northern open sea boundary. However, such model weakness should not affect significantly results obtained for the Belgian EEZ which forms the focus of this study. Figure 4 (lower panel) suggests that the Rhine water spreads a considerable distance southward from the estuary mouth, reaching both the nearshore and the central parts of the Belgian EEZ. On the other hand Scheldt water is limited mainly to the estuary mouth and to a lesser extent to nearshore and central Belgian waters too. It is interesting to note that this simulation suggests that Rhine water extends even into the Scheldt Estuary, a result that may be important for studies of the Scheldt Estuary which traditionally assume a mix between two water masses, Scheldt water and "North Sea" water. In fact, this North Sea water may itself be a mix of Channel water and Rhine water. The current model lacks spatial resolution within the Scheldt Estuary to explore further such a possibility. However, this simulation does provide a warning that the conventional assumption that freshwater within the Scheldt Estuary originates solely from the Scheldt river basin may not be so reliable as it would intuitively seem.

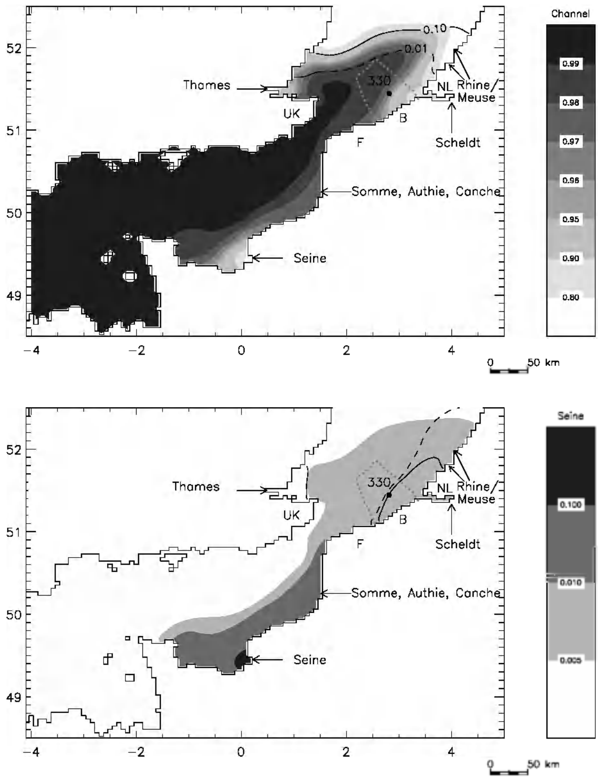

Fig. 4. Map showing model results averaged over the duration of the 1993-2002 simulation for tracer fractions. Upper panel: for Channel water (grey-scale colour map) and Central North Sea water (superimposed black isolines, solid line =10%, dashed line=1%).Lower panel: for Seine water (grey scale colour map, 0.5%, 1%, 10%), for Scheldt and Thames water (superimposed solid line, 1%), for Rhine/Meuse water (superimposed dashed line, 1%). The Belgian EEZ is delimited by the dotted line and the dot denotes the station 330 of the Belgian water quality monitoring network. Redrawn from Lacroix et al. (2004).

Discussion

This paper presents model studies designed to determine the origin of freshwater in the Belgian EEZ. The use of model state variables which trace water originating from different model boundaries, shows clearly that the dominant water mass in this region originates from the Channel. The model reproduces the coastal band of fresher water which is well known from previous studies. However, analysis of the model tracers and numerical experiments where the Scheldt discharge and the Rhine discharge are set separately to zero indicates that the freshwater which reduces salinity in the coastal strip of the Belgian EEZ with respect to offshore water originates primarily from the river Rhine and not, as supposed in previous studies, solely from the Scheldt Estuary (Lacroix *et al.*, 2004). The present study thus suggests a new conceptual model of the origin of water masses in this region (Figure 5), representing a major change from the previously accepted understanding.

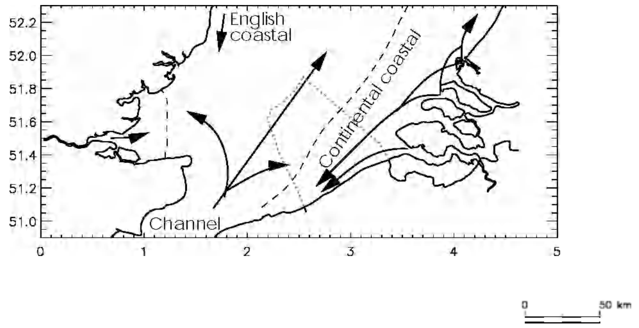

Fig. 5. New conceptual model of water masses and dispersion of river water in the Southern Bight of the North Sea derived from the present study. Arrows denote dispersion paths, not residual currents. The Belgian EEZ is delimited by the dotted line.

This change considers not just the North-eastward residual current which would advect Rhine water away from the Belgian EEZ, but also the horizontal diffusion of freshwater induced by tidal advection which acts in both alongshore directions and over a considerable distance. In this simulation more than 1% of the water found at the French-Belgian coastal border originated from the Rhine estuary and the salinity within the Scheldt Estuary was significantly affected by freshwater from the Rhine intruding via the estuary mouth.

Now that reasonable confidence has been established in the modelling of salinity in the Belgian EEZ work is in progress to couple this 3D hydrodynamic model with the biogeochemical MIRO model (Lancelot *et al.*, 1997) in order to simulate the dispersion of nutrients from coastal rivers and their subsequent impact on the coastal ecosystem, with particular emphasis on algal blooms. This latter application is motivated by the need of environmental managers, as stated in the OSPAR strategy on eutrophication (OSPAR Commission for the Protection of the Marine Environment, 1998), to make every endeavour "to reach, by 2020, and maintain a healthy marine environment where eutrophication does not occur".

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