Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea)

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Abstract

A 3D hydrodynamical model has been set up to describe 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, based on COHERENS, has been applied to the Channel and the Southern Bight of the North Sea using a 5° (longitude) by 2.5° (latitude) grid. The model has been run for the years 1991–2002. 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. This conclusion is further supported by simulation results obtained when each river discharge is separately set to zero. Thus, the `generally accepted' hypothesis of a 'continental coastal river' with freshwater coastal water flowing north-eastward up the French-Belgian-Dutch coast and picking up freshwater from successive outflows seems inappropriate for Belgian waters where horizontal dispersion of Rhine/Meuse water in the opposite direction is significant.

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1. Introduction

The objective of this paper is to describe the distribution and variability of the salinity in Belgian coastal waters and to determine the relative impact of the Scheldt and Rhine/Meuse freshwater plumes.
Practical salinity, referred to hereafter as salinity, is defined (UNESCO, 1981) by relating the electrical conductivity of seawater to the conductivity of a standard solution of potassium chloride and is closely related to the concentration of chloride in water. 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 a salinity of about 35, the salinity of coastal water allows the 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 conservative 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 and by performing simulations with modulation of each river discharge.

The object and domain of interest of the present study is the salinity distribution in Belgian waters, as defined by the Belgian Economic Exclusion Zone (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 Fig. 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

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Fig. 1. The Southern Bight of the North Sea showing the classification of water types suggested by (Laevastu, 1963) and many subsequent studies (HIB, 1973; Lee, 1980; Otto et al., 1990), demarcated here by the dashed line. 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.
Scheeldt and the Rhine/Meuse, hereafter referred to as the Scheeldt and the Rhine, respectively. Such generalisations in terms of water masses have obvious limitations and, for example, climatological monthly mean salinity fields (De Lannoy, 1989) do not show a clear difference between English coastal water and Channel water. However, the existence of a strong salinity gradient parallel to the Belgian coast is very clear from all observations.

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 north-east 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, Scheeldt, Rhine/Meuse, Elbe and Weser and smaller rivers. This corresponds with the well-established tidal residual current (Nihoul and Ronday, 1975; Otto et al., 1990; Delhez and Martin, 1992) which is directed north-eastward along these coasts. At the smaller scale of the Belgian EEZ, the topography of submerged sand banks and the shallow region offshore of the mouth of the Scheeldt Estuary clearly modify the tidal residual current and more complex conceptual pictures emerge such as that of a clockwise residual gyre (Nihoul and Hecq, 1984) carrying water from the Scheeldt estuary south-westward and then offshore before merging with the north-eastward flow.

Such conceptual hydrological models are important because they can be used 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, 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. Proximity to the Scheeldt estuary mouth has also been cited (Warming et al., 1999) as a reason for supposing that freshwater influence on coastal waters is dominated by the Scheeldt discharge.

With one notable exception (Van Bennekum and Wets, 1990), it is generally assumed that the salinity of Belgian waters is influenced primarily by Channel water from the south-west and by the Scheeldt 'plume' presumably on the basis of the appeal of the 'coastal river' conceptual model and on the proximity of the region to the Scheeldt 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 so far by analysis of salinity measurements alone.

Previous numerical simulations (De Ruijter et al., 1987), using a constant 3.5 m s\textsuperscript{-1} north-westerly and a constant 4.5 m s\textsuperscript{-1} south-westerly wind for computational economy, have also shown the potential importance of south-westward spreading of the Rhine plume. In the present study this effect is investigated more thoroughly by performing long-term simulations with more realistic (6-hourly) wind forcing.

Regarding stratification, the vertical structure of salinity and temperature in Belgian waters is generally assumed to be well mixed throughout the year (Lee, 1980). The conductivity-temperature-depth (CTD) profiles which are made regularly in the framework of the Belgian water quality monitoring programme generally confirm this assumption, though slight stratification, e.g. of order 0.2 (for salinity) and/or 1°C (for temperature), is occasionally observed during calm, sunny weather in summer.

In this paper a 3D numerical model of the salinity distribution in the Southern Bight of the North Sea and the Channel is described. Results are presented for the salinity field averaged over the period 1993–2002 and for corresponding tracers showing the contribution of freshwater from the Scheeldt, the Rhine, the Seine and the Thames to this salinity distribution. Two further simulations are presented with the Scheeldt outflow and the Rhine outflow set to zero. Conclusions are drawn from these simulations regarding the origin of freshwater in the Belgian EEZ and the geographical spreading of respectively the Scheeldt and Rhine outflows.

2. Method

2.1. Model description

The salinity in the Southern Bight of the North Sea (SNS) and the Channel is modelled here using the
COHERENS three-dimensional hydrodynamic model, termed hereafter COHSNS-3D. A full description of this model, including the details of numerical discretisation as well as a user guide, is given by Luyten et al. (1999). The source code of the standard version of the model is available publicly on CDROM. Previous hydrodynamical applications of the model include simulation of the Rhine plume (Ruddick et al., 1995), of surface and bottom boundary layers in the North Sea (Luyten, 1996) and of temperature and thermohaline circulation in the North Sea (Luyten et al., 2003).

The 3D model solves the continuity, momentum, temperature and salinity transport equations on a staggered Cartesian, sigma coordinate grid with an explicit mode-splitting treatment of the barotropic and baroclinic modes. Advection of scalar quantities is discretised by a direction-split Total Variation Diminishing (TVD) scheme. Vertical diffusion is modelled using an evolution equation for turbulent kinetic energy and a quasi-parabolic vertical profile for turbulence macrolength scale. Minimal vertical diffusion and viscosity coefficients of $10^{-6}$ m$^2$ s$^{-1}$ are used. Horizontal diffusion is not considered explicitly, but the process of horizontal diffusion arising from the combination of horizontal advection with vertical diffusion is resolved. Advection of momentum is treated with a first order upwind scheme. Full details of all these methods as well as the original references can be found in Ruddick (1995) and Luyten et al. (1999).

2.2. Implementation

The model has been set up for the region between 48.5°N and 52.5°N with the bathymetry shown in Fig. 2 using a 109 × 97 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. The model is run with mode-splitting time steps of 60 s and 900 s for 2D and 3D calculations, respectively.

At the western ('Channel') and northern ('central North Sea') open sea boundaries the time series of cross-boundary transport (vertically-integrated current) and surface elevation are applied using data from a 2D model of the North Sea continental shelf based also on the COHERENS software (Luyten et al., 1999). This 2D model is forced by 6-hourly wind and atmospheric pressure fields from the analysed/forecast data of the UK Meteorological Office, and transfers this meteorological forcing in turn to the

![Fig. 2. Bathymetry of the southern North Sea and the Channel model. The Belgian EEZ is delimited by the solid line. The dots denotes the stations, 330 (central) and 890 (offshore) of the Belgian water quality monitoring network used to present the results of Fig. 6. The model domain is a 109 × 97 horizontal grid with resolution of 5° longitude by 2.5° latitude. Each pixel corresponds to one grid cell.](image)
Fig. 3. Time series of daily-averaged wind in m s⁻¹ at station 330, used as forcing for the 1991–2002 simulation. Bottom: average over the period 1991–2002. Arrows show the direction in which the wind is blowing.
COHSNS-3D model. The wind forcing, spatially variable (on a grid whose size is variable from 1.25° to 5° in longitude and 1.25° to 2.5° in latitude according to available data), is shown in Fig. 3 for station 330 (51° 26.00' N, 2° 48.50' E). A few gaps can be seen in data but not during the years 1993–2002.

In addition to the two open sea boundaries, the four main rivers, the Rhine/Meuse (two different sources; Maasluis and Haringvlietluis), the Scheldt, the Seine and the Thames form further continental boundaries. The transport is imposed at these four boundaries by temporal interpolation of 1991–2002 daily measurements of flow rate for the Rhine/Meuse, Seine and Thames and 1991–2002 10-day measurements of flow rate for the Scheldt as shown in Fig. 4.

At the two open sea boundaries, the vertical current structure is determined by imposing the condition of zero normal derivative of the deviation of current from the vertically-averaged horizontal current (Deleersnijder et al., 1989), while at river boundaries a condition of zero vertical gradient of current is applied.

For temperature, zero flux is assumed at the sea bottom. The spatially variable temperature imposed at the surface is derived from the weekly sea surface gridder (on a grid of 20 × 20 km) temperature obtained from the Bundesamt fuer Seeschifffahrt und Hydrographie (Loewe, 2003). For periods without SST data (1991–1995), a weekly climatological SST (computed from 1996–2002 BSH data) is im-

![Graphs of Rhine, Meuse, Scheldt, Seine, and Thames flow rates from 1991 to 2003.](image)

Fig. 4. Time series of measured discharge flow-rates for the rivers, used as forcing for the 1991–2002 simulation.
posed. At the open sea boundaries, a zero horizontal cross boundary gradient of temperature is specified.

For salinity, zero flux is assumed at the sea bottom and sea surface boundaries. To ensure salt conservation the incoming salinity at the river boundaries is set to zero. At the open sea boundaries, no boundary condition is required when the current is directed out of the domain. For inflow periods, the salinity at the western, 'Channel', boundary is specified as 35 and corresponds to an average from the ICES climatology. At the northern, 'central North Sea', boundary a salinity of 34.45 is specified west of 4°E, based on the Damm (1989) climatology, while east of this longitude a zero horizontal cross boundary gradient of salinity is specified to allow realistic formation of the Rhine plume and associated Dutch coastal current.

Initial conditions were obtained by running the COHNSNS-3D model for the period January 1991–December 1992 with open boundary and forcing as described above. A simulation was then carried out for the period January 1993–December 2002.

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 Schelde, 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.

3. Results

3.1. Salinity distribution—long-term average and spatio-temporal variability

Fig. 5 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

Fig. 5. Surface salinity 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 (BMDC and RIKZ data) and over the period 06/98–10/99 (MAREL–NORMANDIE data) superimposed as coloured circles. The Belgian EEZ is delimited by the solid line.
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 Fig. 5 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 and the RIKZ and averaged over the period 06/98–10/ 99 from DDE are also shown in Fig. 5 for comparison with the model results. The observed inshore-offshore salinity gradient and salinity increase going southwest 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 are generally not well-known. In the results shown here, the main discrepancies are restricted to the area close to the northeast boundary (Fig. 5).

The long-term average shown in Fig. 5 is only one aspect of the salinity distribution and does not reflect the strong dynamics in this region. Fig. 6 shows the 1993–2002 time series of modelled and observed surface salinity at two stations along the inshore-offshore transect. These are station 330 (51° 26.00' N, 2° 48.50' E; Fig. 2) and station 800 (51° 50.83' N, 2° 52.00' E; Fig. 2). The average salinity computed by the model (33.55 ± 0.75 at station 330 and 34.65 ± 0.15 at station 800) is comparable to the one measured (33.81 ± 0.74 at station 330 and 34.66 ± 0.63 at station 800). Superimposed on the long-term average, which gives an overall difference of 1.10 between these stations (comparable to the difference of 0.85 found in data), there is significant variability at different time scales. Sub-diurnal salinity variability, shown by the difference between daily maxima and minima, has a typical range of about

![Fig. 6: Time series of model results for surface salinity in the Belgian EEZ for the central station 330 (red) and the offshore station 800 (green) shown in Fig. 2. The solid lines represent the daily-averaged values, while daily minima and maxima are given by the surrounding dotted black lines. Time series of in situ data (BMDC) for the central station 330 (red filled circles) and for the offshore station 800 (green filled circles).]
0.5 at station 330 and 0.04 at station 800 (Fig. 6). This variability can be attributed mainly to horizontal advection of salinity by tidal currents, with both along-shore (low salinity gradient but high tidal current) and cross-shore (high gradient but low current) advection playing a role. At time scales of a few days, variability in salinity is caused by fluctuations in wind strength and direction. In contrast with studies of sea surface elevation in this area, there is little evidence in this salinity time series of semi-monthly variability relating to the spring-neap tidal cycle. While the amplitude of the dominant semi-diurnal M2 tide is modulated significantly (e.g. 30%) by beating with the S2 tide, the impact on tidally-averaged advection and diffusion is small compared to the effect of wind-driven currents. During periods of relatively low winds (e.g. the summer period), the cross-shore salinity gradient is relatively persistent and wind and tidal variability only slightly influence the general salinity distribution shown in Fig. 5. However, during strong wind events lasting a few days or weeks (e.g. winter period) the salinity field clearly differs significantly from the long-term average such that the cross-shore gradient can become zero or even non-monotonic. Animations of model results (not shown) show that such wind events can either move the entire band of fresher coastal water towards the north-east/south-west, or compress it much closer to the coast or advect it offshore with associated frontal meandering and eddy formation (De Kok, 1997), depending on wind direction. A similar sensitivity to wind of the salinity distribution has been described previously (Yang, 1998) for a smaller area model of the Scheldt plume and has been documented by others for the Rhine plume (De Kok, 1996; De Ruijter et al., 1992; Ruddick et al., 1995; Souza and Simpson, 1997).

3.2. Water mass tracers

Fig. 7 shows the 1993–2002 averaged seasonal variation of the water masses at station 330 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 a negligible contribution (0.002 in average ± 0.003) of central North Sea water. In this simulation the contribution of the Thames water fraction, typically of order 10⁻³, 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

![Diagram](image-url)
indicates that the freshwater influence at station 330 is mainly due to the Rhine estuary (0.019 in average ± 0.016) and that the fraction arising from the Scheldt is 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.

There is an obvious link between Figs. 6 and 7 because if we consider 35 for the salinity of Channel water and 0 for the river water, then the deviation of salinity from the maximum of pure Channel water is given simply by the product of tracer fraction with that maximum, i.e. a river tracer fraction of 0.06 will reduce salinity by 1.4. This correlation can be seen when comparing station 330 time series of salinity (Fig. 6) with the river tracer fractions (Fig. 7).

Fig. 8 shows the 1993–2002 average horizontal distributions of the Channel, the central North Sea, the Rhine, Scheldt, Seine and Thames water fractions. Clearly (Fig. 8 top) 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.

Fig. 8 (bottom) suggests that the Rhine water spreads a considerable distance southward from the estuary mouth, reaching both the near-shore 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 near-shore and central Belgian waters. Interestingly, 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.

3.3. Sensitivity study: relative contribution of Scheldt and Rhine water

In order to better assess the relative contribution of the Scheldt and Rhine to the Belgian EEZ, two additional simulations were carried out with the discharge from the Rhine and from the Scheldt separately set to zero (Fig. 9). Comparing results obtained with (Fig. 5) and without Scheldt discharge (Fig. 9 top) does not show significant change in the salinity field of the Belgian EEZ. The greatest difference is seen close to the Scheldt discharge (Fig. 9 top). This suggests that the band of fresher coastal water simulated along the Belgian and Dutch coasts can be largely accounted for by the Rhine discharge alone. Again even with no Scheldt discharge, the salinity within the Scheldt Estuary is lower than 33 (Fig. 9 top). In contrast, it can be concluded from the very different results obtained when the Rhine river discharge is set to 0 (Fig. 9 bottom) compared to the reference (Fig. 5) that the Scheldt discharge alone reduces salinity in the Belgian EEZ by only about 1 and only for a restricted area from the estuary mouth to about thirty kilometres offshore.

4. 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. The present study thus suggests a new conceptual model of the origin of water masses in this region (Fig. 10), representing a major change from the previously accepted understanding. 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.
This is supported by previous observations of Van Bennekom and Wetsijin (1990), who conclude that the percentage of Rhine water exceeds that of Scheldt water throughout the region considered (approximately within a radius of 40 km of the Scheldt mouth) based on measurements of dissolved silica used as a tracer to distinguish between Rhine and Scheldt water. While we recognise that the use of measured data avoids some of the methodological uncertainties of model studies it is important to stress that the use of dissolved silica as a tracer is not without problems even in winter, because the correlation between dis-
solved silica and salinity will hold only for regions where the time scale for establishing a quasi-equilibrium dissolved silica distribution is shorter than the time scale over which dissolved silica is conserved. In the present study the salinity of coastal waters does not reach such a quasi-equilibrium state until about two years of simulation, which is longer than the time scale over which dissolved silica can be considered as conserved because of spring and summer uptake by phytoplankton.

It is important to assess critically the methodology in case this general conclusion might in some way result from weaknesses in the model assumptions. This is especially important in the present study since the results are somewhat contrary to the conventional understanding of the system which is based on the intuition that the Scheldt discharge will influence more strongly the salinity distribution here than the Rhine Estuary. In the context of numerical simulations of marine processes it is a general rule that the grid is never fine enough and the open boundaries are never far enough. In the particular case of salinity simulations it is moreover noted that realistic hindcasting and comparison with simultaneous measured data is particularly difficult because of lack of knowledge of open boundary conditions and sensitivity to the parameterisation of turbulent mixing (Ruddick et al., 1995). Since Channel water dominates the Belgian EEZ, a reduction/increase of the salinity of the Channel inflow by 1 gives an almost identical reduction/increase throughout the region. Moreover, it is clear that modelling of the estuaries is crude since processes occurring at horizontal spatial scales of a few kilometres and upriver of the modelled river boundaries are poorly represented. Coupling of the current model with estuary models of much finer spatial resolution would provide considerable improvements in this respect. However, the fact that the salinity distribution as established from previous measurement studies can be rather well-represented by the current model with or without inclusion of the discharge from the Scheldt Estuary (Figs. 5 and 9) provides a sound basis for the key conclusion of the study.

Now that reasonable confidence has been established in the modelling of salinity in the Belgian EEZ two directions for future work can be identified. Firstly, in terms of hydrodynamic modelling, applications in the forecasting of the dispersion of dissolved substances at sea can be envisaged. Numerical work should then focus on improving the Scheldt and Rhine estuary model boundaries, refinement of the horizontal and vertical grid and/or assimilation of measured data. Secondly, 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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The 10-day Scheldt and daily Rhine Meuse river flow data, collected by the RIZA (Rijks Instituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling, Ministerie van Verkeer en Waterstaat) and archived into the central data base DONAR, were downloaded from the Waterbase web site http://www.waterbase.nl. The daily river flow for the Seine, collected by the Cellule anti-pollution DDE (Service de Navigation de la Seine de Rouen SNS), were downloaded from the web site http://seine-val.cerihan.fr/rubriques/estuaire_seine/rubriques/donnees_brutes/debits/debits-Seine.htm. Daily Thames flow data were collected under the responsibility of the UK Environment Agency from the NRFA (National River Flow Archive) and were downloaded from the web site http://www.nrel.ac.uk/th/nrfa/webdata.

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References


