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CHAPTER 1

Hydrodynamics and meteorology of the Belgian Coastal Zone

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1.1 Physical oceanography of the Belgian coastal zone: parameters, time and space scales

This chapter describes the physical environment of the Belgian coastal zone (BCZ) as the framework in which eutrophication processes may occur. In addition to the bathymetry, which provides the geometrical constraints for all physical and biological processes, the most relevant physical oceanographic parameters are:

- currents, which advect nutrients and phytoplankton, and turbulent diffusion, which mixes both dissolved and particulate constituents,
- light at the sea surface, and the diffuse attenuation of light in the water column, which control the rate of primary production and hence timing of the spring bloom,
- temperature, which controls the rate of many biological processes, and
- salinity, which does not influence eutrophication processes directly but is a useful diagnostic tracer for water masses, in particular for regions influenced by freshwater inputs.

All these oceanographic parameters are themselves influenced by meteorological processes (wind, clouds and other atmospheric constituents with optical or thermal properties, rain and evaporation) in addition to the tidal effects generated by astronomic gravitational fields. The chain of impacts from meteorology to physical oceanography to biology is illustrated in Figure 1.1.

Regarding time scales, this book focuses on eutrophication processes and hence is mainly concerned with the annual cycle of biology as driven by the annual cycle of light and heat. Interannual variability of this forcing and the associated wind and rainfall which modulate the annual cycle are of particular interest because observed interannual biological variability is thought to be closely related to meteorologically-induced physical variability (Breton *et al.*, 2006). In addition to the long-term average and the interannual variability, higher frequency processes, such as tidal fluctuations and wind events, must also be considered insofar as they impact the long-term average.

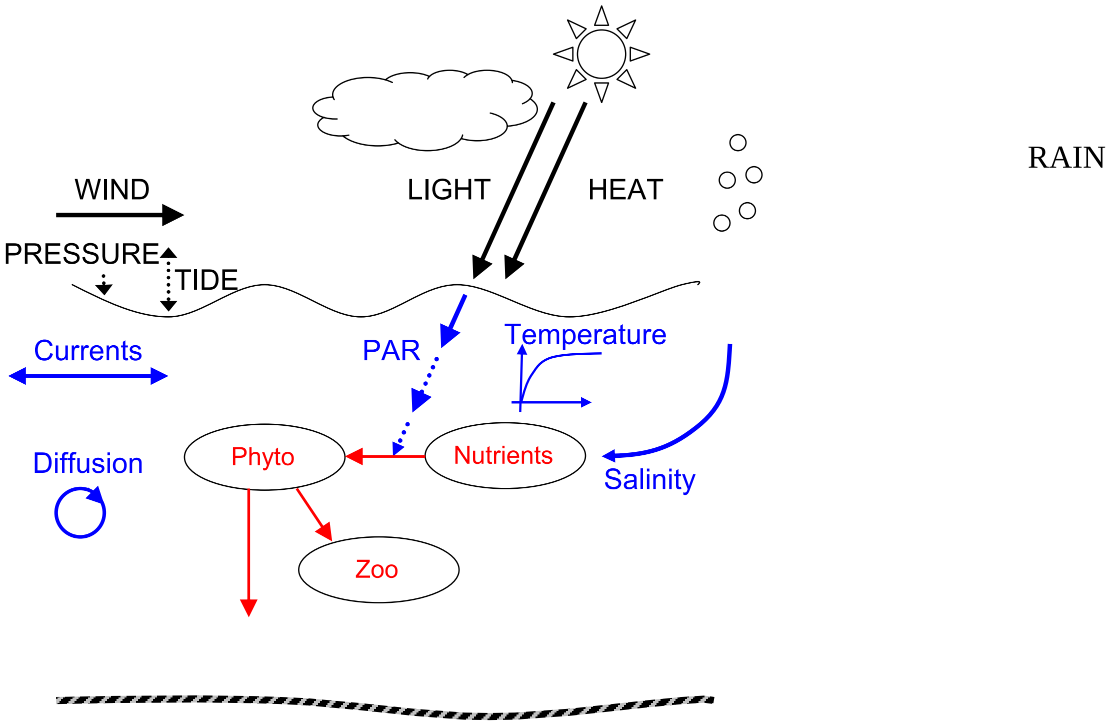

Figure 1.1. Scheme linking meteorological factors (black) with physical factors (blue), which influence the nutrient-phytoplankton-zooplankton cycle (red) by: a) currents and diffusion transporting dissolved and particulate constituents, b) temperature affecting most biological rates, c) PAR affecting photosynthetic rate, d) salinity as a tracer of nutrient-rich river water.

Regarding space scales, the focus is on the Belgian coastal waters. However, natural processes in the sea are obviously not constrained by political boundaries especially in this system with strong horizontal fluxes. This chapter will, therefore, consider also the adjacent sea areas of the Eastern Channel from 4°W and the Southern Bight of the North Sea up to 52.5°N, insofar as the larger area influences eutrophication processes in the Belgian coastal waters. This region, its bathymetry and main river discharges are shown in Figure 1.2. The focus is mainly on large scale processes, determining for example the spatial extent of eutrophication. Processes occurring at horizontal scales less than a few kilometers will not be considered in detail (and are relatively less well-known because of the lack of data and of suitable modeling tools).

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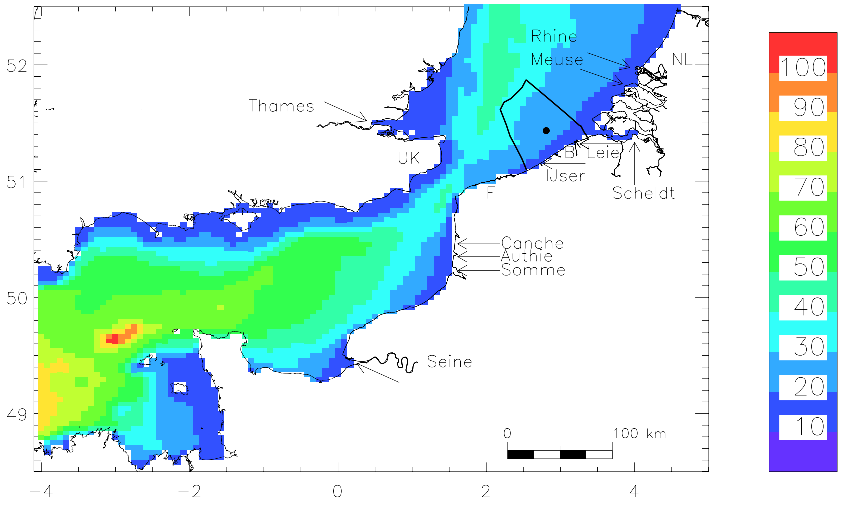

Figure 1.2. The Belgian coastal zone and adjacent marine areas, showing water depth (in metres, see colour scale), the boundaries of the Belgian coastal zone (dark lines) and the main river discharges (arrows). The monitoring station 330 is shown as a solid dot.

The Belgian coastal zone (BCZ) has a maximum alongshore width of about 65 km and extends about 87 km offshore with a surface area of about 3600 km^2. The average and maximum water depths are approximately 20 m and 45 m respectively (Maes *et al.*, 2005). In addition to the large scale gentle sloping of the sea bottom from the coast to offshore, the bathymetry is marked by many large and elongated submerged sandbanks, the Flemish Banks. These reach up to 15 km in length with crest to trough depth differences of up to 20 m, and are oriented approximately parallel to the coast (Ministerie van Openbare Werken, 1980).

1.2 Meteorology

Interannual variability of meteorological factors over the North Atlantic and Europe is highly correlated with the North Atlantic Oscillation index (NAO; Hurrell, 1995), which measures the large scale gradient between the Icelandic Low and the Azores High pressures (Fig. 1.3). This influences winds, precipitation, clouds and air temperatures. The NAO has a significant impact on the North Sea ecosystem via a number of different processes. In periods of high NAO Southwesterly winds are dominant, driving a stronger inflow of water from the Channel into the Southern North Sea (Breton *et al.*, 2006). The wind regime also affects the spreading of river plumes with Southwesterly winds (high NAO) inducing less cross-shore dispersion and greater North-Eastward dispersion of the Scheldt plume that Northeasterly winds (low NAO). High NAO is also positively correlated with rainfall over the Scheldt basin impacting the delivery of

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diffuse nutrients to coastal waters (Breton *et al.*, 2006). The relationship between NAO and cloudiness has not been investigated. A long term decreasing trend has been identified in the NAO from the 1960's to the 1990's as a result of both natural variability and greenhouse gas forcing (Osborn, 2004).

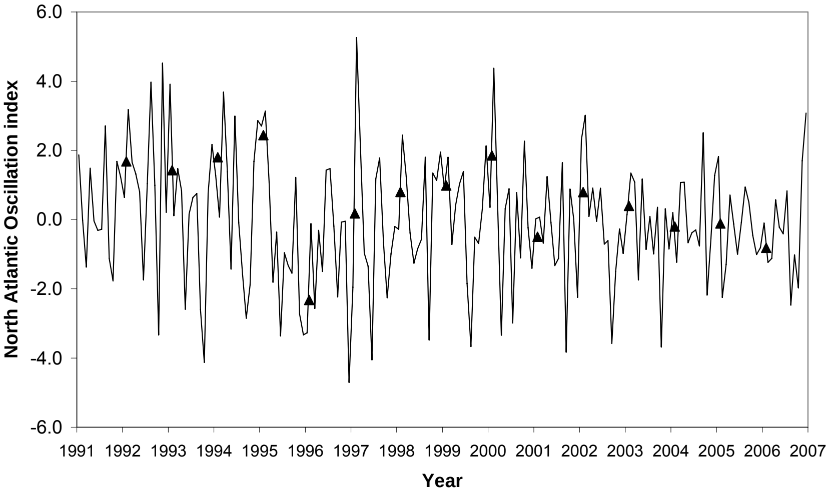

Figure 1.3. North Atlantic Oscillation index for the period 1991-2006 obtained from http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm (Jones *et al.*, 1997; Osborn, 2006). Monthly mean data are given as a continuous line and the winter averages (December-March) are given as triangles.

Because of the shallow water depths in this region the impact of wind stress on currents is more significant than that of local atmospheric pressure gradients (De Vries *et al.*, 1995). Wind speed shows a significant variability at time scales of hours to days associated with the passage of low pressure atmospheric systems superimposed on an annual cycle with generally lower winds during summer (Fig. 1.4). Wind direction is also variable on similar time scales.

The Photosynthetically Available Radiation (PAR; spectral range 400-700 nm) reaching the sea surface (Fig. 1.5) varies over the annual cycle as function of sun elevation and photoperiod and at shorter time scales due to variability of clouds and, to a lesser extent, aerosols.

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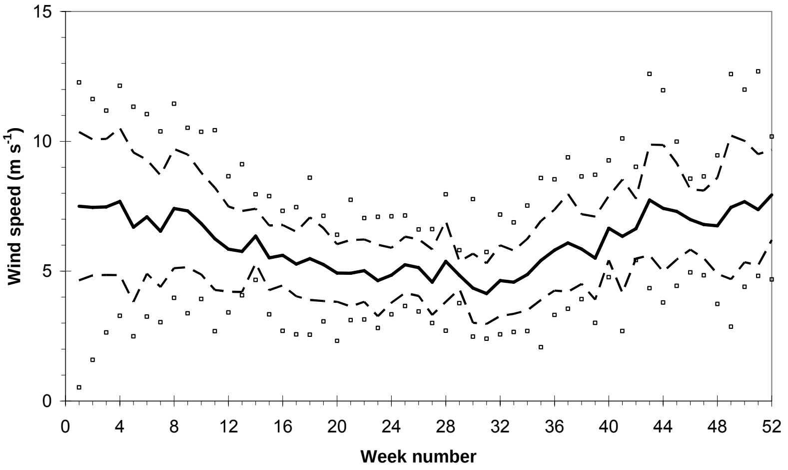

Figure 1.4. Wind speed at 10 m height above sea level at station 330 (51°26'N, 2°48.5'E) derived from data for the period 1991-2004 from UKMO model re-analysed forecasts at 6-hour resolution. Data are first averaged into 7-day bins for each year. The solid black line represents the mean average for all years. The dashed lines represent the interannual standard deviation between the 7-day average for each year and the full period average for the bin. The squares represent the maximum and minimum values of the 7-day average over the full period.

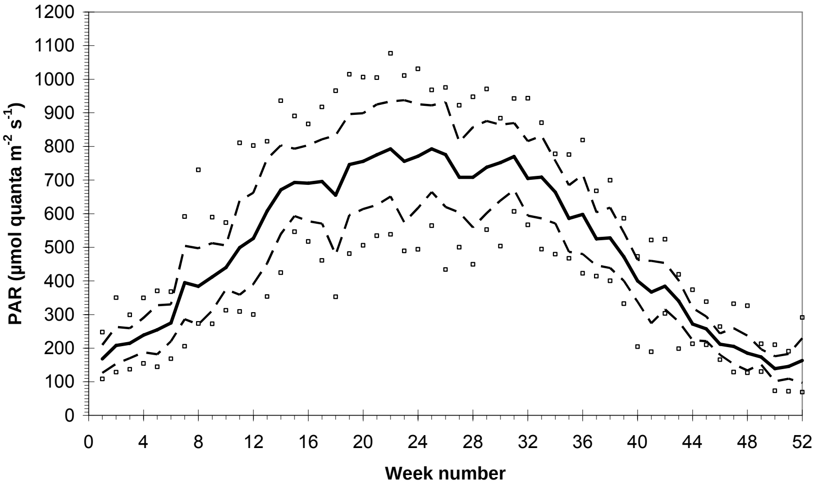

Figure 1.5. PAR averaged over the photoperiod just above the sea surface at station 330 derived from daily global solar radiation data of the Koninklijk Meteorologisch Instituut van België/Institut Royal Météorologique de Belgique for the period 1991-2004 using the empirical relationship described in Rousseau (2000). Labelling of points and lines is the same as for Figure 1.4.

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The annual cycle of solar radiation and, to a lesser extent, wind speed (convective exchange and transport of Channel water) control the annual thermal cycle of the Southern North Sea and result in an annual cycle of sea surface temperature (see section 1.4).

Rainfall affects the ecosystem mainly via river discharge of freshwater and associated land-based. The main rivers in the area are, in order of importance (1991-2004 average discharge): the Rhine/Meuse (2059 $m^3 s^{-1}$), the Seine (524 $m^3 s^{-1}$) and the Scheldt (154 $m^3 s^{-1}$). The Thames does not significantly affect the BCZ (Lacroix *et al.*, 2004). The annual cycle of river discharge is characterized by higher discharge in winter and early spring (Fig. 1.6).

1.3 Currents and turbulent diffusion

The Southern North Sea is a region of strong tides with tidal currents reaching 1 $m s^{-1}$ or more (Nihoul & Hecq, 1984; Otto *et al.*, 1990). The dominant semi-diurnal tides are modulated over the Springs-Neaps cycle by typically 10-30 %. Tidal current ellipses are elongated with the main component being alongshore, but with some changes in orientation caused by topographic features (Yang, 1998). The temporal average of tidal currents provides a net tidal residual current, typically of order about 0.01-0.1 $m s^{-1}$. Frequent wind events generate additional currents typically of order up to about 0.3 $m s^{-1}$ and of duration of a few hours or days. Topographic steering orients these currents primarily alongshore (Yang, 1998). Except within river estuaries and the Rhine/Meuse plume, density gradients in this region are generally insufficient to generate significant density-driven currents.

The combination of tide- and wind-driven residual currents gives a net horizontal transport of salt, nutrients and plankton. In addition to this residual current, the horizontal dispersion caused by the oscillating tidal current is significant (Lacroix *et al.*, 2004). This dispersion is strongest in the alongshore direction and may transport salt, nutrients and plankton against the residual current.

Because of the lack of stratification and the relatively shallow water depths, the vertical variation of horizontal currents is limited as regards both direction and magnitude except within the bottom boundary layer. Vertical currents are determined primarily by topographic steering of horizontal currents, termed “upsloping” by Deleersnijder (1989), with no significant upwelling currents.

The combination of shallow water depths and strong tidal currents, enhanced by wind events, gives strong turbulent diffusion with typical modelled vertical diffusion coefficients of order $10^{-2} m^2 s^{-1}$ or more.

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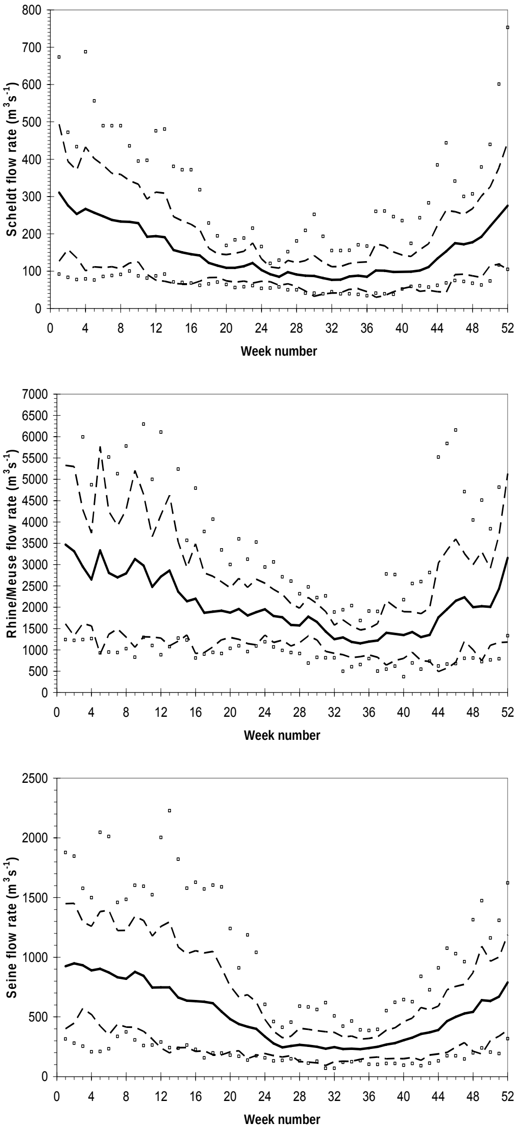

Figure 1.6. River discharge (m^3 s^{-1}) for the Rhine/Meuse, Seine and Scheldt, for the period 1991-2004. Data for the Scheldt were downloaded as 10-day averages at Schaar van ouden Doel from www.waterbase.nl courtesy of RIZA and from Administratie Waterwegen en Zeewegen. Rhine data were downloaded as daily averages from www.waterbase.nl courtesy of Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RIZA) for Hoek van Holland (1997-2004) or estimated from the Maassluis flow (1991-1996). They were added to data from the Meuse which were downloaded from www.waterbase.nl courtesy of RIZA for Haringvlietsluizen (1997-2004) or estimated from Tiel Waal (1991-1996). Data for the Seine were downloaded as daily averages at Poses from http://seine-aval.crihan.fr (1994-2004) courtesy of Cellule anti-pollution DDE and by email from Ifremer. Labelling of points and lines is the same as for Figure 1.4

1.4 Temperature

The main source of variability of sea surface temperature (SST; Fig. 1.7), is the annual cycle of solar radiation. Interannual variability of SST is closely correlated with the NAO index (Tsimplis *et al.*, 2006). This large interannual variability (1-3° C) makes it difficult to establish a long-term trend.

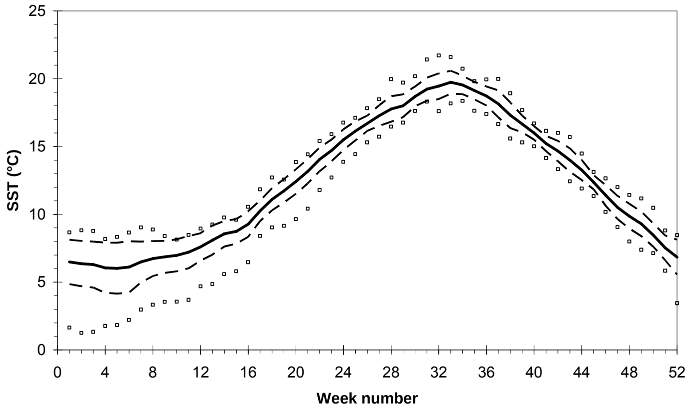

Figure 1.7. Sea Surface Temperature (SST) at station 330 for the period 1991-2004. Data originate from the Bundesamt für Seeschiffahrt & Hydrographie composite analysis of weekly ship and station data at 20 km spatial resolution (Loewe, 2003). Labelling of points and lines is the same as for Figure 1.4.

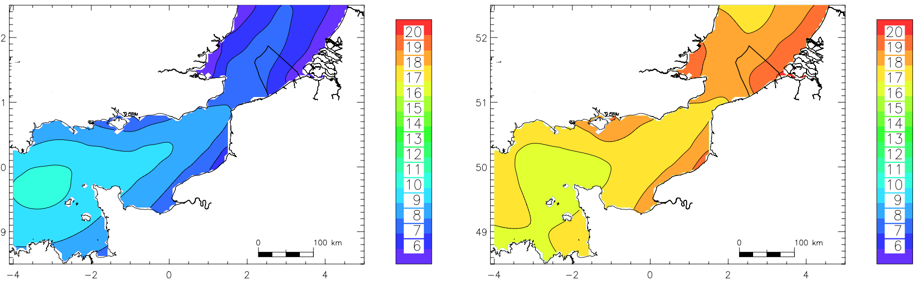

Figure 1.8. Monthly mean Sea Surface Temperature for the period 1993-2003. Left: February. Right: Augustus. Data originate from the Bundesamt für Seeschiffahrt & Hydrographie composite analysis of weekly ship and station data at 20 km spatial resolution (Loewe, 2003). For latitudes below 49°41'N, data have been extrapolated.

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At shorter time scales, wind events, coupled with variations in air temperature give basin-scale modulations of this annual cycle. Some horizontal variability, of order 1-3°C, arises from the inflow of Atlantic/Channel water, which forms a tongue of warmer water in the centre of the Southern Bight in winter, and from faster heating of the shallower, coastal areas in summer (Fig. 1.8).

Because of the strong vertical diffusion, vertical variability of temperature is generally limited (less than 1°C) except within estuaries and the Rhine/Meuse plume, where salinity gradients may cause stratification, and in deeper parts of the Channel.

1.5 Salinity

Except for the fact that certain plankton species which are adapted to waters of certain salinity range, the direct impact of salinity on eutrophication dynamics is negligible. However, salinity distributions provide an excellent tracer for studying the dispersion of freshwater from rivers. At the scale of the Southern North Sea air-sea fluxes of freshwater (evaporation/precipitation) are negligible and there are no internal sources/sinks of salt so that salinity is a conserved parameter at all times.

The main variability of salinity is horizontal with lower salinity plumes forming from the mouths of the main estuaries. In particular, a band of lower salinity continental coastal water is found along the coast of North-East France, Belgium and the Netherlands (continuing into the German Bight) resulting from the discharges of the Seine, Scheldt, Rhine/Meuse and other smaller rivers (Fig. 1.2; Fig. 1.9). Cross-shore gradients of salinity are strong within this continental coastal water. Typical cross-shore variations of salinity of about 3-10 occur over a distance of 10-40 km. The continental coastal water is often bounded by a sharp, meandering front in Dutch waters while weaker fronts can be found in the vicinity of smaller rivers.

This long-term salinity distribution (Fig. 1.9) is modulated by wind events which may push the coastal water further offshore/onshore or deflect the plumes of individual rivers alongshore. The annual cycle of wind and river discharge causes a seasonal trend in salinity in Belgian waters (Fig. 1.10).

Because of the strong vertical diffusion, vertical variability of salinity is generally limited (less than 0.2) and transient in the BCZ. Haline stratification can be more significant (*e.g.* 1-4) in the Rhine/Meuse plume and in the Scheldt Estuary.

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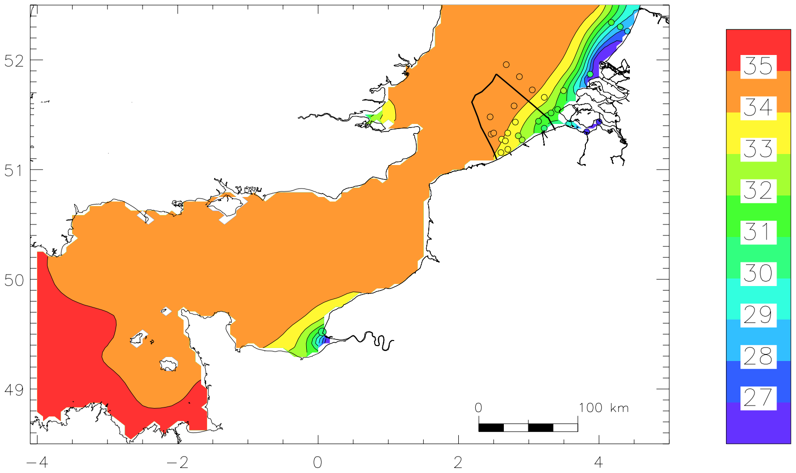

Figure 1.9. Long-term surface salinity distribution modeled for the period 1993-2002 (background coloring) together with in situ measurements superimposed as colored circles. Adapted from Lacroix *et al.* (2004).

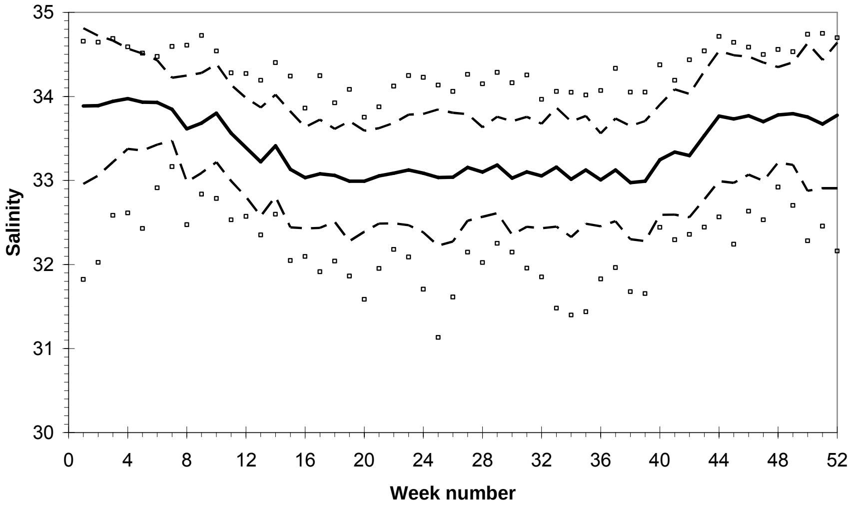

Figure 1.10. Surface salinity at station 330 for the period 1993-2004. Results were obtained from the model of Lacroix *et al.* (2004). Labelling of points and lines is the same as for Figure 1.4

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1.6 Water masses

Model simulations (Lacroix *et al.*, 2004) show that the inflow of Atlantic water via the Channel is the dominant water mass in the BCZ, contributing to some 95.5% of the total water mass at station 330. Continental rivers supply most of the remaining water mass with contributions from the Rhine/Meuse, Scheldt and Seine estimated to 1.9%, 1.3% and 0.8% respectively for the long-term averages but with considerable interannual and high frequency variability. The horizontal distribution of these water masses is shown in Figure 1.11.

The residual circulation has been shown previously (*e.g.* Nihoul & Ronday, 1976; Delhez & Martin, 1992). However, the residual circulation, *e.g.* from the long-term averaged Eulerian currents, does not explain entirely the transport of biogechemical parameters since horizontal mixing is also important and can lead to dispersion of dissolved constituents in other directions.

Mean residence times have been calculated for the Southern North Sea region for water entering via the Dover straits (Delhez *et al.*, 2004). While useful for identifying regions where dissolved constituents may be retained, the concept of water age or residence time must be carefully defined (Deleersnijder *et al.*, 2001) and should not be confused with simplified approximations of transport used in some biogeochemical models (Lancelot *et al.*, 2005).

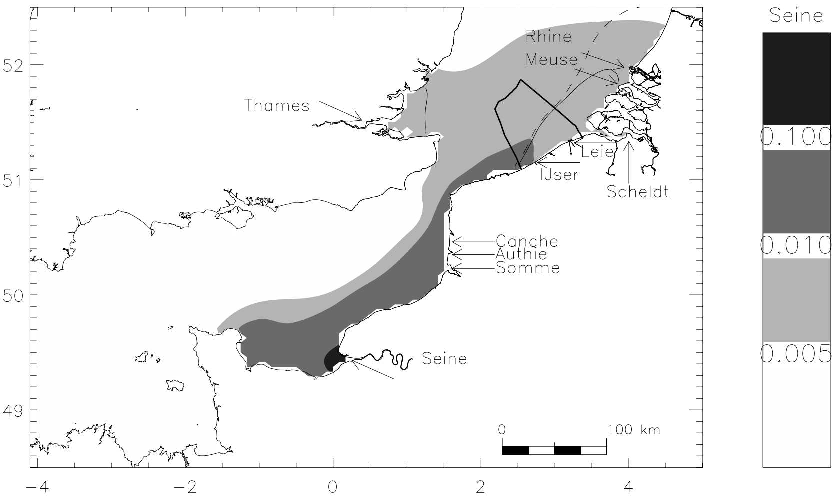

Figure 1.11. Modeled average horizontal distribution of water masses in the Channel and the Southern Bight of the North Sea for the period 1993-2003. Fractions of water from the Seine (and small French rivers) are indicated as grey scale colour map (0.5%, 1%, 10%), from the Scheldt, Leie, IJser and Thames water as superimposed solid line (1 %), from the Rhine/Meuse water as superimposed dashed line (1%). The BCZ is delimited by the continuous line. Adapted from Lacroix *et al.* (2004).

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1.7 Light attenuation

The vertical attenuation of Photosynthetically Available Radiation (PAR) within the water column is generally more important than the intensity of abovewater PAR in controlling primary production (Behrenfeld & Falkowski, 1997). There is significant horizontal variability of PAR attenuation over the BCZ and Southern North Sea (Figure 1.12) because of variability in organic and inorganic suspended particulate matter and in colored dissolved organic matter (CDOM). Thus, the shallow waters close to the Belgian coast, over the Flemish Banks and around the Thames estuary are very turbid with total suspended matter concentrations ranging typically from 1-100 g m^{-3} or higher. Corresponding Secchi depths range typically from about 10 cm to a few meters. Further offshore in deeper water (30-40 m) clearer water is found with Secchi depths in the range 5-15 m. In general the euphotic depth is less than the total water depth and phytobenthos is found only in very limited areas such as tidal flats.

Temporal variability of PAR attenuation is linked essentially to the resuspension and advection of suspended particulate matter, itself modulated by the tide and by wind events over time scales of days to hours. The higher winds encountered in winter generate also a seasonal cycle with higher PAR attenuation during winter. The settling of suspended matter during calmer periods in spring may even influence the timing of spring phytoplankton blooms (Peperzak *et al.*, 1998; Rousseau *et al.*, 2008). Further temporal variability of PAR attenuation may be related to advection of CDOM of riverine origin and to self-shading during phytoplankton blooms.

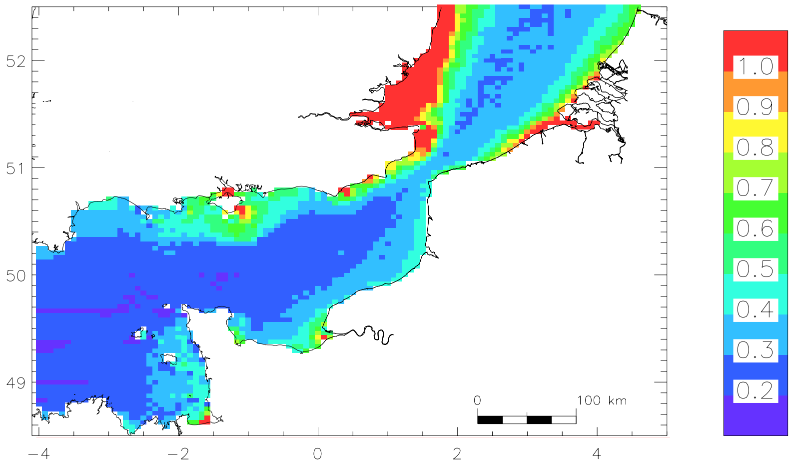

Figure 1.12. Annual (2003) average distribution of PAR attenuation coefficient (m^{-1}) in the Southern North Sea and Eastern Channel calculated from and used by the 3D-MIRO&CO model (Lacroix *et al.*, 2007b) based on the following inputs: TSM maps compiled from SeaWiFS, CDOM deduced from the modelled salinity and CHL deduced from the modelled phytoplankton biomasses. Reproduced from Ruddick *et al.* (2008).

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1.8 Summary and future perspectives

This chapter summarizes the physical oceanography of the BCZ as relevant to eutrophication dynamics. The meteorological forcing, which is correlated with the NAO, is analysed in terms of the mean annual cycle of wind, PAR and river discharge and considers the range of their interannual variability. This meteorological forcing, combined with the astronomical tidal forces, drives variability of currents and turbulent diffusion, temperature, salinity (a proxy for dispersion of river water) and light availability in the water column, each of them influencing in turn nutrient and phytoplankton variability. Spatial variability of salinity and light availability are significant because of the lateral inputs of river water and the horizontal variability of water depth (and hence resuspended sediments).

This characterization of spatial and temporal variability of these parameters provides a reasonably complete description of the physical environment for the purposes of understanding eutrophication. It forms the basis for the MIRO&CO-3D ecosystem model of the region (Lacroix *et al.*, 2007a; Lacroix *et al.*, 2007b; Lancelot *et al.,* 2008). However, improvements in this understanding of the physical environment and in the capability to model it can be expected in the future, with priority on the following points:

- The spatial and temporal variability of underwater PAR is thought to be important in controlling the timing of the spring phytoplankton bloom. However, information on the high frequency variability of this parameter throughout the region is not yet available, particularly as regards PAR attenuation by suspended particles which vary at sub-diurnal time scales because of resuspension by tides and winds. The combination of satellite imagery (Doron *et al.*, 2005) and correlations obtained from high frequency data of PAR attenuation and suspended sediments (Greenwood *et al.*, 2006) could fill this gap in knowledge.
- The identification of long-term trends in physical parameters, particularly SST, their relation to anthropogenic forcing (greenhouse gases) and their impact on eutrophication are an important theme for future research. However, distinguishing long-term trends from the large interannual variability shown here remains a challenge. NAO is thought to characterize much of the large scale meteorology, although the direct links with the various physical factors (wind, rainfall/river discharge and possibly abovewater PAR) have not yet been clearly elucidated.
- The present review considers spatial scales from about 4 km to the scale of the Channel and Southern North Sea. Some extra spatial variability can be expected at smaller spatial scales, controlled by bathymetric features such as the Flemish Banks and by the coastline in very nearshore and estuarine waters. Finer resolution for hydrodynamic modeling will provide information on such processes.
- Incremental improvements should be expected in the validation and the quality of simulation of most physical parameters as more and better

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forcing and validation data becomes available. For model studies, the river discharge data and the representation of estuarine processes are probably the most critical aspects requiring improvement.

1.9 References

Behrenfeld M. J. and P. G. Falkowski. 1997. A consumer's guide to phytoplankton primary productivity models. Limnology and Oceanography 42: 1479-1491

Breton E., Rousseau V., Parent J.-Y., Ozer J. and C. Lancelot. 2006. Hydroclimatic modulation of the diatom/*Phaeocystis* blooms in the nutrient-enriched Belgian coastal waters (North Sea). Limnology and Oceanography 51: 1-14

De Vries H., Breton M., Mulder T. D., Krestenitis Y., Ozer J., Proctor R. , Ruddick K. , Salomon J. C. and A. Voorrips. 1995. A comparison of 2D storm surge models applied to three shallow European seas. Environmental Software 10: 23-42

Deleersnijder E. 1989. Upwelling and upsloping in three-dimensional marine models. Applied Mathematical Modelling 13: 462-467

Deleersnijder E., Campin J.-M. and E. J. M. Delhez. 2001. The concept of age in marine modelling I. Theory and preliminary results. Journal of Marine Systems 28: 229-267

Delhez E. J. M., Heemink A. W. and E. Deleersnijder. 2004. Residence time in a semi-enclosed domain from the solution of an adjoint problem. Estuarine, Coastal and Shelf Science 61: 691-702

Delhez E. J. M. and G. Martin. 1992. Preliminary results of 3D baroclinic numerical models of the mesoscale and macroscale circulations on the North-Western European Continental Shelf. Journal of Marine Systems 3: 423-440

Doron M., Babin M., Mangin A. and O. Fanton D'andon. 2005. Retrieval of the penetration of light and horizontal visibility in coastal waters from ocean color remote sensing data, p. 85-94. In: R. J. Frouin, M. Babin and S. Sathyendranath (Eds), Remote Sensing of the Coastal Oceanic Environment. SPIE.

Greenwood N., Mills D. K. , Howarth M. J. , Proctor R., Pearce D. J., Sivyer D. B., Cutchey S. J. and O. Andres. 2006. High frequency monitoring in Liverpool Bay: variability of suspended matter, nutrients and phytoplankton. In: H. Dahlin, N. C. Flemming, P. Marchand and S. E. Petersson (Eds), European operational oceanography: present and future. European Commission.

Hurrell J. W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676-679

Jones P. D., Jonsson T. and D. Wheeler. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. International Journal Climatology 17: 1433-1450

Lacroix G., Ruddick K. G. , Ozer J. and C. Lancelot. 2004. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). Journal of Sea Research 52: 149-163

Lacroix G., Ruddick K., Gypens N. and C. Lancelot. 2007a. Modelling the relative impact of rivers (Scheldt/Rhine/Seine) and Channel water on the nutrient and diatoms/*Phaeocystis* distributions in Belgian waters (Southern North Sea). Continental Shelf Research 27: 1422-1446

Lacroix G., Ruddick K., Park Y., Gypens N. and C. Lancelot. 2007b. Validation of the 3D biogeochemical model MIRO&CO with field nutrient and phytoplankton data and MERIS-derived surface chlorophyll a images. Journal of Marine Systems 64: 66-88

Lancelot C., Spitz, Y., Gypens, N., Ruddick, K., Becquevort, S., Rousseau, V., Lacroix, G. and G. Billen. 2005. Modelling diatom and *Phaeocystis* blooms and nutrient cycles in the Southern Bight of the North Sea: the MIRO model. Marine Ecology Progress Series 289: 63-78

Lancelot C., Lacroix G., Gypens N. and K. Ruddick. 2008. Ecological modeling as a scientific tool for assessing eutrophication and mitigation strategies for Belgian coastal waters. In: Current Status of Eutrophication in the Belgian Coastal Zone. V. Rousseau, C. Lancelot and D. Cox (Eds). Presses Universitaires de Bruxelles, Bruxelles, pp. 91-110

Loewe P. 2003. Weekly North Sea SST Analyses since 1968. In O. d. a. h. b. B. f. S. u. Hydrographie (Ed.)

Maes F. *et al.* 2005. A flood of space: towards a spatial structure plan for sustainable management of the North Sea. Gaufre Project. Belgian Science Policy

Ministerie van Openbare Werken. 1980. Vlaamse Banken bathymetric map D11

Mulligan D., Bouraoui F., Grizzetti D., Aloe A. and J. Dursaut. 2006. An Atlas of pan-European data for investigating the fate of agrochemicals in terrestrial ecosystems, p. 52. Joint Research Centre, European Commission

Nihoul J.C.J. and J.H. Hecq. 1984. Influence of the residual circulation on the physico-chemical characteristics of water masses and the dynamics of ecosystems in the Belgian coastal zone. Continental Shelf Research 3 (2): 167-174

Nihoul J.C.J. and F.C. Ronday. 1976. Modèles hydrodynamiques. Projet Mer. Final Report volume 3

Osborn T. J. 2004. Simulating the winter North Atlnatic Oscillation: the roles of internal variability and greenhouse gas forcing. Climate Dynamics 22: 605-623

Osborn T. J. 2006. Recent variations in the winter North Atlantic Oscillation. Weather 61: 353-355

Otto L., Zimmerman, J.T.F., Furnes, G.K., Mork, M., Saetre, R. and G. Becker. 1990. Physical Oceanography of the North Sea. Netherlands Journal of Sea Research 26: 161-238

Peperzak L., Colijn F., Gieskes W. W. C. and J. C. H. Peters. 1998. Development of the diatom-*Phaeocystis* spring bloom in the Dutch coatal zone of the North Sea: the silicon depletion versus the daily irradiance threshold hypothesis. Journal of Plankton Research 20: 517-537.

Rousseau V. 2000. Dynamics of *Phaeocystis* and diatom blooms in the eutrophicated coastal waters of the Southern Bight of the North Sea. PhD Thesis. Université Libre de Bruxelles, 205 Pp.

Ruddick K., Lacroix G., Lancelot C., Nechad B., Park Y., Peters S. and B. van Mol. 2008. Optical remote sensing of the North Sea. In: V. Barale and M. Gade (Eds.), Remote sensing of the European Seas. Springer-Verlag, pp. 79-90

Tsimplis M. N., Shaw A. G. P. , Flather R. A. and D. K. Woolf. 2006. The influence of the North Atlantic Oscillation on the sea-level around the northern European coasts reconsidered: the thermosteric effects. Philosophical Transactions of the Royal Society A 364: 845-856

Yang L. 1998. Modelling of hydrodynamic processes in the Belgian coastal zone. Faculteit Wetenschappen. Katholieke Universiteit Leuven. 214 pp.