# Modelling Water Column Processes in the North Sea [and Discussion]

G. Radach, M. Regener, F. Carlotti, W. Kuhn, A. Moll and J. W. Loder

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# Modelling water column processes in the North Sea

By G. Radach[1], M. Regener[1], F. Carlotti[2], W. Kühn[1] and A. Moll[1]
[1] Institut für Meereskunde, Universität Hamburg, Troplowitzstr. 7,
2000 Hamburg 54, F.R.G.
[2] Station Zoologique, B.P. 28, 06230 Villefranche-sur-Mer, France

In the North Sea advective transports are not negligible. Nevertheless, physical properties like sea surface temperature (SST) can be hindcasted with sufficient precision by vertical process water column models. Annual cycles of SST in the southern, central, and northern North Sea can be simulated using physical upper layer models with relatively small RMS errors. For the Fladenground Experiment (FLEX'76) in the northern North Sea the RMS error is less 0.3 °C for the 2 months of the experiment. This justifies the initial use, at least, of vertical process water column models in simulations for investigating transfer processes in the planktonic ecosystem. Experiments have shown that the simulated entrainment velocities at the bottom of the mixed layer during summer are critically dependent on the resolution of the forcing variables. The effects of this resolution on the annual phytoplankton dynamics will be discussed.

Phytoplankton dynamics are strongly influenced by those of the zooplankton, and vice versa. Several field investigations have shown that, seemingly, phytoplankton cannot sustain the observed stock of zooplankton in the northern North Sea: there exists a gap between the abundance of phytoplankton and the need for it to maintain the zooplankton. Revisiting FLEX'76, the simulations with water column models of increasing complexity concerning detritus suggest that pelagic detritus can fill the gap in food availability for the zooplankton. If it is assumed that the zooplankton feeds also on detritus, the zooplankton experiences no food shortage.

## 1. Introduction

Vertical process water column models are useful for initial studies of the North Sea. Even if in nature horizontal transport processes play a major role, the water column model simulations are capable of helping in the understanding of the interactions between physical transport and the many reaction processes involved in the vertical dynamics themselves.

In large areas of the North Sea the biological processes related to the formation and decay of phytoplankton blooms are closely linked to the physical processes responsible for the formation and the decay of the seasonal thermocline. The subject of this paper is to demonstrate the potential of vertically resolved water column modelling for understanding the effects of coupled processes by performing hindcasts and forecasts of observed situations.

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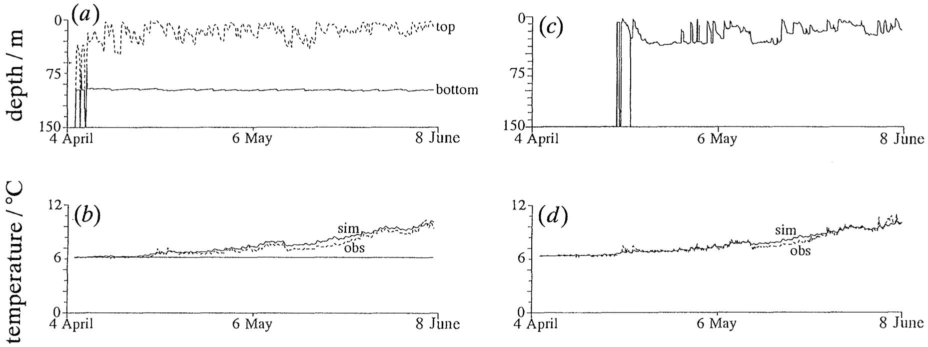

Figure 1. Simulation of top and bottom mixed layer thicknesses and sea surface temperature (SST) at the FLEX'76 site (*a*) layer thicknesses and (*b*) sea surface and bottom temperature with van Aken's model, and observed SST, (*c*) mixed layer thickness and (*d*) SST with Mellor–Durbin's model, and observed SST (data from Soetje & Huber 1980).

## 2. Modelling the physical upper layer dynamics in the North Sea

The set of physical observations obtained during the Fladenground Experiment in 1976 (FLEX'76) has been repeatedly used for testing one-dimensional physical upper layer models by different authors (Friedrich *et al.* 1981; Friedrich 1983; Frey 1991; Regener 1992, and others).

As examples figures 1 and 2 show the results of simulations with the differential mixed-layer model of Mellor & Durbin (1975), using modifications given by Mellor & Yamada (1982), and with the semi-integral model of van Aken (1984). The model of Mellor & Durbin and that of van Aken have been applied to reproduce the formation of the seasonal thermocline at the central station during FLEX'76 (58° 55′ N, 0° 32′ E). Van Aken's model is a three-layer model, with a resolved middle layer. It takes tidal friction in the bottom layer into account and is able to simulate the transitions from 1- to 2- and 3-layer water column systems and vice versa.

The simulation of the FLEX'76 situation shows that observations of SST can be reproduced to an rms error of 0.27 °C or 0.25 °C during a period of 2 months with van Aken's (figure 1*b*) and Mellor–Durbin's model (figure 1*d*) respectively. Temperature rose by 3.35 °C from 6.25 to 9.6 °C during this period.

The causes for the deviations can be manifold. Certainly, advective heat transport plays a role. Soetje & Huber (1980) showed that heat content deviated from the total of local heat input by about 10 % at the end of FLEX'76. During May and June the simulated mixed layer depth is about the same as that measured (figures 1*a* and 2). The full overturning stops too early in the simulation with van Aken's model; it is about right in the simulation with Mellor–Durbin's model (figure 1*c*). The definition of the mixed layer depth in the latter simulation was set arbitrarily at the depth where the temperature gradient became greater than 0.02 °C m$^{-1}$, coming from the surface. The simulated temperature profiles by van Aken's model compare quite well with the observed ones (figure 2).

For other areas of the North Sea no such dense data sets seem to exist. There are only a few sites where annual cycles of meteorological forcing data as well as temperature and salinity profiles exist for one full year. We found two places, one in the central and one in the southern North Sea, where at least the forcing data exist continuously and a comparison of simulations and observations can be performed for the year 1976: at OWS Famita (57° 30′ N, 3° E) and at LV Elbe 1 (54° N, 8° 7′ E).

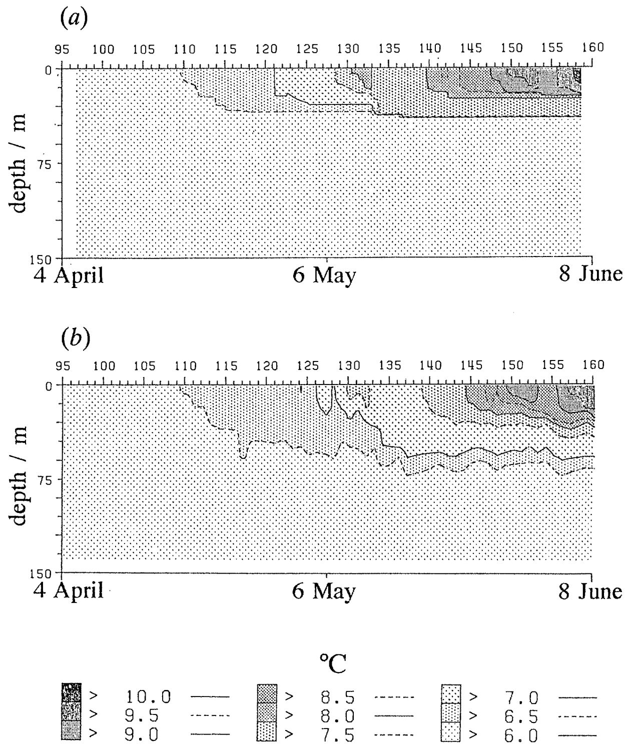

Figure 2. Simulated temperature profiles at the FLEX'76 site (*a*) with van Aken's model, (*b*) from observations (data from Soetje & Huber 1980).

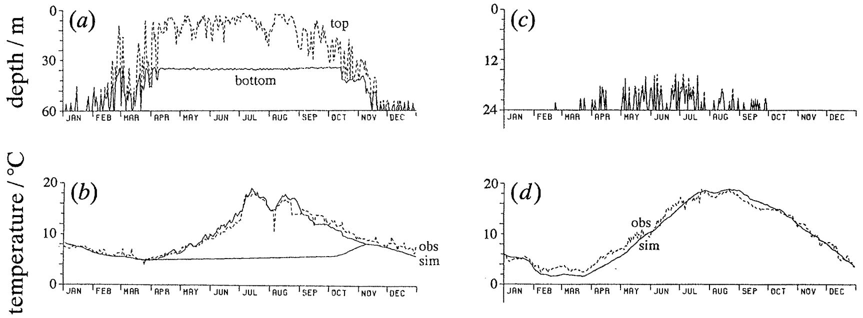

Figure 3. Simulations of the annual cycle of top (dashed) and bottom (full) mixed layer thicknesses, sea surface and bottom temperature at two sites; (*a*) simulated layer thicknesses and (*b*) simulated temperature and SST at OWS FAMITA and (*c*) simulated layer thicknesses, (*d*) simulated temperature and SST at LV ELBE 1 (Regener 1992) with the model by van Aken (1984). (sim = simulated, obs = observed.)

The data sets are reported for LV Elbe 1 by Moll & Radach (1990) and for OWS Famita by Moll (1989).

Regener (1992) used van Aken's model to simulate the annual cycles of temperature at OWS Famita and at LV Elbe 1. Comparing the dynamics from the central North Sea at OWS Famita (figure 3*a*, *b*) with those from the southern North Sea at LV Elbe 1 (figure 3*c*, *d*) the striking difference is in the layer structure: whereas there is during most time of the year an overlap of upper and bottom layer

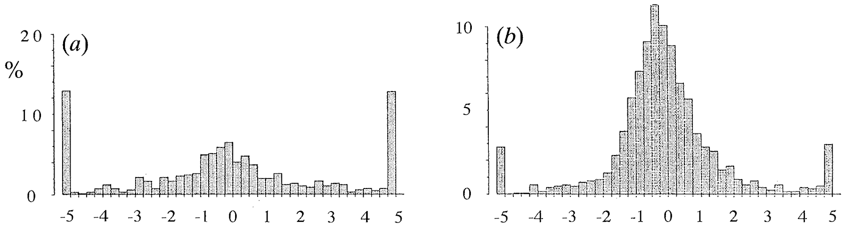

Figure 4. Frequency distribution of the ratio of advective heat transport/local surface heat flux on a weekly basis in the areas considered: (*a*) OWS Famita (Moll 1989) and (*b*) LV Elbe 1 (Moll & Radach 1990).

at the southern site (figure 3*c*), a distinct separation of both boundary layers appears during summer in the central North Sea (figure 3*a*), as in the observations. The sea surface temperature can be simulated well in both cases, with an rms error of 1.18 °C for the southern site and of 0.70 °C for the central North Sea site, compared with annual ranges of observed, monthly mean, temperatures of 15.0 °C and 11.4 °C respectively (Regener 1992).

Simulated and observed SST agree well despite the considerable advective heat transports. The explanation may be sought in the nearly symmetric frequency distributions of the ratios of advective to local heat fluxes (figure 4). The advective heat fluxes were determined as the difference between the local heat input and the heat content of the water column. The frequency distributions suggest that heat inflow and outflow, although being considerable when looked at on weekly timescales, mostly compensate each other on longer timescales, thus leaving the local heat dynamics to dominate. In most of the 1253 cases investigated at LV Elbe 1 (figure 4*b*), advective contributions per week to the heat balance are larger than 10% of local heat input. In 19% of the cases advective heat flux is below 25% of local heat input. The ratio is more than 5 in 6% of all cases. For OWS Famita (figure 4*a*) we found that only in 10% of the 652 cases is advective heat flux less than 25% of local heat flux per week.

Water column models need the proper temporal resolution to be fruitfully applied to problems of the plankton dynamics, where physical, chemical and biological processes are closely coupled. Recently Ridderinkhof (1992) has shown that the results of modelling the vertical structure of physical upper layer dynamics depend strongly on the temporal resolution of the meteorological forcing variables. The entrainment of lower layer water decreases strongly when the forcing data are averaged on scales larger than a few days. Although entrainment events are clearly visible when the forcing was averaged daily, nearly no entrainment could be detected in the case of weekly averaged forcing.

However, from Ridderinkhof's paper it is not clear how he averaged radiation. If values were averaged over several days, the night would also be illuminated, and in the biological simulation the nights would lose their biological function of providing time for respiration without any production. Radach & Maier-Reimer (1975) have shown that a permanent illumination can lead to a forward shift in phytoplankton blooming, which is unrealistic. Thus, for biological simulations the most consistent way of averaging would be the formation of averaged diurnal cycles for all input variables, including air and water temperature, wind speed, global radiation. The averaging of the variability at fixed hours of the day would result in more and more flattened diurnal cycles as the averaging interval increases.

As shown in Radach & Moll (1993), meteorological short-term events, such as heating events and storms, can have great influence on the temporal development of phytoplankton standing stock. Storms can deeply stir the water column, and thus nutrient regenerated at the bottom can be transported back into the upper layers, where it can initiate a new algal bloom. This is especially important in summer, when the upper layers are depleted of nutrients, and in autumn while the light conditions are still favourable.

Summarizing, one-dimensional physical upper layer models are capable of reproducing the main features of the annual cycle of heating and cooling with a rms error of less than 8% of the annual range of sea surface temperature. As the physical dynamics form the basis for the plankton dynamics, these results encourage the use of one-dimensional simulations in the study of the plankton dynamics.

## 3. Simulation of plankton dynamics

Models have to be sufficiently complex to be able to simulate plankton dynamics. This is demonstrated by hindcasting the spring bloom of FLEX'76 by model versions with increasing complexity, depending on the special question considered.

The plankton model used here predicts phytoplankton biomass, phosphate concentration, benthic and pelagic detritus (P/N/BD/PD-model). It is our standard plankton model as described by Radach & Moll (1993), augmented by the dynamics of pelagic detritus. The model consists of three submodels, the meteorological forcing model, the physical upper layer model, and the biological upper layer model. The forcing functions, like wind stress, global radiation, and the heat fluxes at the sea surface, for the physical as well as the biological model, are calculated in the meteorological part from standard meteorological observations. The formation and decay of the seasonal thermocline is simulated by the physical part, using the physical upper layer model developed by Friedrich *et al.* (1981).

In the biological model (figure 5) the equations describing the development of phytoplankton biomass, the nutrient phosphate, and the detritus in the water column as well as detritus at the bottom are solved simultaneously, being forced by profiles of the physical state variables temperature and vertical eddy diffusivity, and by prescribed grazing of herbivorous zooplankton. The change of phytoplankton standing stock is caused by turbulent diffusion, sinking, primary production, respiration, mortality and grazing. Dead material, when transformed to detritus, is mineralized, partly in the water column, partly at the bottom. Hydrodynamic transport redistributes the nutrient accumulated at the bottom throughout the water column. Further details of the standard model are given in Radach & Moll (1993).

For our purposes we programmed the simulation model in such a way that state variables and their links to other state variables can easily be taken out, thus enabling us for example, to investigate a system with (P/N/BD/PD-model) or without pelagic detritus (P/N/BD-model).

We will discuss two specific features in the simulations with the P/N/BD/PD-model: the effect of grazing on the phytoplankton dynamics and the effect of availability of pelagic detritus as a food source for zooplankton. To investigate the effect of the zooplankton on the phytoplankton we considered simulations without (option (0)) and with (option (1)) zooplankton grazing pressure (table 1). The grazing pressure has been imposed as a forcing function calculated from the zooplankton

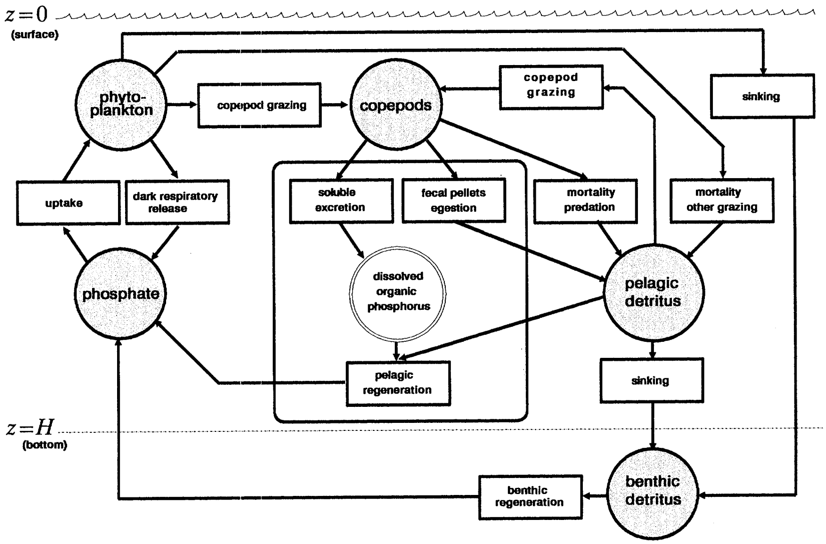

Figure 5. Interaction diagram of the biological plankton model, including the state variables phytoplankton, phosphate, pelagic detritus and benthic detritus. Observed zooplankton standing stock was prescribed to exert grazing pressure. The rectangles denote the processes in the model. The box including dissolved organic phosphorus and 3 processes denotes a parameterization of the effect of the 'small food web'.

Table 1. *Comparison of the results of the simulations for a 62-days period (6 April to 6 June 1976) during FLEX'76 with grazing options (0) and (1), using the P/N/BD/PD-model and the P/N/BD-model: the standing stocks equal the sum of all gain (+) and all loss (−) terms, integrated over the FLEX'76 period of 2 months and over the upper layers (0–27.5 m)*

| | option (0)[a] | option (1)[b] | |
|---|---|---|---|
| pelagic detritus | with | with | without |
| phytoplankton budget/($\mathrm{gC\,m^{-2}}$) | | | |
| standing stock | 6.6 | 2.7 | 2.9 |
| gross primary production | +28.5 | +30.2 | +30.6 |
| respiration | −5.5 | −3.4 | −3.7 |
| mortality | −16.4 | −8.1 | −9.0 |
| grazing | −0 | −15.9 | −15.1 |
| pelagic detritus budget/($\mathrm{gC\,m^{-2}}$) | | | |
| standing stock | 15.6 | 4.1 | 0 |
| detritus production | +16.4 | +8.1 | +0 |
| grazing on detritus | −0 | −3.7 | −0 |
| decay | −0.7 | −0.3 | −0 |
| sinking | −0.1 | −0.1 | −0 |

[a] No grazing.

[b] Grazing pressure derived from FLEX'76 observations.

stocks observed during FLEX'76 (Radach 1983), utilizing the counts of individuals of *Calanus finmarchicus* (Krause & Radach 1989).

First, we simulated the spring phytoplankton bloom with the P/N/BD/PD-model, using the above mentioned two grazing options (figure 6, table 1). The introduction of grazing increases primary production by 6%. For the FLEX'76

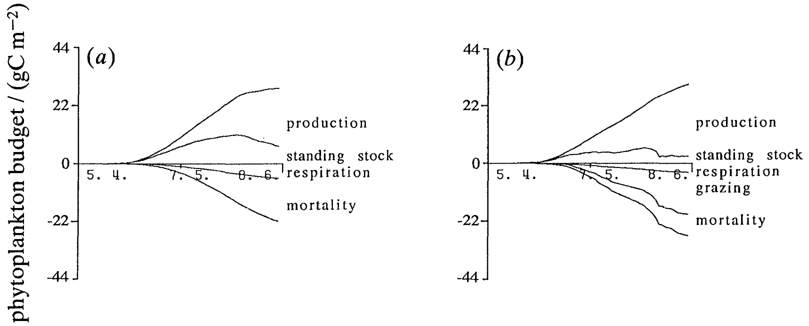

Figure 6. Simulation of the phytoplankton bloom of FLEX'76 with the nutrient/phytoplankton/pelagic detritus/bottom detritus model (P/N/BD/PD-model): budget for phytoplankton (*a*) using no grazing, option (0), (*b*) using potential grazing derived from FLEX'76 measurements, option (1) (Radach *et al.* 1984). The positive and negative contributions (areas) to the budget are added up separately, the increments are denoted by the names of the processes.

period the simulation without any grazing (figure 6*a*) predicted primary production of 28.5 gC m$^{-2}$. The simulation forced by the potential grazing derived from observations (option (1), figure 6*b*) predicted primary production of 30.2 gC m$^{-2}$. Respiration decreased from 5.5 gC m$^{-2}$ in option (0) to 3.4 gC m$^{-2}$ in option (1), and mortality other than copepod grazing decreased from 16.4 to 8.1 gC m$^{-2}$. In the simulation using potential grazing during FLEX'76 (option (1)) the grazing amounted to 19.7 gC m$^{-2}$, composed of 15.9 gC m$^{-2}$ on phytoplankton plus 3.7 gC m$^{-2}$ on pelagic detritus.

The mechanism at work is self-shading, which inhibits an increase of primary production when there is no grazing. The budget of phytoplankton for the simulation with grazing according to option (1) (figure 6*b*) shows that the increase of primary production mediated by the grazing during the last part of the simulated period goes along with increased losses by grazing and mortality. These losses give rise to an increased regeneration of nutrients fuelling production.

Secondly, the introduction of the state variable 'pelagic detritus' enabled us to simulate a situation that had been observed during FLEX'76. It was shown by Fransz & Gieskes (1984) and by Radach *et al.* (1984) that the living phytoplankton could most probably not supply sufficient food to maintain the zooplankton stocks. Thus it was suggested that the zooplankton fed additionally on pelagic detritus. The P/N/BD/PD-model can deal with this problem.

If we omit pelagic detritus in the P/N/BD/PD-model, we obtain a P/N/BD-model. Simulations with the latter model show that the primary production is 30.6 gC m$^{-2}$ (table 1) for grazing option (1). This value is close to that of the simulation including pelagic detritus. The ingestion of zooplankton decreases from 19.7 gC m$^{-2}$ in the former case to 15.1 gC m$^{-2}$ in the latter case (figure 7), and there is no material in the water column to compensate for additional food demands. Observations in 1976 suggested that the food demand of *Calanus finmarchicus* was much higher than 15 gC m$^{-2}$; Radach *et al.* (1984) estimated consumption by all copepods, including *Calanus finmarchicus*, during FLEX'76 to have been between 59 and 84 gC m$^{-2}$.

We conclude that the N/P/BD-model cannot solve the problem of food supply for the zooplankton immediately after the phytoplankton bloom. The simulation results from the model when pelagic detritus was introduced suggest that the food problem

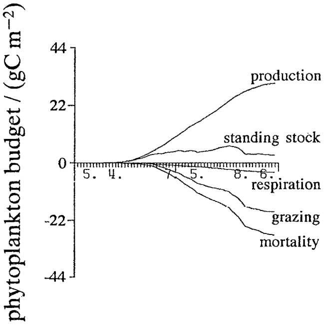

Figure 7. Simulation of the phytoplankton bloom of FLEX'76 with the nutrient/phytoplankton/bottom detritus model (P/N/BD-model): budget for phytoplankton, using potential grazing derived from FLEX'76 measurements (Radach *et al.* 1984).

for zooplankton can probably be solved by prescribing the correct grazing functions for phytoplankton and for pelagic detritus. To further investigate this problem we have a model version under development which is augmented with zooplankton population dynamics (P/N/BD/BD/Z-model) as modelled by Carlotti & Sciandra (1989), applied to *Calanus finmarchicus* in the North Sea.

## 4. Conclusions

Water column models are useful tools for investigating the dynamics in the North Sea despite the non-negligible horizontal transports. The reproduction of the annual cycle of sea surface temperature by modelling the local dynamics is sufficiently close to observations to encourage one to model plankton dynamics with one-dimensional models. However, the imposed forcing has to account for the variability of weather events if the plankton dynamics are to be realistically simulated. Forcing with mean conditions on time scales longer than a few days will wipe out features which have an important impact on the biology.

The simulations of phytoplankton dynamics support the hypothesis that zooplankton grazing, under the given circumstances in the central North Sea, enhances primary production. However, as was shown from field measurements, the food demand of the zooplankton cannot solely be satisfied by the living standing stock of phytoplankton. At certain times, after the spring blooming, there exists a gap in food availability. Our simulations suggest that, if pelagic detritus is introduced into the model as an additional food source, the zooplankton can satisfy its food demand, which is not possible in our simulations omitting pelagic detritus.

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## *Discussion*

J. W. Loder (*Bedford Institute of Oceanography, Canada*). The model results that you presented illustrate clearly the importance of atmospheric forcing in determining the timing of the onset of seasonal stratification in relatively stratified areas of the North Sea. What is the relative importance of tidal mixing to vertical exchange across the pycnocline in these areas as the seasonal stratification evolves?

G. Radach. Comparing the results of a simulation including tidal mixing and omitting tidal mixing shows that tidal mixing does not alter the timing of the onset of seasonal stratification at water depths where the tidally mixed boundary layer does not interfere with the thermocline. The decay of thermal stratification in our simulation for 60 m water depth, however, is influenced during November and December. When tidal stirring is included in the simulation, uniform heat distribution is reached in early November as the surface and bottom mixed layers meet, whereas without tidal stirring, temperature does not become vertically homogenous until early December.