Validation of a temperature model for the Rhine plume
A case study


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Abstract
A three-dimensional numerical baroclinic shallow water tidal model with prognostic salinity and temperature is used to simulate the period May, June and July 1995 for the Dutch coastal zone, using realistic meteorological and hydrodynamic forcing. The model area includes the outflow plume of the Rhine, where salinity stratification often occurs after high river run off or off-shore directed winds.

The computed temperature and salinity distributions are validated with in situ and remote sensing data in various steps. Measured and computed temperature data are in good agreement and show both an increased day/night variability after the onset of salinity stratification.

Introduction
The Rhine is an important source of anthropogenic substances and nutrients in the Dutch coastal area. A detailed description of outflow and mixing characteristics of the fresh Rhine water is therefore necessary to model the quality of the Dutch coastal waters. The main outflow points of river water are located near Rotterdam (fig. 1). Forced by tidal motion, Coriolis effects and prevailing south-westerly winds the Rhine water turns to the North-East after entering the sea and follows the coast line. Mixing with sea water is limited by stratification and by coastal trapping. The width of the river plume is on average about 40 km and seldom exceeds 50 km.

Within a radius of 15 km from the outflow point a strong salinity stratification exists most of the time (de Ruijter et al., 1992, Ruddick et al.,1994), but occasionally the entire plume can be stratified over a length of more than 120 km (de Kok, 1996). This can be caused by high river discharges combined with south-westerly winds, as it occurs almost every spring. The year average river run-off is about 2300 m³/s, but it can become several times higher in winter and spring.

However, when discharges are below the average only a small part of the plume may be stratified, but winds coming from the North-East, the East or the South-East can cause restratification. These winds blow the coastal surface water seaward, where it becomes a relatively fresh and thin upper layer. This process can take place in less than a day and causes sometimes off shore displacements of surface water beyond 10 km (fig. 2). The apparent width of the region of fresh water influence increases rapidly in that case. Near the coast upwelling then occurs and after a few days the appearance of colder and more saline water at the surface can be observed.

These phenomena can often be seen on satellite SST imagery, in periods (e.g. in early summer) when off shore continental winds bring warm cloudless air to the area.

Interpretation of satellite SST images
Remote sensing data such as the NOAA-AVHRR images give information on sea surface temperatures, but in case of stratified river plumes it can also provide information on plume width and degree of stratification. The salinity front, that marks the river plume, coincides very often with a temperature front. Near the outflow point this is caused by the temperature difference between the
outflowing river water and the ambient sea water. In spring and summer this can be more than 10 °C, when the sea water is still cold and the water in the shallow river is rapidly warming up. Sea areas containing 20% river water can then still be discerned by their temperature contrast.

In the stratified part of the river plume however, heat exchange with the atmosphere and solar radiation can change the sea surface temperature very rapidly and within a few days the initial river water temperature is of no importance anymore. Haline stratification causes a very strong damping of vertical turbulent exchange of mass, heat and salinity. Often a more or less discontinuous transition exists between the surface layer and the lower layers. This surface layer has a typical depth of 2 to 5 m and by its shallowness the changes in layer temperature as a result of heat fluxes through the surface are relatively high. On sunny days in early summer the surface layer temperature difference between day and night can exceed 3 °C.

Consequently in spring and summer the stratified part of the plume is on average several degrees warmer than the ambient sea. This gives us the opportunity to discern this stratified part of the plume (often covering the entire plume area) by its temperature contrast with the ambient sea and by its temporal temperature variability and to estimate the width of the region of river water influence. It has to be studied however, to what extent temperature fronts, visible on satellite SST imagery coincide with the real river plume front. In shallow areas (depth < 7 m) for instance the response to surface heating can also be very quick, even when the water is vertically well mixed. The Dutch coastal zone however, is almost everywhere deeper than 10 m, except in a small coastal strip with a width of a few km.

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Figure 1. *Situation of the model area.*
*Main fresh water outlets are the Rotterdam Waterway and the Haringvliet.*
Figure 2. Cross shore salinity and temperature distributions measured in the evening of March 29, 1989 in a transect off Egmond (see fig.4). The year mean salinity distribution is indicated by dashed lines. Below: wind speed vectors from 16-30 March. From the night of March 28 on the wind has easterly components, causing an exceptionally strong stratification at 20 km.

To get an impression of the importance of the effect of surface heating a typical late spring/early summer period, covering the months May, June and July 1995, was simulated with a three-dimensional baroclinic tidal model for the Dutch coastal zone, including fully prognostic salinities and temperatures. The model results were validated with in situ temperature and salinity data and with SST-plots based on NOAA-AVHRR imagery. Also the accuracy or representativeness of the remotely sensed SST data was assessed.
Figure 3. Model grid.
The result can be seen as a skill assessment of the hydro-temperature model, but also as an assessment of the usefulness of daily satellite SST maps as a tool for the monitoring of coastal water quality. It should be remarked, that especially in the nutrient-rich Rhine plume area the development of spring temperatures is decisive for possible harmful algae bloom and that an accurate computation of temperatures and nutrient transport is at the basis of all prognostic ecological modelling in this area.

Numerical model
The model used is based on a three-dimensional finite difference code for the shallow water equations (see Lander et al., 1996), coupled with transport equations for heat and salinity. The hydrostatic and Boussinesq approximations are applied. Salinity and water temperature are coupled via the equation of state to the baroclinic pressure gradient terms in the momentum equations. Horizontal curvilinear orthogonal coordinates are applied. In the vertical a combination of $\sigma$-layers and fixed layer depths is possible. The discretisation of the baroclinic pressure gradient terms takes into account the layer interface slope and the vertical density difference (de Kok, 1992). Vertical turbulence viscosity and diffusivity are determined via a two-equation $k$-$\epsilon$-turbulence model, taking into account the damping of turbulence by stable stratification via buoyancy terms. The horizontal ADI-type numerical scheme is semi-implicit and has only mild time step limitations (Stelling and Leendertse, 1991). It is upstream weighted and of second order accuracy for the momentum equations and of fourth order for the transport equations. In the vertical a fully implicit Crank-Nicolson-type scheme is used. The model allows for drying and flooding of grid cells, e.g. in intertidal areas. The temperature model has a heat flux boundary condition at the surface, determined by solar radiation, cloud cover, atmospheric temperature and humidity, water temperature and wind speed. The modeled area stretches from the Belgian coast until Den Helder with an alongshore distance of 200 km and a cross shore width of 70 km (fig.1). The horizontal mesh width varies between 200 and 5000 m (fig. 3). 10 equidistant $\sigma$-layers were used in the vertical. At the most seaward boundary the vertical mesh width is then less than 4 m, in the river plume area it is 1 to 2.5 m. Time step size was 600 s. Tidal water level boundary conditions were imposed at the open sea boundaries of the model. The tidal constituents were computed using a tidal (and storm surge) model of the entire continental shelf (Gerritsen et al., 1995). Measured river discharges were imposed at the upstream river boundaries of the Scheldt and the Rhine. Temperature boundary conditions for horizontal inflow were imposed at the open boundaries, using data of the permanent temperature station EUR (see fig. 4), located 50 km off shore. From satellite images it is known that no important temperature gradients exist normal to the sea boundaries. Initial condition was 10 °C uniformly. Climatological salinity values were imposed at the open boundaries. The initial salinity condition was also based on a climatological mean. With the model the period May, 1 until July, 31, 1995 was simulated using measured atmospheric conditions.

Wind, river run off, stratification and temperature variability
Stratification of the Rhine plume can be caused by high river run off and by winds with an off shore component. This stratification is always haline, but in summer it can coincide with important thermal differences. The vertical temperature gradient can thus contribute to 30 % of the vertical density gradient in warm periods.
In the months May and June, 1995 the river discharge was well above the yearly mean and in July it was slightly below. From June 21 on the wind was north-easterly, with an exception for July, 4-7 and July, 15-20. Fig. 6a shows the temperature data (black line), measured at 2 m below the surface in the permanent station MPN (see fig.4). The red and blue line represent the model results for top and bottom layer. At this location, 10 km off shore, stratification exists for almost the entire period, with a maximal temperature difference of 5 °C between surface and bottom layer.
It can be seen, that in periods of high stratification the day/night temperature variability increases as a result of the strong reduction of vertical mixing. The maximal difference between model result and in situ data occurs at the moment when the model does not compute any stratification, which is probably erroneous.

Comparison of NOAA-AVHRR SST images with in situ temperature data
SST images based on AVHRR represent only a very thin surface layer (Roozekrans & Prangsma, 1988). In periods with low wind speeds this layer mixes very slowly with the lower layers, and a significant temperature difference can develop.

The in situ stations are located around 2 m below the sea surface, and can be seen as representative for a surface layer of 4 m depth. The difference between AVHRR SST values and in situ data can be interpreted as a real temperature gradient, but AVHRR SST values are also subject to all kinds of error sources and may differ from the real surface temperature.

For these reasons a comparison is made between satellite SST values and in situ data of the five temperature stations shown in fig. 4. This is illustrated in fig. 5 where the correspondence between in situ and AVHRR values is plotted for several typical moments. AVHRR values are the most “accurate” during night and early morning. During night the accuracy is around 1 °C. During the day the deviation is much higher.

Comparison of in situ temperature and salinity data with model results.
In fig. 6b,c the measured and computed upper layer temperatures are plotted for the stations LEG and IJM. For both stations no stratification was computed, but the strong variability in station IJM suggests occasional stratification. The correspondence of the night temperature values however, is very good.
Figure 5. Comparison of NOAA-AVHRR SST values and in situ values.
In a 50 km cross shore transect off Noordwijk (see fig. 4) regular measurements of temperature and salinity were done from ships at about (roughly) 3 m below the surface. These values are compared with the model results by plotting them together (fig. 7a-g). No attempt is made to account for the phase of the tide or the hour of the day.

The depth of measurement was variable and very inaccurately known. It corresponds roughly to the third model layer (blue line) for the positions 1.5 km, 3 km and 5 km, between the second (violet) and third layer at 10 km and with the second layer at km 20, 30 and 50.

The correspondence of the temperature values looks much better than that of the salinities. From the salinity plots for 20, 30 and 50 km it can be seen, that in general the model underestimates the cross shore spreading of Rhine water. The temperature values have still a good correspondence.

The station LJM in fig. 6c is situated 40 km off shore and not far from the locations Noordw30 and Noordw50. The data shown in fig. 6c indicate that the cross shore spreading is related to stratification, as might be expected in case of off shore winds.

We can conclude however, that on average computed temperature data correspond with in situ data within a margin of 1 to 2 °C.

Model results versus satellite data

As both model and NOAA-AVHRR imagery provide synoptic data for the entire model area (on clear days), it is possible to compare directly the observed and computed temperature patterns. On has to take into account however, that the estimated SST values from satellite data are affected by a multitude of disturbing factors and measuring and interpretation errors. One also has to take into account, that in case of a temperature gradient in the upper 2 m of the water column the model has not sufficient resolution to reproduce the real surface temperature gradients. This limits the possibility of a quantitative model skill assessment on the basis of satellite data alone.

It is however still possible to compare horizontal temperature patterns and general features, such as the location of gradients, heating of very shallow water, coastal upwelling, wave lengths of frontal meanders (see de Kok, 1997) and the off shore drifting of surface water. This is illustrated in the figs. 8 and 9, showing the observed and computed night values of surface and upper layer temperature.

The computed values differ less then 1 °C from the AVHRR values, that is within the margin of the correspondence of the latter with in situ data. At the cross shore boundary in the South of the model the imposed inflow temperatures were much to low, leading to a local model error.

The temperature difference between the western sea boundary and the shore is at most 5 °C, both in model and satellite data. The development of the water temperature since the beginning of May shows a rise of minimal 5 and maximal 10 °C which is also reproduced by the model.

Fig. 10 shows the computed surface salinity pattern, which in the Rhine plume area corresponds very well with the computed temperature pattern.

From the comparison with many other SST images (not shown) the following could be concluded: The correspondence of the present model with AVHRR SST patterns is global, but well within the margin of "accuracy" of the latter. The differences in the Rhine plume area amount to 10 % of the temporal variability and to 20% of the spatial variability.

Conclusions and model skill assessment

In the case of a river outflow plume, such as the Rhine plume in front of the Dutch coast, the validation of model results with in situ monitoring data is complicated by the existence of vertical gradients and stratification. The vertical position of the observation has to be known with an accuracy of less than 0.5 m, which is generally not the case.

Also the comparison with AVHRR SST data is complicated by vertical temperature gradients in the surface layer.

Both effects lead to an uncertainty in the interpretation of the data, equivalent with an error of 1 °C. The difference between observed surface layer temperatures and model results is most of the time below 2 °C, with an exection for some day temperatures in stratified areas when differences can become 3 °C.
In the Rhine plume area the difference of computed surface layer temperatures and satellite SST data is maximal 1°C. This is 10% of the temporal variability of the simulated period and 20% of the spatial variability.

For the measured salinities the same uncertainty concerning the measuring depth exists as for the temperatures. In case of stratification the associated interpretation error is 1 PSU and can be as high as 3 PSU, when the measuring position is near the halocline. The difference of most model results with the measured values is smaller.

In the areas situated more than 30 km off shore the model results show insufficient cross shore spreading, leading to salinities at the plume edge, that are 1.5 PSU too high, and a day/night temperature variability that is too small.

References


Temperature near-surface measured (black) and model (red), near-bed model (blue)

Figure 6. Development of temperatures during three months in 1995 at
a) MPN (10 km off Noordwijk),
b) LEG (20 km off shore) and
c) IJM (40 km off shore)
The model does not compute any stratification in the locations LEG and IJM.
Figure 7a

Figure 7b
Figure 7 a-g  Computed and measured (Δ) salinity (upmost graph, in PSU) and temperature (lower graph, in °C) values in the Noordwijk transect at distances of 1.5, 3, 5, 10, 20, 30, and 50 km offshore. The dots indicate measurements at about 3 m below the surface. This corresponds to the third model layer (blue line) for the positions 1.5 km, 3 km, 5 km, to the interface between second (violet) and third layer for 10 km and with the second layer for the positions 20 km, 30 km and 50 km. The first (upmost) model layer is indicated by a yellow line.
Figure 8. *Sea surface temperature values based on NOAA-AVHRR data on July 8, 1995, 2.00 h. The blue spot West of Noordwijk is a small cloud.*
Figure 9. Computed temperature values for the model top layer on July 8, 1995, 00h00. The temperature inflow boundary condition at the south-westerly boundary was not sufficiently known.
Figure 10. Computed salinity values for the model top layer on July 8, 1995, 0.00 h.