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The dynamics of cooling water discharge in a shallow, non-tidal embayment

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Abstract

The dynamics of cooling water spreading in a non-tidal embayment is subject of a modelling-based study of Greifswald Bay, a shallow embayment at the south-western coast of the Baltic Sea. Potential cooling water spreading due to a possible power plant at Greifswald Bay is evaluated as differences between a realistic hind-cast simulation and a similar simulation but including the cooling water pumping. The model results are confirmed with satellite imagery of the embayment during operation of a nuclear power plant in the 1980s. The effect of cooling water pumping on the residual circulation, additional stratification and the heating of near-bed waters in the herring spawning areas is evaluated from the simulation. The model results for an idealised embayment and the realistic scenario, as well as the satellite images, show a clear dependence of the plume spreading on the wind direction. Although the surface plume affects a large area of the embayment, the results show a localised impact on residual circulation, bulk stratification and heating of the waterbody.

Key words: Plume spreading, Greifswald Bay, cooling water discharge, stratification

1. Introduction

In the 1980s, the shallow, non-tidal embayment Greifswald Bay (GWB), located at the south-western coast of the Baltic Sea (see the map in fig. 1), was used to discharge cooling water of a nuclear power plant. It is possible to re-use the present cooling infrastructure of the closed-down power plant for a modern coal or gas and steam power plant (Buckmann (2007)). The possible hydrodynamic effects of the cooling water pumping on the system of the GWB is investigated in the present study.

[Figure 1 about here.]

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The hydrodynamical system of Greifswald Bay is highly influenced by its three lateral openings: a) The wide connection to the brackish Baltic Sea water in the north-east, b) the Strelasund at the western side, which supplies saltier and thus denser water from the area of the Darss Sill, and c) the Peenestrom in the east, which is part of the Oder estuary, providing the main source of freshwater into the the GWB area. Due to a typical water depth of 8 m in the central embayment, the GWB is vertically mixed in periods of strong winds. According to Munkes (2005), increasing nutrient loads between the 1950s and 1980s caused increasing phytoplankton concentrations in the GWB. A consequence was decreasing water transparency that led to a shift from a macrophyte- towards a phytoplankton-dominated ecosystem. Within 30 years, the macrophyte cover declined from 90% to 15%. Despite strongly reduced nutrients loads after 1985, this state remained. Today the GWB is classified as a mesotrophic to eutrophic system, with strong Cyanobacteria blooms during summer (Robakowski (2013)).

The cooling water channels were build such, that the intake of cooling water uses estuarine water from the Peenestrom. A headland between the intake and outlet positions minimises the risk of recirculation and thermal feedback. Satellite images of the bay during operation of the nuclear power plant (NPP) Bruno Leuschner, originally using the cooling water infrastructure, are employed for validation of the model study. Since December, 1973, up to five reactor blocks were built successively, the fifth one was used in an 8 month testing period giving the maximum rate of cooling water pumping in 1989. From February 1990 on, the blocks were shut down successively. The continuous operation period amounts to about 10 years from 1980 to 1989 with four operating blocks and a cooling water pumping of up to $90 \text{ m}^3/\text{s}$ and a maximum heating of the cooling water by 10 K (Sellin (1989)). The specifications are comparable to the hypothetical power plant that is subject in the present model study for the year 2002.

Geophysical-scale plumes are unique in that the aspect ratio of the plume is small, unlike engineering scale plumes, which have a cross-plume aspect ratio of $O(1)$. Because of this, for geophysical-scale plumes, mixing and entrainment happen primarily in the vertical coordinate. The cooling water release through the shallow outlet channel is opposed to, for example, an entraining jet flowing from a diffuser, with entrainment and mixing occurring in the two dimensions perpendicular to the axis of the plume. Small geophysical-scale plumes (as subject in the present study) are characterized by small timescales, with residence times of many hours, as opposed to large river plume systems, with timescales of days to months. Small geophysical-scale buoyant plumes have been observed in a number of different locations (e.g., Luketina and Imberger (1987); Chen and MacDonald (2006)), and have been characterized for a number of discharge and background flow conditions (recently, Jones et al. (2007); Jirka (2007)). For geophysical-scale plumes with a narrow discharge, a supercritical flow region will form near the mouth with elevated entrainment levels (Hetland (2010)). Beyond this region, the buoyant plume will be primarily mixed and displaced by the local winds (e.g., Fong and Geyer (2001); Hetland (2005)). For strong winds, the plume may be mixed away completely; an energy balance may quantify the wind stress magnitude required to vertically mix the plume (Pritchard

and Huntley (2006)).

In the following sections, the dynamics of cooling water discharge plume into the GWB is investigated for the statistically warm year 2002 (Siegel et al. (2006)). Cooling water pumping by a power plant, located at the same area as the NPP Bruno Leuschner, will be considered with a pumping rate of $125 \text{ m}^3/\text{s}$ and an additional warming of the cooling water by 7.55 K. These specifications match the worst-case scenario studied by Buckmann (2007). The estimated spreading of the cooling water plume is compared to satellite images of the GWB during operation of the NPP in the 1980s. After this qualitative validation of the model, we discuss the results in terms of affected area, wind-control on the plume spreading, additional stratification and impacts to the ecosystem.

2. Methodology

The effect of the cooling water discharge is calculated by subtracting the simulation results of the GWB under natural conditions from the results of the same simulation with an additional cooling water cycle. The location of the former power plant on a headland allowed for clearly separated positions of cooling water inlet and outlet, possibly in order to minimise a thermal feedback. In terms of the physical cooling water properties, the location of the inlet at the Peenestrom is of importance. Freshwater outflow of the Szczecin Lagoon together with the small river Peene enhances the salinity difference between the inlet and outlet position. The simulated plumes are compared to the satellite images in order to validate the model approach.

The modified-hindcast strategy of the present study is not meant to be a forecast of particular future conditions. The objective of the present study is to investigate the system of the Greifswald Bay under a possible future scenario.

2.1. The simulation period

The expected impact of cooling water pumping into a shallow estuary is a warm surface plume, which spreads in the embayment deflected to the right hand side of the wind direction, due to Earth's rotation. The stratifying potential of the pumping is enhanced by the lower salinity near the inlet channel, compared to the water in the Greifswald Bay. For the analysis of the realistic spreading of cooling water, the simulation period is chosen to be a whole year. The simulation period thus includes a range of recurring wind conditions together with the annual range of thermal forcing and riverine freshwater supply. Large-scale effects of the barotropic forcing of the embayment due to winds are captured through the boundary conditions. The year 2002 was chosen as simulation period, because it was the warmest year in the period 1990-2005 (Siegel et al. (2008)). Especially the months August to October showed a temperature deviation from the long-term mean of up to 4°C in the western Baltic Sea (Siegel and Gerth (2003)). The cooling water pumping in warm years will lift the absolute temperatures in the embayment above naturally possible conditions and

could accelerate metabolic rates in the biogeochemical system of the GWB. Choosing a warm year will make it possible to consider the present study in the discussion on expected global warming. In terms of wind conditions, the year 2002 shows an above-average duration of easterly winds (35-40% of 2002) compared to the usually dominating westerly wind directions (40% of 2002) in the GWB area. These conditions allow for a better representation of the usually less frequent easterly wind conditions in terms of the plume spreading analysis.

2.2. Remote sensing strategy

Satellite images of the GWB are available for the period 1986 to 1989, when the nuclear power station "Bruno Leuschner" was in operation. The data were acquired by the sensor Thematic Mapper (TM) onboard the satellite Landsat 5, that is operated by the U.S Geological Survey (USGS). Quasi- true colour images derived for the land were combined with false-colour images, which were retrieved from two visible and the thermal infrared channel for the water area. The infrared channel delivers the temperature information in a spatial resolution of 120 m. The visible channels with a spatial resolution of 30 m contribute the detailed coastline, turbidity patterns and the signature of shallow water areas. The channels were combined in the image processing software "ENVI" (as also used in Siegel et al. (2005)). Due to missing temperature calibration, the maximum grey value difference of these images was compared with a more recent Landsat image from Siegel et al. (2008), where we had also calibrated temperatures from NOAA-AVHRR. For the same grey value difference in both Landsat scenes, the temperature difference was derived from the NOAA-AVHRR data. Because of the repeating rate of 16 days, the acquired scenes, and the cloud coverage, 20 scenes were available for the time period to study the distribution of cooling water in relation to wind direction.

2.3. Numerical model design

The three-dimensional circulation model GETM (Burchard and Bolding (2002)) is used for the idealised and realistic simulations. The model uses the hydrostatic assumption here and is coupled to the turbulence model of GOTM, which allows for a realistic representation of turbulence in estuaries and coastal seas. GETM was applied successfully in various realistic simulations of stratified, coastal waters (Burchard et al. (2004, 2009); Hofmeister et al. (2009, 2011)). The baroclinic model of the GWB was set up with a curvilinear grid following the main coastline near the outlet and the main larger-scale Baltic Sea coastline with a horizontal resolution of approximately 60 m in the outlet region. In the vertical, 16 bottom-following, equally distributed sigma layers are used, which leads to a 0.5 m resolution in the central GWB with depths around 8 m. The model has an open boundary to the Baltic Sea, one open boundary to the Szczecin Lagoon and an opening to the Strelasund.

The natural circulation in the GWB, with its large connection to the Baltic Sea and the two connected channels Strelasund and Peenestrom, needs a proper forcing at the lateral boundaries of the study area.

Results of the operational model of the BSH, Hamburg (Bundesamt für Seeschifffahrt und Hydrographie, Dick et al. (2001); Dick and Kleine (2007)) are used for the barotropic forcing at the open boundaries. A barotropic model for vertically mean transports and sea surface elevation with a larger extent, but the same horizontal resolution and bathymetry in the overlapping area with the GWB model, was set up (see figure 1), in order to minimise uncertainty effects of topographical resistance due to different model resolutions. With its curvilinear grid, it follows the main coastlines and resolves the transports through the narrow topographic structures in the outer region of the GWB. The barotropic model provides sea surface elevations at the open boundaries of the GWB model. For a model spinup, the three months October to December 2001 are additionally pre-simulated with the model system, in order to avoid adjustments of mean pressure gradients within the study period.

Lateral boundary forcing for temperature and salinity for the Greifswald Bay model are taken from the operational model of the BSH. The meteorological forcing is the same as used by the BSH model and was originally provided by the German Weather Service (DWD). In the GWB model, the riverine freshwater input by the small rivers Peene, Ryck and Ziese are considered, whereas the rivers Oder and Recknitz are also considered for the barotropic model. The Oder river is the main source of freshwater in the region and is expected to release a fraction of approximately $130 \text{ m}^3/\text{s}$ freshwater together with the Peene river through the Peenestrom (based on Mohrholz and Lass (1998), and data from the local authorities (StAUN)).

The effect of cooling water pumping was arranged by a constant volume transfer of $125 \text{ m}^3/\text{s}$ from the inlet channel to the outlet channel. The transferred volume is additionally heated by a typical value of 7.55 K (as used in Buckmann (2007)). The inlet and outlet channels are positioned along the model grid coordinates with realistic length and width. The curvature of the real channels is of minor importance here. The effect of surface cooling and mixing in the outlet channel is included in the baroclinic model. It should be noted here that the pumped volume is of the same order of magnitude as the natural net outflow of the Peenestrom.

Fig. 2 shows the surface elevations for the reference simulation without cooling water discharge as scatter plot for the 8 stations in the vertically integrated simulation for the simulation period. The coefficient of determination for the comparison of measured and simulated time series is between 0.75 and 0.85 for the different stations. The differences may be explained by locally unresolved bathymetric features in the narrow channels and the monthly-mean river runoff used for the river Oder, which is a major trigger for local sea level variations (see Mohrholz and Lass (1998)). It is assumed thereafter that the used barotropic forcing for the baroclinic simulation works reasonably.

[Figure 2 about here.]

The reference simulation results for sea surface temperature and density stratification are also compared to monitoring measurements in Fig. 3 at the station GB19 (see Fig. 1). For a statistical comparison, the

monitoring intervals are not short enough. The comparison shows that the temperature and vertical stratification can be captured well by the simulation. Salinities stay at about 7 g/kg throughout the simulation period and are overestimated in the simulation by a systematic offset of about 1 g/kg due to the used baroclinic boundary data. However, the natural, vertical density gradients, which are of major importance for the present study of plume spreading, seems to reproduce the typical mixed regime with occasional events of stratification.

[Figure 3 about here.]

2.4. Idealised bay simulation

The spreading of a cooling water plume under controlled wind conditions in an idealised bay is additionally studied in a set of numerical experiments with the same model, that is used in the realistic study. Warm and fresh water is pumped into a rectangular 20 x 20 km basin at latitude 54 ° N and constant water density of 1025 kg/m³. Depths in the idealised basin are 7 m with a linear slope down to 2 m water depth over a distance of 2 km towards the outlet coast. The density difference of the pumping water amounts to 3.5 kg/m³ due to a temperature difference of 7.5 °C and a salinity difference of 2 g/kg. Besides the pumping, a wind of constant speed and direction forces the circulation in the bay. The main spreading direction is partially determined by the depth of the mixing layer, due to momentum transfer under earth rotation. The magnitude of wind speeds thus influences the spreading direction. Since the results of the idealised experiments are compared to satellite images during clear sky, we assume high-pressure atmospheric conditions with weak winds. A fixed wind speed of 3 m/s for the different wind directions is used in the idealised experiments. As sketched in figure 7 (center panel), the bay has two openings similar to Greifswald Bay. The sealevel is treated passively at the openings with a zero-gradient condition, volume fluxes through the openings are possible.

3. Results and Discussion

3.1. Residual circulation

Figure 4 shows the differences in horizontal transports between the vertically integrated, barotropic simulation with and without cooling water pumping for the whole simulation period. Compared to typical, natural currents, the pumping-induced circulation is weak. The simulated currents in the outlet channel amount to 0.4 m/s, whereas the current differences at the boundaries of the bay are in the order of magnitude of 10⁻³ m/s. At the intake channel, the pumping induces a slight decrease of the mean sealevel, which is mostly compensated by inflow into the Peenestrom from the Bodden site, instead of increasing the flow from the Oderhaff through the Peenestrom. Thus, an additional dilution of the Greifswald Bay waters due to a significantly increased Peenestrom transport is not suggested by the simulation results. It has to be noted

again, that the results in fig. 4 are not representing the local effects of density stratification and directional forcing of the pumped water due to winds.

[Figure 4 about here.]

3.2. *Plume spreading in the realistic regime*

Landsat-TM satellite data from the cooling water plume in the GWB during the operation of the in the nuclear power station "Bruno Leuschner" from 1986-1989 are the only existing real measurements for the present study. The propagation of the cooling water occurred in typical patterns for the main wind directions. Examples were found for six main wind directions except for the northerly and southerly winds. A wind statistic for data of the meteorological station Arkona had shown that northerly and southerly winds only occurred in a very low frequency in the area of the island of Rügen (Siegel et al. (2005)). The number of available scenes per wind direction was rather inhomogeneously distributed and the image quality different, such that a statistical analysis was not appropriate and examples were selected. The elevated water temperature is indicated by red colouring in the plots. The derived maximum temperature differences of up to 5 K between the cores of the cooling plume and the open GWB were in a good agreement with in-situ measurements published by Hantke and Oeberst (1991). The visible channels deliver the coastline in high spatial resolution and indicate shallow areas and regions of higher turbidity. In Figure 5, six scenes for different wind situations (NNE, E, SE, WSW, W, and WNW) are presented.

[Figure 5 about here.]

During NNE wind on 12 June 1989 the plume propagated north-westwards and reached the central part of the bay. On 9 May at the prevailing easterly wind direction a wide expansion occurred into the northern areas of the GWB. During SE wind on 29 April 1987, the cooling water was transported north-eastwards, guided by the coast and the shallow area around the headland, and leaves partly the GWB in north-easterly direction. SW and W wind on 11 September 1987 and 3 October 1986, respectively, initiated similar pattern as SE wind in the vicinity of the outlet channel propagating in NE direction. But for W wind at the 3 October 1986, the cooling water was further guided by the coast, passed the shallow headland and left the GWB in south-easterly direction. During NW wind on 13 June 1986 the developed circulation transported the cooling water plume in westerly direction along the coast.

The hindcast simulation for the year 2002 reproduces the dependence of the plume spreading on wind direction as shown in characteristic snapshots in figure 6. Snapshots of temperature differences between the simulation with and without cooling water pumping have been selected in a way that the target wind direction persisted in mean for at least 48 hours within a standard deviation in angle of less than 10 degrees. This analysis is based on the 3-hourly atmospheric forcing data and allows for at least a few scenes for each main wind direction. Additionally to the snapshots, figure 6 provides the extend of the temporal mean

for the available snapshots. In most cases, the mean plume is oriented similarly as the provided snapshot. For NW conditions, the mean plume shows spreading from the outlet to either side along the coast. The idealised simulations (see section 3.3) can confirm the temporally mean spreading, although only a few transient snapshots were identified in the realistic simulations.

[Figure 6 about here.]

Under easterly, north-easterly and northerly winds, the cooling water plume spreads far into the center of the bay and affects large parts of the central GWB surface waters. Plume spreading eastward of the outlet is reproduced in the simulation except for northerly and north-westerly winds similar to the satellite scenes. The plume spreading westward of the outlet is consistently found for the north-westerly and northerly wind conditions in the simulations, which was confirmed by the available satellite image for WNW winds only.

3.3. *Wind-controlled plume spreading under idealised conditions*

The findings on plume spreading from the realistic scenario are further tested in a numerical experiment under idealised conditions. Analogously to the realistic simulation and the satellite images, figure 7 shows the pumping plume at the surface for each wind direction after 24 hours of wind forcing. The patterns in figure 7 are similar to the situations in the satellite images and simulation snapshots. For NW winds, the idealised simulation can confirm the mean spreading in the realistic simulation, such that the related satellite image may show a situation under transient winds. Differences in the plume shape between the realistic and idealised simulations for the outer plume may occur due to a boundary-imposed circulation and the spreading history. The center scenario in figure 7 shows a typical river-bulge shape oriented to the right-hand side due to Coriolis force. Here, missing wind mixing is the reason for the relatively high density anomalies and the wide extend of the plume.

[Figure 7 about here.]

We can conclude here that the plume spreading is highly determined by local wind directions. Due to the size of the Bay, a characteristically oriented plume develops already within 24 hours of stationary wind conditions without considerable, direct interaction with the lateral boundaries of the setup. The influences of varying bathymetry, rough coastline, varying wind speeds and boundary-imposed circulation are not considered in the idealised experiments. However, the results show that wind direction consistently determines the plume orientation, comparable to the findings of the satellite images and the realistic simulation.

3.4. *Pumping induced stratification*

A statistical analysis of the highly variable density stratification is shown in figure 8 for the summer period (1 June to 15 Sept, 2002.) for the realistic and the pumping scenario. Fig. 8 shows the amount of stratified periods and the longest stratification event, whereat a water column is regarded as stratified

if the stratification exceeds 0.1 kg/m^3 per m in the vertical. The density stratification suppresses vertical mixing and thus the ventilation of the benthic zone. Temporary hypoxia may occur during stratification events, which are a major threat for benthic heterotrophs. See section 3.5 for possible consequences on the ecosystem.

The southern Greifswald Bay (GWB) is subject to stratification for approximately 20 % of the summer period in the realistic scenario. The mouth of the Peenestrom shows more than 50 % stratified periods with more than 7 continuous days of stratification. The southern GWB is also subject to continuously stratified periods of up to a week. Deeper bathymetry in the southern GWB enhances the potential energy anomaly increase due to differential transport of fresh water at the surface and saltier water from the Strelasund at the sea bed (Hofmeister et al. (2009) also identified differential advection in a non-tidal lagoon as main process that increases potential energy anomaly). The shallower area at the mouth of the Peenestrom is subject to stratification due to a mean straining effect under the conditions of a mean density gradient between Peenestrom and Baltic Sea.

The cooling water pumping has a significant impact on the stratification (see figure 8). A new, stratified area develops in the deeper areas close to the outlet with continuously stratified periods of more than a week. Also the stratified area at the mouth of the Peenestrom is enlarged due to an increased inflow of more saline Baltic Sea water as result of the pumping (see figure 4). Furthermore, figure 8 shows an enlargement of the stratified water body and a prolongation of continuously stratified periods in the southern GWB (west of the outlet).

[Figure 8 about here.]

3.5. Potential consequences on the ecosystem

Possible, significant and lasting effects on the ecosystem due to the water warming can be expected only in the core area of the plume. Temperature is a major controlling parameter for all organisms. Its changes in the plume area will have consequences e.g. on micro-organisms, phytoplankton, zooplankton, fish, zoobenthos and macrophytes. Shifts in abundance and succession are possible (Philippart et al. (2011)). Temperatures close to 30°C in summer at the release spot might be negative for the survival of several species. Higher temperatures might favour blue-green algae blooms (Paerl and Huisman (2009)), which are a major threat for bathing water quality and tourism in the bay. Important human pathogenic micro-organisms might benefit from increased summerly water temperatures (Roijsackers and Lürding (2007)). *Vibrio vulnificus*, bacteria which caused infections in the bay during recent years, is known to proliferate fast at temperatures above 20°C (Eiler et al. (2007); Baker-Austin et al. (2013)). Temperature changes might allow a broad spectrum of invasive species to survive (Philippart et al. (2011)). In winter, heated water in the plume would prohibit ice-cover. The area of open water would then certainly be used by migration birds for resting

and would allow diatom growth and early blooms (Klamt and Schernewski (2013)). This could alter the phytoplankton succession in the bay.

In brackish seas, such as the GWB, salinity concentrations and its gradients determine the occurrence and spatial distribution of species (Attrill (2002); Zettler et al. (2007); Telesh and Khlebovich (2010)). The Peenestrom is classified as an oligohaline water (0.5-3 psu) while GWB is mesohaline (5-10psu). In the outlet area, the pumping reduces salinity, whereas the inlet area salinity is increased (see figure 9). Many species are very sensitive to salinity changes. For example, Zebra and Blue mussels compete for similar habitats. Both species differ in salinity tolerance and pumping would favour then either Zebra mussels (*Dreissena polymorpha*) or the freshwater species, depending on the location (Klamt and Schernewski (2013)).

[Figure 9 about here.]

Hypoxia due to vertical density stratification (see section 3.4) is a possible, major threat for many zoobenthos species. The flora and fauna in and on the sediment is largely immobile. In the plume area, these organisms are always exposed to the incoming water with its differing properties. Therefore, macrophyte and zoobenthos organisms will be most affected and changes in their spatial distribution, species composition and abundance are very likely.

From an ecological and economic perspective herring is of outstanding importance in the GWB (Klenz (2005)). Herring can serve as an example to show the interactions in the ecosystem and uncertainties in the prediction of pumping consequences. The GWB is the main spawning area of western Baltic spring-spawning herring (*Clupea harengus*) (ICES (1998); Biester (1989)). Herring stocks look for stony, macrophyte-covered shallow areas for spawning. Figure 9 shows statistics of bottom water warming in March overlayed with the spawning areas according to Scabell (1988). The warming due to cooling water pumping would cover most spawning regions, although only a small fraction would be affected for half of the spawning period and longer than 4 continuous days. The eggs, which are sensitive to low oxygen concentrations, are attached to the substrate and larvae eclose usually after 15 days (Scabell (1988); Kääriä et al. (1997)). Higher bottom water temperatures accelerate the process of eclosion under higher risk of food limitation in the early spawning season (Blaxter and Hempel (1963); Oeberst et al. (2009)).

The survival of herring eggs and the transport and nutrition of larvae cannot be addressed directly in the present study. Higher salinities in the Peenestrom may allow for the compensating utilization of new grounds. It is important to keep in mind that the pumping causes the intrusion of waters from a different area, with different properties, nutrient concentrations and different species. Thus, ecological consequences in the GWB cannot be derived from heating or salinity change only.

4. Conclusions

Plume spreading in the non-tidal embayment Greifswald Bay is studied here for cooling water pumping of a power plant at the coast of the bay. Satellite images as well as a high-resolution numerical model of the bay show, that the buoyant plume can spread out largely into the bay. The cooling water spreads mainly wind-driven, which is confirmed by a model of an idealised non-tidal bay. Additional vertical stratification is predicted by the modified hindcast scenario close to the cooling water outlet, but also in the deeper parts of the bay. Effects on the circulation in the system of embayments and lagoons at the south-western Baltic Sea coast are negligible. Effects on the ecosystems of the bay might arise due to additional warming of the water close to the outlet, changed salinities in the intake and outlet area and additional stratification and thus suppressed vertical mixing of oxygen.

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List of Figures

1	Map of Bodden coast (gray-scale) and Greifswald Bay (colours) model area and bathymetry. The picture in the lower left corner of the lower panel is the enlarged area denoted by the black rectangle in the map. The outlet indicates where the cooling water is pumped into Greifswald Bay, the inlet indicates the location of cooling water intake from the Peenestrom.	14
2	The comparison of measured and simulated sea surface height for 8 stations in the Bodden coast setup (see fig. 1) for the simulation period Oct 2001 to Dec 2002.	15
3	Comparison of measured and simulated temperatures and vertical density differences at the monitoring station GB19 (see fig. 1) for the simulation period.	16
4	The residual circulation in the vertically integrated simulation due to the cooling water pumping as temporal mean of the simulation period. The colors indicate the current speed on a logarithmic scale, where red indicate currents of appr. 0.1 m/s, yellow indicates currents of appr. 1 cm/s and blue indicates currents of less than 1 mm/s	17
5	Landsat TM scenes of the Greifswald Bay from the period 1986-1989 show the spreading of the cooling water plume of the nuclear power plant Lubmin during 6 different wind directions. The red colouring indicates enhanced temperature differences.	18
6	Snapshots of plume spreading in the simulations for different wind directions. The colours show temperature differences between the simulation with and without cooling water pumping. The black-white line indicates the simulated, temporally mean plume extent with a threshold of 0.3 °C.	19
7	Plume spreading results under idealised conditions in a rectangular bay. The colours show density anomalies (at most 1.5 kg/m ⁻¹ less density) due too pumping with a line denoting the 5 % contour. The center scenario shows the plume spreading without winds for the full domain. The scale in the upper left panel is not valid for the center panel. The dashed grid lines have a distance of 2.5 km. The center NW to SE grid line is aligned with the outlet.	20
8	Fractional amount of stratified periods and duration of longest, stratified period for the simulation period of 1 June to 15 Sept. The images on the left show the natural, simulated situation and the figures on the right show the simulation results with cooling water pumping. A water column was considered as stratified if the density gradient exceeds 0.1 kg/m ³ .	21
9	Upper left panel: the fraction of periods where bottom waters changed salinity by at least 0.5 psu for the year 2002. Red colours indicate a decrease of salinity, blue colours indicate an increase of salinity. Lower panels: the fraction of periods where bottom waters were warmed by at least 1 K and the longest, continuous period of 1 K warming of bottom waters in March 2002. The hatched areas denote spawning regions as listed in Scabell (1988).	22

Figure 1: Map of Bodden coast (gray-scale) and Greifswald Bay (colours) model area and bathymetry. The picture in the lower left corner of the lower panel is the enlarged area denoted by the black rectangle in the map. The outlet indicates where the cooling water is pumped into Greifswald Bay, the inlet indicates the location of cooling water intake from the Peenestrom.

Figure 2: The comparison of measured and simulated sea surface height for 8 stations in the Bodden coast setup (see fig. 1) for the simulation period Oct 2001 to Dec 2002.

Figure 3: Comparison of measured and simulated temperatures and vertical density differences at the monitoring station GB19 (see fig. 1) for the simulation period.

Figure 4: The residual circulation in the vertically integrated simulation due to the cooling water pumping as temporal mean of the simulation period. The colors indicate the current speed on a logarithmic scale, where red indicate currents of appr. 0.1 m/s, yellow indicates currents of appr. 1 cm/s and blue indicates currents of less than 1 mm/s

Figure 5: Landsat TM scenes of the Greifswald Bay from the period 1986-1989 show the spreading of the cooling water plume of the nuclear power plant Lubmin during 6 different wind directions. The red colouring indicates enhanced temperature differences.

Figure 6: Snapshots of plume spreading in the simulations for different wind directions. The colours show temperature differences between the simulation with and without cooling water pumping. The black-white line indicates the simulated, temporally mean plume extent with a threshold of 0.3 °C.

Figure 7: Plume spreading results under idealised conditions in a rectangular bay. The colours show density anomalies (at most 1.5 kg/m^{-1} less density) due too pumping with a line denoting the 5 % contour. The center scenario shows the plume spreading without winds for the full domain. The scale in the upper left panel is not valid for the center panel. The dashed grid lines have a distance of 2.5 km. The center NW to SE grid line is aligned with the outlet.

Figure 8: Fractional amount of stratified periods and duration of longest, stratified period for the simulation period of 1 June to 15 Sept. The images on the left show the natural, simulated situation and the figures on the right show the simulation results with cooling water pumping. A water column was considered as stratified if the density gradient exceeds 0.1 kg/m^3 .

Figure 9: Upper left panel: the fraction of periods where bottom waters changed salinity by at least 0.5 psu for the year 2002. Red colours indicate a decrease of salinity, blue colours indicate an increase of salinity. Lower panels: the fraction of periods where bottom waters were warmed by at least 1 K and the longest, continuous period of 1 K warming of bottom waters in March 2002. The hatched areas denote spawning regions as listed in Scabell (1988).