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Dynamical processes along the German Baltic Sea coast systematized to support coastal monitoring

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Abstract

Satellite data of different spectral and spatial resolution were combined with model simulations and ship-borne measurements to investigate dynamical features and processes along the Baltic Sea coast of the German federal state Mecklenburg-Vorpommern (MV). Systematization in relation to the local wind was performed to develop an interpretation instrument for the coastal monitoring (SIBIK) of local authorities (LUNG). Satellite data of sea surface temperature and ocean colour of the sensors NOAA-AVHRR, SeaWiFS und Landsat 7 ETM+ were applied. Model simulations were focused on the western Baltic with the coast of the state MV (3-D model) as well as on the Szczecin Lagoon (2-D model) at the border between MV and Poland. The results summarized in a catalogue support the interpretation and the assessment of acquired in situ data as well as optimization of the monitoring program. Regional particularities in the coastal dynamical features and processes are presented for the main wind directions and for changes between dominant wind situations. Consequences for coastal zones and its monitoring programme are discussed.

1 Introduction

The German federal state Mecklenburg-Vorpommern (MV) is located at the western Baltic Sea the transition area between the Baltic and the North Seas. The hydrography of the western Baltic is embossed by a strong structured bottom with the Darß Sill, coastal topography, and different driving forces, which operate in diverse temporal scales. Continuing wind situations may establish large scale sea level differences between the Baltic and the Kattegatt leading to barotropic currents in the area of investigation. Because of the shallow bathymetry the current field and the stratification is strongly influenced by the local wind which may change in scales of hours to a few days. The positive water balance due to the river inflow produces a long-term outflow. Furthermore, the western Baltic is influenced by coastal discharge. The most important coastal outflow from the Oder River enters the western Baltic in the Pomeranian Bight. Systematic investigations of the river discharge in relation to the dominating wind directions were provided by Siegel et al. 1996 and 1999. The results have been applied for the interpretation of Oder flood data in 1997 (Siegel et al. 1998, Siegel and Gerth, 2000).

The Federal State Authority for Environment, Nature Protection and Geology (Landesamtes für Umwelt Naturschutz und Geologie, LUNG) of MV performs a monthly monitoring program of fixed stations for the collection, documentation and evaluation of the environmental conditions.

The measurements at all stations take a few days.

Due to the highly variable dynamical system of the western Baltic Sea the hydrographic situation can change completely in the measuring period. Synoptic satellite data may support the monitoring investigations. Two different ways are conceivable. The operational supply of current satellite data is the most important way for future applications but reliable if the data access for different sensors is improved. Additionally, the cloud coverage in the western Baltic Sea is an important limiting factor.

Therefore, the second way was chosen and the systematic investigations performed in the Pomeranian Bight were extended to the entire coast of the German state MV. Synoptic satellite data of different spectral and spatial resolution were combined with model simulations of circulation processes and ship-borne measurements to validate the derived patterns and to understand the processes producing the dynamical features. Wind data were used to derive the dominating wind directions. The investigation results in a Satellite based Interpretation and Evaluation Instrument for the Coastal Monitoring of Mecklenburg – Vorpommern (SIBIK). The main product of SIBIK is a detailed catalogue containing systemized dynamical features in relation to the wind direction.

2 Area of investigation, methods and database

The area of investigation is the entire coast of the German federal state Mecklenburg–Vorpommern. From a dynamic point of view the coastal area shown in Fig. 1 can be divided into four main regions.

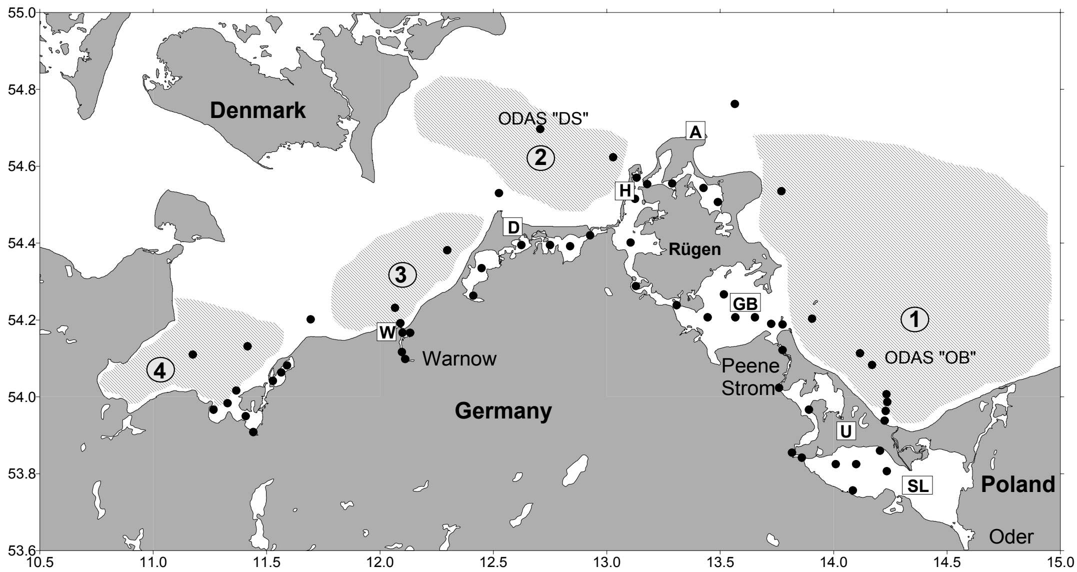


Figure 1: Map of the western Baltic Sea including the four areas under investigation (1, Pomeranian Bight; 2, Hiddensee–Darss; 3, south-eastern Mecklenburg Bight; 4, Lübeck Bay), locations of wind registrations (A, Arkona; ODAS'DS', ODAS Darss Sill; ODAS'OB', ODAS Oder Bank), special locations (W, Warnemünde; D, Darss Peninsula; H, Hiddensee Island; GB, Greifswald Bay; U, Usedom Island; SL, Szczecin Lagoon) and the stations of the coastal monitoring programme.

The stations of the German coastal monitoring programme of MV are illustrated in the map.

The database includes satellite data of different spectral and spatial resolution, wind data, ship-borne measurements, and model simulations. The satellite data evaluation was focussed on sea surface temperature (SST) due to the high repeating rate and availability. The SST was derived from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) weather satellites provided by the German Federal Maritime and Hydrographic Agency Hamburg (BSH) (Siegel et al. 1994). SST data of the years 1996-2002 were used for automatic derivation of typical patterns for the 8 main wind directions and the period 1990-2002 was included for scenario of special situations. Satellite data of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provided by NASA were analysed to retrieve water constituents. Satellite data of high spatial resolution of the sensor Landsat 7 ETM (Enhanced Thematic Mapper, 30m resolution) designed for land applications were used for the investigation of regional characteristics in the Szczecin Lagoon and in individual coastal regions. The sensor has a repeating rate of 16 days but due to the cloud coverage only a limited number of scenes are available.

Wind data for the period from 1980 to 2000 were analysed. The data were taken from the weather station Arkona and from the Oceanographic Data Acquisition Systems (ODAS) 'Darss Sill'. Ship borne measurements were performed during different cruises at selected stations with a CTD cast and with a through-flow system.

For the simulation of dynamical processes in the western Baltic and the Szczecin Lagoon two different models have been used. The 3D Baltic Sea model is based on the Modular Ocean Model MOM 3.0 (Pacanowski and Griffies, 2000). The model was adapted to the Baltic by the digitised bathymetry of Seifert et al. (2001). Because of strong fresh water discharge the free surface option and the consistent, tracer conserving scheme for fresh water input after Griffies et al. (2001) are of importance for the Baltic. A high grid resolution of 1 nautical mile is necessary to resolve the dynamical scales in the western Baltic (Schmidt et al., 1998). The model is driven by meteorological fields as wind stress, air pressure, air temperature, humidity, insolation, and cloudiness. Model simulations with realistic forcing were carried out to show the typical dynamical patterns and the spreading of drifters in the western Baltic which might be compared with satellite images. Idealized model experiments were forced by the dominating wind situations derived from the wind analysis.

In the shallow Szczecin Lagoon the 2D finite element flow model Femflow2D was applied. In Femflow2D, the system of shallow water equations is discretized with the modified Utnes scheme (Utnes, 1990) which is characterized by a semi-decoupling algorithm. The continuity equation is rearranged to Helmholtz equation form. The upwind method by Tabata (1977) is used to approximate the convective terms. A detailed model description is given by Podsetchine & Schernewski (1999) and Schernewski et al. (2000).

3 Results

The different steps for the development of SIBIK are illustrated in Fig. 2. The NOAA SST data were automatically classified for different wind situations to derive the typical SST patterns. These features are directly implemented in the catalogue. From high-resolution satellite data detailed information was derived about regional characteristics in individual coast regions, particularly around Rügen with erosions at the peninsula Jasmund, discharge from the Strelasund between Darss and Hiddensee, as well as thermal fronts and temporary occurrence of eddy structures in the Mecklenburg Bight and Lübeck Bay. The wind data were statistically analyzed to derive the dominating wind directions. The wind analysis for the period 1980-1992 performed in the systematization of the Oder River discharge in the Pomeranian Bight (Siegel et al. 1996) have shown that easterly and westerly winds are dominant for all seasons. The compiled wind statistics for 1992-2000 shows besides the high variability that the wind directions with the longest coherent wind situations were east and west, the dominating number of all wind events west and south, i.e. the wind blows predominantly from western and eastern directions and turns frequently over south. These information has been used to investigate the distribution patterns for changing wind directions from one dominating direction to the other on the basis of satellite data and model simulations of current, temperature and particle transport. The results are systematized in the catalogue and presented with a detailed description.

Hints for the handling of the catalogue are implemented. Based on a systematic intercomparison of all observations the user might assess the position of individual monitoring stations in relation to the dynamical features.

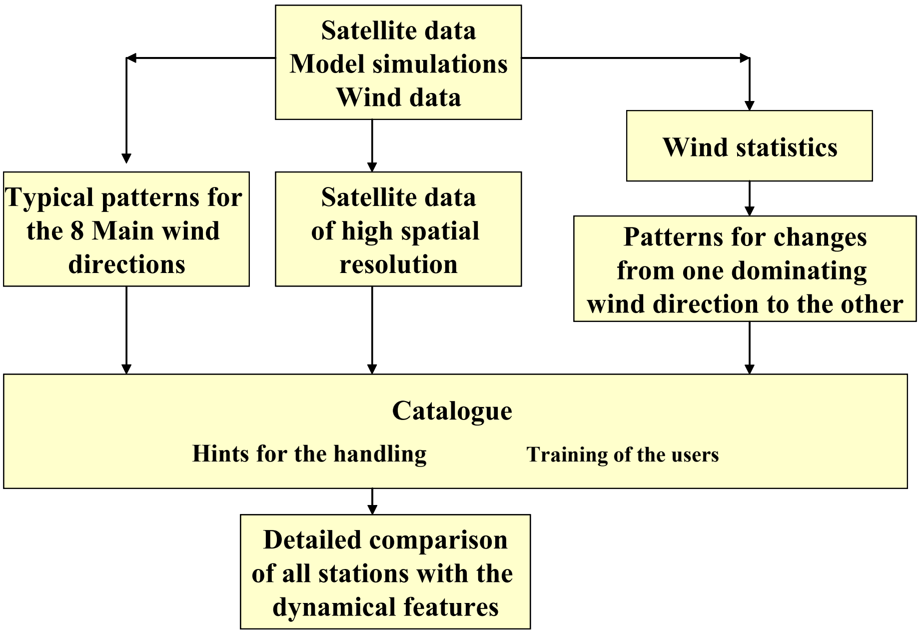


Figure 2: Scheme of the development of SIBIK-catalogue.

The layout of the catalogue is shown in Fig. 3. In chapter 2.1 typical dynamical features for the main wind directions are presented on the basis of satellite data of SST, model experiments and realistic simulations in form of temperature and current snapshots. Spatially high resolution satellite data are utilized to discuss particularities in coastal sub-regions. In chapter 2.2 dynamical features and processes produced by changes in the wind direction are systematized. Response patterns in temperature and current are analyzed for all possible transitions from one main direction East (E) and West (W) to the other and vice versa. In the model experiments additional drifter sources (7 coastal and 3 open sea sources) are implemented and the particle transport is described in detail.

0. Introduction
1. Data base and methods
2. Dynamical features in the western Baltic Sea

2.1 Typical patterns for different wind directions on the basis of SST distribution, model simulations and Landsat TM Scenes

- 2.1.1 N-Wind
- 2.1.2 NE-Wind
- 2.1.3 E-Wind
- 2.1.4 SE-Wind
- 2.1.5 S-Wind
- 2.1.6 SW-Wind
- 2.1.7 W-Wind
- 2.1.8 NW-Wind

2.2 Typical patterns during changes in the wind direction (Main wind directions) on the basis of SST, model simulations of current and particle transport

- 2.2.1 East-North-West (ENW)
- 2.2.2 East-South-West (ESW)
- 2.2.3 West-North-East (WNE)
- 2.2.4 West-South-East (WSE)

3. Dynamical features in the Szczecin Lagoon
3.1 Typical current pattern for the main wind directions
3.2 Particle transport for the main wind directions in different time steps

Figure 3: Table of Content of SIBIK- catalogue.

In chapter 3 the particularities of the Szczecin Lagoon are presented in terms of current and particle transport for the main wind directions based on vertical integrated model simulations.

4 Discussion

In the following, selected results from the SIBIK-catalogue will be presented.

In the overview about the dynamical features during the 8 main wind directions (chapter 2.1) the conditions are discussed on the basis of SST, model experiments and realistic simulations. The example in Fig. 4 show the general patterns for easterly winds in the SST image and modelled surface temperature and current. The LANDSAT ETM composite and drifter simulation represent regional particularities in the Darss-Hiddensee area. In the catalogue the patterns along the entire coast of MV are described in detail as follows for the easterly winds.

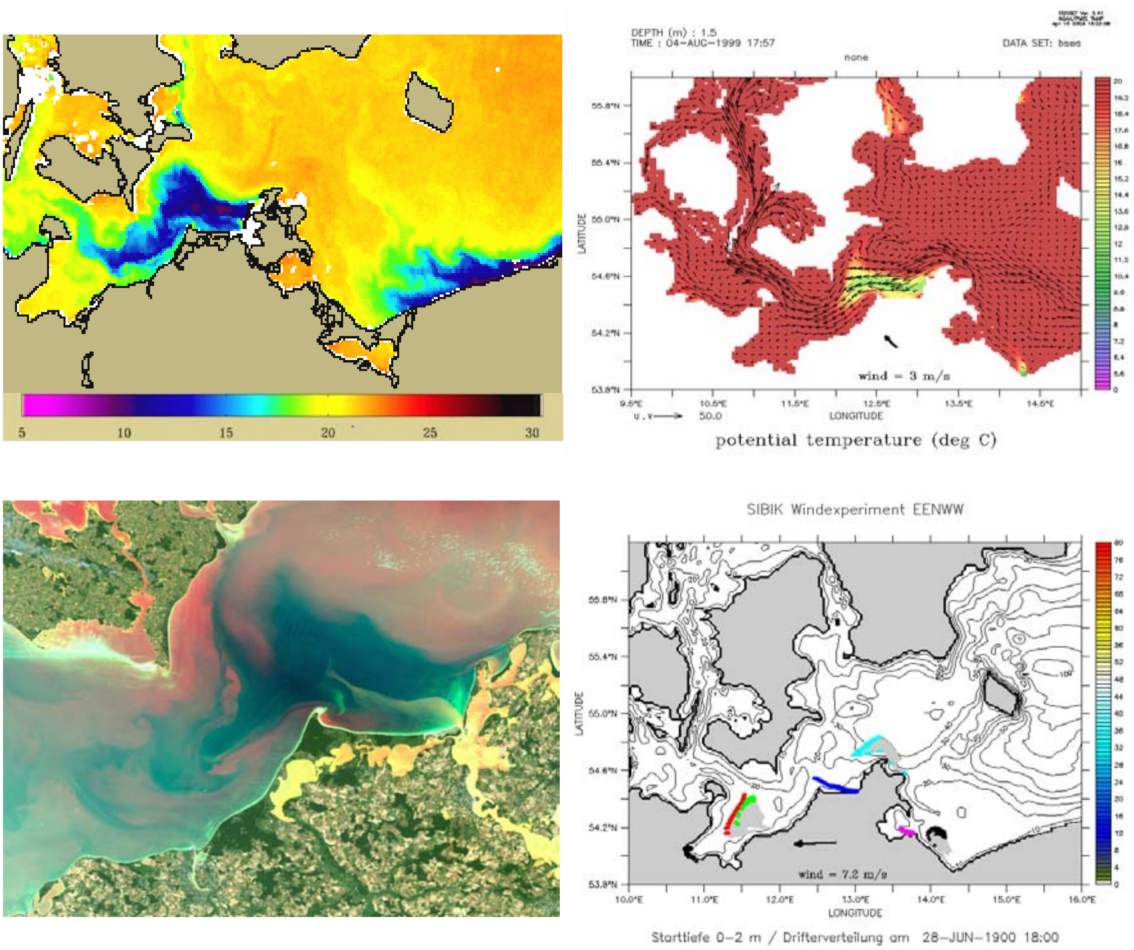
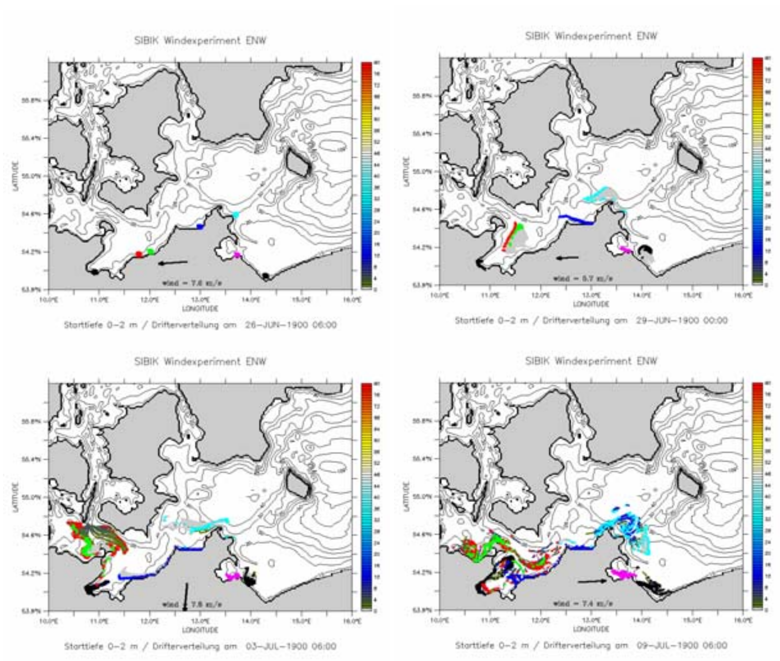


Figure 4: East wind situation: SST distribution, model simulation of temperature and current, LANDSAT ETM composite and drift simulation.

Cold upwelling filaments off Hiddensee develop in the summer months and warm filaments in winter, which cannot be often observed with satellite data due to high cloud coverage. The cold water leaves the Baltic through the Fehmarn Belt. The Mecklenburg and Lübeck Bay are not affected by the outflow regime, a thermal front establishes in the Mecklenburg Bay. The Warnow River water flows due to Ekman transport and induced upwelling north-westwards and does not reach the west beach of Warnemünde. Upwelling water in the area Hiddensee - Darss comes from different sources: In front of Hiddensee it is mainly from intermediate water of the Arkona Sea whereas upwelling off the Darss sucks deep water from the Darss Sill. During long continuing east winds water from Greifswald Bay is pressed through the Strelasund between Hiddensee and Darss and transported in a narrow band north-westward as seen in the Landsat image and in the particle tracks. The discharge of Oder water through the Swine takes place pulsating due to water level variations. Mixed Pomeranian Bight water including the discharge of Oder and Peene Rivers will be transported along the coasts of the islands of Usedom and Rügen and may reach the central Arkona Sea. Upwelling water, which develops along the Polish coast, penetrates into the Pomeranian Bight and guides the PB water. The water level in Greifswald Bay rises strongly by the east wind and the Peene no more flows in Greifswald Bay, but to north. Upwelling occurs at the north coast of Greifswald Oie and at the south coast of the Tromper Wiek. Eroded material of the peninsula Jasmund is transported to the north outside of the Tromper Wiek due to the Ekman transport and induced upwelling. Such detailed visualisations and descriptions are implemented for each wind direction in chapter 2.1.



ENW
Oder,
E: towards NW along Usedom
N: Ekmandrift to Usedom coast
W: to SE and to the Polish coast
Peene,
E: in GB
N: along the south coast
W: stay at South coast
Saßnitz,
W: to NW up to eastern Darß Sill, Eddies during changes
N: North coast Rügen
E: Eddy outside Tromper Wieck and to SE again in the direction of Sassnitz
Strelasund,
E: to NW until about Warnemünde
N: all drifters at the coast between Strelasund und Kühlungsborn
W: all other drifter stay at the coast
Warnow, Kühlungsborn,
E: to W around the deeper part of MB and to Fehmarnbelt
N: at the coast west of Fehmarn
W: partly back until the coast around Warnemünde
Trave,
E: to W as a cloud in the inner Bay
N: to NE separates from the coast
W: completely transported to N

Figure 5: Particle transport for wind changes ENW at starting point, after the east, north and west wind phases, including a detailed description for all coastal sources.

In the chapter 2.2 typical patterns during changes in the dominating wind direction are presented on the basis of SST, model simulations of current and particle transport additionally, and textual interpretation. The reactions are analysed for all possible transitions from one main direction East (E) and West (W) to the other and vice versa. An example is given in Fig. 5 for changes from East over North to West. The figure shows the modelled particle tracks at starting points, after the east, north and west wind phases, including a detailed description for all 7 coastal sources representing coastal discharge or important regions. Looking for example at the source between Darss peninsula and Hiddensee island the particles will be transported during easterly winds in a narrow band north-westwards. During the north wind phase these particles might be distributed at the entire coast between Kühlungsborn and the source. The user can watch a computer animation of 6-hourly snapshots to study the changes in detail. The same presentation is implemented for the particle transport for the 3 open sea sources in the Fehmarnbelt, Kadettrinne and east off Saßnitz.

In the third part the particularities of the Szczecin Lagoon are presented where the vertical integrated model simulations are divided in current field for the 8 main wind directions and in particle transport for the 4 main directions within different time steps. The example in Fig. 6 shows the particle transport of the Oder River in the lagoon in 5 time steps up to 24 days. During easterly wind the main transport occurs along the north and south coast into the western part of the Lagoon. A counter current establishes in the central part. Therefore, the Oder river load propagates along the southern coast into the western part and cannot cross the counter current at the entrance.

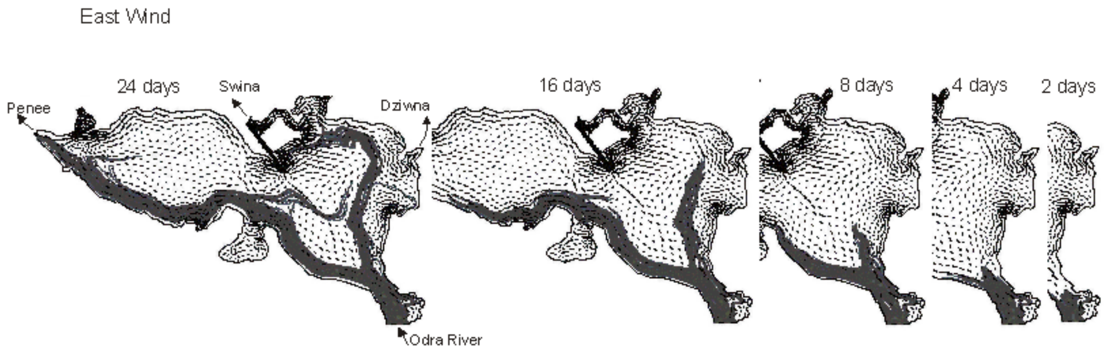


Figure 6: Current and particle transport in the Szczecin Lagoon during easterly winds.

The described SIBIK-catalogue of systematized typical dynamical patterns for dominating wind directions and their changes supports the interpretation of monitoring data and contributes to an optimization of the coastal monitoring programme of regional authorities. Furthermore, the results allow forecasting of transport processes during special events, such as plankton blooms, floods or accidents and of hazard potentials for certain coast regions.

The user may work interactively with the SIBIK-catalogue (Fig. 3). In preparation the user has to determine the wind direction in the period of investigation. The wind data of the MARNET stations in the Baltic Sea are available from the BSH webpage. With this information the user is able to find the illustrated description for the derived pattern for the certain wind situation. The chapter for the selected wind direction contains figures of the satellite derived SST features, extracts of the model simulations and a description of the regional distinctions, which may occur along the coast of MV. The presented model results for the illustration of current features and particle transport during changing wind directions can be studied also by video presentations starting interactively.

LUNG applies SIBIK for interpretation of measurements and in future also operational during the field campaign.

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