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Oceanographic Processes in the German Bight

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Die Küste, 74 ICCE (2008), 60-76

Oceanographic Processes in the German Bight

By Holger Klein and Alexander Frohse

Contents

1. Introduction

The North Sea is a shallow shelf sea connected to the Northeast Atlantic at its wide open northern boundary, which significantly affects the oceanographic state of the North Sea – defined by salinity (S) and temperature (T). Less important is the interaction via the shallow English Channel in the south-western part of the North Sea.

The Baltic Sea is connected to the North Sea via Skagerrak, Kattegat, Belt Sea and the shallow Sound. The less saline Baltic outflow influences the north-eastern part of the North Sea significantly. However, for the southern North Sea and especially the German Bight continental river run-off is a more important factor affecting S distribution and haline stratification. Temperature and thermal stratification vary with the season, whereas circulation pattern and intensity exhibit seasonal as well as a strong inter-annual variations. This paper summarises the major physical processes in the German Bight based on long-term observation and modelling results.

2. Currents

North Sea currents result from the superposition of semi-diurnal tidal currents, wind driven, and density driven currents. If the tidal currents are eliminated by averaging over one or more tidal periods (12.5 hours), we get the so-called residual current which is a measure for the net transport of an individual water particle at a particular point within the observation period.

Generally, the North Sea is a dominated by a cyclonic (anti-clockwise) circulation pattern. During winter and spring its intensity is influenced by the winter (DJFM) North Atlantic Oscillation index (NAO): High values of the NAO index (>2) are associated with a strong zonal wind component causing an intensification of the North Sea circulation which also affects the German Bight (Löwe et al., 2003). The NAO has a typical periodicity of about 7.7 years and is also strongly correlated with the pattern of rainfall and freshwater run-off. If the NAO is low and negative the intensive circulation is restricted to the northern part of the

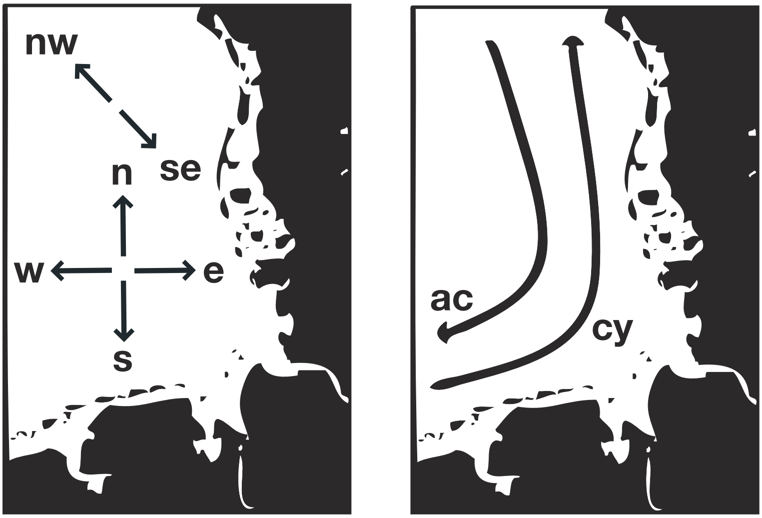

Fig. 1: Typical circulation types in the German Bight. Left: directional circulation pattern, right: cyclonic and anti-cyclonic pattern. The variable pattern is not shown

North Sea. The inflow over the western slope of the Norwegian Trench is reaching the Skagerrak and is then re-circulated within the Baltic Outflow and the Norwegian Coastal Current.

Depending on the NAO index and the local wind field, the German Bight exhibits 9 typical circulation patterns which are determined daily from the residual currents produced by the operational circulation model 'BSHcmod' of the Bundesamt für Seeschifffahrt und Hydrographie (BSH). The dominating pattern is the cyclonic circulation (ca. 43 %) with a broad inflow at the south-western boundary of the German Bight and a pronounced outflow at the northern or north-western boundary. It is followed by the inversely directed anti-cyclonic pattern (13 %) and a variable pattern (25 %). The latter is sometimes characterised by eddy structures which can be observed for several days during periods of calm weather conditions. The 6 directional types (see Fig. 1 left), which are mostly related to strong wind events, are of minor importance.

Apart from their frequency, the circulation types are also characterised by their persistence. Generally, there is a very high variability; the patterns frequently change from day to day. For the cyclonic type a long phase of stable circulation lasts about 8–10 days, but isolated events with a duration of 16 and 28 days have been observed also. Anti-cyclonic and variable phases last up to 6–8 days, whereas directional phases have a maximum duration of 3–4 days only; mostly they last only 1 day.

KLEIN (2002) analysed all current data recorded by BSH between 1957 and 2001 in different areas of the German Bight (see Fig. 3 and Table 1). Mean velocities and residual currents were determined in the near-surface (3–12 m) and near-bottom (0–5 m above bottom) layer. Included were time series with a minimum duration of 10 days and at a minimum water depth of 10 m. Positions strongly influenced by topography were rejected because the data are to represent the conditions in the open sea. Velocities in the small channels between the East and North Frisian islands and close to strong topographic gradients can be much higher. Port of reference for the tidal stream analysis is Helgoland (KLEIN and MITTELSTAEDT, 2001).

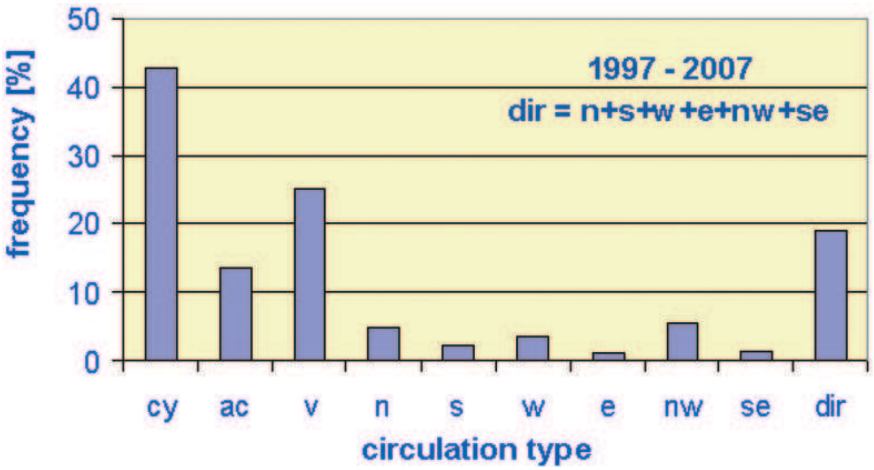

Fig. 2: Frequency percentage distribution of circulation types in the German Bight, 1997–2007

Table 1: Mean velocities, residual and tidal streams in the German Bight

area:	**GB1**	**GB2**	**GB3**	**GB4**	**C1**	**C2**	**C3**	**C4**	**C5**
near-surface:									
mean velocity [cm/s]	35.3	31.8	40.9	37.9	55.9	46.9	38.8	41.4	25.5
std-deviation [cm/s]	6.2	7.7	6.1	4.3	15.6	17.7	5.4	15.9	6.0
max. velocity [cm/s)	116	123	113	105	182	108	151	160	77
vector mean [cm/s]	6.2	2.4	4.5	2.1	1.5	5.8	1.5	0.9	3.5
mean direction [°]	20	27	43	10	18	27	65	204	45
tidal max [cm/s]	52.8	45.2	65.0	66.7	158.8	68.4	75.9	86.0	35.3
data days [-]	412	1522	664	1473	463	420	1166	369	354
near-bottom:									
mean velocity [cm/s]	15.8	20.8	31.9	27.3	42.2	28.0	33.5	33.8	23.5
std-deviation [cm/s]	3.7	5.4	6.2	5.7	5.9	6.5	5.5	8.8	6.2
vector mean [cm/s]	2.1	1.1	2.5	0.7	0.3	1.3	2.1	1.3	3.0
mean direction [°]	13	18	53	172	300	198	35	33	35
tidal max [cm/s]	-	45.1	46.9	53.5	57.1	60.7	72.7	47.5	26.8
data days [-]	142	793	510	1383	204	579	856	290	311

tidal max: maximum tidal current

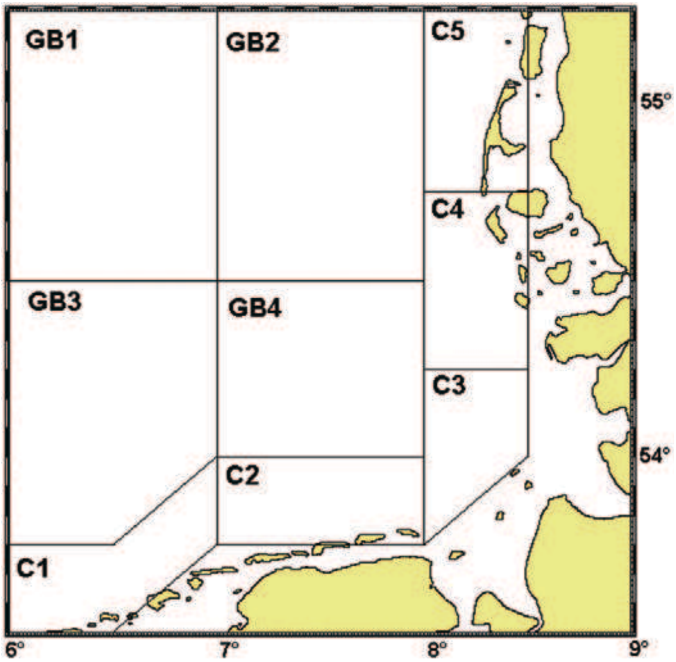

Fig 3: Off-shore (GB) and coastal areas (C) used in Table 1

The large-scale seasonal circulation pattern of the North Sea is shown in Fig. 4. It is a four-year average (2004–2007) based on daily averaged residual currents of BSH's circulation model 'BSHcmod'. The persistence of the currents is given in percent, 100 % corresponds to a constant current direction, 0 % means that all direction occur with the same frequency. During all seasons a cyclonic circulation is prevailing. The topographic guidance in the German Bight generates a high stability of the flow in the coastal areas. A part of the Atlantic inflow is re-circulated in the northern part of the North Sea as the so-called Dooley Current (KLEIN et al., 1994). During summer, the Baltic outflow is hardly discernible. However, the seasonal circulation patterns exhibit a high year-to-year variability.

3. Waves

The observed sea state is a superposition of wind waves generated by the local wind field and swell, which has a greater wave length and a longer period as the local wind sea. Swell was generated elsewhere and has left its area of origin. In the southern North Sea and the German Bight swell is mostly generated by storms in the North Atlantic or northern North Sea.

The height of wind sea depends on wind speed and the length of time the wind has been blowing with this speed. The third factor is the fetch, the unobstructed distance of sea over which the wind blows. In the German Bight the fetch for south or south-easterly winds is much shorter compared to winds blowing from north or north-west. The waves are characterised by their significant wave height which is the average height of highest one-third of all waves observed in a particular time interval.

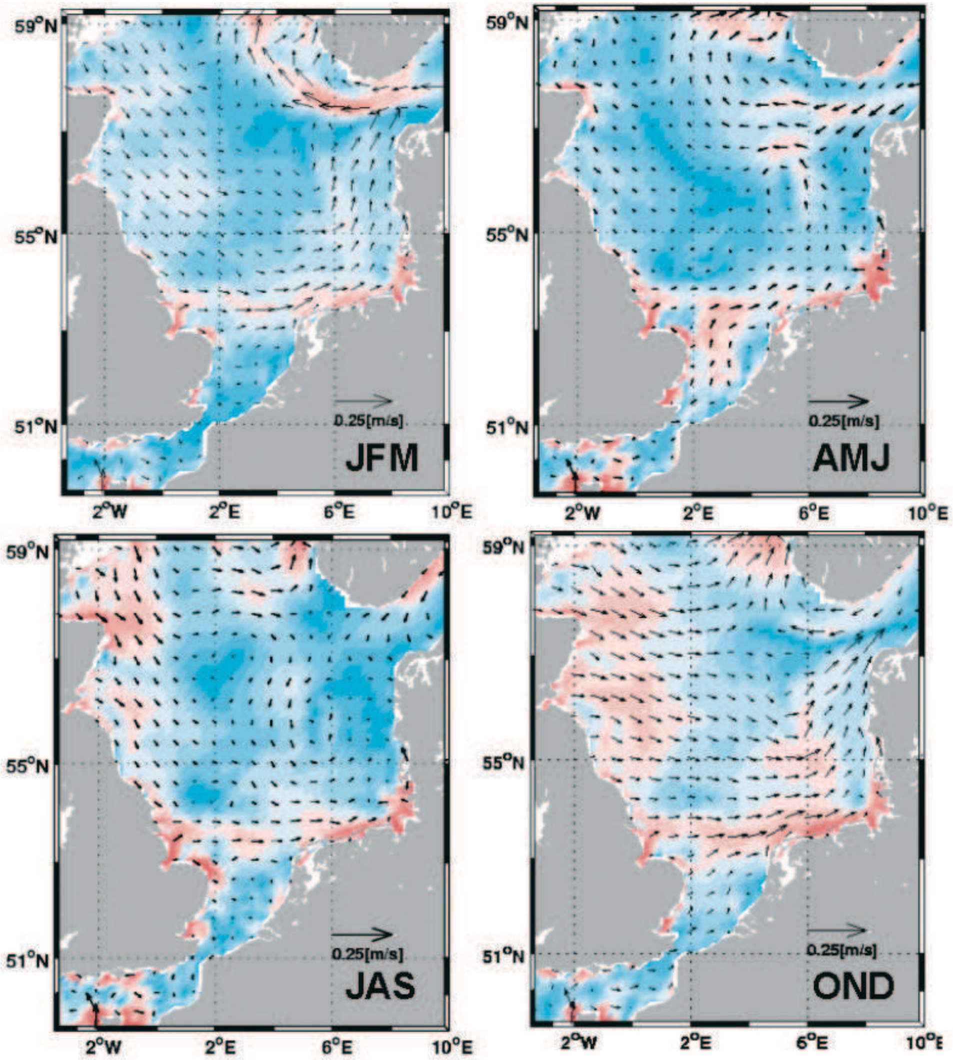

Fig. 4: Seasonal North Sea circulation pattern, BSHcmod model data, 4-year average based on daily residual currents. The colour gives the persistence in percent

In the long-term mean (1950–1986) the highest wind speeds in the German Bight occur in November (9 m/s) and decrease until February to 7 m/s. During March there is a local maximum of 8 m/s, then the values decrease rapidly to a value of about 6 m/s between May and August. Then the values increase again until they reach their maximum at the end of autumn (BSH, 1994). This seasonal cycle based on monthly means is conferrable to the sea state. At the light vessel 'German Bight' the percentage frequency distribution of both wave and wind direction shows a maximum for winds and waves from the West-south-west and a second maximum for East-south-east (Löwe et al., 2003).

Table 2: 5-year-average of wind speed and sea state at the North Sea Buoy II location. Data are from the operational wave model of the German Weather Service (DWD)

	NSB II 55° 00‘ N, 006° 20‘ E				
	mode	**mean**	**std**	**minimum**	**maximum**
wind:					
speed [m/s]	11.0	8.0	4.0	0.7	27.4
direction [°]	240	243			
significant wave height [m]	1.0	1.6	1.2	0.0	10.0
Wind Sea:					
wave height [m]	0.5	1.1	1.2	0.0	9.7
period [s]	3.0	4.0	2.3	0.0	13.8
direction [°]	240	257			
swell:					
wave height [m]	1.0	0.9	0.6	0.1	5.3
period [s]	8.0	7.0	1.7	3.5	18.0
direction [°]	330	302			

Table 2 gives a 5-year statistics of wind speed and sea state at the North Sea Buoy II (NSB II) based on data from the German Weather Service’s operational wave model. The model results are validated by BSH wave rider buoys, however, compared to observational data the model data show no gaps. In addition to a mean value, also the mode is given, which represents the physical conditions much better: At NSB II for example, the most common wind speed is about 11 m/s: But due to periods of calms the average amounts to just 8 m/s. The data are representative for a wide area of the open German Bight. At the position of the light vessel ‘German Bight’ (54° 10‘ N, 007° 27‘ E), the statistics for the same period of time reveal nearly the same values.

4. Sea Surface Temperature and Thermal Stratification

The North Sea temperature is influenced by the advection of warm Atlantic water, local solar heating, and heat exchange with the atmosphere. In the German Bight atmospheric forcing is the dominant influence on temperature, as shown by a strong correlation between the NAO Index and temperatures at Helgoland Roads (KLEIN et al., 2007).

Weekly and monthly maps of area-averaged sea surface temperatures (SST) for the entire North Sea have been produced by BSH since 1968. The 1972–2004 monthly SST anomalies reveal a bistable SST regime with a warm period starting before 1972 followed by a cold period from December 1976 until August 1987. The system switched back rapidly to the warm status in September 1987 (LÖWE et al., 2005). Fig. 5 shows clearly, that the linear trend of 0.3 ± 0.1 K/decade is not an adequate description of the real SST history. In fact, this history is characterised by spontaneous jumps between warm and cold regimes. The mean temperatures of the phases differ by 0.6 – 0.9 °C. These sudden changes between warm and cold phases can also be observed in the Helgoland Roads data for at least 130 years (FRANKE et al., 2004; WILTSHIRE and MANLY, 2004). The last warm period peaked in 2002 which was the warmest year since the beginning of the area-averaged SST records in 1968. Since June 2001 the SST anomalies have been consistently higher than normal, with the exception of June and August 2005 and of March, April, and June 2006. The highest anomaly was observed in October 2006 (+2.4 °C). The summer periods became longer and warmer and winters became less cold. The amplitude decrease of the annual cycle of sea surface salinity, beginning in the mid-nineties, could still be observed in 2007.

Based on data from JANSSEN et al. (1999), Fig. 6 a/b provide the monthly averaged SST distribution in the German Bight; both figures have an identical colour scale. The lowest SST appear in February. Seasonal warming starts in May, and the SST maximum is reached in August. Cooling starts in September. The most extreme SSTs appear in the shallow coastal areas.

The thermal stratification in the German Bight is shown in Fig. 7 based on the investigations of FREY and BECKER (1987). They analysed two data sets: The first set contains observational data from 1919–1985 which are irregularly distributed in space and time. The second data set contains time series of weekly T and S profiles recorded at the former light vessel 'Elbe 1' between 1961 and 1984. The area of investigation was sub-divided into 10' × 10' bins, and it was assumed that the data have been recorded in the centre of these bins. Shown are the borderlines between vertically mixed and thermal stratified water for different months of the year. With increasing solar radiation, thermal stratification builds up in May. In June the extension of stratified water reaches its maximum with a borderline running close to the 20–30 m contour. In shallower areas, tidal mixing is effective and prevents thermal stratification. In the transit area between mixed and stratified water there is a permanent development and decay of tidal mixing fronts (see below). In the long-term mean, the German Bight is vertically mixed again completely at the end of September.

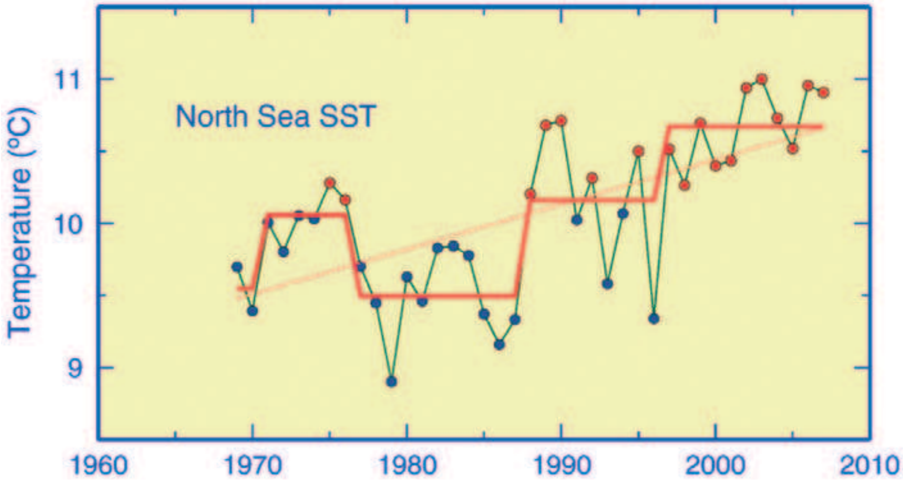

Fig. 5: Yearly means of total North Sea SST 1968-2007 (Courtesy of P. Löwe)

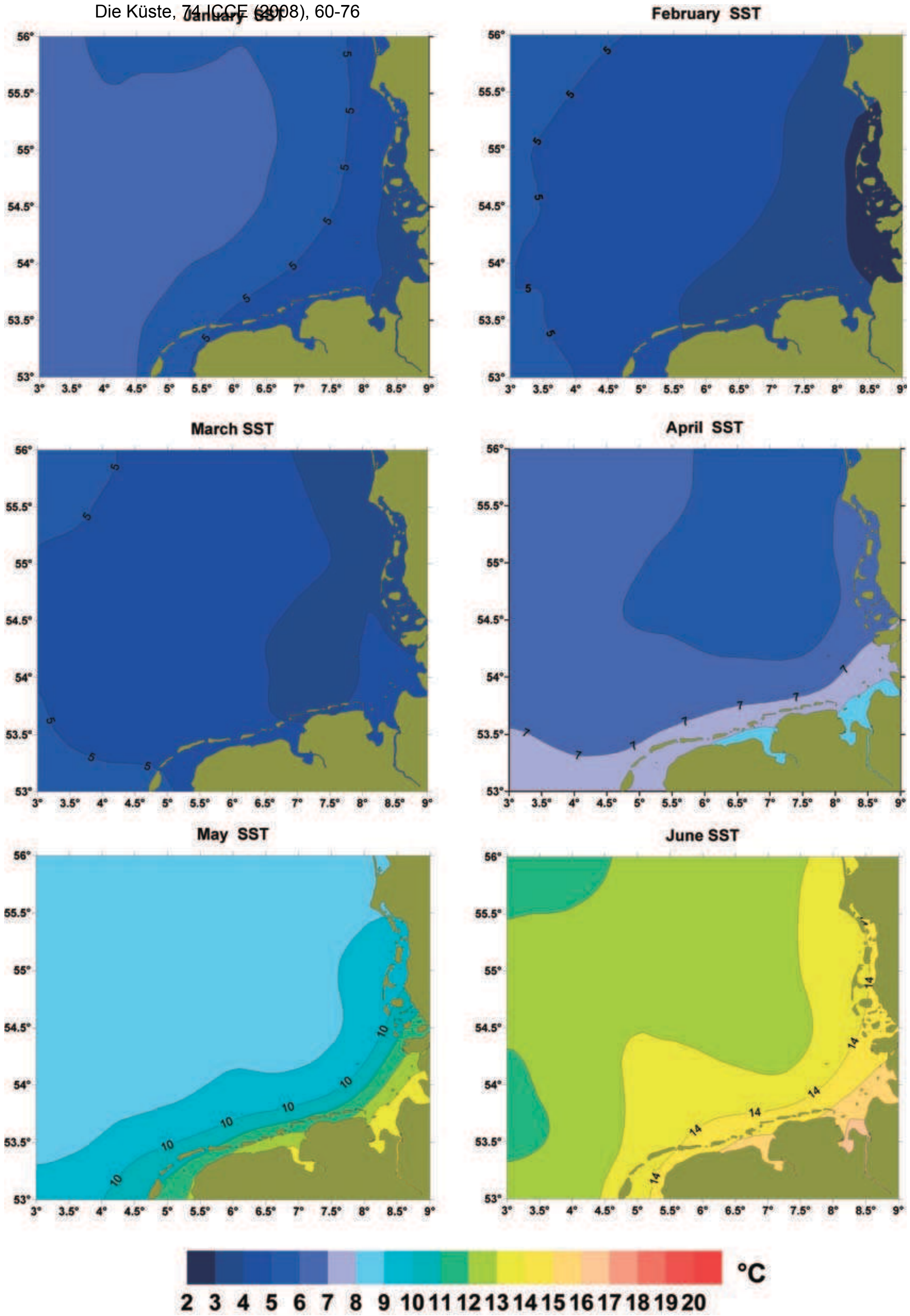

Fig. 6a: Climatological monthly means of sea surface temperature (1900–1996) for January until June (after JANSSEN et al., 1999)

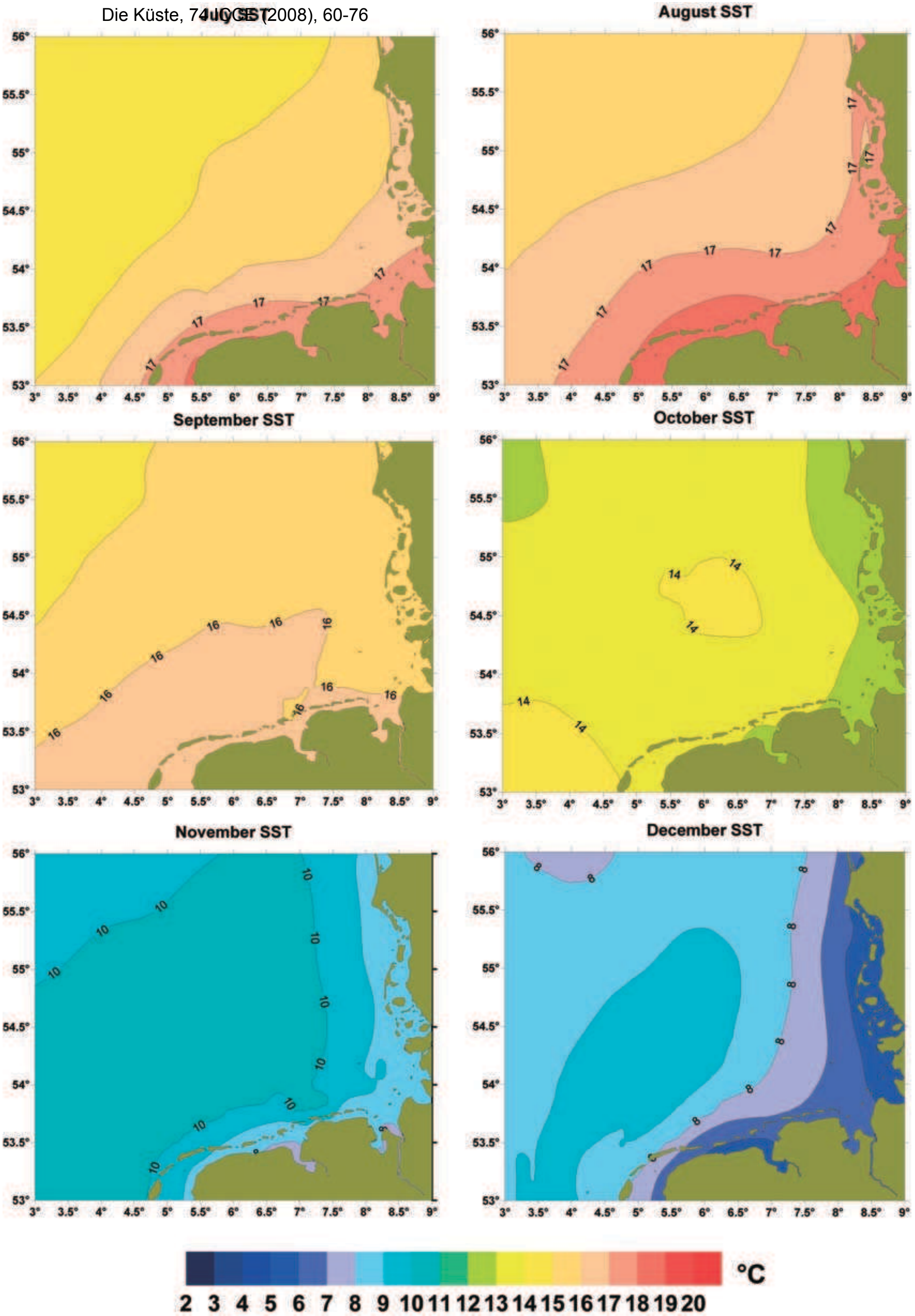

Fig. 6b: Climatological monthly means of sea surface temperature (1900–1996) for July until December (after Janssen et al., 1999)

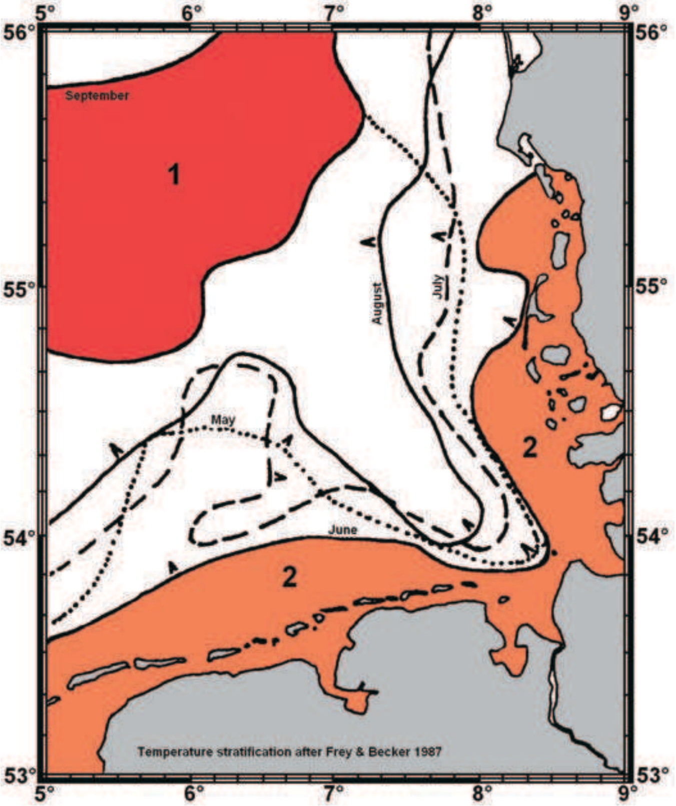

Fig. 7: Thermal stratification of the German Bight according to Frey and Becker (1987).
1: Stratified from Mai until September, 2: all-the-year vertically mixed

5. Salinity Distribution and Stratification

The mean seasonal cycle of sea surface salinity (SSS) distribution is shown in Fig. 8, again based on the data of Janssen (1999). Because the seasonal SSS cycle is less pronounced compared to SST, only every second month is presented. Noticeable are the low salinity values in the estuaries of Elbe and Weser with minimum values of about 12 PSU (Practical Salinity Units) in January, April, and December due to strong river run-offs. Due to a less intensive circulation, the 34-isohaline moves seaward between April and August. Because the rivers permanently supply freshwater, there is an enhanced amount of brackish water in the German Bight during this time. The long-term run-off of the Elbe river, for example, amounts to about 22 km³ per year, that is about 700 m³/s.

The seasonal evolution of salinity stratification according to Frey and Becker (1987) is given in Figure 9. The Dogger Bank area and the North-Frisian wadden sea are vertically mixed all-the-year due to bottom friction and/or tidal mixing. The area of the Elbe outflow is permanently stratified. From spring until summer, the stratified area expands towards North-north-west, while the remaining area is temporarily stratified, depending on the meteorological conditions and the intensity of river run-offs.

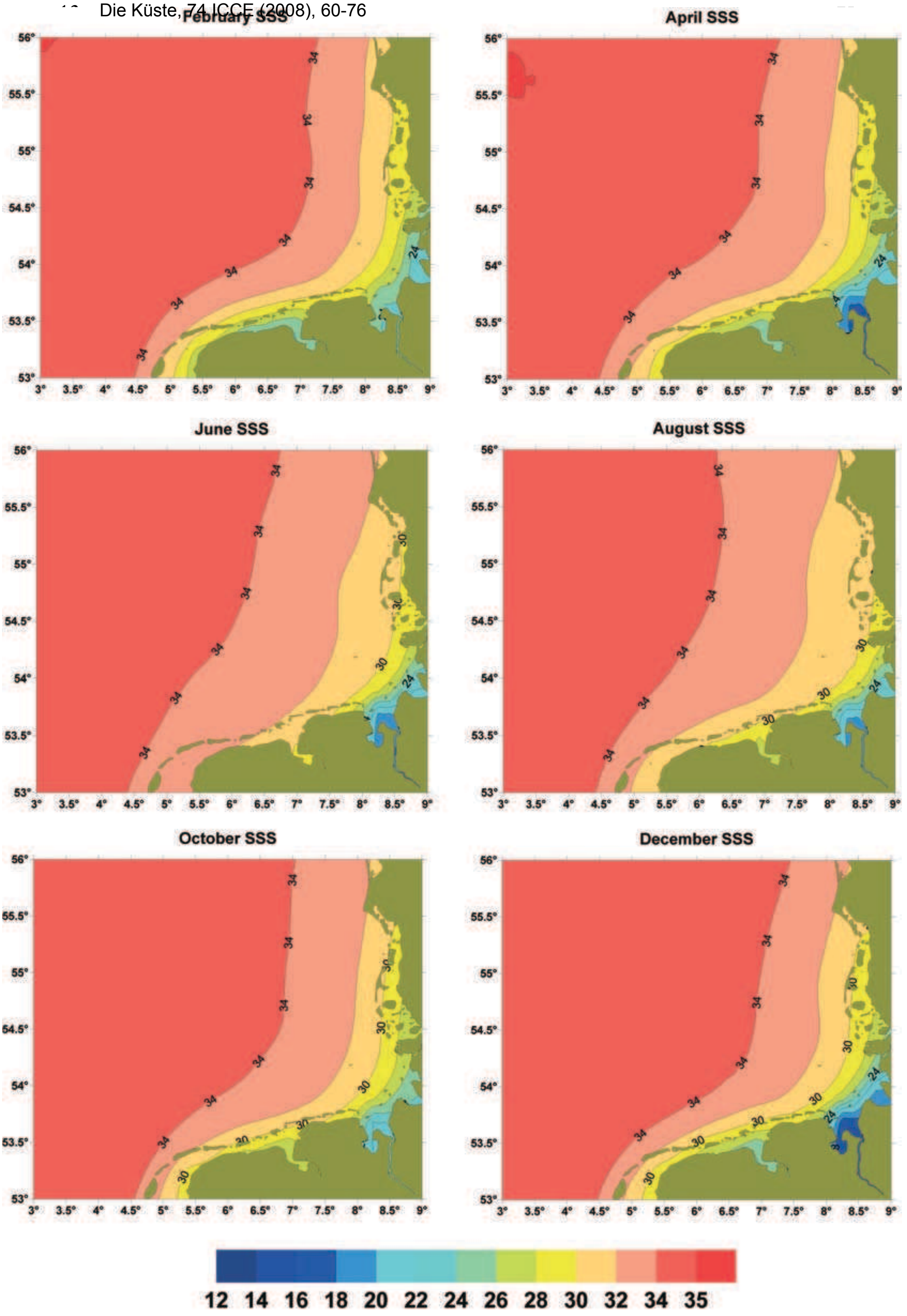

Fig. 8: Climatological monthly means of sea surface salinity for every second month of the year (1990–1996) (after JANSSEN et al., 1999)

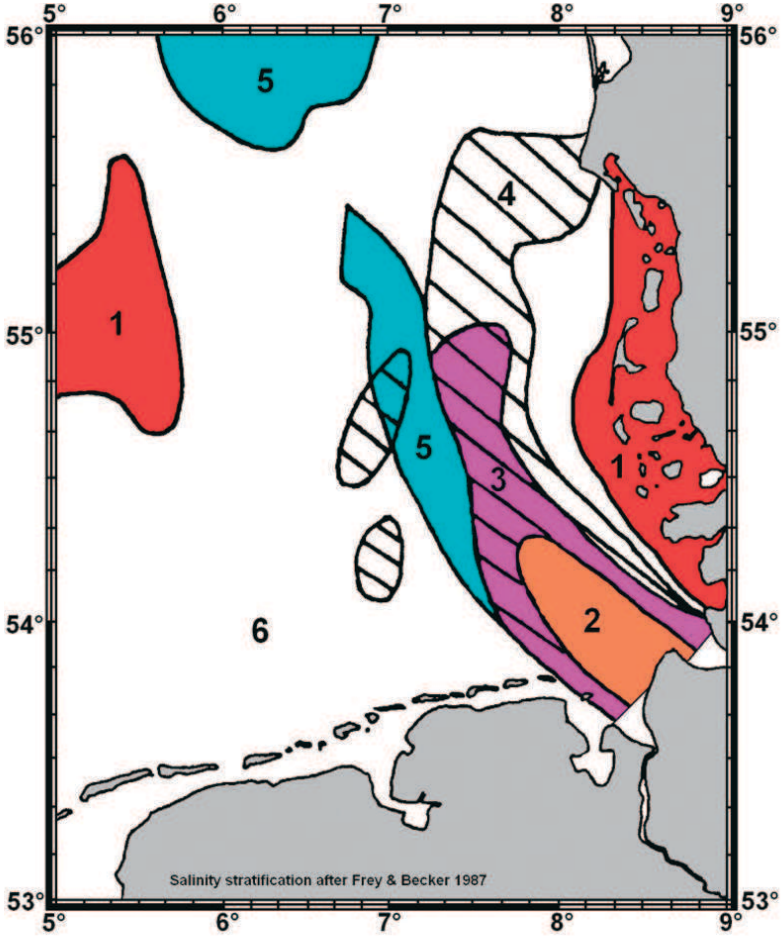

Fig. 9: Haline stratification according to Frey and Becker (1987): 1: all-the year vertically mixed (homohaline), 2: all-the-year stratified, 3: stratified between March and August, 4: stratified between March and May, 5: stratified between June and August, 6: temporarily stratified, covers all areas without area 1

6. Fronts

A front is a transition area between water masses with different properties. The sharpness of a front is defined by its horizontal gradient. Fronts in the German Bight are known for nearly 60 years. Dietrich (1950) and Goedecke (1968) described them as "Konvergenz der Deutschen Bucht" (Convergency of the German Bight), a transition area between the brackish coastal waters diluted by river run-off and denser haline North Sea water. With the invention of self-recording instruments, knowledge grew significantly (Becker and Prahm-Rodewald, 1980). Infra-red satellite data revealed that fronts are no static features but a system of smaller fronts and eddies with a spatial scale of 5–20 km. They permanently develop (frontogenesis) and decay (frontolysis) with a typical time scale of between 1 and 10 days. Rate and intensity of frontogenesis and frontolysis are influenced by meteorological conditions, river run-off, and circulation. Only during calm weather conditions, discrete frontal structures can be observed over several days.

In the German Bight two types of front can be observed, thermal and river plume fronts. The position of thermal fronts can be determined by a stratification parameter (SIMPSON and HUNTER, 1974) that depends on the strength of tidal currents and water depth. Its critical value determines the transition from stratified to vertically mixed water. Due to their dependency on topography these fronts are relatively stationary (OTTO et al., 1990). The stratification parameter divides the German Bight into two areas: The seaward area exhibits the above mentioned seasonal stratification whereas the inner coastal area is vertically mixed. Both areas are separated by the above mentioned tidal mixing fronts.

Fig. 10 shows a seasonal composite picture of thermal gradients between 0.2 and 0.6 °C/km. All available thermal satellite pictures have been analysed in order to identify spatial or seasonal patterns. The summer of 1995 was very cloudy. Therefore, the summer picture (day

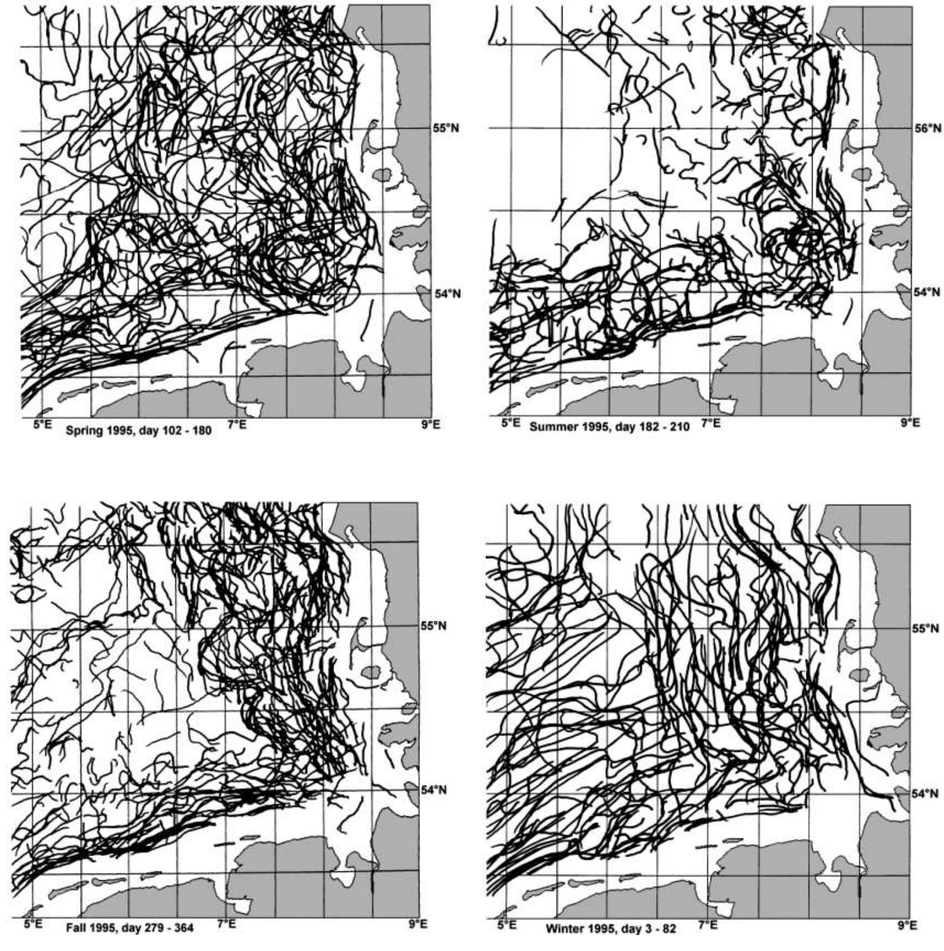

Fig. 10: Thermal fronts in the German Bight during each season of 1995. SST satellite data with horizontal gradients between 0.2 and 0.6°C/km

182–210) is based on 29 single images only. Especially along the East-Frisian coast, a clear concentration along the 30 m depth contour can be seen, but thermal fronts can be observed everywhere in the German Bight and in every season.

The thermal frontal system is superimposed by the so-called river plume fronts with strong salinity gradients generated by the permanent river run-offs of Elbe, Weser and Rhine (FRANZ and KLEIN, 1986; KLEIN, 1986). Due to convergence and down-welling, these fronts accumulate organic and inorganic material and cause an increase of metabolites ('fish follows fronts'). During periods of calm weather fronts can be detected easily by eye due to a meandering strip of foam and flotsam, the so-called 'siome'.

7. Sea Ice

In the eastern North Sea the general weather situation prevents a regular ice formation during winter. During fall and winter westerly winds are dominating, bringing mild air to central Europe which avoids or delays seasonal cooling. Another factor is the advection of warm saline Atlantic water. However, easterly winds can cause a rapid cooling of sea temperatures. Extent and duration of ice cover depends on the strength and duration of the cold spells and on their time of occurrence. A strong ice formation, caused by an early start of winter and long-lasting frost periods, normally does not start before end of January or mid-February.

Normally, in early spring the heat reservoir of the haline North Sea water in the open German Bight is still big enough, so that ice formation occures only infrequently. The open-sea areas between North- and East-Frisian islands are ice-free during two thirds of the winter. In the long-term mean the ice in coastal areas is melts in the third decade of February; only during strong ice winters the last ice melts not before end of March. A detailed description of the ice conditions is given by BSH (1994).

8. Suspended Matter and Turbidity

Suspended matter denotes all suspended particles in sea water with a diameter >0.4 µm. The suspended matter content, called 'suspended particulate matter' (SPM) is the material gained after filtering and drying a water sample of a defined volume with a 0.4 µm pore size filter.

Suspended matter contains organic and/or inorganic material. The organic fraction exhibits a seasonal cycle with high concentrations during the plankton blooms in early summer. During stormy weather with high waves SPM concentration is enhanced within the whole water column due to re-mobilisation of bottom sediments with swell being the most effective mechanism (KLEIN et al., 1999). Intensive low-pressure systems can easily enhance the SPM load by a factor of 10. The dominant signal in SPM time series is the semi-diurnal tidal stream. The ebb-currents carry turbid water from the wadden sea into the open North Sea, whereas the flood currents carry less turbid water into coastal areas. Further sources of suspended matter are the river run-offs from the big European rivers.

Fig. 11 shows the mean SPM distribution on the German continental shelf based on all data available in the German marine environmental data bank (MUDAB, Oct. 2005) between the surface and 10 m depth. It must be kept in mind that these data are ship-born data and that SPM sampling is not possible during stormy weather when SPM concentrations are significantly enhanced. In the wadden areas and estuaries the mean values are of the order of

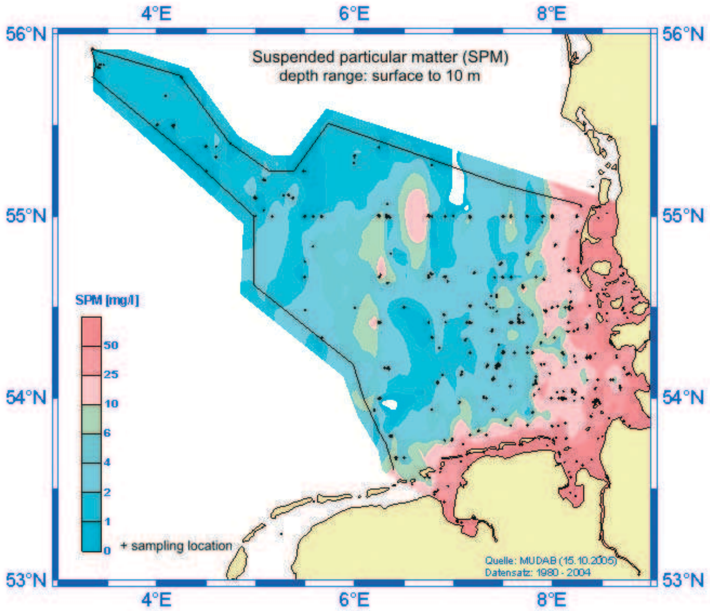

Fig. 11: Mean suspended particulate matter (SPM) concentration on the German continental shelf

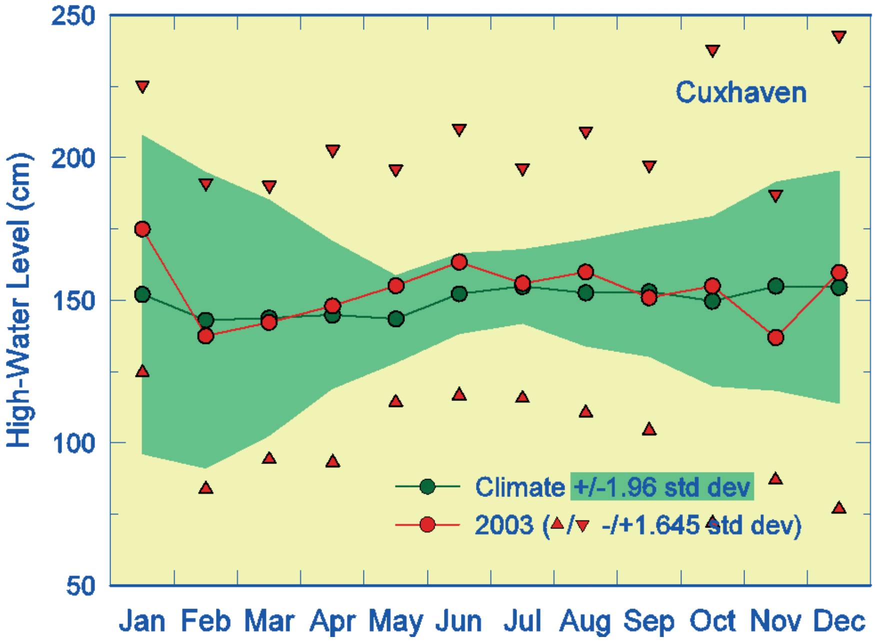

Fig. 12: High water levels at the tide gauge Cuxhaven-Steubenhöft. Green line: monthly means 1971–2000 with 95 % confidence interval of inter-annual variation. Red line: monthly means 2003 with intra-monthly variation (90 % quantile, red triangles)

50 mg/l with extreme values > 150 mg/l. Seaward, the concentrations decrease rapidly ranging between 1 and 5 mg/l.

9. Water Levels

Based on water level records at different locations in the North Sea covering up to 100 years, water levels in the North Sea can be analysed and predicted on different time scales. The tide gauge at Cuxhaven-Steubenhöft, which is not influenced by topographical changes, is used as port of reference by BSH for water level predictions and statistical classification of high waters.

The monthly high water climatology at Cuxhaven for the period 1971 – 2000 is shown in Fig. 12 (green line) together with the 95 % confidence interval. The climatology exhibits a weak seasonal signal oscillating around the mean high water at 150 cm. The variability during fall and winter exceeds that during spring and summer significantly. The broad bandwidth of high water levels during winter and fall clearly documents the effects of meteorological disturbances, with wind being the most effective factor. Generally, air pressure differences are much weaker during summer producing predominantly fair weather conditions. Therefore, water level variations are basically predominated by tides.

As an example, the red line in Fig. 12 gives the values for 2003 which show no significant variations compared to climatology. The intra-monthly variability is marked by red triangles. The enhanced values in May and June (11 cm above the long-term mean) are caused by extreme high waters due to strong north-westerly winds. Owing to its geographical location in the Elbe estuary with its broad opening towards the north-west, the highest water level and strongest storm surges connected with north-westerly winds occur in this area. Accordingly, the lowest water levels occur during south-easterly winds.

Concerning the long-term sea level rise, Jensen and Mudersbach (2004) estimated an increase of 19 cm/100 years for the period 1965–2001 and of 15 cm/100 years for the period 1826–2001, based on the analysis of 12 tide gauge stations along the German North Sea coast.

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