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Currents at the light-vessel "Deutsche Bucht": A comparison between ADCP measurements and the BSH forecast model

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Summary

Between June 15 and August 10, 1999, an **A**coustic **D**oppler **C**urrent **P**rofiler (ADCP) and a **w**ater **l**evel **r**ecorder (WLR) were deployed in the close vicinity of the unmanned light-vessel "Deutsche Bucht" in the German Bight. Together with locally recorded meteorological and hydrographical data (salinity and temperature), this in-situ data set is compared to the forecasts of the BSH circulation model "BSHcmod". The meteorological measurements are used to assess the meteorological model input generated by an atmospheric model of the German Weather Service. Generally, we observed a good agreement between in-situ and model data. Differences between measured and predicted currents were observed at the surface and at mid-depth. They were caused mainly by missing ADCP data within the first 3 metres under the surface and by the coarse vertical grid spacing of the model which prevents the representation of sharp vertical gradients.

Strömungen am Feuerschiff "Deutsche Bucht": Ein Vergleich zwischen ADCP-Messungen und dem BSH Vorhersagemodell (Zusammenfassung)

Vom 15. Juni bis zum 10. August 1999 wurden direkt am unbemannten Feuerschiff „Deutsche Bucht“ ein Akustischer Doppler-Strömungsprofiler (ADCP) und ein Hochseepegel ausgelegt. Zusammen mit vor Ort registrierten meteorologischen und hydrographischen Daten (Temperatur und Salzgehalt), wird dieser In-Situ Datensatz mit den Vorhersagen des BSH Zirkulationsmodells „BSHcmod“ verglichen. Die meteorologischen Messungen werden benutzt, um den von einem Atmosphärenmodell des Deutschen Wetterdienstes berechneten atmosphärischen Input zu beurteilen. Generell stimmen gemessene und prognostizierte Strömungen sehr gut überein. Beobachtete Abweichungen an der Oberfläche und auf halber Wassertiefe lassen sich durch fehlende ADCP-Daten direkt an der Wasseroberfläche und durch eine zu grobes vertikales Modellgitter erklären, das die Bildung von scharfen vertikalen Gradienten verhindert.

1 Introduction

The unmanned light-vessel "Deutsche Bucht", hereafter abbreviated UFS DB, is located about 15 nm west of the island of Helgoland in the German Bight (see Fig. 3 c). From June 15, 1999, to August 10, 1999, the Federal Maritime and Hydrographic Agency (**B**undesamt für **S**eeschiffahrt und **H**ydrographie, BSH) deployed an **A**coustic **D**oppler **C**urrent **P**rofiler (ADCP) and a **w**ater **l**evel **r**ecorder (WLR) in the close vicinity of the UFS DB (54° 10.75’ N, 7° 27.34’ E) at a water depth of 38 m. The ADCP recorded the currents between 4 metres above the bottom (hereafter mab) and 4 m depth with a vertical resolution of 2 m. An automatic sampling station on board UFS DB transmits local weather data to the German Weather Service (**D**eutscher **W**etter**d**ienst, DWD) on an hourly basis. The BSH MARNET (**Marine** Environmental Monitoring **Net**work in the North and Baltic Seas) station on board UFS DB samples temperature data at 3, 6, 10, 15, 20, 25, and 30 m depth, and salinity data at 6 and 30 m depth. These data are also transmitted hourly to the BSH via satellite. The transmitted values are averaged over the last 10 minutes preceding transmission.

This in-situ data set, including local currents, sea level, temperature, salinity, and wind data, is compared to the results of the BSH operational circulation model "BSHcmod". The model output includes currents, temperature, salinity, and sea level data. The meteorological input is generated by an atmospheric model of the DWD in Offenbach. The accuracy of the meteorological input, especially the local wind field which acts as an external force onto the sea surface, is essential for the currents within the surface model layer. The quality of the wind input can be estimated by comparing it to local DWD measurements recorded on board UFS DB. The validation of the model results is essential for several BSH tasks, e.g. water level prediction and storm surge warnings. As the results of BSHcmod constitute basic data which are used to drive Lagrangian and Eulerian drift and dispersion models, a realistic computation of currents is of vital importance.

2 Instrument setups

The ADCP was a 300 kHz BroadBand Workhorse Sentinel manufactured by RD Instruments. It was mounted in a bottom frame with the upward looking transducer 0.5 mab. The ADCP divided the water column into equally spaced depth cells (bins) whose length was 2 m for this application. The sampling interval (ensemble time) was 15 minutes. Using 45 pings per ensemble the standard deviation amounts to 0.9 cm/s. With a beam angle of 20°, the ADCP measurements of the upper 6 % (about 3 m) of the water column are contaminated due to side lobe effects (GORDON [1996]). ADCP current data are means over the whole depth range of each bin.

The Aanderaa water level recorder (WLR7) was attached to the ADCP bottom frame. It had a sampling rate of 10 minutes. The sensor is based on a pressure controlled oscillator with an integration time of 40 seconds and an accuracy of about 1 cm. After recovery the pressure data were corrected for atmospheric pressure variations by means of the meteorological data recorded at UFS DB.

3 Model data

The BSH circulation model (BSHcmod) is a three-dimensional baroclinic numerical model which in nightly routine runs produces forecasts up to 48 hours ahead (KLEINE [1994]). Currents, water levels, water temperatures, salinity, and ice cover in the North and Baltic Sea are computed on two nested and interactively coupled grids. The new model version (DICK et al. [in prep.]) which is in operation since January 1, 1999, was improved with respect to horizontal and vertical resolution. Horizontal grid spacing in the German Bight and western Baltic Sea is 1.8 km, and 10 km in the other North and Baltic Sea areas. The model also simulates the falling dry and flooding of tidal flats, allowing complex processes in the highly structured coastal waters (tidal flats, sandbanks, tidal channels, barrier islands) and water exchange with the open sea to be simulated realistically.

The model is driven by meteorological forecasts of the DWD's atmospheric models, by tides and external surges entering the North Sea from the Atlantic as well as by river runoff from the major rivers (Fig. 1). Heat fluxes between air and water are computed in the BSH model using air temperature, cloudiness, and specific humidity above the sea (MÜLLER-NAVARRA AND LADWIG [1997]). The tidal predictions at the model's open boundaries are calculated from the harmonic constants of 14 tidal constituents. External surges entering the North Sea are computed by a two-dimensional hydrodynamic model of the Northeast Atlantic.

The circulation model BSHcmod simulates density driven (baroclinic) currents which depend on the prevailing temperature and salinity distributions. As hydrodynamics are also influenced by ice conditions in the North Sea and Baltic, the circulation model is additionally coupled to an ice model simulating the formation, melting, and drift of sea ice.

The time step of the model is 1.5 minutes. However, water level and current forecasts are only stored with a temporal resolution of 15 minutes. All other model results are stored with a temporal resolution of 60 minutes.

Table 1 shows the vertical spacing of the model layers at UFS DB and the location of the ADCP bins which are used for the comparison. The model output is a vertical mean over the respective layer. For the comparison we selected those bins which were located at – or close to – the centre of the corresponding model layers.

BSH model	ADCP Data
layer 1: surface 8.0 m	surface - ~3 m: bad data, side lobes 05 - 07 m
layer 2: 8 m - 12.0 m	bin 13: 09 m - 11 m
layer 3: 12 m - 16.0 m	bin 11: 13 m - 15 m
layer 4: 16 m - 20.0 m	bin 9: 17 m - 19 m
layer 5: 20 m - 24.0 m	bin 7: 21 m - 23 m
layer 6: 24 m - 30.0 m	bin 5: 25 m - 27 m
layer 7: 30 m - 37.6 m	bin 1: 33 m - 35 m no data: 35 m - 38 m

Table 1: Vertical spacing of model layers and ADCP bins

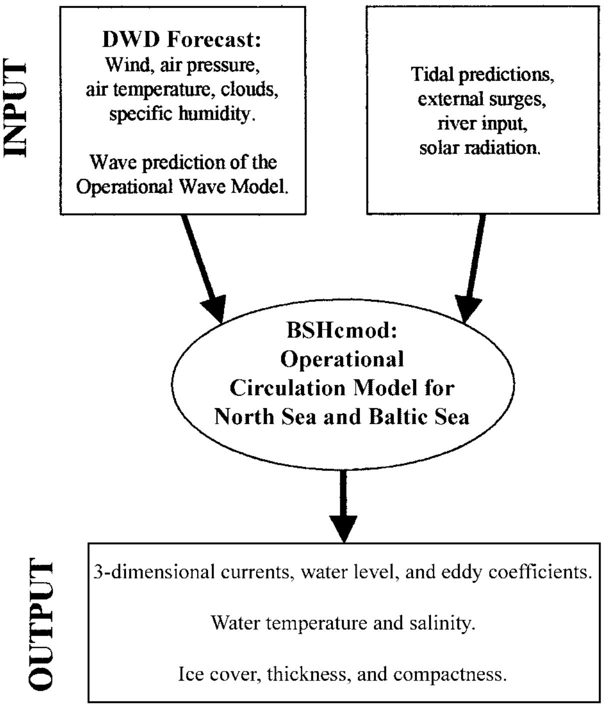

Fig.1 BSH circulation model scheme

4 External Forcing: Wind data

The meteorological data recorded by the autonomous DWD station on board UFS DB represent an average over the 10 minutes preceding the hourly data transmission. The winddirection is given in 10° intervals, and the wind speed in 1 knot intervals. Model wind data, which are stored every 15 minutes, are not provided at fixed intervals. This may partly explain the small differences between both data sets which can be observed in Figure 2 and Table 2. However, these differences are not significant. Figure 2 shows the time series of wind direction and speed for the model wind (red) and the local observations (black). In general, all modelled winds (and also simulated currents) are taken from the 12–36 hour prediction interval (after the meteorological analysis). During the first 2.5 days of the experiment, no observational data are available, but generally there is good agreement between model predictions and observations. Table 2 gives a percentage frequency distribution of wind speed at 3 m/s intervals, and wind direction at 30° intervals. With respect to the different sampling conditions, Table 2 confirms the good agreement between both data sets. There are no events with significant differences between predicted and locally observed winds, i.e. the external forcing onto the sea surface, which is essential for the surface currents, proved to be predicted correctly during this period.

5 Currents

5.1 Current conditions at UFS DB

Due to moderate to weak winds in the summer of 1999, also the current velocities were quite small. Figure 4 shows a **p**rogressive **v**ector **d**iagram (hereafter PVD) of ADCP measurements (a) and model data (b) from June 15 to August 10, 1999. The starting position is marked with a big cross, time marks (X) are given every 5 days. The numbers at the tracks give the sampling depth (bin centre, respectively layer centre) in metres. PVD's for some sampling depths show only small differences between measurements and model predictions. However, stronger deviations occur at the surface and at about 27 m depth. In general, both in the model results and in the measurements, there is an eastward drift at the surface and a southward drift near the bottom. This is also represented in maps of simulated mean Eulerian currents calculated for the whole measuring campaign. Figure 3 shows model results in the area of UFS DB for the surface and bottom layers.

In the surface layer, residual currents mostly run parallel to the depth contours, with eastward currents near UFS DB and northwestward currents northeast of Helgoland. West of Helgoland an anticyclonic gyre appears. In the bottom layer a southwestward current into the inner German Bight is simulated which is caused by long periods of offshore winds during the measuring campaign (see Fig. 2). In the next chapter, these and other model results will be discussed in more detail and compared to the measurements.

speed interval (m/s)		0–3	3–6	6–9	9–12	12–15	15–18	**total direction**
0°– 30°	UFS:	0.9	2.6	1.8	–	–	–	**5.3**
	mod:	0.9	3.0	3.6	0.1	–	–	**7.6**
30°– 60°	UFS:	0.2	3.3	3.4	0.1	–	–	**7.0**
	mod:	0.6	3.2	2.7	–	–	–	**6.6**
60°– 90°	UFS:	0.3	3.3	4.6	0.4	–	–	**8.6**
	mod:	0.7	5.5	7.6	0.8	–	–	**14.4**
90°–120°	UFS:	0.6	3.3	6.8	0.1	–	–	**10.8**
	mod:	0.4	2.1	5.7	0.7	–	–	**9.0**
120°–150°	UFS:	0.3	2.1	3.5	0.1	–	–	**6.0**
	mod:	0.1	1.3	1.0	–	–	–	**2.5**
150°–180°	UFS:	0.2	1.1	0.5	–	–	–	**1.9**
	mod:	0.2	1.2	0.5	0.2	–	–	**2.0**
180°–210°	UFS:	–	1.2	1.5	0.4	–	–	**3.2**
	mod:	–	1.9	1.3	0.9	0.2	–	**4.4**
210°–240°	UFS:	0.5	1.9	4.3	1.0	–	–	**7.8**
	mod:	0.5	3.0	2.9	1.9	0.1	–	**8.4**
240°–270°	UFS:	0.3	3.3	5.9	1.1	0.5	–	**11.1**
	mod:	0.8	3.3	4.0	1.7	1.7	<0.1	**11.5**
270°–300°	UFS:	0.9	2.2	6.6	2.3	0.6	–	**12.5**
	mod:	0.3	3.0	3.9	1.2	0.5	–	**8.9**
300°–330°	UFS:	1.0	5.5	3.5	0.6	0.1	–	**10.7**
	mod:	0.4	4.7	5.2	0.8	1.2	–	**12.4**
330°–360°	UFS:	1.5	5.9	5.0	2.2	0.5	–	**15.2**
	mod:	1.3	5.7	3.0	2.0	0.4	–	**12.4**
total speed	UFS:	**7.7**	**35.7**	**47.4**	**8.3**	**1.8**	**0.0**	%
	mod:	**6.3**	**38.0**	**41.4**	**10.2**	**4.1**	**<0.0**	%

UFS: local observations, mod: predicted model data

Table 2: Percentage frequency distribution of wind speed and direction

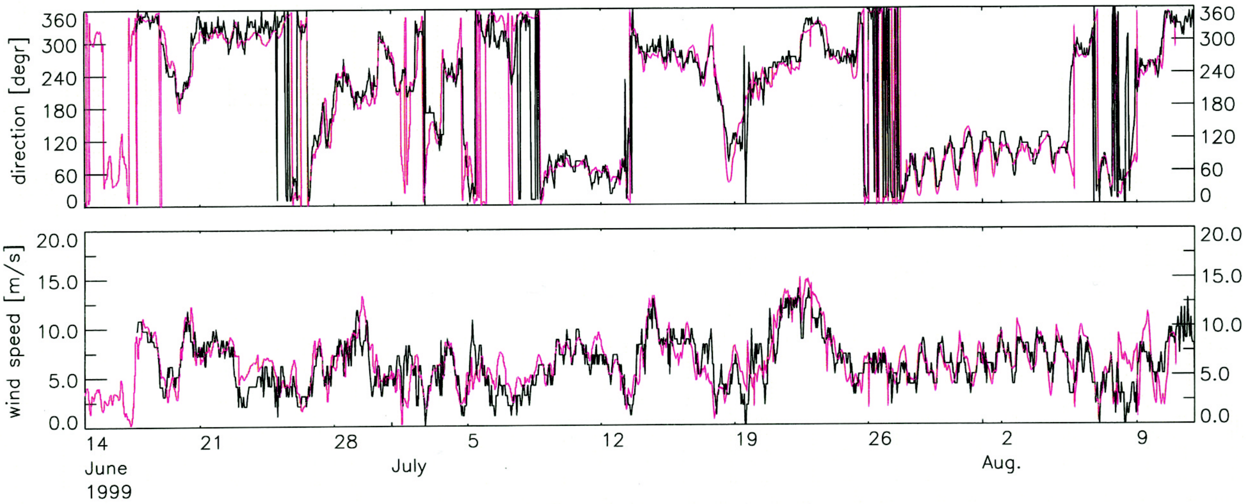

Fig.2 Wind speed and direction. Black curve: Measurements at the light-vessel "German Bight", red curve: model data.

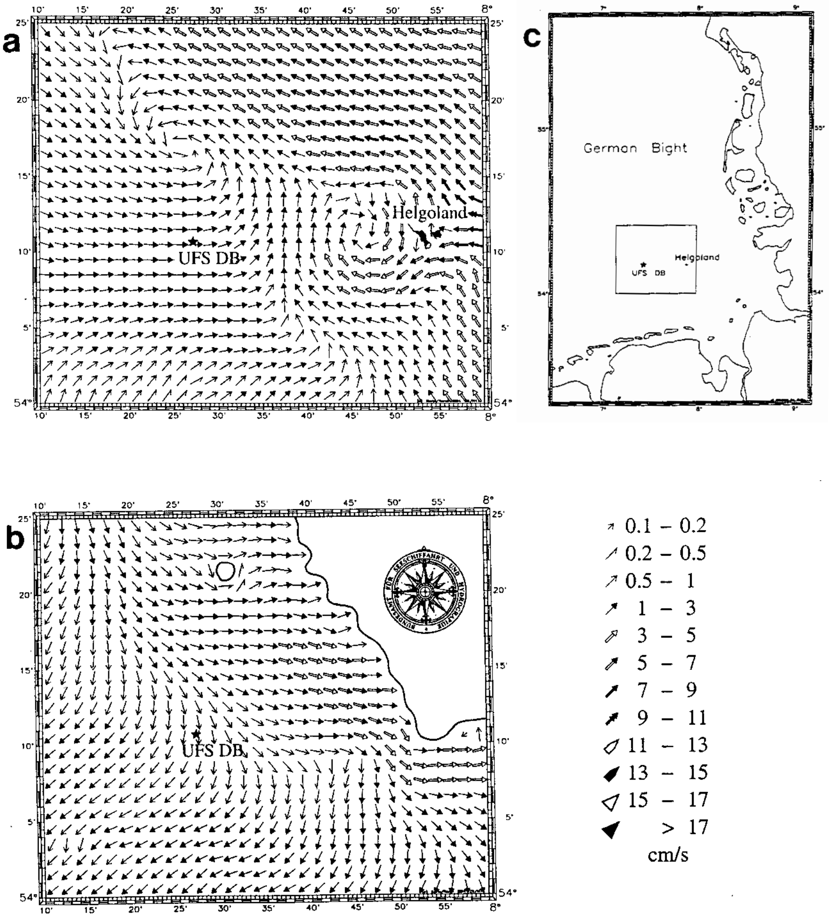

Fig.3 Calculated residual currents in the surface (a, 0 – 8 m) and bottom layers (b, > 24 m). Model forecasts for the period June 15 to August 10, 1999.
c: Location of UFS DB and position of the model sector shown in a and b.

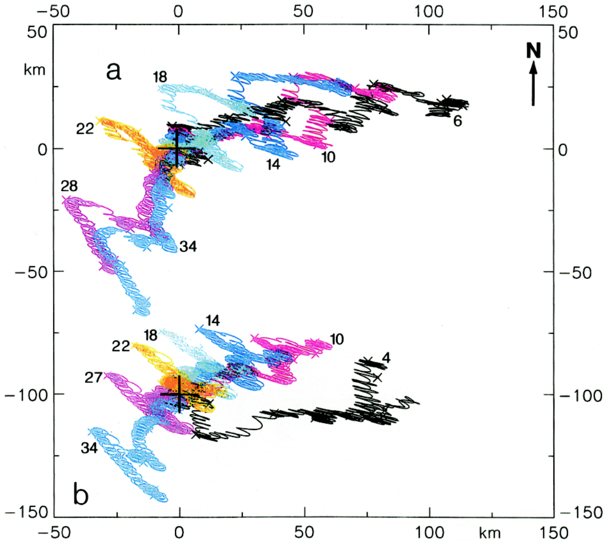

Fig.4 Progressive vector diagram of ADCP measurements (a) and model data (b) 15.6.1999 15:45 – 10.8.1999 08:30. The start position is marked with a big cross, time marks (X) are given every 5 days. The numbers at the tracks give the sampling depth (bin center, respectively layer center) in metres.

5.2 Residual currents

Figure 5 shows the vertical mean profiles of speed[1)], magnitude, and current direction for ADCP and model data. Taking into account the different vertical resolutions – 2 m ADCP bins versus 4 to 8 m model layers – there is considerable agreement between both data sets. The profiles of speed and magnitude are very similar. In the lower half of the water column there are some differences in current direction. The shear at 20 m depth appears to be much sharper in the ADCP data and there are significant differences between 20 and about 30 m depth, while the near-bottom current directions are again very similar. Table 3 gives some basic current statistics, and Table 4 quantifies the relationship between both data sets. The correlation coefficients *r*, given for the zonal and meridional current component, range between 0.87 and 0.96; only in the first layer does the correlation of the meridional component amount to just 0.67. Here we must consider the fact that the model values are vertical means over the complete layer, while the ADCP data represent only the range between 5 and 7 m depth due to the above-mentioned side lobe effects. At all depths there is a slightly higher correlation of the zonal current components as compared to the meridional components.

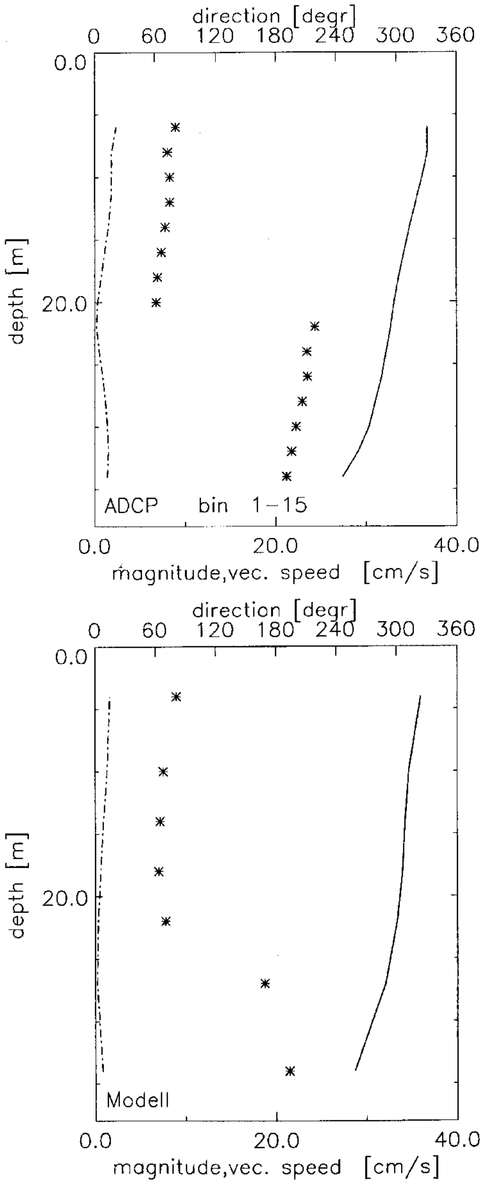

Fig. 5 Vertical mean profiles of current speed (broken line), magnitude (solid line), and current direction (*) for ADCP (above) and model data (below). See also Table 3.

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1)

$$\text{magnitude} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{u_i^2 + v_i^2},\ \text{speed} = \sqrt{\bar{u}^2 + \bar{v}^2},\ \text{with } \bar{u}_i = \frac{1}{n}\sum_{i=1}^{n} u_i$$

Between the surface and about 20 m depth as well as in the bottom layer, the difference in the mean current direction is only a few degrees. As has been mentioned above, significant differences occur in layers 5 and 6 because the model cannot resolve the sharp shear due to its layer thickness. Variances and co-variances, as well as the mean and eddy kinetic energy k_M and k_E[2], also are of a comparable order of magnitude. Due to the strong tides there is much more energy in the current fluctuations than in the mean currents (see k_E/k_M in Table 3).

layer bin –		depth m	u cm/s	v cm/s	mag cm/s	speed cm/s	dir °	k_E $(cm/s)^2$	k_M	$\overline{u'u'}$	$\overline{v'v'}$ $(cm/s)^2$	$\overline{u'v'}$	k_E/k_M –
M	1	4.0	1.6	0.2	36.0	1.6	81	802.2	1.3	1471	133	–392	625
A	15	6.0	2.4	0.4	36.8	2.4	80	832.6	2.9	1558	105	–267	289
M	2	10.0	1.2	0.5	34.7	1.3	68	727.7	0.8	1277	177	–405	897
A	13	10.0	1.8	0.5	36.2	1.9	75	806.1	1.7	1468	144	–380	465
M	3	14.0	0.9	0.4	34.3	0.9	65	698.2	0.5	1192	205	–396	1565
A	11	14.0	1.4	0.5	34.8	1.5	70	735.5	1.2	1289	182	–405	627
M	4	18.0	0.6	0.3	34.0	0.6	63	677.4	0.2	1136	218	–380	3272
A	9	18.0	0.6	0.3	33.6	0.7	63	673.7	0.2	1136	209	–386	2716
M	5	22.0	0.3	0.1	33.4	0.3	70	645.1	0.0	1071	219	–348	11130
A	7	22.0	–0.1	–0.1	32.7	0.2	219	622.9	0.0	1014	229	–352	54705
M	6	27.0	0.0	–0.2	32.1	0.2	168	586.2	0.0	958	214	–291	27418
A	5	26.0	–0.5	–0.7	31.7	0.9	212	572.5	0.4	907	238	–304	1543
M	7	34.0	–0.2	–0.8	28.7	0.8	193	453.0	0.3	720	186	–194	1360
A	1	34.0	–0.3	–1.4	27.4	1.4	191	414.4	1.0	639	190	–181	398

Table 3: Current statistics model (M) and ADCP (A) data

layer –	bin –	depth m		r –	r^2 %	delta cm/s
1	15	5	zonal	0.95	91	0.7 ± 12.1
			merid.	0.67	45	0.2 ± 8.9
2	13	10	zonal	0.96	91	0.5 ± 11.2
			merid.	0.87	76	0.1 ± 6.5
3	11	14	zonal	0.95	90	0.5 ± 11.3
			merid.	0.93	86	0.2 ± 5.3
4	9	18	zonal	0.95	90	0.0 ± 10.9
			merid.	0.94	88	0.1 ± 5.1
5	7	22	zonal	0.95	90	–0.5 ± 10.3
			merid.	0.94	88	–0.1 ± 5.3
6	5	27	zonal	0.95	91	–0.5 ± 9.5
			merid.	0.94	88	–0.4 ± 5.3
7	1	34	zonal	0.95	90	–0.1 ± 8.5
			merid.	0.93	86	–0.5 ± 5.2

r = correlation coefficient

delta = mean ($V_{adcp} - V_{model}$) ± std. deviation

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[2] $k_M = \frac{1}{2}(\bar{u}^2 + \bar{v}^2)$, $k_E = \frac{1}{2}(\overline{u'u'} + \overline{v'v'})$, with $u' = u - \bar{u}$

5.3 Tidal currents

For both data sets we made a tidal analysis and determined the hourly mean tidal currents from 6 hours before until 6 hours after **h**igh **w**ater (HW) in Helgoland (port of reference) for spring and neap tides. There is a very good agreement between both data sets. Figure 6 shows the spring tidal stream figures for the near-surface, mid-depth, and near-bottom layers. The same good agreement is observed at neap tide. At the surface, the tidal stream is alternating in an east-west direction. Towards the bottom, the tidal stream figure becomes more circular, representing a nearly continuous anti-clockwise rotation of the tidal stream in the near-bottom layer.

Energy density spectra show significant peaks at periods of 12.4 (M_2), 6.2 (M_4, MS_4), and 4.2 (M_6, $2MS_6$) hours. With respect to the M_2-tide, good agreement is found between the ADCP and model data. A difference is only observed in the meridional component of the near-surface layer (see Table 5). The other tidal constituents exhibit significant differences between both data sets.

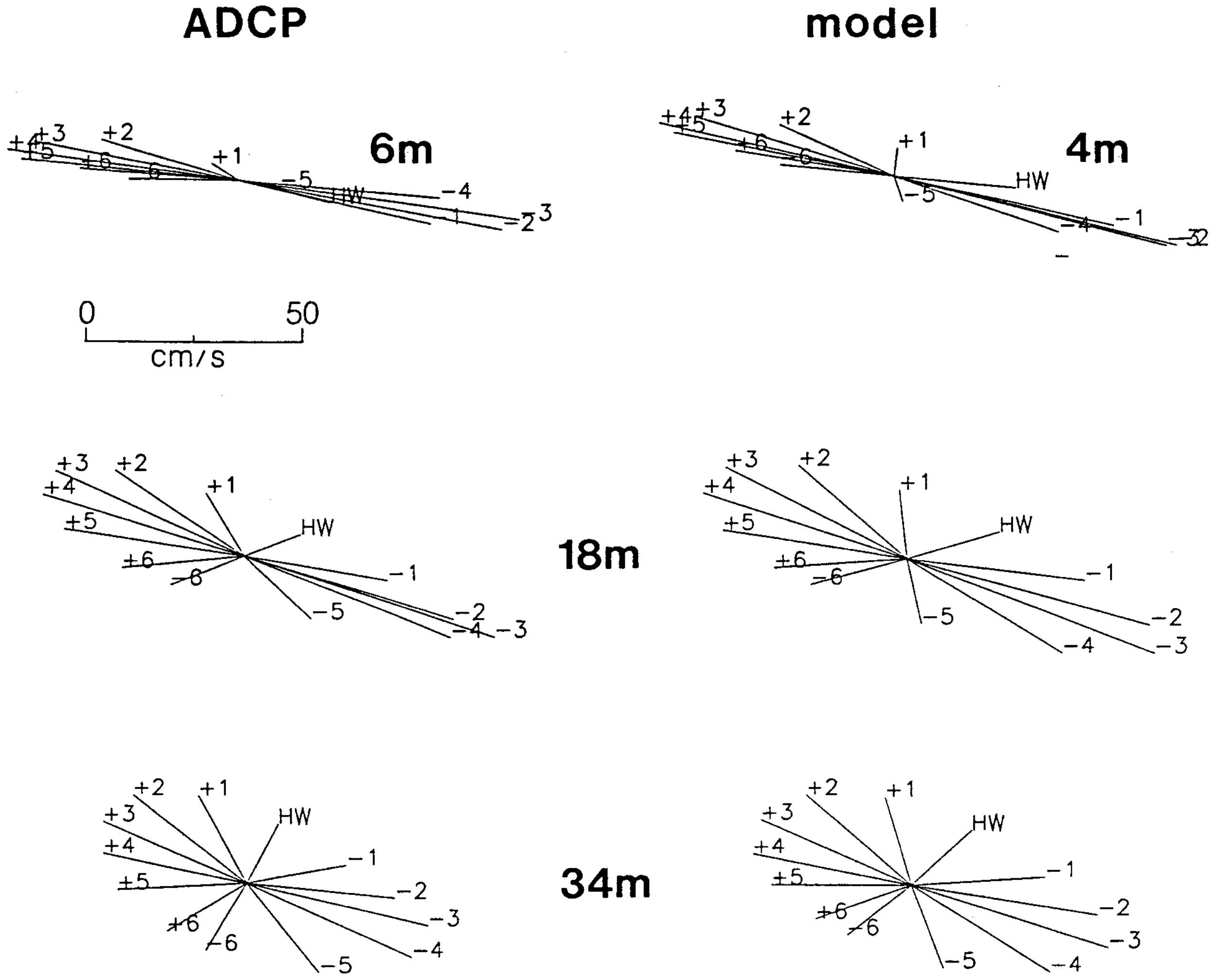

Fig. 6 Mean tidal stream figures evaluated from ADCP data (left) and model data (right). The vectors give the hourly averaged spring tidal currents from 6 hours before (–6) until 6 hours after (+6) high water (HW) in Helgoland. The bold numbers give the sampling depth, i.e. the centre of the ADCP bin, respectively model layer.

tide period [h]			**energy density [(cm/s)^2/cph]**		
			M_2 **12.4**	**M_4, MS_4** **6.2**	**M_6, $2MS_6$** **4.2**
model	u-comp.	4 m:	303941	1682	373
	v-comp.	4 m:	25749	255	42
ADCP	u-comp.	6 m:	311958	2947	312
	v-comp.	6 m:	12216	1341	223
model	u-comp.	18 m:	237147	1822	199
	v-comp.	18 m:	44562	197	32
ADCP	u-comp.	18 m:	234280	3061	327
	v-comp.	18 m:	40134	179	77
model	u-comp.	34 m:	150306	1098	280
	v-comp.	34 m:	37854	165	182
ADCP	u-comp.	34 m:	131285	1384	789
	v-comp.	34 m:	37009	200	269

Table 5: Spectral energy density distribution

6 Water level

The modelled water level data are given in metres relativ to NN. The WLR data give the absolute pressure at the sensor in dbar. After recovery, the data were corrected for atmospheric pressure variations and related to the mean pressure value to be comparable to the model data. The correlation between both curves is 0.99, the mean difference amounts to 0.11 ± 0.08 m. Figure 7 shows the time series of both curves for the first 30 days and the difference (WLR - model) between both curves. For this figure, the time series have been averaged to 30-minute values. During neap tide the amplitude of the model data is smaller than the amplitude of the measured values while during the spring periods a small offset of the model values is observed.

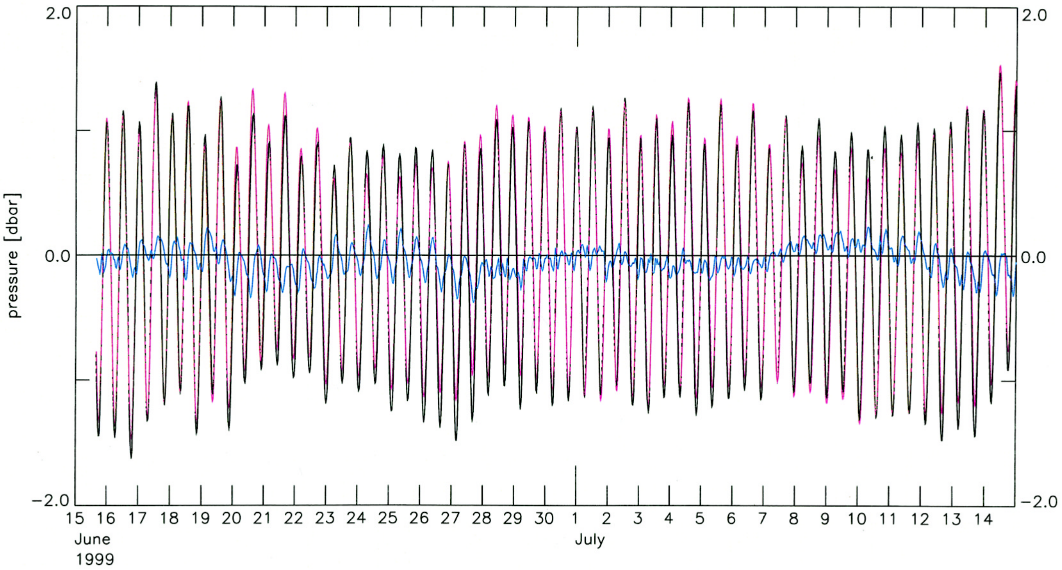

Fig. 7 Model sea level data (red), WLR measurements (black), and difference WLR-model (blue). The data are averaged to a 30 minutes time interval.

In a next step we determined the high (HW) and low water (LW) times for both curves and compared the values. At the WLR the HWs appeared 16.3 ± 10.7 minutes earlier than the model HWs, and the LWs appeared 8.3 ± 10.8 minutes earlier. This difference may be partly due to the different sampling intervals (10 and 15 Minutes). However, the delay of the model is significant.

7 Discussion

It has been demonstrated that the BSH model represents tidal conditions quite well. Tidal analysis of currents at different depths showed good agreement in direction and speed. Differences were found with respect to some higher harmonics (M_4, MS_4, M_6, $2MS_6$). This is in accordance with the comparison of water level data. The differences for high and low water times between both data sets may also be caused by a spurious representation of higher harmonics. As higher harmonics are mostly generated within the model area by non-linear effects, the error could probably be reduced by improving the representation of topography or bottom friction. However, the low standard deviation of water level differences (± 0.08 m), reflecting not only tidal but also surge effects, shows that the model's tidal error at UFS DB is very small.

Looking at the representation of residual currents, the current structure is found to agree in general. Differences in the surface layer are mainly caused by missing ADCP data near the surface (side-lobes). In general, current magnitude, vector speed, and kinetic energy agree quite well. However, some differences are observed in the current direction in the layer between 20 and 30 m. While measurements show a sharp shear at about 21 m depth, the gradient in the model predictions is much smoother. A reason for this is the coarse vertical grid spacing of 4 respectively 6 m which prevents the formation of sharp gradients.

On the other hand, density distribution also affects the baroclinic residual currents and their vertical structure. As a wrong representation of the density structure would cause wrong residual currents, the salinity and temperature profiles measured at UFS DB will be compared with model results in the following. Figure 8 shows the temporal evolution of measured and computed temperature profiles at UFS DB for the period of current measurements. Both figures demonstrate the warming of the whole water column in summer and show a succession of periods with stratification and mixing. In general, model temperatures are somewhat above the measured values. The mean deviation is approximately 0.6 °C at the surface and in the bottom layer and 0.8 °C in the middle of the water column. Larger differences at mid-depths are attributable to a weaker stratification in the model than in nature. As has been mentioned above, the model is not capable of simulating sharp vertical gradients. However, as temperature stratification and current shear occur at different water depths, there was no direct link between both phenomena. Looking at the salinity profiles, there was only weak haline stratification in the summer of 1999. The difference between surface and bottom salinities was 0.3 in nature and 0.1 in the model, with a mean deviation of 0.5 between model data and measurements. Therefore, the density field at UFS DB – and hence the baroclinic currents – was influenced much more by temperature than by salinity.

We may conclude that in summer 1999 the operational circulation model of the BSH in principle predicted a realistic description of hydrodynamics at UFS DB. Earlier comparisons in the close vicinity of Helgoland exhibited significant deviations between ADCP and model currents resulting from strong topographical gradients which could not be resolved by the model grid. At UFS DB, which is located in an area without significant topographical gradients, differences between ADCP and model data were found at depths where strong current shear or strong stratification occurred. One reason for this is that gradients cannot be simulated with a vertical resolution of more then 4 metres. Another possible cause could be an error in the parameterization of vertical eddy diffusion. This will be investigated in a future experiment.

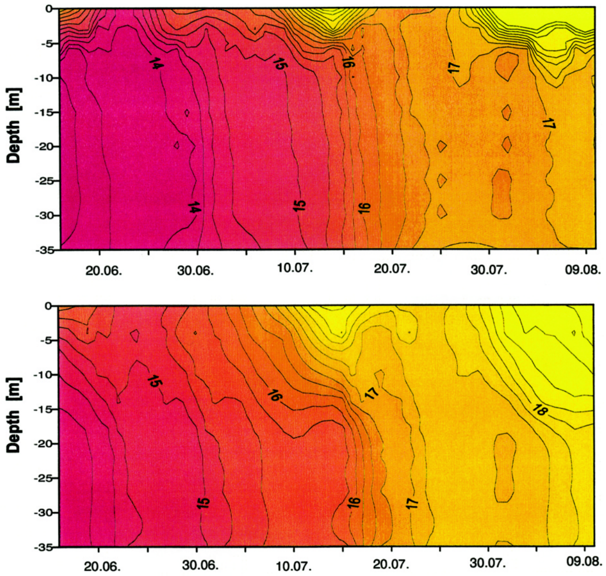

Fig. 8 Temporal development of the vertical temperature profile at UFS DB. Top: MARNET data, bottom: model results.

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