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Observational data sets for model development

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Abstract

The requirements of ‘comprehensive’ or ‘compatible’ observational data sets for developing and verifying models are examined. ‘Compatibility’ over the range of key parameters involves accuracy, spatial and temporal extent, and resolution. The importance of documentation is emphasised on all aspects from experimental strategy to sensor calibration. Likewise, maximising accessibility involves listing in international directories, quick-view summary facilities as well as detailed data listings. Such accessibility generally includes: multi-media dissemination involving the Internet; printed papers and reports; CD ROMs.

Experiences from two coastal observational experiments are reviewed: Holderness on the UK east coast and Sylt-Rømø in the German Bight. These examples provide particular illustrations of the generalised principles. They extend to usage of satellite, aircraft, radar, ship, surface and sea bed moorings, and piles as platforms. Specific capabilities, limitations and idiosyncrasies of a range of instruments are described. Effective monitoring strategies must aim to exploit the associated synergies between this full range of platforms and instrumentation.

Keywords: Currents; Data calibration; Data dissemination; Data documentation; Data processing; Measurement strategy; Suspended sediments; Waves

1. Introduction

Development of the predictive power of mathematical models depends strongly on the availability of high quality, comprehensive observational data sets for: initialisation,

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forcing and verification. Sequential improvements through more sophisticated algorithms or data assimilation techniques can only be properly assessed as long as the data are of comparable accuracy and resolution. While such developments have been implemented in the field of weather forecasting, there is a lack of comparable data sets in marine sciences, especially in the study of suspended particulate matter (SPM) dynamics in coastal areas. One of the reasons for this is the requisite sensor maintenance and checks on calibration necessary to maintain data quality over longer time periods, e.g., for measuring SPM concentrations.

Recognising the above, one objective of Pre-operational Modelling in the Seas of Europe (PROMISE) was to assemble and disseminate comprehensive observational data sets associated with both earlier and on-going field campaigns with a quality sufficient to test and improve present state-of-the-art models. In this paper we discuss the general requirements of comprehensive data sets. These ‘guidelines’ are then illustrated using as examples, data sets from the Holderness area close to the east coast of England and the Sylt-Rømø Bight in the Danish/German Wadden Sea.

Subsequent sections describe: general ‘guidelines’ to the planning, execution and processing of test-bed observational data sets (Section 2); hence, examples from Holderness (Section 3) and Sylt-Rømø (Section 4). Section 2 was largely compiled by R. Riethmüller who, along with co-authors from GKSS is responsible for Section 4. A. Lane was responsible for the data processing for the Holderness Experiment, and acknowledgement is due to the experimentalists listed in Prandle et al. (1996).

2. General requirements for comprehensive data sets

A ‘comprehensive’ data set must be complete, consistent, well documented and accessible. The first two attributes are concerned with the quality of the data set; the remainder deal with long-term usability.

Assessing the quality of the data set is a critical aspect of model validation (Lynch et al., 1995) — it cannot simply be regarded as absolute values. In addition to achieving a high level of data correctness (such as accuracy and consistency), the data set also has to be appropriate for the intended purpose (Rothenberg, 1996; Rothenberg and Kameny, 1994). These checks are most important before data sets are disseminated to the community, since subsequent applications cannot be foreseen. Extensive documentation on sampling, processing and objectives in generating the data set are, therefore, required to provide ready assessment of its potential usefulness for a specific application.

In the following sections, general requirements for a comprehensive data set will be discussed in detail.

2.1. Formulation of hypotheses

Hypotheses on the governing processes provide the basis for selecting the parameters of the data set and the sampling strategies and methods to be applied. The key processes considered and, hence, the formulation of the respective hypotheses, may depend on the temporal and spatial scales and the study area considered. In the case of SPM dynamics, the following hypotheses were found to be applicable both in the Holderness area and the Sylt-Rømø Bight:

Hypothesis 1. Wave action and tidal currents are the main erosion and resuspension processes, whereas advective fluxes are predominantly associated with tidal currents.

Hypothesis 2. The loss of bed material is mainly triggered during storm events.

Hypothesis 3. Erosion and resuspension of SPM are influenced significantly by sea bed characteristics.

Hypothesis 4. Sedimentation of SPM is strongly influenced by the settling velocities of the suspended material.

Hypothesis 5. Microturbulence plays a significant role in the tidal cycle of sediment erosion or resuspension, advection and settling.

2.2. Data accuracy

Despite the best intentions of those making observations, data quality cannot be constantly verified throughout field campaigns. This is especially true for long-term data sampling, and for parameters that require much effort in sensor maintenance and calibration (e.g., measuring SPM concentration). Users need to be made aware of these problems when data sets are disseminated — they depend on those who produce the data sets to perform these checks, and to document the results and any corrective steps taken.

2.3. Completeness

The 'completeness' of a data set encompasses the following aspects:

1. The data set should contain all parameters identified in the hypotheses. The parameters listed in Table 1, derived from the above hypotheses, form a complete description of the SPM dynamics in coastal regions.

Table 1
Parameter list for a comprehensive data set for SPM dynamics in shallow coastal waters

Region	Parameter	Interior	Boundary
Atmospheric boundary layer	Air pressure	x	
	Wind	x	
Water body	Water level	x	x
	Waves	x	x
	Current	x	
	Salinity	x	x
	Water temperature	x	x
SPM	Concentrations	x	x
	Settling velocities	x	
Bottom	Bathymetry	x	
	Sediment type	x	
	Erosion shear stresses	x	

2. Data are collected, both from within the study area and along its boundaries.
3. Raw and processed data are stored together with the processing programs and a list of parameters.
4. Relevant documentation is included, enabling users to independently interpret (and, if necessary, process or reprocess) the data.

2.4. Consistency

The data set may be described as ‘consistent’ if it satisfies these conditions:

1. Data from different observations and/or model calculations can be intercalibrated.
2. Data are provided together with their accuracy (e.g., in form of standard deviations, confidence intervals, statistical errors, systematic errors, etc.).
3. They can be transferred onto common temporal and spatial scales.

2.5. Documentation

Documentation, an integral part of a comprehensive data set, serves as a user guide and should facilitate the following:

1. It enables users to assess the appropriateness of the data set for their requirements.
2. It identifies the parameters measured.
3. It provides a basis to assess the quality of the data set.
4. It explains how the data set is referenced and can be retrieved.

The first three items are essential for data set quality assurance (Rothenberg, 1996; Rothenberg and Kameny, 1994). The documentation may also include the following: specification of hypotheses; sampling strategies; accuracy intended and achieved; methods, scales, quality status of parameters; applied programs; persons and institutions involved, etc. These form part of widely used environmental data standards, e.g., the Global Change Master Directory’s (GCMD) Data Interchange Format (DIF) operated by NASA (Irvine and Scialdone, 1992); the Federal Geographic Data Committee’s Metadata Standard (FGDC, 1998); the International Council for the Exploration of the Sea (ICES) Format used by the European marine researchers. Such documentation is necessary for community use of the data set; however, it may in future become significantly different from the standards as these are constantly evolving. The solution to this potential problem is to ensure that the data set is as self-contained and self-explanatory as possible by storing together the data, documentation and software with which the data were created (Rothenberg, 1995). Use of hypertext documents is an effective means of achieving the above.

2.6. Dissemination

Data sets may be publicised by submitting an entry to catalogue databases, such as European Directory of Marine Environmental Data (EDMED) (British Oceanographic

Data Centre, 1992), the European Catalogue of Data Sources (CDS), or GCMD via its national partners. Additionally, the Internet is a relatively inexpensive medium for publicising and disseminating information, by setting up a website and advertising it through search engines. The security, availability and distribution of the data themselves via storage media or Internet tools have to be guaranteed by the responsible institutions over several years.

3. The Holderness data set

3.1. Planning of the Holderness experiment

The Holderness coastline, consisting of rapidly retreating clay cliffs, forms a major source of sediment to the North Sea (Prandle, 1994a). The aims of the Holderness Experiment were to monitor the transport of these sediments away from the coast, and to measure directly contributions to erosion, suspension and transport.

Major milestones include the following: definition of objectives; consultation of end-users, collaborators and potential funding organisations; estimation of controlling mechanisms with feedback from a pilot phase. Planning for Holderness incorporated all of the latter (Prandle, 1994b and Prandle et al., 1996). Growing widespread interest continuously expanded both the goals and the potential scale and scope of the experiment. As a result the experiment ultimately embraces components concerned with: (i) estimating sediment fluxes directly from measurements, (ii) process studies of specific mechanisms (e.g., wave-induced bed stress), (iii) technology development (X-band and H.F. radar), and (iv) establishing bench-test data sets for formulating, running and verifying predictive models.

The experiment made use of satellite and aircraft remote sensing, H.F. and X-band radar, ship surveys, in situ sea bed and sea surface instrumentation. Expenditure was carefully balanced between capital purchase of instruments required for long-term deployments, hire over shorter terms, significant costs for data deployment, recovery, losses and subsequent data processing. The guiding principles were concentration on ‘core’ measurements, with duplication in instruments (including a range of acoustic, optical and electromagnetic sensors) to cover malfunctioning and questions of calibration. Likewise, location of fixed rigs in reasonably close proximity allowed questions of representativeness to be addressed. Conversely, for the more ambitious elements, shorter-term deployments without contingency planning were scheduled.

The major success of the experiment was in synchronising as many as possible of the disparate elements.

3.2. The observational campaign

Currents, wave parameters, pressure, temperature and conductivity were recorded together with transmittance and (optical and acoustic) backscatter, which gave indications of SPM concentrations. The experiment consisted of three phases; an initial small-scale pilot study provided feedback on the range of conditions to be anticipated

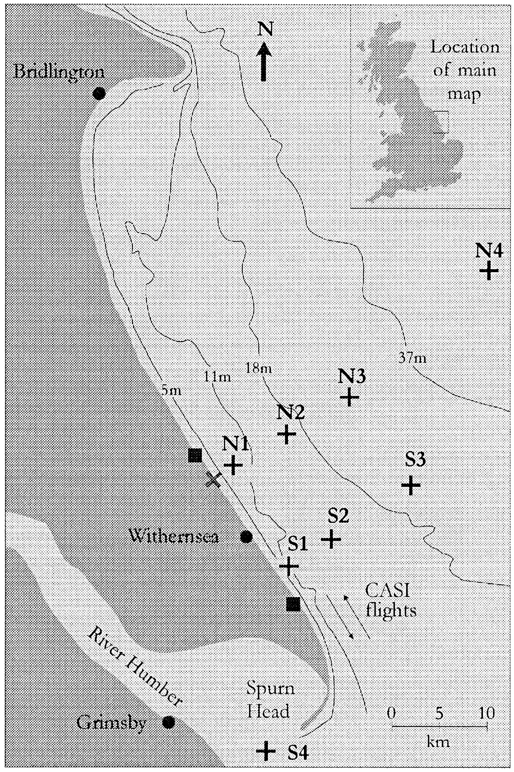

Fig. 1. Holderness Coast. Positions of moorings N1–N4, S1–S3.

and an evaluation of the suitability of the rigs and instrumentation. The major experiment followed a year later, with a final phase a further year later to complete gaps in coverage.

The pilot study was conducted between November and December 1993. Bottom-mounted POL-monitoring platforms (PMPs) were deployed at six mooring sites close to the shore (Fig. 1).

3.2.1. Phase one, 1994–1995

In the main Holderness Experiment (October 1994–March 1995), two lines of PMP stations were located perpendicular to the coast. The northern line consisted of four moorings (three of which were close to the pilot study PMP positions — N1, N2, N3; one further offshore — N4) and the southern line consisted of three moorings (S1, S2 and S3).

3.2.2. Phase two, 1995–1996

A second Holderness Experiment (October 1995–January 1996) concentrated on currents and waves at the near-shore sites N1 (two sites — N1A and N1B) and N2 (three sites — N2, N2A and N2B), S1 and S2. These measurements coincided with the deployment of the OSCR H.F. radar system configured for measuring waves (Wyatt and Ledgard, 1996).

3.2.3. Concurrent observations

Other observations concurrent with the above experiments included waverider buoys at sites N1, N2 and N3 (Wolf, 1996a,b); X-band radar, STABLE, and regular compact airborne spectrographic imager (CASI) flights along the coast. Lane (1997) provides a description of the instrumentation deployed. The PMPs were used to house an acoustic Doppler current profiler (ADCP), a S4 electromagnetic current meter, a high-frequency water level (pressure) recorder and a transmissometer. The rigs closest to the shore were equipped with the S4DW, which included an optical backscatter (OBS). Acoustic backscatter (ABS) sensors were also used where available.

3.3. Data processing and dissemination

3.3.1. Processing steps

Separate processing packages (one for each type of instrument) were developed. The programs convert the raw data (often given in counts) to engineering units. The mooring positions, calibration coefficients, deployment and data start/end times are stored in control files, one for each associated data file. A suite of graphic routines enabled the visualisation of the data. The quality of the data can be inspected and when necessary, the calibration stage repeated after editing or flagging the raw data.

Many of the routines used in the current processing packages were from Knight (1995). Software to extract wave parameters from the S4DW and PWR instruments was written by Wolf (1996a).

3.3.2. Data dissemination

A guiding principle of the experiment was to ensure open access to the data sets following calibration and quality assurance processing. The data were initially distributed via the World Wide Web (http://www.pol.ac.uk/coin/Holderness/) and, subsequently, on a CD ROM from the British Oceanographic Data Centre at the Proudman Oceanographic Laboratory.

3.4. Data comparisons and evaluations

Fig. 2 illustrates the range of instrumentation used, indicating the varying nature of the associated coverage. While remote sensing from satellite and aircraft provide occasional surface snapshots of SPM concentrations (subject to complex calibration/geographical atmospheric correction), most in situ instruments provide continuous long-term time series but at a single point. By contrast, although radar only measures surface signals, it does provide continuous time series. Moreover, for waves, the general validity of linear theory allows such surface signatures to be extrapolated into depth profiles; for the X-band radar, this gives an indirect estimation of bathymetry (Bell, 1999). The ADCP is exceptional in providing both vertical current profiles and, subject to interpretation (Holdaway et al., 1999), SPM profiles.

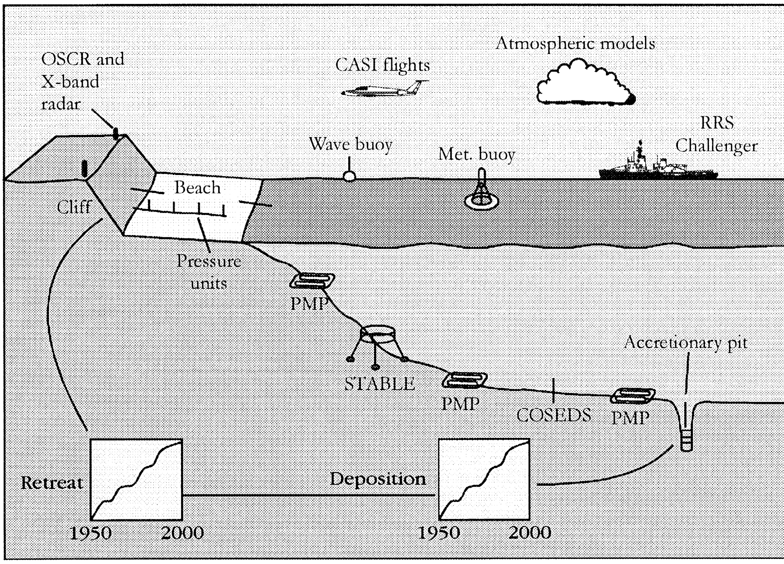

Fig. 2. Schematic of instrumentation deployed in the Holderness Experiment.

Subsequent sections compare data from the above sources to further illustrate their usefulness.

3.4.1. Current measurements

Fig. 3 shows comparisons of currents measured synoptically by the S4DW electromagnetic current meter (0.8 m above the sea bed), the POL 1 MHz ADCP at bin intervals of 0.5 m through the vertical and by the OSCR H.F. radar close to the sea surface (Player, 1996).

Although there is good overall agreement between ‘tidal’ currents measured by these three instruments, subtle and sometimes significant discrepancies can be encountered. The S4 measurements can indicate erroneous long-term drifts of up to 0.05 m s^{-1}, possibly associated with flow interference from the PMP frame. The POL ADCPs are two-beam experimental current meters with low-power transducers, and these may show an apparent reduction in tidal current amplitude with increasing height above the bed. This is attributed to a loss of backscatter strength with increasing range (Knight and Marsden, 1994). Occasional spurious currents may be present in OSCR H.F. radar currents, due to some idiosyncrasy in the ‘peak-picking’ software used to extract the offset of the Bragg peaks in the recorded spectra. The radar currents can also be aliased by residual components associated with oscillatory wave currents.

3.4.2. Wave measurements

The following comprehensive review of wave measurements is extracted from Wolf (1998a). It serves as a useful indication of the many aspects to be considered, e.g., platform, sensor, calibration, duration, analysis techniques, and range of applicability.

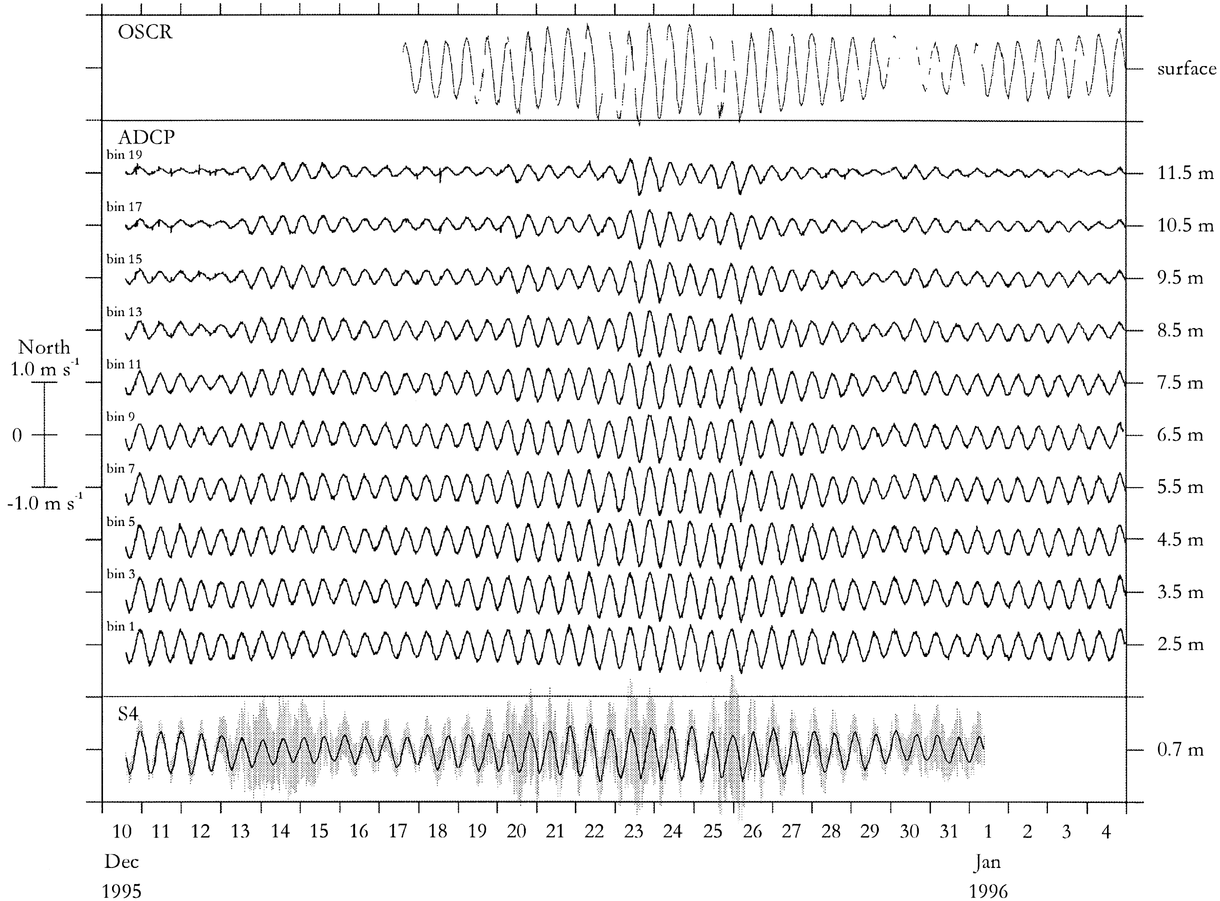

Fig. 3. Comparison of current measurements at N1 (minimum water depth of 12 m). North–south component of tidal currents measured by: H.F. radar (OSCR) at the sea surface; S4DW current meter at the sea bed (1 Hz grey, 20 min average black); POL ADCP (odd numbered bins).

Wave data were obtained from the OSCR H.F. radar, a coastal deployment of X-band radar, nondirectional and directional Waverider buoys, bottom-mounted S4DW current meters and pressure sensors, as well as from beach pressure sensors and SAR images. The remote-sensing systems generally provide wave-number spectra over a finite area rather than the frequency spectra obtained from single-point mooring systems.

Analysis of wave data is by statistical methods (because the nature of real sea waves is an essentially random process). Background on the analysis of pressure data for waves is given in Bishop and Donelan (1987), Lee and Wang (1984). Tucker (1991, 1993) discusses standard analysis of wave data. The details of statistical analysis have been worked out elsewhere, e.g., Long (1980), Krogstad (1991). It is also necessary to attempt to distinguish between various sources of error due to the instrument, calibration or sampling variability. Details of the processing and calibration are given, for example, by Barstow et al. (1985) and Wolf (1997). Further discussion of the intercomparison of other wave measuring systems is treated elsewhere, e.g., Krogstad et al. (1999). Here, we concentrate on the data from the bottom-mounted pressure sensors and S4DW wave-current meters and the surface-following Waverider buoys. The aims are the identification of instrumental characteristics (strengths and weaknesses) and identification of most useful methods of data intercomparison from a practical point of view. The following conclusions were drawn (Wolf, 1996b).

(1) The bottom pressure instruments (PWR and S4DW) provide a robust bottom-mounted system, which should be able to withstand severe weather conditions (even a hurricane as in Taylor and Trageser, 1990). They are particularly good for long-period waves, especially swell and for higher sea states. The disadvantage is the depth limitation due to attenuation of high frequency waves. A bottom-mounted deployment is useful in that it also provides total water levels. The limit of usefulness is about 20 m depth. Since high frequency waves are not recorded this type of instrument is poor for fetch-limited growth. The results are good for swell. The Waverider has a resonant response at the low frequency end of the spectrum, and the bottom pressure instruments may thus be more accurate for frequencies less than 0.1 Hz. Both PWR and S4DW gave very similar results up to about 0.25 Hz. The high frequency pressure response of the different transducers may not be identical and problems of drift may occur.

(2) The S4DW instrument measures the p–u–v triad (pressure and two components of current). The addition of the current data is very valuable; in particular, it enables the calculation of wave direction and spread. It also facilitates the improved computation of wave number and depth-attenuation. However, examination of the mean currents show an asymmetry between deployments (offsets of a few cm s^{-1}), suggesting possible interference from the supporting frame. A larger frame or a different mounting for the S4DW on the POL PMP is needed.

(3) The advantage of the Waveriders is in their simplicity of deployment, which can be carried out from a small boat. The instruments are robust and they have been extensively used for wave measurements, but systematic errors may be being accepted without query. A worrying feature is the low-frequency resonance, which makes them inaccurate for measurement of long period swell. The mooring is the weak point of the system, leading to possible capsize in high sea states, underestimates of highest waves and resonant overestimates of energy at low frequencies. The recommendation for two

elastic strops to be used in the compliant mooring may not be practicable in very shallow water. In shallow water, the lack of measurement of total water depth and ambient current is a limitation, preventing accurate determination of wave number. There is also a possible underestimate of energy at high frequencies, which may again be due to the movement of the buoy on its mooring. It is known that Waverider time series are more symmetrical than the real sea state with less sharp crests since the system is not a perfect wave follower. The buoy can also avoid the higher crests by horizontal displacements in short-crested seas (Barstow et al., 1985). The measurement of wave direction using directional Waveriders is desirable if possible.

(4) The peak wave direction and period are measured satisfactorily by both S4DW and Waverider instruments.

3.4.2.1. Wave climate at Holderness. The wave data from the Holderness Experiment were collected over two successive winters, 1994/1995 and 1995/1996 (Wolf, 1996a, 1999). The results served to highlight the fact that two winters are insufficient to establish the wave climate. There are likely to be longer-term variations in wave height due to possible variations in the wave height in the North Atlantic possibly related to the North Atlantic Oscillation. The differences between the two winters were quite marked (Wolf, 1998a). The first was more typical with prevailing westerly winds and, therefore, the waves were characterised by swell and fetch-limited wave growth. The second winter (more atypical) had a preponderance of winds from offshore (easterlies) with characteristic wind-sea spectra. The mean spectra from the two phases of the Holderness Experiment, divided into onshore and offshore wind cases for stations N1 and N2, are shown in Fig. 4. Onshore (i.e., from east quadrant) winds give higher waves and are seen to be more prevalent in the second winter. Offshore winds give typical bimodal spectra where wind-sea and swell can be separately identified. In the Holderness region

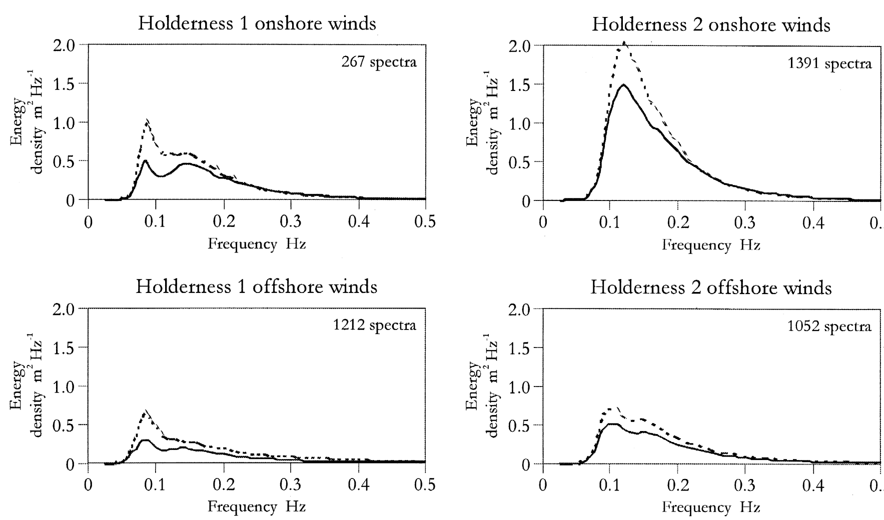

Fig. 4. Mean spectra for the first and second phases of the Holderness Experiment, subdivided into onshore and offshore winds. — site N1, --- site N2.

the tidal range is up to 5 m with current speeds up to 0.7 m s^{-1}. Significant wave heights exceeded 3 m on several occasions. The largest waves observed (5.8 m) were on 2nd January 1995 at N3. Wave-current interaction can be significant (Wolf, 1998b; Wolf and Prandle, 1999).

3.4.3. SPM measurements

Fig. 5 shows a comparison of SPM time series measured by OBS, transmissometers and ABS. Each of these instruments has their own calibration peculiarities. Additionally, all of these calibrations vary as the 'mean' particle size changes. Since the optical devices rely on occlusion of light (transmissometer) or reflection (OBS), the signal is dependent on the surface area of the particle. The recorded signal, therefore, needs to be multiplied by a representative particle 'radius' to indicate concentration, i.e., the apparent concentrations are more sensitive to finer scale particles. The plate-like character of some fines adds additional complication. Conversely, ABS in the range of frequencies used in ABS instruments) increases with particle volume and, hence, this instrument is more sensitive to coarse particles. Thus, the close agreement indicated in Fig. 5 may obscure the sensitivity of the calibrations to variations in particle size spectra, which occur between sea bed and sea surface, over a tidal period, over the spring-neap tidal cycle, seasonally and during storm and wave 'events'. The optical instruments also experience fouling and all of the instruments can be swamped above certain concentrations.

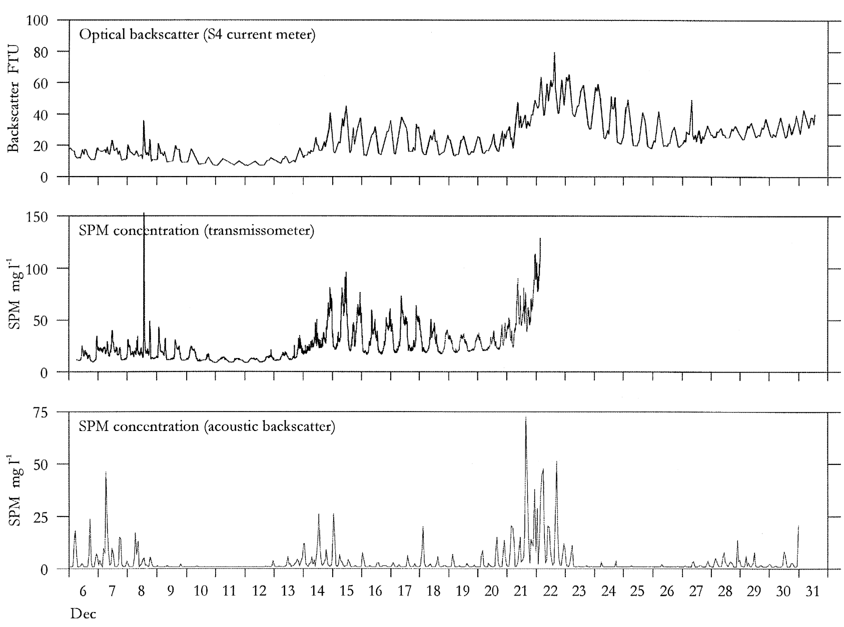

Fig. 5. Comparison of suspended particulate material (SPM) concentrations. Concentrations measured by optical backscatter transmissometer and acoustic backscatter instruments at site S2.

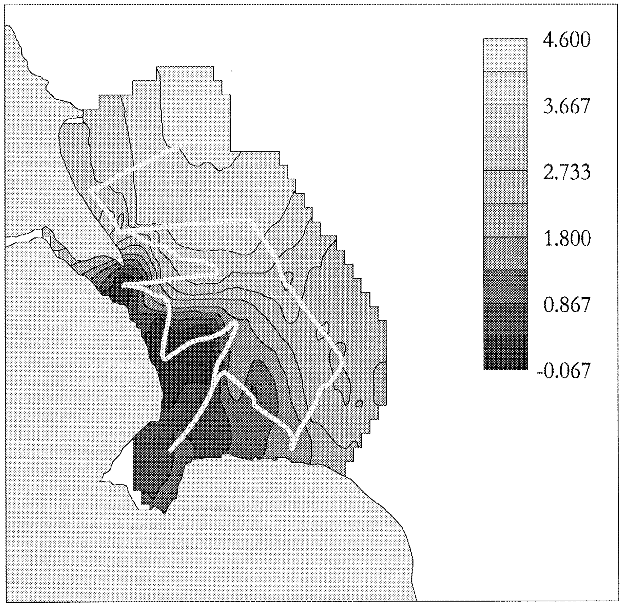

Fig. 6. Surface distributions of SPM, transmittance (uncalibrated units) measured from on-board pumped sampler, 15–16th October 1994.

The SPM distribution in Fig. 6 is based on pumped sample transmissometer measurements on board RRS Challenger (Prandle, 1994b). Fortuitously, the associated 3 days of cruise time coincided with tranquil weather and, hence, the pattern is sensibly synoptic (with tidal modulation). The CASI images in Fig. 7 provide similar distributions under cloud free conditions. The associated flight times are less than 1 h and, hence, these results are more effectively synoptic. However, the calibration of these images is more complex and their availability in cloud free conditions can provide a distorted representation of average conditions.

3.5. Summary

For preoperational model simulations, observational data are required for setup, initialisation, boundary conditions, forcing, assimilation (where employed) and verification. The provision of accurate fine-scale bathymetry is widely recognised as a major deficiency in the setup stage. In simulations where the bathymetry evolves dynamically, there is a need for techniques, such as shown in Fig. 8, to monitor this. Initialisation of SPM simulations involves specification of sea bed deposits ‘available’ for erosion. This is a fundamental difficulty sometimes circumvented by a spin-up simulation based on original sources to redistribute these accordingly. Boundary conditions involve specification of inputs or outputs along the coast, within estuaries and at seaward boundaries of the model. Figs. 6 and 7 can be used to provide indications of the more sensitive sections. Forcing by tides, surges or waves along the open boundaries are generally

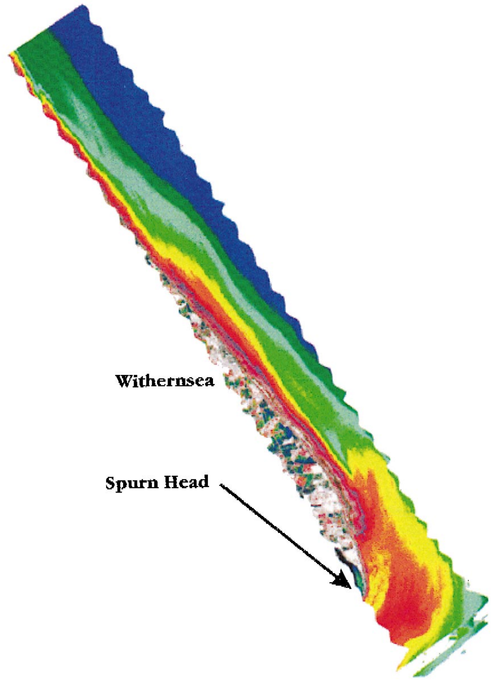

Fig. 7. CASI image of the Holderness coast, 21st September 1995 09:50 LW + 30 mins. (Raw image courtesy of the Environment Agency. Image processed by Susan Shimwell at ARGOSS.).

provided by larger-scale 'preoperational' modelling simulations — but prescription of oceanic inputs can be inadequate. Verification data should include the full range of

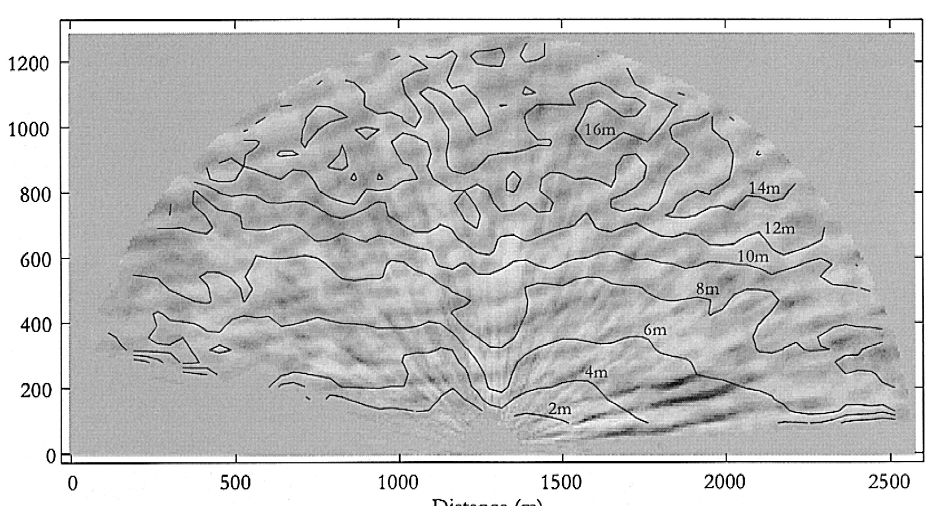

Fig. 8. X-band radar image of near-shore waves. Contours of derived bathymetry are superimposed.

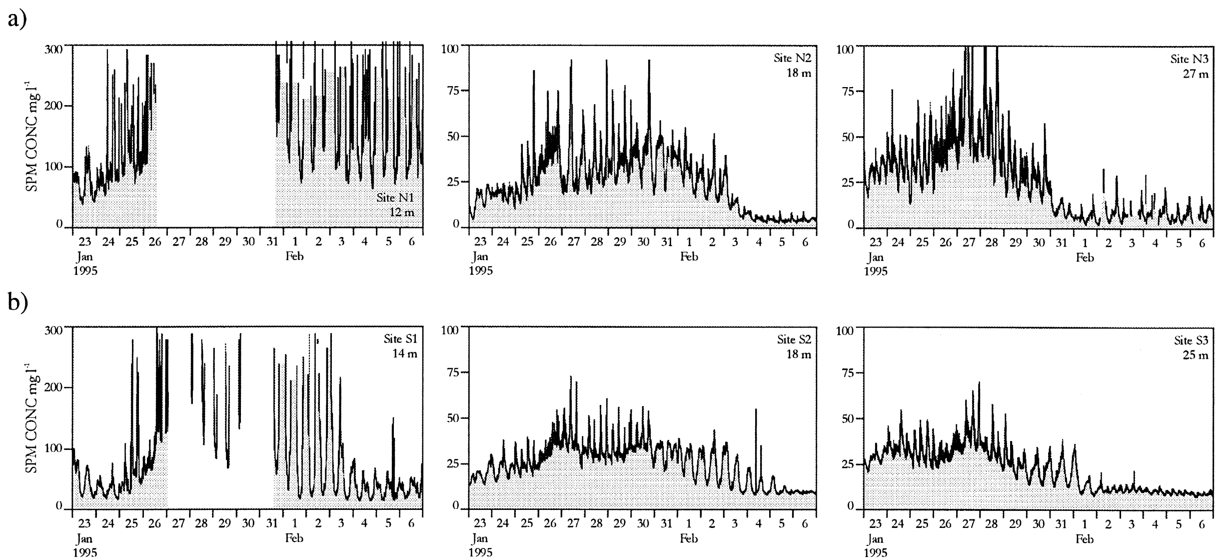

Fig. 9. SPM concentrations during 23rd January–6th February 1995 at sites (a) N1, N2, N3 and (b) S1, S2, S3.

conditions at sufficient strategic/representative locations. Fig. 9 illustrates examples of a range of conditions at three representative cross-shore sites. Distinction can be seen between intervals of well-ordered tidally dominated regimes and wave-dominated events. The importance of tidal advection in regions of strong concentration gradients at sites N1 and N2 differ from the more dispersive regime at station N3. Interpretation of these observations by reference to single-point modelling (Baumert et al., 2000) indicates how the influence of the limited availability of sediments can be deduced.

The various stages are described: planning, implementation, data processing and analyses of a major observational experiment to provide bench-mark data sets for model formulation and development. With a focus on simulation of coastal sediment movement, the choice and adequacy of a range of instrumentation for measuring currents, waves and SPM distributions have been described. The characteristics of remote sensing, radar, in situ and shipborne instrumentation have been illustrated together with their synergistic aspects. The Holderness data set is shown to be well suited for development of the latest coupled tide-surge-wave models. However, it should be noted that bathymetric evolution represents the time integration of the spatial divergence of sediment fluxes. Thus, although present models are often sufficiently accurate to reproduce observed sediment concentrations, this may not be adequate for predicting bathymetric evolution. Clearly, nonlinearities resulting from coupling of wave and tidal motions and from large amplitude perturbations of each will influence net residual fluxes of sediment. Thus, while this data set is adequate for testing short-term forecasts, further observational data sets will be necessary, including detailed synoptic measurements of changes in bathymetry with LIDAR in intertidal regions or from X-band and SAR (Bell, 1999), further offshore will be necessary. Likewise, more detailed airborne imagery coincident with in situ calibration data should add further to the value of future experiments.

4. The Sylt-Rømø Bight data set

4.1. Description of the Sylt-Rømø

The Sylt-Rømø Bight is a semi-enclosed lagoon located in the North Frisian Wadden Sea on the Danish–German border (see Fig. 10). A complete description of ecosystem, hydrodynamic and sediment properties in the Bight is given by Gätje and Reise (1998) and Austen (1996).

The tidal basin has an area of 400 km^2 of which 67% is subtidal (10% above, 57% below -5 m in the deep channels) and 33% is intertidal. The maximum depth is 40.5 m at the inlet. This region consists of predominantly sandy flats with mud flats and salt marsh, each covering < 10 km^2. The tides are semidiurnal and the mean range is 2 m. Water levels of -3.5 m and $+4.0$ m have been recorded during prolonged periods of wind forcing. The low water volume is about 570 m^3 and the intertidal volume is of the same order of magnitude. Maximum depth-averaged currents in the tidal channels are of the order of 0.6 m s^{-1}. Salinity remains close to 30–32 psu in most parts since atmospheric input and fresh water discharge from rivers are less than one thousandth of

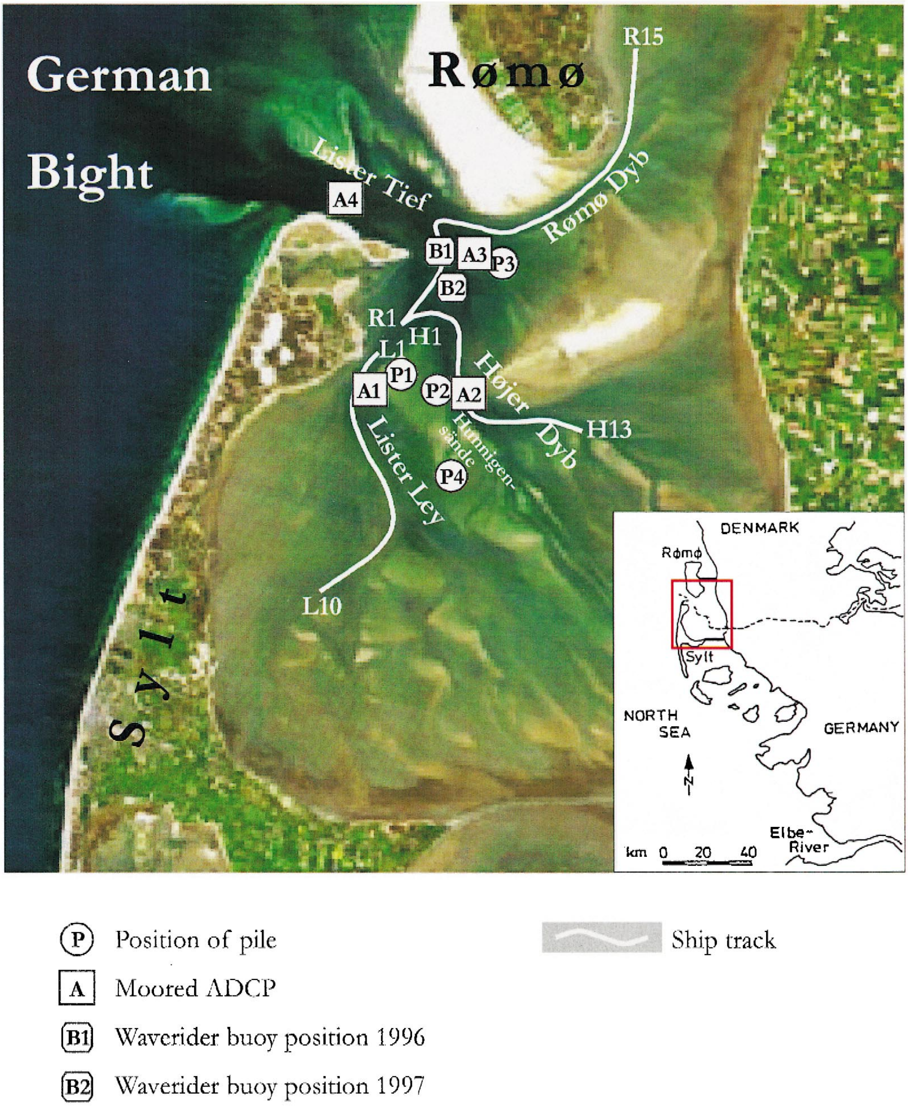

Fig. 10. Landsat TM image of the Sylt-Rømø Bight. Superimposed are locations of instruments and ship survey tracks.

the water exchange with the North Sea. Only in the vicinity of the mouths of the Breda Å and Vida Å does the fresh water input become detectable. The suspended sediment concentrations range from a few mg l^{-1} at the Lister Tief to more than 100 mg l^{-1} towards the coast at high-water and close to the river mouth where the characteristic estuarine turbidity zones exist.

The Bight is drained through three main tidal channels: the Rømø Dyb in the north along the Rømø coast from the mouth of the Breda Å; the Højer Dyb in the middle starting at the mouth of the Vida Å; and the Lister Ley running north–south along the Sylt coast. Two causeways in the north and south connect the islands of Sylt and Rømø with the mainland. The Bight, therefore, exchanges water with the adjacent North Sea exclusively through one narrow tidal gully, the Lister Tief.

4.2. Experimental objectives — site selection

Previous investigations have shown that the Bight has sustained a significant and still unexplained loss of bed material in the regions close to the low water level (Higelke, 1998). Additionally, for fine-grain material (diameter < 63 μm), the net input rate, averaged over the past thirty years, was found to be ten times smaller than in other Wadden Sea back barrier areas (Bayerl et al., 1998). One explanation for the material loss may be the observed increased frequency of heavy storm floods combined with progressive coastal protection measures in the last century: more material is stirred into the water column more often and the usual sediment settling in parallel flat retention areas ceased.

The Bight is also interesting from a modelling perspective: the area has only one boundary with the adjacent North Sea. Pilot studies have shown that the currents inside the Bight are nearly all controlled by the North Sea boundary, which in turn is a function of tidal phase and wind direction and speed. The water depth in the Bight is typically in the range 0–20 m, with variations due to subsidence in dry areas. Therefore, the interaction of currents and waves in very shallow, tidally dominated areas can be studied with coupled models. Bed erosion, resuspension of SPM and advective transports are also expected to depend on: tidal currents in the deeper parts of the gullies, wave action in the shallow areas. Both mechanisms will act in intermediate regions, the extent and location of which migrate with tidal phase and wind conditions.

4.3. Sampling strategies

Based on the hypotheses formulated in Sections 2.1 and 4.2, the quantities required to study suspended sediment dynamics (see Table 1) were recorded both in moderate and in stormy weather conditions over periods of several months. Two sampling strategies were combined: (i) time series recorded at fixed positions from stable platforms (piles, moored ADCPs, wave rider buoy), (ii) ship cruises between these positions to study representativeness of the fixed positions and for spatial interpolation and extrapolation of the time series.

The locations of instruments and cruises are shown in the map (Fig. 10). The fixed instruments recorded data from April–October 1996 and April–May 1997. Cruises were conducted in 1996 only: the first from 22nd April–2nd May, the second from the 10th to 30th of September. Due to instrument failure and loss, not all of the equipment delivered data during these periods. Four periods with significant wind events (maximum wind speed greater than 15 m s^{-1}) were selected from the PROMISE data set. These were quality controlled, documented and disseminated. Table 2 gives an outline of the recording periods, instruments and cruises.

Table 2
Timetable of deployments and cruises in the Sylt-Rømø Bight

Period	Piles				ADCP				Wave-rider	Cruise 1	Cruise 2/ PROMIX
	P1, Lister Ley	P2, Højer Dyb	P3, Rømø Dyb	P4, Hunnigensände	1, Lister Ley	2, Højer Dyb	3, Rømø Dyb	4, Lister Tief	Bight Centre		
1–15th June 1996	x	x	x	x	x				x	April/ May	
10–30th September 1996	x	x	x	x	x	x		x	x		x
10–31th October 1996	x	x	x	x							
1–27th April 1997	x		x		x				x		

4.3.1. Time series

4.3.1.1. Piles. At four locations within the Bight, piles were driven into the bed as carriers for instruments. Three piles (P1–P3) were positioned at the side of each of the main tidal channels. The lateral position was the 2-m-mean low-water line, the optimum location considering the maximum pile length for stability and the need to have constant coverage of instruments when mounted at 1 m above the bed. The longitudinal position was chosen to be close to where cross-sectional measurements had been carried out in previous years in the SWAP project (Fanger et al., 1998). The fourth pile (P4) was positioned in a shallow water area at Hunnigensände.

Equipment on the piles measured the complete set of parameters (except wave direction and settling velocities) and data were regularly transferred via real-time telemetry to a remote land station. SPM concentrations were determined by optical transmission; wave spectra recorded by means of a floater with magnetic readout moving freely along a vertical rod. The wave recorders measured water levels at 2 Hz every 5 min (when triggered by a threshold change of 10 cm in water level between subsequent records). Other data were averaged over 10 min.

4.3.1.2. Moored ADCP systems. Broadband ADCPs were moored at the bed in the channel close to the main current axis, near to positions P1–P3. The vertical position of the transducer heads was some 1 m above the bed to avoid unwated effects of ripples. This was sufficient for most of the time except after strong winds, which caused the development, and movement of larger bedforms.

The ADCPs recorded time series of vertical profiles of current velocities and backscatter intensities with a vertical resolution of 0.25 m averaged over 10 min. The data were stored on magnetic tapes that were regularly exchanged by divers during maintenance work.

4.3.1.3. Directional wave rider buoy. In the central part of the Bight, a directional wave rider buoy registered both the contributions of the North Sea swell entering through the

Lister Tief and the wind seas generated inside the Bight itself. Current and wind conditions, and ship traffic, meant that the position of the buoy had to be altered slightly during the data acquisition phases. The wave rider buoy yielded wave heights and directions for frequencies 0–0.6 Hz. Data were regularly transferred in real-time to a remote land station.

4.3.2. Ship cruises

Ship cruises took place during April/May and August/September 1996, each lasting two weeks. The ship tracked back and forth along the main tidal channels over a length of about 15 km (see Fig. 10), the most upstream position was defined by a safety margin water depth of 3 m. Vertical profiles were taken at 1-km intervals at predefined positions. The drift in the ship's position during data recording was typically about 20 m. One of the three tidal channels was covered per day, with sampling over a full tidal cycle, during which up to six longitudinal sections could be covered.

The current velocity profiles were measured by a narrow-band ADCP, profiles of other hydrographic and SPM parameters were by a vertical profiler recording at 8 Hz with a fall velocity of 0.25 m s^{-1}. Altogether, some 700 vertical profiles were acquired.

4.3.3. Micro turbulence — PROMIX

A joint PROMISE/MICSOS measurement campaign (named PROMIX and funded by the German project on mixing processes in estuaries) was undertaken on 26–27th September 1996 close to the Højer Dyb station P2/A2. The turbulent microstructure was measured every 15 min by a free-falling profiler (from which the total turbulent kinetic energy and its dissipation rate can be derived; see Prandke and Stips, 1996) together with SPM concentration (for process studies to determine the impact of waves, currents and turbulence on SPM dynamics). Vertical profiles of TKE were also derived from shipborne narrow-band ADCP (data recorded at 1 Hz). A broadband ADCP moored nearby provided data on local hydrodynamics.

4.3.4. Data processing and quality assurance

Data processing was organised into the following steps:

1. The raw data was calibrated to physical values for derived parameters, such as salinity from temperature and conductivity.
2. Spectral moments were calculated from the wave recorder data; SPM concentrations were obtained from ADCP backscatter and optical transmission sensors in conjunction with filtered water samples.
3. The data sets were merged together: in time (10 min) for the piles and moored ADCPs, and in depth (0.25 m) for the vertical profiles.

Quality assurance steps were taken at different stages of data generation:

1. Regular recalibrations were made during sampling and sensor maintenance for sensitive devices, such as optical transmissometers or oxygen cells.

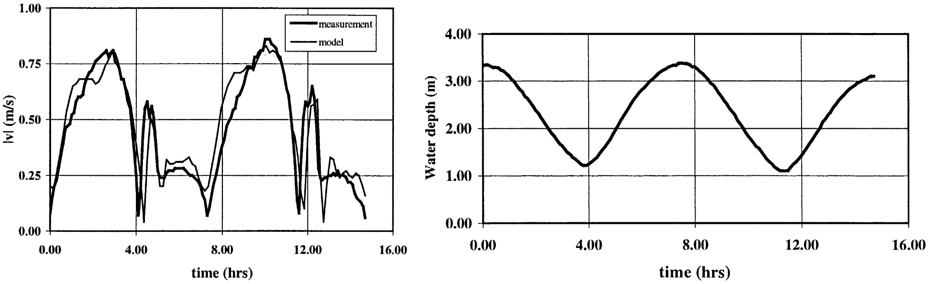

Fig. 11. Left: Observed and modelled tidal dependence of currents at pile P1 (Lister Ley); Right: observed water depth at P1.

2. The accepted extreme values were derived from existing knowledge about the study area before and during data processing through minimum/maximum criteria.

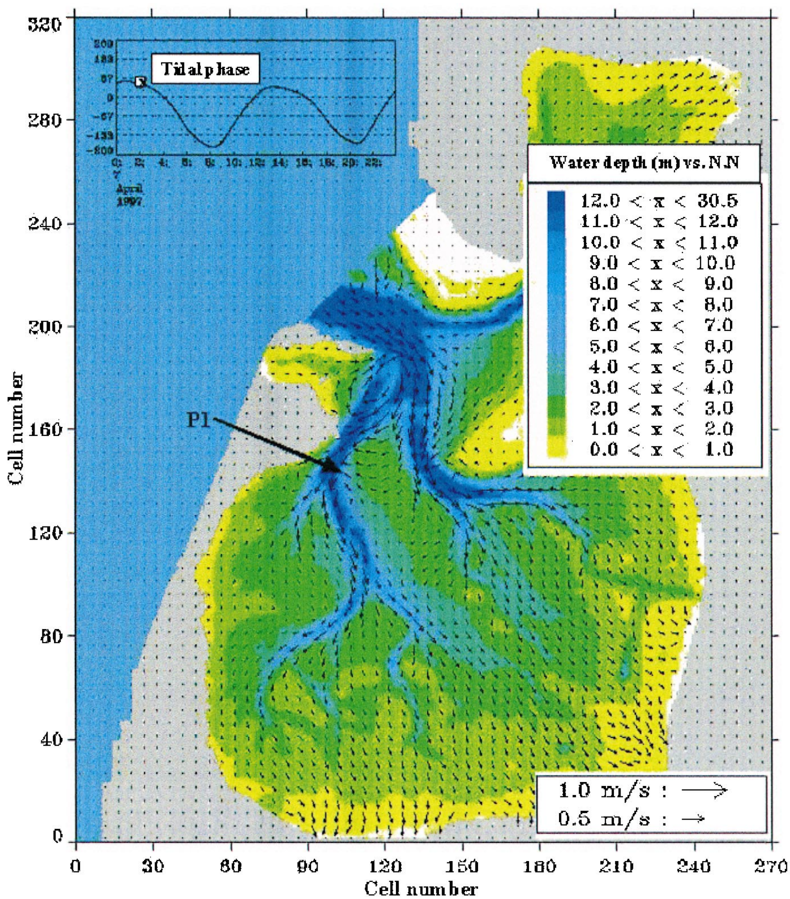

Fig. 12. Eddy at flood tide in the Sylt-Rømø Bight.

3. Data were inspected visually after processing, e.g., qualitative consistency with tidal phase or weather situation.
4. Data were compared with model results (if available) after processing.

Some detailed examples of quality assurance are given below.

4.3.4.1. Current velocities measured at P1 (Lister Ley). The currents were expected to be mainly alternating with the ebb and flood tide and nearly aligned with the main channel axis. This behaviour was observed only for ebb tide; during flood, however, measured current directions rotated away from the channel, indicating that the water was flowing from south east over the tidal flats (Fig. 11). Since no instrument failure was detected, the data were compared to numerical model simulations for comparable wind situations using a depth-averaged version of the TRIM model (Cassuli and Cattani, 1994) on a 100-m grid (Behrens et al., 1997). The model results for this location showed the same structure except for a small offset in current direction. This unexpected behaviour is explained by the overall current pattern in this region (Fig. 12). During the flood, a clockwise eddy develops in the lee spur of the northern Sylt and the currents in the flats around P1 are refracted away from the gully direction. The differences between model and data may be explained by the spatial model resolution.

4.3.4.2. Wave measurements at P3 (Rømø Dyb). The time series of significant wave height computed from the estimated power spectra showed considerable scatter (Fig. 13). Close inspection of the 2-Hz time series exhibited a number of outliers, which were replaced at first by interpolating between the two neighbouring values. Next, the time series with more than one outlier in a row were completely rejected from further

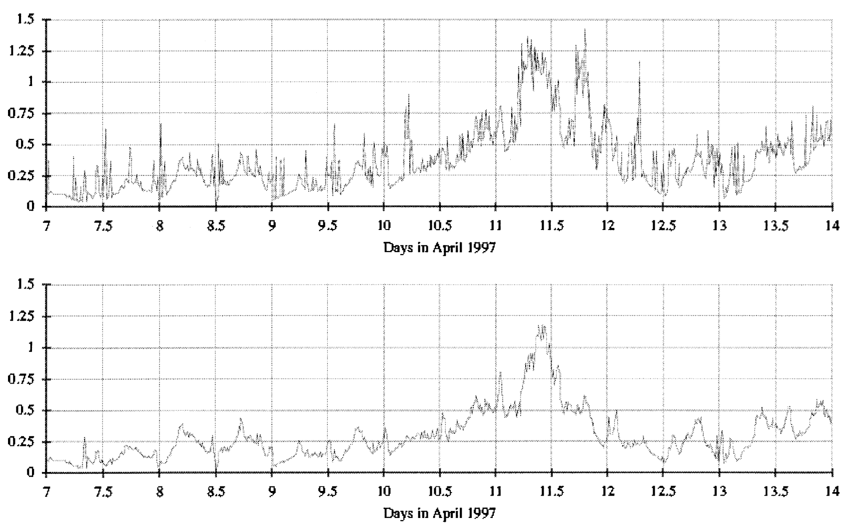

Fig. 13. Wave height computed from time series for the periods 7–14th April 1997 at pile P3 (Rømø Dyb). Upper panel from original time series, lower panel from corrected time series.

processing. The time series with significant wave heights from the corrected spectra then showed smoother behaviour, comparable to that from the wave rider buoy data. This correction procedure was applied to the wave measurements at all stations (P1–P3).

4.3.4.3. SPM concentration from optical transmission. SPM concentrations were derived from optical transmission. The relationship between the optical attenuation coefficients and the SPM concentration was derived from repeated calibration with water samples taken in parallel, which had been pressure filtered. The transmissometers both on the piles and on the vertical profiler were identical and had been used previously in the SWAP project. During SWAP, extensive calibration had been performed in all tidal gullies, over a number of tidal cycles. The full data set could be described well by a single calibration function, which accounted for over 80% of the variance (Fig. 14). During the PROMISE ship cruises, fewer samples were taken, but much higher SPM concentrations were experienced. The calibration function obtained is fully compatible with the SWAP result, which does not appear to be time-dependent and is valid over the entire survey area.

The main obstacle to deriving reliable SPM concentrations from optical transmission at the pile sites is the unpredictable fouling of the optical devices after maintenance. Its effect is clearly visible, but to find an almost unbiased correction for this is very difficult and has as yet not been done. Quality assurance strategy in this case is to provide a description of the status quo, namely: to present the optical attenuation coefficients and calibration curves as separate entities and to warn users not to apply this function to the optical data without scrutiny. In future, all corrections applied will define new levels of processed data that have to be described carefully in the documentation of the data set.

4.3.5. Boundary data

The data set contains boundary data for the:

- bathymetry;
- tidal elevation at the North Sea boundary across the Lister Tief;
- SPM concentrations at a position close to the North Sea boundary;
- local wind fields, depth-averaged currents (Behrens et al., 1997) and waves (Schneggenburger, 1998; Schneggenburger et al., 1998) within the Bight from numerical model calculations.

Technical details on the generation of the boundary data are given in the references and the documentation files of the data set.

4.3.6. Documentation

Data set documentation is provided at four levels: data set, sampling device, probes and parameters, data values. The documentation structure listed in Table 3 corresponds to the format of the CERA-2 Metadata Model (Lautenschlager et al., 1998), the standard structure for climate research in Germany. This type of documentation satisfies the

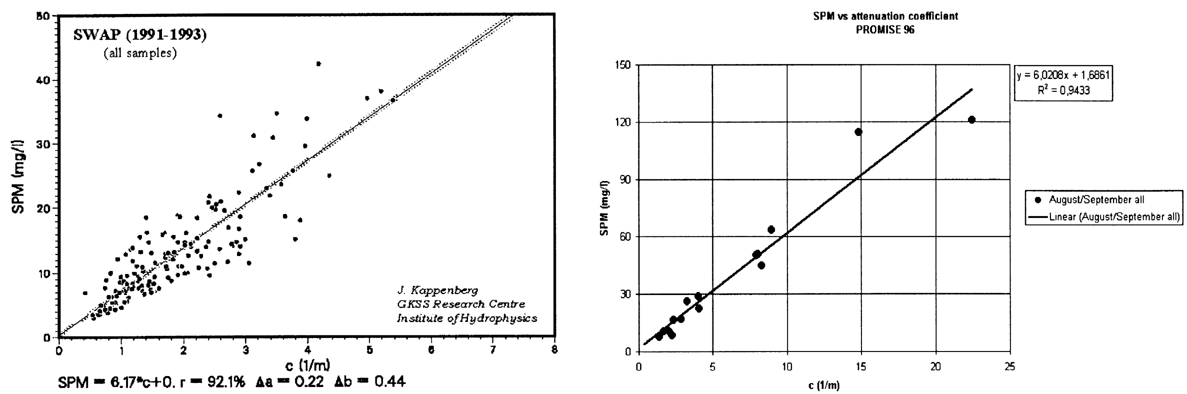

Fig. 14. Calibration curves for optical attenuation in PROMISE and SWAP.

Table 3
List of documentation parameters for the PROMISE/Sylt-Rømø data set

Data set		Sampling device	Probes and parameters	Data values
Entry	project title, objectives, main hypotheses, intended scales and accuracy, sampling strategies, keywords, links to related data sets	type coordinates of position list of probes list of measured and derived parameters	meaning physical units abbreviations probe resolution	horizontal sampling position vertical sampling position sampling time merge interval (space, time)
Publications	comprehensive data report, scientific publication related to the data set	run-charts data processing levels software source code	probe accuracy calibration procedures calibration functions	No. of merged data standard deviation of merged data
Contact	addresses of institutions and persons involved	data file description	quality status during sampling	
Spatial information	coordinate systems used		version of processing level	
Coverage	spatial and temporal range covered by the data, maps, time schedule of devices and gadgets probes		applied quality assurance method quality status of processing level	
Status	information on data set version and data processing applied		achieved accuracy in processing level	
Dissemination	storage devices, formats, access authority			

'Skinny DIF Standard' (NASA, 1998) of the GCMD, and is adapted to match the FGDC metadata standard (FGDC, 1998).

4.3.7. Dissemination

To make the data retrievable by the community, it has been reported to the EDMED catalogue. Additionally, it is included in the Land Ocean Thematic data Search Engine (LOTSE) developed at the GKSS Research Centre to document interdisciplinary research and monitoring projects on German coasts (Gehlsen et al., 1999). The documentation in the LOTSE-project-homepages is compatible with the 'Skinny-DIF Standard'. Links to data sources are included, which can be of any format, ranging from highly advanced systems, such as relational databases to simple ASCII files. The

LOTSE-project-homepages are regularly scanned by most of the Web search engines making them searchable worldwide.

The data set is password-protected but will be made available on request for scientific and administrative purposes. A pilot system guides users through the documentation as well as the data files. The data set, including the pilot system, is also stored on CD ROM, the status of the information has been updated to the end of the PROMISE project. Subsequent updated versions will be available via the Internet.

5. Summary and conclusions

The requirement for comprehensive observational data sets against which to develop numerical models is universally recognised. However, elucidation of what constitutes ‘comprehensive’ is rarely rigorously examined. The PROMISE project provided experience in exchanging such data sets between partners for use with a range of models. These exchanges emphasised the necessity for rationalised protocols and also the opportunity to address this question from a generalised perspective. The account of these experiences reported here provide useful complementarity for subsequent papers (in this volume) on related modelling studies and, hopefully, useful guidelines for future planning of such observational experiments.

The broader interrelationships between observational data sets and modelling are summarised in Fig. 1 of the Introduction to this volume. The data sets must be adequate in quality, i.e., be sufficiently complete and be consistent with the model, and be usable, i.e., well documented and accessible. Completeness requires overlapping in range of parameters, duration and spatial extent; consistency infers compatibility in accuracy, and in both spatial and temporal resolution. Documentation must indicate suitability (especially for ‘third-party’ future users), usability, and must include details of the overall strategy, platforms and sensors as well as actual data and their quality status. Access may involve several media, typically an international data inventory for initial location (permitting Internet search system), an Internet homepage for graphical summaries and a CD ROM for ‘permanent’ raw-data exchange. As much effort needs to be invested to document the data sets and make them readily accessible as in the data processing and quality assurance itself.

Specific experience from two coastal observational experiments are then reviewed, Holderness on the UK east coast and Sylt-Rømø in the German Bight. The value of an initial pilot phase is indicated and the importance of duplication (sensors and systems) in ‘core’ observations together with the choice between usage of satellite, aircraft, radar, ships, buoys, sea bed moorings and piles as platforms is illustrated. Recognition of the synergies between such observations and the importance of synchronisation is emphasised. Resources are always limited and selection of strategic/representative sections and locations for monitoring is important. Observational system sensitivity experiments may be valuable at this stage.

Examples of the peculiar characteristics of both sensors and platforms are reported. Attention to quality assurance is shown to be necessary at four stages, during sampling (biofouling, etc.), during processing (basic checks), via post-processing ‘visual’ inspection and during observation-model intercomparisons, which must allow for calibration errors, etc.

Finally, referring again to Fig. 1 in the Introduction (Prandle, 2000), the usefulness of bench-test data sets will depend critically on: the accuracy and resolution of setup data (bathmetry, surficial sediments, etc.); boundary and surface exchanges from associated marine, atmospheric and terrestrial (modelling) systems; and specification of empirical or nonmeasured parameters where necessary.

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