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Advances in meteorological services to the offshore and shipping industries

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SYNOPSIS

The establishment of the UK Meteorological Office in the 1850s was a direct recognition that weather advice was needed by the shipping industry of the day. In recent years, developments in technology and in our understanding of weather processes have resulted in a dramatic increase in our ability to diagnose and forecast global weather for a wide range of users. This paper gives a general introduction to the operational models now in use in the Meteorological Office to forecast winds and ocean waves, and describes how daily output from these models can be tailored to meet the needs of a wide range of users. Examples given include offshore operations, the routeing of merchant vessels and civil engineering work on the shoreline. In addition to real-time applications, weather data from the oceans have considerable value for planning, design and research purposes. Further advances in marine weather services are envisaged as a result of satellite observations of sea-state, and of increasing computing power enabling more physical realism to be achieved in numerical models.

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THE ORIGINS OF MARINE METEOROLOGICAL SERVICES

The beginnings of formalised weather services for the marine community can be traced to the energy and enthusiasm of individuals in the United States of America and the United Kingdom in the first half of the 19th century. Matthew Maury was principally responsible for the convening of an International Conference on Safety at Sea in Brussels in 1853. Losses at sea at this time were very significant (see Table I) and although parliamentary committees in the UK had investigated the question of safety in 1836, and again in 1843, little action had been taken, largely because of the antipathy of shipowners, who opposed expensive safety measures. Following the Brussels conference, the UK government established a Meteorological Department at the Board of Trade in 1854 and appointed Robert Fitzroy as head. These developments had the strong support of the Hydrographer of the Navy, then Admiral Sir Francis Beaufort, whose scale for assessing wind force had been accepted by the Admiralty for official use in 1839. For the next few years Fitzroy devoted his time to collection of data and their analysis, but the total loss of HMS *Royal Charter*, off Anglesey in October 1859, gave the impetus to the establishment of the first operational storm warning service around the coasts of the UK.[1]

Further significant dates in the development of services to shipping include 1911, when gale warnings were extended to include the eastern North Atlantic in addition to UK coastal waters, and 1924 when weather bulletins for defined sea areas around Britain were first broadcast; the sea areas presently in use were introduced in 1949 and have undergone only minor changes since then.

A detailed history of weather forecasting is out of place here, but clearly the development of telegraphic facilities was vital for the improved collection of observations, and assimilation of data naturally led to the evolution of ideas on the structure of cyclonic storms and their movements. The concept of representing atmospheric behaviour mathematically, and of solving equations of motion to derive a forecast, was formulated by L F Richardson whose ideas developed over the first two decades of this century. The translation of his concept into reality had to wait for more than 30 years until computing facilities had advanced sufficiently to handle the vast amount of calculation which a numerical forecast required. In that time data collection and transmission facilities, as well as the understanding of the behaviour of the atmospheric fluid, had advanced considerably, and so further significant progress could then be made in weather prediction by modelling the atmosphere mathematically.

METEOROLOGY AND THE OFFSHORE INDUSTRY

Just as the weather has always provided a major hazard for shipping, the petrochemical industry also recognised that offshore exploration and production would be very sensitive to weather factors. The increase in activity on the European Continental Shelf through the 1960s and 1970s generated rapid expansion in the provision of specialist weather support, both from national meteorological services and from independent weather consultants. However, it remains an unfortunate fact that, just as in the shipping industry, weather-related accidents continue to occur. The Institut Francais du Petrole,[2] has compiled a database of 850 offshore accidents since 1955, all of which resulted in unplanned work stoppages of at least 24h. A list of accidents worldwide causing the highest number of casualties among crew members shows that, of the 8 most severe (each with 20 casualties or more), the weather was a factor in 6. Perhaps the most notable recent incident involving major loss of life was the capsize of the US drilling-ship '*Seacrest*' in the Gulf of Thailand in early November 1989, during the passage of a typhoon. Closer to home, and fortunately not involving loss of life, was the breakaway of the *Fulmar FSU* during a storm in the North Sea on 24 December 1988.

The detailed significance of the weather in the overall context of each incident can often be resolved only after lengthy investigation, but in general two types of problem are exposed: first, weather action may reveal a weakness in design (perhaps implying inadequate allowance for environmental extremes at the design stage) and, second, the conditions as forecast may not have provided sufficient warning of the actual weather development to enable safety precautions to be taken in good time. The former problem can be tackled by improving both the acquisition and analysis of appropriate weather data and the understanding of the effects of environmental forces on the structure; the latter problem requires fundamental progress in the understanding of atmospheric and oceanic behaviour, primarily by developing improved numerical models.

WEATHER FORECASTING AND THE USE OF ATMOSPHERIC MODELS

The organisation of weather-observing networks in the second half of the 19th century led to the recognition that mid-latitude storms had certain characteristic pressure and wind patterns, and this, in turn, enabled rudimentary warnings of severe conditions to be issued for the benefit of shipping some hours ahead of the event. When observations of winds and temperatures in the upper air became feasible, links between surface weather features and the upper flow patterns were recognised, and it became apparent that the development and movement of the surface features were largely determined by conditions aloft. The features in the upper air varied on a somewhat larger space-scale than did the features at the surface, and the first numerical weather prediction models attempted to represent only these upper air patterns, leaving the human forecaster to infer the appropriate surface weather. As computing power increased, so the models could increase in complexity and resolution to represent more closely the behaviour of the real atmosphere.

All numerical weather prediction models use the laws of motion and thermodynamics applicable to a compressible fluid in a rotating frame of reference. Early models had spatial coverage over only a limited part of the hemisphere and were represented in the vertical by only two or three layers; the current Met Office model specifies conditions at over 23 000 points, at each of 15 levels over the globe. The observed variables (winds, temperatures, humidities) are interpolated from observation points to the model grid points to specify the initial conditions, and then the equations of motion are integrated forward in time to 120h in order to produce the appropriate forecast fields. The effects of moisture, and the transitions between solid, liquid and vapour phases, are included to produce quantitative rainfall forecasts, and the heating and cooling due to radiative transfers between cloud layers and the surface are also represented in a simple way.

Table I: Annual shipping casualties near UK coasts 1852–56

	1852	*1853*	*1854*	*1855*
Ships wrecked or damaged	1015	832	987	1141
Lives lost	920	689	1549	469

These 5-day forecasts usually provide very good prediction of changes in synoptic type and, of particular interest to the offshore industry, help to identify weather windows some days in advance. Naturally, the confidence which can be attached to the detail of predictions at 5 days is normally less than can be associated with a 2-day forecast (see discussion of forecast verification in the section on applications of model output), but comparison of results with those from other models often helps to establish a confidence level. Global models are also operated by the US Weather Bureau and by the European Centre for Medium-Range Forecasts; these models all use slightly different formulations of the atmospheric dynamics, and may start from slightly different initial conditions especially in areas of sparse data. Thus, when the models' evolution is in broad agreement, it is possible for relatively high confidence to be attached to the predictions; when the models diverge, confidence in any one is correspondingly reduced.

To cover the shorter end of the predictive time-scale (ie 0–48h), where better spatial resolution and more precise timing of events are required, a limited-area model is operated which takes its boundary conditions from the global model. The Met Office limited-area model has a spatial resolution of about 75 km around the UK, and is run out to 36 or 48h three times each day. The area covered extends from 80W to 40E and from 30N to 80N (Fig 1), so fast-moving depressions likely to be of significance to the weather over the UK and surrounding waters over the coming 36h can normally be handled satisfactorily.

The role of the human forecaster in the numerical prediction era is constantly evolving as models improve and new observational methods become available. At present, the experienced human forecaster is able to add significant value to the numerical products in the short term (ie 0–24h); this is largely due to limitations of present models to handle the detail of cloud cover, upon which so many other variables depend, and also those variables which are closely dependent on geography/topography, where the model resolution is still inadequate to represent small-scale effects. To assist in the monitoring of developments, the forecaster now has such weapons as weather radar and satellite images and measurements to augment conventional surface observations. Monitoring of changes on an hour-by-hour basis can often help the experienced forecaster to identify or anticipate departures from model evolution, and enable advice or warnings to be issued to customers as necessary.

Moving out to the medium- and longer-terms (ie over 24h ahead), weather changes are usually dictated by the larger-scale dynamical evolution of the atmosphere, and here models are generally better than the human brain in working through the complexity of atmospheric dynamics to produce prognoses of consistent quality. Even on this timescale, however, models display certain characteristics (eg tendency for faster westerly progression when the real atmosphere may be moving towards a meridional flow pattern), which the forecaster can perhaps identify at an early stage and so tune his advice accordingly.

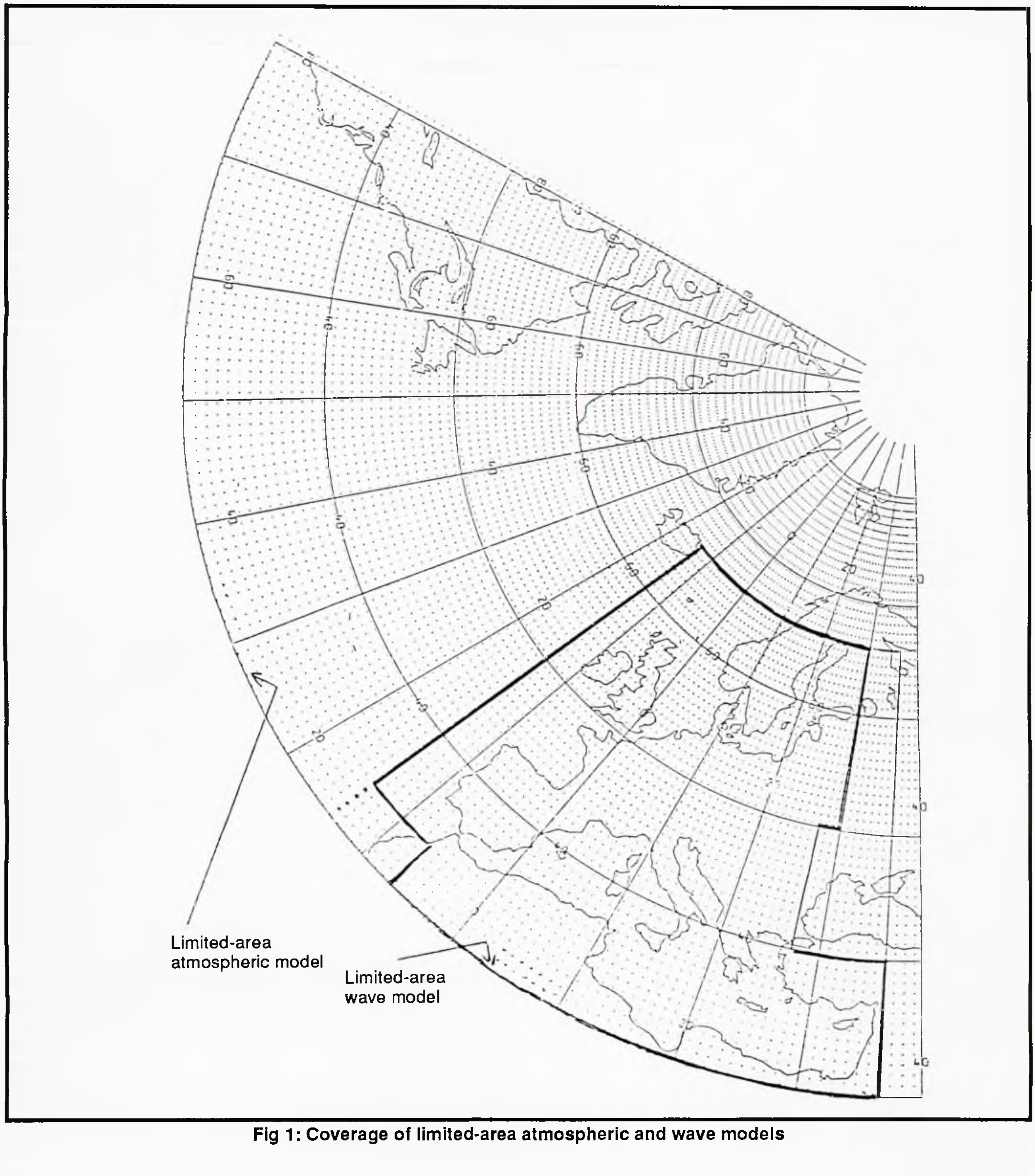

Fig 1: Coverage of limited-area atmospheric and wave models

DEVELOPMENTS IN WAVE MODELLING

The growth of the offshore industry in the North Sea in the early 1970s provided a great stimulus for progress in sea-state prediction in the UK. Traditionally, wave forecasting was carried out using empirically-derived relationships between forecast wind speed, duration and fetch but these were obviously difficult to apply in fast-moving meteorological situations with rapidly-varying wind speeds and directions. Incorporation of swell components propagated from distant locations was also difficult. Numerical models for sea-state forecasting were developed in the early 1970s in several countries and the first Met Office model was brought into operational use in 1976, covering the Northern Oceans to around 20N. A higher-resolution model, nested within and taking its boundary conditions from the hemispheric model, was introduced in 1977 to cover the European continental shelf. This dual-model philosophy, of operating both a larger-scale model, within which swell can be generated and propagated, and a limited-area model of high resolution, continues to the present time.[3]

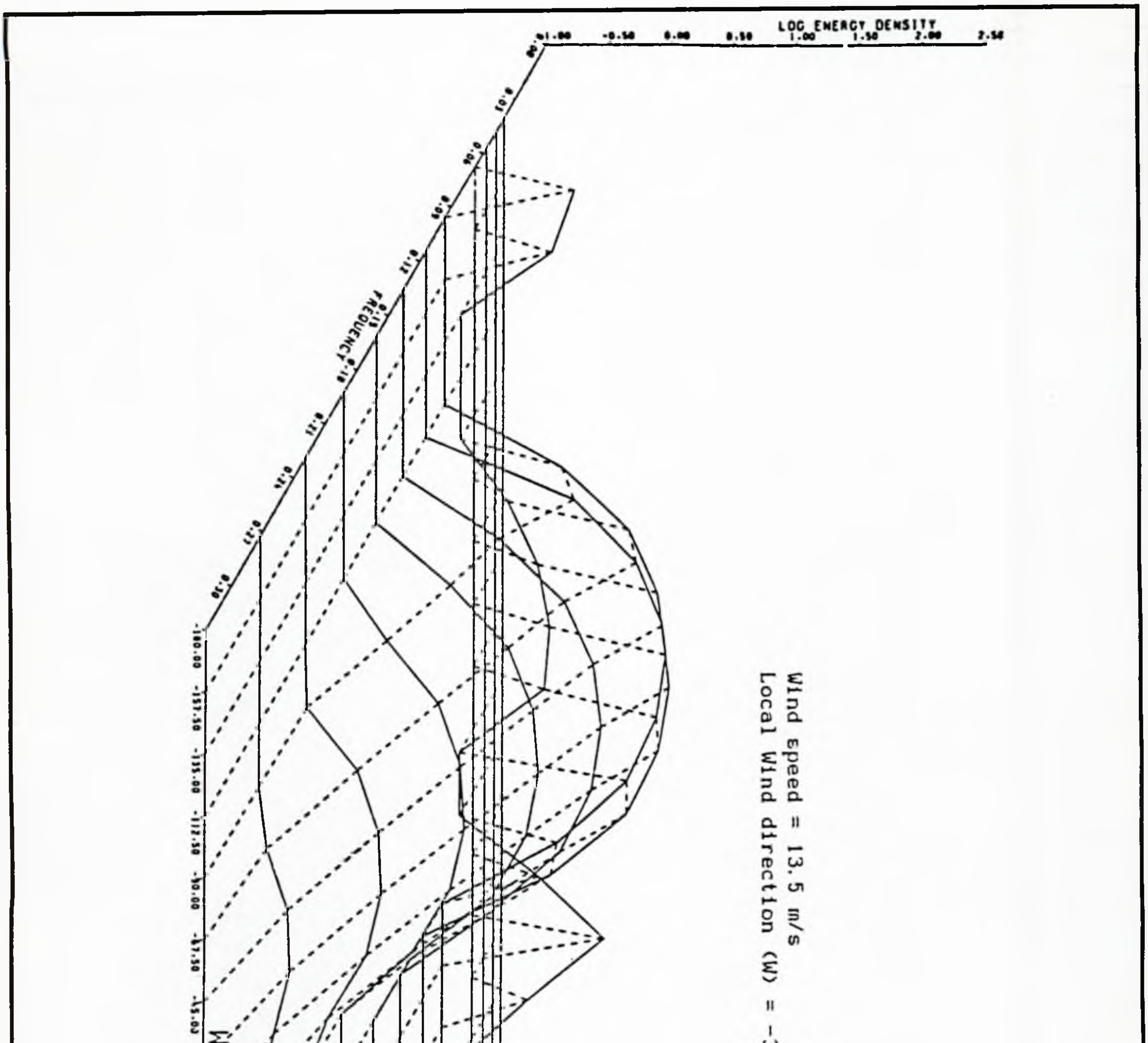

Fig 2: Example of a two-dimensional wave spectrum (16 directions; 13 frequencies)

Table II: Details of Met Office operational wave models from 1976

Period in operation	*Area covered*	*Spatial resolution*	*Spectral resolution*	*Archived information*	
				Type	*Time interval*
			Dirs x freqs		
Aug 1976–Oct 1979	Northern oceans to 20°N	300 km on polar stereog proj	12 x 6	two-dim spectrum	12h
July 1977–Oct 1979	*Europ contin shelf to 20°W	50 km on PS proj	12 x 6	two-dim spectrum	12h
Oct 1979–Sept 1982	Both models as above		12 x 11	two–dim spectrum	12h
Sept 1982–June 1986	Northern oceans to 20°N	150 km on PS proj	16 x 14	integrated components	12h
Sept 1982–June 1986	*Europ contin shelf	25 km on PS proj	16 x 14	two-dim spectrum	6h after Oct 1985
Sept 1982–June 1986	Mediterranean Sea	50 km on PS proj	16 x 14	integrated components	12h
July 1986 to date	Global (80°N to 75°S)	1.5° lat x 1.875° long (166 x 133 km)	16 x 13	one-dim spectrum	6h after June 1988
July 1986 to date	*Europ waters to 14°W (incl Med and Baltic Seas)	0.25° lat x 0.4° long (28 x 28 km)	16 x 13	one-dim spectrum	3h after June 1988

Notes:
1. All model archives include surface wind speeds and directions.
2. From October 1986, hindcast wind speeds and directions have been achieved every hour over the European grid, and every 2h over the global grid.
3. Where spectra are available, so too are integrated components.
4. Models marked * incorporate shallow water processes.
5. Some short gaps occur in the archive.

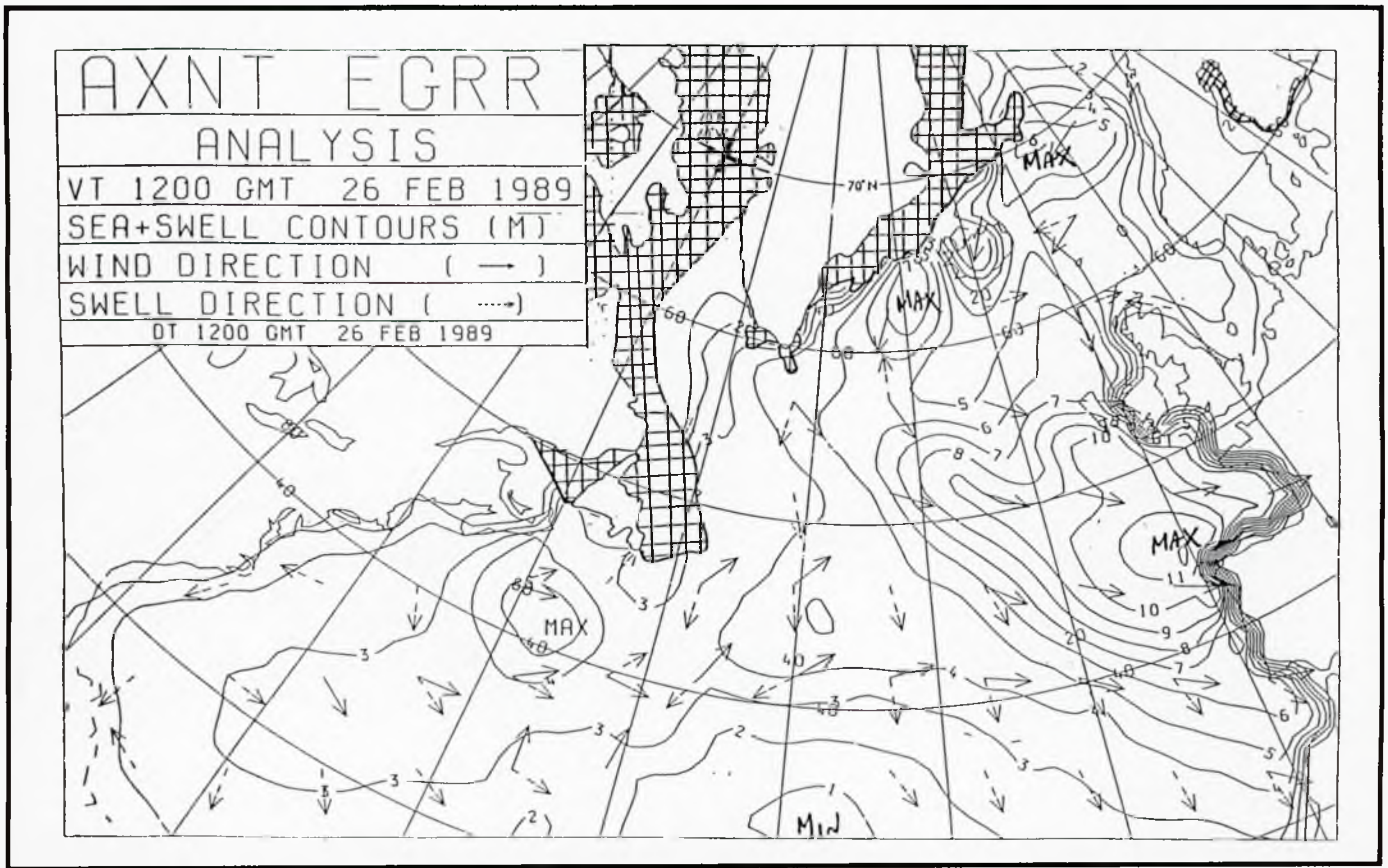

Fig 3: Example of global wave model analysis of North Atlantic wave field; resultant sig wave heights with wind and swell directions

Continuing research gave rise to further improvements in the representation of the physics of wave generation and decay, and these were introduced in 1979. The arrival of the CDC Cyber 205 supercomputer at Bracknell in 1981 provided a further opportunity for upgrading and 1982 saw a doubling of spatial resolution in both models, together with an increase in the number of spectral components to represent the sea-state. Most recently, in 1986, the model was reformulated onto a latitude/longitude grid and coverage was extended to include the tropics and southern oceans. Further improvements in the

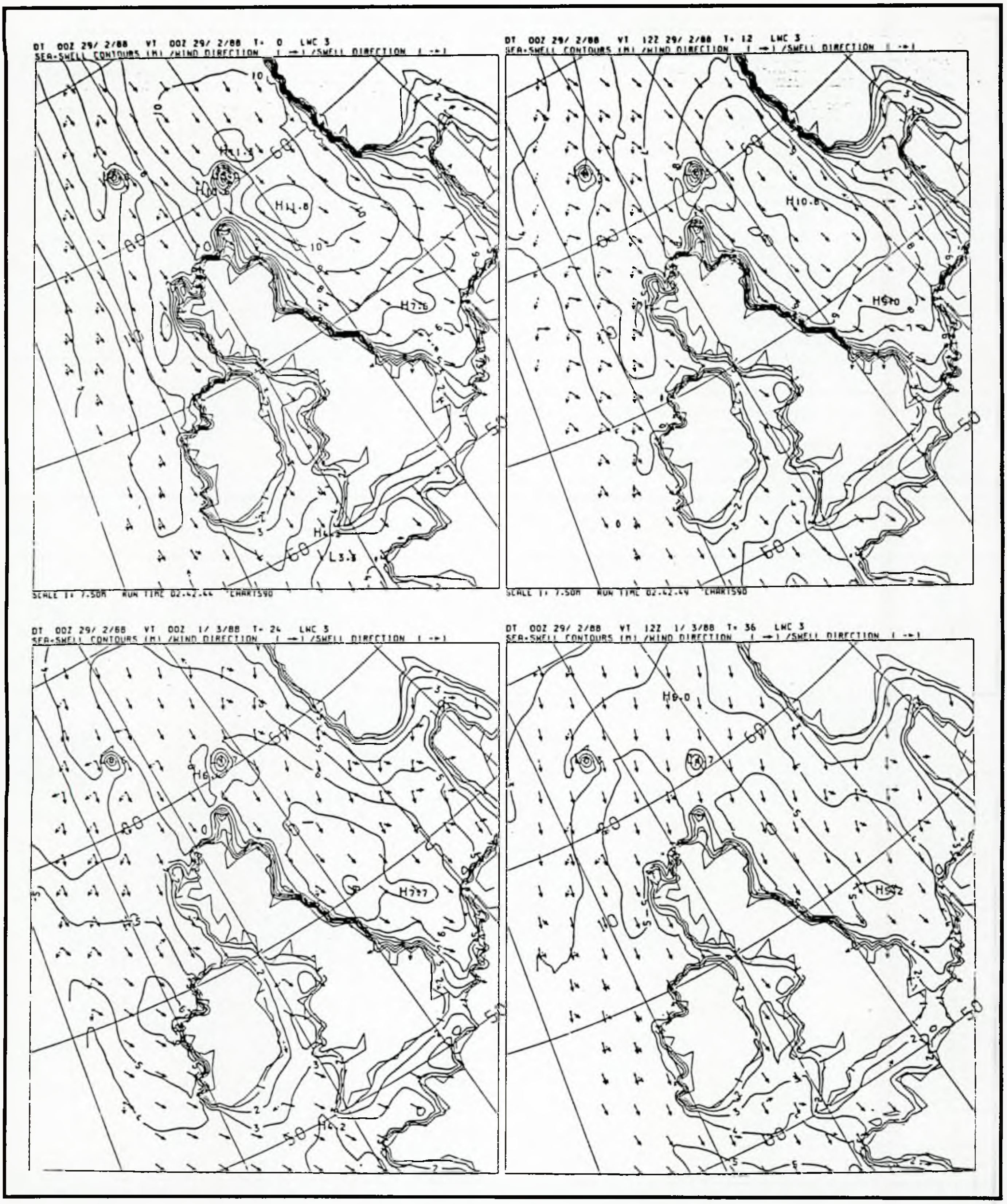

Fig 4: Example of limited-area wave model analysis and forecast fields; resultant sig wave heights with wind and swell directions; analysis and forecasts at 12h intervals

model physics were introduced in 1987. Table II summarises the characteristics of the various models.

The basis of all these models has been to represent the sea-state at each grid point as an energy spectrum; the energy is a function of wave frequency, and also of wave direction, and so we speak of a two-dimensional energy spectrum. The models seek to quantify the changes in the energy spectrum (Fig 2). Energy is injected into the wave system by the action of the

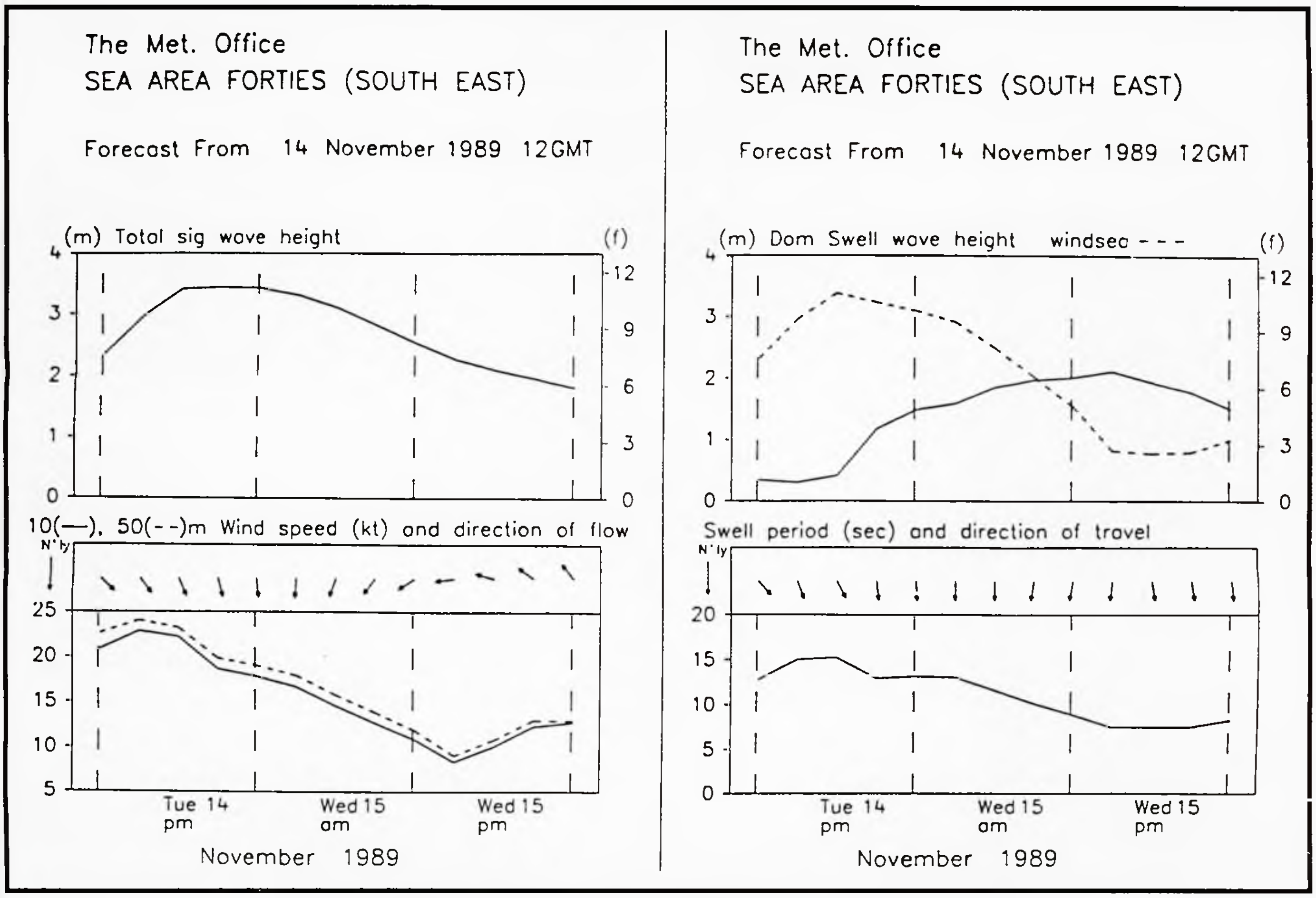

Fig 5: Example of wind/wave/swell meteograms for offshore operations

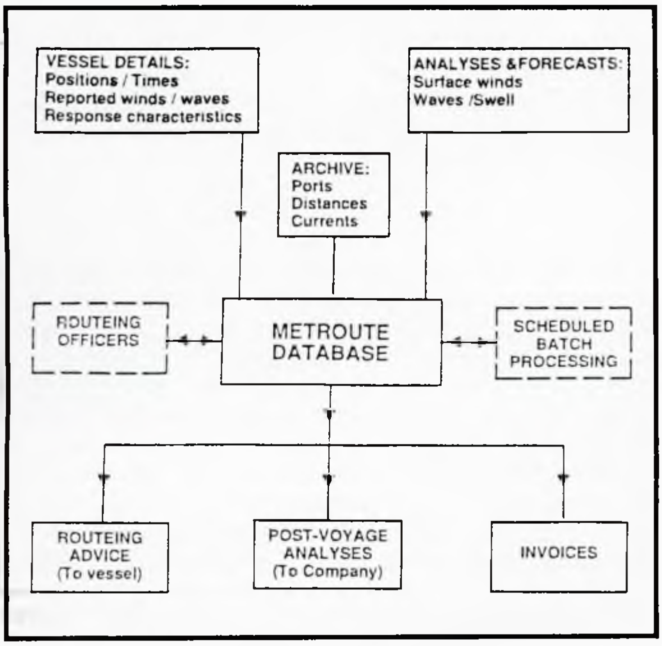

Fig 6: The Metroute database

local wind; this energy is propagated across the ocean at an appropriate group speed, and is dissipated by white-capping when waves exceed a critical size. All these processes are functions of wave frequency and there is internal redistribution of energy between frequencies. In shallow waters less than a critical depth (this depth again dependent on wave frequency), two additional processes are important: the diffraction of a wavetrain, which changes the direction of propagation, and friction with the sea bottom which leads to energy loss. At coasts, energy is also lost in the surf zone. All these complex processes must be built into the model if it is to be at all realistic in representing the observed behaviour of ocean waves.

Because of limitations on computing power, a fixed number of discrete frequencies must be defined to represent the range of observed wave frequencies, and the number of directional sectors must also be limited. Even so, the amount of information generated by each run of the model is very large: ie two-dimensional spectra at each grid point for all forecast times out to 120h from the datum time. It would clearly be difficult for most users to handle all this information in real time. Thus, for most practical purposes, the spectral form of the output is condensed into the traditional division of sea-state between 'wind-sea' and 'swell'. The wind-sea component can be assumed to arise from the action of the local wind, and is broadly aligned with the local wind direction, whereas the swell (generally of lower frequency) is the result of wind action over remote areas and is propagated into the area. Various rather complex rules have been devised to allow the full spectrum to be integrated to produce components which approximate to the wind-sea and swell which an experienced marine observer might report.

At this stage, it is worth emphasising the point that reports of sea-state received from voluntary observing vessels and offshore installations are not injected into the model analysis.

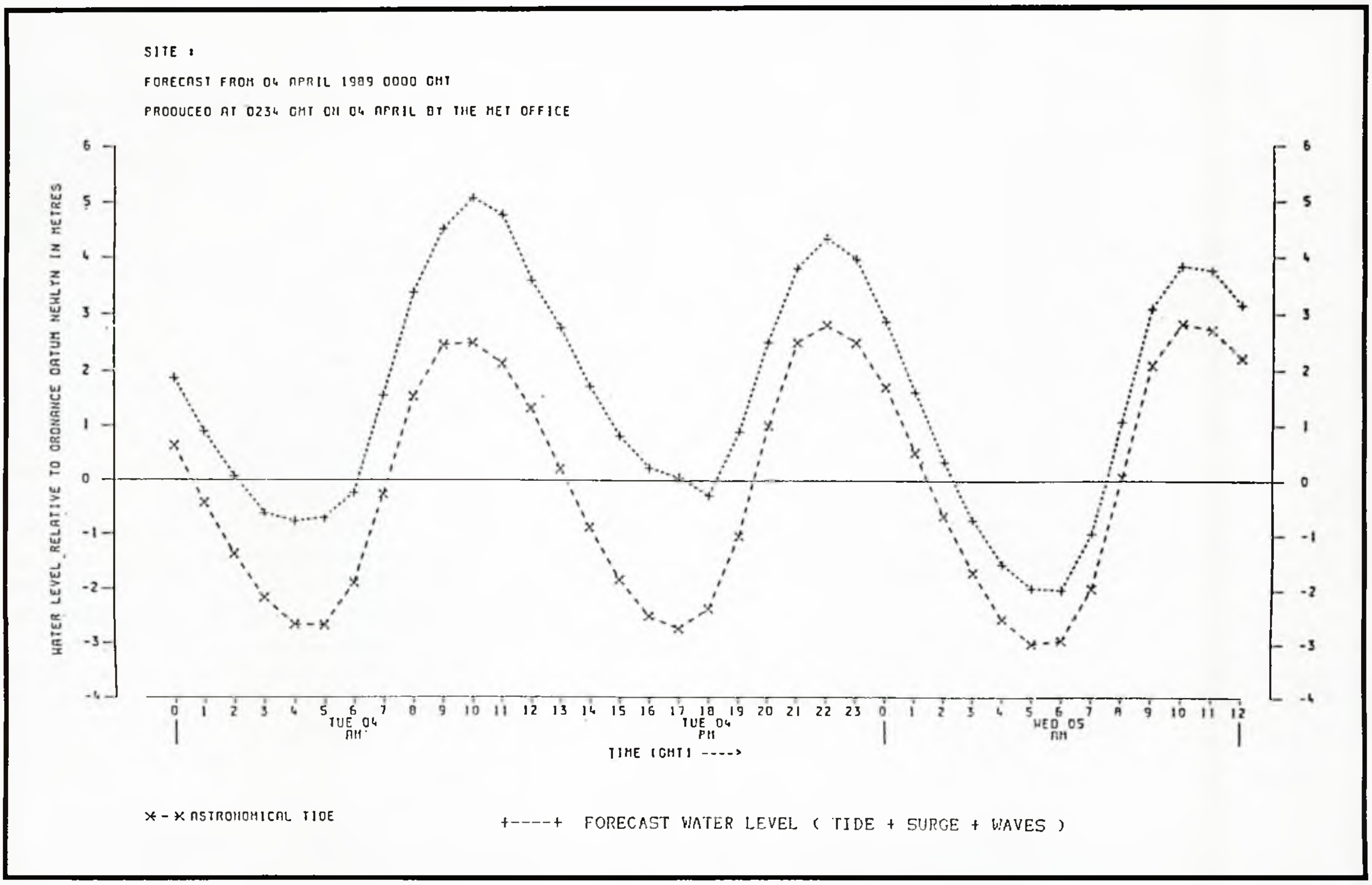

Fig 7: Example of water-level forecast for coastal engineering

The number of these reports, especially in the tropics and southern oceans, is insufficient to define the wave field, and it has been found by experiment that the inclusion of these wave reports does not improve the quality of the forecast fields. Thus, at present, the model relies solely on the analysed wind field to generate the waves, and it is worth bearing this fact in mind when we look later at the verification of analyses and forecasts.

Regarding the dissemination of the wave model products, the Met Office has responsibility to broadcast the analysis and T+24, T+48h forecasts of waves/swell by facsimile every 12h for the North Atlantic (see Fig 3). Digital information is available via the Global Telecommunication System to other national meteorological services and specialist users; heights, periods and directions for wind wave, swell wave and resultant wave are available on rather coarser grids (2.5 deg for global, 1.25 deg for European) than the models use, because of limitations on transmission time. Model output is also transformed into specialist formats to meet the needs of individual customers or groups.

APPLICATIONS OF MODEL OUTPUT

Forecasting for offshore operations

To achieve his aim of providing the best possible guidance of conditions expected offshore, the forecaster must use his skill and experience in a developing situation to recognise changes which may have significant consequences later. His prime guides are the output from the numerical models (eg Fig 4 showing forecast wave heights over the North Sea at 12h intervals and Fig 5 indicating changes at a specific site over a 36h period), but these can only approximate the true evolution of the atmosphere and ocean; he will, therefore, attempt to refine the model's guidance, adding detail where possible. To illustrate the range of issues to be considered when preparing a forecast, the most significant elements – wind, waves, swell – will be considered in turn.

Wind

The most difficult problem arises from small-scale developments in the pressure field which may not be well enough defined by available observations to be accepted by the model analysis on the current spatial resolution. These developments may lead to winds either stronger than the model predicted (especially near sharp pressure troughs) or weaker (perhaps due to the formation of a new low pressure area to the lee of Scottish or Norwegian mountains). In either event, the wind direction may become significantly different from that predicted by the model, and for some operations a directional shift of less than 30 deg may be crucial. Careful analysis of pressure tendencies, on an hourly basis, can often give early clues to such developments.

Waves

If adjustment to the model predicted winds has been necessary, then of course forecast wave fields will also require adjustment to account for changed wind speed, fetch and duration. The direction and magnitude of tidal flow may also be important, since the tide can serve to amplify or attenuate

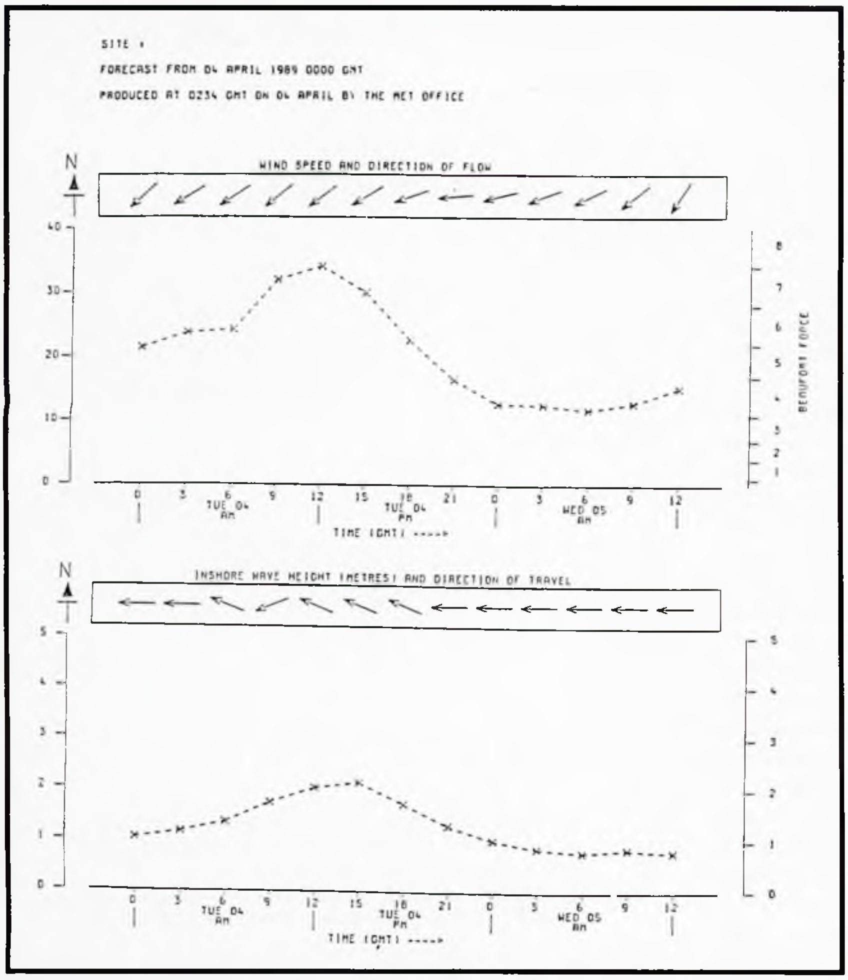

Fig 8: Example of wind/inshore wave meteogram for coastal engineering

waves, depending on relative directions. The effects of bottom topography, although taken into account by the limited-area wave model, also need special consideration in locations where variations in depth occur over short distances.

Swell

In general, the model tends to underestimate long-period swell over the open ocean, but provides good guidance in shallower waters. In the central North Sea, swells either from the north or from the southeast may be especially troublesome for certain installations; a modest change in swell period can be crucial in generating unacceptable heave. Thus the forecaster will wish to make his own assessment of any refraction due to shallower waters and also of reduction in swell due to any opposing local winds.

Weather routeing of merchant vessels

In the days of sail, the choice of a route by a vessel could be critical in determining whether the voyage would be speedy, slow or end in disaster, and so early mariners quickly learned some rudimentary climatology for route-planning purposes. In the 1840s and 1850s, Maury's compilations of observations into advisory wind and current charts were a great step forward. However, reliance on climatology meant that individual voyages could still meet with disaster when conditions departed from the norm, and so further significant advance had to wait until weather forecasting became sufficiently accurate for reasonable guidance to be available several days ahead. The Met Office began a ship-routeing service (Metroute) in 1968, and as forecasting models improved in accuracy and length of forecast period, so the benefits of ship-routeing became clearer. Significant further developments have occurred over the last few years as a consequence of wind and wave forecast guidance now being available on a global scale from numerical models.

Computer technology now allows us to devise a system which brings together the forecast products and the vessel details in a specially designed database. This database is accessed both by the routeing officers, via on-screen dialogues, and also by standard programs, some of which are run to a time schedule linked to the availability of updated forecast products (Fig 6). The dialogues provide rapid interaction between the database and the routeing officers, allowing them to handle many more voyages than was the case with a paper-based logging system. Information on new voyages, and also updated reports from ships already on passage, can be inserted into the database at any time, and routeing officers can display information either in tabular or chart form for easy assessment and cross-checking.

Most voyages require an advised route which will minimise time on passage and so minimise fuel and other operating costs. However, certain special requirements can be stipulated; for example, tows may demand that wind/wave conditions remain below a specified threshold over the whole voyage, and this consideration is more important than achieving a minimum passage time.

The calculations to produce an optimum route solution, using vessel performance characteristics and forecast weather, are rather time consuming to be run on an 'ad hoc' basis, and so are usually batched to be run overnight. Thus, new predicted positions for vessels on passage are available to routeing officers at the start of each working day, based upon the output from the midnight (OO UTC) run of the forecast models. The routeing officers are all master mariners and so they can apply their professional judgment to the predictions produced objectively before passing guidance to the vessel. Since the Metroute team is located within the Central Forecasting Office at Bracknell, the routers also have access to experienced meteorologists for further forecasting guidance. The philosophy of the 'man-machine mix' (ie nautical skills and meteorological experience allied to numerical predictions from soundly based atmospheric and sea-state models) is one which we are keen to preserve, since both components are vital to the credibility and consistency of the advice provided.

Post-voyage analyses are important components of the service offered; the owner or charterer may wish to have an independent assessment of the vessel's performance over the voyage, taking into account the weather experienced; and of course, comparison of time taken along the advised route with that along a least-distance alternative route provides an immediate indicator of the time benefit provided by the routeing service. Such comparisons for a whole fleet over periods of a month or quarter can show that the cost of the routeing service is quickly recouped in operational savings.

The final role of the database is to ease the handling of the mundane (but important) administrative details, such as the raising of invoices. Since all relevant details have been added to the database at an earlier stage, the generation of these final products in a clear and accurate fashion requires only a little further effort.

Water-level forecasts for coastal engineering

As a direct result of the catastrophic coastal floods around the southern North Sea on 31 January 1953, a Storm Tide Warning Service (STWS) was established at the Meteorological Office funded by the Ministry of Agriculture. Research at the Institute of Oceanographic Sciences, Bidston (now Proudman Oceanographic Laboratory) and in the Met Office led to the development of empirical regression methods for forecasting storm surges likely to affect the east coast of the UK. A network of remote-reading sea-level gauges was established along the east coast, and the data from these, plus some variables representative of the expected pressure and wind fields over the North Sea, were used as input to these empirical predictors. With advances in computing power and numerical modelling techniques, it later became feasible for the storm surge process to be modelled more realistically, using a 35 km grid covering much of the continental shelf, and using the output from the Met Office atmospheric model to provide the meteorological forcing for the POL surge model.[4,5] The output from the surge model, supplemented by astronomical tidal predictions, provides the primary guidance for the STWS. In critical situations, the well established regression techniques using water level observations as input, can often provide further useful guidance. Warnings from STWS pass to appropriate authorities for local action such as evacuations or raising of the Thames barrier.

Given the availability of these tidal and surge predictions in real-time, the possibility of making use of this information for site specific applications on the shoreline have been explored. Many engineering activities (eg construction of harbours, outfalls, sea defences) are sensitive to the water level, and so the planning of manpower and plant deployment on a day-to-day basis would be significantly improved if accurate forecasts of water level could be supplied. Naturally, published tide tables provide a first-order prediction of water levels, but surge and wave run-up effects can advance or retard the water level to a significant degree, and for major projects an hour's work gained or lost due to an unexpected high or low tide can be economically important.

The Met Office already supplies customised forecasts for many land-based and offshore activities, but the specific problems of contractors working on the shoreline seemed to deserve some additional attention. At the outset it was decided that, in order to keep the cost of the service as low as possible, the products would be completely automated by being directly derived from the model output without forecaster intervention. Also, the products would need to be presented in a form which could be readily interpreted by contractors' personnel on site.

The tidal and surge of components for an individual site were obtainable fairly readily from information to hand, but the effects of water level set-up by inshore waves required some additional processing. From the output of the Met Office continental shelf wave model, the two-dimensional wave spectrum was extracted at the nearest offshore model grid point, and then transformed to produce an equivalent spectrum near the shoreline. This transform was achieved using a reverse-ray refraction model developed by Hydraulics Research and was specific to each site, being dependent on coastline shape, local bottom topography and the nature of the sea bed. Different transfer functions were applied for different still water levels, as defined by the sum of tidal and surge predictions. The inshore significant wave height, derived from the near-shore energy spectrum, was then converted to a run-up height to be added to the tide plus surge level. This latter conversion was a function of wave steepness, the type of seawall or beach, and, again, the still water level. The resultant water level supplied was the vertical height which would be exceeded by x% of waves, where x could be specified by the customer, depending on the nature of the work being undertaken. After some experiments, an x value of 30 was found to provide useful guidance on 'typical' water levels.

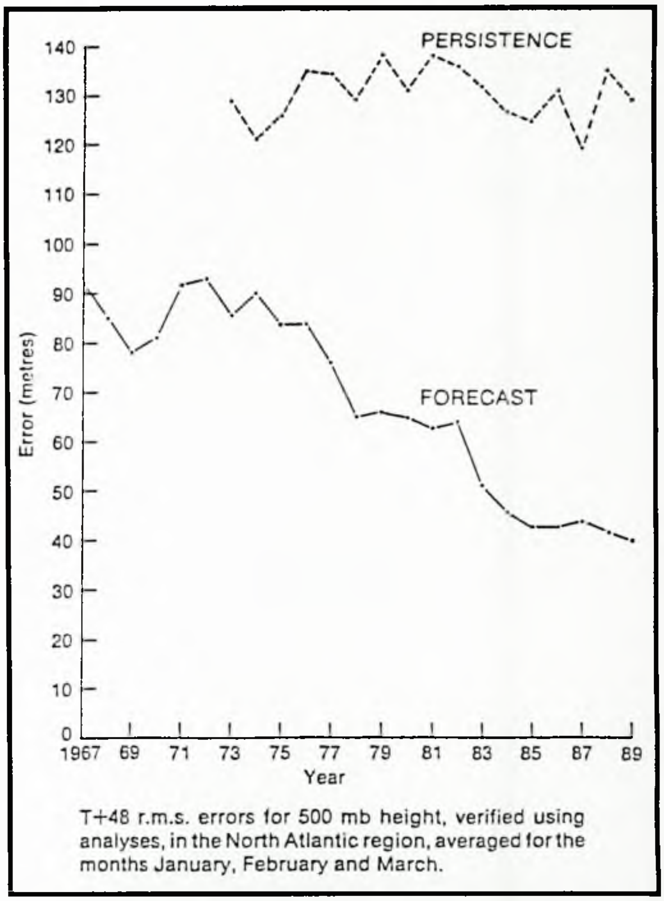

Fig 9: Trend in forecast errors since 1960s

The service was operated in trial mode by two customers over winter 1988/89; output from the OO UTC run of the models was transmitted by facsimile to users at around 0600 UTC, so as to be available for early morning planning decisions. The output included water level forecasts out to T+36h (Fig 7) plus other material on inshore wave heights, wind speeds and directions (Fig 8). Given the relative coarseness of the model representations and the limitations in the treatment of some of the physical processes concerned, the overall results were encouraging and served to demonstrate the feasibility of providing a service of this kind based on model output. At the time of writing, no final decisions have been made regarding the promotion of this service. However, given current concerns regarding possible sea level rises over the next 50 years, it seems likely that coastal protection works will continue to be required on a fairly large scale around some UK coasts. Under these circumstances, a water level forecasting service of the kind described here could make a substantial contribution to the efficiency of contractors' operations.

Table III: Verification results from global and limited-area models

Mean error/RMS error				
Area: Northeast Atlantic – from global model				
	Winds (m/sec)		*Waves (m)*	
	1986	*1989*	*1986*	*1989*
T+O	0.2/2.2	0.4/2.6	1.0/1.2	0.2/0.9
T+24	0.7/3.5	1.1/4.5	1.0/1.5	0.7/1.3
T+48	0.4/4.1	1.1/5.4	1.0/1.5	0.7/1.3
T+72	not	1.2/5.9	not	0.8/1.7
T+96	available	1.4/6.4	available	0.9/1.9
T+120		1.1/6.9		0.9/2.1
Area: European continental shelf – from limited-area model				
	Winds (m/sec)		*Waves (m)*	
	1986	*1989*	*1986*	*1989*
T+0	0.9/2.1	0.5/2.0	0.3/0.8	0.1/0.6
T+12	0.9/2.9	0.9/2.7	0.3/0.8	0.3/0.6
T+24	1.4/3.5	1.2/3.2	0.4/0.9	0.4/0.7
T+36	1.6/4.0	1.2/3.7	0.5/1.1	0.4/0.8

Note: Wind and significant wave forecasts against measured data from buoys, rigs, platforms and weather ships over winter months January to March.

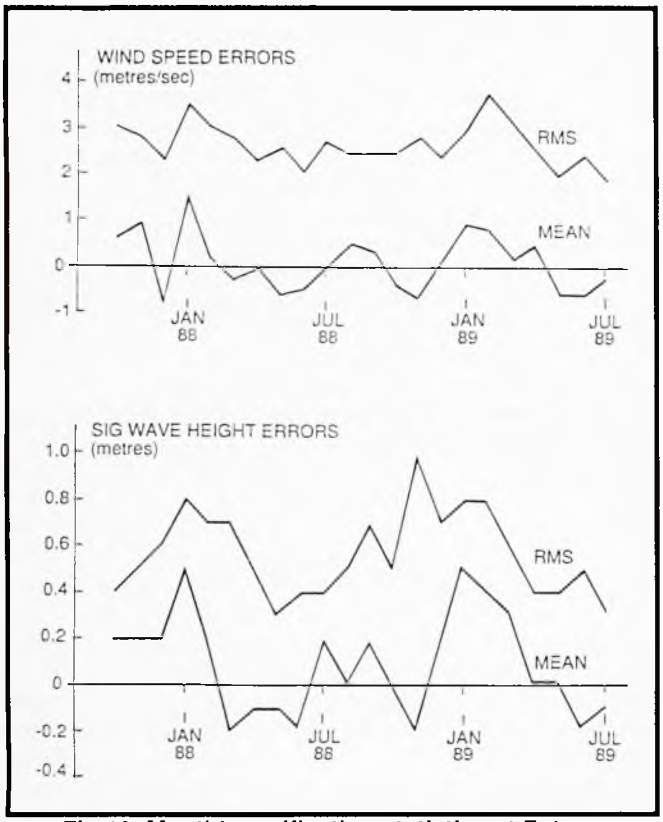

Fig 10: Monthly verification statistics at Fulmar (56.4N.2.OE); 24h forecasts from limited area models

VERIFICATION OF FORECASTS

It is important that forecasts are verified by comparison against observations for several reasons; to quantify the benefits of new methods/data, to identify fruitful issues for further investigation and research, and to enable individual forecasters to be aware of their performance and to learn from experience. Verification may be either against observations or against analysis fields; the former can be done only where observations exist, and so it can be argued that the comparison is weighted towards data-dense areas; the latter can only be done globally if necessary, but some reservations may be necessary regarding the quality of the analysis over some areas.

The overall progress of atmospheric models since the 1960s can be demonstrated in Fig 9, which shows errors in 48h forecasts of the 500 mb height field over the North Atlantic. This variable, while perhaps appearing far removed from the problems of surface wind and waves, which beset the engineer and the mariner, is closely associated with the mid-atmospheric wind field and if this variable is incorrect, it is highly unlikely that the surface conditions will be correct. Figure 9 shows a steady reduction in RMS error over the years, with the more significant reductions in error occurring when new models came into use. The 'persistence' graph indicates what would have been achieved if a forecast of 'no change' had been made in each case.

Variables of more immediate concern are analysed in Table III – surface wind and significant wave height forecasts in the winter months over NW European waters. Forecasts from both global and limited-area models are compared with all available observations in the area. These results demonstrate; firstly, the relatively small errors in the T+0 wave fields, bearing in mind that the wave analysis does not incorporate wave observations; secondly, how both mean and RMS errors increase as the forecast period lengthens; thirdly, how most errors have reduced over time as a result of model improvements; and finally, how the higher resolution model gives a much lower RMS error than the global model at T+24h. Errors at a single site on a month-by-month basis are shown in Fig 10; 24h forecasts of winds and waves against observations at the Fulmar platform show an increase in both mean and RMS error in the winter months when synoptic developments occur more rapidly and with greater intensity. Differences between the years illustrate that some weather situations are inherently more difficult than others to forecast well, and the experienced forecaster will readily confirm this.

Analysis of forecast errors in individual variables is of interest, but in general, the operator requires forecasts of all relevant variables together, so that he may judge their relative importance in the context of the operations in hand. Also, an indication of the trend, whether the situation is likely to improve over a given time period or not, is often as valuable as a quantitative forecast for a specific time. Further, over a season, one or two really successful forecasts in crucial situations may be worth much more financially to the operator than the maintenance of an overall low RMS error. In other words rigorous verification statistics, while of natural interest to the originator of the forecast, may be only one indicator of the value of the service to the client.

DATA AND SERVICES FOR DESIGN AND PLANNING

As mentioned above, the efforts of Maury in the USA and Beaufort and Fitzroy in the UK to standardise observing methods at sea began to bear fruit from the 1850s onwards, and the earliest observations in the Met Office Marine Data Bank are from that time. Other maritime nations, such as the Netherlands and Germany, began collecting marine weather data around that time also, and these data continued to accumulate as sailing ships were replaced by powered vessels. Observations were carried out by ships on passage, and so the spatial distribution was very dependent upon the main pattern of trading routes. Light Vessels were established around Britain and in the southern North Sea in the latter part of the 19th century, but only after the Second World War were fixed-station observations begun in deep water when Ocean Weather Ships were positioned at several locations in the North Atlantic and North Pacific.

As wireless telegraphy facilities developed, national meteorological services began to collect ships' observations in real-time to aid their forecasting efforts, but until computer storage became feasible, the effort involved in data sorting and archiving for climatological applications was considerable. In 1960 the World Meteorological Organisation established a formal scheme for the routine collection of marine observations for climatological purposes, and this step considerably enhanced the volume of data being collected, exchanged and stored.[6] The Met Office Marine Data Bank now contains around 70M observations, covering all oceans of the world.

This volume of data clearly represents a vast resource, of great potential value for a wide range of planning and design applications. Of course the data have their limitations, since the majority of the wind and wave observations are eye estimates, but in general they have been carried out by experienced mariners according to well-defined criteria. Where comparisons with instrumental observations at fixed sites have been possible, it has been concluded that the ship data are sufficiently reliable to define the general nature of the wind and wave climates.[7,8] It should be remembered that instrumental data are often plagued by calibration and maintenance problems, and offshore instrumental records are generally available only over limited time spans.

Over the years since the Marine Data Bank was established, a wide and flexible range of analysis software has been developed, so that almost any kind of statistical analysis or summary can be produced at short notice to meet the needs of the engineer or scientist. Observations of wind speeds, wave heights, air or sea temperatures or any of the other recorded weather variables can be summarised over an area of any size. Suitable class intervals can be chosen in bi- or tri-variate analyses to demonstrate the range of conditions and frequencies of occurrence which are likely to be crucial to the project in hand. These data have been used extensively as source material for national design standard publications.[9]

For application to specific projects, meteorological information may be required during the various planning stages, starting with the desk study and moving through the exploration phase, the assessment of the economics of the development, the exploratory drilling and subsequently the production phase. At each stage, more detail and greater precision are required in order to demonstrate the continuing viability of the project and to warrant progress to the next planning stage.[10]

The most significant recent addition to the marine climatologist's information sources is the hindcast output from the global and local wave models.[11] As indicated earlier, the analysed wind and sea-state fields are preserved every day, so that an archive of increasing length is now available for analysis in exactly the same way as observed data can be analysed. The advantages of such an archive are especially obvious in areas of sparse data where conventional wind and wave information would be difficult, if not impossible, to obtain. Also, for applications where spectral representation of sea-state is required, the hindcast archive can provide at low cost a first estimate of conditions in the area of interest. Where a wave-recorder has been deployed for a short period, the archive can perhaps be used to extend the effective period of record to several years by cross-calibration.

It can be seen from Table II that, as the power of our computing facilities has increased, the resolution has also been improved. However, increased resolution, both in the spatial and spectral domains, does create problems for the archivist, and although it was possible to retain the two-dimensional spectra at 12h intervals in 1976, limitations on storage preclude doing the same at 6 or 3h intervals at the very much larger number of grid points used in the later formulations. If there were to be a clear demand from potential users of the information for more detail to be retained in the archive, then some further thought might be given to the problem, but already the number of clients recognising the value of this hindcast archive for design and planning work is increasing, and of course the archive itself will become increasingly valuable as it is extended in time.

In this context, it is also worth mentioning progress on the North European Storm Study (NESS), a co-operative project sponsored by a group of oil companies and European governmental agencies (including the UK Department of Energy), to produce a hindcast database over the continental shelf area. Winds, waves, surges and currents have been hindcast over a 25 year period, with analyses through all the winter seasons and over selected periods in the summer months. All the computational work has been carried out at the UK Met Office; a vast volume of output from these hindcasts has now been produced, which will allow definitive assessment of combined probabilities and extremes for design purposes at individual model grid points, with resolution down to 10 km in certain areas. The results will initially be confidential to the members of the consortium, but the experience gained in the formulation and operation of these detailed models will obviously be of value to the industry generally.[12]

THE WAY AHEAD

There are three areas where developments already in train will have important consequences for weather services to the offshore and marine industries. First, the acquisition of a new supercomputer to replace the CYBER 205 is now well under way; a CRAY Y-MP machine is expected to come into operational use in the Met Office during 1990, and plans include a doubling of the spatial resolution of the global models and the limited-areas atmospheric model, as well as enhanced vertical resolution. Thus low-level wind fields used as input for the wave models will be specified in greater detail.

Second, satellite-borne devices measuring sea-state on a global scale by radar altimetry or scatterometry will provide valuable input to the specification of initial conditions for the wave forecasting models.[13] The launch of ERS-1, planned for later in 1990, will provide significant wave height measurements from the radar altimeter in real-time, and work is well advanced in the Met Office to assimilate these data into the operational wave model. It is expected that these data will improve the wave field analyses, especially in the tropics and southern oceans, and this improvement will be carried through into the forecast wave fields.

Further developments are also likely in the formulation and operation of integrated atmosphere/ocean models, both for short-term forecasting purposes and for climate research. Experience with the operational surge model (see section on developments in wave modelling above) and with NESS suggests that, given additional computing power, an integrated wind/wave/surge/tide model could be run operationally, to simulate and predict those processes taking place over the continental shelf area which would be of significance to offshore and coastal operations.[14] Continuing co-operation between the Met Office and the Oceanographic Laboratories with expertise in these areas is expected.

From April 1990, the Meteorological Office will become an Executive Agency within the Ministry of Defence. There will be little change in the provision of services, especially those which are disseminated freely as part of national responsibilities under the SOLAS convention. More specialised requirements, however, some of which have been outlined in this paper, will continue to be met on a repayment basis, with charges set to make sensible contributions to the costs of core activities such as observing, data archiving and R&D.

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Discussion

Dr B L Miller (Global Maritime) Firstly, I would like to congratulate the author on presenting a very interesting and informative paper. I have two questions relating to forecast accuracy as follows.

In the design and installation phases of offshore projects the engineer is concerned with establishing extreme environmental criteria to ensure adequate strength both of the final structure and in any temporary installation configurations. In designing for, planning, scheduling or resourcing these temporary operations the availability of accurate long range weather forecasts would be invaluable.

The author has clearly shown the steady improvement in forecast accuracy over the past 25 years and in his concluding comments on the way ahead shows that this is expected to continue with increases in computer power and data acquisition. A recently published popular book on the subject of Chaos (James Glieck) describes work by Lorenz at MIT in the 1960s. As I understand it, Lorenz demonstrated that even a simple model of weather processes, because of its non-linear characteristics, could relatively quickly behave markedly differently when run with almost imperceptibly different starting conditions. Does this mean that even with unlimited computing power, and perfect modelling, both of the physics of the atmosphere and the topography of the earth, that there are natural limits to weather forecasting and what might these be? I am curious as to whether it might ever be possible to predict the likely climatology (in a statistical sense) of the next few months with confidence.

My second question concerns swell forecasting. As the author notes, some operations are very sensitive to waves, especially swell – for example, the mating of integrated decks to fixed or floating platforms in exposed locations. In principle it would seem that swell ought to be inherently more amenable to *prediction* and I was interested to note the author's comments that the numerical model tends to underpredict it. I would be interested to know approximately what sort of accuracy one might expect in height and dominant period from the model in generally mild to moderate weather and, if appropriate, how much an experienced forecaster might consistently improve on this.

J S Hopkins (Meteorological Office) Regarding predictability, as I indicated in my paper, there are some weather situations which are inherently more difficult to forecast than others, due to the varying degree of instability which is present in the atmospheric flow patterns. Some types of flow will be more sensitive to minor analysis errors than others, and so an ensemble of initial states, perhaps differing only in relatively minor detail due to sparse data coverage over oceanic areas, when integrated forward in time by a numerical forecasting model will yield a range of solutions. Recent research at the Met Office and at the European Centre for Medium-Range Forecasts, has shown that useful probability forecasts can be formulated from this range of solutions, eg there is a 90% probability that the wind speed at location X will remain below 25 kn in the period 5–7 days from now. Of course, the size of the ensemble (and so the precision of the probability) is limited by available computing power, but given the predicted power of arrays of parallel-processors, it is reasonable to expect that such probability forecasts for up to 10 days ahead will be operationally feasible within a few years. Extending the forecast time-scale from weeks into months will require greater refinement of the models' treatment of such physical processes as energy and momentum transfers between the ocean and the atmosphere; to achieve the necessary data to quantify these processes, improved coverage from both surface observations and from satellites will continue to be necessary, and the launch of ERS-1 later in 1990 is the next step on this road.

Regarding swell, the underprediction of heights is due to the wave energy in the model being partitioned into 16 discrete directional sectors; this results in rather greater energy losses during long-distance propagation than are observed in reality. Model swell periods in the 10–15s range tend to be too high by between 1 and 3s, when compared with good-quality (Weather Ship) observations. The forecaster, knowing of these tendencies, can make appropriate fine-tuning adjustments to the model guidance in the light of the relevant synoptic situation, site and customer activity.

Mr F Lynagh (Noble Denton) Is it not the case that developments in computer technology are racing far ahead of the developments in data collection? We have probably reached the stage where the benefits gained by ever faster computers and more sophisticated models will become smaller because we do not have enough raw data to enable accurate analysis and modelling of the initial state.

International efforts to improve data collection will probably become at least as important as national efforts to improve numerical weather prediction.

Mr F Singleton (Meteorological Office) I would like to make the following comments in response to Mr Lynagh of Noble Denton. The importance of data is fully recognised by meteorologists but there is a resource problem and this has led, over the years, to a reduction in Ocean Weather Ships (ie 'fixed' ships) from eight or nine to two over the Atlantic plus one in the Norwegian Sea. The World Meteorological Organization has recently undertaken a study known as Observing World Weather Watch System Experiment – North Atlantic (OWSE-NA) the object of which was to try to define the optimum mix of data needed for operational meteorological services.

Part of the OWSE-NA work was to try to assess the impact of different kinds of observation but such trials are notoriously difficult and have become increasingly so as numerical weather prediction has advanced. Operational analyses start with a 'background field' produced from all the data available 12h before the new observation time. The quantity and quality of data over the land areas on both sides of the Atlantic, together with data over the Atlantic coupled with human assessment of the data, are such that 12h forecasts generate extremely good background fields. Poor data, especially a lot of poor data, can have serious adverse effects whereas some good data can have very positive advantages.

One of the findings of the OWSE-NA was that computer analyses techniques do not handle large amounts of poor quality data as well as was previously thought.

The emphasis placed by Meteorological Services on the North Atlantic are:

1. use of upper air equipment (semi-automated) on ships of opportunity;
2. use of automated transmission equipment, using meteorological satellite systems, to improve data recovery during radio operation stand-down periods;
3. use of drifting buoys in data sparse areas;

4. use of tethered buoys, rigs, platforms and islands for automatic weather stations;
5. use of automated transmission systems via satellite, using aircraft wind and temperature sensors to increase data volumes.

Of particular importance is the ability of the current numerical weather prediction models to generate new features. A notable example was the forecast on the previous Sunday of the Thursday 25 January 1990 storm. On the Sunday the feature responsible did not even exist.

A recent survey over a one year period showed an average of 1000 separate surface weather reports being received from ships over the Atlantic to the North of 30 degrees N.

J S Hopkins (Meteorological Office) To illustrate the ability of current atmospheric models to recognise limited amounts of erroneous data, it is perhaps worth relating the case of the Marion Island winds. Analysis of upper-air winds from the very isolated Marion Island (47°S, 38°E) showed that directions were consistently biased by a few tens of degrees with respect to the model's analysed wind fields. When technicians next visited the island, they discovered a calibration error in the wind-finding radar which coincided exactly with the diagnosed error.