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LEWEX: MOTIVATION, OBJECTIVES, AND RESULTS

This overview article outlines the major events that led up to the Labrador Sea Extreme Waves Experiment, describes its international multidisciplinary scope, and summarizes the major results.

INTRODUCTION

In early March 1987, ocean researchers from eight North American and European countries converged on a pair of sites in the southern Labrador Sea to explore methods for measuring, predicting, and applying directional ocean wave spectra. The researchers were supported by ship, aircraft, and satellite estimates of wind and waves, further complemented by a number of numerical wave model estimates. From the surface, the Canadian research vessel CFAV *Quest* (see Nethercote, this issue), and the Dutch research vessel HNLMS *Tydeman* (see de Jong and Vermeij, this issue), used wave buoys[1-3] and their navigation radars.[4] From the air, a Canadian CV-580 aircraft and a NASA P-3 aircraft employed radar remote sensors. From space, the U.S. oceanographic satellite Geosat monitored wind speed and wave height with its precision radar altimeter (see Dobson and Chaykovsky, this issue). The two ships used both moored and drifting directional buoys, the NASA P-3 used both a surface contour radar[5] (SCR) and a radar ocean wave spectrometer (ROWS),[6] and the Canadian CV-580 used a C-band synthetic aperture radar (SAR),[7-11] generally at two altitudes (or two range-to-velocity ratios).

Each of six agencies[12-17] used numerical models and its own (or others') estimates of the wind field to hindcast (i.e., forecast after the fact) directional spectra at the ship positions, and nine agencies[12-20] (including the first six) later used a common wind field[12] to generate a second set of hindcasts to expose even subtle differences among the various models. Over a seven-day interval (from 1200 UT on 12 March to 1200 UT on 19 March), about 2000 spectral estimates were produced, with as many as twenty-five nearly simultaneous and coincident estimates at each of the two ship locations (four from the ship, six from the aircraft, six from models using separate winds, and nine from models using common winds). This comprehensive set of evolving directional spectra, all processed and displayed in a common format, is unique and unprecedented. Not surprisingly, no set of spectral estimates from a single source is identical to that from any other source. These disparities among the spectral intercomparisons have provoked valuable controversy on the source wind fields[12,21] (see also Pierson, Ezraty, and the panel discussion, all in this issue), the surface spectral estimates,[1-4] the aircraft spectral estimates,[5-11] and the wave model spectral estimates.[12-20] The resulting exchange of ideas promises to advance our ability to measure, to model, and ultimately to predict directional ocean wave spectra.

The comprehensive spectral intercomparison effort was named the Labrador Sea Extreme Waves Experiment (LEWEX). There was no single impetus for LEWEX, but the momentum that sustained it is an indication of the international interest in improving ocean wave prediction. With improved wave models, driven by anticipated satellite directional wind estimates and verified by complementary satellite directional wave estimates, wave forecasting skill should also improve, but only if the satellites sample both the wind and the wave fields with sufficient density. In general, there will be biases, uncertainties, and undersampling. LEWEX has revealed that many of the biases and uncertainties reside in unexpected places.

MOTIVATION FOR LEWEX

Improved ocean wave predictions are important for ship guidance in coastal areas and along the major ocean routes. They are a necessary component of any serious attempt to improve safety at sea. For example, as Kjeldsen describes in this issue, Norway has a notorious problem in ensuring ship safety all along its exposed western coast. Complex, multimodal seas are transformed by variable coastal currents and bathymetry to produce some especially hazardous regions along the coast. Knowledge of the multimodal seas (or more specifically, the directional energy spectrum) can be combined with specific vessel transfer functions to predict vessel motions, and to assign safety risk factors to the vessel as a function of time and location. The accuracy of these calculations, however, can be extremely sensitive to errors in the initial (deep-water, current-free) spectral estimate. Figure 1 shows an example of an open-ocean operation in which the vessel motion clearly creates a nuisance.

On a less immediate but ultimately more profound scale, an accurate description of the sea surface can help refine our knowledge and understanding of global climate dynamics. Large-scale ocean currents (e.g., the Gulf Stream, which acts as a conduit to transfer heat from equatorial to polar regions) are driven largely by the mean surface winds over the ocean. The atmosphere is coupled to the ocean through the surface drag; higher drag allows more efficient coupling. But the drag depends intimately on the properties of the surface waves. Short, steep, wind-driven ("young") waves offer much more drag than long,

Figure 1. A U.S. Navy ship refueling in moderate to heavy seas. (Reprinted from Ref. 31.)

gentle ("old") swell for the same wind speed. Even though this wave-dependent aspect of drag is now commonly recognized (see the panel discussion in this issue), its behavior as a function of the underlying directional wave spectrum is still poorly understood. Consequently, none of the wave models at the major forecast centers incorporates a wave-dependent drag. This omission (even assuming that all other things are perfect) likely results in substantial modeling errors in the initial stages of wave growth or in rapidly evolving winds. When these and other subtle but important effects are more clearly understood, the physics can be incorporated into numerical wave models. Such models, in turn, will become an essential component of the coupled ocean–atmosphere specification, and will lead to more accurate descriptions of many of the fluxes that influence global change. Hasselmann (in this issue) further elaborates on the importance of improved wave models to global climate models.

These two major problems—the first operational and immediate, and the second scientific and long-term—helped shape LEWEX and influenced the composition of its participants. But another, equally central, issue was this: the prediction of future directional wave spectra is fundamentally limited by our ability to specify it in the present. In the open ocean, especially in high seas, no absolute or even primary standard exists for determining the directional wave spectrum, either by model or by measurement, either *in situ* or remotely. Consequently, LEWEX also became a search for consensus, for systematic anomalies, and for unexpected agreements. All three issues—safety at sea, climate dynamics, and the search for consensus—become most problematic in extreme (e.g., growing, high, multimodal) seas.

THE LEWEX INTEREST GROUPS

LEWEX was spawned by a fortuitous conjunction of three separate interest groups: numerical ocean wave modelers (mainly oceanographers and physicists), radar remote sensing scientists (mainly electrical engineers and radio scientists), and ship motion experts (mainly naval architects and hydrodynamic engineers). Rarely have all three groups joined in a common enterprise. In 1987, circumstances conspired to create an exception, and thus to provide an unusual opportunity.

Ocean Wave Modelers

Quantitative schemes for predicting ocean waves through estimates of the time–space history of the surface wind have been available since the early 1950s. (For a more complete historical perspective, see Hasselmann in this issue.) The first ideas were largely empirical, based on ship observations. Nevertheless, they yielded rough estimates of the wave height and period. This primitive (but useful) empiricism yielded in the 1960s to the realization that the predictive problem was better characterized by a spectral evolution based on an energy balance of generation, dissipation, and wave–wave interaction terms. Since then, as physical insight has followed careful measurement, three generations of wave models have emerged, all having the common goal of predicting directional wave spectra in the open ocean from twelve hours to three or more days in advance. All three generations use finite difference schemes to grow, propagate, disperse, and dissipate the waves. The first differs fundamentally from the second and third in assumptions about the physics that shapes the equilibrium spectrum; in particular, second- and third-generation models incorporate a wave–wave interaction mechanism that acts to enhance energy in the region of the spectral peak.

Despite their empirical refinement, second-generation models are not uniformly superior in performance to first-generation models. Most recently, third-generation models, in which approximations of the wave–wave interactions are calculated at each time step (important in rapidly turning winds), have become practical. In their present form, however, they are computationally intensive, and their superiority in performance to existing first- and second-generation spectral predictions has not been conclusively demonstrated. In early March 1987, the first and most highly refined third-generation wave model (WAM)[22] became operational at the European Centre for Medium Range Forecasts, just in time to participate in LEWEX.

Remote-Sensing Scientists

The science and technology of radar has evolved roughly in parallel with the development of wind wave models. The first crude realization of a synthetic aperture came in the late 1950s, but synthesis did not become practical until the 1960s, when large-diameter optics were introduced to accomplish signal correlation.[23] By 1965, oceanographers were advocating "present day radar technology to give a complete description of the sea state."[24] By then, potential scientific applications for military radar technology were beginning to emerge. Many of the applications were based on exploiting environmentally dependent backscatter from the ocean. In the 1970s, three quite distinct aircraft radar techniques were explored by NASA for probing the ocean surface on scales (tens to hundreds of meters) that might yield remote estimates of the directional wave spectrum: (1) the surface contour radar (SCR), a narrow-beam, nadir-centered, raster scanning altimeter;[25] (2) the radar ocean wave spectrometer (ROWS), a fan-beam, off-nadir-centered, conically scanning altimeter;[26] and (3) the synthetic aperture radar (SAR).[27] All three could gather directional wave information; the raster-scanning SCR is the most direct and primary method, relying primarily on precise timing to map ocean surface elevations. Only ROWS and SAR can be practically configured for a satellite, however, and both (especially the SAR) must rely on less direct properties of radar backscatter from the ocean for their spectral estimates.

In 1978, NASA flew the first civilian SAR on Seasat, the world's first purely oceanographic radar satellite.[28] The Seasat SAR was indeed able to monitor important aspects of the spatially evolving spectrum over hundreds of kilometers, but the moving ocean scatterers created a Doppler spread in the radar signal that acted as a severe wave filter in the along-track direction.[29] Unfortunately, few opportunities existed under Seasat to compare the SAR-estimated directional wave spectrum with other independent estimates. This situation was partially rectified in late 1984, under the much lower-altitude (and thus less severe Doppler smearing) shuttle imaging radar (SIR-B). Off the southwest coast of Chile on four separate days, spectral estimates from the shuttle SAR and from the SCR and ROWS, both mounted on a NASA aircraft, further indicated that a lower-altitude orbiting SAR could (three times out of four) give reasonable spectral estimates.[30] Those skeptical of remote sensors, however, could (and did) protest that no "direct" *in situ* measurements existed to verify any of the remote estimates. Indeed, previous, but far from comprehensive, separate comparisons had been made of both the SCR and ROWS against directional buoys. Since those comparisons were only two-way intercomparisons, they did not permit any consensus-building, and could not be construed as definitive. By the time of LEWEX, all three radar techniques, properly used, clearly could yield something closely related to the actual directional wave spectrum, but the subtleties of the SAR instrument transfer function were still very much in question.

Ship Motion Experts

Accurate prediction of ocean waves in coastal areas has been an important component of maritime planning ever since World War II. In the intervening half-century, understanding ship motion, internal stress, and fatigue (both to material and to personnel) have been central issues to hydrodynamicists and naval architects. By applying concepts of linear systems theory, the surface ocean wave spectrum (or, in the case of a moving vessel, the "encounter" spectrum) is transformed into vessel motion (pitch, roll, and heave) by way of the vessel transfer function.[31] To the extent that the vessel response is linear and its transfer function is known, knowledge of the encounter directional spectrum is sufficient to determine the ship motions. In such cases, the problem can be scaled down by a factor of 10 to 100, permitting motion and capsize studies in model basins. By exciting synchronized orthogonal sets of paddles, the more sophisticated of these basins can simulate full directional wave spectra (see Kjeldsen in this issue).

Even though ship design criteria are still specified simply in terms of wave height, or at most in terms of a one-dimensional (unimodal) spectrum, these simplifications are not normally justified (see the articles by Nethercote and by de Jong and Vermeij in this issue). The open ocean wave spectrum is often (perhaps usually) multimodal. Accurate forecasts of directional wave spectra are therefore essential to predict vessel and offshore tower motions, internal stresses, and safety factors for various deck and tower operations. (Significantly, this point was also made nearly thirty years ago in a similar conference on ocean wave spectra.[32]) Accurate three- to ten-day forecasts would be extremely useful for transoceanic ship guidance and for more reliable estimates of port arrivals.

In 1984, a NATO research study group on full-scale wave measurements was formed to investigate methods of measuring and specifying the multimodal (directional) behavior of the sea using ship instrumentation such as buoys and navigation radar. By 1985, "full-scale" (i.e., at-sea) trials were being planned in the North Atlantic using the *Tydeman* and the *Quest*. Also by the mid-1980s, the three-way (SCR, ROWS, and SAR) spectral intercomparisons from SIR-B were indicating remarkable agreement among sensors,[30] and the WAM developers were testing global versions of their third-generation model on the Cray computer at the European Centre for Medium Range Weather Forecasts.[33]

By 1985, then, the time seemed ripe for a field experiment in high seas that would include as many methods as possible for estimating—nearly simultaneously and coincidentally—the directional wave spectrum. Those methods included first-, second-, and third-generation wave models, the three most promising radar remote sensing techniques, and various ship-based techniques, including directional buoys and marine radars.

CHOICE OF TIME AND PLACE

By early 1985, LEWEX began to take tentative form. At that time, LEWEX was envisioned as a direct successor to the NASA SIR-B Chile experiment, but to occur in the

North Atlantic under the SIR-B reflight (designated SIR-B′), then scheduled for March 1987. To support the international polar ice research, SIR-B′ was to have been launched from the western U.S. Test Range in California into a nearly polar (88° inclination) orbit with a slight westward drift (0.6°/day). Canadian researchers were particularly interested in exploring whether spaceborne SAR could monitor ice dynamics on the Grand Banks during March, when the ice field reaches its maximum extent. For Canada, improved ice monitoring and prediction would directly affect the economics of fisheries and oil exploration in the eastern maritime provinces. As a precursor to their own Radarsat program, the Canadians were planning the Labrador Ice Margin Experiment (LIMEX) under the SIR-B reflight, to be supplemented by their own multifrequency aircraft SAR, which in 1985 was still under development.

Meanwhile, in the NATO research study groups, support was building to join the SIR-B′ ocean waves experiment. NATO scientists secured commitments for both the *Quest* and the *Tydeman* to conduct at-sea full-scale trials during March 1987. The ship commitments were an essential component of LEWEX, making it possible to extend the scope of the spectral intercomparisons well beyond the 1984 SIR-B experiment off Chile.

Then in January 1986, the *Challenger* accident occurred, taking with it all hope of obtaining SAR ocean imagery from orbit for several years. The next few weeks were an uncertain time for LEWEX, but by April a modified strategy had emerged, wherein the Canadian aircraft SAR came to play a central role not only for LIMEX, but also for LEWEX. A commitment from the Canada Centre for Remote Sensing for five flights of their CV-580 SAR aircraft was the final catalyst that ensured the experiment. Coordination between the two experiments became essential: LIMEX required broad near-shore coverage for generating ice mosaics, but LEWEX required multiple passes over ships well out in open water. Conversely, the merging of LIMEX and LEWEX eventually proved to have logistically important side benefits, and some of the imagery of waves traveling through floating ice provided new insight into the SAR wave-imaging mechanisms.[10]

The final choices of time and place for LEWEX, then, emerged from the following basic constraints:

1. The *Quest* and the *Tydeman* were available only for the month of March, including two-way trans-Atlantic passage for the *Tydeman*.
2. LEWEX and LIMEX competed for a single common resource, the aircraft SAR based from a single airfield; LEWEX flights were looking for passing storms with evolving multimodal spectra, while LIMEX flights were looking for dynamic ice field conditions.
3. The NASA P-3 aircraft, containing both the SCR and ROWS, was supported for only four flight days (eighteen flight hours), including two-way transit from Wallops Island, Virginia.

Among the elements of risk and uncertainty were (1) daily constraints on the aircraft to secure acceptable alternate landing sites and to fly complicated patterns at various altitudes in one of the world's busiest air corridors; (2) constraints on the ships to deploy and recover large experimental buoys in high seas; and (3) the possibility that ice might completely close St. John's harbor just before the onset of the experiment, when both ships needed access both to enter and to exit.

Some salient features of the wave and ice climate in the winter North Atlantic are shown in Figure 2, along with the route of the *Tydeman* from southern England to St. John's, Newfoundland, during the first days of March. The figure shows a steep gradient in wave climate north and east of Newfoundland, with a broad region in which the significant wave height (SWH) exceeds 10 m at least ten times a year. The final LEWEX sites were located well within this region, and yet close enough to the aircraft base in Gander (within 375 nmi, as it turned out) to allow overflights by the two aircraft, and sufficiently southward to allow exposure to substantial wave energy arriving from three quadrants. Figure 2 also gives a hint of a major winter storm that slowed the *Tydeman* on 8 March, and the extensive ice sheet just east of Newfoundland that nearly immobilized the ship as it approached St. John's harbor.

By March, the wave climate in the winter North Atlantic is rapidly ameliorating. Figure 3 shows that the probability of encountering a 20-ft (6.1-m) wave event in the LEWEX region in March is scarcely more than half what it is in January.[34] Moreover, Figure 4 (from Geosat wave height estimates)[35] shows that 1987 was one of the quieter years, with the LEWEX region experiencing only a 3-m March average, down from more than 4 m in March 1986. Ironically, the last major event of the 1986–87 winter (at least 9.5-m waves driven by 25-m/s winds) passed through the LEWEX region on 8 March and was encountered by the *Tydeman* en route to St. John's. (See Kjeldsen's Figs. 7 and 8 in this issue.) These two ob-

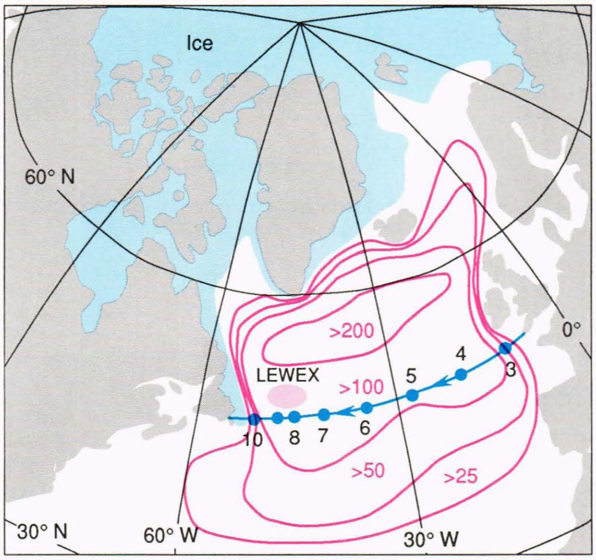

Figure 2. Wave and ice climate in the North Atlantic in winter, also showing the route of the *Tydeman* from southern England to St. John's, Newfoundland, from 3 through 10 March 1987. Contours show number of occurrences of waves exceeding 10-m significant wave height in the 10-year interval from 1959 to 1969, from U.S. Navy model hindcasts. Ice coverage is for 10 March 1987.

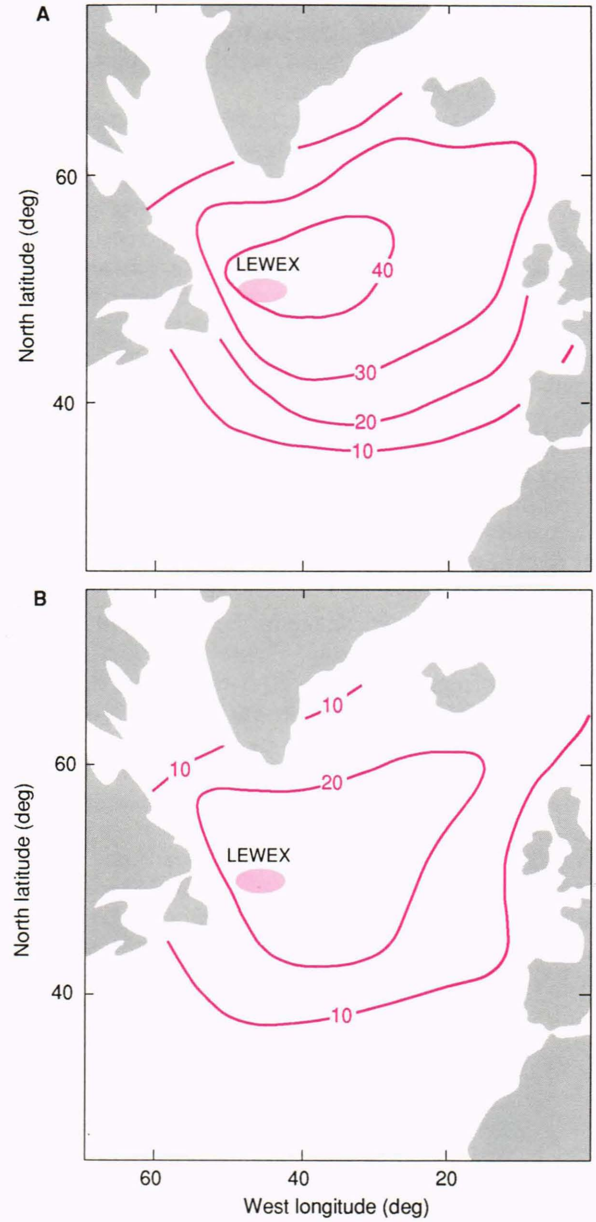

Figure 3. Probability of significant wave height exceeding 20 ft (6.1 m) in the North Atlantic. **A.** January. **B.** March.

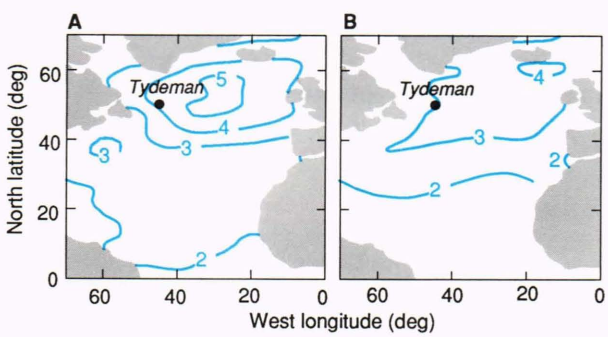

Figure 4. Monthly averages of significant wave height for the North Atlantic in March from Geosat. **A.** The year 1986. **B.** The year 1987.

stacles (the storm and the ice pack) ultimately prevented both ships from reaching their LEWEX sites until early on 14 March. McCloskey[36] gives a further chronology of events from 9 March to 19 March.

Figure 5 shows the extent of the ice field around St. John's harbor as the two ships traveled south on 10 and 11 March around the ice pack and then northeast into strong headwinds on 12 and 13 March. By 14 March, the two ships were positioned at adjacent numerical model grid points of the U.S. Navy Global Spectral Ocean Wave Model, GSOWM (the *Quest* at 50°N, 47.5°W; the *Tydeman* at 50°N, 45°W). From Gander, the Canadian CV-580 and the NASA P-3 planned their flights to travel eastward at 50°N latitude from 50°W to 45°W, and to pass over the *Tydeman* daily at about 1200 UT (0830 local time), coincident with the various model forecasts. Aside from a single moored buoy at each ship, all buoys were deployed several hours before aircraft overpasses and were recovered several hours after the overpasses, all generally in daylight hours, but sometimes after dark and with great difficulty.

The problem of successfully deploying and recovering buoys was a major concern. Not only was personnel safety at stake, but expensive "one-of-a-kind" experimental buoys were at risk. Before the experiment, each ship had determined its own guidelines for both deployment and recovery. The larger and more versatile *Tydeman* could deploy buoys in seas up to 24 ft (7.4 m) and recover them in seas up to 15 ft (4.6 m). Comparable limits for the *Quest* were 12 ft (3.7 m) for both deployment and recovery. For this reason, the *Tydeman* was positioned at the more open (eastward) site, where sea

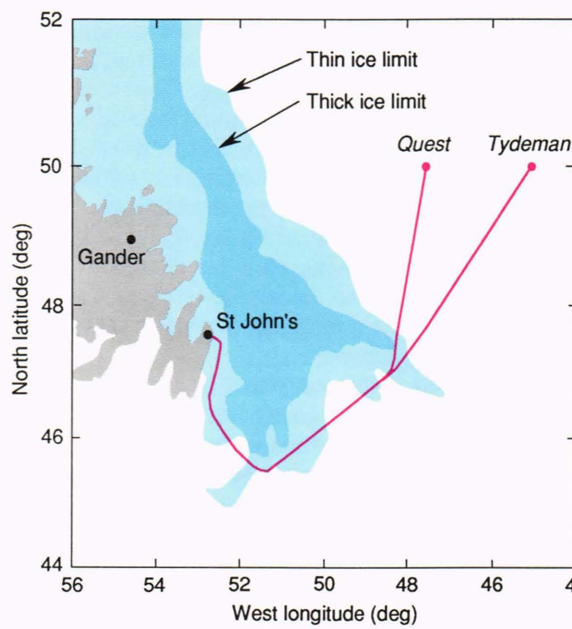

Figure 5. Ice field in the LEWEX region on 10 March 1987 (adapted from Canadian Atmospheric Environmental Service data). Also shown are the ship tracks of the *Quest* and the *Tydeman* from St. John's to their LEWEX sites. The two aircraft departed from Gander to rendezvous with the *Tydeman*, usually around 1200 UT. "Thick ice" is greater than about 1 m.

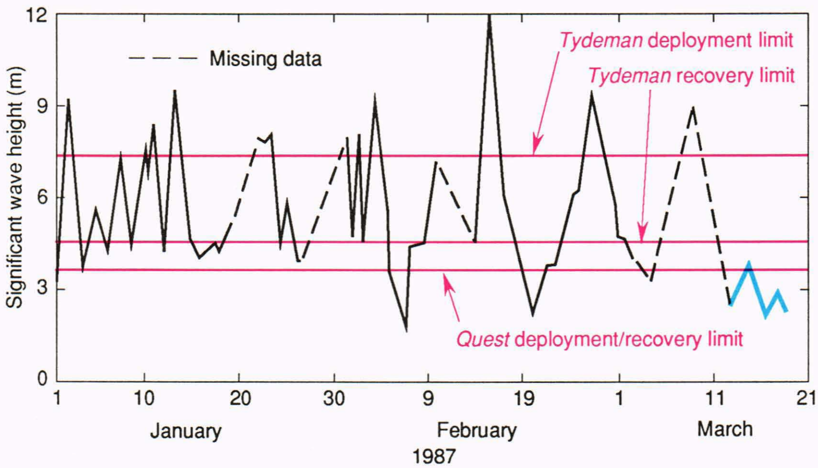

Figure 6. Twelve-hour wave height forecasts from the U.S. Navy Global Spectral Ocean Wave Model for most of the first quarter of 1987, including the LEWEX interval (the blue line) beginning around 12 March. Also shown are the buoy deployment and recovery limits for both the *Quest* and the *Tydeman.*

conditions were expected to be more severe. As a graphic illustration of the potential buoy recovery problem, Figure 6 shows U.S. Navy wave forecasts in the LEWEX region for the first quarter of 1987, along with deployment and recovery limits for the two ships. Clearly, daily recovery of buoys in January or February would not have been feasible, even during the relatively quiet 1986–87 winter.

LEWEX WIND AND WAVE CONDITIONS

By the onset of the experiment, four independent sources of North Atlantic wind fields were available to drive six separate wave models, three in North America and three in Europe. Even though some models were driven well after the experiment itself, the results provide a good estimate of the confidence limits of modern wave forecasting. Figure 7 shows the wide spread in 12-hour advance predictions in SWH from four models at the *Tydeman* site from 0000 UT on 12 March through 1200 UT on 19 March. Each model was driven with separate wind field estimates, but all winds were derived from essentially the same set of available ship reports. Table 1 summarizes salient features of the data sources and the pedigree of the wave models. Also included in Figure 7 for comparison are the measurements from the Norwegian Wavescan buoy, moored at the *Tydeman* site from 0430 UT on 14 March until 2200 UT on 18 March.

The disparity among estimates in even such a simple descriptor as SWH aptly illustrates the need for improved forecasts. Although each forecast correctly predicts the passage of two events separated by about three days, individual predictions of the strengths of both events vary by nearly a factor of 2, and predictions of passage time differ by up to a day. Because each model was driven by a separate wind field, individual model performance cannot be assessed from these results. Neither can the model estimates be compared with measurements for the earlier and stronger event, since the Wavescan buoy was deployed too late to capture the first peak. Differences are just as likely to be caused by the wind fields as by the model (see Pierson, and also Ezraty, in this issue). To investigate model differences *per se*, a common LEWEX wind field was created[12] to drive all wave models with identical winds. The results[12–20] are not shown here, but indicated that the variability seen in Figure 7 was caused at least as much by the wind fields as by the

Figure 7. Twelve-hour wave height forecasts during LEWEX from four different numerical wave models, each using its own estimate of the wind field (WAM with ECMWF winds in red, ODGP with ODGP winds in blue, GSOWM with FNOC winds in green, and UKMO with UKMO winds in orange). Also shown are measurements from the Norwegian Wavescan buoy (in purple).

Table 1. Sources of wave forecasts in Figure 7 using independently generated wind fields.

Model*	Generation	Source
GSOWM	First	Fleet Numerical Oceanography Center
ODGP	First	Ocean Weather, Inc.
UKMO	Second	U.K. Meteorological Office
WAM	Third	European Centre for Medium Range Weather Forecasts

GSOWM—Global Spectral Ocean Wave Model
ODGP—Ocean Data-Gathering Program
UKMO—United Kingdom Meteorological Office
WAM—Wave Model

models. This result was, in fact, one of the major outcomes of LEWEX—that wind field errors remain one of the single largest sources of forecast errors, often masking all the potential advances made in wave model physics over the last three decades.

Although LEWEX was concerned peripherally with wave height estimates, its central interest was with the associated evolving directional wave spectrum. Figure 7 suggests that multiple wave systems were present at the *Tydeman* during LEWEX, but it reveals nothing of their character. In fact, at least six or seven separate, spatially and temporally evolving wave systems were passing through LEWEX during the seven-day period, each having a characteristic persistence of from one to three days. Usually two, but occasionally even three, separate wave systems coexisted at least in some of the model estimates.

The complete time history of the evolving directional spectrum cannot be conveyed in only two dimensions. Even the evolution of the dominant wave vectors (their wave number, direction, and amplitude), however, conveys much of the information about the multiple generating sources that are totally lost in a simple time history of SWH. Figure 8 is a graphical format, further refined by Gerling,[20] that attempts to capture the temporal wave history of LEWEX at the *Tydeman*. In this figure, the logarithm of the dominant wave number (converted to equivalent wavelength and wave period) is plotted against time. Vector sets whose base positions represent wave number, and whose direction and amplitude correspond directly to their counterparts in vector wave number, separate naturally into nearly autonomous clusters. The behavior of these clusters can reveal much about their generating sources. For example, in Figure 8, negative slopes (wave vector sets with decreasing wave number versus time) suggest developing, locally wind-driven waves, and positive slopes suggest dispersive swell arriving from a distant source. Within a cluster, negative slopes are associated with wave growth, positive slope with time and place of wave generation, and minimum wave number with time of closest approach and maximum generating winds. These associations suggest that clusters of evolving vector wave numbers contain specific information on the nature of the generating winds. For example, if a spaceborne SAR can make reliable estimates of the vector wave number at sufficient density, it may be possible to deduce corrections to the generating wind fields.

EXAMPLES OF LEWEX DIRECTIONAL SPECTRA

Figure 8 shows how the dominant peaks of the seven (more-or-less) separate wave systems of LEWEX evolved in time. The figure also shows sample times of the three aircraft remote sensors (daily at about 1200 UT when possible) and the intervals over which the two moored buoys were operating. The wave number evolution is only schematic, of course, since substantial scatter existed among the various estimates, and the evolution at the *Quest* was measurably different from that at the *Tydeman*. Nevertheless, the figure suggests that daily sampling by the remote sensors, if that would have been pos-

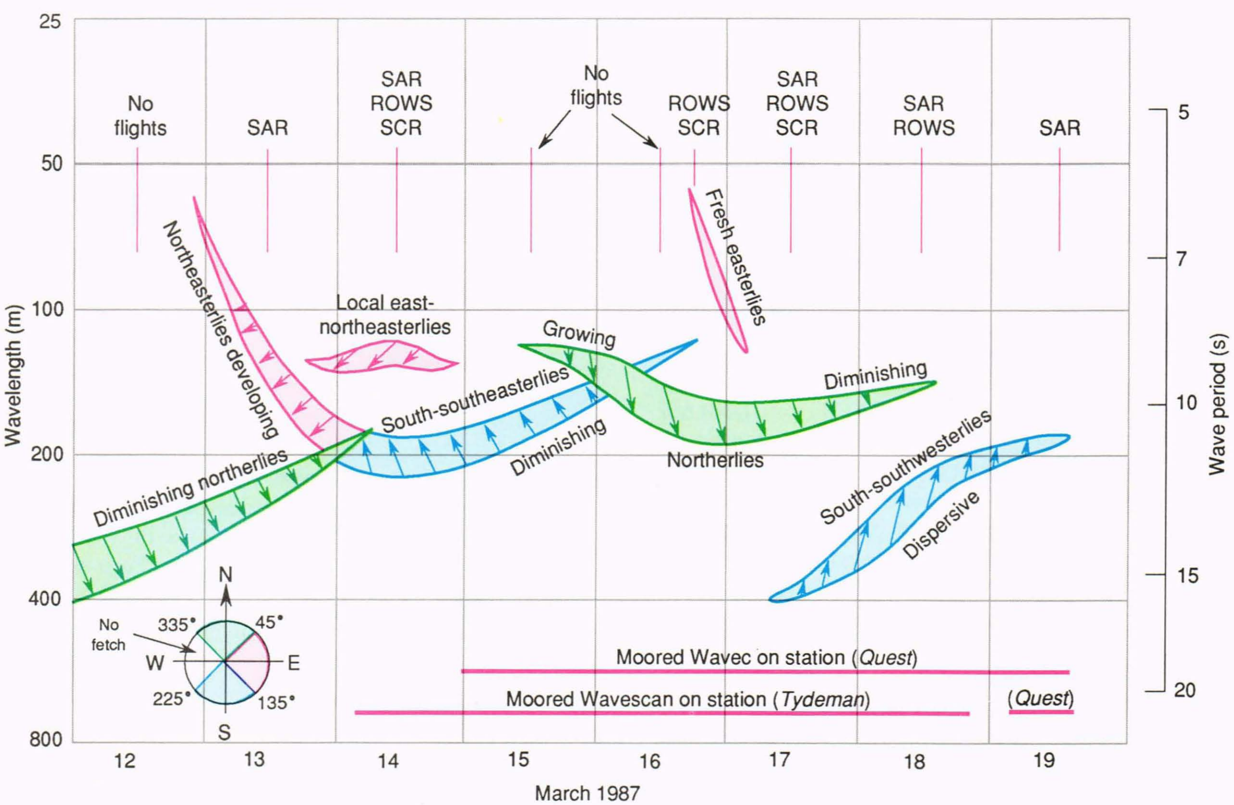

Figure 8. Temporal wave vector history of LEWEX at the *Tydeman*, showing the evolution of several distinct wave systems, along with the approximate times for both aircraft and ship measurements. The *Tydeman* moved to the *Quest* position late on 18 March.

sible, would have captured the dynamics of all but the shortest (< 100 m) wave systems. For various reasons alluded to above, daily sampling from all three sensors was impractical. However, at least one sensor flew on each of six days, at least two flew on four days, and all three flew on two days. On all but the first flight day, collaborating buoy estimates were available from at least one and usually both of the ships.

The most dynamically interesting conditions occurred around 1800 UT on 13 March, just after the first (trial) SAR flight, and before either of the two ships were in position. At that time, diminishing dispersive northerly swell was yielding to strong northeasterlies that were in turn being overtaken rapidly by a strong south-southeasterly system.[12] Figure 9 shows a spectral intercomparison from nine separate wave models at 1800 UT on 13 March, all driven by a common wind field, which at the *Tydeman* was turning from northeast to southeast at about 6°/h. In this rapidly changing wind field, large differences among models appear. Although some models retain a substantial component of old swell (e.g., both first-generation models,[12,13] the NOAA second-generation model,[15] and the NASA third-generation model[19]), others show a nearly completed transition to the fresh wind-driven system (e.g., the second-generation U.K. Meteorological Office [UKMO] model[14] and the third-generation Bedford Institute of Oceanography [BIO][18] model [WAM with ice-field modeling]).

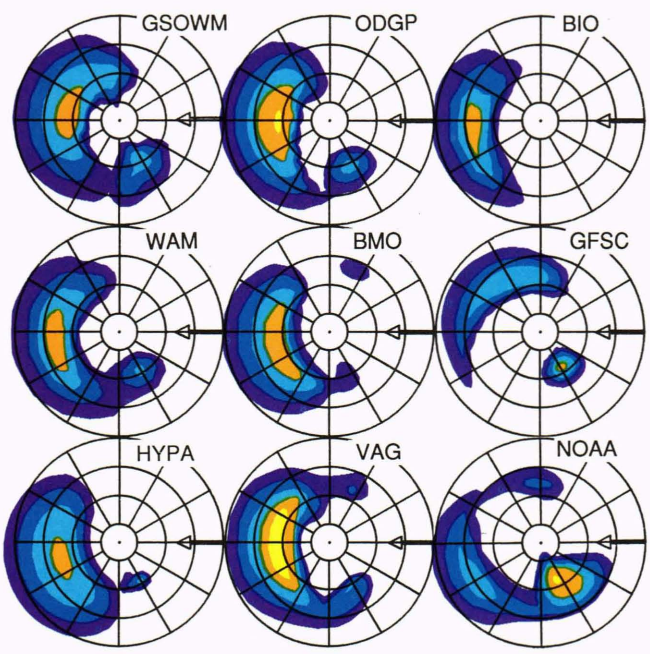

Figure 9. Directional frequency spectra at 1800 UT on 13 March from nine separate numerical wave models, all driven by a common wind field. The logarithm of spectral energy density is separated into evenly spaced contours, with each spectrum normalized to its individual peak. The radial dimension is proportional to the logarithm of frequency, with the outer circle at a frequency equivalent to a wave number of $2\pi/50$ rad/m. Circles are separated by factors of 2 in equivalent wave number; contours are separated by factors of about 2 in spectral energy density ($m^2 \cdot s^2$). Arrows indicate strong easterly wind at the time of the estimates.

Unfortunately, no simultaneous measurements of the spectrum were available, but even if they had been, uncertainties in the wind field would have cast doubt on any attempt to determine absolute model performance. Again, this uncertainty in the driving wind fields pervades LEWEX and would pervade any similar open-ocean experiment in which the far wind field was an important source of wave energy. Without sufficiently dense wind-field monitoring over all the potential generation areas (typically hundreds or even thousands of kilometers from the site), no wind field can be certified as being accurate and complete. In the next few years, satellite scatterometers will alleviate, but not eliminate, this problem, since the (unknown) surface wave field influences the scatterometer wind algorithm through the surface drag relation, and fine-scale wind field variability, although extremely important (see Janssen's comments in the panel discussion in this issue), is typically unknown.

At 1200 UT on 17 March, near the time of the second peak in SWH (Fig. 7), the directional wave spectrum was simultaneously estimated at each ship by the full set of sensors and models. Figure 10 shows this full set of twenty-five spectral intercomparisons at the *Tydeman*. Here the format is similar to that of Figure 9, but in a linear normalized wave number plot. The figure clearly illustrates a number of inherent limitations in both sensors and models. Figure 8 (schematic only) shows two nearly opposing wave systems (one from the south, one from the north) passing through LEWEX at 1200 UT on 17 March. From Figure 10, depending on which of the twenty-five estimates is assumed to be true, one can conclude that either of the two wave systems, or various amounts of both, were present. Moreover, estimates of the direction of both systems vary by up to 45°, and estimates of the spectral width (in both wave number and angle) vary by more than a factor of 3. More specific conclusions than this are not justified, since the spectra are all individually normalized to the spectral peak, and a linear display will not expose broad-band, low-energy systems in the presence of strong narrow-band systems.

Even so, systematic, and sometimes curious, similarities occur among spectra:

1. Aside from the 15° direction anomaly, the Wavec drifting buoy and the Wavescan moored buoy give essentially identical estimates, while the Endeco drifting buoy and the ship radar agree with each other in direction, but differ radically in angular width. (Note: The Endeco buoy was the only buoy not analyzed by maximum entropy.)
2. Again, aside from a 15° to 30° direction anomaly, the (radially ambiguous) aircraft estimates, including both the low-altitude (a range-to-velocity ratio of about 30) and high-altitude (a range-to-velocity ratio of about 50) SAR, agree with one another and with the Wavescan and Wavec buoys.
3. Each of the six wave models, when driven with one of four separate wind fields, produces a dominant northward-traveling system, opposite to that measured by the buoys, and also differing from one another by

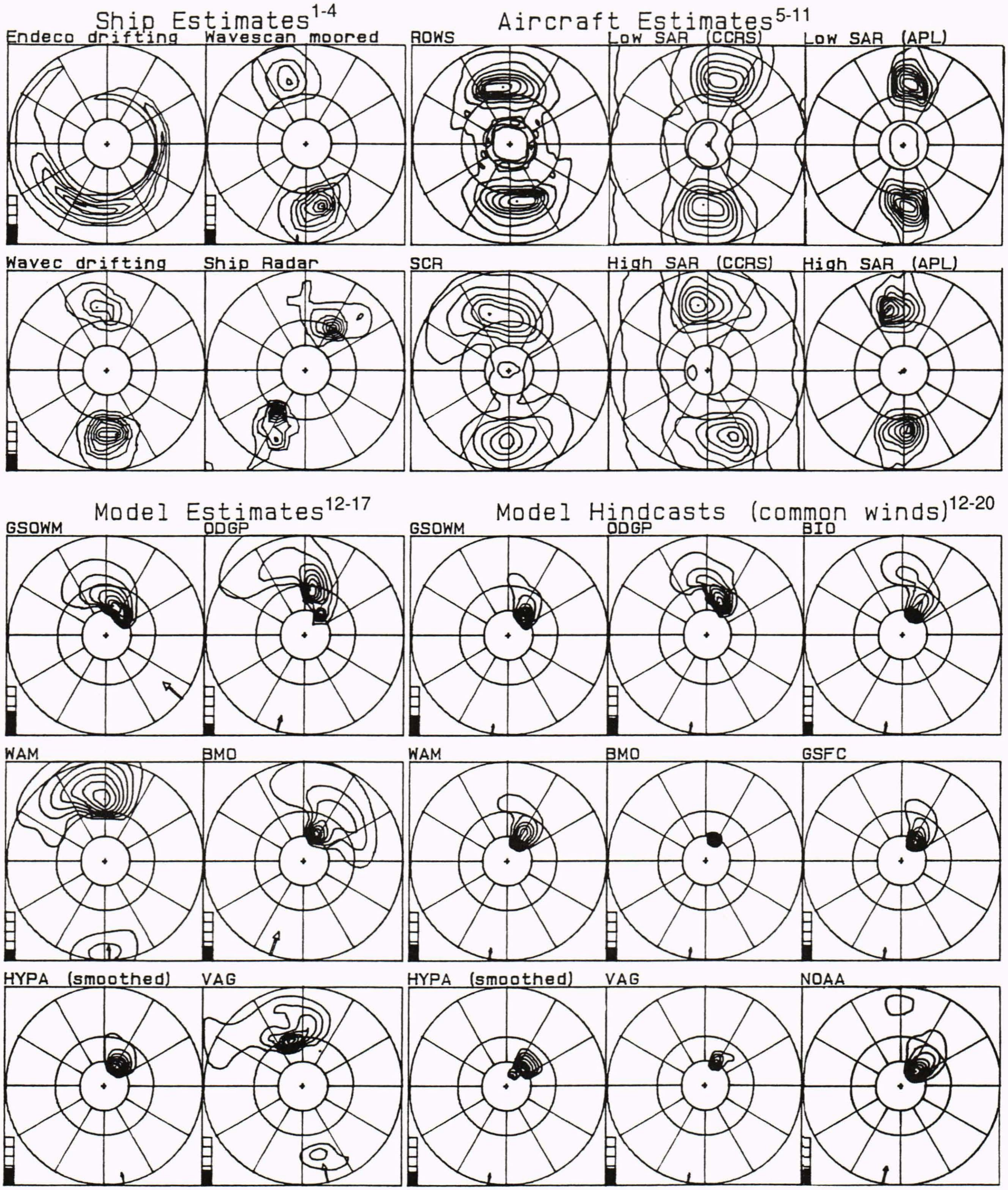

Figure 10. Twenty-five nearly simultaneous and coincident estimates are of the directional wave number spectrum at 1200 UT on 17 March at the *Tydeman*. Ship-based estimates are at upper left, aircraft estimates are at upper right, model hindcasts with separate winds are at lower left, and model hindcasts with common winds are at lower right. Buoy frequency spectra have been converted to wave number spectra through the deep water dispersion relation. Spectra are individually normalized and are linear in wave number and spectral energy density (m^4), with the outer circle at $2\pi/100$ rad/m. Contours are linearly spaced. Model winds (3 to 10 m/s) are shown by the arrows; estimates of significant wave height are shown by the vertical bars (full scale is 10 m).

up to a factor of 2 in wave number and up to 45° in angle.

4. The nine wave models, when driven with a common wind field, all produce similar (but not identical) estimates, but they too are all northerly, contrary to the results of the buoys.

One explanation for this curious set of anomalies is that insufficient strength and/or incorrect timing was assigned to the wave-generating region to the north. Alternatively, all models may contain a common error in their propagation algorithm, creating excess spatial diffusion over long distances, and causing distant swell to arrive early (see the comments by Pierson and the response by Hasselmann in the panel discussion in this issue).

Regarding the variability within the measurements, the evidence suggests that the true wave spectrum was highly variable in both time and space, but that significant directional biases also occurred among the buoys, occasionally as high as 45°. This degree of natural variability and cross-instrument variability was somewhat unexpected. A further set of estimates two days later, however, suggests that the variability was not unusual. At 1200 UT on 19 March, after the *Tydeman* had left its original position to rendezvous with the *Quest*, both vessels encountered simple unimodal swell from the southwest with an SWH of about 2 m. Figure 11 shows spectral estimates for a six-hour interval from three separate buoys, all processed identically[20] by the maximum entropy method.[1] All three buoys were located within a few kilometers of one another over the six-hour interval. The evidence indicates that the Wavescan buoy was biased 15° from the other two, but also that the spectrum varied up to 15° in a three-hour interval. Thus, discrepancies of up to 30° between model and measurement are within the possible measurement error.

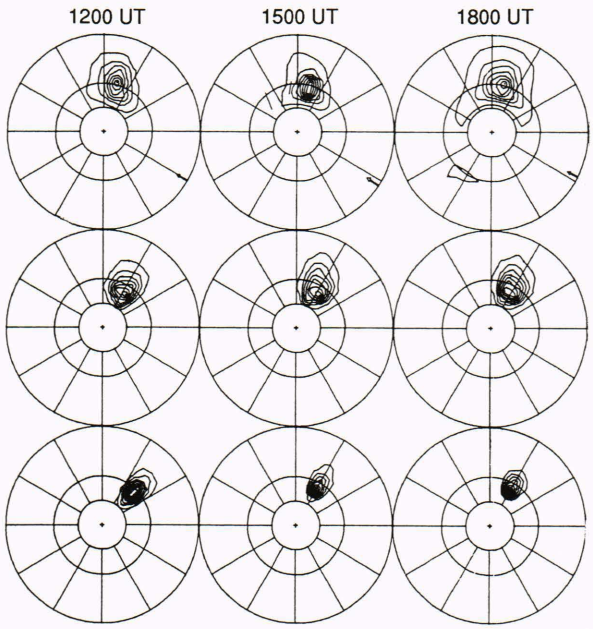

Figure 11. Three sets of three-hourly wave number spectra (converted through the deep water dispersion relation) from three directional wave buoys at the *Quest* location on 19 March 1987, all processed identically using maximum entropy. Spectra are plotted in a form identical to that of Figure 10. Top row: Wavescan buoy. Middle row: Wavec buoy No. 1. Bottom row: Wavec buoy No. 2.

LESSONS FROM LEWEX

Although not covered explicitly in this overview article, the results from LEWEX support the following general conclusions:

1. Wave model forecasts and hindcasts often disagree with one another because they are not driven by identical wind fields. Wind field differences often overwhelm model differences. The strongest model differences emerge from dynamic rapidly changing winds that commonly produce a combination of swell and wind-driven waves. Some reasons for these differences are discussed in the various model references.[12-20]

2. The directional wave spectrum in the open ocean is often multimodal; waves are therefore inadequately characterized by either their SWH or their one-dimensional (or unimodal) spectrum. Vessel motion calculations based on a unimodal spectrum will also be inadequate (see Kjeldsen; Nethercote; and de Jong and Vermeij in this issue).

3. Instruments for estimating the directional spectrum include ship sensors such as directional buoys and ship radars,[1-4] and aircraft sensors such as the SCR, ROWS, and SAR.[5-11] When properly used, each instrument appears to adequately discriminate among wave models in the open ocean. Satellite estimates of spectra can be obtained from either ROWS or SAR, but ROWS will yield a spatial average over distances equal to about half its altitude (and, therefore, distort rapidly changing spectra). The SAR will work best for near-nadir geometry at orbital altitudes of 300 km or less, and even there may still exhibit some nonlinearities.

4. Forecasts of directional wave spectra are unlikely to improve, even with perfect models, until the wind field estimates improve. Properties of the wind field may be deduced by monitoring the wave field it produces. To the extent that wave field estimates are wind-dependent (and vice versa), any inversion process must be iterative. In the future, the use of SAR estimates from satellites will depend not only on knowing both dependencies, but also on better understanding the nature of the SAR nonlinearities.[7-11] Proper modeling of the SAR transfer function will be especially important for suboptimum SAR geometries (e.g., high-altitude orbiting SAR's, such as the European ERS-1 or high off-nadir incidence angles, such as often occurred during LEWEX, for which the SAR spectrum can be appreciably distorted).

5. The temporal evolution of the dominant wave vectors at a given position is well-behaved; in LEWEX the vectors usually separated into autonomous clusters associated with individual wave systems.[20] The analogous parameter—the spatial evolution of dominant wave vectors at a (nearly) fixed time—can be monitored with either a spaceborne SAR or ROWS, and will separate into similar clusters associated with individual wave systems. The behavior of these autonomous clusters will contain clues regarding the properties of the corresponding source wind regions, so the clusters can be expected to form an important part of any inversion strategy. Indeed, the proper use of the clusters may well become an important problem in the coming decade, when simultaneous directional wind and wave measurements from spacecraft will be available.

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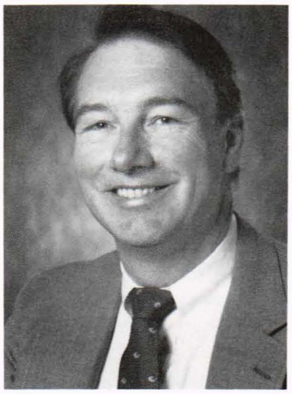

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