CHAPTER 49

SOME RESULTS FROM THE LABRADOR SEA EXTREME WAVES EXPERIMENT

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ABSTRACT

The Labrador Sea Extreme Waves Experiment (LEWEX), is an international basic research programme concerned with full-scale measurements, analysis, modelling and simulation in test basins of 3-dimensional seas. The research is carried out in order to assess the significance of 3-dimensional sea states in engineering applications. The first phase of the programme full scale wave measurements in the North Atlantic Ocean was performed at a site and time that had a high probability of encountering severe sea states.

The present publication shows examples of measured bi-modal directional sea spectra obtained with the WAVESCAN buoy and directional sea spectra measured with an airborne Synthetic Aperture Radar (SAR). Directional spectra of gravity waves are obtained with the SAR both in open waters and below an ice cover. Further work is needed in order to verify SAR-measurements with in-situ observations. In-situ measured directional spectra are also compared with hindcast spectra from the 3G-WAM model. Hindcast significant wave heights were found to be lower than the in-situ measurements.

1. INTRODUCTION

The Labrador Sea Extreme Waves Experiment (LEWEX) is a large scale international research programme currently underway with participation from United States, Canada, Norway, Netherlands, France, West Germany, Spain and the United Kingdom. LEWEX is supported by a total of 17 research institutions from these countries, and has a variety of resources available for its activities (see BALES, BEAL and FREEMAN, 1987). The first phase of the LEWEX-programme full scale sea trials was successfully performed 9-27 March 1987. Fig. 1 shows the location of the experiment offshore the great banks of Newfoundland along with the positions of vessels, aircrafts and

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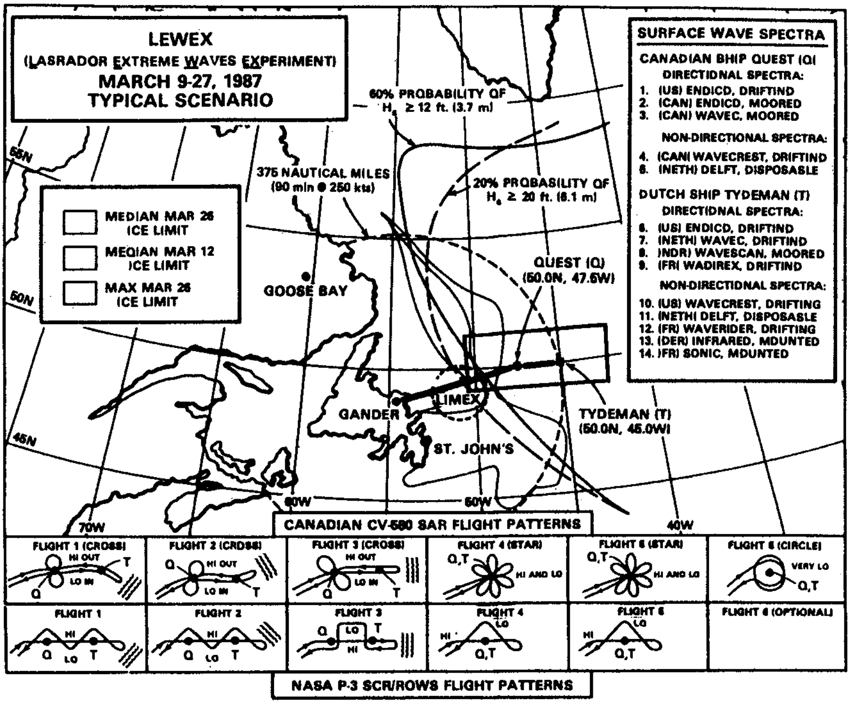


Fig. 1 LEWEX (Labrador Extreme Waves Experiment) March 9-27, 1987, typical scenario.
Measurements of directional wave spectra were made with buoys as listed in the upper right corner and with the following airborne instruments: Synthetic aperture radar SAR, Surface Contour radar SCR, Radar Ocean wave spectrometer ROWS. (From BALES, BEAL and FREEMAN 1987).

participating in-situ and airborne instruments for directional wave measurements. Field measurements were supplemented with 9 numerical wave models developed for forecast and hindcast purposes. Two of these are global models. The LEWEX field activities were coordinated with a large marginal ice zone experiment LIMEX (Labrador Ice Margin Experiment) see (BHOGAL et al., 1987). Altogether, nearly 350 people have been involved in the planning, preparation and field work associated with these two experiments. The field experiment is now being followed up with a comprehensive data analysis, comparison of results as well as a reconstruction of selected measured sea states in the advanced 3-dimensional Ocean Wave Basin at MARINTEK, Norway.

The present paper which contains only a limited number of examples of results, shows directional bi-modal sea states obtained with the WAVESCAN buoy and examples of directional spectra obtained with SAR in open waters and below ice-covers. Finally, the paper contains a comparison between the 3G-WAM model and in-situ measurements for a bi-modal sea state.

2. SCOPE AND OBJECTIVES OF LEWEX

The major aim of the LEWEX-project is to evaluate the applicability and usefulness of directional wave data for engineering design. The largest responses in terms of motion of floating structures and associated sea loads are not always encountered in the most extreme sea state (see BALES, 1987). It turns out that less severe crossing seas in some cases lead to larger responses. Bi- and tri-modal directional seas were fairly common during LEWEX and even four modes were observed in a few cases. However, none of these sea states represent really heavy seas.

The performance of the various wave directional instruments under such complicated conditions is not well known. Therefore, one of the main scientific objectives of the LEWEX project is to recommend/identify new procedures where existing techniques of measurement or analysis are inadequate. A series of measurement systems for directional seas were used during the experiment:

- Moored oceanographic buoys: ENDECO, WAVESCAN, WAVEC.
- Freely floating oceanographic buoys, WAVEC, WADIREX, ENDECO.
- Shipborne navigation radar connected to a bow-mounted wave gauge.
- The NASA Surface Contour Radar (SCR).
- The NASA Radar Ocean Wave Spectrometer (ROWS).
- The CCRS' C-band Synthetic Aperture Radar (SAR).

In addition, a large number of drifting buoys were deployed for measurements of one-dimensional frequency spectra. From the measurements it was possible to determine the capability of the airborne remote sensing radars (SCR, SAR and ROWS) for estimation of the directional wave properties over a variety of sea states.

A second major aim of the LEWEX-project is to compare various idealized wave models and operational wave forecasts with observations. In particular, the LEWEX analysis intend to assess the relative performance of the recently developed "third-generation" (3G-WAM) wind wave model against earlier first and second generation models. The 3G-WAM model incorporates superior physics over all of its predecessors at the expense of a significant increase in computational demands. The 3G-WAM model is most likely to exhibit its superiority in a complex, rapidly-changing sea state, as may occur associated with a major storm or frontal passage. No less than 9 operational wave forecast models have been run in hindcast mode for the LEWEX measurement period using common wind fields. One is thus able to assess the adequacy of directional wave estimates derived from various first, second and third generation wave forecast models in realistic complex sea states, and in situations for which a pre-existing wave field is likely to influence new wave growth. A final important objective of LEWEX is to examine the penetration of waves into the ice pack in cooperation with the Labrador Ice Margin Experiment, LIMEX, as shown in section 4.

3. EXAMPLES OF RESULTS - IN-SITU DIRECTIONAL WAVE MEASUREMENTS

The WAVESCAN metocean data acquisition buoy is shown in Fig. 2. It was first deployed from "Tydeman" at (50.0°N, 45.0°W) on 14 March 0345Z, see Fig 1. The water depth at the site was 3955 m. The buoy remained in this position until 18 March 2110Z. The buoy was then recovered and moved to (50.0°N, 47.5°W) where it remained from 19 March 0950Z to 20 March 1835Z. The buoy was finally deployed using a drag anchor for two periods between the 23 and 25 March. Data was recorded every 90 minutes throughout the experiment. During such operations, the buoy is checked daily by means of the ARGOS surveillance system. A pre-selected set of wave and meteorological parameters as well as various housekeeping data are transmitted to shore via ARGOS.

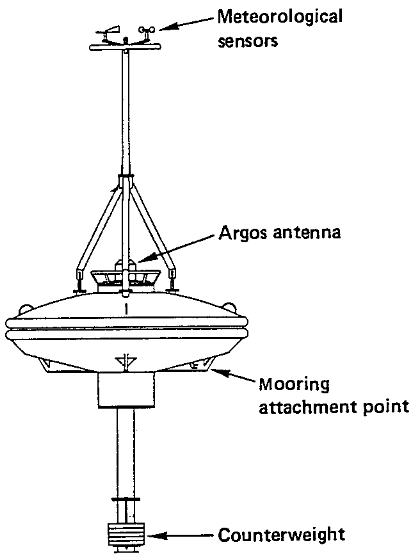
The directional analysis is carried out on the time series after the pitch/roll series have been rotated into the north-east reference system using the wave compass series. A Fast Fourier Transform is carried out on each of the time series and the resulting discrete Fourier transform of the heave series is compensated for by the manufacturer's transfer function. Similarly, the discrete Fourier transforms of the slope series are corrected for the buoy's hydro-mechanical behaviour which exhibits a response similar to a forced linear oscillator with eigenfrequency, f_0, and damping ratio, λ. For WAVESCAN, $f_0 = 0.43$ Hz and $\lambda = 0.11$. The nine possible auto- and cross-spectra are computed from 2048 data point/1Hz time series and smoothed using a moving average over 16 adjacent frequencies giving spectral estimates with 32 degrees of freedom. The directional wave spectrum may be expressed as:

$$E(\theta,f) = S(f)\, D(\theta,f) \tag{1}$$

where S is the one-dimensional frequency spectrum and D is the directional distribution:

$$D(\theta,f) = \frac{1}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{\infty}\{a_n(f)\cos n\theta + b_n(f)\sin n\theta\}, \tag{2}$$

and $\int_0^{2\pi} D(f,\theta)\, d\theta = 1$. The Fourier coefficients a_1, b_1, a_2 and b_2



Measured Variable	Sensor Type and Manufact.	Measuring Technicue	Sensor Location	Range	Accuracy
Waves: Heave Pitch Roll	Datawell Hippy 40 or 120	Double integrated accel. Signal Magnetic inclinometer	Near the buoy's COB	± 10 m ± 90° ± 90° ± 10 m/s²	< 3.0% < 0.5% < 0.5% < 3.0%
Wind direction	Wind vane	Vector averaged over a 10 min.	3.7 m above sea level	0-360°	± 4°
Wind Speed	Cup Anemometer B&G MOD 152	Vector averaged over a 10 min.	3.7 m above sea level	0-90 knots	± 4%
Pressure	Monolithic AE880 AME		3.7 m above sea level	920-1070 mBar	± 0.5 mBar
Air temperature	Platinum		3.7 m above sea level	-40°C - +45°C	± 0.4°C
Sea temperature	Termistor Aanderaa 1229		0.3 m above sea level	-4°C - +30°C	± 0.2°C
Compass	Fluxgate	Fluxgate DigiCOURSE 101E		0° - 360°	± 1°C
Internal Temperature		Trancduer LM 235		- 40°C - + 125°C	± 1°C

Fig. 2 The WAVESCAN metocean data acquisition buoy with instrumentation. (From KROGSTAD 1987).

are defined as follows (LONG, 1980):

$$a_1 = Q_{HE}/(C_{HH}(C_{EE} + C_{NN}))^{½} \quad (3)$$

$$b_1 = Q_{HN}/(C_{HH}(C_{EE} + C_{NN}))^{½} \quad (4)$$

$$a_2 = (C_{EE}-C_{NN})/(C_{EE}+C_{NN}) \quad (5)$$

$$b_2 = 2C_{EN}/(C_{EE} + C_{NN}) \quad (6)$$

In these relations, C denotes the co-spectrum and Q the quad-spectrum and the indices H heave, N slope in northerly direction and E slope in easterly direction. The main directional parameters are mean wave direction, $\theta_1(f) = \arctan(b_1/a_1)$, and circular standard deviation $\sigma_1 = 2(1-(a_1^2 + b_1^2))^{½}$.

A full directional estimate $D(\theta,f)$ based on a_1, b_1, a_2 and b_2 is the maximum entropy (MEM) spectral estimate (LYGRE and KROGSTAD, 1986):

$$D(\theta,f) = \frac{1}{2\pi}\left(1 - \phi_1 c_1^* - \phi_2 c_2^*\right)/\left(1 - \phi_1 e^{-i\phi} - \phi_2 e^{-2i\theta}\right)^2 \quad (7)$$

where

$$\phi_1 = (c_1 - c_2 c_1^*)/(1 - |c_1|^2) \quad (8)$$

$$\phi_2 = c_2 - c_1\phi_1, \quad (9)$$

$$c_1 = a_1 + ib_1 \quad (10)$$

$$c_2 = a_2 + ib_2 \quad (11)$$

c^* is the complex conjugate of c. An example of a bi-modal wave number spectrum is shown in Fig. 3. The outer circle corresponds to a wave number, $k=2\pi/L=0.01m^{-1}$, while the inner circle corresponds to $k=0.005m^{-1}$. The energy scale is linear. The plot is oriented with North at the top and shows the direction towards which the waves are travelling. The observed wind direction is indicated with an arrow. The directional spectrum shows one wave system travelling towards the north in alignment with the prevailing wind direction and another system coming in as a swell and travelling nearly perpendicular to the first system towards west. The corresponding one dimensional frequency spectrum is shown to the right. The one-dimensional spectrum is not, however, bi-modal and the superiority and necessity of a complete directional resolution is clearly demonstrated.

Fig. 4 shows the development of two swell systems with nearly opposing directions at (50°N, 47.5°W). The time interval between the displayed spectra is 1.5 hour. Finally, Fig. 5 shows an example of directional sea spectra collected in the Gulf stream where wave-current refraction will be important. These measurements were obtained at (43°N, 55°W) where a very strong current shear was detected. At this position the cold Labrador current coming from the north

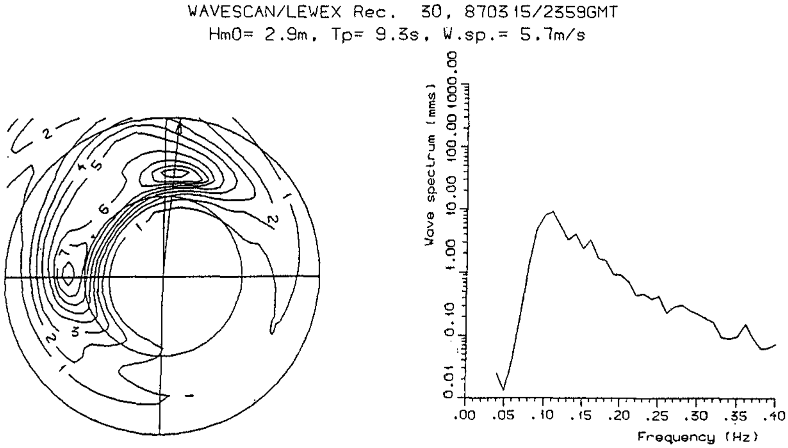


Fig. 3 Left, example of bi-modal directional wavenumber spectrum measured at grid point 1, on 16th March at 0000Z. Outer circle $k=0.01m^{-1}$, inner circle $k=0.005m^{-1}$. Right, the corresponding one dimensional frequency spectrum.

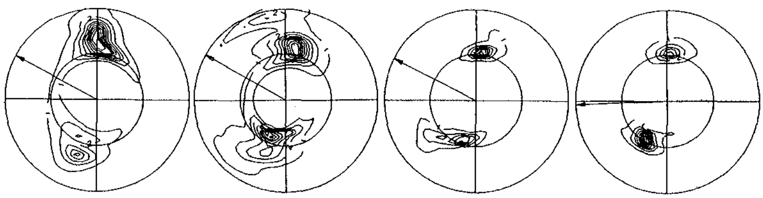


Fig. 4 Examples of development of two swell systems with nearly opposing directions at grid point 2, on 20th March at 0600Z, 0730Z, 0900Z, 1030Z.

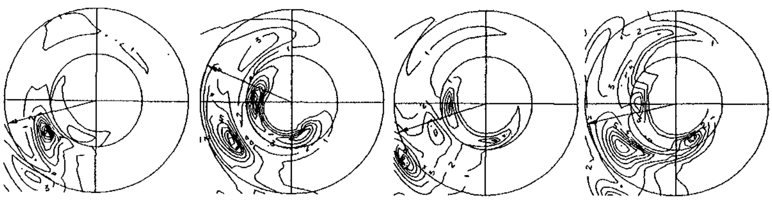


Fig. 5 Examples of wave-current refraction of the directional sea spectrum observed in the current shear between the Labrador current and the Gulf Stream at 55°W, 43°N, on 24th March at 0600Z, 0730Z, 0900Z, 1030Z.

east encounters the warm Gulf Stream coming from the south west. In this case the buoy was operated with a drag anchor and moved through the current shear. At least 3 individual wave systems can be identified in the observed directional spectra. Propagation of swell from this area may be influenced by strong currents. Such an influence shall be taken into account in wave models.

4. EXAMPLES OF RESULTS FROM THE C-BAND SAR

Part of Canada's participation in the LEWEX experiment was to fly an airborne Synthetic Aperture Radar (SAR), belonging to the Canada Centre for Remote Sensing. The radar operates in the C-band, and is designed, among other things, for research work related to the European ERS-1 and Canadian RADARSAT satellites, planned to be launched in 1990 and 1994, respectively. The CCRS Convair 580 C-band SAR was flown operationally for the first time during LEWEX. It is a digitally controlled radar, with a digital recording system, and a sophisticated real time processor. Motion compensation is carried out in real time, using output from the inertial navigation system to control the antenna drive and to perform digital corrections to the in-phase and quadrature data before processing and recording. In addition to recording the real time processed data, raw signal data may also be recorded, allowing post-flight ground processing. A more detailed description may be found in (LIVINGSTONE et al. 1987).

The SAR was flown on 6 dedicated wave flights during the experimental period, in addition to 4 ice mapping flights for LIMEX, which took place place further west in the same period. Fig. 6 (left) shows an image from the first flight on March 13 during the transit from Gander to "Quest"'s location, when waves were observed to propagate from the open water into the ice. Although we do not have ground truth data for this location, the image provides a very interesting situation for studying mechanisms of SAR imaging of ocean surface waves. SAR imaging of oceans waves is widely discussed in the literature, and a full understanding of all the mechanisms leading to SAR detection of ocean waves has not been reached at present. The imaging of waves propagating azimuthally, or along-track, is a particular point of discussion. The effects of scene motion may be divided into coherent and non-coherent classes. The most important coherent effects include velocity bunching, acceleration defocus and coherence time limitations. Non-coherent effects include scanning distortion and look mis-registration. It is important to understand the scene motion effects when interpreting SAR imagery and information, such as directional wave spectra. More detailed discussions may be found in the literature, e.g, (RANEY 1985), (RUFENACH and ALPERS 1981), ALPERS, ROSS and RUFENACH (1981), (RANEY and VACHON (1988), (HASSELMAN et. al. 1985). One of the limiting factors in imaging azimuthally travelling waves is the maximum available scene coherence time. This is often determined by estimating the target decorrelation time scale. For open water, where Bragg scattering is the dominant mechanism this is dominated by the wavelengths of the order of cm for C-band. For ice covered waters, however, the Bragg length waves are effectively filtered out and other back-scatter mechanisms dominate, providing the opportunity to study other effects, such as the velocity bunching mechanism and the look-misregistration.

Fig. 6 (left) shows a SAR scene from the marginal ice zone recorded 13th of March. The waves are propagating from the open water into the ice. Mechanisms contributing to the modulation of the image intensity could primarily be either tilt modulation or velocity bunching, or a combination of both. However, if we consider the variation of cross-section with incidence angle, this varies continuously from near nadir to more than 70 degrees. In the image, the average of this variation is compensated for, along with range and antenna pattern effects, through a real-time Sensitivity Time Control (STC). Removing the incidence angle component of the correction, averaging an ice covered portion of the image in the azimuth direction, and scaling the resulting curve with scatterometer data also acquired from the CV-580 during the experiment, we end up with a cross-section variation with incidence angle of 0.24 dB/degree in the midswath. In the same part of the image, wave image contrast was measured to 8.3 dB. Combining these two figures, we find that if tilt modulation were to be the only mechanism contributing to the wave imaging, a significant wave height of 20 m would be required, which is far higher than any wave observation reported in the area on this day. Ocean Data Gathering Program (ODGP) wave model forecasts actually predicted 3.4 m significant wave height. Velocity-bunching models in the literature (e.g. ALPERS and RUFENACH 1979) predict very narrow peaks in wave pattern image intensity. In examining the image, we find that the wave pattern in the ice, indeed has this character. The open water wave pattern, however, is somewhat broader but this could also be due to reduced resolution caused by scene coherence time limitations. Propagation of wave energy below the ice cover shall be considered in further developments of wave models.

Fig. 6 (right) shows examples of image spectra computed from the 512x512 pixel squares, at near, mid and far range for waves in ice and waves in open water. SAR image spectra will always be symmetric and the interpretation of wave direction has to rely on in-situ measurements or hindcasts. The circles correspond to wavelengths L = 50, 100 and 200 m. The spectra from the ice-covered regions are notably more complex than the open water spectra which indicate a single dominant wave system in all 3 cases. This system is also apparent in the ice spectra, but in these there are also additional contributions. In particular, the near and mid-range cases indicate a shorter wavelength component at a different propagation angle, which is not evident in the open water spectra. The reason for the latter may be scene coherence time limitations. Alternatively, this mode may be an artifact of velocity bunching when imaging waves with a relatively slow platform velocity and the geometry of this example. Theoretical work is currently being carried out in order to examine this effect more closely (VACHON, 1988). An intercomparison of SAR and WAVESCAN spectra where the latter are modified for scanning distorsion is reported in (KROGSTAD and OLSEN 1988).

5. COMPARISON WITH 3-G WAM MODEL

The third generation (3-G) WAM-model is a wave model developed by an international team of ocean wave scientist. The model takes the non-linear transfer between wave frequencies due to resonant four-wave interactions fully into account and is based on ideas

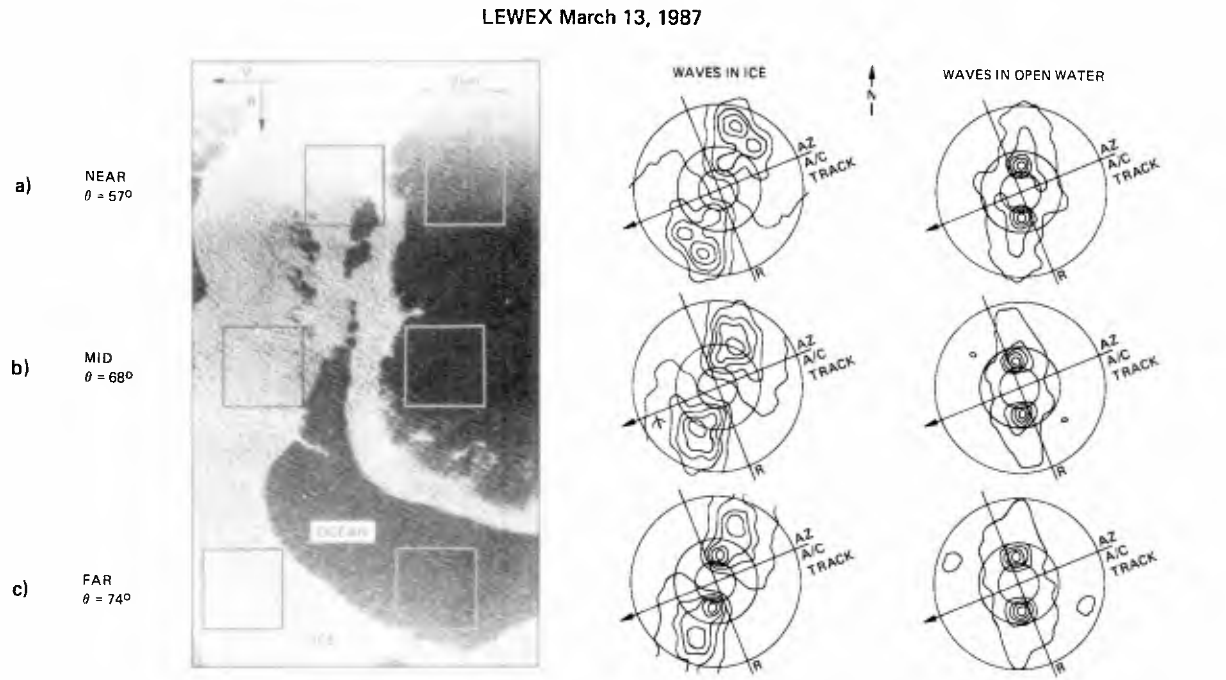


Fig. 6 Left: Real time SAR image of the ice margin obtained on March 13th. The six sub areas indicated were subjected to spectral analysis with the results appearing to the right. V is the aircraft vector, R is the range dimension, and θ is the angle of incidence. Right: SAR image spectra of the near, mid-, and far range subscenes extracted from the image. The contours of the spectra represent 10%, 30%, 50%, 70% and 90% of the peak spectral energy present. Circles correspond to wavelengths 50, 100 and 200 m.

developed at the Max Planck Institute for Meteorology (HASSELMANN et al. 1988). It is now operational at the European Centre for Medium-Range Weather Forecasts (ECMWF) and produces daily directional wave spectra over the entire globe. The model has been programmed in such a way that it can be interfaced with different wind field sources. In the LEWEX analysis a common wind field is used for all 9 wave models. However, in the present publication an alternative choice is made namely ECMWF-wind fields. The LEWEX-experiment is one of the opportunities that is available for calibration and tuning of the 3-G WAM model. Fig. 7 shows an example of hindcasted significant wave heights for the North Atlantic during the LEWEX-experiment. The position of the WAVESCAN buoy is also shown. On 16 March at 1200Z, a large storm with significant wave heights up to 10 m is present about 1130 nautical miles southwest of the WAVESCAN buoy and swell from the storm is propagating towards the buoy. Fig. 8 shows examples of directional spectra hindcasted with the 3-G WAM model and the corresponding directional spectra measured with the buoy. The directional spectra are shown in a plot with a logarithmic frequency scale. The circles correspond to frequency f = 0.05, 0.10 and 0.20 Hz. The wave energy scale is linear with constant contour. Wave direction is defined as the direction towards the waves are travelling. The wind direction is indicated by arrow.

On 16 March at 0600Z, the wind is weak and from SE. A swell is evident from the same direction. By 1200Z, the wind has increased and veered to NE. A secondary swell is now propagating out of the Labrador Basin travelling towards SE. At 1800Z a new wind-driven sea is evident, superimposed upon the two previously existing wave systems. This tri-modal sea is predicted by the 3G-WAM model, but the model overestimates the energy content in the swell travelling towards NW. On the 17th March the wind gradually turns to SE and SW, and increases again, see Fig. 9. There is a good qualitative agreement between measured and hindcasted spectra for this complex bimodal sea, although, the hindcast spectra appear to overestimate the SW swell travelling towards NE. The timing of the swell is important. The 16th at 0600Z the hindcast swell has not yet arrived at the buoy. It arrives by 1200Z and from that time there is a good qualitative agreement between bi-modal measured and hindcast directional spectra. There is also good agreement for the case shown on the 17th March. However, the hindcast significant wave heights are biased, and 20-30% lower in these examples than in the measurements. Further analysis and comparisons are ongoing.

6. CONCLUSIONS

1. - Results from the LEWEX-experiment indicate that some of the most important parameters for a proper description of directional sea states are the number of individual sea systems contained in the directional sea and their relative orientation. It is expected that directional spectra to be used in the future for engineering design will be more complex, and thus closer to realistic sea states. Thus, the demand that ocean basins be able to simulate more realistic directional sea states for engineering applications, will increase. A swell-corrupted wind sea is a quite common situation, as the LEWEX full scale directional wave measurements show.

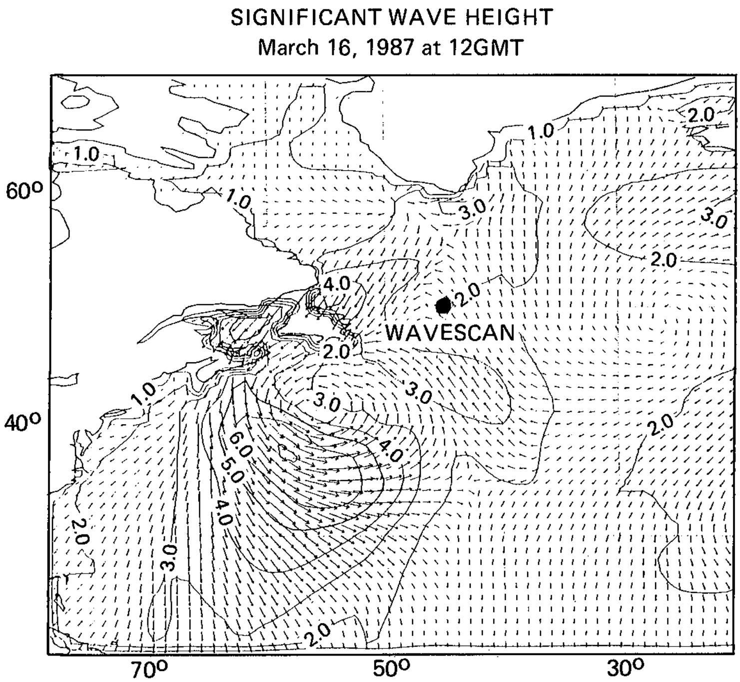


Fig. 7 Hindcast of wave height fields for the North Atlantic made by the 3G-WAM model driven by ECMWF wind fields. The contours are of wave height in meters and the arrows point in the mean wave direction. The location of the WAVESCAN buoy is shown. (From ZAMBRESKY 1988).

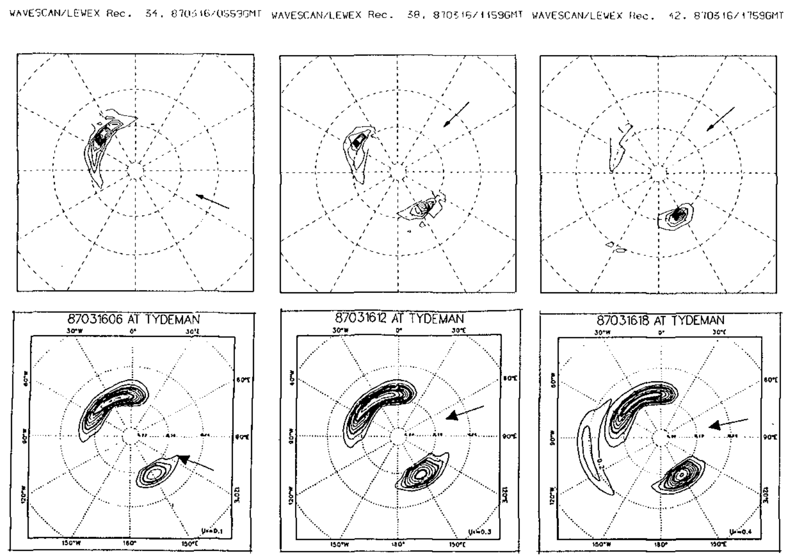


Fig. 8 Above: Directional spectra measured with WAVESCAN for 16th March 0600Z, 1200Z, 1800Z. Below" Hindcast directional spectra from the 3G-WAM Model (From ZAMBRESKY 1988).

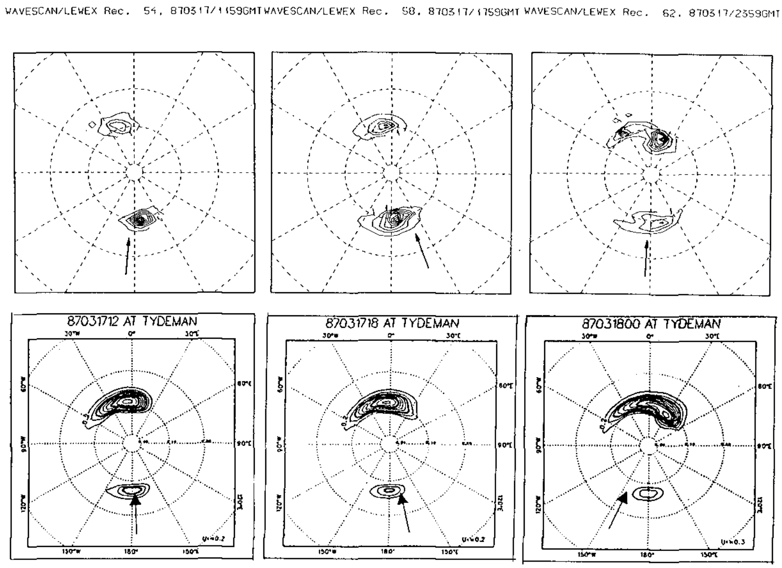


Fig. 9 Above: Directional spectra measured with WAVESCAN for 17th March 1200Z, 1800Z and 18th March 0000Z. Below: Hindcast directional spectra from the 3G-WAM Model (From ZAMBRESKY 1988).

2. - Validation of the capability of airborne and spaceborne (shuttle) SAR, SCR and ROWS to detect directional distributions of ocean gravity waves will be an important aspect of the LEWEX-programme. A method is suggested by (KROGSTAD and OLSEN 1988) for modifying in-situ data to provide spectra which are equivalent to those expected from an ideal airborne scanning instrument. Still much validation of results is needed in this area. In the future it is foreseen that global orbiting space shuttles and satellites will provide us with a large quantity of directional sea spectra covering all sea areas of the world. Such data should be assimilated into wave forecasting models.

3. - Significant wave heights hindcast with the 3G-WAM model were found to be 20-30% lower than in-situ measurements and measured swell components were somewhat delayed in time. Accuracy of wave forecasts/hindcasts will depend on accuracy of the chosen input wind fields.

4. - Propagation of wave energy below the ice cover shall be considered in further developments of wave models.

5. - Propagation of swell in this part of the North Atlantic may be influenced by strong currents, and such an influence shall be taken into account in wave models.

7. ACKNOWLEDGEMENTS

The LEWEX-project is organized within NATO as a multi-lateral scientific research programme. Two working groups are responsible for the performance of the LEWEX-project. These are RSG-1 and RSG-2. A list of participating scientists is found in (BALES, BEAL and FREEMAN 1987).

8. REFERENCES

ALPERS, W.R. and RUFENACH, C.L., 1979: "The effect of Orbital Motions on Synthetic Aperture Radar Imagery of Ocean Waves" IEEE Transactions on Antennas and Propagation, Vol. AP-27 (5) pp. 685-690.

ALPERS, W.R., ROSS. D.B. and RUFENACH, C.L., 1981: "On the Detectability of Ocean Surface Waves by Real and Synthetic Aperture Radar". J. Geoph. Res. Vol. 86 (C7) pp. 6481-6498.

BALES, S.L., BEAL, R.C., FREEMAN, N.G., 1987: "LEWEX-Science Plan". DTNSRDS. Bethseda, Maryland, USA.

BALES, S.L., 1987: "Practical Seakeeping Using Directional Wave Spectra" in Symposium on Measuring Ocean Waves from Space Johns Hopkines APL Technical Digest, Vol 8 No. 1 January - March 1987. The Johns Hopkins University Applied Physics Laboratory. Laurel, Maryland, USA.

BHOGAL, A.S., ARGUS, S.A., FREEMAN, N.G., 1987: "LIMEX/LEWEX Operations informations". Canada Centre for Remote Sensing. Ottawa, Canada, January 1987.

HASSELMAN, K., RANEY, R.K., PLANT, W.J. ALPERS, W.R., SHUCHMAN, R.A., LYZENGA, D.R., RUFENACH, C.L. and TUCKER, M.J., 1985: "Theory of Synthetic Aperture radar Ocean Imaging". A MARSEN View. J. Geoph. Res. Vol. 90 (C3). pp 4659-4686.

HASSELMANN, S., HASSELMANN, K., BAUER, E., JANSSEN, P.A.E.M., KOMEN, G.J., BERTROTTI. L., LIONELLO, P., GUILLAUME, A., CARDONE, V.C., GREENWOOD, M., REISTAD, M., ZAMBRESKY. L., and EWING, J.A., 1988: "The WAM model - a third generation ocean wave prediction model", submitted to J. Phys. Ocean.

KROGSTAD, H.E., 1987: "Wave Data Collected by WAVESCAN during the Labrador Sea Extreme Waves Experiment (LEWEX)", Rep.no. 87.111, OCEANOR, Oceanographic Company of Norway, Trondheim, Norway.

KROGSTAD, H.E., OLSEN, R.B., 1988: "An Intercomparison of SAR and Buoy Directional Wave Spectra from LEWEX". To be presented at IGARSS'88 - International Geoscience and Remote Sensing Symposium. Edinburgh, Scotland 1988.

LIVINGSTONE, C.L., GRAY, A.L., HAWKINS, R.K., DEANE, R.A., HALBERTSMA, J.G. and OLSEN, R.B., 1987: "CCRS C-band Airborne Radar - System Description and Test Results". Presented at the 11th Canadian Symposium on Remote Sensing.

LONG, R.B., 1980: "The Statistical Evaluation of Directional Spectrum Estimates Derived from Pitch/Roll Data". J. Phys. Ocean. 10, pp. 944-52.

LYGRE. A. and KROGSTAD, H.E., 1986: "Maximum Entropy Estimation of the Directional Distribution in Ocean Wave Spectra", J. Phys. Ocean, 16, pp. 2052-2059.

RANEY. R.K., 1985: "Theory and Measure of Certain Image Norms in SAR". IEEE Transactions of Geoscience and Remote Sensing, Vol. GE-23 (3), pp 343-348.

RANEY. R.K. and VACHON. P.W., 1988: "SAR Imaging of Ocean Waves from an Airborne Platform: Focus and Tracking Issues". Submitted to J. Geoph. Res.

RUFENACH, C.L. and ALPERS, W.R., 1981: "Imaging Ocean Waves by Synthetic Aperture Radars with Long Integration Times". IEEE Transactions on Antennas and Propagation Vol. AP-29 (3) pp. 422-428.

VACHON, P.W., 1988. Canada Centre for Remote Sensing. Ottawa. Canada. (Personal communication).

ZAMBRESKY, L.F., 1988. GKSS Forschungszentrum Geesthacht. Federal Republic of Germany, currently at European Centre for Medium-Range Weather Forecasts. (Personal communication).