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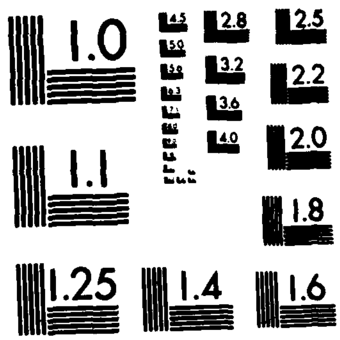

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18. SUPPLEMENTARY NOTES

Due to fiscal constraints and management decisions the SEBEX program has evolved into NRL Remote Sensing Program on wave-current interactions. The aims of the present program are the development and validation of appropriate hydrodynamic and electromagnetic models by (Continues)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Remote sensing
Surface effects
Bathymetry
SAR imagery
Bragg scattering
Ocean currents
Atmospheric stability

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A remote sensing experiment in the Nantucket Shoals (SEBEX) is proposed for delineating and quantifying the oceanographic processes responsible for the surface expressions of bathymetry in the wave field and radar imagery (i.e., SAR and SLAR) over shallow water. For this purpose simultaneous and coordinated remote sensing, oceanographic, meteorological, hydrographic and bathymetric measurements are suggested. A successful experiment of this type requires precise navigation, better than ±0.1 nmi, achieved with Loran C, and detailed three-dimensional sampling

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18. SUPPLEMENTARY NOTES (Continued)

ocean field experiments, controlled wavetank studies, and mathematical descriptions of the physical processes responsible for the surface expressions of bottom topography among others.

Three ocean field experiments are contemplated: one took place in July 1982 in Phelps Bank, Nantucket Shoals, Mass.; one in the fall of 1984 exploiting the availability of SIR-B shuttle flight; and another one in 1986.

20. ABSTRACT (Continued)

of the subsurface current field and temperature structure for proper correlation between the parameters. On the surface the Bragg resonant waves should be sampled at least at the resolution of SAR and SLAR radar systems. In SEBEX the dynamics of fronts and their interactions with internal waves also will be investigated.

CONTENTS

A REMOTE SENSING EXPERIMENT IN THE NANTUCKET SHOALS (SEBEX)*

1. Introduction

SEASAT synthetic aperture radar (SAR) images of the ocean contain a wealth of information on ocean features ranging from the mesoscale to internal and surface waves (see Beal et al. 1981). In particular the SAR imagery of shallow water (i.e., English Channel and Nantucket Shoals) have features related almost in a one-to-one basis with the bathymetry of the region. Airborne SAR and SLAR (side-looking airborne radar) imagery also contain similar manifestations.

There is no doubt that DeLoor (1978) was the first to realize SLAR images of shallow water (off the Dutch coast) contained features relating to the bottom topography. Moreover in a recent study Kasischke et al. (1980) found high correlation, up to one hundred percent in some cases, between linear traces of image intensity and corresponding bathymetry profiles for five different shallow ocean sites.

The basic scattering mechanism of electromagnetic (EM) waves from the ocean surface is well accepted to be Bragg scattering (see Wright 1978; Valenzuela 1978). Short gravity waves, of length proportional to the EM radiation wavelength, traveling along the line of sight, are the main contributors to the backscattered power (for depression angles between 20 and 70 degrees) to SAR and SLAR, except for some other contribution by wave breaking (see Keller et al. 1981). The penetration of microwave EM radiation into sea water is small. The amplitude of the EM fields is reduced to e^{-1} (where $e = 2.71828...$ the Napierian number) for the "skin depth" which is of the order of a centimeter for the *L*-band 23.5 cm radiation of SEASAT SAR, while the water depth even for shallow water is in the order of meters. Clearly, the radar imagery content cannot be the result of direct probing of the bottom topography by the EM radiation. The surface manifestations of bathymetry must be related to hydrodynamic processes which couple the surface waves to the local bathymetry through the water column. Some of the processes involved are cross-shoal overflow, refraction of surface waves, turbulent tidal flow and modification of Bragg scatterers amplitude on the surface by nonuniform shear currents and breaking long gravity waves. There also exist thermal effects on mixing over shoals on stability, wave generation rate and on surface temperature signature.

Considerable evidence on surface expressions of bathymetry from SEASAT SAR images and airborne SAR and SLAR systems is already available. Figure 1 is one such case from SEASAT SAR, with spatial resolution of about 25 m, taken over the Nantucket Shoals on August 27, 1978. A number of other features such as internal waves, current shears and temperature structure variability are also observed in this image. Fortunately during May 1978 to May 1979 bimonthly hydrographic measurements at 5 n.mi. resolution were performed by Limeburner & Beardsley (1979); also see Limeburner et al. (1980). The set of September 14-19, 1978 was the closest to the time the SAR image (Fig. 1) was taken. Figures 2-4 are temperature, sigma-*T* and salinity surface contours obtained during these measurements. Other similar results were obtained at 10, 20, 30, 40 m, and 5 m above the bottom.

Although these measurements did not coincide exactly when the SAR image was taken, they are close enough to provide a great deal of physical insight into the processes involved in Fig. 1. For

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Fig. 1 — A SEASAT SAR image, digitally processed by JPL, of the Nantucket Shoals taken on August 27, 1978 **(8 hours, 34 minutes, 14 seconds; Eastern Standard Time).** The resolution is about 25 meters

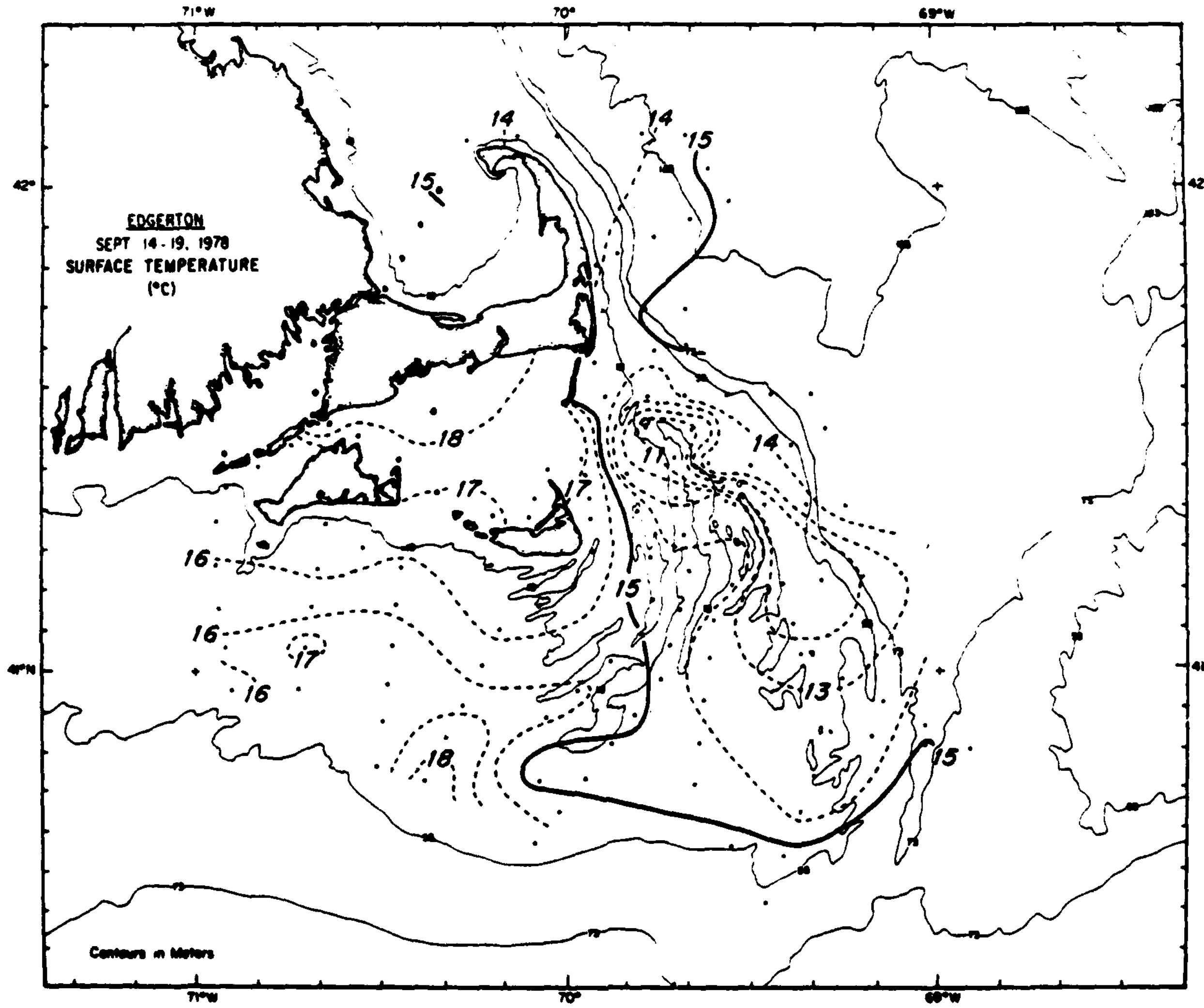

Fig. 2 — Contours of surface temperature (°C) during September 14-19, 1978 from Limeburner & Beardsley (1979)

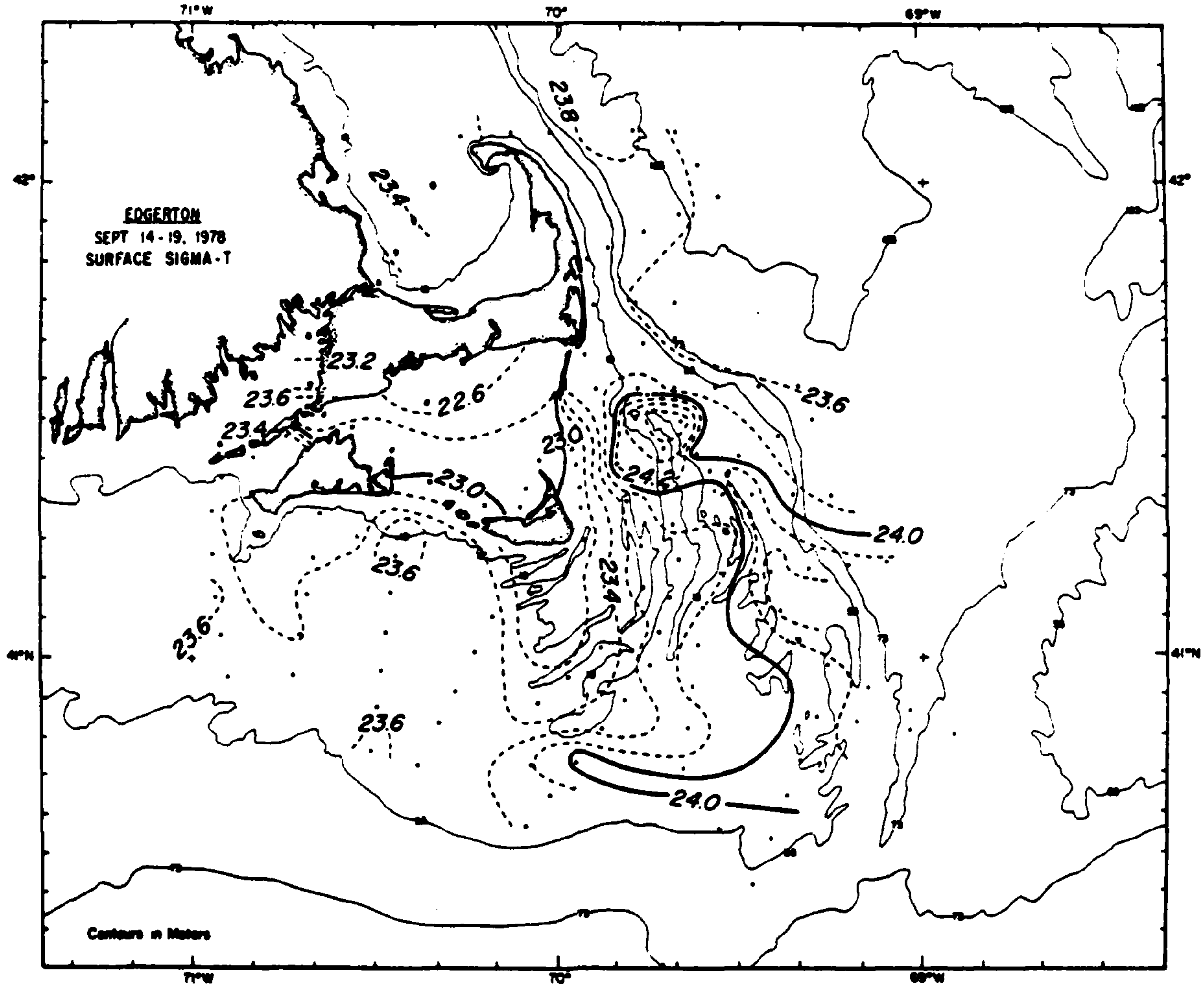

Fig. 3 — Contours of surface sigma-T $(\rho_w - 1) \times 1000$ during September 14-19, 1978 from Limeburner & Beardsley (1979)

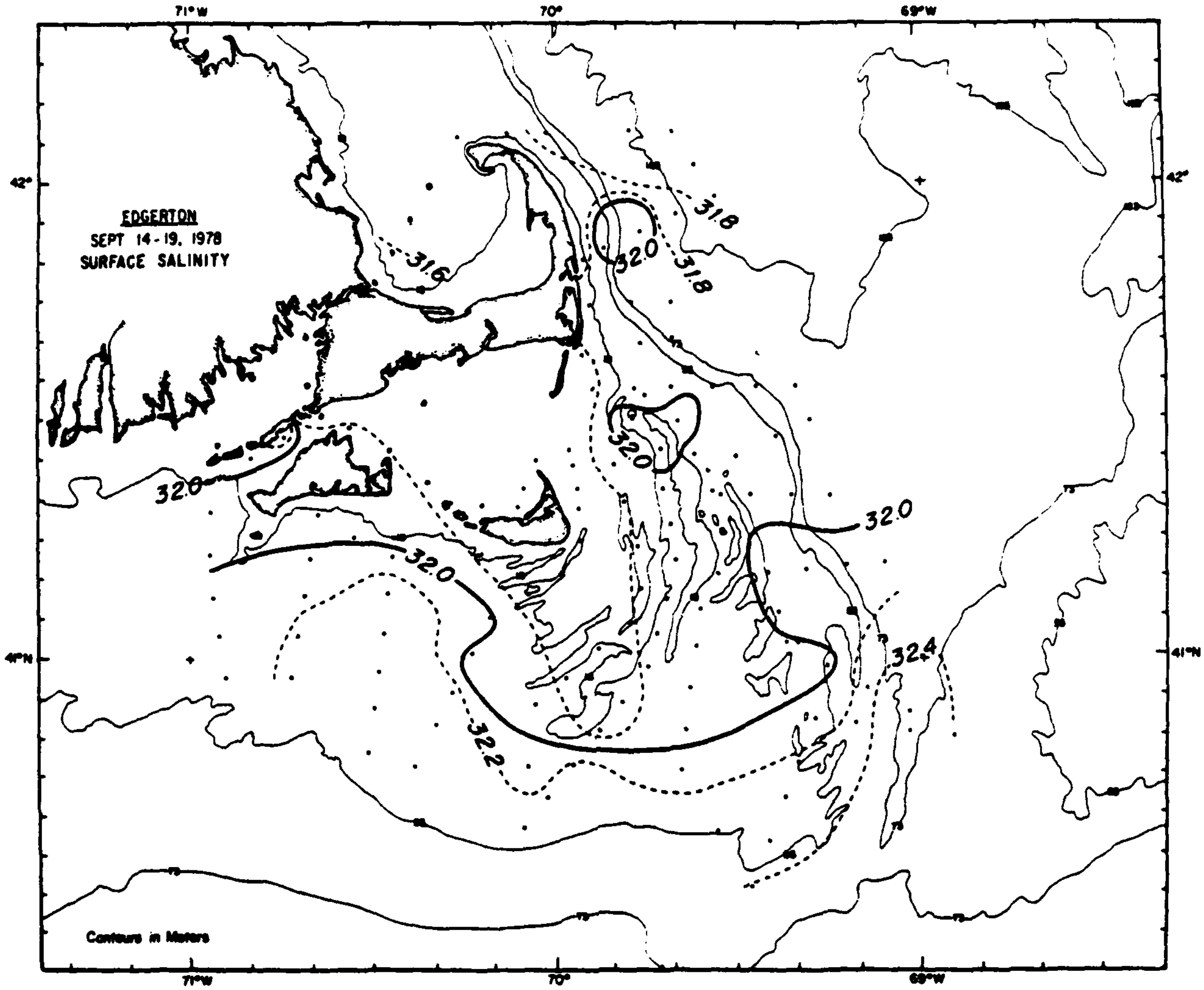

Fig. 4 — Contours of surface salinity (‰) during September 14-19, 1978 from Limeburner & Beardsley (1979)

example the region of cold "upwelling" water evident in Figs. 2-4 appears dark in the SAR image, since the Bragg scatterers (waves 30 to 40 cm in length) have relative small amplitude as the water is colder than the air (region of stable atmospheric conditions) and the backscatter power is small. On the other hand in the area of warmer water on the shoals, the SAR image is bright, the backscatter is stronger from the well developed Bragg resonant waves (region of neutrally stable or nearly unstable atmospheric conditions).

What is needed next to keep progressing is a repeat of Limeburner & Beardsley's measurements over the shoals, but in a more synoptic manner and complemented with measurements of the surface waves, 3-dimensional current field in the water column, the meteorology, bathymetry and remote sensing to quantify the processes responsible for the surface expressions of bathymetry. With this purpose in mind about 30 leading scientists from a number of academic institutions (i.e. MIT, JHU, WHOI, etc.) and governmental agencies (i.e. NOAA, NASA, ONR and NRL) joined with the support of NASA, NOAA and ONR in a workshop organized by NRL and hosted by WHOI during August 4-5, 1980 to review the present knowledge on this problem and discuss the possibility of a remote sensing experiment in the Nantucket Shoals for Fall 1982 or 1983 to address this question.

The ideas and recommendations that resulted from the Woods Hole Workshop on SEBEX (acronym for surface expressions of bathymetric remote sensing experiment) are given in Valenzuela & Chen (1980) and in expanded form by Phillips & Mollo-Christensen (1981).

The MARSEN 1979 experiment in the German Bight and off the Dutch coast collected some SAR and SLAR images containing bottom related features. Analysis of these images with environmental data available could be a valuable input to the planning of SEBEX. Additional input should also be forthcoming from the ARSLOE experiment which took place during October-November 1980.

2. Scientific objective and organization

The scientific objective of SEBEX is to perform simultaneous and coordinated remote sensing, meteorological, oceanographic and hydrographic measurements in the Nantucket Shoals, including a high resolution (25 to 100 m spacing) survey of the bottom topography to quantify the processes responsible for the surface expressions of bathymetry in the wave field, radar and other imagery of shallow water (Fig. 5 is an illustration of SEBEX). In particular will be considered the effects of air-sea temperature difference (atmospheric stability), nonuniform currents, complex bottom topography with current fields and temperature structure. Furthermore, in SEBEX the dynamics of fronts and their interaction with internal waves will be investigated. Every year (except during the winter months of well mixed water) a thermal front develops about 40 km east of Nantucket Island as a result of cold upwelling water on the continental slope. Limeburner & Beardsley (1980) have investigated this phenomenon and conclude the upwelling, in this case, is not due to local wind forcing.

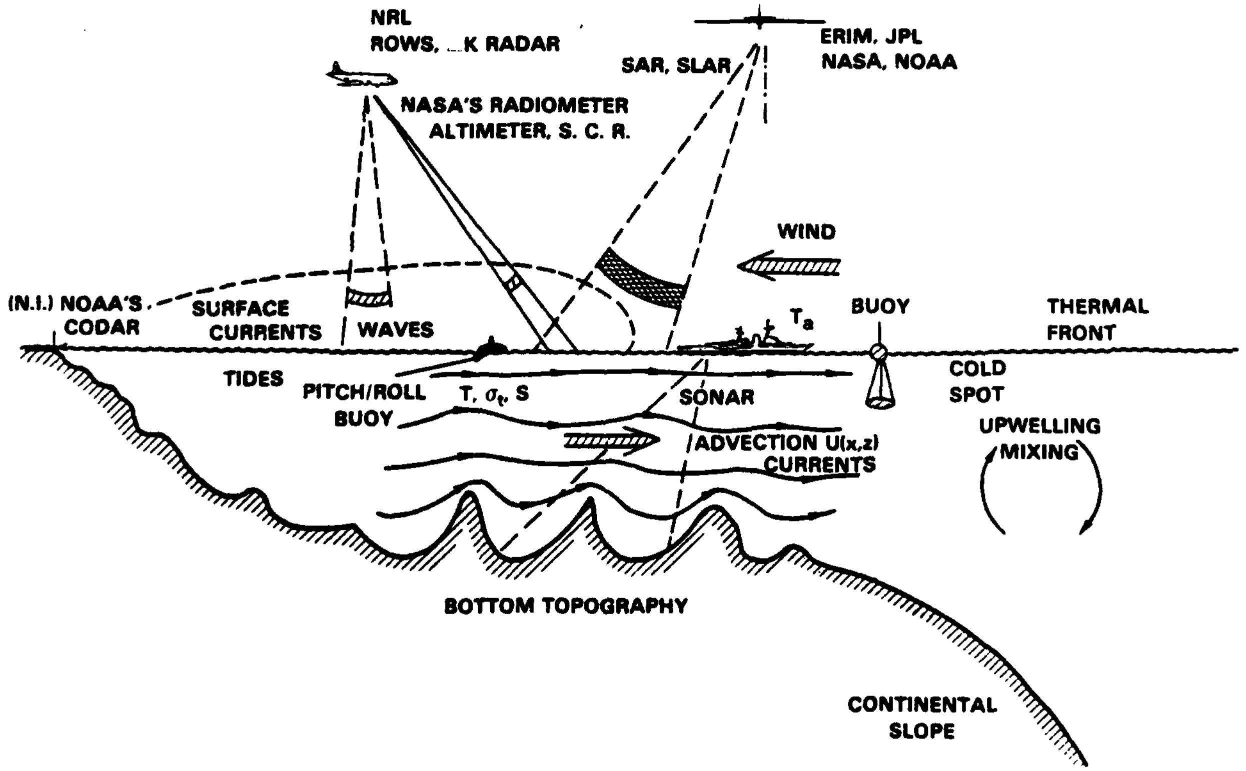

Fig. 5 — Illustration of a remote sensing experiment in the Nantucket Shoals—SEBEX

A Steering Committee was formed to advise in the organization and planning of SEBEX, members are:

G.R. Valenzuela, Naval Research Laboratory—Chairman
D.T. Chen, Naval Research Laboratory—Executive Secretary
R.C. Beardsley (replaced by G.T. Csanady),
  Woods Hole Oceanographic Inst.
W.E. Esaias, NASA/Langley Research Center
N.E. Huang, NASA/Wallops Flight Center
E. Mollo-Christensen, Massachusetts Institute of Technology
O.M. Phillips, The Johns Hopkins University
L.J. Pietrafesa, North Carolina State University
R.A. Shuchman, Environmental Research Institute of Michigan
D.J.P. Swift (replaced by D.B. Ross), NOAA/Atlantic Oceanographic
  & Meteorological Laboratories
P. Twitchell, ONR/ Eastern-Central Regional Office.

3. The coupling of the surface wave field with the bathymetry

The coupling of the surface waves with the bottom topography is accomplished through the subsurface current field, and the temperature field and other parameters may also be involved. Generally currents in the ocean may be divided into constant and time-dependent flows. In the Nantucket Shoals the dominant mixing process is tidal related and the currents can be as large as 1 m/sec or so. So in the Nantucket Shoals we are mostly interested in flows with periods equal or less than the tidal period. The mean currents are of smaller magnitude. The effect of bottom topography on ocean circulation is a very complex problem and even today this is an active area of research.

Fofonoff (1962) showed the total mass transport in the ocean may be decomposed into Ekman, baroclinic and barotropic contributions. The Ekman transport is wind stress driven, the baroclinic transport is related to the density field, and the barotropic part is driven by the divergences of the Ekman and baroclinic transports. Assuming that bathymetry does not penetrate up to the depth of appreciable horizontal density gradients, Rattray & Dworski (1978) find bathymetry affects mostly the barotropic part of the transport. Topographic influences on tidal currents have been investigated by Loder (1980), who found significant tidal rectification by the slopes of the Georges Bank. There are also available a number of numerical models for computing the flow near coastal areas, such as those by Hulburt & Thompson (1973) and Prell & O'Brien (1980).

It is well known that ocean waves are refracted near coasts and the phase speed of shoaling waves depends on water depth. For a constant depth "h" the phase speed C of infinitesimal waves is given by

$$C = \left(\frac{g}{k}\right)^{1/2} \tanh^{1/2}(kh), \qquad (3.1)$$

where g is gravity and k is the wavenumber. As the amplitude "a" of the shoaling waves increases the phase speed also increases, but ultimately breaking takes place as the a/h ratio becomes larger than 0.827 (for sloping bottoms wave breaking occurs for smaller a/h ratios, see Keller et al. (1981).

Horizontal shearing currents $\mathbf{u}(x, y)$ advect, refract and modify the amplitude and wavenumber of surface waves (see Phillips 1981). These effects on surface waves may be analyzed with the Boltzmann transport equation for the waveheight spectrum $F(\mathbf{k}, \mathbf{x}, t)$ (see Hasselmann 1968). That is

$$\left(\frac{\partial}{\partial t} + \frac{\partial \omega}{\partial k_i}\frac{\partial}{\partial x_i} - \frac{\partial \omega}{\partial x_i}\frac{\partial}{\partial k_i}\right) F(\mathbf{k}, \mathbf{x}, t) = S,$$

where

$$\frac{\partial x_i}{\partial t} = \frac{\partial \omega}{\partial k_i} = v_i \qquad \frac{\partial k_i}{\partial t} = -\frac{\partial \omega}{\partial x_i} \tag{3.3}$$

specify the trajectories of the wave field and the angular frequency is $\omega = \omega_0 + \mathbf{k} \cdot \mathbf{U}(x, t)$. $\mathbf{k}$, is the wavenumber vector, v_i is a component of the group velocity $\mathbf{v}$ and S is the source function.

For waves propagating in a vertical shear current $U(z)$ the frequency of the wave is modified according to

$$\omega = \omega_0 + \alpha(k)\ \mathbf{k} \cdot \mathbf{U}(0), \tag{3.4}$$

where $\alpha(k) \leqslant 1$ (see Shemdin (1972)). The value of $\alpha(k)$ is obtained from the solution of the corresponding boundary value problem.

In practice the shear flow in the air should also be included in the analysis. Plant & Wright (1980) used the variational method to derive the phase speed of a surface wave for coupled logarithmic shear flows in the air $U_a(z)$ and water $U_w(z)$ and find

$$C \doteq \pm C_0 + U_w(-0.044\ \mathrm{L}) \mp O\left(\frac{\rho_a U_a^2}{\rho_w}\right), \tag{3.5}$$

where L is the water wave wavelength and ρ_a, ρ_w are the densities of air and water, respectively. For arbitrary flow profiles the phase speed may be obtained by numerical solution of the boundary value problem (Valenzuela 1976). Periodic flows such as the orbital speed of long gravity waves modulate the amplitude and wavenumber of short gravity waves (see Keller & Wright 1975).

Another process of concern to SEBEX is the effect of atmospheric stability on the amplitude of the Bragg resonant waves as was discussed in the Introduction in relation to Fig. 1. The coupling of short gravity waves with capillary waves was investigated by Valenzuela & Wright (1979) using a phenomenological model including the input from the wind, energy transfer by second order nonlinear resonant interactions, and quadratic dissipation. If we denote by $F(k_1)$ the waveheight spectrum of short gravity waves and by $F(k_2)$ the spectrum of capillary waves, then the initial value problem of the coupling of these two wave systems may be expressed in the form

$$\left.\begin{aligned} \frac{dF(k_1)}{dt} &= \beta(k_1)F(k_1) - \alpha F(k_1)F(k_2) \\ \frac{dF(k_2)}{dt} &= \beta(k_2)F(k_2) + \alpha F(k_1)F(k_2) - \gamma F^2(k_2) \end{aligned}\right\} \tag{3.6}$$

and for water wave systems $\gamma/\alpha >> 1$.

At equilibrium the magnitudes of $F(k_1) = F_0(k_1)$ and $F(k_2) = F_0(k_2)$ are given by

$$\left.\begin{aligned} F_0(k_1) &= \alpha^{-1}\left[\frac{\gamma}{\alpha}\beta(k_1) - \beta(k_2)\right] \\ F_0(k_2) &= \alpha^{-1}\beta(k_1) \end{aligned}\right\}. \tag{3.7}$$

According to this model, both the magnitude of $F_0(k_1)$ and $F_0(k_2)$ depend on the growth rate $\beta(k_1)$ of the short gravity waves. α is the strength of the second order nonlinear resonant interactions, and γ is the strength of the quadratic damping.

In experimental studies by Plant & Wright (1977), it was found the wind growth rate of short gravity waves is well approximated by the expression

$$\beta(k_1) = 0.04 \frac{u_*^2}{\omega(k_1)} \cdot k_1^2. \qquad (3.8)$$

where u_* is the air friction velocity and $\omega(k_1)$ is the angular frequency of the short gravity waves. u_*^2 is proportional to the tangential stress on the surface and this quantity depends on the atmospheric stability (i.e., the air-water temperature difference) (see Kondo 1975). Therefore substituting (3.8) into (3.7) we find the spectrum of short gravity waves depends on the atmospheric stability. For neutral stability ($T_a = T_w$)

$$u_* = u_{*0} \doteq 0.05 \text{ Wind}, \qquad (3.9)$$

where T_a and T_w are the temperature in the air and water, respectively. Therefore the amplitudes of short gravity waves are larger for unstable atmospheric conditions than for neutral or stable conditions since

$$u_{*_u} \geqslant u_{*_o} \quad (T_w > T_a, \text{ unstable atmospheric conditions}) \qquad (3.10)$$

and

$$u_{*_s} \leqslant u_{*_o} \quad (T_w < T_a, \text{ stable atmospheric conditions}). \qquad (3.11)$$

Accordingly our phenomenological model (3.6) for the coupling of short gravity waves and capillary waves seems to explain the observations regarding Fig. 1 made in the Introduction.

4. Radar imaging of the ocean surface

In this section we discuss briefly the mechanisms involved in the imaging of ocean waves with SLAR and SAR systems. As we discussed earlier, the main mechanism in the scattering of EM waves from the ocean surface is Bragg scattering (Wright 1978). The principal scatterers of microwaves are short gravity waves traveling along the line of sight of wavelength proportional to the radar wavelength (see Keller et al. 1981).

For SLAR the intensity of the radar image is directly related to the normalized radar cross-section $\sigma_0(\mathbf{x})$ of the ocean which is proportional to the backscattered power (see Valenzuela 1980; Alpers et al. 1981). Therefore, for SLAR the image intensity I_{SLAR} is given by

$$I_{SLAR} = \sigma_0(\mathbf{x}). \qquad (4.1)$$

For SAR the image intensity is more complex since it depends not only on the normalized radar cross-section, but also on the phase of the backscattered power which is related to the line of sight velocity of the Bragg resonant waves including advection by the orbital velocity of the dominant waves of the ocean and currents. Hence the image intensity in SAR I_{SAR} is a complicated expression (see Hasselmann 1981; Alpers et al. 1981; Harger 1981). However in the limiting case of high resolution I_{SAR} has a simple interpretation; it is the map of the stationary points on the surface (see Valenzuela 1980) such that

$$I_{SAR} = \frac{\sigma_0(\mathbf{x} + \delta x)}{\kappa_\phi(\mathbf{x} + \delta x)} \qquad (4.2)$$

depending on the normalized radar cross-section of the ocean and is weighted by the curvature of the phase distortion $\kappa_\phi(\mathbf{x})$ introduced by the wave motion and azimuthally displaced by δx because of radial components of velocity on the surface.

We emphasize that in SEBEX the highly developed Bragg scattering models will be used fully to interpret the output of the remote sensors. Also "inverse" scattering techniques (see Long 1981) are available for inferring the surface wave field from the radar images.

5. Discussion and conclusions

It is not possible to give a detailed description of the experimental program in SEBEX at this time, since fiscal constraints and uncertainties have not allowed a finalization of plans. The preliminary ideas on SEBEX have been given in Valenzuela & Chen (1980) and in Phillips & Mollo-Christensen (1981). The original plans concentrate on the measurements in the Davis Bank and in the quasi-stationary thermal front east of Nantucket Island (see Fig. 6) for 2- to 3-week periods during the Fall of 1982. However, now it seems more likely that SEBEX will take place in the Fall of 1983 at the earliest, with some preliminary pilot experiments for the Summer or Fall of 1982.

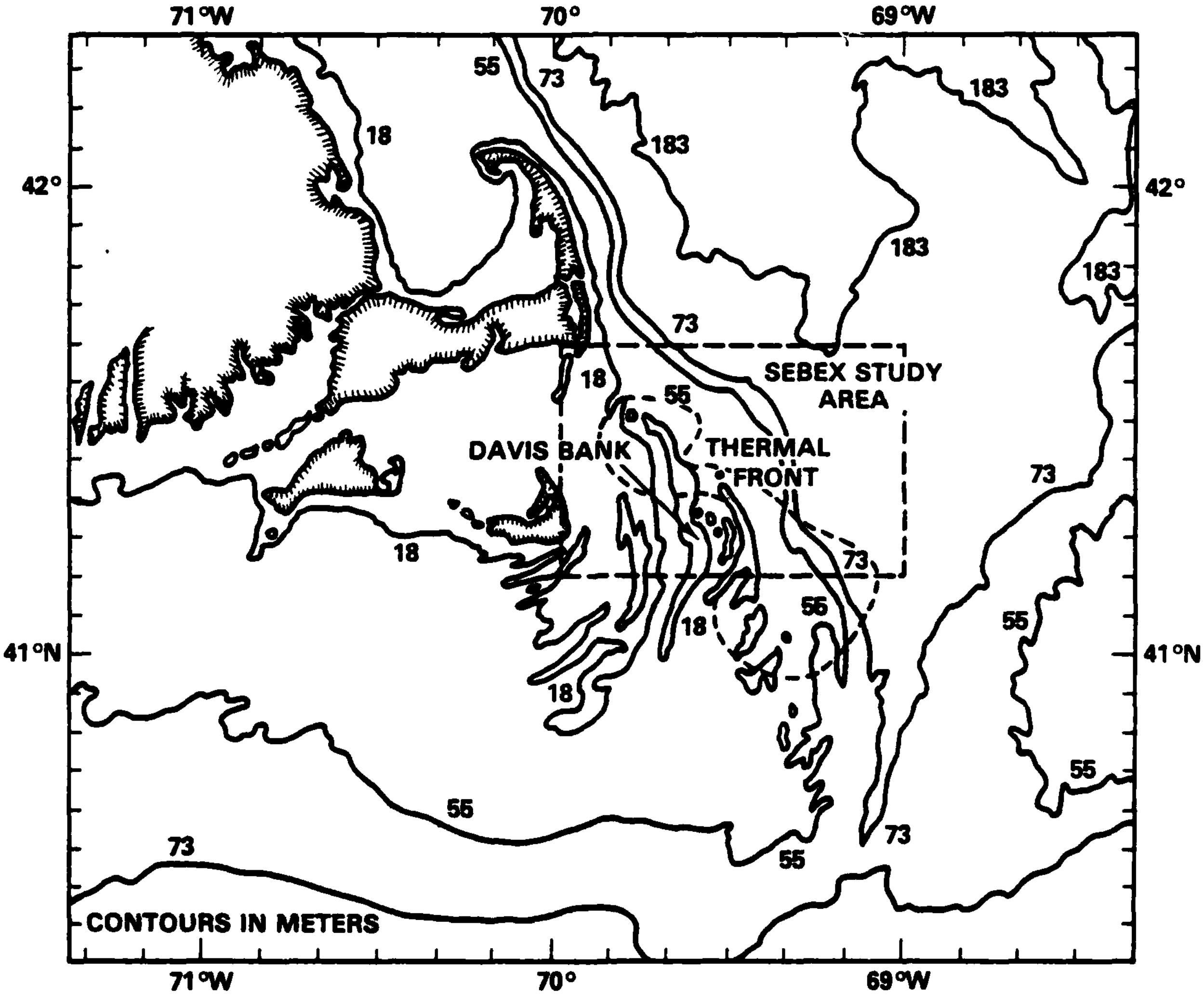

Fig. 6 — Study area in SEBEX

The success of an experiment such as SEBEX is intimately related to accurate navigation/positioning, better than the ±0.1 n.mi., achievable with Loran *C*, for proper cross-correlation between the surface wave field, radar imagery, bathymetry and other subsurface measurements such as currents and temperature. A high-resolution survey of the local bathymetry is required with a spacing of 25 m. Also the current fields should be sampled horizontally according to the scale of the bathymetry features, 1-2 km in a transverse direction and 5-10 km in the longitudinal direction. The sampling in depth should probably be in the order of 2-5 m, except near the surface where a finer sampling might be required to characterize the highly sheared current profile. The Bragg resonant waves on the surface should be sampled at least within the resolution of SAR and SLAR images, 10-20 m. Near-surface currents probably will be measured with NOAA's CODAR HF measuring system, although the resolution of CODAR is only 2.4 km. Other remote sensors that will be involved are SAR & SLAR systems of course, NASA's/WFC altimeter to profile the dominant waves, NASA's surface contour radar for obtaining directional spectra, NRL's remote ocean wave spectrometer, wave-interferometer and dual-frequency radar, and so forth. Also surface temperature will be obtained with I.R. airborne systems from the University of Wisconsin and NORDA (Naval Oceanographic Research & Development Activity).

Finally there is a great deal of interest in SEBEX from the scientific community and this should contribute to the overall success of the experiment.

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