Riding the Crest: A Tale of Two Wave Experiments

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Abstract

This paper gives a general overview of two ocean wave experiments. The experimental goals of the Surface Wave Processes Program (SWAPP) and of the Surface Wave Dynamics Experiment (SWADE) are quite different but complementary. In general terms, SWAPP is focused on local processes: principally wave breaking, upper mixed layer dynamics, and microwave and acoustic signatures of wave breaking. SWADE, on the other hand, is concerned primarily with the evolution of the directional wave spectrum in both time and space, improved understanding of wind forcing and wave dissipation, the effect of waves on the air-sea coupling mechanisms, and the radar response of the surface. Both programs acknowledge that wave dissipation is the weakest link in our understanding of wave evolution on the ocean. SWAPP takes a closer look at wave dissipation processes directly, while SWADE, with the use of fully non-linear (third generation) wave models and carefully measured wind forcing, provides an opportunity to study the effect of dissipation on spectral evolution. Both programs involve many research platforms festooned with instruments and large teams of scientists and engineers gathering and analyzing huge datasets. The success of SWAPP and SWADE will be measured in the degree to which the results can be integrated into a far more complete picture than we have had heretofore of interfacial physics, wave evolution, and mixed layer dynamics.

1. Introduction

Two geographically separate but conceptually related wave experiments were planned for 1990. SWAPP (Surface Wave Processes Program) was an experiment conducted in the spring of 1990 off the coast of California and was concerned principally with wave dissipation, upper mixed layer dynamics, and microwave and acoustic signatures of wave breaking. SWADE (Surface Wave Dynamics Experiment) followed in the fall of 1990 off the coast of Virginia and was concerned primarily with the evolution of the directional wave spectrum, wind forcing and wave dissipation, the effect of waves on air-sea coupling mechanisms, and microwave radar response of the surface.

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These two field experiments were spawned by the United States Navy's Office of Naval Research (ONR) through an Accelerated Research Initiative (ARI) to explore "Sea Surface Wave Processes." The ARI covers a period of five years starting in fiscal year 1988 and is organized by ONR's Physical Oceanography Program in cooperation with its Fluid Mechanics Program and the Physical Oceanography Branch at the Naval Ocean Research and Development Activity (NORDA). The central goal of the ARI (Curtin et al. 1987) is to improve our understanding of the basic physics and dynamics of surface waves with emphasis on:

a. Precise air-sea coupling mechanisms,
b. Dynamics of nonlinear wave-wave interactions under realistic environmental conditions,
c. Wave breaking and dissipation of energy,
d. Interaction between surface waves and upper ocean boundary layer dynamics,
e. Surface wave statistics,
f. Boundary layer coherent structures related to waves.

During a series of meetings (Woods Hole, Massachusetts, 5-7 August 1986; San Francisco, California, 9 December 1986; Woods Hole, 23-25 April, 1987), it became clear that the goal of the ARI would be most accessible via two separate, cooperative experiments. The plans for these two experiments evolved considerably through further discussion and meetings (most recently at Burlington, Ontario, August 1989) and led to SWAPP and SWADE. The background, scientific objectives, goals, and field plans for SWAPP and SWADE are summarized below. The Office of Naval Research provided the initial stimulus and remains the main source of general financial support for both experiments, although NASA support to its own personnel and facilities is an essential part of the SWADE program. Other U.S., Canadian, and European agencies also plan on providing considerable resources: these include the National Oceanic and Atmospheric Administration, The U.S. Army Corp of Engineers Coastal Engineering Research Center, the U.S. Department of Energy, the Canada Centre for Remote

Sensing, Environment Canada, and Fisheries and Oceans Canada.

2. The Surface Wave Processes Program - SWAPP

The scientific motivation for SWAPP is drawn from issues related primarily to wave breaking and to the interaction between surface waves and upper ocean boundary layer dynamics. It has been three decades since Phillips (1960) showed that surface gravity waves interact through a resonant quartet and laid the groundwork for our present understanding of the role of nonlinearity in the evolution of surface wave fields. Recent models of wind waves (Hasselmann et al., 1985) include input from the wind, nonlinear transfers across the spectrum, and dissipation due to wave breaking. At present, the least understood of these three processes is that of dissipation through wave breaking, although the form of the source function for rapidly veering winds remains unknown as well.

Breaking waves are intermittent, yet they play a key role in the dissipation of energy fed into them by the wind and in the transfer of momentum, heat, and gas from the atmosphere into the ocean. The details of the breaking mechanism, its distribution in space and time, the processes of bubble and fluid injection and the generation of turbulence in the upper ocean remain difficult to address theoretically; it is apparent that field observations of wave breaking in the open ocean are essential to further progress.

For several decades physical oceanographers have largely avoided explicit consideration of the role of surface waves. Experimentalists have begun their measurements at depths below the wave zone or developed instruments that averaged out the variability at surface wave frequencies and theoreticians and modelers have parameterized the impact of the waves on the upper ocean and air-sea transfers. More recent evidence, of the dependence of the air-sea fluxes on sea state (Donelan 1990), of the mixing and direct injection associated with breaking waves (Rapp 1986; Kitaigorodskii et al. 1983), and of strong three-dimensional Langmuir circulation in the mixed layer driven by wave-current interaction (Weller and Price 1988), has led to the belief that further progress in understanding the upper ocean will require more explicit consideration of the role of surface waves in air-sea transfers and mixed layer dynamics.

a. Scientific goals

Reflecting this belief, SWAPP was formulated specifically to address the following goals:

1) To improve the understanding of: wave breaking, including what determines the occurrence of breaking in space and time; the processes of bubble and fluid injection; the generation of turbulence in the upper layer of the ocean by waves.

2) To improve the understanding of the upper ocean and of the processes that determine its structure by explicit consideration of the role of surface waves in air-sea transfers and in mixed layer dynamics, with particular emphasis on the structure and dynamics of Langmuir circulation.

b. Experimental objectives

The field program formulated to address these goals was designed to maximize the likelihood of achieving the following objectives:

Waves and wave breaking

1) To determine the incidence of breaking as a function of spatial position and of its relation to wave and wave group parameters.

2) To determine the likelihood of breaking with respect to spatial patterns in the underlying, lower frequency surface currents (such as those associated with Langmuir cells).

3) To determine the relationship of the incidence and spatial coverage of wave breaking to the state of the wave spectrum (growing vs. fully developed) and to changing wind conditions (varying wind direction in fully developed seas).

4) To characterize bubble clouds produced by breaking waves and their relation to wave field parameters, concentrating on the issues of bubble size distribution, horizontal spatial distribution of bubble clouds, and shape and penetration depth of bubble clouds.

5) To determine the signature of wave breaking using passive acoustic, active acoustic, and microwave radar techniques.

6) To examine correlations of radar and acoustic measurements of wave breaking with independent estimates of wave energy dissipated by breaking.

7) To determine whether there is a detectable modulation of waves by surface currents, in particular by strong downwind surface currents in the convergence zones of Langmuir cells.

8) To develop a technique to measure surface wave directional spectra using multi-beam Doppler sonar, including the ability to estimate spectral levels of waves travelling in opposite directions at like frequencies and wavelengths.

9) To determine the depth to which the direct effects of breaking are dynamically important, and the relationship of this depth to wave field parameters.

The impact of waves on other upper ocean processes

10) To observe the velocity structure of the upper ocean from the sea surface through the base of the

mixed layer, resolving the shear in the wave zone, and to determine: a) the relationship between near surface shear and the area coverage of breaking and the depth of penetration of bubble clouds; b) whether there is a relatively shallow wave-mixed layer near the surface, resulting from direct turbulence production by wave breaking; c) the role of a wave-mixed sub-layer as a boundary condition for the interior of the mixed layer; d) the importance of the temporal variation in downwind shear near the surface to the growth and decay of Langmuir cells; and e) the incidence of reversed or upwind shears in the presence of Langmuir cells.

11) To observe the rate of dissipation in the mixed layer, at the base of the mixed layer, and in the upper thermocline and determine correlations between the dissipation of energy transferred to the ocean from wave breaking and the size and strength of Langmuir cells and position within the cell.

12) To characterize the horizontal and vertical structure of Langmuir cells, attempting to resolve the hierarchy of cell sizes and determine the relationship between the size of the first cells observed after the onset of forcing and those predicted from theory, and between the largest scales observed and the depth of the mixed layer.

13) To investigate the transience of Langmuir cells and the physical processes that may contribute to this transience such as wave breaking, the presence or absence of near-surface shear, the directional characteristics of the wave field, and the variability of the wind field.

14) To observe simultaneously the surface velocities from Doppler radar and subsurface velocities from Doppler sonar to determine the relationship between surface and sub-surface orbital velocities in breaking waves and also the relationship between surface velocities in the convergence zones of Langmuir cells and velocities in the subsurface downwind flow.

15) To investigate the influence of the near-surface medium on acoustic wave propagation, including the spatial correlation of ambient sound in the presence of breaking waves and bubble clouds.

16) To determine the correlation between the crosswind derivative of crosswind velocity and the depth of bubble clouds in the convergence zones of Langmuir cells.

TABLE 1. SWAPP measurement summary.

Air-sea fluxes
1. momentum flux
   •anemometers for mean wind *(FLIP* and *Parizeau)*
   •fast response sonic anemometers *(FLIP)*
2. sensible and latent heat flux
   •mean air and sea surface temperatures by thermistor *(FLIP)*
   •radiometric sea surface temperature using a Barnes PRT-5 *(FLIP)*
   •fast response air temperature using sonic *(FLIP)*
   •mean relative humidity *(FLIP)*
   •fast response relative humidity using Ophir infrared absorption hygrometer *(FLIP)*
3. radiation
   •incoming shortwave, longwave *(FLIP)*

Wave spectra
1. frequency spectra
   •wave staff, wave staff array *(FLIP)*
2. directional spectra
   •surface scatter sonar *(FLIP)*
   •aircraft dual interferometer (DC-8)

Wave breaking and dissipation
1. space-time distribution of breaking
   •acoustic backscatter from drifting side scan sonar (deployed from Parizeau) and surface scatter sonar *(FLIP)*
   •radar backscatter *(FLIP)*
2. shape and composition of bubble clouds
   •multi-frequency echo sounder (drifter, deployed from *Parizeau)*
3. kinetic energy dissipation
   •tethered microstructure profiler (deployed from small boat from *Parizeau)*

Upper ocean structure
1. near-surface velocity and temperature profiles
   •themistor string *(FLIP)*
   •VMCM array *(FLIP)*
2. mixed layer and upper ocean velocity structure
   •VMCM strings *(FLIP)*
   •fixed and profiling RTP's *(FLIP)*
   •Doppler sonars *(FLIP)*
3. mixed layer and upper ocean density structure
   •profiling CTD *(FLIP)*
   •profiling and fixed RTP's *(FLIP)*
   •tethered microstructure profiler (deployed from small boat from *Parizeau)*
4. horizontal variability
   •XBT survey (tug)

c. Experimental plan

The objectives listed above were addressed by a cooperative experiment involving the Research Platform (RP) *FLIP*, the Canadian Survey Ship (CSS) *Parizeau*, research aircraft, and one drifting and one profiling free instrument package. The principal measurements made during the experiment and the individuals responsible for each measurement are summarized in Tables 1 and 2. *FLIP* was moored throughout the experiment. *Parizeau* worked in the immediate vicinity of *FLIP*. The experimental site was 35° N, 127° W, approximately 500 km west of Point Conception, California (Fig. 1), and was occupied from 26 February to 18 March, 1990. The choice of location and time of year was driven by the desire to experience a range of wind and wave conditions, including synoptic vari-

Table 2 SWAPP Investigators.

Investigator	Contribution
Bill Crawford (IOS, BC)	Microstructure profiler
David Farmer (IOS, BC)	Acoustics drifter
Dick Goldstein (NASA, JPL)	Aircraft dual interferometer
Carl Friehe (UCI)	Barnes PRT-5, sonic anemometer
Rob Pinkel (SIO) Jerry Smith	Doppler sonars, CTDs, Wave gauge array on FLIP
Tim Stanton (NPGS)	Coherent Doppler profiles from acoustic drifter
Ken Melville (MIT)	Microwave radar and video imagery
Bob Weller (WHOI) Al Plueddemann	Temperature and velocity profiles, three-dimensional velocities, meteorology, wave height on FLIP
Walt McKeown (CIMSS)	Satellite infrared imagery

Key to affiliations:

IOS, BC	Institute of Ocean Sciences, Sidney, British Columbia, Canada
NASA, JPL	Jet Propulsion Laboratory, Pasadena, California
UCI	University of California Irvine, Irvine, California
SIO	Scripps Institution of Oceanography, La Jolla, California
NPGS	Naval Postgraduate School, Monterey, California
MIT	Massachusetts Institute of Technology, Cambridge, Massachusetts
WHOI	Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
CIMSS	Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin Madison, Wisconsin

ability in the local meteorology, and to work in an oceanic mixed layer of modest depth (50 - 100 m) so that changes in mixed layer structure in response to turbulence and mixing could be readily observed. In addition, the site needed to be convenient to the home ports of *FLIP* (San Diego) and *Parizeau* (Vancouver) in order to minimize steaming time.

A schematic view of the SWAPP field experiment is shown in Fig. 2. Because of the range of the Doppler sonars on *FLIP*, it was possible to deploy the drifting and ship-based instruments within the acoustic field of view of the sonars. Near-surface shear measure-

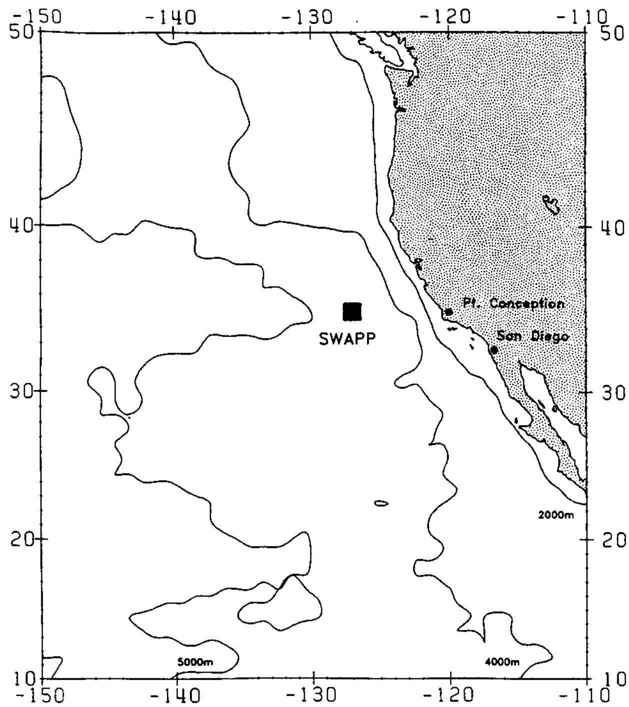


Fig. 1. Location of the SWAPP field work. RP *FLIP* was moored at 35°N, 127°W; shipboard work from CSS *Parizeau* and the tow tug was done within 30 km of *FLIP*.

ments, acoustic measurements of bubble cloud structure and the ambient sound signature of breaking waves were carried out from instruments released from *Parizeau* near *FLIP*. Microstructure profiles were made from a small boat launched from *Parizeau*. Detailed measurements of the vertical structure of the upper ocean were made from instruments deployed from *FLIP*'s booms, effectively at the center point of the sonar array. The measurements made by investigators on *Parizeau* and on *FLIP* are complementary and provide a picture of surface processes simultaneously at both large and small space scales. For example, *FLIP*'s long-range sonars capture the large horizontal scale structure of Langmuir cells at the same time that their vertical structure is probed by the free instrument packages and the boom-mounted instruments on *FLIP*. The measurements made from each platform during SWAPP are described briefly below.

1. RP *FLIP*

Aboard FLIP were both direct and remote sensing devices for the measurement of air-sea fluxes, the surface wave field and wave breaking events, and the vertical structure of the mixed layer (Fig. 3). Two vertical arrays (Fig. 4a) of current meters were suspended from booms. Two Real Time Profilers (RTPs) and one modified Vector Measuring Current Meter (VMCM) (Fig.4b) measured the vertical component of

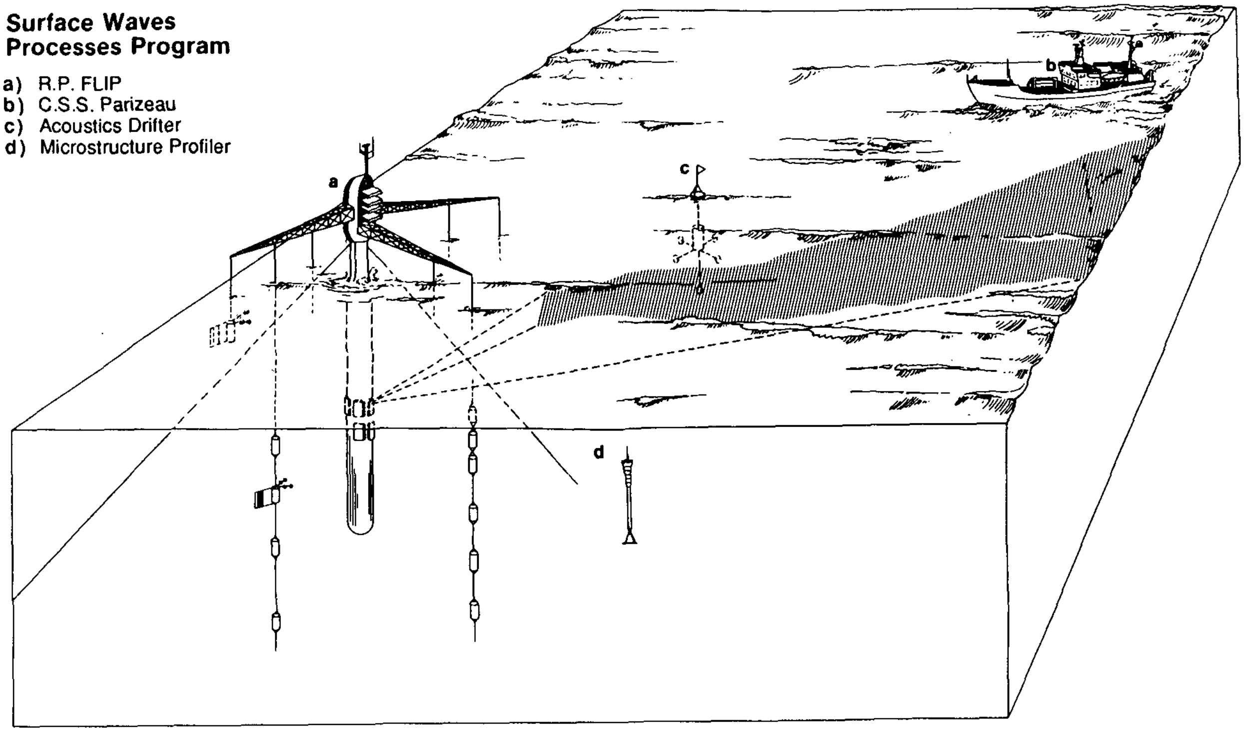


FIG. 2. Overview of the SWAPP field program. RP *FLIP* was moored, CSS *Parizeau* worked in the vicinity of *FLIP*, releasing the acoustics drifter and a small boat from which the microstructure profiler was deployed.

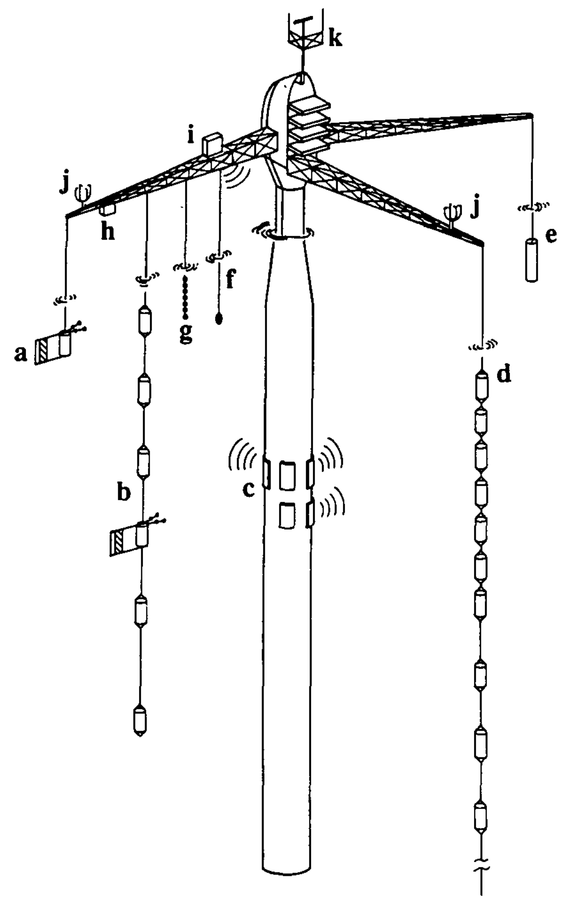
flow directly. A microwave Doppler radar and video system sensed wave breaking events. A single wave staff and a wave gauge array, a multi-frequency, multi-beam Doppler sonar array with both surface scattering and volume scattering beams, two profiling CTDs (conductivity, temperature, depth profiler), and both turbulence and mean meteorological sensors were also deployed.

The two current meter arrays were deployed by Weller and Plueddemann from booms extending to the port and aft of *FLIP*. The first array carried 14 Vector Measuring Current Meters (VMCMs) closely spaced in the vertical over the upper mixed layer and extending to 130-m depth; the modified VMCM or W-VMCM that measured vertical flow was located approximately 1/3 of the way down from the surface into the mixed layer. The second array consisted of 5 VMCMs between 2 and 40 m with an RTP at 29 m. The horizontal spacing between instrument arrays was approximately 15 m. The second RTP was deployed as a manually controlled profiler suspended from the port boom.

Each VMCM measured vector-averaged horizontal velocity (u,v) and temperature every 2 sec. The modified VMCM provided two redundant w's and temperature every 2 sec. The two RTPs, one at fixed depth and one profiling, provided three-dimensional velocities (u, v, and two redundant values of w), temperature, and conductivity data every 14 sec. Both RTPs and the modified VMCM were equipped with tilt sensors to measure their inclination.

Temperature measurements were made near the surface (from the surface down to 2 m) with a string of 8 thermistors. At the surface, temperature was measured by a thermistor beneath a surface float and with a Barnes PRT-5 radiation thermometer looking down from the port boom. These temperature measurements will provide ground truth for satellite infrared images collected by McKeown. Conductivity and temperature profiles were acquired over a wider depth range by a pair of automatically profiling CTD winches, one covering from just below the surface to 200 m and the other spanning 200 to 400 m; these profiles were made every 2 min.

A multi-frequency, multi-beam Doppler sonar array (Fig. 5) was deployed by Pinkel and Smith. There were ten individual beams of two different types; 4 200 kHz surface scatter beams with 3-m range resolution and 400-m total range, and 6 75-kHz surface scatter beams with 10-m resolution and 1200-m total range. The 75 kHz beams formed a 2.4-km by 2.4-km array with *FLIP* at the center. The beams were oriented with their broader axis in the vertical plane, minimizing the effects of *FLIP*'s tilt, which was about 5° maximum. This system was suitable for obtaining detailed direc-



Measurements to be made from FLIP during SWAPP

- a. Real-Time Profiler (RTP)
- b. RTP and Vector Measuring Current Meters (VMCM)
- c. Multi-frequency Doppler Sonar array
- d. High-resolution VMCM array
- e. Profiling CTD
- f. Wave staff
- g. Near-surface thermistor string
- h. IR thermometer (PRT-5)
- i. Doppler radar and video camera
- j. Sonic amemometer
- k. Meteorological instruments

FIG.3. Measurements made from RP *FLIP* during SWAPP. The meteorological instruments were 23 m above the sea surface; the port boom was 20 m long; and the aft boom was 15 m long.

tional spectral estimates for wavelengths longer than about 60 m or wave periods of 6-7 sec and up (Pinkel and Smith 1987). The 200-kHz sonars were used to extend measurements further into the smaller scale wind wave spectrum and provided spectral estimates for wave periods as short as 2 to 4 sec. Improved techniques for estimating the surface wave spectrum using data from multiple sonar beams are being developed for use in SWAPP (Smith 1989). Of specific interest is the ability to estimate accurately the spectral levels of waves travelling in opposite directions at like frequencies and wavelengths. These waves are thought to interact nonlinearly, producing double frequency pressure fluctuations on the sea floor that constitute a major source of low frequency acoustic noise.

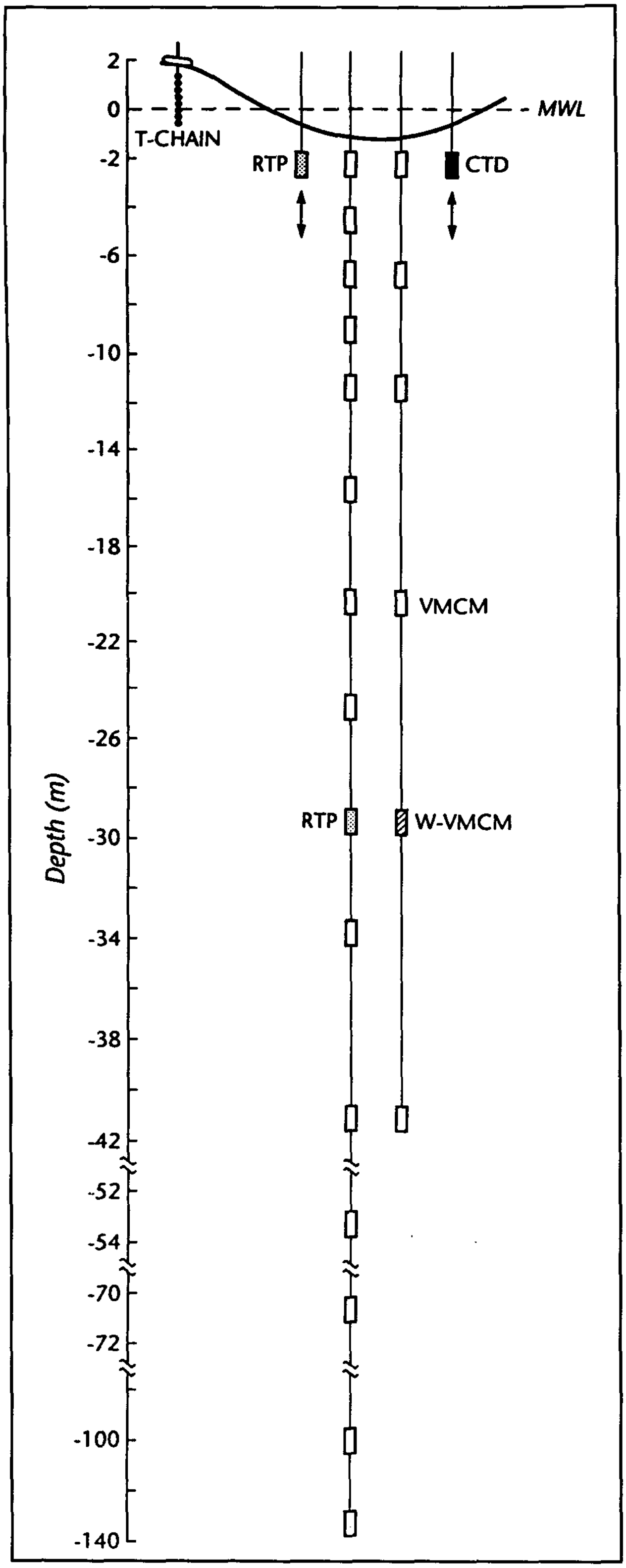
The surface wave field was measured from *FLIP* using both direct and other remote sensing techniques. A single wave staff and a wave staff array were deployed to provide wave height and frequency spectra. Melville deployed a dual polarized, CW, Ku-band radar and a video camera that looked at 45° angle of incidence from *FLIP*'s masthead.

During the scientific analyses now underway the current meter and RTP arrays and the Doppler sonars will provide information about the variability in the velocity field around *FLIP* at periods longer than those associated with surface waves. The vertical structure of the wind-driven and upper ocean flow fields should be well-resolved at *FLIP* by the VMCMs, and the larger scale flow field in the immediate vicinity of *FLIP* (out to a range of 1.2 km) can be described, using the Doppler sonar. The RTPs and the modified VMCM measured the vertical velocity and provide a method of directly detecting the three-dimensional flow associated with strong Langmuir circulation. Because the primary near-surface scatterers of acoustic energy are bubbles, the backscattered intensity measured by the Doppler sonars also provide a means to track the bubble clouds associated with breaking waves and with the convergence regions between adjacent Langmuir cells. The current meter and sonar measurements were supplemented by a program of observations, using computer cards or other surface drifters and smoke flares, to visualize both the sea surface flow patterns and the near-surface wind.

Air-sea fluxes will be estimated using both bulk methods and direct methods. Mean wind velocities, air and sea temperatures, barometric pressure, relative humidity, incoming shortwave radiation, and incoming longwave radiation were measured at *FLIP*'s masthead (23 m above the sea surface). Precipitation and redundant mean meteorological measurements were made from the port boom (11 m above the sea surface). These measurements were averages of values collected over a several minute interval. The fluxes of heat and moisture will be estimated using these mean measurements and the bulk formulae. The momentum flux may have a significant dependence on sea state, and direct measurements of the wind stress were made with sonic anemometers (Applied Technologies Inc.) mounted at the end of the port and aft booms. These instruments provided measurements of u', v', w', and T' at a rate of 10 Hz. In addition, an Ophir infrared absorption hygrometer was mounted close to the ATI sonic anemometer on the port boom and will be used to estimate <w'Q'> in addition to u'w',v'w', and w'T'.

2. CSS *PARIZEAU*

The CSS *Parizeau* was responsible for the deployment and recovery of the drifting instruments, including the acoustics drifter and the tethered microstructure profiler. Farmer's acoustics drifter (Fig. 6) was freely drifting, with the bulk of the instrumentation supported by a rubber cord beneath a Waverider buoy. It included vertically oriented, multi-frequency echo sounders together with orthogonal side scan sonars oriented so as to cover the surface wave field out to about 300 m. Current meters and thermistors were supported beneath the acoustic package. The multi-frequency echo sounders will yield estimates of the shape and size distribution of bubble clouds; the Doppler (vertical) components will give vertical velocities in areas of strong downwelling such as Langmuir cell convergence zones; and the sidescan sonars will yield a two dimensional view of bubble cloud distribu-



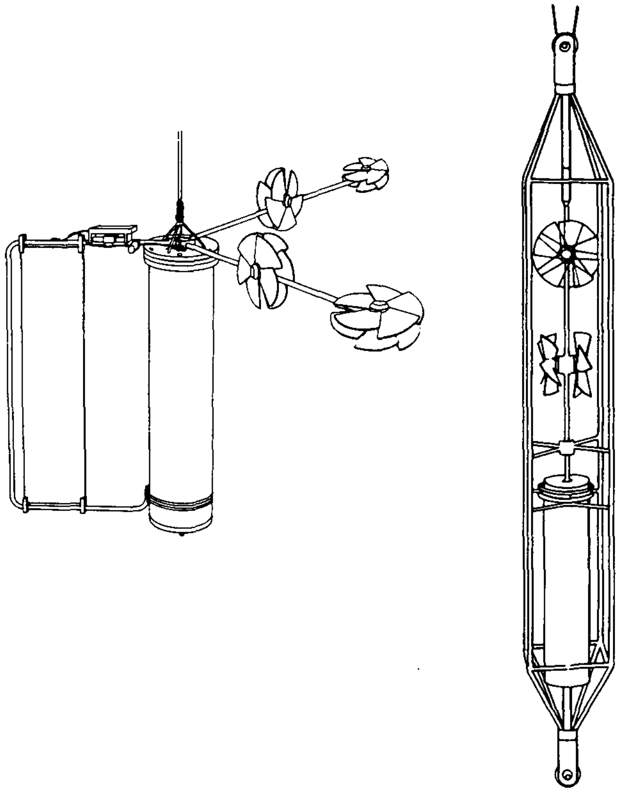


Fig. 4a. (above) Current meter and temperature sensing arrays deployed from RP *FLIP*.

Fig. 4b.(right) The Real Time Profiler (RTP) and a Vector Measuring Current Meter (VMCM). The propellers in these sensors are 11 cm in diameter. The VMCM is approximately 2 m in total length while the height of the RTP is roughly 1 m.

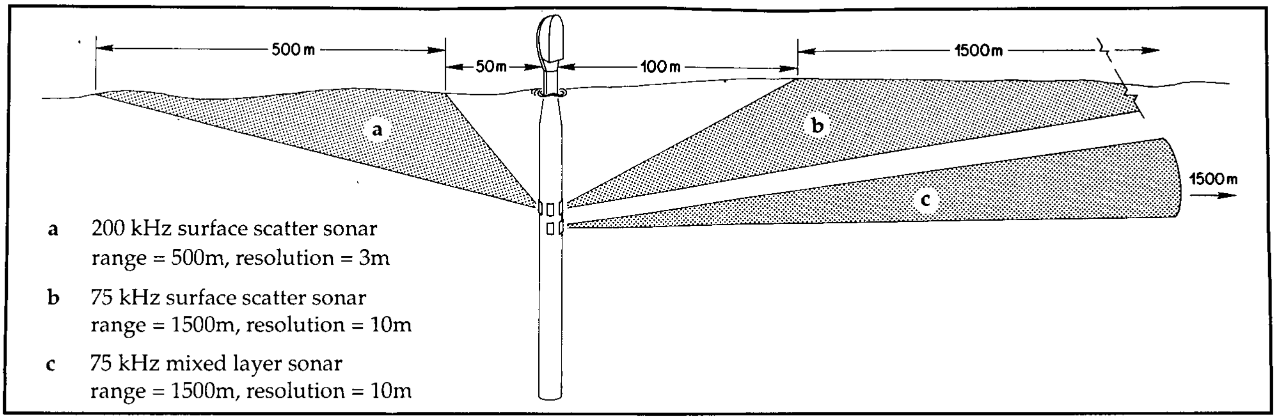


FIG.5. Schematic of the *FLIP* Doppler sonar array.

tions and wave-induced orbital motion. A second operating mode allowed vertical profiles of three-component velocities to be measured for Stanton. The side-scan transducers received backscattered, Doppler-shifted acoustic energy from the narrow beam pulsed acoustic transmitter located at the center of the array. By using coherent sampling, high temporal and spatial resolution velocity profiles to the ocean surface were achieved.

The acoustics drifter also had directional capability for ambient sound measurements. The instrument has four electrically actuated arms that unfold to provide a baseline of nearly 9 m in two directions. At the end of each arm is a broad-band hydrophone. One application of the hydrophone array was to track the locations of individual breaking waves on the ocean

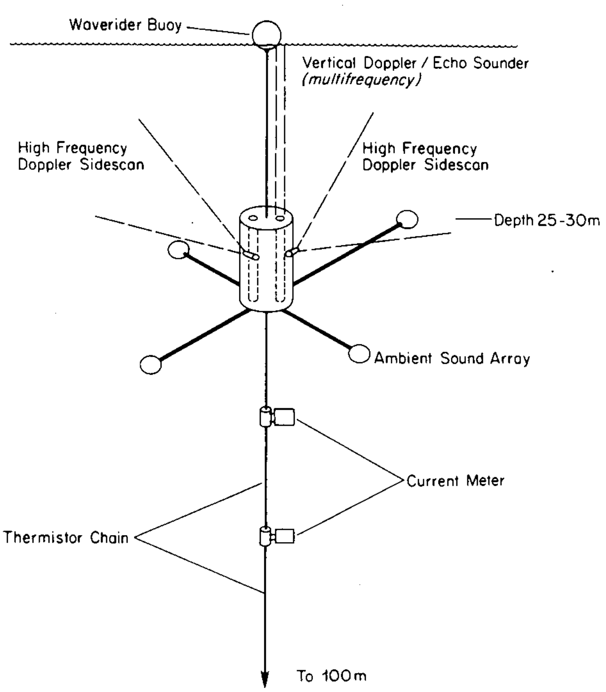


FIG.6. Acoustic drifter deployed from CSS Parizeau.

surface, providing information about the spatial and temporal distribution of breaking events in the immediate vicinity of the drifter. Such measurements, combined with sidescan data, will contribute to our understanding of the distribution of bubble clouds relative to breaking events and Langmuir circulation. The sound of breaking events will be analyzed to resolve breaker duration, breaker density, breaker intensity, and fine structure related to the influence of the near-surface bubble layer.

A small boat was deployed from *Parizeau* so that Crawford's tethered microstructure profiler, *FLY II* (Fig. 7), could be launched away from the ship's wake. On other occasions the profiler was launched directly from the ship. *FLY II* measured temperature, conductivity, and velocity shear from which the rate of dissipation of turbulent energy will be determined (Dewey et al. 1987; Crawford and Gargett 1988). This profiler thus provides simultaneous dissipation rate and density profiles over the top 250 m of the water column. One of the difficulties in interpreting previous mixed layer microstructure data has been the lack of a larger picture of the relevant processes within which the profiles are imbedded. During SWAPP, the microstructure measurements were made in the field of view of *FLIP*'s Doppler sonars and in relation to features in the surface flow field identified with computer cards.

3. NASA JPL DC-8

The NASA Jet Propulsion Laboratory DC-8 overflew the SWAPP experiment carrying a dual receiver interferometer for Goldstein. The detailed wave and upper ocean data sets collected from *FLIP* and *Parizeau* will provide good ground truth data to assist in interpreting the interferometer data, which will give a measure of wave orbital velocities, in terms of wave spectra.

4. ANCILLARY MEASUREMENTS

The Navy tug that towed *FLIP* out to the site spent time in the vicinity of *FLIP* and *Parizeau*. Initially, after *FLIP*

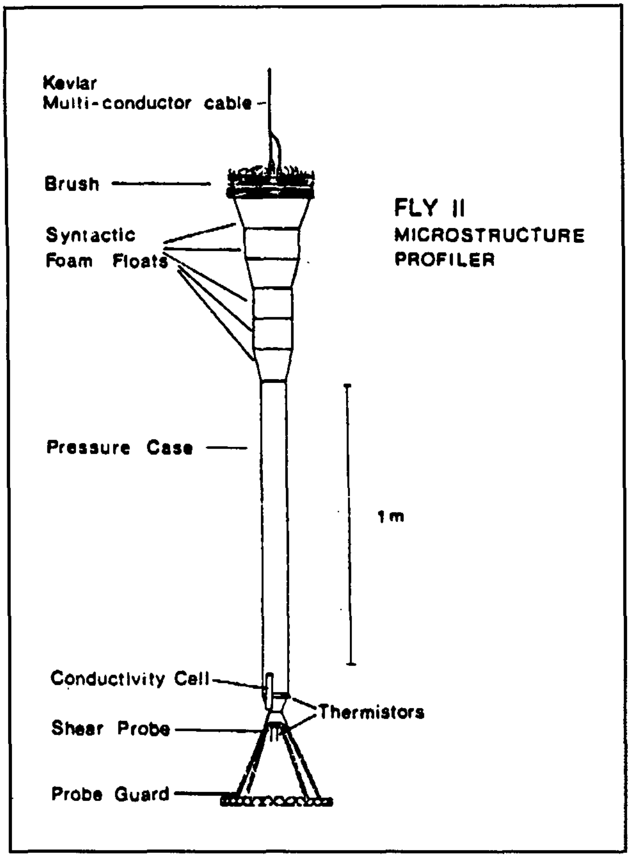


Fig. 7. *FLY II*, the tethered microstructure profiler to be deployed from a small boat launched from CSS *Parizeau*.

was moored, XBTs (eXpendable BathyThermographs) were launched from the tug to determine the depth of the mixed layer and the amplitude of the internal tidal displacement of the base of the mixed layer. This information was used in setting the depths of the current meters to be deployed from *FLIP*. As a last minute addition to the experiment the *Parizeau* and *FLIP* were joined by the USNS *DeSteiguer*, which deployed both sea floor seismometers and a vertical hydrophone array, under the direction of Drs. Bibee, Dorman, and Hildebrand. Their objective was to obtain measurements of deep ocean and sea floor acoustic noise fields which will be correlated with the surface wave measurements.

d. Status

The field experiment was executed relatively smoothly. In contrast to typical winter conditions, the first ten days were unusually moderate. The winds built significantly early in the second week of March, peaking with an 18 m/s event. Subsequently, the winds fluctuated as several synoptic weather systems passed through and variations in wind and wave conditions were experienced.

Analysis of the data is now underway. The first post-cruise meeting was held in early October 1990, and subsequent gatherings, in conjunction with the SWADE group, are planned.

3. The Surface Wave Dynamics Experiment- SWADE

The joint North Sea Wave project (JONSWAP, Hasselmann et al. 1973) was a significant milestone in our understanding of the evolution of wave frequency spectra in fetch-limited conditions. Although JONSWAP provided some measurements of directional spectra, the resolving power of the instruments used was poor. Nonetheless, experiments such as this have been very valuable in establishing the fetch-limited growth of waves in steady offshore winds from simple shoreline geometries. At the same time, our understanding of the physics of the evolution of wind driven waves and the concomitant development of wave prediction models are unable to proceed without detailed observations of the evolution of wind-waves particularly in conditions of strong temporal and spatial (wind) forcing gradients — very far from the classical situation of offshore growth in response to a steady and homogeneous wind that experiments such as JONSWAP were designed to explore.

The development of remote sensing methods of estimating directional spectra has made it possible to explore the response of waves to the highly inhomogeneous wind fields characteristic of developing storms, while the use of airborne microwave scatterometers permits the acquisition of sufficient spatial detail in the wind field to support accurate modelling of wave evolution and testing of "model physics" (i.e., the rendering of physical processes within a model). Such detailed spatial coverage is necessarily limited by cost to a few carefully chosen brief moments in time, and it is inevitable that many interesting situations will be played out unobserved by airborne instruments. On the other hand, surface observations from moored buoys permit continuous temporal coverage, but rather sparse spatial sampling.

The Surface Wave Dynamics Experiment employs a mix of these observational approaches. A surface network provides continuous point records at a few locations. These may also may be used to check and calibrate the airborne measurements made during the three "intensive" observation periods of the experiment.

a. Scientific goals

SWADE's scientific goals are:

1) To understand the dynamics of the evolution of the wave field in the open ocean.

2) To determine the effect of waves on the air-sea transfers of momentum, heat, and mass.

3) To explore the response of the upper mixed layer to atmospheric forcing.

4) To investigate the effect of waves on the response of various airborne microwave systems including radar altimeters, scatterometers, and synthetic aperture radars.

5) To improve numerical wave modeling.

b. Experimental objectives

In order to achieve these scientific goals, the design of the field program focused on the following specific objectives:

1) To determine the evolution of the wave spectrum and the source functions, especially in unsteady or inhomogeneous wind conditions, in order to investigate the characteristics of the source functions and their role in establishing a spectral balance.

2) To measure the directional distribution of waves in considerable detail over large areas using airborne instrumentation on several occasions.

3) To measure the directional distribution of waves at several points, over the entire experiment. In particular, a high resolution wave array at a central location will observe the adjustment of the spectrum to changing conditions.

4) To measure the acoustic signature of wave breaking at the central wave station and to attempt to quantify the dissipation source function.

5) To measure the pressure-slope correlation of the long waves at the outer stations and to attempt to quantify the wind input function to the longer (>20 m) waves.

6) To measure the fluxes of momentum and heat at each of three wave stations over the full experiment.

7) To measure the fluxes of momentum, heat, and moisture in considerable spatial detail over the experimental domain on several occasions, using the NRL airship.

8) To measure the radar signal in various microwave bands from active and passive airborne sensors to explore the effect of waves on the response of the instruments to the desired parameter(s).

9) To measure the surface meteorology (wind velocity, air temperature, and water temperature) with sufficient accuracy and spatial coverage that the wind input to numerical models will not be the source of overwhelming uncertainty that it has been in most field experiments to date.

10) To determine breaking distributions as a function of sea state, wind, and boundary stability.

11) To use numerical modelling as an interpolation and analysis tool and to test various hypotheses regarding modelling of wave physics.

c. Experimental plan

To achieve these objectives an experimental plan using moored buoys and aircraft (see cover) was developed; the geographic locations of the moored buoys are shown in Fig. 8. The principal components of the array are: 1) three wave and flux measuring buoys; 2) three wave and wind measuring buoys; 3) four meteorological buoys; 4) four thermistor chains; 5) an acoustic Doppler current profiler. All of these were installed prior to 9 October 1990 and are to be on station in continuous operation for the six months following. In addition, there are seven existing NDBC (National Data Buoy Center of the U.S. National Oceanic and Atmospheric Administration) data buoys and four NDBC coastal stations in the experiment domain. The instrument and data systems on these surface stations are outlined in Table 3.

The principal objective of the experiment is to observe the evolution of the directional wave spectrum in response to well-defined meteorological inputs. The task of continuously monitoring the waves rests with the Brookhaven Spar Buoy (Fig. 9) and two NDBC discus buoys (Fig. 10). These three buoys were to be deployed in a right angle triangle with the spar at the 90° vertex, moored on the shelf-break in water 200 m deep. This spacing will be large enough to permit useful gradient calculations, given the relatively weak directional resolving power of pitch-roll-heave buoys, and small enough so that the triad will generally be influenced by the same meteorological system. All three buoys were equipped to measure air-sea fluxes of momentum and heat as well as the directional spectra. In addition, three other discus buoys (WHOI, CERC/NDBC, and WAVESCAN) are equipped to measure wave directional spectra and mean meteorological parameters (Table 3).

1. THE BROOKHAVEN SPAR BUOY

The centerpiece of the moored array is the Brookhaven Spar Buoy (Fig. 9). Continuous monitoring of the data acquired on board the spar is planned, thereby placing heavy demands on the power systems. These will be met with a dual recharging system using both solar and wind energy. Wave information will be obtained from an array of six capacitance wave gauges arranged in a centered pentagon of radius 1 m. A smaller array of the same type was used by Tsanis and Donelan (1989) in Lake Ontario. When the data are analyzed using an iterative maximum likelihood method, good resolution (less than 10° beam width) of waves of lengths from twice to 300 times the array radius has been demonstrated. Waves longer than 300 m (or 14-sec period) are rare in the SWADE experimental site.

Air-sea fluxes of momentum and heat will be estimated using the direct (eddy correlation) method. The wind turbulence sensors will be K-vanes (Atakturk and Katsaros 1989). Temperature fluctuations will be obtained via low powered acoustic velocimeters, developed at the Canada Centre for Inland Waters (CCIW,

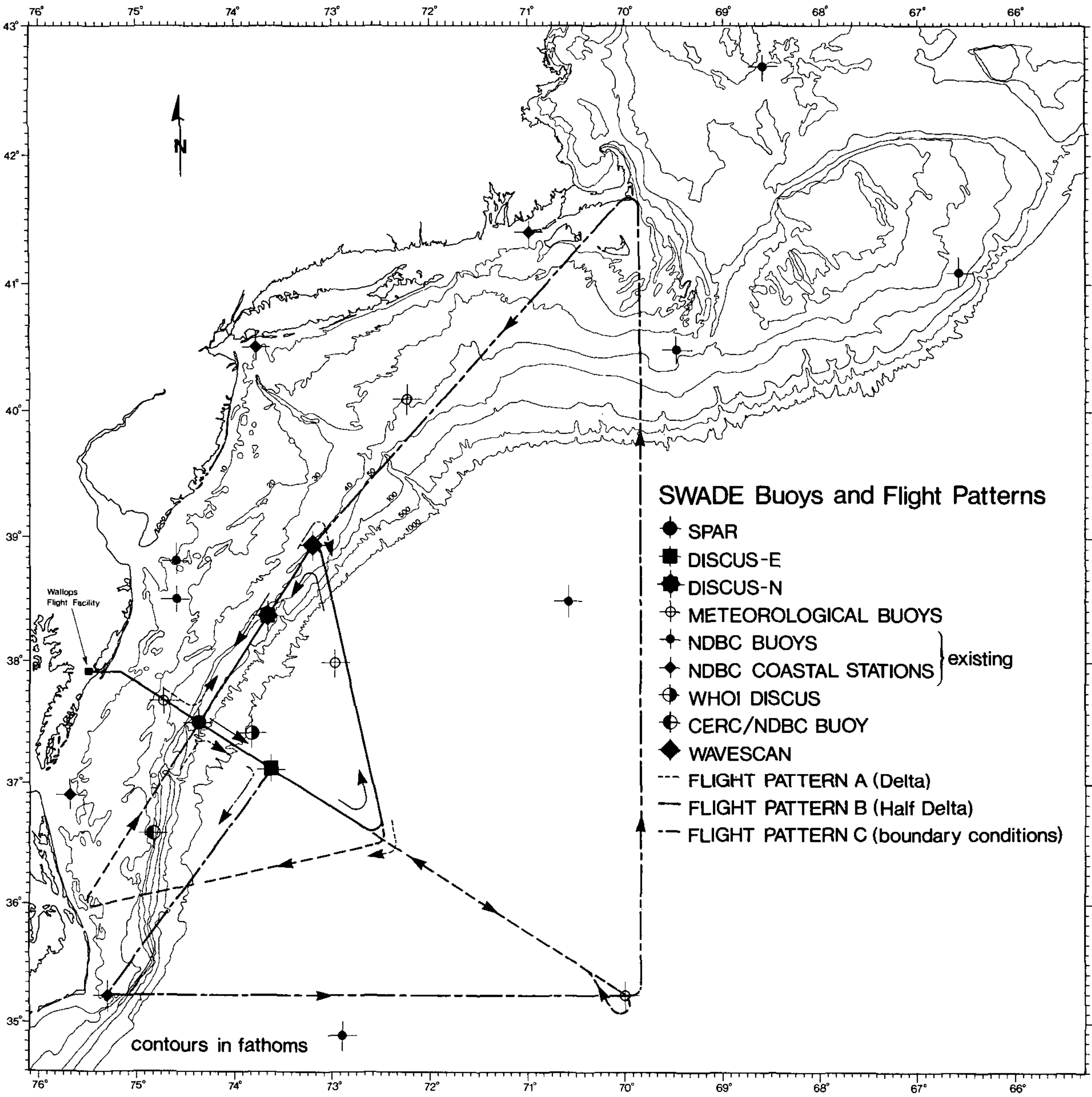


Fig. 8. Geographic location of the SWADE program and the various sampling patterns and arrays that comprise the field work.

Burlington, Ontario); the K-vanes have been developed by the R. M. Young Company (Traverse City, Michigan). Duplicate turbulence sensors will be installed on the main mast (Fig. 9). Redundant sensing of the wind components reflects their importance to the goals of SWADE. Mean temperature and humidity will be monitored via wet and dry bulb psychrometry. To complete the energy flux measurements, solar, long wave, and net radiation sensors will also be mounted on the spar. Mean wind (two independent anemometers) and temperature will also be measured at 6 m so that the differences between 10 m and 6 m may be used to estimate the non-dimensional gradients of wind and temperature.

The dominant source of underwater sound arises from wave breaking (Ffowcs Williams and Guo 1988) and recent experiments (Melville et al. 1988) have demonstrated good correlation between underwater sound energy and wave dissipation. Thus, measurements of the ambient sound using a hydrophone mounted near the bottom of the spar will provide some indication of the intensity of wave dissipation.

The motion of the spar affects all of the above measurements to some degree and so the platform will be instrumented with tilt and acceleration sensors, the data from which will be used in the initial stage of analysis to reduce the data to a fixed reference frame.

All signals will be recorded continuously throughout

TABLE 3. Surface data systems.

Station type	Qty.	Directional spectra	Freq. Spectra	Turbulent Fluxes	Mean Meteorology
Brookhaven Spar Buoy	16	Gauge array of capacitance wires		K-vane, (u,v,w), acoustic temp., Lyman-a humidity	R.M. Young Wind Monitor (u,v) and Thermometer, Wet/Dry Bulb psychrometer, Rotronics humidity Atmos. Press.
SWADE/NDBC 3m Discus	2	Hippy heave-pitch-roll sensor system		K-Gill (u,w), acoustic temp., turbulent pressure	R.M. Young Wind Monitor (u,v) and Thermometer, Atmos. Press.
WHOI 3m Discus	1	Hippy heave-pitch-roll sensor system			R.M. Young Wind Monitor (u,v) and Thermometer, Rotronics humidity, Atmos. Press.
CERC/NDBC 3m Discus	1	Hippy heave-pitch-roll sensor system			R.M. Young Wind Monitor (u,v) and Thermometer, Atmos. Press.
WAVESCAN 3m Discuss	1	Hippy heave-pitch-roll sensor system			Brooks and Gatehouse cup anemometer & vane (u,v) Thermometer, Atmos. Press.
Coastal Climate (modified) Mini-Met Buoys	4				R.M. Young WInd Monitor (u,v), Thermometer Atmos. Press. (on 2 of 4 buoys)
NDBC (existing) buoys	7		Strapped-down accelerator		R.M. Young Wind Monitor (u,v), and Thermometer, Atmos. Press.
NDBC (existing) Coastal Stations	4				R.M. Young Wind Monitor (u,v) and Thermometer, Atmos. Press.
Thermistor chains	4				
Acoustic Doppler Current Profiler	1				

the six-month experimental period using two LOPACS (Low-Powered Acquisition System) computers with 16 bit A to D converters and storing to optical disks. One computer is to be dedicated to the high data rate sonar channels. The other computer will accept 50 data channels at data rates from 0.1 Hz (housekeeping and mean sensors) to 4 Hz (atmospheric turbulence sensors). Housekeeping information and mean interfacial parameters will be monitored via an ARGOS satellite link. In addition, a sample of the recorded data will be telemetered via S band on command via a UHF radio link to an overflying aircraft. The telemetry is intended to permit detailed analysis of interesting events without having to visit the site to recover an optical disk.

An acoustic Doppler current profiler (ADCP - cover figure) will be placed on the bottom near the spar to measure horizontal currents to within 14 m of the surface. Four thermistor chains will be moored within 25 km of the spar. Together, these instruments will yield information on the behaviour of the upper mixed layer.

TABLE 3 Continued. Surface data systems

Station Type	Water temp/vel.	Acoustics	Radiation	Precipitation	Data Retrieval
Brookhaven Spar Buoy	Water Temp.	Passive sonar	Solar, Long, Net	Self-siphoning rain gauge	On board Optical discs (4x400 MBytes) with ARGOS monitoring and facility for down-loading last 3 days to aircraft on command
SWADE/NDBC 3m Discus	Water temp. Current at 10m depth			Self-siphoning rain gauge	On board Optical disks (5x120 MBytes) with ARGOS monitoring and facility for down-loading last 3 days to aircraft on command
WHOI 3m Discus	Water temp.		Eppley Short and Long Wave	Self-siphoning rain gauge	On board recording and ARGOS monitoring
CERC/NDBC 3m Discus	Water temp.				Spectra, means, extrema transmitted via ARGOS and GOES
WAVESCAN 3m Discus	Water temp.				Spectra, means, extrema transmitted via ARGOS and GOES Raw data on board
Coastal Climate (modified) Mini-Met buoys	Water Temp.				20 min means via ARGOS
NDBC (existing) Buoys	Water temp.				Spectra, means, extrema transmitted by ARGOS and GOES
NDBC (existing) Coastal Stations					Means, extrema transmitted by ARGOS and GOES
Thermistor chains	Temperature profiles and spatial variation near Spar				On board
Acoustic Doppler Current Profiler	Velocity profiles near Spar				On board

2. THE SWADE/NDBC DISCUS BUOYS

The National Data Buoy Center has been using 3 m discus buoys for wave and mean meteorological measurements since 1987 (Steele et al. 1990). Several modifications to the buoy have been made in preparation for SWADE (Fig. 10). These include the addition of: 1) a large (2 square m) vane to orient the buoy to the wind and thus simplify the flux and pressure measurements; 2) a 3-axis accelerometer and magnetometer to complement the Hippy system, of Datawell design that is already installed in the buoys, to allow complete correction of the relative wind turbulence to a fixed reference. Also, the additional surge information may be helpful in identifying large breakers; 3) a complete momentum and heat flux system as installed on the spar buoy except with a K-anemometer (2 propellers at +/- 45° to horizontal) replacing the K-vane, since the buoy will orient with the wind and a wind vane (an underdamped second order system) is often excited by the buoy motion thus hopelessly contaminating the turbulence measurements; and 4) an onboard LOPACS computer and optical

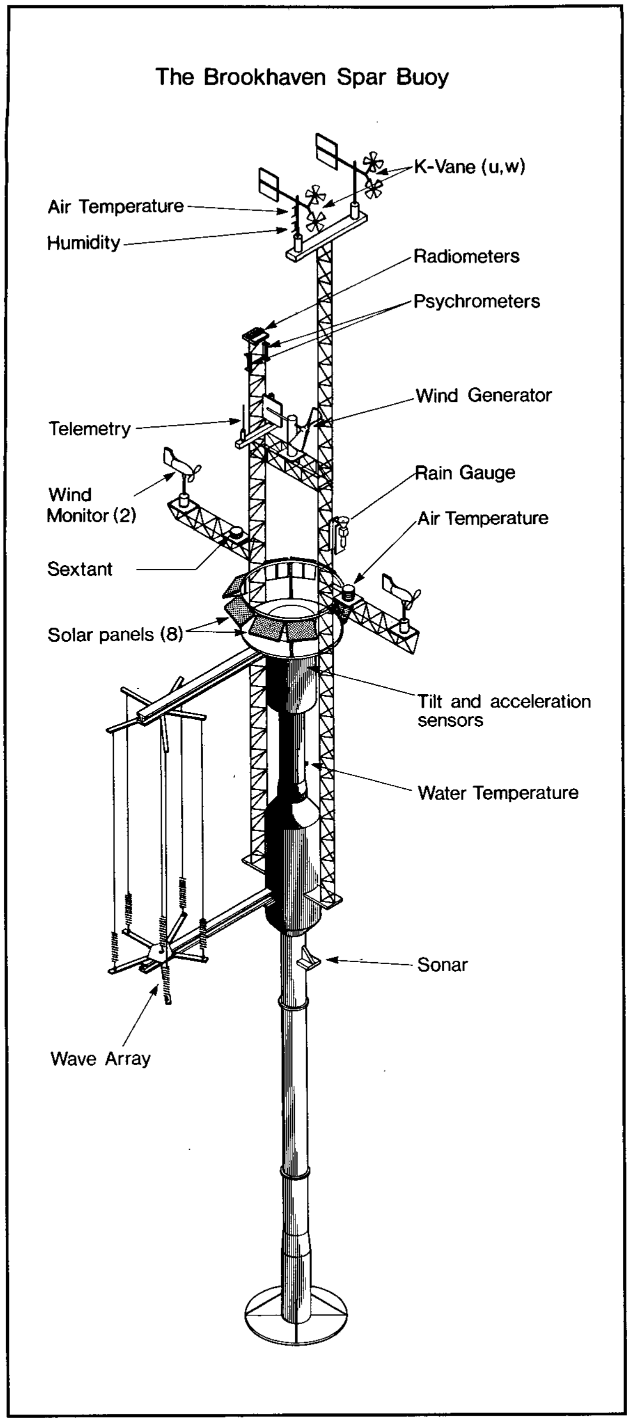


FIG. 9. The Brookhaven spar buoy. The spar measures 30 m from K-vanes to drag plate. The K-vanes are at a height of 10 m and the wind monitors are at 6 m. The wave gauges are 6 m in length.

disk recording system for continuous recording of 16 bit A to D samples at 1 Hz from 14 channels and 2 Hz from the K-anemometer channels. These buoys will also be equipped with on-command telemetry to aircraft, similar to the spar buoy.

3. THE METEOROLOGICAL BUOYS

There will be four small meteorological buoys (modified Coastal Climate buoys) in which the wind speed, relative wind direction, air temperature, water temperature, pressure (on two), and buoy compass direction will be sampled frequently, accumulated, and averaged every 20 min. The buoys will report via ARGOS satellite telemetry, which will also be used to track the buoy positions in case of mooring failure. The principal modification to these buoys consists of the addition of an extra propeller-vane system (Wind Monitor, R. M. Young Co.) for redundancy in wind speed and direction. These will be the only sensors with moving parts and therefore the most susceptible to error in the corrosive marine environment. Agreement of the two wind systems will be taken as a fair indication that both anemometers have retained their calibrations and performance.

SWADE will apply the most advanced technology for directional sensing of surface waves in order to observe the evolution of waves in response to forcing from temporally and spatially varying winds. Success in interpreting the observed behavior in terms of wave dynamics hinges to a very large extent on an accurate description of the forcing. In the terminology of control engineering, we seek the transfer function linking atmospheric forcing to surface response. To this end, the input (wind) is as important as the output (waves). In fact, since the waves integrate the temporally and spatially varying forcing that they experience, more detail will be required in the winds than in the waves. Dobson et al. (1989) have demonstrated significant effects of wind variability with fetch on the interpretation of wave growth data. A major thrust of SWADE is to monitor the winds in the generating area (extent of approximately 500 km) with accuracy and resolution commensurate with that of the wave observing systems. In this context, the wind variability may be separated into microscale and mesoscale variations; the former being prescribed by the properties of the interface and the surface boundary layer, while the latter are influenced by planetary boundary layer and larger scale dynamics. Evidently the wind variability on all scales must be important to the wave evolution. This is apparent if the wave generation rate (wind input) depends non-linearly on the wind speed as suggested by Plant (1982) and Hsiao and Shemdin (1983). However, even if wind input is linear in the wind speed (Snyder et al., 1981), the response will not likely be so, on account of the non-linearity of some of the other elements of the transfer function. One can predict the microscale variability of the wind using a mix of measured and modelled wave characteristics, along with winds and interfacial temperatures. On the

Table 4. SWADE airborne instruments.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Aircraft	Directional Spectra	Line Spectra	Scatterometry Wind Vector	Radiometry Sfc Temp	Foam	Optical Images	Oceanographic Soundings	Air-Sea Fluxes
NASA P-3	Surface Contour Radar (SCR)	Airborne Oceanographic LIDAR (AOL)		PRT-5		TV Camera Recorder 35mm & 70mm cameras	AXBT, AXCP Deployment Tube	
NASA T-39	Radar ocean Wave Spectrometer (ROWS)							
NASA C-130			Nu-Scatt (Ku-Band) Mass-Scat C-Band	PRT-5		TV Camera Recorder 9x9" Photog., IR		
NRL RP-3A	Laser profiler Real Aperture Imaging Radar		X-Band Scatterometer	PRT-5	SSM/1			
CRS Corvair 580	Synthetic Aperture Radar (SAR) C-Band							
NRL Airship	Laser profiler		X-Band Scatterometer Ku-Band Scatterometer	PRT-5			Δk Radar SFC Currents	Turbulent pressure and direct fluxes of monentum, heat and moisture in the atmospheric boundary layer 5 m to 100 m.

Intensive Periods: Three intensive periods have been chosen for the aircraft flights over the SWADE array of buoys. These are: 5-9 November 1990; 14-25 January 1991, and 25 February - 8 March 1991.

other hand, the spatial and temporal scales of the mesoscale variability, and the other parameters on which they depend, have not been explored extensively in the marine boundary layer.

The division of temporal meso- and microscale is usually taken to be about 20 min(Pierson 1983), which for the mean climatological conditions of SWADE, corresponds to a spatial scale of about 14 km. Our approach in SWADE is to explore the space-time variability of the mesoscale in the range of about 37 km to 407 km and, at larger scales, to observe the wind directly. The dense array of meteorological buoys in the vicinity of the spar and discus buoys will yield correlations of the mesoscale at several values of the lag vector. This strategy will permit realistic modelling of the wind input in finescale wave models based on the assumption that the correlation statistics observed by the dense array are applicable to the wind variability over the SWADE area.

4. AIRCRAFT

Several aircraft are scheduled to fly in SWADE during designated intensive periods (Table 4). These aircraft will be equipped with various radar, passive infrared, video imaging and optical laser ranging systems designed to: 1) estimate line spectra, directional spectra, or significant height of waves; 2) measure backscattering cross section of the surface at centimetric wavelengths and to infer the surface wind vector; 3) make radiometric measurements of surface temperature and emissivity; and 4) measure atmospheric turbulent fluxes. Table 4 lists the aircraft and airborne instruments important to the SWADE objectives.

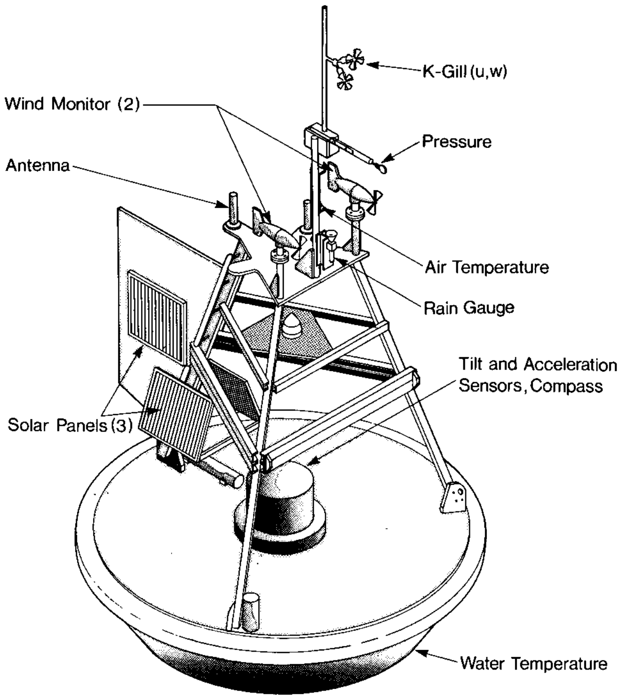


FIG. 10. An NDBC/SWADE 3- m discus buoy. The K-Gill anemometer is at a height of 5 m with pressure, humidity, temperature, and the mean wind monitors in order of descending height to 4 m.

The first and second columns of the table contain the instruments of particular value to the first objective of the experiment — to explore the evolution of the directional spectrum. The operating principles of the three instruments in the first column are quite different. The Surface Contour Radar (Walsh et al. 1985, 1987) constructs the directional spectrum from an elevation map of the surface, while the Radar Ocean Wave Spectrometer (Jackson et al. 1985 and Jackson 1987a,b) measures the wavenumber spectrum of samples of sea surface slope, from which the wavenumber spectrum of the surface deflection is estimated. Of the three instruments, the Synthetic Aperture Radar is the least direct and depends principally on the modulation of the centimetric scattering waves by longer waves (see Lyzenga 1987, for a concise overview).

Columns 3, 4, 5, and 6 are all relevant to the estimation of surface winds and to the exploration of the effects of waves and surface properties on the microwave reflectivity.

The AXBT soundings and Δk radar (column 7) will complement the sub-surface temperature and velocity profiles and will help in monitoring the response of the upper mixed layer to atmospheric forcing. SWADE is particularly well suited to examine the effects of underdeveloped waves on surface fluxes. Significant differences in the atmospheric forcing will be reflected in the oceanic response and may be a useful indicator of the importance of wave effects in the atmosphere-ocean coupling mechanisms.

The exploration of the dynamics of the evolution of wind-generated waves depends on a proper characterization of the surface fluxes, since these are affected by the waves and the wind input to the waves is, in turn, related to the air-sea flux of momentum and to the atmospheric boundary layer stability. Thus, the detailed measurement of air-sea fluxes from the NRL Airship (Blanc et al. 1989) is central to the goals of SWADE and complementary to the continuous point flux measurements on the spar and discus buoys. Moreover, the airship may be readily moved from, say, one side of an atmospheric front to another to explore the changes in the fluxes in different regimes of stability or wave age with much the same long wave characteristics. The airship system will also be used as a means of cross-calibrating the surface flux measurements from buoys.

During SWADE, the winged aircraft will fly in one of three patterns (Fig. 8) depending on the particular investigation. Patterns A and B are designed to take the aircraft over most of the wave measuring buoys. Pattern A (delta) includes two pairs of orthogonal paths rotated by 45° and will permit the acquisition of appropriate spatial variation in the wave field for most meteorological conditions. Under some circumstances, a reduced flight path will be followed to conserve resources. This is designated pattern B (half-delta).

The third pattern is designed to prescribe the boundary conditions on the fine scale SWADE array numerical model. It is expected that this pattern will be flow principally by the fast T-39 carrying the Radar Ocean Wave Spectrometer.

d. Numerical modelling

The role of modelling in realizing the principal goals of SWADE is two-fold: 1) during the intensive measurement periods the operations team will need accurate wind and wave forecasts of the SWADE area and surrounding areas in order to plan the use of aircraft time effectively; 2) once all meteorological stations have reported, their data will be assimilated into the analysis and the analyzed winds used to drive the wave models as a test bed for understanding the physics of wave evolution and improving the methodology of wave modelling.

The objectives of this second role of the numerical modelling aspect of SWADE are summarized as follows: 1) Use of a wave model as an analysis tool for SWADE; 2) Evaluation of wave models using the SWADE wave data sets; 3) Comparison of measured and modelled source terms; 4) Modelling of wave evolution with the measured source terms; 5) Investigate the incorporation of currents into a model.

In order to accomplish these objectives, a hierarchy of models at different spatial and temporal scales will be employed to predict ocean surface waves in the

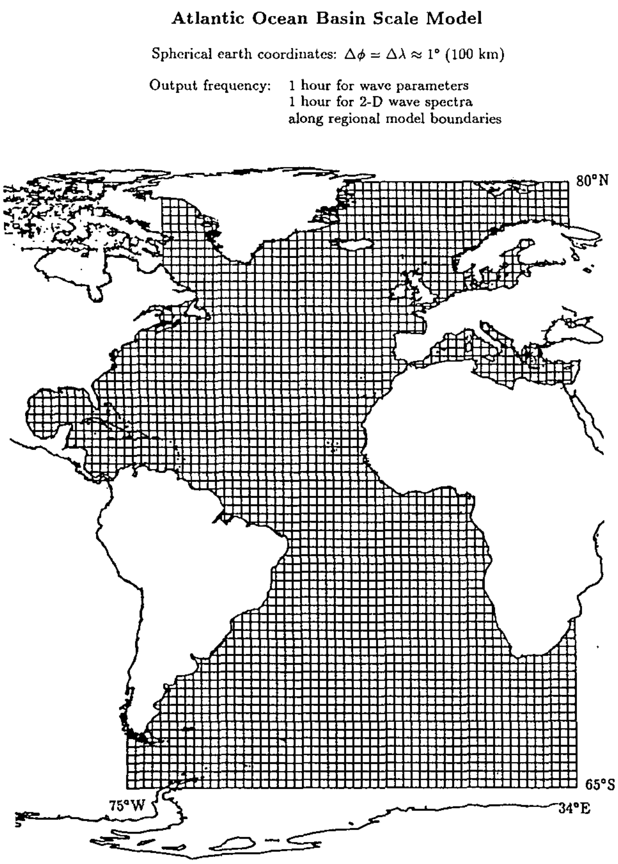


FIG. 11a. Numerical grid.

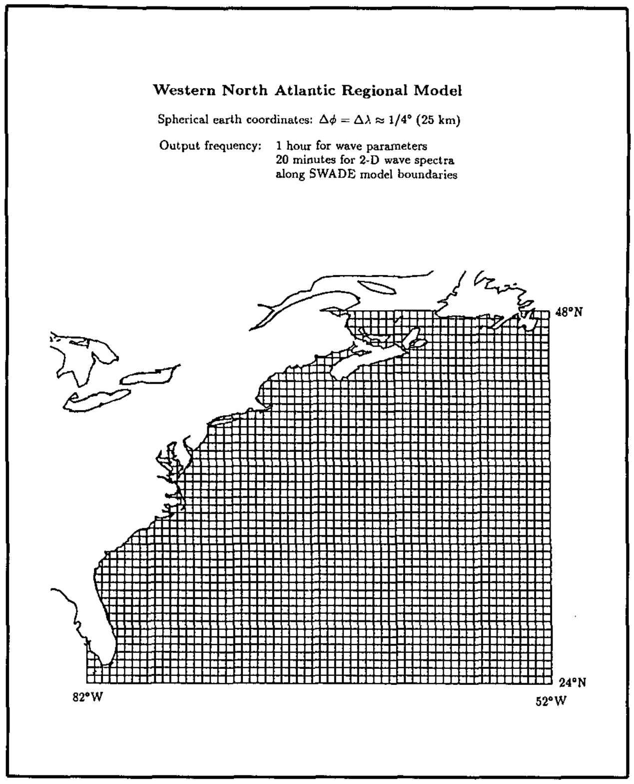


FIG. 11b. Numerical grid.

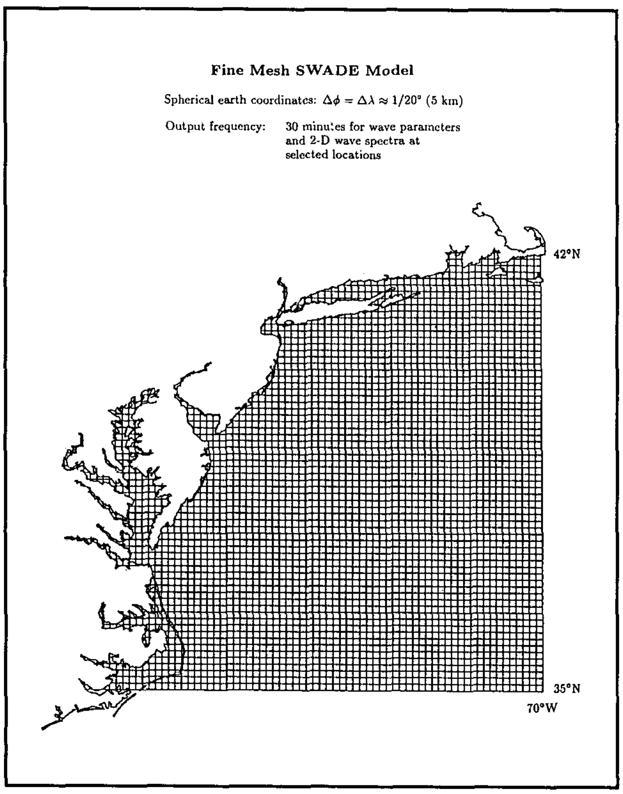


FIG. 11c. Numerical grid.

northern and southern Atlantic (Fig. 11a), along the east coast of the U.S. (Fig. 11b) and within the experimental region (Fig. 11c). A summary of the functions and anticipated results from the different models is given in Table 5.

e. Analysis approach and general organization

The many facets of this complex experiment pose some difficulty in drawing the results into a coherent whole. Accordingly, the analysis will be done in teams, with each team leader having responsibility for coordinating all the work on a particular scientific theme. The teams are listed in Table 6. The planning and execution of the experiment and the activities of the analysis teams are coordinated by a Steering Committee consisting of: Mark Donelan (Chair), Norden Huang, Erik Mollo-Christensen, Dave Oberholtzer, Owen Phillips, and Bill Plant.

The facility for satellite reporting and downloading data to an aircraft provides a unique opportunity to work with buoy data as well as aircraft data during the experimental phase. After each intensive period, selected datasets will be calibrated, analyzed, and distributed to various team members. In addition, the SWADE dense network of meteorological data will be assimilated and used in running model tests. Just before the next intensive period, all SWADE scientists will meet at the Wallops Island Flight Facility of NASA for a week-long workshop, in which the mornings will

Table 5. Model hierarchy.

	BASIN-SCALE MODEL (Fig11a)	REGIONAL MODEL (Fig.11b)	SWADE MODEL (Fig.11c)
FUNCTION	Provide boundary conditions and feedback to wave and circulation modellers	Provide context for SWADE cases and model evaluation questions	Evaluation of model physics
SOURCE OF WIND	ECMWF NMC FNOC	NASA/NMC Reanalysis to get best windfield	Measured meteorology and different interpolation/ assimilation schemes
MODE	Forecast and hindcast	Forecast and hindcast	Hindcast
SPATIAL SCALES	0 (100 km)	0 (25 km)	0 (5 km)
FREQUENCY	Forecast: intensive periods Hindcast: entire period	Forecast:Intensive periods. Hindcast: entire period	Selected cases
RESULT	Quality of forecast and subscale variability	High quality regional wind and wave field analysis	Improvement for verification of source term physics

be devoted to presentations of results and ideas, the afternoons to further analysis and discussions. The SWADE scientists will be at "sea," so to speak, on the *RV Wallops* and the interactions should be interesting. Two months after the third (and final) intensive period there will be a final (two week) workshop. It is expected that the information exchanged, the ideas generated and the teamwork spawned there, will set the course for many of the significant scientific investigations that should be possible with such an extensive dataset. The post-experiment analysis phase is expected to continue for one year, with a second year dedicated to publication efforts and a final report in the third year.

4. Summary

If we succeed in meeting all the experimental goals of SWAPP and SWADE, we will be well-positioned to advance our understanding of wave processes, air-sea coupling, and mixed layer dynamics. Specifically, we will focus our efforts in analysis and interpretation to elucidate the following areas:

1) Wave breaking — its energetics, distribution in time and space, bubble injection, turbulence generation, sound generation, sensitivity to secondary flows, effect of unsteady conditions.

2) Wave generation — its relation to atmospheric stability and to wave slope and speed.

3) Wave directional spectrum — its evolution, relaxation to equilibrium, response to wind changes, response to current shears.

4) Air-Sea fluxes — the effect of waves on boundary fluxes of momentum, heat and mass, stability effects on flux-profile relations.

5) Radar response — effect of log waves on scatterometry, effect of height statistics on altimetry, modulation of short waves by long, effect of wave breaking.

6) Langmuir circulation — the role of surface waves in forcing the three-dimensional circulation and the effect in turn of that circulation on the mean structure within the mixed layer.

7) Oceanic response — development of velocity and temperature structure, entrainment of bubbles, wave-turbulence interaction, dissipation rates.

8) Acoustic methods — wave directional spectra, bubble distributions, dissipation rates.

9) Numerical modelling — improvements in model physics and methodologies.

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Table 6. SWADE analysis teams

SCIENTIFIC THEME	TEAM LEADER	TEAM	AFFIL.
Wind field analysis	D. Duffy (GSFC)	R. Brown	(UW)
		V. Cardone	(OW)
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		W. Gemmill	(NMC)
		E. Michelena	(NDBC)
		E. Mollo-Christensen	(GSFC)
		T-W Yu	(NMC)
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		H. Graber	(RSMAS)
		D. Hauser	(CRPE)
		F. Jackson	(GSFC)
		P. Kjeldsen	(MAR)
		E. Mollo-Christensen	(GSFC)
		K. Steele	(NDBC)
		E. Terray	(WHOI)
		I. Tsanis	(McM)
		E. Walsh	(GSFC)
Dissipation source function	N. Huang (GSFC)	M. Banner	(NSW)
		K. Hasselmann	(MPI)
		A. Jenkins	(BSC)
		P. Kjeldsen	(MAR)
		K. Melville	(MIT)
		M. Su	(NORDA)
Wind input source function	M. Donelan (CCIW)	M. Banner	(NSW)
		R. Desrosiers	(CCIW)
		K. Kahma	(FMR)
		K. Katsaros	(UW)
		O. M. Phillips	(JHU)
		W. Plant	(NRL)
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		F. Jackson	(GSFC)
		P. Liu	(GLERL)
		S. Long	(WAL)
		M. Su	(NORDA)
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		M. Colton	(NOARL)
		M. Donelan	(CCIW)
		H. Graber	(RSMAS)
		A. Guillaume	(MN)
		Y. Yuan	(IOQ)
Remote sensing	W. Plant (WHOI)	T. Blanc	(NRL)
		M. Colton	(NOARL)
		L. Gray	(CCRS)
		D. Hauser	(CRPE)
		F. Jackson	(GSFC)
		W. Keller	(NRL)
		P. Kjeldsen	(MAR)
		F. Li	(JPL)
		R. McIntosh	(UM)
		W. Plant	(WHOI)
		P. Vachon	(CCRS)
		E. Walsh	(GSFC)
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		E. Mollo-Christensen	(GSFC)
		E. Terray	(WHOI)
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		H. Graber	(RSMAS)
		A. Guillaume	(MN)
		A-K. Magnusson	(NMI)
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		H.S. Chen	(NMC)
		H. Graber	(RSMAS)
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		R. Desrosiers	(CCIW)
		C. Flagg	(BNL)
		L. Gray	(CCRS)
		F. Jackson	(GSFC)
		W. Keller	(NRL)
		F. Li	(JPL)
		D. Oberholzer	(WAL)
		K. Steele	(NDBC)
		P. Vachon	(CCRS)
		E. Walsh	(GSFC)

ment are listed in Table 3.4. The assistance of Nancy Pennington and Kay Goodwill was essential to the preparation of this manuscript and is gratefully acknowledged. This is Contribution Number 7380 from the Woods Hole Oceanographic Institution and 90-125 from the Canada Centre for Inland Waters.

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TABLE 6 continued. Affiliation list.

BIO	Bedford Institute of Oceanography Dartmouth, Nova Scotia, Canada	**MIT**	Massachusetts Institute of Technology Cambridge, Massachusetts, U.S.A.
BNL	Brookhaven National Laboratory Upton, Long Island, New York, U.S.A.	**MN**	Meteorologie Nationale Paris, France
BSC	Bergen Scientific Centre, IBM Bergen, Norway	**MPI**	Max-Planck Institut für Meteorologie Hamburg, Federal Republic of Germany
CCIW	Canada Centre for Inland Waters Burlington, Ontario, Canada	**NDBC**	National Data Buoy Center NSTL, Mississippi, U.S.A.
CCRS	Canada Centre for Remote Sensing Ottawa, Ontario, Canada	**NMC**	National Meteorological Center Camp Springs, Maryland, U.S.A.
CERC	Coastal Engineering Research Center Waterways Experiment Station Vicksburg, Mississippi, U.S.A.	**NMI**	The Norwegian Meteorological Institute Bergen, Norway
CRPE	Centre de Recherches en Physique de l'Environnement Terrestre et Planétaire 38-40 rue du Général Leclerc 92131 Issy-les-Moulineaux France	**NORDA**	Naval Ocean Research and Development Activity NSTL, Mississippi, U.S.A.
FMR	Finnish Institute of Marine Research Helsinki, Finland	**NOARL**	Naval Oceanographic and Atmospheric Research Laboratory - West Monterey, California, U.S.A.
GLERL	Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, U.S.A.	**NRL**	Naval Research Laboratory Washington, D.C., U.S.A.
GSFC	Goddard Space Flight Center Greenbelt, Maryland, U.S.A.	**NSW**	University of New South Wales Kensington, N.S.W., Australia
IOQ	First Institute of Oceanography Qingdao, Shangdong, China	**OW**	Oceanweather Inc. Cos Cob, Connecticut, U.S.A.
JHU	Johns Hopkins University Baltimore, Maryland, U.S.A.	**RSMAS**	Rosenstiel School of Marine and Atmospheric Science, Miami, Florida, U.S.A.
JPL	California Institute of Technology Pasadena, California, U.S.A.	**UM**	University of Massachusetts Amherst, Massachusetts, U.S.A.
MAR	Marintek Trondheim, Norway	**UW**	University of Washington Seattle, Washington, U.S.A.
McM	McMaster University Hamilton, Ontario, Canada	**WAL**	Wallops Flight Facility Wallops Island, Virginia, U.S.A.
		WHOI	Woods Hole Oceanographic Institution Woods Hole, Massachusetts, U.S.A.

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Editor's Note: On 26 October 1990, the Spar buoy was sunk, probably as a result of a collision with a ship. Its location was occupied by another NDBC/SWADE 3m discus buoy from 15 January 1991. During the second and third intensive periods, the SWATH (Small Waterplane Area Twin Hull) ship, *Frederick G. Creed,* was employed to acquire high resolution wave data and turbulent air-sea fluxes.