OCEANIC ENVIRONMENTAL MODELS HAVE REACHED A POINT OF SOPHISTICATION WHEREBY THEY DEPICT NUMEROUS OBSERVED HYDROGRAPHIC FEATURES. ADVANCES IN NUMERICAL TECHNIQUES AND COMPUTER PROCESSING CAPABILITIES HAVE HELPED ACHIEVE THESE GOALS. HOWEVER, SPARSE OCEANOGRAPHIC DATA HAVE HISTORICALLY LIMITED OCEAN FORECAST MODELING EFFORTS. RECENT SATELLITE PROGRAMS UTILIZING PASSIVE AND ACTIVE MICROWAVE INSTRUMENTS (SEASAT-A, Nimbus-G, AND GEOS-3) HAVE INDICATED A POTENTIAL TO PRODUCE A QUANTUM LEAP IN SATISFYING NUMERICAL MODEL INPUT PARAMETER REQUIREMENTS. PREVIOUS RESULTS AND THE POTENTIAL OF SCATTEROMETER, SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMWR) AND ALTIMETER DERIVED MEASUREMENTS WITH REGARDS TO OCEAN MODELS WILL ALSO BE EXPLORED.

1. INTRODUCTION

PRESENT DAY NUMERICAL MODELS AT NORDA HAVE PRODUCED REALISTIC FLOW PATTERNS IN THE GULF OF MEXICO (HURLBURT AND THOMPSON, 1980), EASTERN CARIBBEAN SEA (HEBURN, ET AL., 1982) AND THE ALBORASea (PRELLER AND HURLBURT, 1982). THESE MODELS REPRESENT A STAGE OF NUMERICAL SOPHISTICATION WHEREBY FEATURES ON SEVERAL SPATIAL SCALES ARE PRODUCED THAT QUALITATIVELY MATCH THOSE OBSERVED BY IN SITU OBSERVATIONS. HOWEVER, ONE OF THE MAJOR STUMBLING BLOCKS TO PROGRESS IN OCEAN MODELING IS THE SPARSITY OF DATA (SEA SURFACE HEIGHTS, SEA SURFACE TEMPERATURES (SST), CURRENT VELOCITY FIELDS, WIND STRESS, ETC.) NEEDED FOR Initialization AND FORCING. WITHOUT A SYNOPTIC PICTURE OF SUCH DATA AVAILABLE TO THE MODELS, AN UNWELCOME PLATEAU OF MODEL FORECASTS WILL LIKELY BE REACHED. THE ONLY MEANS TO ACQUIRE A SYNOPTIC OCEANOGRAPHIC QUANTITATIVE PICTURE OF MOST OF THESE PARAMETERS IS BY SATELLITE REMOTE SENSING TECHNIQUES.

SIGNIFICANT STRIDES FORWARD IN OCEAN REMOTE SENSING HAVE OCCURRED IN THE LAST 5-7 YEARS. PASSIVE MICROWAVE INSTRUMENTS ON NIMBUS 5, 6, 7 AND ON THE SEASAT SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMWR) HAVE PERMITTED THE SENSING OF SST, SEA ICE (EDGE, CONCENTRATION, AND AGE) AS WELL AS WIND SPEED. ACTIVE MICROWAVE SENSORS LIKE THE SEASAT SCATTEROMETER CAN DERIVE NOT ONLY THE SURFACE WIND SPEED, BUT THE WIND DIRECTION (WITH SOME AMBIGUITIES) WHICH LEADS TO THE MORE MODELING RELEVANT PARAMETER OF WIND STRESS. THE ALTIMETER (GEOS-3 AND SEASAT) CAN MEASURE THE SEA SURFACE TOPOGRAPHY OR HEIGHT VARIATIONS WHICH LEADS DIRECTLY INTO OCEAN SURFACE CIRCULATION APPLICATIONS.

THE MICROWAVE INSTRUMENTS HAVE OPENED UP A WHOLE NEW AREA OF OCEANOGRAPHIC REMOTE SENSING. WHILE THIS TECHNOLOGICAL ADVANCE HAS TAKEN PLACE, IMPROVEMENTS TO THE OLD STANDBY, DIGITAL INFRARED (IR) IMAGERY IN THE FORM OF MULTICHANNEL SSTs, HAS ADDED FURTHER FLEXIBILITY TO REMOTE SENSING USERS. THE MEASURING CHARACTERISTICS AND POSSIBLE UTILIZATIONS OF THESE THREE (3) INSTRUMENTS: PASSIVE AND ACTIVE MICROWAVE AND IR, IN SATISFYING THE VOID OF DATA NECESSARY FOR OCEAN BASIN MODELS, IS EXPANDED ON IN THE FOLLOWING SECTIONS.

2. REMOTE SENSING INSTRUMENTS

AS NOTED BY STEWART, 1981, "NO INSTRUMENT IS SENSITIVE TO ONLY ONE OCEANOGRAPHIC VARIABLE; RATHER, EACH INSTRUMENT RESPONDS TO A COMBINATION OF ATMOSPHERIC AND OCEANIC PHENOMENA." THUS, THE ABILITY TO OBTAIN AN ACCURATE GEOPHYSICAL UNIT FOR AN OCEAN PARAMETER IS BASED ON THE AVAILABILITY AND PROPER USE OF A NUMBER OF INSTRUMENTS AND/OR CORRECTION ALGORITHMS.

PASSIVE MICROWAVE RADIOMETERS SENSE AND RECEIVE MICROWAVE SIGNALS (USUALLY IN THE RANGE 6-37 GHZ) CAUSED BY A WIDE VARIETY OF LAND-SEA COMPONENTS. THE LAND, SEA SURFACE, SEA ICE, AND WATER VAPOR ARE JUST A FEW OF THE SOURCES OF MICROWAVE RADIATION. MULTICHANNEL MICROWAVE RADIOMETERS HAVE THE CAPACITY TO MEASURE RADIATION IN SEVERAL BANDS THAT RELATE TO DIFFERENT SOURCES OF RADIATION. HOWEVER, THE INEXACT NATURE OF THE RELATIONSHIPS BETWEEN EACH PARAMETER AND THE RADIATION AT EACH FREQUENCY HAS RESULTED IN ERRORS.

THE FIRST SATELLITE SYSTEM OF THIS BASIC
type was launched aboard Nimbus-5 as the Electrically Scanning Microwave Radiometer (ESMR) in 1972. It was followed with a similar instrument on Nimbus-6 in 1975. Nimbus-5 (still sending useful data today), was used for SST and sea ice data (ice edge and concentration). In 1978, a SMMR was launched on both Nimbus-7 (G) and SEASAT (a dedicated oceanographic satellite). Their multiple channels permitted the sensing of SST, sea ice, surface wind speed, and several water vapor related parameters over large swaths of the ocean during each pass. The positive results obtained via specific scientific evaluation teams, assures SMMR type instruments will be on future remote sensing platforms.

Nimbus-7 SST verification efforts generally agree with the latest SMMR estimates of 1°C accuracy (Lipes, 1982). It should be noted that passive microwave radiometers can penetrate clouds to the surface below but only at the relatively poor resolution of 150 km for SST. Surface oceanographic features that have sharp SST gradients, thus cannot be adequately sensed via this instrument. Side-lobe contamination also precludes accurate SST retrievals within 300-600 km of land, eliminating many fishery applications.

The SMMR instruments have renewed the interest in sea ice research and polar oceanography in general. The 50 km data from SMMR on ice edge location and concentration has greatly expanded ice mapping in the desolate polar seas where cloud cover may rule out IR imagery. Surface oceanographic features that have sharp SST gradients, thus cannot be adequately sensed via this instrument. Side-lobe contamination also precludes accurate SST retrievals within 300-600 km of land, eliminating many fishery applications.

Investigations have found that Nimbus sea ice edge location data is accurate to about 50 km. Unfortunately, ice age algorithms have met with less success since many factors (snow cover, melting snow, etc.) can lead to incorrect estimates. Current work in this area by NORDA's Polar Oceanography Branch, the Naval Research Lab (NRL), NASA, and others with airborne platforms, will test the capabilities of the Navy's Special Sensor Microwave Imager (SSM/I) in all three sea ice categories.

Passive microwave radiometers can also measure the surface wind speed (magnitude only) over a ocean swath ~1500 km wide with a resolution of ~25 km. SEASAT SMMR evaluations reveal an accuracy of ~2 ms⁻¹ over a range of 4-25 ms⁻¹. Studies also reveal sensitivity to higher winds, but an inexact knowledge of sea foam and wave slope characteristics have thus far limited the upper value of accurate detection to 25 ms⁻¹. This sensor can thus partially fill the huge void in oceanic wind data, but lacks the ability to compute vector winds since it measures only the scalar quantity.

### 5. Active Microwave Radars

A scatterometer's benefits become apparent when it comes to specifying surface wind directions. This active microwave radar emits a pulse to the ocean surface and measures the amount of back-scattered radar energy. Small capillary waves (1-2 cm) are sensed by the scatterometer pulse (14.6 GHz for SEASAT) and their characteristics change as a function of wind speed. Also, by virtue of having two (2) antennas per spacecraft side, direction with some aliases can be derived due to the bi-harmonic nature of the anisotropic radar return.

Subjective removal of these ambiguities can be accomplished by a synoptic meteorologist who has accurate surface weather maps. More recent efforts by Hurtele, et al., 1982 and Hoffman, 1982 indicate automatic dealiasing has made considerable progress. A future scatterometer with 3 antennas per side will largely reduce the number of wind retrievals with 3 and 4 aliases. The remote sensing of the surface wind vector, when combined with stability data enables wind stress measurements to be made.

The SEASAT-A Scatterometer System (SASS) has been evaluated by a number of scientific teams to assess its verification. Lane and Born, 1982 report that the root mean square (RMS) error of SASS in winds from 4-26 ms⁻¹ was 1.3 ms⁻¹ (well within the original design specifications). The SASS comparisons with surface truth indicate the error increases with increasing speed once the wind is above gale force (17-18 ms⁻¹). However, Hawkins and Black, 1982 reveal that SASS meets its original expectations in winds up to 25 ms⁻¹. The 50 km resolution of SASS over a swath 1500 km across, thus provided a wealth of accurate surface wind data over the vast ocean basins (especially the tropics and southern hemisphere).

The satellite altimeter represents another active microwave radar capable of benefiting oceanographic models. One purpose of the altimeter is to measure the distance from the spacecraft to the sea surface with an accuracy of a few centimeters. This then leads to the sea surface height if the earth's geoid is accurately known and subtracted out. Another means of obtaining quality height variability data is using altimeter data over repeat tracks (i.e., the geoid is not time dependent). SEASAT altimeter studies reveal a precision of ~8 cm was achieved in conditions where the significant wave height (H 1/3) was <5 m (Lane and Born, 1982).

The sea surface height varies about the geoid by 0-2 m, while the geoid undulates 100-200 m with respect to a reference ellipsoid. The sea surface signal is thus two orders of magnitude smaller than geoid variation. Care must be taken to provide an accurate geoid
and atmospheric corrections to adjust the raw data. Otherwise, typical eddy sea height variations of 20–50 cm will be entirely masked. The geostrophic surface velocity can then be retrieved and thus provide oceanographers with a synoptic view of ocean circulation never before imaginable. The altimeter pulse also contains information on the significant wave height and the surface wind speed along the narrow instrument swath directly below the spacecraft. Comparisons with in situ data disclosed errors of 10° or 0.5 m over a range of H 1/3 from 0–13 m and ±2 ms⁻¹ in winds of 0–10 ms⁻¹. An altimeter can thus supplement a WIR instrument in obtaining surface wind speed data.

4. Infrared SST

Infrared imagery has been used in a qualitative manner for about 20 years to detect strong sea surface thermal features. Large SST gradients have been mapped under "cloud free" conditions to locate fronts and eddies. Quantitative SST values were extracted from digital satellite IR imagery as early as 1972 by NOAA-NESS (McClain, 1982). However, only within the last year has the accuracy of these high resolution measurements crossed the 1°C threshold.

The use of multiple IR bands to account for the potentially large atmospheric attenuations of the IR signal has provided an important step forward. NESS now operationally calculates 8 km resolution SST values every 25 km in "cloud free" areas. By virtue of the Advanced Very High Resolution Radiometer (AVHRR) 30–40,000 SSTs can be calculated over the globe's oceans every 24 hours. A synoptic picture of the SST on global basin scales is now feasible, virtually overwhelming the number of surface ship SSTs previously obtained via a laborious method.

5. Potential Applications to Numerical Models

The oceanographic community saw a number of satellites go up in the late 1970's that contained "proof of concept" instruments. Verification teams from a variety of countries and backgrounds have arrived at the conclusion that they worked as well or even sometimes better than anticipated. These extremely positive results only came after years of algorithm development and tests with independent data sets. Many questions have been answered, but many more have surfaced and remain to be explained. However, remote sensing instruments can now provide a variety of synoptic data vital for initialization and forcing of numerical ocean models.

Environmental numerical ocean models are typically initialized via two methods. Many are spun up from rest with prescribed forcing functions and boundary conditions and integrated to statistical equilibrium. Others are begun by specifying climatological values as initial conditions. This has been necessary due to the sparsity of oceanographic data, whether it be wind stress, sea surface height, SST, etc.

Previous investigators have spent a considerable effort collecting many years of ship wind observations that are screened, binned, averaged, and interpolated to grid points. This laborious method can now be laid to rest once an operational scatterometer is flying. High accuracy and resolution over large swaths would quickly cover the world's oceans. Many of the enclosed seas could be covered in one to three passes while the large ocean basins would take 6–10 days to be adequately sensed. Thus, domains the size of the Atlantic would have a questionable synoptic coverage of wind stress if only one scatterometer was flown and the surface wind field was rapidly changing due to large energetic storm systems.

SMMR and altimeter retrieved wind speeds and GES low level winds could be used to augment the scatterometer wind stress data base. A SWH type instrument on a satellite other than the scatterometer based platform (i.e., SSM/I) would significantly increase coverage and provide a more comprehensive snapshot view of the wind field. Assimilation problems will arise, but the capability to provide accurate real time atmospheric forcing would exist. Oceanographic features strongly dependent on wind forcing (upwelling, waves on many scales, etc.) could thus be modeled to an extent never before possible.

An accurate knowledge of the sea surface height world wide would lead directly to specifications of the global ocean surface circulation. The resulting fields of geostrophic current velocity could impact models of various basin sizes. An altimeter with the design precision and orbit of Topex (Report of the TOPEX Science Working Group, 1981) could provide the oceanographic community, especially modelers, with an invaluable sea surface height data base between 64°N and S. Models previously limited by extremely poor initial and boundary conditions would thus be greatly improved and likely show more realistic ocean structure on a number of spatial-temporal scales. Such an instrument could initiate a true revolution in our understanding of ocean circulation and ability to predict ocean thermal structure and climate over vast regions.

The advent of operational hardware and software to derive multichannel SSTs (MCSST) with an RMS better than 1°C (McClain, 1982) also opens up another means of deriving sea height data. In ocean regions where there is 1) a well defined temperature-salinity (T/S) relationship and 2) availability of a "generic" temperature profile of the water type(s) in the area, one can calculate the sea surface dynamic height via the thermal wind relationship after assuming a level of no motion. This method would be
restricted to the mid and low latitudes due to extensive cloud cover limiting IR coverage in the polar regions. It would be quite interesting to compare altimeter, XST, and HCSSS derived sea surface heights for a dynamic ocean region such as the western Atlantic. The HCSSS method may prove helpful to supplement altimeter data or more likely provide models like MOMA's Gulf of Mexico version with acceptable sea height data until an operational altimeter is launched.

Thermodynamic ocean models have been forced to rely on questionable SSTs based almost exclusively on surface ship opportunity that traverse relatively few well sampled shipping lanes. The result has been SST fields that rely on climatology over broad areas of the ocean. This is an unacceptable method which now is being directly influenced by new remote sensing platforms. NOAA-7 (polar orbiting meteorological satellite) has three (3) IR bands in the "atmospheric window" region. The differential absorption in the bands (3.55-3.93, 10.3-11.3, and 11.4-12.5 um) allows corrections for atmospheric attenuation of the IR signal by water vapor. High resolution (8 km cells every 25 km) SSTs with accuracies better than 1°C (McClain, 1982) are now being obtained operationally at NOAA-7 in "cloud free" areas.

These SSTs and sophisticated optimal interpolation contour regimes are revealing thermal features never seen in such detail before. The synoptic nature of the data will allow accurate initialization of SST in thermodynamic models that even include very high resolution (10-25 km). These HCSSS could be supplemented by SMMR derived values in areas characterized by extensive persistent cloud cover. The poor resolution would be a drawback, but could provide values on the northern boundaries of some of the larger basin models.

6. Future Satellites

The technology is presently available to satisfy many of the parameter requirements necessary for oceanic environmental models. However, budget restrictions have severely curtailed planned missions. The deletion of NSOSS was a serious blow to the development of oceanographic remote sensing in the U.S. SEASAT represented a significant technological advance, but the momentum it generated has been lost and only now are viable alternatives appearing to appear. The U.S. will likely launch an altimeter in the late 80's and possibly a scatterometer in the mid 80's on a polar orbiting NOAA satellite. Other countries have recognized the potential of remote sensing and are no longer waiting in the wings.

Japan appears the most energetic with a SMMR type instrument in 84-85 and an altimeter-scatterometer shortly thereafter. The Europeans will fly a SMMR platform in the mid 80's and Canada a Synthetic Aperture Radar (SAR). All have certain advantages and disadvantages with regards to oceanographic applications, but the diversity has not yet been unified to present proper exploitation of the data.

The U.S. Navy has recognized the potential of remote sensing platforms with respect to modeling efforts. The Special Sensor Microwave Imager (SSMI) in FY-84 will provide wind speed and sea ice information to appropriate fleet models for oceanographic use. Water vapor data will be used to correct the altimeter signal from GEOSAT, an FY-84 geodesy mission, in an effort to provide accurate sea height data for the detection of significant fronts and eddies as well as model initialization. The proposed Navy Remote Ocean Sensing System (NROSS) will provide the full complement of sensors similar to SEASAT (altimeter, scatterometer, SMMR), and thus in an operational mode provide the Navy and civilian users with accurate, high resolution data needed to advance numerical models covering domains of all sizes.

7. References

Hawkins, J.D. and P.G. Black, SEASAT scatterometer detection of gale force winds near tropical cyclones. (Submitted to J. Geophys. Res.)


