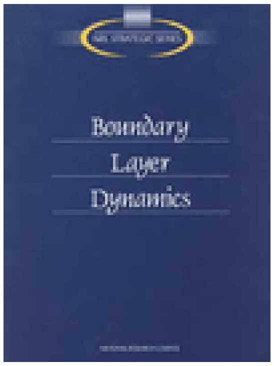

Boundary Layer Dynamics

Panel on Boundary Layer Dynamics, National Research Council

ISBN: 0-309-59037-X, 50 pages, 8.5 x 11, (1997)

NRL STRATEGIC SERIES

Boundary Layer Dynamics

Panel on Boundary Layer Dynamics
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

This work was performed under Department of Navy Contract N00014-93-C-0089 issued by the Office of Naval Research under contract authority NR 201-124. However, the content does not necessarily reflect the position or the policy of the Department of the Navy or the government, and no official endorsement should be inferred.

Copies available from:
Naval Studies Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418
Printed in the United States of America

Panel on Boundary Layer Dynamics

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Preface

To assist with its long-range strategic planning, the Naval Research Laboratory (NR.L) requested that the Naval Studies Board of the National Research Council (NRC) form a panel to study research opportunities and related issues in boundary layer dynamics. NRL's request for independent advice acknowledged the importance of this area of science for a broad range of naval applications. Generally, boundary layer dynamics (BLD) is concerned with observing, modeling, and predicting the structure of and changes in the atmospheric and upper ocean environment in which the Navy operates. Besides nonlinear dynamics of the marine atmospheric and oceanic boundary layers, radiative fluxes and thermodynamic phase changes are involved in BLD, all of which must be understood to serve the Navy's interests in such topics as signal propagation and ocean wave prediction. Coastal areas are particularly challenging, because it is in nearshore environments that BLD processes are most complex. Coastal atmospheric phenomena and processes have been addressed in the NRC report *Coastal Meteorology-A Review of the State of the Science* (National Academy Press, Washington D.C., 1992), which discusses many scientific opportunities specific to coastal regions and provides a valuable complement to the present report.

In response to NRL's formal request, the Panel on Boundary Layer Dynamics was established and was directed to assess research challenges in the area, identify leading research groups worldwide, and discuss the best use of NRL's research facilities for work in BLD. As with the other parallel efforts in the NRL Strategic Series studies, the panel was requested to meet with NRL researchers working in BLD and receive briefings on existing and planned research efforts. These briefings would guide the panel as it considered potential characteristics of and research thrusts for a coordinated and focused program in boundary layer dynamics to make the best use of NRL capabilities and facilities, particularly the most recently assimilated NRL laboratory on the West Coast, in BLD research.

The formal charge to the panel was as follows:

The environment has considerable impact on the ability to detect, localize, and identify objects remotely. Boundary layer meteorology appears to be a dominant factor affecting the Navy environment. Critical aspects of this will be examined and discussed according to the following:

a. The air/sea interface has been investigated experimentally and theoretically for decades, with many sophisticated models currently available. Yet, there are inconsistencies between models and between theory and experimental observations in a number of cases. An assessment of the experimental and theoretical scientific opportunities is desired. Particular emphasis is desired for the examination of leading R&D activities worldwide and a priority ranking of the frontiers currently anticipated.
b. Hydrodynamic modeling is an important aspect of predicting the ocean surface patterns resulting from wind/wave interaction. The formation of wave roughness patterns, slicks, and other phenomena is the result of a complex process. What are the scientific principles which are highest priority to pursue in order to understand these phenomena? Where are the leading groups in this endeavor?
c. The effect of microwave scattering from the ocean surface is a complex phenomenon. Rough surfaces are more difficult to handle due to breakdown of the Fourier approximation normally used to model scattering from minimally perturbed surfaces. The surface takes on complex patterns involving nonlinear wave-wave/current interactions, surface tension effects, etc. Millimeter waves demonstrate a number of

these complexities. What scientific principles are currently being pursued and/or appear to be the leading endeavors during the next decade in this field? Where are the leading efforts worldwide?

d. Given the pockets of technical expertise currently pursuing these efforts, what facilities should be emphasized by various types of participants (academic, government laboratory, industrial) for maximum progress in this field?

During the course of the study, the Panel on Boundary Layer Dynamics held meetings at NRL-East, Washington, D.C., on May 19, 1992; at NRL-West, Monterey, California, on July 9–10, 1992; at NRL-S, Stennis Space Flight Center, Bay St. Louis, Mississippi, on October 29–30, 1992; and at the Monterey Bay Aquarium Research Institute, Pacific Grove, California, on November 18, 1993.

Contents

Executive Summary

The Panel on Boundary Layer Dynamics has critically examined the opportunities that exist to make substantial advances in experimental probing, and in theoretical studies and modeling, of the marine atmospheric boundary layer (MABL) and the oceanic boundary layer (OBL). These two boundary layers are the primary operating environment of the Navy. Quality-controlled observational data from various sensors provide an essential foundation for naval operations. Understanding the variability of boundary layer structure and fluxes, particularly in coastal regions, is essential to the Navy's capability for evaluating the level of uncertainty in weather and undersea forecasts, and in detection capabilities.

Wave properties at the interfacial surface between the MABL and OBL have a direct impact on at-sea operations. Knowledge of signal propagation in all marine environments is absolutely critical for assessing and predicting the performance of diverse defensive and tactical weapons systems as well as for detecting and localizing targets. Properties (physical, chemical, and biological) of the OBL often determine the nature of the working environment and the margin of safety afforded for underwater naval operations.

In this report, the panel describes research opportunities in the following areas: (1) geophysical processes in the MABL and OBL, specifically MABL fluxes and coupled turbulent flows; (2) the important topic of assimilation of data obtained from probing these marine environments; (3) the fundamental techniques for acquiring necessary data and reaching a new level of understanding of surface wave dynamics and electromagnetic propagation and signature physics; and (4) boundary layer dynamics (BLD)-related acoustical and optical oceanography. The order in which these topics are addressed reflects the panel's judgment of their relative priority for NRL research.

Chapter 1 outlines the relationship of the topics to the panel's charge; the topics for research are discussed in detail and related recommendations are made in Chapter 2.

The panel' s chief conclusions and recommendations are as follows:

1. The spatial and temporal variability of marine atmospheric boundary layer fluxes is large, particularly in coastal regions. This variability greatly affects the reliability and stability of forecasts. *The panel recommends that NRL support the development, evaluation, and use of a diverse set of sensing and measurement systems for the marine environment, steered by a small group of scientists, to study marine atmospheric boundary layer fluxes for their fundamental geophysical importance. An additional benefit of such work would be an improved understanding of the effects of these fluxes on aspects of system performance, e.g., on propagating signals*. In this NRL effort a visiting scientist and postdoctoral study program is particularly encouraged.
2. Coupling of the Navy's atmosphere and ocean predictive models has a natural place in the Navy's research mission, and the coupling of the atmospheric and oceanic turbulent flows through computational fluid dynamics techniques, such as large eddy simulation, is an important research area. The panel notes that coupling of these models might lead to little immediate improvement in atmospheric forecasts but should have a real impact

on understanding and prediction of flows in the oceanic mixed layer. NRL has many capabilities and significant needs for application of results of research in this area. *The panel recommends that NRL significantly expand the scope of its theoretical expertise in the areas of computational fluid dynamics related to boundary layer dynamics and that it guide and be guided by ongoing experimental efforts in air-sea physics and the development of remote sensing technology, with coupling of the atmosphere and ocean predictive models as a major goal*.

3. The goal of a focused, advanced research program in BLD at NRL-East, -Stennis, and -West should be to enhance the Navy forecasts produced at the Fleet Numerical Meteorological and Oceanographic Center (FNMOC)/NRL-West facility. An unusual synergistic opportunity exists at NRL-W that could improve the cohesiveness of efforts made at the three NRL sites; establish a research orientation at NRL-W extending beyond highly applied operational support; and build intersite teams to tackle important initiatives. *The panel recommends an integrated multisite program in the area of ocean data assimilation and, in particular, the creation of a new center located at NRL-W to take advantage of the special resources at the Fleet Numerical Meteorological and Oceanographic Center. The European Centre for Medium-range Weather Forecasting may serve as a model*. This program will require new observational data, obtained from a sparse set of distributed sensors, or from new satellite-borne sensors. The aim is to ensure that all available environmental data that have the potential for improving forecast products be identified, evaluated, and assimilated.
4. Although progress has been and continues to be made in understanding nonlinear interactions between wave modes, between waves and shear layers, and between waves and variable currents, this work has had little influence thus far on practical ocean wind-wave modeling. OBL and MABL modelers may need better parameterization of the sea state. Better algorithms are needed to interpret and analyze data from remote sensing, and experimentalists need help to improve techniques for measuring air-sea interaction, surface fluxes, and gas transfer in the presence of waves. There is a real opportunity to make progress in BLD by exploiting progress in surface wave dynamics to develop improved deterministic and statistical models that can guide advanced experiments on ocean wind-waves. An active group with a strong theoretical and experimental background in wave physics could interact with many research groups already in existence at NRL, or could provide linkage between disciplines and sites. *The panel recommends that NRL initiate a new program in the field of surface wave dynamics that has well-balanced theoretical, numerical, and experimental components*. For NRL to achieve this balanced program will require new leadership, particularly in the theoretical components of the research. Scientific talent drawn from present in-house areas such as plasma dynamics may well provide the necessary human resources.
5. The panel is keenly aware that ocean sensing active microwave instruments all make highly indirect measurements of geophysical quantities. The quantitative interpretation of data is hampered by ignorance of both (1) the detailed scattering mechanisms by which the incident radiation is reflected

back to the receiver from the rough ocean surface and (2) the precise relationship between oceanic and atmospheric processes of interest and the small-scale surface geometry. These issues, while not completely separable, are distinct. Historically, because of the operational (naval or geoscientific) imperative for obtaining data of any sort, the details of the processes have been ignored, and the apparent correlations between backscatter cross sections and the geophysical quantities of interest have been used to generate empirical or semiempirical models. However, the persistent scatter in all extant microwave data sets, the limited range of conditions over which high-quality radar and correlative measurements have been obtained, and the continuing controversies over the accuracies and forms of the empirical models all testify to the fundamental inadequacy of the empirical approach alone. *The panel recommends that NRL undertake a strong experimental and theoretical program in electromagnetic propagation and signature physics, particularly in developing and exploring passive microwave techniques such as multispectral and polarimetric methods. In the active microwave sensing area, the panel urges a strong collaborative program with academic (e.g., Office of Naval Research [ONR]-sponsored) groups*.

The panel believes that the Navy has unique resources to contribute to the passive multispectral microwave sensing area. Spaceborne or airborne passive microwave instruments sense not only signals generated at the ocean surface, but some integrated atmospheric properties as well. The problem requires the resources and teamwork that only a large integrated laboratory complex such as NRL can supply. The panel's suggestion of a new theoretical approach is based on this observation. In recommending a collaborative program with ONR-sponsored groups in active microwave sensing, the panel notes that there have been highly successful models (e.g., the High Resolution Remote Sensing [HRRS] Advanced Research Initiative) from which to draw.

6. On the small scale, the marine microlayer—the thin interfacial boundary between the atmosphere and the ocean—plays a critical role in air-sea interactions. The presence of surface slicks attributable to man-made alteration of this surface can be recognized by the effects of changes in the visco-elastic modulus. There is strong evidence that coastal areas are zones of naturally high levels of surface compounds that alter capillary wave propagation. Understanding of this natural background is essential for improving signal detection. *The panel recommends that NRL undertake a strong, coordinated research program that includes simultaneous underwater acoustic, electromagnetic, and optical measurements of the oceanic and marine atmospheric boundary layers in carefully selected coastal zone and continental shelf environments, in which different conditions of atmospheric forcing and the influence of surface slicks can also be quantitatively documented*. This effort should involve active and passive electromagnetic and optical (visible and infrared) measurements from above the sea, as well as active and passive undersea probing of the ocean surface and mixed layers.

NRL should pay immediate attention to the opportunities identified in this report and to the recommendations of the panel. During the time that this report has been in preparation, key personnel have retired and major wind-wave facilities at NRL-E have been torn down. The balanced approach of experimental and theoretical work recommended here, combined with the potential of a new center to exploit the gains in BLD understanding expected from this work, presents a very special opportunity to produce improved forecasts for the Navy. In all endeavors a commitment to ship time is essential; the Navy's working environment is not the laboratory bench top or a computer, but rather the open ocean and coastal waters of the real world.

Chapter 1— Introduction

This report describes selected opportunities for the Naval Research Laboratory (NRL) in a broad spectrum of research related to boundary layer dynamics (BLD). Generally, research programs in BLD are concerned with observing, understanding, and predicting the structure and evolution of the atmospheric and oceanic boundary layers, which are the environment in which the Navy operates (Figure 1.1). To support naval operations effectively, remote and in situ observing systems must provide quantitative data on a broad range of scales about physical and dynamical processes in both the atmosphere and ocean, as well as detailed information about the structural dynamics and interfacial surface between the two fluids. Remote sensing from above the ocean surface —primarily with electromagnetic and electro-optical systems designed to observe the atmospheric and oceanic mixed layers and the ocean's surface—requires knowledge of signal propagation, scattering, and emission. Below-surface remote sensing of the ocean and its mixed layer, and of surface and near-surface wave dynamics, is conducted principally with diverse active and passive acoustical systems. Interpretation of these acoustical observations, particularly those obtained in coastal and continental shelf waters, continues to provide a broad class of challenging basic and applied research problems.

Particularly with the current emphasis on littoral warfare, successful Navy and Marine Corps operations are increasingly dependent on reliable predictions of environmental conditions, such as sea state and atmospheric moisture distributions in shallow coastal waters. A thorough understanding of the level of uncertainty in these forecasts is needed to guide planning and execution of such operations.

The panel believes strongly that there are important synergistic opportunities among the capabilities for BLD research in the NRL organizational framework. While many of these opportunities are mentioned in Chapter 2, a major synergistic opportunity is discussed in detail in Chapter 3, which emphasizes, in particular, the establishment of a new center at NRL-W to assimilate the results of BLD research, and takes advantage of the capabilities at the Fleet Numerical Meteorological and Oceanographic Center facility with the goal of improving forecasts for the Navy. Chapter 4 addresses the issue of infrastructure resources and needs, including facilities. The panel's closing comments are given in Chapter 5. A list of some of the leading research institutions and groups in the topical areas discussed in Chapter 2, also requested in the terms of reference, is contained in Appendix A. Appendix B defines the acronyms and abbreviations used in this report.

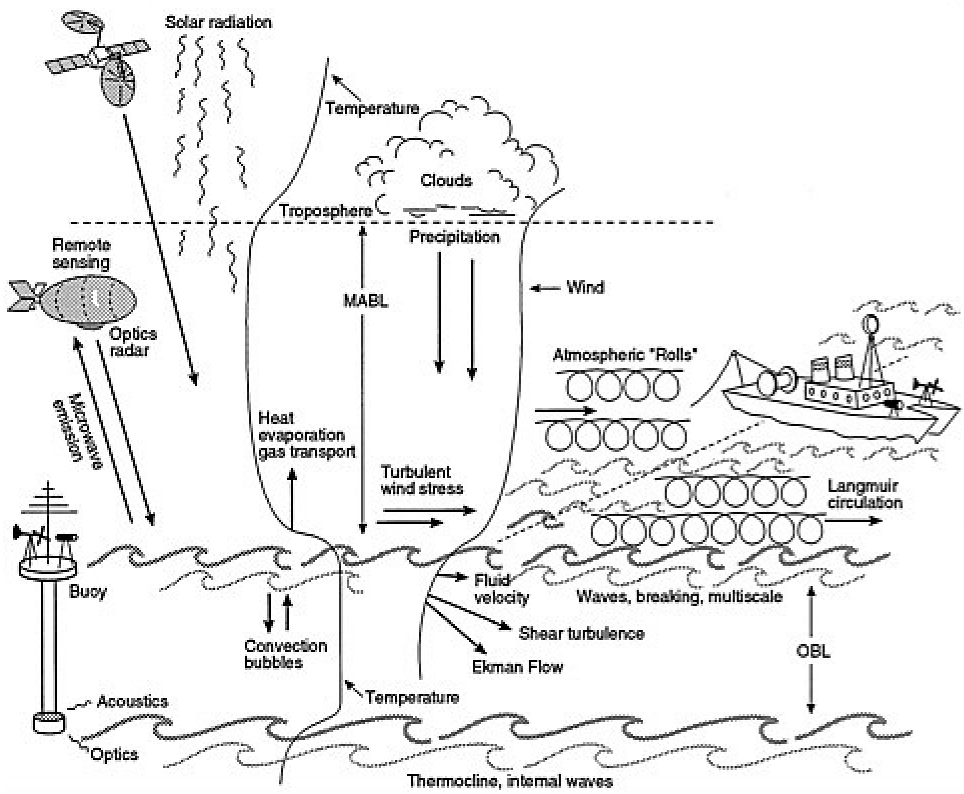

Figure 1.1 Structure and processes in the marine boundary layers. MABL, marine atmospheric boundary layer; OBL, oceanic boundary layer.

Chapter 2—

Scientific Opportunities and Recommendations

In this chapter the panel discusses various research topics related to boundary layer dynamics (BLD) and makes recommendations bearing on work in these areas. For each topic, the basic elements and their research significance, status (experimental and theoretical), and questions of current interest are summarized, a possible role for NRL is suggested, and recommended steps for NRL are outlined. The topics are ordered so as to address the geophysical environment represented by, and processes in, the marine atmospheric and oceanic boundary layers; the important topic of assimilation of the data obtained from probing these layers, and the key technologies and observational imperatives necessary for acquiring data and for reaching a new level of understanding of marine meteorology and ocean processes and their impact on naval operations. Throughout, the panel emphasizes that modeling and theoretical components are absolutely necessary, but also that modeling without adequate supporting and confirming data, or theory without experimentation, will not give the information the Navy needs.

MARINE ATMOSPHERIC BOUNDARY LAYER FLUXES

Definition

Marine atmospheric boundary layer fluxes describe the quantitatively measurable transport of radiation, momentum, thermal and moist energy, gases, and particles in and through the marine atmospheric boundary layer (MABL). These fluxes control the dynamical state and evolution of the MABL because they determine its stability and, consequently, how closely the marine surface layer is connected both to the overlying atmosphere and to the underlying ocean. Understanding the spatial and temporal variability of these fluxes, particularly in coastal regions, is essential to evaluating the uncertainty of weather and undersea forecasts and, consequently, to predicting the performance of a variety of weather and sea-state-sensitive surveillance, mobility, and weapons systems.

Characterizing fluxes of mass, momentum, heat, moisture, and gases across the ocean-atmosphere interface, and the dependence of these physical processes on mean conditions of the ocean and atmosphere, is critical to understanding the vertical mixing of mass and material components, momentum, and heat within the upper layer of the ocean; air-sea interaction and its effects on wind stress; and the results of remote sensing of the ocean surface.

Research Status

Investigation of MABL fluxes is perhaps central to research on air-sea interaction because of the difficulty of directly measuring such interaction. Ideally, experiments yielding measures of the impact of near-surface conditions on MABL fluxes could be used as a basis for explaining the effects theoretically. Despite the fact that good experimental techniques have been developed, it has proven difficult to make direct measurements of the layers. Theoretical work continues to be largely ad hoc. Turbulent fluxes have not yet been measured in or over the open ocean, leaving knowledge of the oceanic boundary layer (OBL) and the MABL far behind that of the terrestrial atmospheric boundary layer where vertical profiles of fluxes are commonly measured.

Understanding and modeling the effects of the wave field on surface fluxes are still in initial stages. Long waves and currents can modulate the near-surface flow in the MABL. The internal MABL readjusts during early stages in wave growth, and in the land-sea transition.

Since the heat capacity of a few meters of water is equivalent to that of the entire dry atmosphere above, reliable measurements of temperature in the first few meters of the ocean are crucial for improved models of air-sea heat transfer. Simultaneous temperature and turbulence measurements would permit direct measurements of heat flux in the marine boundary layer. Buoys are the primary platform for making such measurements in the open ocean. New techniques and small low-power instruments are needed to accurately measure fluxes near the ocean surface.

Oceanic fluxes are inferred or modeled based on observations of mean fields (velocity, temperature, density, and so on). Improved parameterization of fluxes for use in coupled ocean-atmosphere models is needed for investigations of global change and for climate variability studies.

Accurate measurements of boundary conditions will most probably come from networks of observations of mean conditions. Ultimately, remote sensing will provide, directly or indirectly, data on fluxes over a global scale. Indeed, there have been great advances recently in our ability to monitor ocean properties over large time and space scales.

Questions of current research interest include the following:

- How well are fluxes in calm seas understood?
- How do ocean surface waves affect marine surface fluxes?
- When can the standard Reynolds averaging techniques be applied to define marine surface fluxes?
- Do our stability parameterizations, which were determined over land, really work well over the ocean?
- How well can energy and momentum budgets be computed at the air-sea interface?

Experimental Approach

The experimental determination of near-surface fluxes is difficult not only because of the difficulty of working in open ocean conditions, but also because the measurements nearly always disturb the process being measured. Varied solutions to this problem have been tried. Slender towers and masts have been erected that, although they pierce the water surface, cause minimal distortion of the fluxes. Buoys follow the ocean surface, and special care has been taken to remove this motion from the measurements. Other environmental factors may also affect measurements, and new theoretical developments are required to take into account the possibility of such contamination. Aircraft measurements have been attempted, but aircraft have trouble staying in the surface layer and cannot make measurements in the water. Measurements have been made from a blimp using a suspended platform to obtain atmospheric fluxes near the surface, and using towed sensors in the water to measure conditions in the water. Remotely piloted (or operated) vehicles (RPVs or ROVs) are becoming available for making measurements in the atmosphere and under the ocean.

The development of fast-response, stable, dissolved-gas sensors, which can be deployed for periods of months without losing calibration, is making possible field tests of gas transfer models and of their relationship to remotely sensed MABL and OBL properties. The simultaneous measurement of turbulence and dissolved gas will lead to improved models of gas transfer.

Theoretical Approach

At present, the theoretical basis for determining how near-surface stability affects atmospheric fluxes to the ocean rests on the similarity theory developed in the 1950s by Monin and Obukhov. Homogeneity and stationarity are assumed in this theory, so that it may not be adequate in general. Moreover, current theory on surface wave effects on fluxes is not derived from first principles and involves approaches that quickly present problems in dealing with waves in vertical shear flows. Obviously, the problem of wave effects on fluxes is intimately associated with the problem of the growth and dissipation of ocean waves.

Possible Role for NRL

NRL should not be concerned with flux parameterizations in terms of standard meteorological variables, because there is little room for improvement. However, surface wave parameters can be included in these parameterizations. Also, a capability for directly measuring flux is needed for determining flux on short space and time scales where bulk flux estimates are unreliable. NRL instrumentation-related technologies could play a key role in developing this capability.

Recommendation

The panel recommends that NRL support the development, evaluation, and use of a diverse set of sensing and measurement systems for the marine environment, steered by a small group of scientists, to study marine atmospheric boundary layer fluxes for their fundamental geophysical importance. An additional benefit of such work would be an improved understanding of the effects of these fluxes on aspects of system performance, e.g., on propagating signals. Work in this area should be done cooperatively with other university and laboratory groups that have scientific leadership in the relevant areas, e.g., atmospheric turbulence and radiative transfer. In these areas, the development of a visiting scientist and postdoctoral study program is particularly encouraged.

COUPLED TURBULENT FLOWS

Definition

Coupled turbulent flows are the physical processes that control the exchanges of matter and of thermal and dynamical quantities through the air-sea interface. Currently, the best theoretical basis for modeling the complicated, nonlinear processes at the interface is large eddy simulation (LES) of the atmospheric and oceanic mixed-layer turbulent flows. The LES approximation involves a dynamical model of the atmosphere or ocean in which turbulent physical quantities are averaged over a scale smaller than the size of the large energy-containing eddies. In LES, the important turbulent scales are resolved, so that the effects of parameterized subgrid-scale turbulence are secondary. Coupling of dynamical LES models is a challenging area in fundamental fluid dynamics research. NRL-East (Washington, D.C.), -Stennis (Bay St. Louis, Mississippi), and -West (Monterey, California) apply the results of coupled turbulent flow research to specific problems such as surface signature, aerodynamic forcing of waves, and ocean-air heat and moisture fluxes. Coastal regions also pose a particular challenge in coupled turbulent boundary layer physics. Understanding the detailed structure and dynamics of the ocean's surface is critical to interpretation of satellite, airborne, and underwater remote sensing data that are required for both environmental diagnostic and forecast models.

Research Status

Marine Atmospheric Boundary Layer

A major challenge in large-scale atmospheric modeling is to adequately represent the unresolved physics of the boundary layer. Current problems include extending the influence of surface fluxes properly in the vertical; modeling the correct amount of wind veering through the baroclinic boundary layer; providing the information required to model clouds; and modeling properties into, through, and out of the boundary layer. A particular opportunity exists for NRL to acquire an enhanced capability for analyzing and predicting boundary layer structures and properties that are of special interest to the Navy. Basic research is required by NRL to support this capability, because other research and forecast centers do not have the same special needs. In all cases there is an opportunity to exploit LES techniques.

However, it is important to state that LES techniques are not perfect and are themselves still an area of research. For example, LES boundary layers typically do not produce the familiar logarithmic profile near the surface, which is a serious flaw in wave and ocean models. Also, it is not certain that an individual researcher will fully understand the implications of LES solutions obtained from imported computer codes.

Questions of research interest include the following:

- How does the boundary layer interact with the free atmosphere, and what are the resulting effects on cloud formation and radiative feedback?
- Are boundary layer properties, such as the refractive index, being adequately analyzed and predicted?
- How important are secondary flows (roll vortices)?
- How does the ocean surface feed back to the MABL?

Experimental Approach: Boundary layer structures are typically observed from low-flying aircraft, which will probably remain the primary research platform. The Aerosonde RPV will be used in a field measurements program in Australia. At present many more data are collected than are analyzed.

Theoretical Approach: Most theoretical advances in understanding the turbulent atmospheric boundary layer have been either semiempirical or numerical. Most recently, LES approaches have led to much greater understanding of the convective boundary layer and to more rigorous testing of boundary layer turbulence parameterizations.

Oceanic Boundary Layer

The issues raised above for study of the MABL also hold true for the OBL, with the exception of clouds. However, the OBL is far less well understood and hence presents even greater challenges and opportunities. There is, for example, a significant opportunity to progress beyond the familiar concept of a homogeneous mixed layer, which is not always valid. The challenge is to quantify the physics unique to the OBL. One obvious difference from the MABL is surface waves, whose height and orbital velocities penetrate a large fraction of the OBL.

A significant fraction of the momentum flux from the atmosphere passes through the wave field before surface wave breaking transfers it to currents. Breaking surface waves almost certainly are the direct source of much of the turbulent mixing in the ocean near the surface. In the ocean, velocities are usually greatest near the surface, and rotation then leads to dominant inertial motions not found in the atmosphere. A further complication is that the OBL absorbs solar radiation, which somehow must affect the turbulence in ways not found in the transparent atmosphere. Again there is a great opportunity to exploit LES, but a challenge is to develop the technique for problems in the ocean.

Questions of current interest include the following:

- What are the similarities between the OBL and the MABL, and to what extent can atmospheric boundary layer theories and models be applied to the ocean?
- Is distinctive OBL physics to be expected from the presence and breaking of surface waves and from the dominating presence of inertial motions, surface films, precipitation, and radiation absorption?

Experimental Approach: Ocean observations are difficult and are likely to remain so. New instrumentation, such as ROVs for probing of the OBL, always requires considerable development, but the return on investment can be high. As mentioned above, turbulent fluxes have not yet been measured in the open ocean because of technical problems, such as the availability of stable measurement platforms.

The prospective Tropical Rainfall Measuring Mission (TRMM) satellite may offer an opportunity to obtain data to infer effects of precipitation on the OBL.

Theoretical Approach: There has been little theoretical advance in our understanding of the OBL for many years. Instead, understanding has come by analogy with the atmospheric boundary layer and numerical modeling. In principle, direct numerical simulations could provide a firm foundation for the subgrid-scale parameterizations required by LES, which, in turn, could be used to verify parameterizations required by the less sophisticated, larger-scale models of most practical use, up to and including climate-scale models. At present, this promising approach of building up a hierarchy of models, fundamentally based on firm, small-scale fluid dynamic principles, is in its infancy, with no organized, orderly effort being made to accomplish it.

Possible Role for NRL

NRL should consider a major research effort in turbulent boundary layer physics, including measurement of velocity and fluxes, and investigation of the parameterization in atmospheric, oceanic, and wave models. The NRL is strategically positioned to make significant scientific contributions in this research area. Boundary layers and turbulence are relevant to research activities at all three NRL sites. Atmospheric models would clearly benefit from better characterization of boundary layers. In addition, nonstandard but Navy-relevant boundary layer parameters could be added to the suite of prognostic variables to improve the prospects for successful prediction. The case for research in this area is even stronger for the ocean in coastal regions because of the potential for exciting new physics yet to be discovered.

Recommendation

The panel recommends that NRL significantly expand the scope of its theoretical expertise in the areas of computational fluid dynamics related to boundary layer dynamics and that it guide and be guided by ongoing experimental efforts in air-sea physics and the development of remote sensing technology, with coupling of the atmosphere and ocean predictive models as a major goal. If this cannot be accomplished by hiring new experts or transferring existing skilled personnel, a cooperative program with one or more of the leading university groups could be established.

OCEAN DATA ASSIMILATION

Definition

Assimilation of ocean data depends on developing and validating the methods necessary to optimally utilize diverse in situ and remote sensing measurements for the purposes of better initializing, updating, and evaluating oceanic and marine atmospheric analysis and prediction models. Exploiting new observational data sources as diverse as a sparse set of distributed sensors having high temporal resolution, or new satellite-borne sensors having varying spectral bandwidths and footprints, requires particular and often quite different data filtering and model initialization techniques. Improved analysis and modeling of the marine environment require that ocean models more effectively incorporate information about atmospheric forcing. Similarly, models of the MABL should include effects of the ocean. Quality-controlled observational data from diverse in situ and remote sensors are the essential foundation for operational activity in, as well as our knowledge of, the marine environment.

Research Status

Perhaps the greatest challenge presented by remotely sensed data is its assimilation into operational ocean and atmospheric models. A particularly important use for remote sensing data products is the verification of the long-term performance of models of the ocean and atmosphere.

Currently, satellite infrared imagery is being used to produce global sea surface temperature maps every two weeks, which then become the basis for the bottom boundary conditions for many atmospheric forecast models. The European Centre for Medium-range Weather Forecasting is currently evaluating the impact of assimilating satellite scatterometer wind vectors into such models. An important research issue is the assimilation of single-level data such as surface winds into atmospheric models, sea level height into ocean models, and wave heights into wave models.

One of the most fundamental issues to be resolved is the relationship of the data obtained from sensors to the actual properties of the ocean or the atmosphere. Satellites observe many different oceanic and atmospheric parameters with sensors operating in different frequency bands of the electromagnetic spectrum. Some satellite observations are direct measurements of the oceanic parameters (e.g., sea surface and wave height from altimeters, or directional spectrum from synthetic aperture radar), while others are indirect measurements (e.g., wind speed from altimeters and scatterometers). In order to extract oceanic or atmospheric variables from these indirect observations, model functions must be developed that often depend on additional parameters not necessarily available in the same time and space frame.

Currently, model function algorithms are tested primarily against in situ data, which is the very same type of data used to develop the algorithm in the first place. In situ data also have limitations; e.g., buoy observations may not have a dynamic range large enough to validate the model function algorithm. A complementary approach would be to develop the model function algorithm with global data sets (i.e., weather analyses) or by investigating the results of their use in numerical ocean models. At present, no systematic approach exists to cross-validate satellite data. One approach might be the following: sea surface topography could be obtained directly from altimeter measurements. Similarly, the sea surface height could also be generated based on scatterometer measurement of winds. Then it should be possible to determine whether these remotely sensed data used in models produce the same circulation. Inherent to the type of sensor used are different spatial and temporal sampling patterns that need to be accounted for. An important question is what effect, if any, different sampling characteristics would have on the results obtained.

Another fundamental problem is the merging of data sets intelligently, so that they can be used effectively. For example, it is possible to prepare global maps of evaporation from the ocean, but without companion information on precipitation and heat flux neither the fresh water nor thermal forcings can be obtained.

Other questions of current interest include the following:

- Can measurements of satellite cloud fields be used to improve cloud models?
- What monitoring data would have the most influence on ocean models?
- How well can coupled ocean-atmosphere models predict precipitation and cloud generation?
- How well can precipitation be measured by satellite?

Experimental Approach

The vast amounts of data flowing from modern satellite observing systems (e.g., NASA's Earth Observing System program) raise troubling questions about data assimilation. Data storage, transfer, and analysis also pose difficult technical problems. Merging data sets properly is another challenge. This is a fertile area for research.

Theoretical and Numerical Approach

The theory of data assimilation is well developed. In addition, considerable effort of a more empirical nature is being expended. Various assimilation schemes are being implemented and tested for their impact on model performance. However, generally, progress is needed in assimilation of data into models to allow cross-validation of multisensor input, testing of different assimilation techniques for scalar versus vector variables, and determination of optimum space-time sampling and assimilation cycles. Data and sampling sensitivities are also issues.

Possible Role for NRL

Currently, NRL-S performs most of the ocean modeling and related assimilation of satellite data, and NRL-W carries out the atmospheric modeling component. An opportunity exists to couple the two modeling activities by including surface wave dynamics. Most of the atmospheric forcing fields employed for these studies are derived from the ECMWF or are climatological and historical data sets. A focus for collaborative activity could be the combining of these models, using the products from the Fleet Numerical Meteorological and Oceanographic Center.

Another opportunity is for modelers at NRL-E and NRL-W to test their work on the FNMOC database and make comparisons with the existing FNMOC models.

The objectives of these coupled modeling efforts would be to validate multisensor data sets; improve understanding of the physics of air-sea interaction by coupling the MABL with the OBL; validate and improve operational models; and provide high-resolution products of interest to the operational Navy and to the climate modeling and research community at large.

Recommendation

The panel recommends an integrated multisite program in the area of ocean data assimilation and, in particular, the creation of a new center located at NRL-W to take advantage of the special resources at the Fleet Numerical Meteorological and Oceanographic Center. The European Centre for Medium-range Weather Forecasting may serve as a model. This recommendation is developed in more detail in Chapter 3.

SURFACE WAVE DYNAMICS

Definition and Introduction

Surface wave dynamics describes the forcing and characteristics of wind-and current-generated waves on the ocean surface. Understanding surface wave dynamics requires information on the overlying turbulent atmosphere, on waves and turbulence in the ocean mixed layer, on the many nonlinear interactions that occur between wave modes, and on the processes of forcing and dissipation.

Surface waves play a central role in many oceanic and atmospheric processes as well as in remote sensing and probing of the ocean surface by instruments. Surface waves occur over a wide range of scales. The associated discrete "micro-breaking" of short gravity-capillary waves is far more widespread than the visually obvious whitecapping of large gravity waves. Most microwave remote sensing devices utilize the gravity-capillary wavelength region of the spectrum. Also these small waves have the largest influence on gas transfer. The more energetic gravity waves dissipate energy by breaking, affecting upper-ocean mixed-layer dynamics. Spray, when generated from breaking waves, may be an important transfer mechanism. The degree of roughness of the ocean surface influences the frictional resistance experienced by the atmospheric flow. Proper determination of the surface wind stress must account for the presence of waves and depends on the stage of wave growth and on variations in space and time. Longer waves affect the radar reflectivity by modulating the shorter waves, and by tilting facets of the ocean surface. Wave properties have a direct impact on all naval at-sea operations.

Research Status

This section discusses the theoretical and experimental research status of surface wave dynamics in four areas: (1) the physics of wind-wave growth and equilibrium, (2) visco-elastic effects on processes at the ocean surface (3) monitoring and modeling of ocean waves on a regional and global basis and (4) wave-current interactions.

Physics of Wind-Wave Growth and Equilibrium

Details of the processes involved in the growth and equilibrium of wind-generated waves are not well understood. In the last few decades, a common framework for investigation has been developed based on the wave action equation, in which the temporal and spatial development of wave action (spectral energy density/ intrinsic frequency) is expressed as a resultant of sources and sinks of action. These sources and sinks are, respectively, the transfer of action from wind to waves, and the dissipation of action via breaking, turbulence, and interaction among spectral wave components. Experimentally and theoretically, wind input and nonlinear transfer are much better understood than is dissipation. Further theoretical and experimental advances are needed to couple atmospheric boundary layer dynamics with wave growth and decay.

Questions of current interest include the following:

- What is the nature of waves on an interface between vertical shear flows in air and water? Indeed, what is the nature of the flow itself very near the surface?
- How do the various Reynolds stresses and wave-induced stresses vary above and below the interface between two turbulent shear flows?
- How can the exchange of energy and momentum between wind and waves be logically and mathematically explained?
- Can wind shear and variability effects be included in theories of nonlinear interactions?
- Can strong nonlinearities such as breaking waves be handled theoretically and measured experimentally? How can breaking be best defined and quantified so that it covers the range between plunging breakers and micro-breaking?
- Can the dissipation of wave energy be measured accurately?
- How can wave spectra be measured over the wide range of frequencies and spectral densities seemingly needed to fully characterize air-sea interactions?
- What is the effect of precipitation on wave growth?
- How important is spray as a transfer mechanism?

Experimental Approach: Much insight into air-sea interactions has been gained through wave tank investigations. Details of gravity-capillary wave growth and equilibrium are difficult to determine on the ocean due to the ubiquitous presence of longer waves. Nevertheless, these experiments, as well as those in the field, generally must deal with questions of the effect of the local environment (the tank or tower, bottom topography, and coastline shape) on the measurements. Recent field measurements have concentrated on gathering data on wind-generated waves from either buoys or aircraft. The difficulties of long-term measurements have been well illustrated by the surface wave dynamics experiment (SWADE) on waves, in which buoys pulled loose from their moorings and were lost at sea. More recently, acoustic methods have proved useful in measuring wave properties ranging from spectral densities, to breaking statistics, to dissipation.

Theoretical Approach: In general, there is a need to develop nonlinear models of surface wave generation that adequately include the turbulence in the atmosphere, and to test these models against laboratory and field data. Due to the difficulty of fully characterizing waves on an interface immersed in a turbulent airflow, much theoretical work has been done in the past by ignoring many, or even all, aspects of the airflow and shear in the water. All well-developed theories on nonlinear interactions neglect airflow. Current theoretical understanding of initial wave growth is unsatisfactory owing to the difficulty of working with fully turbulent flow. And the most widely used dissipation model is not based on first principles.

Difficult theoretical work remains to be done in order to fully incorporate turbulent shear flow into existing wave theories. Furthermore, many aspects of surface wave theory, especially those dealing with strong nonlinearities, are not amenable to a spectral approach. In fact, surface wave interactions at disparate scales may be fast and strong, and can modulate the wave field to leading order in times comparable to a wave period. In contrast, the near-resonant gravity wave interactions are weak and occur over large space and slow time scales compared to those of the waves involved.

Visco-Elastic Effects on Processes at the Ocean Surface

At low wind speeds, up to perhaps 7 m/s, surfactants are very common on the ocean surface, particularly in coastal regions, owing primarily to chemical and biological activity but also to accidental oil spills. These surfactants suppress short waves on the surface due to their visco-elastic properties and thus may affect the physical, chemical, and biological fluxes across the interface. They can affect the OBL and MABL and also cloud growth. It should be emphasized that evanescent surface films are not at issue here. The bulk chemical properties of natural seawater constantly produce this surface damping effect, which is strongest in coastal and continental shelf waters. Its signal is detectable from spaceborne sensors, but signal recognition is in its infancy.

The damping effect is enhanced in surface convergence zones, thus accentuating surface patterns of subsurface phenomena such as internal waves. Furthermore, since ship-released surfactants drift with the surface currents, polluting spills may affect shorelines at some distance from the spill. For these reasons, the study of surfactants is of both scientific and economic importance.

Questions of current interest include the following:

- What is the effect of surfactants on fluxes across the air and sea interface?
- How do surfactants affect surface waves? How is wave growth affected?
- Can slicks be detected and classified remotely?
- Are natural and man-made slicks distinguishable?
- Is the related oceanic signature changing with increased industrialization?

Experimental Approach: The continuous monitoring of surface films as a function of time and space is a difficult problem that has not been completely solved. Techniques such as monitoring the spreading of oils with video cameras and the microwave detection of shortwave damping have been used to determine the nature of surfactants and their effect on surface properties such as surface tension and elasticity. These techniques are difficult and time-consuming to perform, however, and simple techniques that can be used on a routine basis to continuously monitor surfactant properties are only now being developed. Measurements made to date have clearly indicated the compaction of surfactants in surface convergence zones and their importance in remote sensing of the surface at low winds.

Theoretical Approach: The theory of damping effects of surfactants on waves in the absence of wind is well developed and verified. The treatments begin from a fundamental consideration of the pressure difference across a curved air-water interface on which a surfactant resides. The resulting expressions for the distance damping coefficient have been well verified experimentally in wave tanks. One prediction, that of a peak in this damping coefficient at a certain frequency, has also been observed on the ocean. However, the question of how surfactants affect the input of wind to waves has not been adequately addressed to date. This gap is understandable in light of the difficulties, discussed above, of completely describing wind input to clean water surfaces.

Monitoring and Modeling of Ocean Waves on a Regional and Global Basis

Monitoring: Many practical applications ranging from ship routing, to beach management, to weather prediction require the routine monitoring of ocean waves on a global basis. Techniques are now available that promise to be able to supply such information from satellites. The European satellite ERS-1 carries a synthetic aperture radar (SAR) that is being used to monitor ocean waves. One other SAR that is currently in space and could also be used to monitor waves is the Japanese JERS-1. A short-pulse radar, the radar ocean wave spectrometer (ROWS), is now routinely employed by NASA Goddard to measure directional ocean wave spectra; it is capable of satellite operation. A recent experiment called the Labrador Sea Extreme Waves Experiment (LEWEX) compared these remote sensing techniques with buoy-derived spectra and found that ROWS measurements surpassed those of the buoys, while SAR had to be interpreted carefully to obtain wave spectra.

It has also become obvious in recent years that both theoretical air-sea interaction studies and active microwave remote sensing of the ocean are concerned with directional ocean wave spectra over a range of wave lengths extending from centimeters to hundreds of meters. This range cannot be continuously covered by any existing techniques. In fact, one of the most challenging problems in surface wave studies is the development of techniques for measuring the spatio-temporal structure of the surface wave field. Several techniques concentrating on short waves are being developed to supplement measurements of longer waves. These techniques are primarily optical, employing either laser or stereo photography, and are currently operational in a wave tank environment; this is not yet the case in the field.

Modeling: Modeling of the surface wave field has improved with the advent of the third-generation wave model and the assimilation of satellite data into such models. While such models perform well on a global scale and in deep water, the physics of waves propagating into shallow water is complex. One of the least-understood mechanisms is dissipation, which in deep water is due primarily to breaking, and in shallow water is also due to the interaction of the waves with a rough bottom. Improvements of source term physics in wave models depend primarily on reducing the uncertainty in the initial wind fields. In addition, the uncertainty of the bottom bathymetry will play a role in shallow water. High-order numerical schemes appear to be important to accurately represent wave propagation over long distances and the processes expressed by the source and sink terms.

Advances in numerical modeling, in general, will require theoretical, experimental, and numerical improvements for an adequate parameterization of the physics incorporated in ocean wave models. For example, numerical experiments are needed to test completely the impact of data assimilation in wave models.

Questions of current interest include the following:

- What are the long-term patterns of large-scale wave distributions on a global basis?
- Can routinely monitored global directional wave spectra be assimilated into wave models to update and initialize them?
- Where are extreme, or rogue, waves most often found? What causes them?
- Can gravity-capillary wave spectra be incorporated into microwave scattering models to give better predictions?
- Can wave spectra covering a wide dynamic range be used to better understand the transfer of momentum and energy between atmosphere and ocean?

Interactions of Waves and Currents

Up to the present, most models of the physics of wind-generated waves have ignored the interactions of waves with ocean currents.

Since such currents are always present in the ocean in the form of boundary currents, eddies, or tidal flow over bottom topography, it is essential that their effects on waves be considered. Such wave and current interactions are almost certainly the reason that bottom features can be imaged by SAR, and are a likely cause of the appearance of extreme wave conditions that are highly localized.

Questions of current interest include the following:

- Can wave and current interactions result in localized areas of unexpectedly large wave amplitude? If so, does this localized phenomenon affect the flux of momentum from wind to waves?
- How do variable currents due to bottom topography affect short waves and hence microwave imagery of the ocean?
- Do wave and current interactions significantly affect the output of wave models?

Experimental Approach: Spatial and temporal maps of ocean currents are difficult to obtain experimentally, especially away from shorelines. Recent developments with high-frequency (HF) radars have allowed experimentalists to obtain such maps out to about 70 km offshore with resolutions of about a kilometer. Some success has been achieved by looking at wave refraction at current boundaries in SAR images of the ocean. But the simultaneous, accurate measurement of spatially separated directional wave spectra, and of currents and current gradients, has not yet been done. Thus, testing models of wave and current interactions in actual ocean conditions has not been fully achieved up to the present.

Theoretical Approach: Although wave and current interactions are included in the wave action balance equation mentioned above, the resulting equations describing the modulation of wave amplitude, direction, and amplitude by the current are difficult to solve. Perturbation approaches have been used in the past but are somewhat limited. More recently, attempts to solve the equations more exactly have been successful. Their ultimate accuracy remains to be fully tested and will probably be improved by a better understanding of source and sink functions, as mentioned above.

Possible NRL Role

Although progress has been and continues to be made in understanding nonlinear interactions between wave modes, between waves and shear layers, and between waves and variable currents, this work has thus far had little influence on practical ocean wind-wave modeling.

OBL and MABL modelers may need better parameterization of the sea state. Better algorithms are needed to interpret and analyze data from remote sensing, and experimentalists need help to improve on techniques for measuring air-sea interaction, surface fluxes, and gas transfer in the presence of waves. Thus there is a real opportunity to make progress by exploiting progress in surface wave dynamics to develop improved deterministic and statistical models for, and to guide advanced experiments on, ocean wind-waves.

The NRL optics group could be particularly encouraged to address instrumentation issues related to surface wave measurement. There is an opportunity for NRL to become a center of excellence in this area. An active group with a strong theoretical and experimental background in wave physics could interact with many groups already in existence at NRL or could provide linkage between disciplines and sites.

The theoretical work is well suited to staff with strong backgrounds in mathematics, nonlinear dynamics, or plasma physics. Actual experience in working on the wind-wave problem, or on other oceanographic problems, is not necessarily a prerequisite for making new contributions in this area; however, this experience should soon be acquired and links established with ocean-wave theoretical groups at NRL and elsewhere.

Problems of current interest include the following:

- Dynamic stability conditions for short waves on long waves, with shear layers above (air) and below (water). This bears directly on the growth of waves in wind.
- Unsteady wave breaking, as waves propagate through modulated systems.
- Multimode nonlinear wave interactions, including internal waves and directional effects.

Perturbations of the wave field by ships and submarines and the relaxation of the wave field back to its initial state are processes that are poorly understood. These processes involve wave turbulence interaction, surface tension effects, and perhaps the dynamics of the entrained bubbles. Except for the detection and attribution of oil spills, this is an area that is of little direct interest outside the Navy but nevertheless presents a challenging set of research problems.

A strong theoretical base in this area can provide motivation and direction to computational and experimental investigations. Without a strong theoretical base, however, there is a danger that such efforts might generate data of little use for development of a more complete understanding of wave physics. The full range of experimental environments, from laboratory to open ocean, can be usefully exploited. Individual mechanisms can be isolated and studied in quantitative detail in the laboratory, whereas conditions in the field are ultimately more complicated and realistic. None of the experimental or numerical activities should be allowed to proceed except in partnership with a strong theoretical effort.

Recommendation

The panel recommends that NRL initiate a new program in the field of surface wave dynamics that has well-balanced theoretical, numerical, and experimental components. If NRL is to develop such a program, new leadership will be required, principally in the theoretical components of the research. The panel believes that the necessary expertise could be obtained by involving or reassigning talented personnel whose primary training is in areas such as nonlinear waves in plasma dynamics.

ELECTROMAGNETIC PROPAGATION AND SIGNATURE PHYSICS

Definition

Electromagnetic propagation and signature physics is studied through electromagnetic and optical probing, both active and passive, of the ocean surface. Interpreting properties of the ocean surface requires understanding of signal propagation at the marine surface and in the MABL, the nonlinear wave dynamics discussed above, and the scattering and emission of electromagnetic radiation from the highly heterogeneous ocean surface. Knowledge of signal propagation in all marine environments is necessary for assessing and predicting the performance of diverse naval defensive and tactical weapons systems.

Research Status

This section includes an overview of research in electromagnetic and signature physics and discussion of the status of experimental and theoretical research in the areas of (1) physical mechanisms, including SAR imaging and microwave backscatter at intermediate incidence angles and at low grazing angles; (2) improved sensors for active microwave sensing; and (3) development of passive microwave techniques.

Overview

In spite of two decades of effort, the end-to-end physics of electromagnetic (EM) remotely sensed data is still not completely understood. The challenge still is to be able to predict the EM signal, given the environmental conditions in the atmosphere and at the sea surface affecting scattering and propagation. The opportunity would then be to invert the physics so that the environmental parameters of interest can be reliably derived from EM observations. Without progress in this regard, remote sensing will continue to rely overly on empiricism. A fundamental question is whether algorithms relating environmental parameters to remotely sensed EM radiation can be developed from first principles.

The experimental approach has been to use wind-wave tanks as a controlled environment in which to study EM emissions and scattering from surface water waves. Unfortunately, these results cannot be simply scaled up for comparison with the limited data available from open ocean conditions. Until this situation is rectified, empirical relationships drawn from limited data will continue to be the basis for geophysical algorithms. Another fundamental question is whether laboratory wind-wave tanks can produce surface conditions similar to those of the ocean, so that their EM-related properties can be scaled up to represent the open ocean case.

As mentioned above, one of the most challenging problems in surface wave studies is the development of field techniques for measuring the spatio-temporal structure of the surface wave field. Scanning radar altimeters are able to resolve the wave field down to wavelengths of approximately 3 to 5 meters. Techniques are needed to extend this coverage down to smaller scales. This capability is important in its own right for wave studies, and also for verification of electromagnetic and acoustic scattering studies.

Physics of Synthetic Aperture Radar Imagery of the Ocean

Imaging the ocean surface using synthetic aperture radar (SAR) is complicated by the motions of the surface, because SAR is a coherent microwave technique that obtains azimuthal resolution through a measurement of Doppler offsets. The motion of the surface changes the relationship between the position of a scatterer on the surface and the Doppler offset of rerum from that scatterer. The result is a rearrangement of the scattering centers in the image, which distorts the image and reduces the resolution that can be achieved in azimuth. This problem has been considered for nearly two decades now and is rather well understood. Unresolved issues pertain more to the physics of microwave backscatter, dealt with below, or with the physics of the air-sea interface, discussed above, than to the physics of the imaging mechanism.

Questions of current interest include the following:

- How accurately can our present imaging theories predict actual imagery?
- Can other SAR processing methods be found that will accentuate features on the ocean surface more than do the standard methods?
- Can polarimetry be applied to obtain more information about the ocean surface from SAR images?
- What is interferometric SAR really imaging?
- How well can SARs image strong localized forcing events, such as downbursts?

Experimental Approach: Many field experiments have been conducted to collect data from SAR observations of ocean waves and compare them with simulations. These experiments include MARINELAND, the Marine Remote Sensing Project (MARSEN), Tower Ocean Wave and Radar Dependence Experiment (TOWARD), Synthetic Aperture Radar and X-Band Nonlinearities at Chesapeake Light Tower (SAXON-CLT), the High Resolution Environmental Sensing (HIRES) project, and SAXON experiments at Forschungs Platformnordsee (FPN). SAR data in these experiments have been collected primarily by the Jet Propulsion Laboratory (JPL) and the Environmental Research Institute of Michigan (ERIM), with a few images coming from a German aerospace research establishment (DLR). Additional information on SAR imaging mechanisms has come from the analysis of satellite data, primarily from SEASAT and Shuttle Imaging Radar-B (SIR-B). Russian aircraft flights have also provided insight into imaging mechanisms. SAXON-FPN, which was designed as a stringent test of current theories, is now in the final phase. Future work in this area will probably involve applying current theories to extract information from SAR imagery, developing new processing methods, and developing new types of SAR such as interferometric SAR or spotlight SAR.

Theoretical Approach: Theory and experiment have been intimately tied together in the SAR imaging area, with theories providing simulated images to compare with actual data; however, several investigators have made major contributions primarily on the theoretical side. These contributions include providing for the imaging mechanism a model that is independent of the mechanism of backscatter itself, and clarifying focusing and resolution issues Several theories have been contradicted by experiment, and those that remain have been shown to be simply variants of each other.

Physics of Microwave Backscatter from the Sea at Intermediate Incidence Angles

The incidence angle regime from 20 to 70 degrees is probably the most important for applying microwave backscatter to understanding air-sea interactions from low-and high-altitude sensors. This is the case both because theory is better developed in this regime and because the backscatter depends on the spectral wave parameters on which the community has concentrated. Both SARs and scatterometers for measuring wind speed and direction over the ocean use incidence angles that are in this regime. The ruling theory, for more than two decades, has been Bragg scattering and composite surface theory, in which the backscatter depends on gravity-capillary wave spectral densities. Since these scatterers are generated, modulated, and advected by longer waves, this theory can be applied to provide information on both long and short waves and on their interactions.

Questions of current interest include the following:

- How well does Bragg scattering and composite surface theory work in the intermediate incidence angle regime? What are the limitations of the theory?
- How does the scattering cross section depend on properties of the surface and near-surface flow? Does scatterometry depend strongly on parameters other than the wind?
- Can backscatter be utilized in this regime to infer wave growth rates? Long-wave spectra? Modulation of short waves by long waves?
- Can ocean currents be measured using backscatter in the intermediate incidence angle regime?
- Can one apply Bragg scattering and composite surface theory to understand surface features seen in real and synthetic aperture radar images?
- Can information on breaking waves be obtained from backscatter in the intermediate incidence angle regime?

Experimental Approach: The relationship between wind speed and direction for application to satellite scatterometry has largely been determined experimentally. The status of this relationship is still not satisfactory because the importance of surface layer parameters other than the wind has not been adequately determined. The limitations and accuracy of Bragg scattering and composite surface theory are still not adequately known owing to the difficulty of measuring the parameters, primarily the short-wave spectrum, on which the backscatter depends according to theory. Nevertheless, the theory has been used to extract information on wind wave growth and wave-wave interactions from the backscatter. Major experiments have been conducted to determine how well backscatter in this region can be utilized to obtain quantitative information about important features on the ocean surface that show up in high-resolution microwave imagery of the ocean.

Theoretical Approach: For the past few decades theoreticians have concentrated on trying to improve upon the Bragg scattering and composite surface theory. Some more general scattering theories have been developed that seem to compare as well with data as the composite theory, but improvements in accuracy have not been completely established.

The best of these theories either reduce to composite theory in some limit, or use more theoretically defensible methods to include the impact of longer waves on the backscatter. A few attempts have been made to develop theories based on mechanisms completely different from those in composite surface theory. An example is a theory based entirely on scattering from sharp edges rather than on the short Fourier components of the rough surface. In general, however, these methods have not been as successful as has composite surface theory in explaining the variety of effects observed in ocean backscatter.

Finally, some numerical models have been developed that require fewer approximations than do analytical models. These models are very computer-intensive, however, and most have been implemented in only two dimensions to date. Their main use at present is for determining limitations on the approximations made in analytical theories.

Physics of Microwave Backscatter from the Sea at Low Grazing Angles

Understanding of the physical processes involved in microwave backscatter from the sea at incidence angles above 70 degrees is not as well developed as that in the lower incidence angle regime. For many years, this area has been dominated by studies of "sea spikes," or short waves. The importance of these spikes lay in the possibility that they could be mistaken for targets when radar surveyed the sea surface from shipboard. Recently, however, interest in low-grazing-angle backscatter from the sea has been stimulated by the realization that many features on the surface show up better in images made at low grazing angles than in those made at higher angles. The importance of this realization both for detecting submerged vehicles and for imaging natural ocean features has not been lost on the community.

Questions of current interest include the following:

- What causes sea return at low grazing angles outside of the sea spike areas?
- How can we measure the surface parameters that may be responsible for the backscatter independently of radar? How do we characterize them?
- How important is multiple scattering in the low-grazing-angle regime?
- Why do Doppler offsets often fail to correspond to surface currents for backscatter in the low-grazing-angle regime?
- Are opportunities opened at low grazing angles for time-space studies that can distinguish among different processes by their different dispersion relations?
- What happens when ultrashort pulses are scattered at very low grazing angles?

Experimental Approach: A wide variety of experiments have been conducted in the past at these low grazing angles because of the ease with which they could be conducted from shoreline stations, but it has been difficult to characterize conditions in the scattering area. Recently, more work has been done in wave tanks and from towers, where it is easier to characterize the surface scattering conditions. Furthermore, real aperture radar (RAR) images have been obtained at these angles from aircraft. All of these recent experiments show that backscatter at low grazing angles is very different from that at higher angles and is not well understood.

Theoretical Approach: The theory of low-grazing-angle scattering is complicated by the possibility of multiple scattering and shadowing of parts of the surface by other parts, and also by atmospheric refractive effects. Furthermore, in this range of high incidence angles, the very real possibility exists that Bragg scattering is not the dominant scattering mechanism. The possibility has been examined of scattering from discrete features of the surface, such as wedges or shoulders, representing spilling breakers. If these are indeed the dominant scattering mechanisms, then the problem arises of characterizing and counting such features on the open surface. Without such characterization, many low-grazing-angle scattering theories will remain unconfirmed.

Development of Improved Sensors for Active Microwave Remote Sensing

The development of better sensors for actively sensing the ocean surface with microwaves is a continuing pursuit. New ideas for SAR imagery of the ocean such as polarimetry, interferometry, and spotlight methods are now in use at ERIM, JPL, and the Naval Air Development Command (NADC). Satellite sensors such as NASA's scatterometer, NSCAT, and future generations of satellite SARs are currently under development by NASA, the European Space Agency (ESA), Japan, and Russia. Canada is nearing launch of its C-Band SAR satellite called RADARSAT. Airborne RARs have been developed at NRL, at the Institute for Space Research in Moscow, and at the Institute of Radio Physics and Electronics in the Ukraine. NASA Goddard has developed new versions of the surface contour radar and radar ocean wave spectrometer (ROWS) for measuring directional surface wave spectra, while the French also have an operating version of ROWS. ROWS is ripe for satellite application.

Furthermore, instruments for sensing the sea surface from low-altitude platforms such as towers, piers, or blimps are now being developed in various places. The University of Kansas has developed a Ku-band vector slope gauge for measuring the two components of surface slope at a spot on the ocean. The University of Massachusetts has developed a multi-offset delta K radar for measuring currents and wave dispersion relationships, as well as a fully polarimetric radar to investigate polarization characteristics of backscatter. The same group is also working on a focused phased-array imaging radar (FOPAIR) that will be capable of following surface features as they evolve. Delta K radars have also been developed in Japan and Norway. The Applied Physics Laboratory of the University of Washington has under development a coherent microwave wave spectrometer for use on a blimp. Portable HF radars for measuring near-shore currents have been developed by CODAR, Inc. in the United States and by Marconi, Ltd. in the United Kingdom.

Obviously, the development of active microwave remote sensors for air-sea interaction studies is a very active field and one that promises to revolutionize the amount of information available about various aspects of the air-sea interface.

Development of Passive Microwave Techniques

There is considerable excitement in the EM community over the opportunities that are likely to occur in the application of microwave radiometry in the next decade. Passive microwave techniques are well developed for measuring a variety of atmosphere, ice, land, and ocean parameters. In the past, the primary ocean-related variables measured using passive microwave techniques have been sea surface temperature, salinity, and wind speed over the ocean. Recently, there has been growing empirical evidence that wind direction information may be obtained from radiometers currently flying, and that wave direction information may be obtained from polarimetric radiometers. This evidence has been accumulating both from recent Russian aircraft work and from the Defense Meteorological Satellite Program, and it opens the possibility of supplementing scatterometry with radiometer measurements of the wind vector over the ocean. The principal limitation of radiometry, in comparison to active microwave sensing, then becomes its inability to obtain high-resolution (on the order of meters) maps of the ocean surface.

The panel anticipates that the use of microwave radiometry to obtain vector wind data will prove feasible in the next few years and will be based solidly on theoretical developments, especially those involving polarimetric properties of the ocean surface. It has long been known that sea foam (whitecaps) is an emitter of microwave radiation; however, little appears to have been done to quantify field measurements in terms of wave breaking and whitecap coverage. If breaking waves are responsible for much of the brightness temperature of the ocean, and also for contributing to the ambient underwater sound background, then one would expect that ocean acoustic models would benefit from assimilation of data from microwave radiometers. This is an area that would benefit from a program of detailed acoustic and radiometric field studies to quantify the relationship.

Ocean salinity may be determined approximately from passive microwave emissions in the 1-GHz region, although this technology has not been exploited. At present, no remote sensing capability for sea surface salinity exists.

The panel also anticipates that correlations of microwave radiometric measurements with measurements of ambient noise due to breaking waves, and with surface reverberation due to bubble clouds, will confirm the benefit of microwave radiometry as input to real-time ocean acoustic models.

Questions of interest include the following:

- How accurately can wind direction be measured using microwave radiometry at various angles?
- Is the Russian theory of "critical phenomena" viable as an explanation for the dependence of radiometry on wind direction?
- Can ocean salinity maps be produced accurately by microwave radiometers?
- Can radiometry be used to improve models of sea surface acoustic noise?

Possible NRL Role

A great deal of research is currently being done on applications of active real aperture radar and synthetic aperture radar to remote sensing of the oceans. Although there is still much to be learned, considerable progress has been made in recent years, and numerous groups are working actively in the field. Passive millimeter and microwave sensing, on the other hand, is less well developed, but as improvements are made in spatial resolution and sensitivity, it promises to be highly productive for remote sensing of the ocean, especially where covertness is an advantage. This is an area that should be of direct interest to the Navy and is one in which considerable progress is anticipated in the next decade. The important topics are (1) polarimetric radiometry, including wave directional effects, and indirectly, remote sensing of wind vectors; and (2) breaking wave signatures, due to whitecap emission. The latter topic has strong ties to acoustics, through ambient noise due to wave breaking; to bubble-mediated gas transfer; and to heat transfer. The panel noted above that sea foam (whitecaps) is an emitter of microwave radiation. NRL-S is already involved in one of the few programs that is exploring this relationship. NRL has hardware capability and experience and could leverage these advantages with additional resources to pursue a true leadership role in passive millimeter and microwave sensing.

NRL also has sensor development and data collection activities that need to be complemented by research and exploratory development related to improving sensor performance, and to the physics of potential signature phenomena on the ocean surface, such as that owing to ships, oil slicks, and the like. GEOSAT follow-on altimeter data could provide a basis for studies of techniques to resolve smaller waves and could also be an additional focus for a collaborative research effort in remote sensing, numerical models, and data assimilation. Use of radar altimeters and passive microwave radiometers for investigations of continental shelf and littoral areas could be of particular interest at the present time.

It is important to realize that, to some extent, active and passive microwave sensing are related. For example, one proposed Russian explanation of the wind direction dependence of sea surface brightness temperature involves Bragg scattering. Therefore, it would be desirable not to completely forego work in active sensing areas, but to maintain it at a relatively low level, and to encourage collaboration with research involving passive remote sensors. As in all research areas recommended in this report, it is important that a balanced mix of theory and experimentation be encouraged.

Recommendation

The panel recommends that NRL undertake a strong experimental and theoretical program in electromagnetic propagation and signature physics, particularly in developing and exploring passive microwave techniques such as multispectral and polarimetric methods. In the active microwave sensing area, the panel urges a strong collaborative program with academic (e.g., Office of Naval Research-sponsored) groups.

BOUNDARY LAYER DYNAMICS-RELATED ACOUSTICAL AND OPTICAL OCEANOGRAPHY

Definition

Boundary layer dynamics-related acoustical and optical oceanography involves the passive optical (visible and infrared) and active and passive undersea probing of the ocean surface and mixed layers. Interpreting structural, chemical, and biological properties of the uppermost ocean requires knowledge of the environmental factors that control bubble size spectra: the acoustical and optical scattering by bubbles; and the species and populations of color-modifying, photosynthesizing dependent marine organisms. Optical and infrared properties of and propagation in the MABL are also important for remote sensing, signal transmission, and signal detection. On the small scale, the marine microlayer—the thin interfacial boundary between the atmosphere and the ocean—plays a critical role in air-sea interactions. The presence of surface slicks attributable to man-made alteration of this surface can be recognized by effects of changes in the visco-elastic modulus. There is strong evidence that coastal areas are zones of naturally high levels of surface compounds that alter capillary wave propagation. Understanding of this natural background is essential for improving signal detection. Properties, physical and biological, of the ocean's mixed layer determine the nature of the working environment and margin of safety afforded for virtually all underwater naval operations.

Research Status

This section discusses the status of experimental and theoretical research in two areas: (1) OBL-related acoustical oceanography, and (2) MABL-related optical oceanography.

Oceanic Boundary Layer-Related Acoustical Oceanography

The development of acoustic Doppler current meters over the last decade has provided the tools to begin measuring waves, currents, Langmuir circulation, and turbulence in the OBL. These instruments were originally developed for the measurement of deeper internal waves and currents, and there are significant technical problems to be resolved before unambiguous near-surface measurements can be made on a regular basis. These problems include the distribution of scatterers (bubbles) and the resulting bias in measurements near the surface, side-lobe interference for measurements near the surface, and reverberation limits on the Nyquist frequency. However, it is anticipated that innovative solutions to these problems will be forthcoming in the next few years, which will permit the measurement of the velocity field within the surface wave depth zone (about 1 to 10 meters).

The development of ocean acoustics has depended on the Navy's interest in acoustic detection, which has involved either passive acoustics for detecting objects by the sound they radiate, or active acoustics scattering sound from objects. The natural and man-made background noise in passive acoustics, and in active acoustics reverberation and scattering from the surface, all are important factors for Navy acoustic systems. In recent years, the field of acoustical oceanography has developed to exploit the acoustic properties of the ocean, and acoustic instrumentation has been developed to obtain a better knowledge of ocean physics. Examples include the use of Doppler sonars as mentioned above; acoustic tomography to measure ocean currents over large path lengths; acoustic scintillation to measure turbulence intensities; ambient sound to characterize surface wave breaking; and most recently, acoustic thermometry for global climate studies.

Both passive and active acoustic techniques are of direct interest for boundary layer studies. Surface conditions (e.g., slicks) can affect noise and scattering. Near the surface the scatterers are the bubbles entrained by breaking waves. The distribution of bubbles near the surface is of interest in its own right, and bubble characteristics can be measured by both active and passive means. Due to bubble resonances, the scattering cross section of bubbles is a strong function of bubble size. Thus bubble size distributions can be measured by scattering. The speed of sound at low frequencies is a function of the volume fraction of the bubbles in the water column, and the attenuation of sound is a function of the size distribution of bubbles; thus complex sound speed and attenuation measurements can be used to measure the gas fraction and bubble size distribution. Breaking waves are the dominant source of bubbles and ambient sound at the ocean surface. The air entrained by breaking waves breaks up into bubbles that individually radiate sound as they relax toward their equilibrium spherical shape. The frequency of the sound radiated is a strong function of the bubble size; thus the spectrum of sound at 500 Hz or more is a function of the bubble size distribution.

Rain striking the ocean surface generates sound. Recent idealized laboratory and numerical experiments show that the source of this sound is mainly the entrainment of bubbles having a resonant frequency near 14 kHz, although more realistic experiments show that the addition of wave effects and wind broadens the frequency range somewhat. If this work continues to develop a rational basis for rain-induced sound, it could point the way for the use of sound to monitor rainfall.

Marine Atmospheric Boundary Layer-Related Optical Oceanography

The field of ocean optics has undergone a renaissance in recent years, due both to the very active involvement of the civilian science community in ocean remote sensing (the Joint Global Ocean Flux Study [JGOFS] program) and to technical advances in underwater technology from ROVs and submersibles. ONR maintains a strong program in the ocean optics area.

At the fundamental level accurate measurements of inherent, as opposed to apparent, optical properties are now being made. Fully calibrated sensors are being used in field programs, and their results are being linked to models; some predictive capabilities are beginning to exist. The next decade will see a host of spaceborne multiwavelength optical sensors in polar orbit, including the sea viewing wide-field-of-view sensor (SeaWIFS; NASA); the Advanced Earth Observing System (ADEOS; Japan Space Agency); the medium-resolution imaging spectrometer (MERIS; ESA); and the moderate-resolution imaging spectrometer, nadir viewing (MODIS-N; NASA-EOS). All are basically nadir-viewing sensors.

Oblique-angle viewing offers significant potential and is largely unexplored, although the images of ship tracks and surface films from

NASA space shuttle sun-glint imaging have attracted widespread attention. Outside the glint region, calmer surface areas such as slicks can be identified by changes in both brightness and color. The only potential NASA-EOS sensor is the JPL-derived multiangle imaging spectroradiometer (MISR), which is devoted principally to cloud and aerosol signal detection.

Subsurface laser scanning devices and range-gated viewing systems have been developed that have the potential for imaging of, and obtaining fundamental data on, the motions of the OBL. These systems, deployed from ROVs and able to approach and scan the OBL from below, offer a potential for active optical sensing that has been largely ignored.

Possible Role for NRL

Several NRL groups, in a combined thrust involving colleagues at different NRL sites in optics, remote sensing, acoustics, and chemistry, could develop a very strong effort in acoustical and optical oceanography as outlined below.

Oceanic Boundary Layer-Related Acoustical Oceanography

Given the Navy's interest and experience in acoustics, acoustic remote sensing is an area in which a major impact could be made. The use of acoustic techniques to study the OBL is likely to be a rewarding area of research in the next decade, and NRL is well positioned to make significant contributions at a number of levels. Such an effort would involve the acoustics groups in OBL problems.

The important topics in acoustical oceanography are the dynamics of the OBL in the bubble zone, which can be measured using active acoustics; acoustic properties of the bubbly layer using active and passive acoustics; acoustic measurements of rainfall rates; gas transfer across the air-sea interface; and adaptation of sonobuoy technology to global monitoring. Indeed, it seems that sonobuoy technology could be readily adapted to using ambient sound to monitor wave breaking and rainfall, and active sound to measure bubble cloud properties in the surface layer. NRL-S's involvement in ONR's surface reverberation project is a good beginning.

Marine Atmospheric Boundary Layer-Related Optical Oceanography

A second area that NRL should emphasize, and in which it is already strong, is passive optics for characterizing ocean optical properties. The work at NRL-S on ocean optical properties involves a good coupling of air-sea phenomenology with remote sensing. The data on ocean optical properties (e.g., that generated by SeaWIFS), and the facilities to process and manipulate the data, are resources that a research group in ocean optics can use to great advantage. NRL-E could contribute, on the actual remote sensing side, in optical instrumentation and theory. Also, NRL-W could make use of this work and these data, becoming involved in the coupling of ocean models to the optical data.

Recommendation

The panel recommends that NRL undertake a strong, coordinated research program that includes simultaneous underwater acoustic, electromagnetic, and optical measurements of the oceanic and marine atmospheric boundary layers in carefully selected coastal zone and continental shelf environments, in which different conditions of atmospheric forcing and the influence of surface slicks can also be quantitatively documented. This effort should involve active and passive electromagnetic and optical (visible and infrared) measurements from above the sea, as well as active and passive undersea probing of the ocean surface and mixed layers.

Chapter 3—
Synergistic Opportunities

The panel believes strongly that a number of important synergistic opportunities could enhance boundary layer dynamics research and offers several suggestions toward developing this potential. NRL has the potential to continue as a major contributor to both theoretical and observational boundary layer and remote sensing research in the United States. It has a wealth of facilities and human talent; many of its resources are the envy of university departments. To achieve this potential, however, NRL must effectively integrate and coordinate these resources.

MULTISCALE AND INTERSECTING-SCALE RESEARCH PROJECTS

The present status of NRL work related to marine boundary layer dynamics has been conditioned by the historical fact that naval research in oceanography, from the mid 1970s on, was to be performed by the former Naval Ocean Research and Development Activity (NORDA) in Bay St. Louis, Mississippi, while new developments in naval meteorology were to be pursued by the former Naval Environmental Prediction Research Facility (NEPRF) in Monterey, California. Although NRL-E had some ongoing activity in each of these areas, the principal work carried out at NRL-E that related to the marine boundary layers was in remote sensing, both electromagnetic and acoustic. Although these three institutions have been combined administratively into the single Naval Research Laboratory, the physical separation of the NRL's work in oceanography, meteorology, and remote sensing remains largely intact. The challenge is to focus this work intellectually.

The air-sea interface and its adjoining boundary layers represent a common meeting point, both physically and intellectually, for the work of the scientists located at the three sites. However the phenomenological scales, spatial and temporal, of interest at the three NRL sites differ significantly (Figure 3.1). The success of interunit collaborations will depend strongly on how well cooperating scientists from all the sites are able to define and focus their efforts on multiscale and intersecting-scale joint research projects. Formation of a new center as an organizational focus to help accomplish this integrated effort is addressed in the next section.

For successful collaboration, it is imperative that effective and efficient communication be established among the different groups at NRL's three sites. Although communication is made difficult by the geographical separation of the respective units, use of electronic mail and networking can assist collaboration. Regular laboratory-focused scientific meetings should be encouraged. One of the main objectives of these meetings should be to identify a few specific areas for focused research and then concentrate on these in a coordinated way. These areas should involve a mix, appropriate to NRL, of mission-oriented and independent, unsolicited research. This suggestion is discussed more fully below.

Once such NRL focus would involve collaboration in the instrumentation area. This could have a major impact because, ultimately, advances in BLD are very likely to depend on innovations in instrumentation, leading to naval field measurements.

Another specific step toward coordination of efforts at NRL would be to incorporate, in models of both the atmosphere and ocean, the presence of ocean surface waves, as mentioned in Chapter 2. This step could lead to improvement of the models as well as bring recognition to NRL-E, -W, and -S. The necessary data sets exist, from either satellite remote sensing or wave model predictions, and it would not be difficult to begin testing the impact of the sea state on either model. For example, the literature describes numerous approaches to including sea-state effects in specifying the aerodynamic drag coefficient, such as parametric MABL models, which require integral parameters of the sea state, and spectral MABL models, which require detailed descriptions of the directional wave field. Most of these models are constructed from limited data sets derived from buoy measurements. None of them have been rigorously tested in a global and/or regional model to determine the effects of and sensitivities to sea-state inputs. Similarly, the ocean modelers could test the sensitivity of their models with improved predictions of the wind stress.

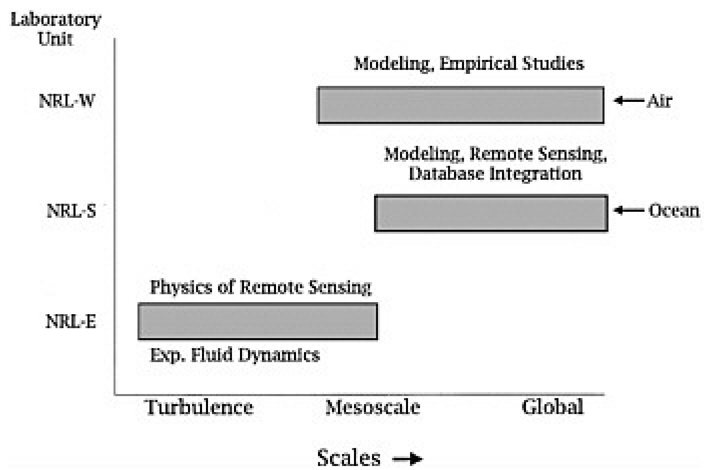

Figure 3.1 The phenomenological scales currently addressed in boundary layer dynamics research at NRL's three sites. A new center would serve to integrate the combined assets.

A NEW CENTER AT NRL-W

As a result of its consideration of capabilities at the NRL complex, the panel recognized that an unusual opportunity exists to focus the advanced research in BLD at NRL-E and NRL-S to enhance the Navy forecasts produced at the Fleet Numerical Meteorological and Oceanographic Center (FNMOC)/NRL-W facility.

Historically, NRL-W's role has been to support the efforts of FNMOC. Its work on the FNMOC atmospheric forecast model has been of major importance. Another applied activity involves making the forecasts available and useful to the fleet. Thus, NRL-W, as inherited by NRL, seems at present to be primarily a service facility. Service should continue to be one of its primary responsibilities; however, with one of the largest collections of marine meteorologists in the country, NRL-W has the potential to be a valuable national resource.

In fact, NRL-W's access to the huge FNMOC database represents an enormous and unique advantage, and present trends in declassification of databases should facilitate broader cooperation, generally, in its use for research. This capability, coupled with the advantages that come from having a group of modelers that must work in continual contact with an operational user organization, makes NRL-W a special facility. These advantages should not be lost.

Further consideration of NRL capabilities for BLD research led the panel to conclude that there is an outstanding opportunity to focus this research by formation of a new center, located at NRL/FNMOC and modeled after the European Centre for Medium-range Weather Forecasting (ECMWF), where NRL personnel could work, together with researchers and investigators from academia, on global and high-resolution regional coupled models of the atmosphere and ocean. Such a center would have several purposes: (1) to ensure that the operational side of the Navy would be aware of, and understand, the newest developments in the models, and provide for transfers of specific technologies; (2) to give NRL personnel the opportunity to take the lead in certain areas or at a minimum, remain up to date on current problems being addressed in academic research; and (3) to increase academic researchers' awareness of the complexities of naval operations.

ECMWF is one of the world's model facilities that strongly fosters the interrelationship between operational activities and research performed by member research and academic institutions. No similar facility currently exists in the United States. However, NRL-W with its ties to FNMOC and several surrounding academic institutions, e.g., Stanford University, the University of California at Berkeley, the Naval Postgraduate School, and the University of California at Santa Cruz, would be in a unique position to establish a center similar to the ECMWF facility. There are several reasons for doing so.

First, the atmosphere and ocean can no longer be treated as separate, disconnected entities. Much research has been devoted to establishing linkages and interactions among these environmental components in order to improve capabilities for predicting numerous processes such as marine and severe weather, ice movement along the marginal ice edge, and the evolution of the mixed-layer and surface waves on a global scale affecting the Navy's daily operations across a broad spectrum. The suggested center would also provide a means to explore the feasibility of assimilating a variety of remotely sensed data sets and perform end-to-end tests of a combined model of the atmosphere-ocean system.

Second, to make progress in a timely way, operational personnel and researchers from academia and government laboratories must work side by side (at the same facility) in a collaborative mode to exchange ideas and thoughts that then would be evaluated in research and prototype models of operational forecast and prediction models. These research and prototype models would run in parallel, or reprocess historical data sets, to assess the impact of new coupling and feedback schemes and/or assimilation of heterogeneous data sets. At regular intervals, operational models could then be updated with those algorithms and components that are robust and computationally efficient, and could be used to generate either an improved product or new output for use in other relevant models.

Third, the new NRL-W facility could be co-located at an operational facility, FNMOC, where a wide diversity of expertise exists from government and academic institutions (i.e., those in the greater San Francisco area). An active visiting scientist program could complement and/or enhance local expertise. Such a center would have to maintain very high standards and provide leadership in many research areas in order to attract leading scientists and researchers from government and academic institutions. Young and promising scientists would benefit from closer interactions with leaders already working at the center, whereas established scientists would appreciate the problems and complexities associated with operational modeling and prediction. Thus the new center would provide an environment encouraging direct and rapid transfer of concepts and models between academia and government.

Fourth, the center would have to provide adequate access to high-speed computers and resources such as powerful workstations, peripherals, networking capabilities, graphics, and video software. Also, the center should maintain an adequate permanent staff of researchers, programmers, data processors, and systems analysts for support to visiting scientists. The duration of visits should be no less than six months and not longer than two years. All research work should be unclassified but should not compromise FNMOC operational and/or classified activities. For example, operational and classified activities should involve separate computers and strictly partitioned networks, and access to operational and classified locations should be restricted. ECMWF, the model for the new center, in fact operates in this way. However, the products and methods of the operational models should be unclassified within the new center, to encourage discussion and different approaches to interpretation of the results. There must be several common areas where visiting personnel can interact, exchange ideas, and discuss problems, as well as mechanisms (e.g., seminars, discussion, and small task groups) to explore existing problems with operational models and output products and to evaluate new model components and reprocessed historical data to maintain leading-edge modeling capabilities.

ADDITIONAL SUGGESTIONS

Joint Interagency Activity

As a result of the general reduction of federal budgets, and of NASA's and NOAA's in particular, NRL's programs will have greater national importance and a national "critical mass" of science in the areas discussed above may be difficult to achieve. The possibility of joint interagency activity directed to the advancement and use of remote sensing for boundary layer dynamics research should be seriously considered.

Internal Meetings and Workshops

One way to encourage atmospheric modelers, air-sea investigators, and others to couple their work more directly with remote sensing needs and capabilities of the kind required by the Navy would be to have periodic (annual or semiannual) internal NRL meetings at which the various research groups would present their current work, plans, and problems to one another. These meetings could be run at the scientific level expected at an open scientific meeting but be internal to NRL. Research in progress could be discussed candidly, specific naval priorities could be considered, and plans could be made to direct future efforts toward greater interaction and coordination in this research. In addition, talks by outside experts, and workshops including outside participants, could be encouraged.

Enhanced Academic Relations and Postdoctoral Programs

NRL currently has in place programs to involve outside scientists in NRL activities through their appointment as summer faculty, consultants, and temporary personnel. It also has a variety of postdoctoral programs. The panel strongly encourages active recruitment of postdoctoral scientists, development of increased contact and collaboration with outside scientists, and an emphasis on visiting appointments for scientists working in BLD research areas.

A possible difficulty in straightforwardly implementing this suggestion is that, in oceanography at the present time, postdoctoral positions are relatively abundant, and NRL is unlikely to have much success in recruiting at this level. However, there are insufficient positions at the end of the postdoctoral time of typically two years. A possible strategy would be to identify and contact oceanographers as they finish their postdoctoral work and to offer them longer-term "visiting scientist" positions with term commitments on both sides. Some of these scientists could then become permanent staff, and the others could continue their collaborations after moving on to other positions.

Chapter 4—

Infrastructure—Resources and Needs

Maintenance of a strong technological infrastructure base is essential to NRL's ability to realize its potential for excellent research in BLD areas. Two important aspects of this infrastructure are (1) instruments and facilities; and (2) ships and aircraft.

INSTRUMENTS AND LABORATORY FACILITIES

One of the outstanding strengths of a government laboratory such as NRL is its ability to purchase and maintain expensive instruments and computers that are often beyond the reach of university laboratories. Especially if NRL develops a concentration of researchers working on marine atmospheric and oceanic boundary layer problems, a solid complement of high-quality equipment is essential. To carry out the data assimilation and modeling efforts recommended in Chapter 2, first-class computer and networking capabilities are needed. For doing controlled experiments to study fundamental processes such as wind-wave and wave-wave interactions, and to develop and test new instrumentation, laboratory facilities including wave and wind-wave tanks are absolutely necessary. Likewise, state-of-the-art networking environments and capabilities will have to be maintained to make use of data sets and modeling in various collaborations, within and external to NRL. Meteorological, oceanographic, acoustic, and microwave equipment remain expensive tools of the trade with good instruments often costing in the $100,000 to $500,000 range. To achieve excellence, NRL must assure that funds are available in the future to purchase such instrumentation and to provide personnel and facilities to maintain equipment in good, operating condition. One of the best ways to attract talented young researchers to NRL is to provide them with access to such instrumentation and facilities.

SHIPS AND AIRCRAFT

In an experimentally driven field such as marine boundary layer research, it is essential that instrumentation be taken into the field to measure nature as it exists, not as one imagines it. Thus, the panel believes that an NRL commitment to providing ship and aircraft time to boundary layer researchers is essential. Also, aircraft and ships should be properly outfitted and instrumented for atmospheric and oceanic boundary layer research. How to provide such time and platforms must, of course, be decided by laboratory management but it should be done in such a way that even modest programs can have access to ships and aircraft. Once again, providing such access can be a strong point of the NRL program that will attract talented people to its ranks.

A related issue is the fact that an ocean-atmosphere research tower can be useful for obtaining high-quality, long-term data in coastal environments. Possibly one or more inactive drilling towers in the Gulf of Mexico or Santa Barbara areas could be leased for this purpose.

Chapter 5—

Closing Comments

This report has been some time in preparation, and events during the intervening period have absolutely served to confirm some of the trends the panel has observed, make more acute some of its concerns, and positively reinforce some of its recommendations. In a short period of time, key personnel in BLD research have retired or died. The wind-wave tank facilities at NRL-E have been torn down, and satellites that once delivered critical data are no longer in orbit. The commitment to observing capabilities will be absolutely essential if progress in BLD research is to be made, and only a laboratory of the scale and sophistication of the NRL complex can provide these capabilities.

NRL researchers need access to both ship time and large laboratory facilities. Ship time is essential because the Navy's working environment is not a laboratory bench top or a computer, but rather the open ocean and coastal waters. This reality will not change. Research on coupled ocean-atmosphere models at NRL-W has led to significant advances (e.g., development of the Coupled Ocean-Atmosphere Mesoscale Prediction System [COAMPS] model). This supports the recommendation that a new center there would initiate and foster new leadership toward improvements in operational forecast models as a focus for NRL's BLD research.

Appendix A—

Some Leading Research Groups in Opportunity Areas

This appendix lists some leading research groups in the research areas discussed in Chapter 2.

MARINE ATMOSPHERIC BOUNDARY LAYER FLUXES

Experimental Approach

Leading experimental groups include those at:
Centre for Inland Waters
University of California at Irvine
University of Washington
IFREMER (France)
National Oceanic and Atmospheric Administration
Royal Netherlands Meteorological Institute
Bedford Institute of Oceanography (Canada)
Naval Postgraduate School
National Center for Atmospheric Research
Woods Hole Oceanographic Institution

Theoretical Approach

Leading theoretical groups include those at:
Royal Netherlands Meteorological Institute
University of Michigan
Norwegian Meteorology Institute

COUPLED TURBULENT FLOWS

Atmospheric Boundary Layer

Experimental Approach

Leading experimental research groups include those at:
University of California at Irvine
National Center for Atmospheric Research
Pacific Marine Environmental Laboratory, Seattle, Washington

Theoretical Approach

Leading theoretical research groups include those at:
Oregon State University
National Center for Atmospheric Research
Pennsylvania State University

Oceanic Boundary Layer

Experimental Approach

Leading experimental research groups include those at:
Woods Hole Oceanographic Institution
Applied Physics Laboratory, University of Washington
Scripps Institution of Oceanography
Institute of Oceanographic Sciences (Canada)
Rennel Center (United Kingdom)

Theoretical Approach

Leading theoretical research groups include those at:
Woods Hole Oceanographic Institution
Naval Postgraduate School
National Center for Atmospheric Research

OCEAN DATA ASSIMILATION

Experimental Approach

Leading experimental research groups include those at:
Max Planck Institute for Meteorology (Hamburg, Germany)
Remote Sensing Systems, Inc.
Oregon State University
Jet Propulsion Laboratory, California Institute of Technology

Theoretical and Numerical Approach

Leading theoretical research groups include those at:
National Oceanic and Atmospheric Administration
National Aeronautics and Space Administration, Goddard
National Center for Atmospheric Research
European Center for Medium Range Weather Forecasting
Massachusetts Institute of Technology

SURFACE WAVE DYNAMICS

Physics of Wind-Wave Growth and Equilibrium

Experimental Approach

Leading experimental groups include those at:
Canada Centre for Inland Waters
NASA Goddard
University of New South Wales (Australia)
Scripps Institution of Oceanography
Tohoku University (Japan)
Kyushu University (Japan)

Bedford Institute of Oceanography
Woods Hole Oceanographic Institution
Stanford University
Royal Netherlands Meteorological Institute

Theoretical Approach

Leading theoretical groups include those at:
Johns Hopkins University
Max Planck Institute for Meteorology (Hamburg, Germany)
LaJolla Institute
City College of New York
LaJolla Institute
TRW, Inc.
Scripps Institution of Oceanography
Oregon State University

Visco-Elastic Effects on Processes at the Ocean Surface

Leading research groups include those at:
ORINCON, Inc.
Woods Hole Oceanographic Institution
Naval Research Laboratory
University of Hamburg (Germany)
Case Western Reserve University

Monitoring and Modeling of Ocean Waves on a Regional and Global Basis

Leading modeling investigators include:
Max Planck Institute for Meteorology (Hamburg, Germany)
Applied Physics Laboratory, Johns Hopkins University
Institute for Space Research (Russia)
Institute of Radio Physics and Electronics (Ukraine)
Scripps Institution of Oceanography
University of Massachusetts
University of New South Wales (Australia)
Canada Centre for Inland Waters
Royal Netherlands Meteorological Institute

Interactions Between Waves and Currents

Experimental Approach

Leading experimental investigators include those at:
University of Miami
Forschungszentrum fur Marine Geowissenschaften der Universitat Kiel (GEOMAR; Germany)
Scripps Institution of Oceanography

Theoretical Approach

Leading theoretical research groups include those at:
Naval Research Laboratory
Applied Physics Laboratory, Johns Hopkins University
Defense Research Establishment Pacific (Canada)

ELECTROMAGNETIC PROPAGATION AND SIGNATURE PHYSICS

Physics of SAR Imagery of the Ocean

Experimental Approach

Leading experimental research groups include those at:
University of Hamburg (Germany)
Applied Physics Laboratory, University of Washington
Environmental Research Institute of Michigan
Jet Propulsion Laboratory, California Institute of Technology
ORE, Inc.
SCAN (Russia)

Theoretical Approach

Leading theoretical research groups include those at:
Max Planck Institute for Meteorology (Hamburg, Germany)
University of Maryland
ORE, Inc.
Canada Centre for Remote Sensing
Marconi Research Centre (United Kingdom)
Imperial College (United Kingdom)

Physics of Microwave Backscatter from the Sea at Intermediate Incidence Angles

Experimental Approach

Leading experimental research groups include those at:
University of Hamburg (Germany)
University of Kansas
Applied Physics Laboratory, University of Washington
Hofstra University
Jet Propulsion Laboratory, California Institute of Technology
Remote Sensing Systems, Inc.
TRW, Inc.
Applied Physics Laboratory, Johns Hopkins University
Scripps Institution of Oceanography

Theoretical Approach

Leading theoretical research groups include those at:

Applied Physics Laboratory, Johns Hopkins University
Virginia Polytechnic Institute & State University
Logicon-RDA, Inc.
TRW, Inc.
University of Michigan
University of Texas
Case Western Reserve University
Applied Physics Laboratory, University of Washington
University of Nebraska
Naval Research Laboratory

Physics of Microwave Backscatter from the Sea at Low Grazing Angles

Experimental Approach

Leading experimental research groups include those at:
Naval Research Laboratory
Applied Physics Laboratory, University of Washington
Royal Signals and Radar Establishment (United Kingdom)
Institute of Radio Physics and Electronics (Ukraine)
Scripps Institution of Oceanography

Theoretical Approach

Leading theoretical research groups include those at:
Naval Research Laboratory
Environmental Research Institute of Michigan
Virginia Polytechnic Institute & State University
Logicon-RDA, Inc.

Development of Improved Sensors for Active Sensing

Leading research groups include those at:
Environmental Research Institute of Michigan
Jet Propulsion Laboratory
Institute for Space Research (Russia)
Institute for Radio Physics and Electronics (Ukraine)
University of Kansas
Applied Physics Laboratory, University of Washington

Development of Passive Microwave Techniques

Leading research groups include those at:
Naval Research Laboratory
University of Massachusetts
Remote Sensing Systems, Inc.
Institute for Space Research (Russia)
SCAN (Russia)
Aerojet ElectroSystems, Inc.

BOUNDARY LAYER DYNAMICS-RELATED ACOUSTICAL AND OPTICAL OCEANOGRAPHY

Acoustical Oceanography

Leading research groups include those at:
Woods Hole Oceanographic Institution
Scripps Institution of Oceanography
University of British Columbia
Applied Physics Laboratory, University of Washington
FWG (Germany)

Optical Oceanography

Leading research groups include those at:
University of Southern California
University of California at Santa Barbara
NOAA/NOAA Environmental Satellite Data and Information Service
University of Miami
Biospherical Instruments, Inc.
Monterey Bay Aquarium Research Institute
Naval Research Laboratory-Stennis
Oregon State University
University of California at Santa Barbara

Appendix B—

Glossary

ADEOS	Advanced Earth Observing System
ARI	Advanced Research Initiative
BLD	Boundary layer dynamics
COAMPS	Coupled Ocean-Atmosphere Mesoscale Prediction System
DLR	Deutsche Forschungsanstalt für Raumfahrt Angelegenheiten (Germany)
ECMWF	European Centre for Medium-range Weather Forecasting
EM	Electromagnetic
EOS	Earth Observing System
ERIM	Environmental Research Institute of Michigan
ERS	Earth resources satellite
ESA	European Space Agency
FNMOC	Fleet Numerical Meteorological and Oceanographic Center
FOPAIR	Focused phase-array imaging radar
FPN	Forschungs Platformnordsee
GEOSAT	Geodesy satellite (U.S. Navy)
HF	High frequency
HIRES	High Resolution Environmental Sensing project
HRRS	High Resolution Remote Sensing Advanced Research Initiative
JERS	Japanese ERS
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
JSA	Japan Space Agency
LES	Large eddy simulation
LEWEX	Labrador Sea Extreme Waves Experiment
MABL	Marine atmospheric boundary layer
MARSEN	Maritime Remote Sensing Project
MBL	Marine boundary layer
MERIS	Medium-resolution imaging spectrometer
MISR	Multiangle imaging spectroradiometer
MODIS-N	Moderate-resolution imaging spectrometer, nadir viewing
NADC	Naval Air Development Command
NASA	National Aeronautics and Space Administration
NEPRF	Naval Environmental Prediction Research Facility
NOAA	National Oceanic and Atmospheric Administration
NORDA	Naval Ocean Research and Development Activity
NRC	National Research Council
NRL	Naval Research Laboratory
NRL-E	Naval Research Laboratory (Washington, D.C.)
NRL-W	Naval Research Laboratory (Monterey, California)
NRL-S	Naval Research Laboratory (Bay St. Louis, Mississippi)
NSCAT	NASA scatterometer

OBL	Oceanic boundary layer
ONR	Office of Naval Research
RADARSAT	Canadian C-Band SAR satellite
RAR	Real aperture radar
ROV	Remotely operated vehicle
ROWS	Radar ocean wave spectrometer
RPV	Remotely piloted vehicle
SAR	Synthetic aperture radar
SAXON-CLT	Synthetic Aperture Radar and X-band Nonlinearities at Chesapeake Light Tower
SAXON-FPN	Synthetic Aperture Radar and X-band Nonlinearities at Forschungs Platformnordsee
SEASAT	Sea satellite
SeaWIFS	Sea viewing wide-field-of-view sensor
SIR-B	Shuttle Imaging Radar-B
SWADE	Surface Wave Dynamics Experiment
TOWARD	Tower Ocean Wave and Radar Dependence Experiment
TRMM	Tropical Rainfall Measuring Mission