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Waves and Operational Oceanography: Toward a Coherent Description of the Upper Ocean

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The availability of new operational services for ocean circulation modeling presents a unique opportunity to rethink the operational forecasting of ocean waves and how circulation and waves may be combined to provide a better understanding of the upper ocean and enhanced services to society. The large-scale oil spill caused by the wreck of the tanker Prestige off the Spanish coast in November 2002, and uncertainties on the fate of that pollution, illustrated the gaps in means of observations and knowledge of relevant processes.

The idea of a coupled atmosphere-waves-ocean model was proposed by Klaus Hasselmann [*Hasselmann*, 1991], in the context of climate modeling. As waves are the "gearbox" between the atmosphere and the ocean, a detailed understanding of waves can significantly improve the parameterization of air-sea fluxes and surface processes. Besides, Earth observation systems rely extensively on satellite remote sensing techniques for surface winds, temperature, sea level, ocean color, and sea ice, all affected by surface waves. Hasselmann viewed the future of wave modeling as the development of this central gearbox of a general Earth observation and monitoring system, providing fluxes between ocean and atmosphere in a way consistent with satellite observations. This vision, though slow to materialize, is highly relevant for short-term forecasting in the coastal ocean.

Waves: From Global to the Near-Shore

Wave forecasting became a science in the wake of the wartime efforts of H. U. Sverdrup and W. H. Munk, and was greatly improved in recent years with the development of accurate global wave models. Many operational centers are now predicting waves from wind forecasts by using a spectral frequency-direction decomposition of the wave field; this method predicts the change of energy for every component of this wave spectrum, which varies in space over scales from kilometers to ocean basins.

It is now also possible to make reliable predictions of wave breaking statistics on beaches and the induced long-shore currents. However, the forecasting of the transformation of waves over shallow continental shelves still needs to reach that same level of accuracy. Such an improvement would provide offshore boundary conditions to hydrodynamic models for the surf zone and for the resulting short-term sediment transport and beach erosion [*Reniers et al.*, 2004]. Around the surf zone, an important role is played by the low-frequency motions, associated with wave groups, that are still poorly predicted.

The Case for a Combined Ocean Circulation-Wave Forecasting System

Currents, temperature, and salinity in the world ocean pose a more complex problem because they are dominated by energetic small-scale (50–100 km) eddies that have internal, albeit slow, dynamics. These eddies and the large-scale currents are only indirectly forced by surface winds, heating, or cooling. However, there are clear signs of significant effects of waves on the surface temperature and currents [*Mellor and Blumberg*, 2004]

Existing wave models have been invoked to better parameterize surface mixing and air-sea fluxes in ocean circulation models, and surface currents can be used in wave models to improve forecasts, in particular for areas where dangerous waves are created by opposing currents.

Besides these two main reasons for forcing one model with the other, global and regional

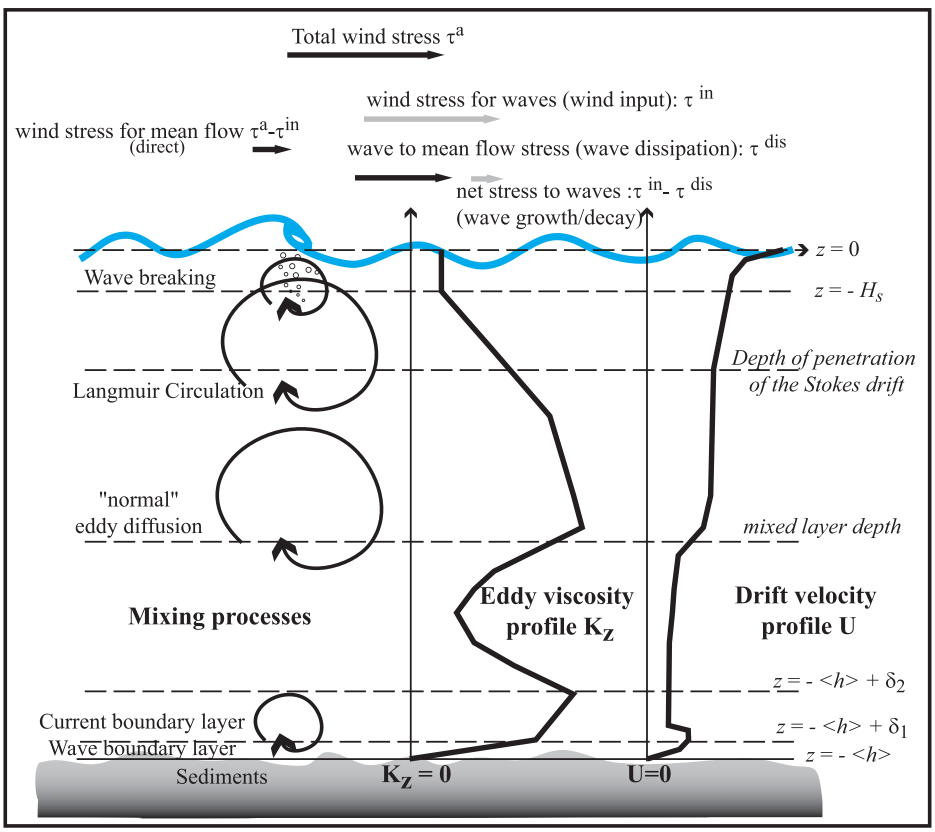

Fig. 1. Momentum fluxes and mixing processes coupling waves and currents. Processes for horizontally uniform conditions, and possible profiles of eddy viscosity and drift velocity.

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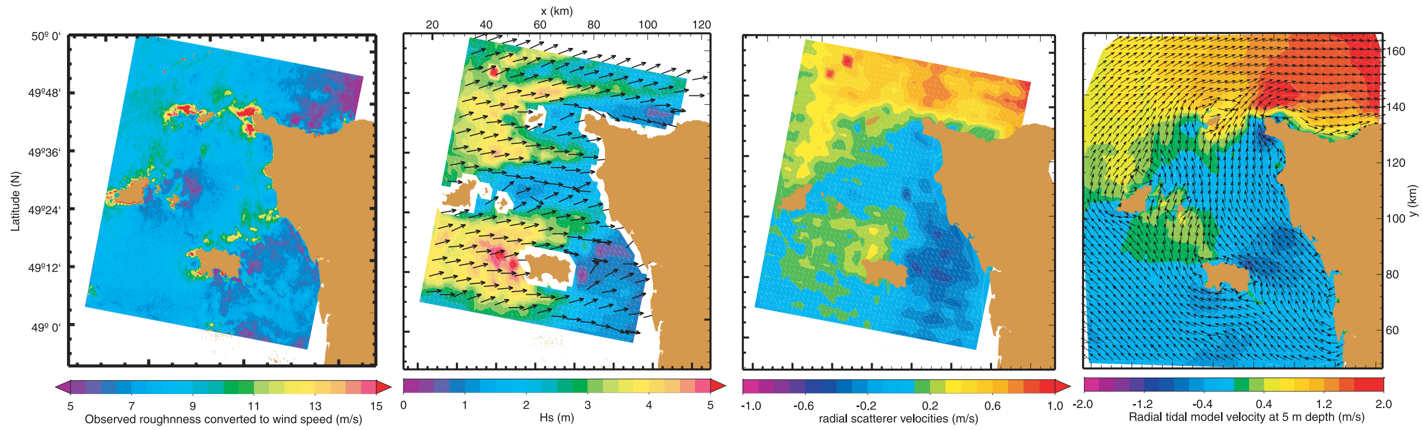

Fig. 2. Illustration of sea-state impact on remote sensing. High-resolution information is extracted from a single synthetic aperture radar image acquired by ENVISAT over the coast of Normandy and the Channel Islands in March 2003. (Left) Surface roughness (radar cross section) interpreted in terms of wind speed but partly due to currents. (Middle left) Significant wave height computed from wave spectra. (Middle right) Radial velocity, positive to the west-southwest, due to surface drift, as seen by the radar. This surface drift is well correlated with the strong tidal currents (right panel shows modeled astronomical tidal currents) in that area and likely contains the Stokes drift due to waves. SAR data were provided by ESA, and image processing was performed by Fabrice Collard, Boost Technologies, Plouzané, France.

circulation models rely on satellite range measurement of the sea surface height. These measurements must be corrected for the sea state bias, a phenomenon mostly related to the geometry of waves, and the largest source of error for the current operational instruments. This bias could be computed from a reliable model of the wave spectrum.

Wave effects also influence other observations that should be assimilated soon into ocean circulation models. The remote sensing of surface salinity faces the difficult challenge of removing the first order effects of surface roughness and wave breaking, effects that also influence the interpretation of ocean color. From space, surface velocity can be estimated using the Doppler information of synthetic aperture radars, either by interferometry, with several satellite missions in planning, or by Doppler centroid analysis using today's satellites. The interpretation of these velocities will require a careful understanding of wave kinematics.

Among other remote-sensing techniques, High Frequency radar surface velocity estimates have been experimentally assimilated in circulation models. However, these measurements of "drift currents" include the wave-induced Stokes drift [*Broche et al.*, 1983], estimated to be 20–80% of the surface drift. (Profiles of Eulerian velocity by *Santala and Terray* [1992] or *Mellor and Blumberg* [2004] can be compared to the often used formula for the surface drift: 3% of the wind speed).

Although this Stokes drift is important for applications such as search and rescue, or forecasting of pollution drift, it is not properly represented in "circulation-only" models. One solution could be the assimilation of these measurements in coupled wave-circulation models that describe the full surface drift velocity.

It is All One Single Ocean

Recent works by specialists in ocean circulation modeling [e.g., *Mellor*, 2003] attempt to look at wave effects on circulation and mixing. These efforts should be encouraged, because a coherent formalism (i.e., methods for separating the scales of motion and expressing the conservation equations that would be valid for the global ocean, the near-shore and surface layer mixing) may be just around the corner.

A consistent depth-integrated formalism for the coupling of surface waves and the mean flow is now well established. However, some effects of surface mixing can only be represented by vertically distributed equations of motion. The recent derivation by *Mellor* [2003] of three-dimensional equations for the current, with wave effects represented by "forcing terms" is a clear step toward a coherent description of ocean dynamics that needs to be verified, with wave forcing translated into ready-to-use forms.

Jenkins [1989] proposed to compute wave-forcing terms from the wave spectra computed by a wave model. Although the details of the parameterizations must be worked out, this approach will benefit from the capability of wave models and their continual improvements. As comprehensive parameterizations of wave effects are developed from wave models, the wave models themselves will benefit from a careful check on the reliability of new parameters that will have to be derived from the wave spectrum: Stokes drift, Stokes transport, mean surface slope, etc.

The demand for consistency between wave and mean flow dynamics and energetics is already promoting a re-examination of the basic physics of wave "dissipation" due to the formation of whitecaps (the most uncertain parameterized process in wave models), and important insights will likely come from properly understood radar measurements.

This joint use of wave and circulation models is an opportunity to bring the air-sea flux parameterizations used in atmosphere and ocean models in line with recent advances, in particular on the effect of wave age on the wind stress [e.g., *Drennan et al.*, 2003]. This effect is probably the largest and easiest improvement that can be made in today's ocean or atmosphere circulation models by using wave information. Great benefits were demonstrated for storm surge modeling [e.g., *Mastenbroek et al.*, 1993] and weather forecasting at the European Centre for Medium-Range Weather Forecasts (ECMWF) [*Janssen et al.*, 2002].

New observations have revealed strong effects of swells on the magnitude and direction of the wind stress [e.g., *Grachev et al.*, 2003], and other studies suggest that the wind drag coefficient may saturate at large wind speeds. These findings have important implications for climate models and hurricane forecasting, and have yet to be translated into predictive parameterizations.

In summary, wave and circulation models can already be modified in the following ways to account for wave effects: modification of the wind drag coefficient (dependence on wave age); use of surface currents for wave forecasting; inclusion of wave radiation stresses for the inner shelf/surf zone circulation; addition of a dynamically consistent formulation for Stokes drift for calculating near-surface drift velocities, in both deep and shallow water, and interpreting remotely sensed surface currents [e.g., *Broche et al.*, 1983]; and use of the wave energy dissipation as an energy flux into the ocean to determine surface mixing bottom friction accounting for the roughness induced by the wave boundary layer roughness. Formalism and parameterizations exist for all these effects, but only the first, second, and third (for the surf zone only) have been tested and validated in field conditions.

Thus, a wide research field is open. This research field also includes the following effects for which parameterizations, if they exist, are not well tested and observation and theory are sometimes still shaky: modification of the wind drag coefficient by swell, sea state impact on air-sea heat fluxes, surface mixing due to Langmuir circulations (LCs), and wave propagation over LCs.

However large the uncertainty on these latter effects, it is held that the first set of wavedependent parameterization is enough to make the wave-circulation combination useful, in particular when surface drift or sediment suspension and transport is considered. The argument that ocean circulation models may not be able to accommodate the complexity and computer time required for a wave model does not stand, and many coupled numerical experiments have disproved it.

Operational Oceanography

The distribution of temperature and salinity, beyond its impact on ocean biology, is all-important for the propagation of sound waves, and this has led to the establishment of operational circulation prediction models, essentially catering to naval needs. The needs of the military persist, but new applications are emerging.

Information demanded by the public varies greatly with activities. Fishermen are interested in sea state, to determine whether they can go out to fish, and in surface temperature to know where fish are to be found. Surfers want to know the height and shape of breakers in particular spots. The offshore industry requires design criteria (wave plus current forces) for structures and routine forecasts of waves and currents for the operation of platforms. The shipping industry would like to gain time and money by optimizing routes, which requires wave forecasting and benefits from surface current forecasts. And, authorities need to understand the transport and evolution of pollutants and nutrients. All of this information can be provided by short-term forecasting systems fed by real-time data.

Some of this capability is being put in place in the framework of admirable collaborative efforts such as the Global Ocean Observing System (GOOS) and its regional associated programs, side by side with ocean modeling efforts performed on a routine basis in civilian weather centers (such as forecasting waves, surface drift, and storm surges) or dedicated oceanographic centers. There is still an effort needed to make consistent use of these resources.

In coastal areas, waves have a large influence because their energy is not so much dwarfed by large-scale vorticity dynamics. Improving our understanding and capacity to forecast waves requires better coastal measurements; the dissemination of those measurements (many wave gauges around the world do not report data to the World Meteorological Organization); and a better description of the offshore wave field, including its directional properties, because waves generally come from offshore. Observing systems should benefit from a wider use of synthetic aperture radars (SARs), using the extended capabilities and wider swath coverage of recent instruments such as ENVISAT's ASAR. A great step forward can also be made with short-lived, low-cost satellite missions to measure wave spectra more directly and more accurately, such as the SWIMSAT mission being considered by the European Space Agency.

Increasing the accuracy of wave and circulation models for those applications will necessarily lead to more realistic parameterizations of unresolved processes. Some of this realism can be obtained by coupling wave and circulation models in a consistent way. This task requires looking at the full complexity of the ocean, using well-tested parameterizations based on first principles for, e.g., drag coefficients, roughness lengths, and mixing coefficients.

A truly integrative effort with contributions from atmospheric sciences and oceanography, including waves and remote sensing, is needed to put all current knowledge to work and thereby identify the weaknesses that will open the way to new research.

Further information can be obtained from the Web site: http://surfouest.free.fr/WOO2003/.

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