Waves and operational oceanography

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As the forecasting of the ocean mesoscale circulation is entering the "operational" age with the Global Ocean Data Assimilation Experiment, a workshop was held last June in Brest, France, to discuss how to make consistent use of ocean observations, circulation modelling, and wave modelling. This last activity is indeed one of the first-established aspects of operational oceanography. The two-day workshop, organised by the French Navy Hydrographic and Oceanographic Service (SHOM), and supported by Ifremer, was provided the opportunity for a gathering of a number of experts within the fields of ocean surface processes and remote sensing. The meeting was triggered by a recent event that clearly highlighted the need for a coherent description of the upper ocean: the large-scale oil pollution event caused by the wreck of the tanker Prestige off the Spanish coast in November 2002. This event unfortunately demonstrates the importance of applying the currently rapidly evolving ideas on wave-mean flow coupling to better assess the spill trajectory.

The idea of a coupled atmosphere-waves-ocean model was forcefully proposed by Klaus Hasselmann in his visionary LEWEX speech [1], in the context of climate modelling. In Hasselmann's vision, wave observations and models were indispensable and central tools in the general Earth observation and monitoring system. As waves are the "gearbox" between the atmospheric "engine" and the ocean "wheels", a detailed understanding of waves can significantly improve the parameterization of air–sea fluxes and surface processes. Besides, observation system rely extensively on satellite remote sensing: radar altimetry, visible and infra-red imagery, scatterometry, passive microwave radiometry, and synthetic aperture radar (SAR). All these techniques are affected by surface waves. In 1991 Hasselmann viewed the future of wave modelling as the development of this central gearbox, providing fluxes between the ocean and atmosphere in a way consistent with remotely-sensed properties of the ocean surface. This prophecy is, however, materializing rather slowly, and we would like to show here that it is still relevant and should give large benefits, not only in the context of climate change, but also for operational short-term forecasting in the coastal ocean, where air-sea fluxes are a often a major contributor to ocean dynamics.

1 A BRIEF HISTORY AND TODAY'S CHALLENGES

Physical oceanography emerged a few centuries ago from a need to understand the miscellaneous observations collected by mariners and explorers. This knowledge was put to use, thereby becoming "operational" as early as the 18th century when, for example, the Gulf Stream was mapped and mariners learned to take advantage of it.

1.1 Waves: from global to the near-shore

This operational use of oceanography was restricted to the use of climatological data until recently, when the variability of some phenomena could finally be predicted. First among these, wave forecasting, which became a science in the wake of the wartime efforts of Sverdrup and Munk [2], was greatly improved in recent years with the development of accurate global wave models by the WAMDI Group [3], [4], thanks to increased computer Many operational centers are thus predicting waves from wind forecasts using a spectral frequency-direction decomposition of the wave field, thus predicting the change of energy for every component of this wave spectrum that varies in space over scales from kilometers to ocean basins. Although the assimilation of wave observations can help, these predictions for deep water are generally very accurate without complementary information.

We are now also able to make reliable predictions of wave breaking on beaches since the work of Battjes and Janssen [5] and induced long-shore currents [6]. There is, however, much work to be done to obtain better spectral shapes and high-resolution forecasts of the transformation of waves in waters of intermediate depth, particularly on continental shelves, where empirical parameters such as bottom roughness are still used for model tuning. Providing good wave fields as forcing or offshore boundary conditions to hydrodynamic models for the surf zone is a crucial requirement for the modelling of sediment transport and near-shore morphodynamics.

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Still deficient to this day, the prediction of the frequency and directional sea/swell wave spectrum is important for the prediction of infragravity waves within the nearshore [7]. The latter play an important role in the nearshore surf- and swash-induced dune erosion and related safety during (extreme) storm events.

1.2 *The case for a combined ocean circulation-wave forecasting system*

The 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 dynamics, albeit slow. These eddies and the large scale currents are only indirectly forced by surface winds, heating or cooling. Temperature and salinity, beyond their impact on the ocean biology, are all-important for the propagation of sound waves, and this has lead to the establishment of operational circulation prediction models, essentially catering for naval needs. These needs are being overtaken by a wider societal agenda, calling for the monitoring of our ecosystems, with a great emphasis on the coastal and littoral ocean, and for the detection and monitoring of climate changes, in which air–sea interactions and fluxes of greenhouse gases are clearly important.

To better describe the distribution of water masses with an ocean model, existing wave models have been invoked to better parameterize surface mixing and air–sea fluxes. On the other hand, knowledge of surface currents and their variations in time can improve wave forecasts, in particular for areas where dangerous waves are created by opposing currents.

It can further be mentioned that, today, global circulation models rely heavily on satellite altimetry data. But needs still exist to correct altimeter range measurements for the sea state bias, a phenomenon mostly related to the sea surface peculiar geometry. Altimeter bias is the largest source of error for the current operational nadir-looking altimeters. It is also expected to affect the wide swath altimetry experiment (WSOA) planned for the future Jason-2 satellite.

Wave effects also impact other remote sensing observations that could be assimilated into ocean circulation models. Indeed, the remote sensing of surface salinity also faces the difficult challenge of removing the order one effect of surface roughness and wave breaking [8], processes which also affect ocean color interpretation [9].

Among other remote sensing techniques, HF radar surface velocity estimates have been experimentally assimilated in circulation models [10]. However these measurements are surface “drift currents”, and include a wave-induced component [11], estimated to by 20–50% of the surface current by Weber [12], [13] and Jenkins . Although this Lagrangian drift velocity is more relevant to some applications such as search and rescue, or forecasting of pollution drift, the wave-induced drift is not accounted for in ”circulation-only” models. Further research is therefore needed to understand these measurements but it already appears that they should be compared or assimilated in coupled wave-circulation models that will describe the full surface drift velocity. From space, surface velocity can be estimated using synthetic aperture radar’s Doppler information, either by interferometry, such as the proposed mission TerraSAR [15] or by Doppler centroid analysis [16].

2 BRIDGING THE GAP BETWEEN WAVES/NEAR-SHORE AND BLUE WATER OCEANOGRAPHY

Klaus Hasselmann’s vision of wave observation and modelling at the center of a Grand “Earth System Model” and ‘Global Ocean Observing System’ may still be for tomorrow but it is more relevant than ever before, in particular as integrated ecosystem modelling moves closer to coasts, where waves are the main driving force. Significant impact of waves on the Mediterranean sea circulation have already been demostrated by Lionello et al. [17] through air-sea fluxes of momentum and heat. These results are relevant to coastal ocean situations where variable fetch is important, resulting in locally generated (young) seas and seas propagating from the open ocean (old seas or swell), that have markedly different effects on these fluxes.

Recent works by specialists in ocean circulation modelling [18], [19] attempt to look at wave effects on circulation and mixing. These efforts are to be encouraged, as a common formalism for the global ocean, the near-shore and surface layer mixing, may be just round the corner.

A consistent depth-integrated formalism for the coupling of surface waves and the mean flow was proposed by Phillips [20]. However, some effects of surface mixing can only be represented by vertically-distributed equations of motion that can be cast in different forms , [22], [23]. Some equations miss one or other of the wave-circulation coupling processes, surface or bottom boundary layer effects, and may not be directly usable. The recent derivation of three-dimensional current and surface wave equations by Mellor [19] is a clear step in that direction that needs to be verified, with wave forcing translated into ready-to-use forms.

In this regard, Jenkins [23] proposed that one could compute the different wave-forcing terms from wave spectra as computed by a model such as WAM, and this is probably the sort of parameterization that should be sought. These models are being run operationally all around the world, and there is no excuse for not using that information. However, as practical and comprehensive parameterization which use wave spectra should emerge in the near future, wave models will benefit from a careful check on the confidence one can have in these derived parameters. As pointed out by Mellor [19], some hypotheses, such as vertically uniform currents, will have to be re-examined in the light of the common wave-mean flow formalism. Consistency between waves kinematics and momentum and the mean flow may further promote a re-examination of the basic physics of wave breaking, a major wave to mean flow momentum flux, and the most uncertain parameterized process in wave models (e.g. [24]).

This joint use of wave and circulation models is certainly an opportunity to bring the air–sea flux parameterizations used in models in line with recent advances, in particular on the effect of wave age on the wind stress drag coefficient C_d (see e.g. [25], [26], [27], [28], [29]). This parameterization of sea state effects on wind stress is probably the largest and easiest improvement that can be made in today's ocean circulation models and that has demonstrated great benefits for storm surge modelling [30]. These issues are also relevant for the atmospheric circulation, and wave model coupling with atmospheric circulation models has led to significant improvements in medium range weather forecasts at the European Centre for Medium-Range Weather Forecasting (ECMWF).

More recently, observations of wind stress over swell [31], [32], [33], [34] have revealed, a strong swell effect on the stress magnitude and direction, in particular for moderate winds. This should have a significant impact on the ocean circulation, with implications for climate. Finally, recent observations of the saturation of the drag coefficient at large wind speeds will be important for hurricane track forecasting, and extreme wave heights warnings.

In discussions of the ocean surface between wave and circulation specialists, it appears that some problems have been disregarded, falling into the gap that has unfortunately widened between these two specialties. For example, wave models routinely compute the flux of energy from the atmosphere to the ocean, which is quite variable and different from the usual ($\propto {u_*}^3$) bulk parameterization, u_* being the friction velocity at the air–ocean interface. This energy flux determines the mixing at the very top of the ocean, and thus the surface current velocity profile and the depth of the mixed layer when it is very shallow [35]. It can be fed into the turbulence closure schemes of ocean circulation models [36]. It is also now fairly clear that waves influence mixing in the surface mixed layer through Langmuir circulations (LCs) (e. g. Smith [37], [38]). These LCs are convection roll vortices aligned with the wind, arising from a coupling of the wave-induced Stokes drift and the current vorticity [39]. If we trust their subgrid schemes, Large Eddy Simulations (LES) apparently reproduce most of these features qualitatively [37], [38], but the parameterization of LCs in mixed layer models is still a challenge.

In summary, 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)
- Addition of a dynamically consistent formulation for Stokes drift for calculating near-surface drift velocities, both in deep and shallow water
- Inclusion of wave radiation stresses for the inner shelf / surf zone circulation

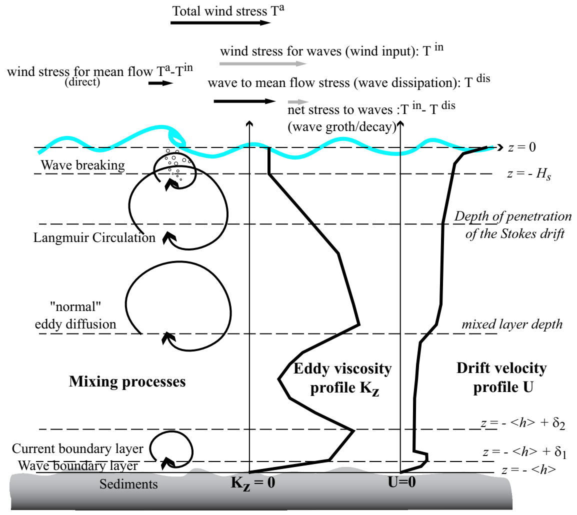

Figure 1: Momentum flux and mixing processes coupling waves and currents for horizontally uniform conditions, and possible profiles of eddy viscosity and drift velocity.

- 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 has really been tested and validated [40], [30]. To these points, one may also add the feedback influence of the ocean surface currents and temperature on the wave evolution.

This means that a wide research field is open which also includes the following effects for which no parameterization is yet available 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
- wave propagation over Langmuir circulations

However large the uncertainty on these latter effects, we hold that the first set of wave-dependant 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 accomodate complexity and computer time required for a wave model does not stand, and many coupled numerical experiments have disproved it. This should be a first step towards a more coherent coupling.

3 THE OPERATIONAL OCEANOGRAPHY THAT SOCIETY NEEDS

What people want to know about the ocean varies greatly with their activities. Fishermen may want to know the surface temperature for fishing tuna, surfers want to know the height and shape of breakers in particular spots, the offshore industry wants design criteria (wave plus current forces) for their structures and routine forecasts of waves and currents for the operation of platforms, the shipping industry would like to optimize routes to gain time and money, which requires wave forecasting and also benefits from surface current forecasts, societies need to understand the transport and evolution of pollutants, nutrients, and the evolution of climate. All this information can be provided by short-term forecasting systems fed by real-time data at a reasonable cost. Many applications need a description of the ocean which is as accurate as possible, and that includes waves, in particular in coastal areas where their influence is larger because their energy is not so much dwarfed by large-scale vorticity dynamics.

Some of this is being put in place in the framework of admirable collaborative efforts such as the Global Ocean Observing System (GOOS) and its regional associated programmes, and ocean modelling efforts performed on a routine basis in civilian weather centers (forecasting waves and surface drift), or dedicated oceanographic centers. There is still an effort needed to make a consistent use of these resources, and ensure, in this general framework, that priorities are well set.

With the push towards high resolution coastal applications, measurement techniques are likely to be different from those used in global deep water applications. Amongst other things, waves in shallow water and their detailed directional properties will have to be better understood and modelled. Which requires better coastal measurements and a better description of the offshore wave field, including its directional properties, because waves generally come from offshore with predictible transformations near the coast. This may benefit from a wider use of Synthetic Aperture Radars (SARs), using the extended capabilities and wider swath coverages of recent instruments such as ENVISAT's ASAR. This need could also certainly be addressed by short-lived low-cost satellite missions to measure wave spectra more directly and more accurately, as proposed earlier by Jackson [41], and currently considered by the European Space Agency as the SWIMSAT mission. These instruments are of course well suited to provided both global and coastal high-resolution information.

As ocean models grow more complex, the careful verification against routine observation that can be performed in operational centers is a major way of improving our understanding of the ocean. This has been the case for weather forecasting, and the prospect of performing similar verifications within operational oceanography systems should lead to corresponding improvements in both the science itself and its practical application. However, before a truly coupled wave - circulation model is run operationally, realistic regional modeling experiments should demonstrate the benefits that will hopefully balance the complexity of a coupled system.

The *Waves and operational oceanography* workshop illustrated the need for a deeper dialogue across disciplines, within oceanography and with meteorology. Until now, many working groups have stressed the importance of one or another of these areas. A truly integrative effort with contributions from atmospheric sciences, oceanography, including waves, and remote sensing, is probably needed to reap the benefits of current knowledge and prepare a solid ground from which future advances will be possible.

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