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

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Abstract:

The availability of new operational services for ocean circulation modelling 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 modelling. 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, 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. Hasselmann viewed the future of wave modelling as the development of this central gearbox of coupled atmosphere-ocean models, providing fluxes between ocean and atmosphere in a way consistent with remotely-sensed properties of the ocean surface. This prophecy is materializing rather slowly. However, it is highly relevant for operational short-term forecasting in the coastal ocean.

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 became a science in the wake of the wartime efforts of Sverdrup and Munk, and was greatly improved in recent years with the development of accurate global wave models [1994]. Many operational centers are now predicting waves from wind forecasts, all 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.

We are now also able to make reliable predictions of wave breaking statistics on beaches and the induced long-shore currents. There is, however, much work to be done to obtain better predictions of the wave spectrum, and high-resolution forecasts of the transformation of waves in waters of intermediate depth. 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 beach erosion. In this process a very important role is played by the long infragravity waves, associated with wave groups, that are still poorly predicted.

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.

Existing wave models have been invoked to better parameterize surface mixing and air–sea fluxes in ocean circulation models, while 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.

Besides these two main reasons for forcing one model with the other, global circulation models rely heavily 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 may even be worse for the wide swath altimetry experiment (WSOA) planned for the future Jason-2 satellite.

Wave effects also impact other observations that could be assimilated into ocean circulation models. The remote sensing of surface salinity faces the difficult challenge of removing the order one effect of surface roughness and wave breaking, effects that also impact interpretation of the ocean color.

Among other remote sensing techniques, HF 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 by 20–50% of the surface drift [Jenkins 1987]. From space, surface velocity can be estimated using synthetic aperture radar’s Doppler information, either by interferometry, with several satellite missions in planning, or by Doppler centroid analysis using today’s satellites [Collard et Chapron 2003] and is likely contaminated by wave effects.

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

3 Bridging the gap between waves/near-shore and blue water oceanography

Recent works by specialists in ocean circulation modelling [e. g. Mellor, 2003] 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 is now well established. However, some effects of surface mixing can only be represented by vertically-distributed equations of motion that can be cast in different forms. 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 [2003] is a clear step in that direction 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 model such as WAM. This is likely to be the best parameterization because wave models have proven their capability and they are continually being improved. With wave models run operationally all around the world, there is no excuse for not using that information. With the development of comprehensive parameterization of wave effects from wave models, these models will benefit from a careful check on the confidence one can have in new parameters derived from the wave spectrum. Consistency between wave kinematics and momentum and 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.

This joint use of wave and circulation models is 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 [see e.g. Drennan et al. 2003; Makin 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 modelling [e. g. Mastenbroek et al., 1993], and weather forecasting at the European Centre for Medium-Range Weather Forecasting (ECMWF).

New observations have revealed a strong swell effect on the stress magnitude and direction [e. g. Grachev et al., 2003;], in particular for moderate winds. This should have a significant impact on the tropical ocean circulation, with implications for climate, while recent observations of the saturation of the drag coefficient at large wind speeds will be important for hurricane track forecasting, and extreme wave height warnings.

Other air-sea fluxes are also explored. Wave models routinely compute the flux of turbulent kinetic energy from the atmosphere to the ocean (through the waves). It was shown to be quite variable and different from the usual ($\propto {u_*}^3$) bulk parameterization, u_* being the friction velocity at the air–ocean interface. This 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 [Craig and Banner, 1994]. It is also now fairly clear that waves influence mixing in the surface mixed layer through Langmuir circulations (LCs) [e. g. Thorpe et al., 2003]. These LCs are convection roll vortices aligned with the wind, arising from a coupling of the Stokes drift and the current vorticity. Their parameterization in operational 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
- 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. In turn, wave models can include the feedback influence of the ocean surface currents and temperature on the wave evolution.

This means that a wide research field is open. It 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 uselful, 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.

4 Operational oceanography

The distribution of temperature and salinity, beyond its impact on the ocean biology, is 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.

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, authorities 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.

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, side by side with ocean modelling efforts performed on a routine basis in civilian weather centers (such as 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.

In coastal areas waves have a large influence because their energy is not so much dwarfed by large-scale vorticity dynamics, but their detailed directional properties will have to be better understood and modelled. This requires better coastal measurements and a better description of the offshore wave field, including its directional properties, because waves generally come from offshore. This should 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, and the Doppler information on surface velocity. This need could also certainly be addressed by short-lived low-cost satellite missions to measure wave spectra more directly and more accurately, as 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.

Increasing the accuracy of wave and circulation models for those applications will necessarily lead to more realistic parameterizations of some of the popular tuning knobs in use: drag coefficients, roughness lengths, mixing coefficients. Some of this realism can be obtained by coupling wave and circulation models. This increase in model complexity will increase the need for careful verifications of models against dedicated measurement campaigns. The use of these operational models and the existence of good routine observations will also make this verification more complete, and will be a major way of improving our understanding of the ocean.

A truly integrative effort with contributions from atmospheric sciences, 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 reasearch.

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

Figure 2: Illustration of sea-state impact on remote sensing with high resolution information 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: significant wave height computed from wave spectra, right: radial velocity, positive to the west-south-west, due to surface drift as seen by the radar. This surface drift is well correlated with the strong tidal currents in that area and likely contains the Stokes drift due to waves. Image processing was performed by Dr. Fabrice Collard, Boost Technologies, Plouzané, France.

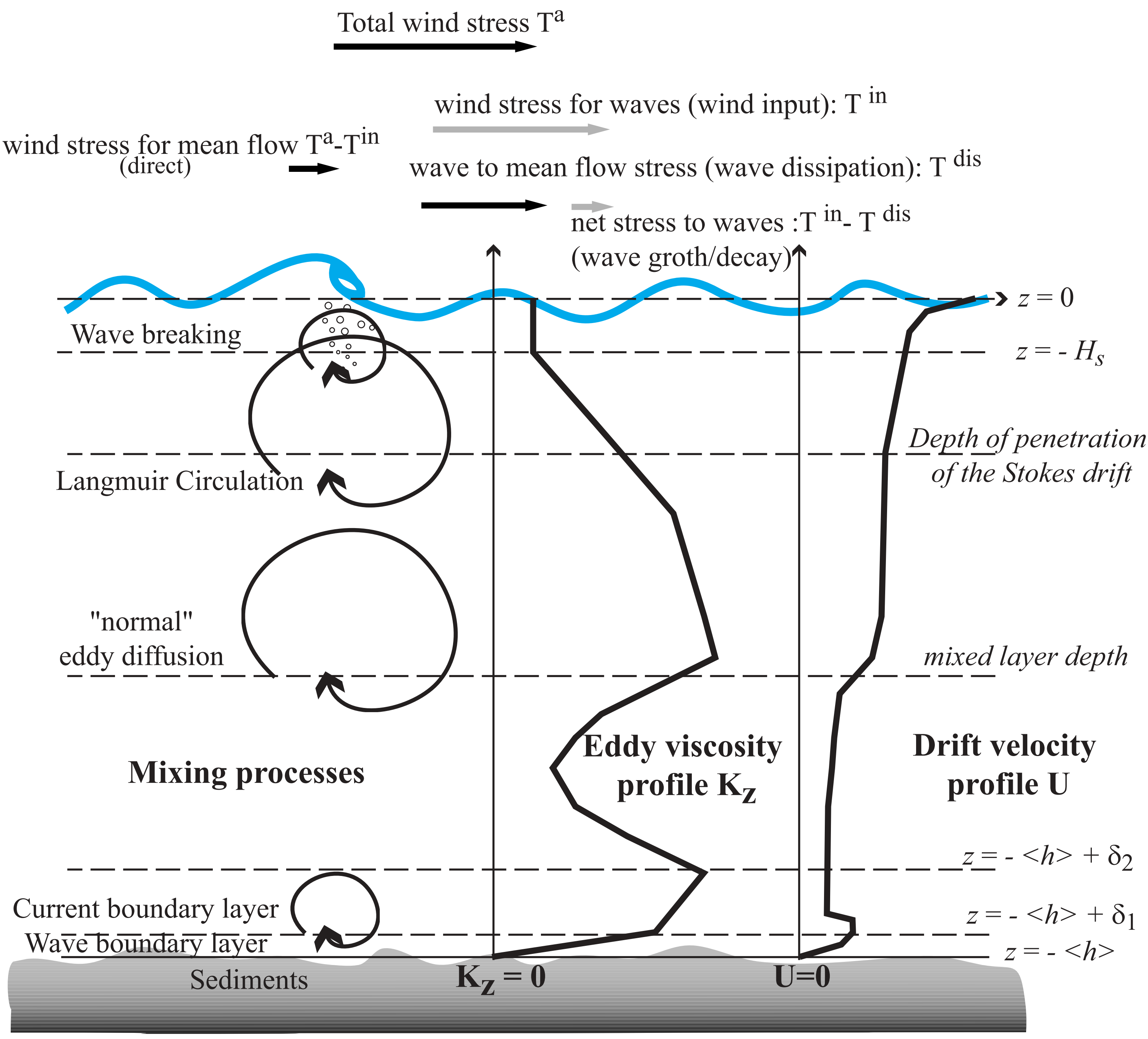
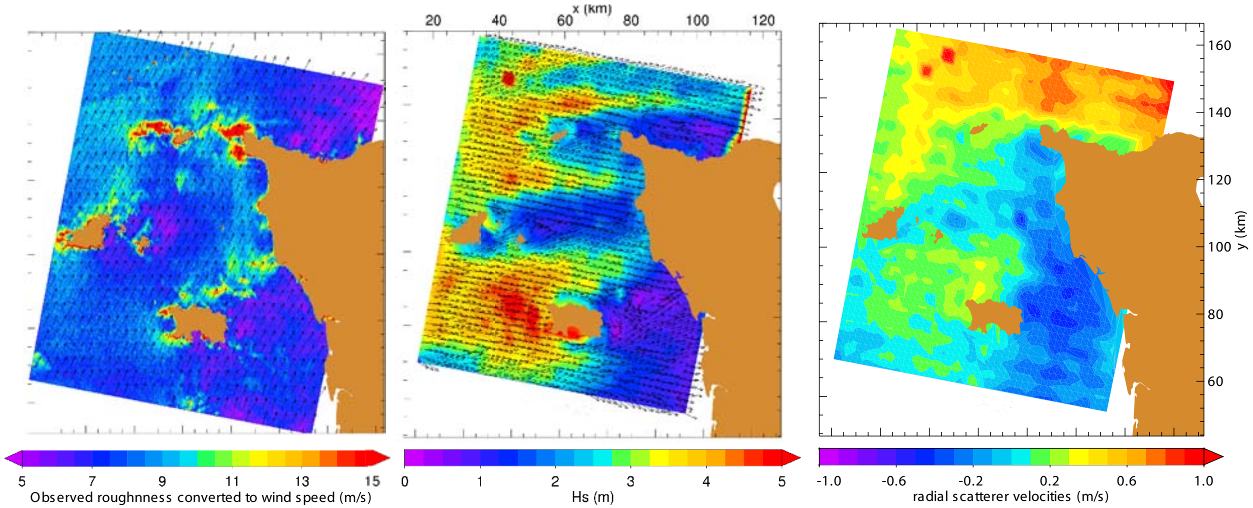

Total wind stress T^a
wind stress for waves (wind input): T^{in}
wind stress for mean flow T^a-T^{in}
(direct)
wave to mean flow stress (wave dissipation): T^{dis}
net stress to waves :T^{in}- T^{dis}
(wave groth/decay)
$z = 0$
Wave breaking
$z = -H_s$
Depth of penetration
of the Stokes drift
Langmuir Circulation
"normal"
eddy diffusion
mixed layer depth
Mixing processes
Eddy viscosity
profile K_z
Drift velocity
profile U
$z = - \langle h \rangle + \delta_2$
Current boundary layer
$z = - \langle h \rangle + \delta_1$
Wave boundary layer
$z = - \langle h \rangle$
Sediments
$K_z = 0$
U=0

FIG 1.



x (km)
20
40
60
80
100
120
160
140
120
100
80
60
y (km)
5
7
9
11
13
15
Observed roughness converted to wind speed (m/s)
0
1
2
3
4
5
Hs (m)
-1.0
-0.6
-0.2
0.2
0.6
1.0
radial scatterer velocities (m/s)

FIG 2.