Proposal for a SCOR Working Group on
Surface Waves in Ocean Circulation and Climate System

Abstract Surface waves, as the most energetic motion in the ocean, are traditionally left out of large- scale ocean general circulation and climate models. Recent studies have shown that ocean surface waves could have decisive influence on basin scale temperature structure and circulation pattern through the surface wave-induced vertical mixing. This working group will explore and identify the crucial importance of surface waves in the upper ocean and climate system through modulation of the ocean vertical mixing and air-sea interaction, and will assess new observational programs needed to better parameterize the wave-induced vertical mixing in the upper ocean and the air-sea interaction processes at sea surface. This will make it possible to improve ocean and climate models by including the mixing effects associated with the surface waves through the whole water column. .

1. Rationale

Wind energy input to surface waves is estimated as 60~70 TW (Wang and Huang, 2004; Rascle et al., 2008), which is much greater than the mechanical energy from all other sources in the ocean. A review by Wunsch and Ferrari (2004) clearly states the critical role of surface waves in vertical mixing of momentum and energy in the global ocean. However, nearly all previous scientific studies of large-scale oceanic and climate phenomena treat waves as a superfluous nuisance. Part of the reason is that waves were thought to be of small scales and therefore irrelevant; the other factor is that wave studies have been confined to studying waves for the sake of understanding the dynamics of waves only (Yuan and Huang, 2012). In fact, vertical mixing in the upper ocean and air-sea fluxes at the sea surface are not only strongly modulated but also determined by the surface wave conditions.

Climate and weather are essentially ocean-atmospheric interaction phenomena. Their dynamic and thermal regimes imply physical coupling of atmosphere and ocean in such a complicate way that the physical details are still elusive. The past parameterization approach to study such coupled models appear to have reached a limit in their performance, and failed to reproduce aspects of important observed air-sea interaction phenomena such as the phase of the ENSO cycle and tropical-cyclone intensity, among others. There is an urgent need for better physics for related numerical models.

Air-sea interaction phenomena, including weather and climate, represent a complicated chain of inter-connected and coupled processes. If, for example, global warming is happening non-uniformly, it will lead to changes of the atmospheric pressure gradients and therefore of wind systems, which should bring about alterations to the wave fields. The latter will provide feedback on the winds and, most importantly, on the ocean mixing (Cavaleri et al., 2012). If the average prevalence or size of surface waves increases, which appears to be the case over the last 25 years (Young et al., 2011), they can mix the ocean deeper (Babanin, 2006). Since 2-3m of ocean water has the same heat capacity as the entire dry atmosphere (Soloviev and Lukas, 2003) and the deeper ocean is cold, such extra mixing should dampen the surface ocean warming. So, surface wave plays crucial role in the climate system.

2. Scientific Background

Simulations of the wave-mixing effects in climate models clearly demonstrate significant feedbacks from the ocean because of the additional mixing due to wave actions. This feedback impacts both the magnitudes and global distribution of primary atmospheric features such as temperature oscillations, pressure patterns and rainfall. When wave mixing is included, rainfall in summer months in Southeastern Asia, for example, is increased by 3mm per day. When full GCMs are explicitly coupled with the wave models (i.e., climate-model winds are used to generate and drive the waves, whose effects are then fed to the upper ocean), the correlation between simulated and observed sea temperatures increases by as much as 30% (Qiao et al., 2010). Note that the outcome is not entirely local, for the ocean circulation is affected, which makes the sea surface temperature is not necessarily decreased locally.

This working group will bring together the wave-coupled effects on the upper ocean, weather and climate. Weather and climate are phenomena of very different scales (days vs. years and decades, respectively). Both scales, however, are much larger with respect to the scale of ocean surface waves (seconds). Consequently, wave-related air-sea interactions in weather and in climate research have not been coupled due to the following two main reasons: In terms of geophysics, there is a traditional perception that processes of such distant scales can be studied and modeled separately, and exchange between the scales can be parameterized as some larger-scale average (mean fluxes of energy and momentum in this case). In terms of technicality, the computational costs of such coupling have been prohibitive until recently, and are still very expensive.

The fluxes, however, are not constant in the course of wave evolution, even if the wind is constant. These fluxes are determined by a great variety of wave-related properties which vary at time scale of hours, which is comparable with the lower time scale of evolution for weather patterns. Since the concurrent wave pattern is very complicated, it appears necessary to know the wave properties explicitly at each step of cyclone development.

On the atmospheric side of the ocean interface, waves determine the surface drag that is how much the surface winds are slowed down because of the wave presence. In very simple terms, the drag should increase as the winds grow, but there is experimental evidence that this growth slows down and even decreases at higher wind speeds (Powel et al., 2003), either due to aerodynamic effects imposed by waves (e.g., Donelan et al., 2006) or due to spray produced by the waves (e.g., Kudryavtsev and Makin, 2011), or due to a combination of these and other influences. Recent hurricane-wave coupling investigations have demonstrated the significance of such feedback processes (Moon et al., 2008).

Below the surface, the effects of turbulence induced by breaking waves have long been appreciated (Soloviev and Lukas, 2003). The mixing and the turbulence induced by non-breaking waves, however, are new concepts (Yuan et al, 1999; Qiao et al., 2004; Babanin, 2006). The non-breaking wave-induced mixing can affect the water column to a depth of the scale of the wavelength, which is of the order of 100m and is comparable with the mixed layer depth; while, the wave breaking-related mixing only affects the scale of wave height. Therefore, the non-breaking wave effects provide a ready explanation for turbulence diffusion or advection in order to mix the seasonal ocean layer through the thermocline below. Ever since the proposal of this concept, it has been confirmed through extensively tested in the laboratory (Babanin and Haus, 2009; Dai et al, 2010; Savelyev et al, 2012) and in the field (Pleskachevski et al., 2011).

Implementation of this wave-turbulence mixing in climate models leads to significant impacts, as mentioned above, both on the atmospheric side and in the ocean (Qiao et al., 2010). This implementation is particularly necessary since the wind/wave climate itself has been changing, both in the mean and in its extremes (Young et al., 2011). The wind/wave growth is most relevant for ocean mixing, air-sea interactions and extreme oceanic conditions. The sea drag coefficient, which is the main property to describe the air-sea interaction in GCMs, also explicitly depends on the waves as discussed above. Thus, it appears that neither climate trends nor wave trends can be adequately addressed unless GCMs are fully coupled with wave models.

In short, without accounting for the wave effects directly, the physics of large-scale ocean circulation and air-sea interactions is inaccurate, inadequate and incomplete. The proposed working group will bring together experts in ocean waves, ocean circulation and climate models. Two main reasons make coupling of waves with the dynamics of large-scale phenomena necessary and feasible now: First, since the waves evolve in response to air/sea forcing, by receiving energy and momentum from the winds and by passing it on to ocean turbulence and currents, their feedback cannot be efficiently averaged and parameterized, but has to be unambiguously evaluated and accounted for at every instant. Second, modern-day computer facilities have caught up with the needs of coupling small-scale and large-scale phenomena.

3. Terms of Reference

The proposed working group would

(1) Summarize past results of surface wave effects on upper ocean and lower atmosphere through upper ocean vertical mixing and air-sea fluxes;

(2) Identify new observational programs and improved observational techniques needed to fill gaps in understanding essential physics and dynamics of the wave-induced vertical mixing in upper ocean and air-sea fluxes to provide useful information for parameterization;

(3) Explore new and effective ways to make the atmosphere, wave and general ocean circulation models to couple together seamlessly and efficiently. This would be the necessary steps to establish new generation coupled atmosphere-ocean general circulation models for research and operational forecast from ocean/atmosphere dynamical process, tropical cyclones to climate;

(4) Convene both open and by invitation working group meetings and publish the progressive assessments in open literatures such as publishing a special issue of a major journal dedicated to this topic, or proceedings of the Air-Sea Symposium;

(5) Finally, produce a comprehensive final report incorporating the study results and the state-of-the-arts summary of the above topics in a monogram to be published by a leading publishing house, such as the Cambridge University Press, as a milestone and land mark for the air-sea fully coupled climate modeling.

4. Working Group Membership, Group Activities and Capacity Building

(1) Membership

Ten full members are as follows (Profs. Fangli Qiao and Alexander V Babanin will co-chair WG)

No	Name	Institute/University	Nation	Gender
1	Fangli Qiao	First Institute of Oceanography	China	M
2	Alexander V Babanin	Swinburne University of Technology	Australia	M
3	Mikhail Dobrynin	University of Hamburg	Germany	M
4	Yign Noh	Yonsei University	Korea	M
5	Erick Rogers	Naval Research Laboratory	USA	M
6	Anna O. Rutgersson	Uppsala University	Sweden	F
7	Fredolin T. Tangang	National University of Malaysia	Malaysia	M
8	Hendrik L. Tolman	NCEP	USA	M
9	Yuliya Troitskaya	Institute of Applied Physics	Russian	F
10	Judith Wolf	National Oceanography Centre	UK	F

Seven Associate members are as follows:

No	Name	Institute/University	Nation	Gender
1	Tal Ezer	Old Dominion University	USA	M
2	Safwan Hadi	Institute of Technology Bandong	Indonesia	M
3	Norden E Huang	National Central University	China	M
4	Somkiat Khokiattiwong	Phuket Marine Biological Center	Thailand	M
5	Nadia Pinardi	University of Bologna	Italy	F
6	Ian Young	Australian National University	Australia	M
7	Yeli Yuan	First Institute of Oceanography	China	M

Note: All 10 members and 7 associated members are Professors.

(2) Working group activities

Annual meetings (by invitation only): The attendees would be limited to the members and invited experts in the proposed subject to summarize the progress and assess the future direction of action for the working group. It is proposed that three annual meeting will be organized during 2013- 2015. The first and second meetings will be in China and Australia in 2013 and 2014, an article to EOS (2013) and an article to BOMS (2014) are expected respectively. The venue of the third meeting in 2015 will be discussed among working group members and a proceedings or a special issue of a journal is expected in the third year.

Scientific sessions (Open to public): organize 2 scientific sessions at the General Assembly of the European Geosciences Union and in 2014 and 2016 to announce the progress and to solicit a wider view from the community on the proposed subject

Symposium: In 2016 of the last year of this working group, a special Air-Sea Interaction Symposium will be organized in China, dedicated to the wave-coupled effects in ocean circulation, weather and climate.

Additional editorial meeting of selected members in the last year will be organized, if necessary, to work out the final report which will be published by a leading publishing house, such as the Cambridge University Press.

(3) Capacity building

Other than the open meetings, capacity building will be accomplished mainly through two additional kinds of activities:

Firstly, establish and maintain a Web site as a "virtual workshop" that can be used by the scientific community for exchange and discussion of ideas, results, and future planning on the surface wave effects in ocean and climate; and secondly, to host two training courses on wave effects on ocean and climate, and support at least 25 trainees from all different countries each time on the platform of the UNESCO/IOC Regional Training and Research Center on Ocean Dynamics and Climate (http://www.fio.org.cn/english/training_center/index.htm). The chair of this working group will seek additional financial support for the related capacity building.

5. The Relationship with Previous SCOR Working Groups and Other Organizations

WG 28 air-sea interaction focused the traditional air-sea exchange processes, while the present WG will focus on the surface wave effects on air-sea interaction with a special emphasis on the effects in the water column through mixing. WG 69 studied small-scale turbulence and mixing in the ocean, while the present WG will focus on the surface wave-induced mixing; WG 103 focused on wave breaking on upper ocean dynamics, while the present WG will focus on the non-breaking surface wave-induced mixing; WG 121 focused on mixing in the deep ocean, whereas the present WG will focus on the ocean mixing in the upper ocean. The work of this group is closely relevant to the SCOR-IGBP-WCRP-CACGP Surface Ocean – Lower Atmosphere Study (SOLAS), Intergovernmental Oceanographic Commission (IOC), as well as to the World Climate Research Programme (WCRP) and the International Association for the Physical Sciences of the Ocean (IAPSO)

Reference

Babanin, A.V., 2006: On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophysical Research Letters*, 33, doi:10.1029/2006GL027308.

Babanin, A.V., and B.K Haus, 2009: On the existence of water turbulence induced by non-breaking surface waves. *Journal of Physical Oceanography*., 39, 2675-2679.

Babanin, A.V., 2011: *Breaking and Dissipation of Ocean Surface Waves*. Cambridge University Press, 480pp.

Cavaleri, L., B. Fox-Kemper, and M.Hemer, 2012: Wind-waves in the coupled climate system. *Bull. Amer. Met. Soc.*, In press.

Dai, D., F. Qiao, W. Sulisz, L. Han, and A.V. Babanin, 2010: An experiment on the non-breaking surface-wave-induced vertical mixing. *Journal of Physical Oceanography.*, 40, 2180-2188.

Kudryavtsev, V.N., and V.K. Makin, 2011: Impact of ocean spray on the dynamics of the marine atmospheric boundary layer. *Boundary-Layer Meteorology*, 140, 383-410.

Moon, I., I. Ginis, and T. Hara, 2008: Impact of reduced drag coefficient on ocean wave modeling under hurricane conditions. *Monthly Weather Review*, 136, 1217-1223.

Pleskachevsky, A., M. Dobrynin, A.V. Babanin, H. Gunther, and E. Stanev, 2011: Turbulent diffusion due to ocean surface waves indicated by suspended particulate matter. Implementation of satellite data into numerical modelling. *Journal of Physical Oceanography*, 41, 708-724.

Powell, M.D., P.J. Vickery, and T.A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature,* 422, 279-283.

Qiao, F., Y. Yeli, Y. Yang, Q. Zheng, C. Xia, and J. Ma, 2004: Wave-induce mixing in the upper ocean: Distribution and application to a global ocean circulation model. *Geophys. Res. Lett.*, 31, doi:10.1029/2004GL019824.

Qiao, F., Y. Yuan, T. Ezer, C. Xia, Y. Yang, X. Lu, and Z. Song, 2010: A three-dimensional surface wave-ocean circulation coupled model and its initial testing. *Ocean Dynamics,* 60, 1339-1355.

Rascle, N., F. Ardhuin, P. Queffeulou, and D. Croizé-Fillon, 2008, A global wave parameter database for geophysical applications. Part 1: Wave-current-turbulence interaction parameters for the open ocean based on traditional parameterizations. Ocean Modell., 25, 154-171.

Savelyev I. B., E. Maxeiner and D. Chalikov, 2012, Turbulence production by non-breaking waves: laboratory and numerical simulations. *Journal of Geophysical Research*, submitted.

Soloviev, A.V., and R. Lukas, 2003: *The Near-Surface layer of the Ocean: Structure, Dynamics and Applications.* Springer, NY, 572pp.

Wang, W., and R. X. Huang, 2004, Wind energy input to the surface waves. *J. Phys. Oceanogr.*, 34, 1276-1280.

Wunsch, C., and R. Ferrari, 2004, Vertical mixing, energy and the general circulation of the oceans. *Ann. Rev. Fluid Mech.*, 36, 281-314. doi:10.1146/annurev.fluid.36.050802.122121.

Young, I.R., S. Zieger, and A.V. Babanin, 2011: Global trends in wind speed and wave height. *Science*, 332, 451-455

Yuan, Y., F. Qiao, F. Hua, and Z. Wan, 1999, The development of a coastal circulation numerical model: 1. Wave-induced mixing and wave-current interaction. *J. Hydrodyn.*, Ser. A, 14, 1–8.

Yuan, Y. and N. E. Huang, 2012, A reappraisal of ocean wave studies. *Journal of Geophysical Research*, submitted.