JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C00J01, doi:10.1029/2012JC007932, 2012

Surface waves and wave-coupled effects in lower atmosphere and upper ocean

Alexander V. Babanin,[1] Miguel Onorato,[2,3] and Fangli Qiao[4]

Received 30 January 2012; revised 18 September 2012; accepted 18 September 2012; published 7 November 2012.

[1] The article introduces the Special Issue of the *Journal of Geophysical Research – Oceans* which is based on the papers presented at or related to the new session of the General Assembly of the European Geosciences Union, first conducted in 2011. Topic of the session on the Surface Waves and Wave-Coupled Effects highlights a new dimension of the present state of wind-wave research. The surface waves is an important oceanographic topic in its own right, but it is also rapidly becoming clear that many large-scale geophysical processes are essentially coupled with the surface waves, and those include climate, weather, tropical cyclones and other phenomena in the atmosphere and many issues of the upper-ocean mixing below the interface.

Citation: Babanin, A. V., M. Onorato, and F. Qiao (2012), Surface waves and wave-coupled effects in lower atmosphere and upper ocean, *J. Geophys. Res.*, *117*, C00J01, doi:10.1029/2012JC007932.

1. Introduction and Historical Excurse

[2] The water-wave science, and even its more specific branch of wind-generated waves is an old research field by oceanographic standards. Started with classical works of *Airy* [1841], *Stokes* [1847, 1880], *McCowan* [1894], *Jeffreys* [1924, 1925], *Langmuir* [1938], *Miche* [1944] in the 19th and first half of the 20th century, it received a boost driven by navy needs during World War II and has been enjoying a period of close attention of the scientific community, not only oceanographers, ever since.

[3] Indeed, the wind-generated waves represent an exciting physical object and a considerable challenge due to complexity of the processes involved into wave generation, dissipation and interactions both within the wavefields themselves and with other oceanographic processes and objects in the air-sea-ice-bottom-coast system. Besides, as an environmental factor, this is the major problem for any human activity at sea or the coastal areas. Therefore, the waves have continued to attract attention of scientists, engineers and meteorologists.

[4] Analytically, this phenomenon is a unique blend of turbulent theories of atmospheric and oceanic boundary layers and wind-wave two-way interactions, of weakly nonlinear resonant and quasi-resonant interaction mechanisms, complemented by strongly nonlinear processes such as wave breaking. This poses formidable difficulties, enhanced by the fact that some of the processes are continuous, e.g., wind-wave exchanges, others are sporadic, i.e., whitecapping, and yet others can be intermittent such as wave-induced turbulence. Time/space scales involve a range from thousands of wave periods/lengths for the resonant wave-wave interactions to a fraction of a period for the breaking. And yet all the processes mentioned and implied are often equally important in the general context of wave development. In specific conditions, such as finite depths, presence of currents or internal waves, very strong wind-forcing (e.g., tropical cyclones), additional host of physics comes into significance or even dominance.

[5] It is mostly the analytical studies which drove the early cutting edge of wind-wave research in modern times. It started with now classical works on generation of waves by the wind [*Miles*, 1957, 1959, 1960; *Phillips*, 1957] and of turbulence by wave orbital motion [*Phillips*, 1961], on the similarity theories of wave spectrum by *Phillips* [1958] and wave growth by *Kitaigorodskii* [1962]. The 60s also signified breaks through in potential theories of wave motion which then defined the development of analytical research and drove experimental research in this field for decades to come. The milestones in this regard are the kinetic theory of *Hasselmann* [1962], discovery of the modulational instability [*Zakharov*, 1966, 1967; *Benjamin and Feir*, 1967], derivation of Zakharov Equation and Nonlinear Schrödinger Equation [*Zakharov*, 1968], concept of the weak turbulence in surface waves [*Zakharov and Filonenko*, 1966]. Series of spectacular works by Longuet-Higgins and his colleagues allowed to reveal and explain many details of wind-wave physics within both rotational and potential approaches [*Longuet-Higgins*, 1953, 1969; *Longuet-Higgins and Stewart*, 1960; *Longuet-Higgins and Fox*, 1977]. In this regard, seminal books by *Kinsman* [1965] and *Phillips* [1966] should also be mentioned which summarized the analytical and some

[1]Centre for Ocean Engineering, Science and Technology, Swinburne University of Technology, Melbourne, Victoria, Australia.
[2]Dipartimento di Fisica, Università di Torino, Turin, Italy.
[3]Sezione di Torino, INFN, Turin, Italy.
[4]First Institute of Oceanography, Qingdao, China.

Corresponding author: A. V. Babanin, Centre for Ocean Engineering, Science and Technology, Swinburne University of Technology, PO Box 218, Hawthorn, Melbourne, Vic 3122, Australia. (ababanin@swin.edu.au)

0148-0227/12/2012JC007932

experimental knowledge on ocean surface waves and remain relevant nowadays.

[6] In the experimental context, the 60s and 70s signified transition from early visual and descriptional ocean observations to the systematic experimental research, both in the field and laboratory, based on recording the measured data and their subsequent analysis. These became possible due to developing the increasingly diverse and sophisticated instrumentations and methods and, exceedingly, due to development of computing facilities which provide three-in-one possibility to login the data, to store them and to analyze. Experimental results of these days which are used as benchmark today are measurements of mean square slope of wind waves [*Cox and Munk*, 1954]; method for buoy observations of the directional wave spectra [*Longuet-Higgins et al.*, 1963]; verifications of the Kitaigorodskii similarity theory which led first to the parameterization of fully developed wave-spectrum shape [*Pierson and Moskowitz*, 1964] and experimental dependences for wave growth [*Mitsuyasu et al.*, 1971], and culminated in the JONSWAP wave-growth and spectrum-shape parameterizations [*Hasselmann et al.*, 1973]. Other milestones of this era to be mentioned are the sea-drag parameterizations (see a review by *Wu* [1969]); dependences for whitecapping coverage [*Monahan*, 1971]; field experiments with wave-induced non-breaking turbulence [*Yefimov and Khristoforov*, 1971a, 1971b]; extensive studies of one-dimensional modulational instability (summarized in *Yuen and Lake* [1982]); first field measurements of wind-to-wave energy fluxes [*Snyder*, 1974; *Snyder et al.*, 1981]; first detailed studies of wave breaking in laboratory and at sea [*Longuet-Higgins*, 1974; *Melville*, 1982]; among many others.

[7] In the last three decades, research and understanding of wind-generated waves and air-sea interactions, and to a lesser extent of waves in the contexts of their influences in the upper ocean, exploded. Literature in this regard is enormous and we refer the reader to the books by *Young* [1999] and *Holthuijsen* [2007], wave modeling reviews by *Komen et al.* [1994], *Lavrenov* [2003], and *Cavaleri et al.* [2007], wind-wave interaction reviews by *Donelan* [1998] and *Janssen* [2004], a book on the nonlinear features of wave-fields by *Osborne* [2010], and a book on wave breaking and dissipation by *Babanin* [2011].

[8] Apart from academic interest, the wind-wave research was greatly motivated by practical needs of wave forecast and led to creation of the third-generation wave models based on parameterizing the known physics of major energy source/sinks in the wind-wave system in spectral terms, i.e., three international models WAM [*Komen et al.*, 1994], WAVEWATCH-III [*Tolman and Chalikov*, 1996; *Tolman*, 2009], SWAN [*Booij et al.*, 1999], Chinese national model MASNUM [*Yuan et al.*, 1992; *Yang et al.*, 2005], Japanese national model MRI-III [*Ueno and Kohno*, 2004], among other national models. The spectral models, however, are essentially based on random phase approximation approach, and they leave problems of individual-wave dynamics, for example, generation of rogue waves, evolution of wave groups, wide open. As such, they also need updates of their physics in view of recently acquired knowledge, and guidance into a broad range of circumstances which they had originally not been designed for. Among those are change of wave dynamics and wave-atmosphere-ocean interactions in extreme conditions, a broad suit of specific behaviors in shallow areas, in presence of currents, in icy seas, and others. Recent developments of numerical aspects of the wave modeling should also be mentioned such as multigrid model structure, implementing the subgrid bathymetry, unstructured meshes [e.g., *Roland*, 2009].

[9] Most exciting, however, are new developments required in the context of coupling wave models with large-scale air-sea and ocean-circulation models which bring the ocean-wave science into a completely new area of research and applications. These and other topics and issues of the current status and future perspectives of wave research are discussed in the next two Sections.

2. Current Status and Future Perspectives

[10] Current status and perspectives of the ocean surface wave research is so diverse that it is apparently not feasible to systematize or even outline in a journal article. An intriguing example of the recent developments appears a possible link between physics of rogue wave events on the water surface and in nonlinear wave trains in other media. In particular, such analogy has been pursued in nonlinear optics through interpretations of modulational instability of packets of nonlinear waves in dispersive environments [*Solli et al.*, 2007; *Akhmediev et al.*, 2011]. If proven, this analogy will allow, for example, to use the optical fibers in order to investigate statistics of very rare ocean wave events indirectly, since even a very short fiber segment accommodates a very large number of wavelengths in the optical range. It should be mentioned that such analogy should be used with caution: in the nonlinear optics (as well as in equations for the water waves without dissipation), the waves can grow virtually unlimited, whereas height of physical waves is limited by wave breaking. In turn, ocean conditions provide a great variety of additional physics to be tried in the optical nonlinear media: for example, triggering the modulational instability by adverse currents with horizontal velocity gradient [*Onorato et al.*, 2011] can be interpreted by means of optical fiber with non-uniform deflection.

[11] While the analogy is attractive, the modulational instability is only one of a number of possible causes of large and breaking waves in the ocean. Even then, it is expected to be impaired or even suppressed in three-dimensional wave-fields which the ocean waves typically are. Understanding these limits of applicability of modulational instability is very important for statistical descriptions of extreme wave events and for the formulations of whitecapping dissipation function in wave-forecast models, and active research in this direction is now under way [*Yuan et al.*, 2009; *Onorato et al.*, 2009; *Babanin et al.*, 2011].

[12] For the whitecapping dissipation [*Young and Babanin*, 2006] and wind input spectral source terms [*Donelan et al.*, 2005, 2006; *Chalikov and Rainchik*, 2011], new parameterizations have become available, which revealed new features of these physics not accounted for in the present third-generation operational wave models. Therefore, need for the model updates is apparent, as well as needs to update modeling the swell propagation [*Ardhuin et al.*, 2009; *Babanin*, 2011], the wave-current interaction physics [*van der Westhuysen*, 2012], waves in finite-depth and shallow environments [e.g., *Rogers and Holland*, 2009;

Smith et al., 2011], waves in marginal ice seas [e.g., *Kohout and Meylan*, 2008; *Wang and Shen*, 2010].

[13] Fourth generation wave models are also foreseeable. These would require parameterizations of the source terms to be replaced by modeling the physics based on first principles. Obviously, they will be coming into existence as hybrids first: that is some physics is simulated explicitly, while other terms remain parametric. The nonlinear term of *Hasselmann* [1962] is the apparent first candidate. It has always been known exactly, and the actual use of DIA [*Hasselmann et al.*, 1985] and other parameterizations is dictated by operational needs due to its heavy computational expense. With the coding algorithms advancing and computer power rapidly growing, employing the exact computations of nonlinear term can become feasible soon. In this regard, new developments are also available, intended on more realistic scenarios for nonlinear wave-wave interactions in non-homogenous and non-stationary wavefield, with account for Stokes corrections and quasi-resonant windowing [e.g., *Annenkov and Shrira*, 2009]. In this context, it is worth mentioning that the Hasselmann interaction term does not depict all the nonlinear dynamics of wave trains/fields, such as, for example, Benjamin-Feir instability, i.e., nonlinear interactions of collinear waves.

[14] Also realistic is including the boundary layer models into wave models, in order to replace the wind-input parameterizations in foreseeable future. Such models as that of *Chalikov and Rainchik* [2011] are fast, accurate and capable to bring about explicit wind-wave exchange physics into the wave-forecast modeling. It should be also stressed in this context that the directional distributions of wind-input and whitecapping-dissipation functions are embedded in every third-generation model, but have never been measured apart from qualitative estimates of *Young and Babanin* [2006] for the dissipation term. For the fourth generation wave models, all these issues will be necessary to attend.

[15] Much more problematic would be explicit physics for wave breaking and whitecapping dissipation in spectral models. Unlike other sources/sinks, wave-breaking dissipation is an intermittent rather than continuous process, local in the physical space, and therefore by definition is subject to assumptions and approximations in the Fourier domain. As such, breaking can only be studied in the physical space. Even then, dynamic simulation of breaking-in-progress from the first principles is a formidable numerical task as it has to describe the two-phase fluid behavior, with air bubbles below and sea droplets above the mean interface. With the rapid growth of computer power, such dynamic wave models became available over the last decade [e.g., *Abadie et al.*, 1998; *Dalrymple and Rogers*, 2006; *Iafrati*, 2009; *Janssen and Krafczyk*, 2010; *Lakehal and Liovic*, 2011], but still they are only capable of simulating only a few periods of wave evolution.

[16] In this regard, one-way coupling of these models with outputs of potential models based on non-stationary conformal mapping could be a very practical scenario. Such models [*Chalikov and Sheinin*, 1998, 2005; *Zakharov et al.*, 2002] deliver the highest accuracy in simulating fully nonlinear one-dimensional surface wave trains, combined with very low computational cost over hundreds and even thousands of wave periods. Since the potential theory provides an accurate description of wave motion in most of physical scenarios (but notably, not in the case of wave-turbulence production), then such coupling could solve majority of the problems of surface wave dynamic simulations.

[17] This brings us to the main difference between the present state of the wave research and the previous era. While of course the physical experiment remains the ultimate truth and the analytical theory provides explicit understanding of the physical phenomenon, numerical modeling these days took on an essentially new function. Provided that the physics of the model is well defined and the limits of the model are well understood, it can play a role of a laboratory tank with unlimited number of sensors and probes in every location in space and at any moment in time, and of an analytical tool to scrutinize known features and discover new phenomena. In this regard, to simulate the oceanic waves, three-dimensional models of potential, rotational and two-phase wave surfaces are needed and they are under development and rapidly becoming available [e.g., *Perignon et al.*, 2011].

3. Wave-Coupled Effects in Lower Atmosphere and Upper Ocean

[18] The wave-coupled effects were singled out the previous Section on the current status and future perspectives of the wave research, because they bring the wave modeling into uncharted waters of large-scale and long-term simulations of the climate and general oceanic circulation. Here, 'large-scale' means large by comparison with the scale of wind-generated waves. Weather and climate are phenomena of very different scales (days and years or even longer in time, hundreds of kilometers and global in space). Both scales, however, are much larger with respect to the scale of ocean surface waves (seconds in time and hundreds of meters in space).

[19] It is rapidly becoming clear that many large-scale geophysical processes are essentially coupled with the surface waves, and those include climate, weather, tropical cyclones and other phenomena in the atmosphere and many issues of the upper-ocean mixing below the interface. Basically, as was pointed out by our reviewer, local wave effects produce teleconnections in the large-scale oceanic and atmospheric system. Besides, the wind-wave climate itself experiences large-scale trends and fluctuations, and can serve as an indicator and moderator for changes in the weather climate [*Wentz et al.*, 2007; *Young et al.*, 2011].

[20] So far, coupling of the wave-related air-sea interactions into weather and climate research has not been conducted due to two main reasons. In terms of geophysics, the reason is the 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 technical terms, the computational costs of such coupling have been prohibitive until recently, and are still very expensive.

[21] The fluxes, however, are not constant in the course of wave evolution, even if the wind is constant. They are determined by a great variety of wave-related properties which vary at the scale of hours [*Babanin and Makin*, 2008]. The lower time scale of weather phenomena is also of the

order of hours. For example, in tropical cyclones, the wave pattern is very complicated, depending on the cyclone's intensity, size, direction and speed of propagation, and cannot be represented by some average wavefield model [*Young and Burchell*, 1996; *Young*, 2006; *Moon et al.*, 2008]. If so, wave-induced effects on the cyclone evolution cannot be parameterized, and it appears necessary to know and model the wave properties explicitly at each step of cyclone development in order to predict its evolution and intensity accurately.

[22] Thus, modeling of the large-scale processes in the ocean-atmosphere system, without having explicit knowledge of the wave characteristics, has a limited capacity even if some average wave properties are taken into account parametrically. Here, we will concentrate on dynamic effects of waves in providing surface drag for the lower atmosphere boundary layer and in facilitating mixing in the upper ocean, but role of the waves is principal in air-sea gas exchanges, in aerosol production and in other dynamic, thermodynamic and chemical exchanges across the interface (see, e.g., *Babanin* [2011] for a review).

[23] The air-sea coupling in the general circulation models is usually parameterized in terms of the drag coefficient C_d as a function of wind speed, but the scatter of experimental data around such dependences is very significant and has not improved noticeably over the past 30 years. Reality is such that it is not the wind speed, but the momentum and energy fluxes determine such coupling. The drag coefficient, should it be constant or a simple function of known properties, would allow us to convert the mean wind speed which is an output of large-scale atmospheric models into the momentum flux. The sea drag, however, is not and cannot be described by some simple coefficient because it is determined by the structure and physics of the boundary layer and of the surface waves. Therefore, although it does depend on the mean wind speed, it exhibits a very large scatter if measured in different circumstances under the same wind speed. And this scatter cannot be removed through accurate and precise measurements.

[24] *Babanin and Makin* [2008] suggested a complex approach to the problem. They argued that a list of physical properties and phenomena, whose effect on the sea drag should be investigated and incorporated in the final parameterization to reduce the scatter, includes, among possible others, mean wind speed, sea state dependence, wave steepness, full flow separation for strongly forced wind waves, enhancement of sea drag due to wave breaking, rising and falling winds, gustiness of the wind, temperature stratification in the atmospheric boundary layer, swell, nonlinear wind-wave interactions, wave horizontal skewness and vertical asymmetry, variation of the wavy surface properties at wave group and wavelength scales, wave directionality, wave short-crestedness, coupled effects in the air/sea boundary layers. An additional separate item would be that due to peculiarities of air-sea interaction at extreme wind-forcing conditions which include an entire set of new features irrelevant or insignificant at moderate winds. And this list, already extensive, does not include properties and processes which breach validity of the constant-flux-layer approximation, e.g., non-homogenous or non-stationary conditions, as in such circumstances the notion of the drag coefficient becomes uncertain [*Komen et al.*, 1994, chapter I.3]. Since a significant number of large-scale processes in the atmosphere disrupt the constant-flux physics, parameterizations for the drag coefficient are bound to have some residual scatter.

[25] In order to reduce this scatter, the multiple mechanisms contributing into the sea drag, are to be singled out, studied separately, evaluated and then reunited in a joint parameterization for C_d. This is a formidable and complicated task, unnecessary if coupling of the wave models with the boundary layer models is conducted directly. As a result of such coupling the fluxes at the ocean surface can be obtained explicitly, depending on the wind speed outside the boundary layer, on the dynamics and thermodynamics of the boundary layer, and on the wavefield on the ocean surface.

[26] Even less attention by comparison, have been paid by the large-scale modelers to the role of the waves in the upper-ocean mixing. If at all, it is usually attributed to the wave breaking and is parameterized through the surface fluxes of the energy and momentum. Physically, the wave-breaking turbulence penetrates the water depth at the scale of wave height and then needs to be diffused down in order to participate in the ocean mixing [e.g., *Chalikov and Belevich*, 1993; *Craig and Banner*, 1994].

[27] In the meantime, the non-breaking wave turbulence have been known for the long time to be depth-distributed at the scale of wavelength [*Phillips*, 1961; *Kinsman*, 1965; *Benilov et al.*, 1993; *Qiao et al.*, 2004; *Babanin*, 2006], it was measured in the laboratory [e.g., *Babanin*, 2006; *Dai et al.*, 2010] and estimated in the field [*Yefimov and Khristoforov*, 1971a; *Huang et al.*, 2008]. The wavelength scale is of the order of 100 m and is comparable with the mixed layer depth. Therefore, such turbulence does not need additional assumptions, diffusion or advection in order to mix the seasonal ocean layer through the thermocline below.

[28] In this regard, a key step in linking this knowledge to the ocean mixing models is to express the non-breaking wave-induced vertical mixing analytically, as a function of wave spectrum which can be estimated from a coupled wave numerical model [*Qiao et al.*, 2004, 2010; *Pleskachevsky et al.*, 2011]. Then turbulence production due to waves has been successfully used in climate, ocean-circulation, sediment suspension models, with significant improvements to the simulations of the respective properties. As we know, the shear-induced mixing has been regarded as the main source of vertical mixing, this understanding may need to be revised.

[29] Since the upper ocean mixed layer is the flywheel of climate system, feedback of the wave mixing on climate models is also very significant. It can even potentially assist the common problems of climate models such as the tropical bias and the ENSO periodicity [*Huang et al.*, 2008; *Babanin et al.*, 2009; *Song et al.*, 2011].

[30] Therefore, in order to advance quality of the large-scale modeling, it is necessary to couple respective models with ocean-wave models. For example, tropical cyclones generate large waves which enhance the upper-ocean mixing and thus involve deeper layers of the ocean water and can essentially change sea surface temperature (SST) in the course of cyclone development [e.g., *Wang and Qiao*, 2008]. Since SST is the key input property to the cyclone energy source, such mixing can subsequently affect its intensity or even genesis. As mentioned above, the wave heights and

periods are very non-uniform over the hurricane area [*Young and Burchell*, 1996; *Young*, 2006], and thus it can be expected that mixing and SST alterations vary across the area, a fact which has indeed been observed [*Pudov et al.*, 1979]. Since dynamical hurricane-intensity forecasting has only been improving slowly over recent decades, in spite of improvements in atmospheric models of tropical cyclones, it can potentially be expected that coupling the hurricane air-sea physics with waves will provide a necessary leap in understanding of this physics and in tropical cyclone forecasting. Furthermore, in the context of tropical cyclones the waves control the saturation of the sea drag at extreme winds [*Powell et al.*, 2003; *Jarosz et al.*, 2007]. They play major roles in air-sea gas exchange, in spume production, and the processes for these exchanges transforms in hurricane conditions [*Babanin*, 2011].

[31] Similar effects take place in the climate processes. Although the scales are different, the physics with respect to wave-coupled effects is basically the same. The global wave climate exhibits wave-height growing trends over the last 20 years, both in the mean and in its extreme [*Young et al.*, 2011], which needs understanding of its driving forces, but in turn should associate with deepening the mixed layer and thus increasing the heat absorption. Besides, changes of the ocean circulation caused by the wave-induced mixing provide feedback on the atmospheric circulation and are a likely cause of some observed variations of large-scale atmospheric phenomena. Implementation of this wave-turbulence mixing in climate models leads to significant impacts, as mentioned above, both on the atmospheric side [*Babanin et al.*, 2009] and in the ocean [*Huang et al.*, 2008; *Qiao et al.*, 2010; *Song et al.*, 2011].

[32] Currently, such wave-induced mixing and the respective ocean-to-atmosphere feedback mechanism are missing entirely in the ocean-circulation, tropical-cyclone, weather and climate models. Since this is a physical phenomenon of importance, future modeling efforts will inevitably include its simulations, and in order to do so explicit knowledge of the waves in every particular situation, and therefore coupled wave-ocean-atmosphere modeling will be needed.

4. Summary

[33] This article introduces the Special Issue of the *Journal of Geophysical Research* on Surface Waves and Wave-Coupled Effects, based largely on the respective session of the General Assembly of the European Geosciences Union held in 2011 for the first time. Interest to the topic is apparent as similar sessions are now organized in other scientific gatherings round the world, such as those by the American Geophysical Union and the Australian Meteorological and Oceanographic Society.

[34] In the article, a brief review of the ocean wave topic is offered, both in historic and future context. While the topic is not new, its physics is so complicated that many scientific issues remain outstanding and new issues appear, such as physics of rogue waves and its similarity to the rogue-wave events in other nonlinear dispersive physical media. Many such issues have been outlined here, others remain outside this review, for example, remote sensing of the ocean waves.

[35] Modeling the ocean waves with the purpose of their forecast is now undergoing a surge of attention since the new physics of wind-wave generation, wave-breaking dissipation and swell attenuation has been discovered and new detailed experimental guidance has become available. It is argued that the fourth generation of these spectral models is also foreseeable, when the parameterizations of the energy source functions will be replaced by their physical modeling.

[36] Discussion of the dynamic modeling of the surface waves points out that such modeling takes on a new role in the modern circumstances. New computing capacities and advances in physics and mathematics allow us to use basic equations for simulating wave evolution. Thus, the dynamic modeling is effectively taking on and expanding the function of the laboratory experiments and field observations.

[37] Most important in our view, however, is the conclusion that the wave simulations need to be coupled into large-scale air-sea models, from weather and all the way to climate scales. Such models, in spite of the apparent progress in their development, seem to have been reaching saturation in their performance and still unable to reproduce observed air-sea-interaction phenomena such as the ENSO cycle and tropical-cyclone intensity, among others. There is an apparent need for additional physics for such models, and coupling with the waves does offer such physics.

[38] As discussed in the article, the waves essentially affect the dynamics and thermodynamics both of the atmospheric boundary layer and of the upper ocean, which in turn define the air-sea interactions at scales larger than wave periods and storm duration. Besides, the waves and surface winds have been growing globally, both in the mean and in their extremes. Thus, it is feasible that wave-ocean-weather-climate coupling will be one of the main thrusts of the wave research in the coming decades.

[39] In conclusion, we will group the papers of this special issue by their topics in order to identify the themes which attract attention of the ocean wave community today. With the ocean-wave science being a mature research field, time is apparently ripe for analysis and reviewing the past and the future perspectives of wave research and its methods as such. Apart from this introductory article, another review paper, on issues of the wave theory from the beginning to the present-days, is presented [*Yuan and Huang*, 2012] and one paper suggests a novel technique of wave measurements and observations, by means of seismogram records [*Ardhuin and Roland*, 2012].

[40] The mainstream research of ocean waves forms a group of five papers. *Chabchoub et al.* [2012a] investigated rogue waves which are represented by deep troughs (holes in the water) rather than steep crests (walls of the water). *Chabchoub et al.* [2012b] continued the topic of the rogue waves, by observing the Peregine solution for the water waves in a tank and confirming that for these water waves the observed spectrum has the general triangular form. *Stiassnie* [2012] offered a new analytical solution for the old problem of fetch-limited wave evolution. A new dissipation term for spectral wave models, capable of describing the dissipation in the general case, from deep water all the way to surf zone was suggested by *Filipot and Ardhuin* [2012]. *Badulin and Grigorieva* [2012] investigated the traditional topic of separation of swell and wind seas, and suggested

criteria based on the theoretical concept of self-similar wind-driven wavefields.

[41] Wave modeling is represented by five papers. *Donelan et al.* [2012] developed a new full spectral model, which accommodates the physical constraints based on observed wind stress, and tested it in a variety of conditions including hurricanes. In some way this article is connected to the topic of extreme weather conditions which forms another group of papers described below. *Cavaleri et al.* [2012] use WAM model to investigate an accident in the Mediterranean Sea where a cruise ship was hit presumably by a rogue wave, and indeed show that the rogue wave solution for the sea state at the time is feasible. This paper has an apparent connection to the topic of rogue waves mentioned above. Three other papers deal with wave-current interactions, that is effectively with coupling the traditional wave modeling with models of other phenomena in the ocean. *Van der Westhuysen et al.* [2012] applied SWAN model to tidal inlets of the Wadden Sea and achieved improvements in the model terms for wave-current interaction, depth-induced breaking and wave propagation. *Roland et al.* [2012] used WAVEWATCH-III and a 3D current model to produce a coupled wave-current interaction model. M. A. Dutour-Sikiric et al. (Hindcasting the Adriatic Sea near-surface motions with a coupled wave-current model, submitted to *Journal of Geophysical Research*, 2012) used such model to hindcast near-surface circulation at the Adriatic Sea.

[42] Similarly to the wave modeling, the traditional topic of wave statistics takes on new issues investigated by new, remote-sensing means. *Young et al.* [2012] uses the altimeter database of *Zieger et al.* [2009] to study the trends in extreme value return period for wind speeds and wave heights. For the 100-year return period of the wind, trend is positive. A. Mironov et al. (Statistical characterization of short wind waves from stereo images of the sea surface, submitted to *Journal of Geophysical Research*, 2012) researched the statistics of very short waves. They used stereo imaging of the water surface to obtain data for such a rare application.

[43] Bulk of the Issue is dedicated to the wave coupled effects, both in the atmosphere and in the ocean. Five papers study the wind flow and wind stress over the waves, with further four – atmospheric wave boundary layer in extreme conditions. One more article investigates rogue waves in such severe circumstances.

[44] *Ting et al.* [2012] and *Toffoli et al.* [2012b] studied sea drag dependences, other than the traditional dependences of the drag on the wind. As was discussed in Section III, potentially sea drag can depend on very many properties in the boundary layer and on the ocean surface. *Ting et al.* [2012] demonstrated that, for a given wind speed, the sea drag can grow as much as 25% as a function of the wave directional spreading. Results of *Toffoli et al.* [2012a] indicate that the sea drag depends on water depth and wave steepness, which make the wave profile more vertically asymmetric, and on the concentration of water vapor in the air, which modifies air density and friction velocity. *Druzhinin et al.* [2012] suggest a numerical algorithm to conduct direct numerical simulations of the wind flow over steep waves. They demonstrate the flow separation and over features known from observations, and provide comparisons with an analytical quasi-linear model of wind-wave interactions. *Zavadsky and Shemer* [2012] took a detailed look at very young waves in a laboratory tank. Their fine measurements produce results on the vertical extent of wave-induced boundary layer in the air, on the phase relation between the wave-induced velocity fluctuations and the surface elevation, on the wave-induced Reynolds shear stress at very early stages of wave development. *García-Nava et al.* [2012] investigated effect of swell on wind stress at strong winds and found that in such conditions swell suppresses short waves and leads to a reduction of the sea drag. This paper links the research of wave effects in the boundary layer to the group of papers dedicated to such effects at extreme weather conditions as well as to the topic of wave effects in the atmosphere, such as *Rutgersson et al.* [2012] as described below.

[45] The environmental extremes have been gaining significant attention over recent years, and this topic is well reflected in the current special issue. Papers by *Soloviev et al.* [2012], *Liu et al.* [2012], *Holthuijsen et al.* [2012] are dedicated to air-sea interface and boundary layer in the hurricane-like conditions. Specifically, *Liu et al.* [2012] suggested a new parameterization for wind stress which takes into account the spray effects in the boundary layer and is able to describe the sea drag across all weather conditions, from low- to hurricane-like winds and agrees with the available observations. *Holthuijsen et al.* [2012] offered explanations of the spray effect, i.e., breaking of the large waves produces foam-like spray which smooths the surface roughness. Important observations of this paper are the different magnitudes of sea drag in different parts of the hurricane footprint. *Troitskaya et al.* [2012] conducted laboratory measurements of air-sea interactions under such extreme conditions and also found the saturation of sea drag. They, however, were able to explain their observations by means of aerodynamic theory only, without having to invoke the effects of spray. Article by *Mori* [2012] has links with the groups of papers on rogue waves and on wave modeling above and with the paper by *Holthuijsen et al.* [2012] above. It investigated likelihood of freak waves in typhoons and found that they are most likely in the fourth quadrant of the tropical cyclone due to resonant four-wave interactions, that the sea state in typhoon is characterized by two wind-wave systems and that because of this the cross seas are expected behind the eye of the typhoon.

[46] The topic of wave-induced oceanic turbulence is also gaining the attention, with four papers dedicated to such turbulence explicitly and further four to large-scale mixing due to this turbulence. *Benilov* [2012] offered a framework of the most general importance for the topic. The ocean is always turbulent, and his results show that pre-existing three-dimensional turbulent vortexes are unstable with respect to the wave orbital motion in the planes perpendicular to the plane of the orbit. *Babanin and Chalikov* [2012] developed a numerical model for such turbulence. The model is based on full two-dimensional (x-z) equations of potential motion with the free surface in cylindrical conformal coordinates, and the non-potential motion is described directly with 3D Euler equations, with very high resolution. *Savelyev et al.* [2012] conducted laboratory measurements of such turbulence combined with numerical modeling by means of *Babanin and Chalikov* [2012] model. Turbulent velocities at the water surface were measured using the

thermal-marking velocimetry technique, the turbulence was found to be anisotropic and the turbulent kinetic energy is a function of time, wave steepness, wave phase and initial turbulent conditions. To complete this group of the papers, *Huang et al.* [2012a] measured the wave-induced turbulence in field conditions in the South China Sea. The measurements were conducted by a free-falling MSS profiler, and in deep water the profile of the dissipation rate within the mixed layer generally exhibited an exponential decay with the depth, in accordance with theoretical expectations.

[47] *Qiao and Huang* [2012] conducted direct comparison of the upper-ocean mixing due to vertical shear of the mean currents, the mechanism which is routinely attributed with such mixing, and the surface wave-induced mixing. Based on a series of numerical experiments and comparisons with realistic temperature profiles they concluded that the surface wave-induced mixing is dominant, and the ocean circulation model can perform well even without the shear-induced mixing due to the mean current. *Toffoli et al.* [2012a], *Huang et al.* [2012b] and *Song et al.* [2012] investigated particular phenomena and circumstances in the ocean and climate system when the wave-induced mixing was essential. *Toffoli et al.* [2012a] demonstrated effect of such turbulence on the mixed layer at the synoptic scale, in case of passage of the tropical cyclones, through observations in the Indian Ocean. The measurements also show that a considerable deepening of the mixed layer occurs during tropical cyclones, when the production of wave-induced turbulent kinetic energy overcomes the contribution of the current-generated shear turbulence, and the effects of a background current, atmospheric forcing, wave breaking are not on their own capable of justifying the observed deepening. *Huang et al.* [2012b] investigated the effect on the seasonal scale. They used four different models with two different mixing schemes and concluded that the addition of the wave-induced mixing to the turbulence production increased depth of the mixed layer in Southern Ocean summer up to 20 m, which trend is consistent with observations. *Song et al.* [2012] applied the phenomenon to processes of even a large scale – the well-known and most elusive for explanations tropical bias of the sea surface temperature. Their coupled atmosphere-wave-ocean general circulation model showed that on the ocean-basin scale the wave-induced vertical mixing can generate “West-Positive and East-Negative” pattern for the equatorial SST, the pattern which can reduce the tropical bias.

[48] Two more papers research other large-scale coupled effects due to waves in the system ocean and atmosphere. In the paper of *Janssen* [2012], the TKE equation includes production of turbulence due to wave breaking, as well as wave-induced turbulence and Langmuir turbulence, effects of buoyancy and turbulent dissipation. *Janssen* [2012] applied his scheme to the simulation of the daily cycle in SST at a specific location in the Arabian Sea and concluded that the dominant processes that control the diurnal cycle are the buoyancy production and turbulent production by wave breaking. *Rutgersson et al.* [2012] investigate effect of the wave mixing in the atmospheric boundary layer rather than in the ocean. Specifically, they show that surface waves propagating faster than the wind (swell) alter the surface exchange as well as turbulence properties in the atmosphere and conclude that the impact of swell waves on the mixing in the boundary layer is not insignificant and should be taken into account when developing wave-atmosphere coupled climate models. It is worth mentioning in this context that there are areas of the ocean where the wind climate appears to be dominated by such wave-driven winds [*Hanley et al.*, 2010].

[49] Finally, different kinds of waves are researched in the remaining two papers of the special issue. *Narapusetty et al.* [2012] explore influence of the weather noise in the tropical Pacific on the dynamics of tropical instability waves. *Gimbert et al.* [2012] study inertial oscillations of the ice cover in the Arctic which reveal ice weakening throughout the year over the last decade.

[50] In summary, the special issue of JGR on the ocean waves attracted a significant attention of the wave research community. This fascinating topic of oceanography continues to draw attention to numerous unresolved and new problems of its complex physics. Lately, this community also ventured into the new areas of importance, coupled effects due to ocean waves in the atmosphere and the ocean which are essential in the context of large-scale modeling and are gaining significant momentum.

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