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TSA - A Two Scale Approximation for Wind-Generated Ocean Surface Waves

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LONG-TERM GOALS

(a) To provide an accurate, efficient, computational model (two-scale approximation, TSA) for the 4-wave interactions, in operational wave forecast models, suitable for global, basin and coastal scale applications, and able to transition seamlessly from deep to shallow water.

(b) Fully test TSA with respect to exact codes for the full Boltzmann integral (FBI), for duration-limited, fetch-limited wave growth, turning winds, swell-windsea, interactions, etc.

(c) Numerically investigate and clarify the basis for TSA, its limitations, errors, enhancements, improvements, self-similarity properties, and spectral flux properties.

(d) Implement TSA in a variety of modern operational wave forecast models, e.g. WAVEWATCH^{TM} (WW3) and SWAN for extensive tests on important, realistic wave conditions.

(e) Derive, adapt and implement new formulations for source terms, S_{in} and S_{ds}, from recent literature and the NOPP partnership, with TSA, in modern wave models, for tests, including veering or accelerating winds, sea and swell interactions, and real storm cases.

OBJECTIVES

For this reporting period:

1) To formulate a relatively extensive set of reference spectra with corresponding FBI results, in order to facilitate definitive comparisons with TSA, and to lead to better understanding of limitations and areas in need of improvement in the TSA formulation.

2) Results for TSA (in comparison with FBI) for directionally varying spectra, rapidly veering wind conditions and other difficult spectral cases where the formulation may fail.

3) Preliminary implementation of TSA in WW3, re-structuring of code as necessary

APPROACH

The project initially needs to focus on TSA's performance with respect to the fundamental properties of the FBI (full Boltzmann integral) code.

1) **Reference spectra and FBI.** The spectral tests presented in Resio and Perrie (2008) and Perrie and Resio (2009) are limited and somewhat idealized. Further work is needed to develop a reasonable set of reference spectra and their corresponding FBI results, in order to facilitate more definitive comparisons for TSA. This would lead the way, in terms of clarifying numerical limitations of the present TSA formulation, and determination of areas where further development is needed. This activity is done by Resio (USACE), Long (USACE) and Perrie (BIO).

2) **Reference spectra for TSA.** How does TSA perform for directionally varying (sheared) spectra, for example in rapidly veering winds, compared to fundamental properties of the FBI code? Perrie and Resio (2009) show that this test is critical for TSA, using buoy data from hurricane Wilma. Clearly TSA has ability to reproduce results suggested by FBI, but in more extreme cases shows some evidence of divergence from FBI in critical tests. We will test difficult spectral cases, in order to clarify limitations of the present TSA formulation, and to determine areas where more TSA development and improvements are needed. This work is done by Resio (USACE), Long (USACE) and Perrie (BIO).

3) **TSA put into WW3.** We will make a preliminary implementation of TSA in the latest WW3 version. This is relatively straightforward because we have used versions of WW3 for many years in the Gulf of Maine Ocean Observing System - GoMOOS; moreover, it is preliminary in the sense that TSA is going to evolve and be enhanced, with bugfixes implemented, as required, becoming more optimal as the project progresses. This task is preparatory in laying the basis needed to implement TSA in operational wave models; and yet this work is fundamental, requiring re-structuring of the TSA code to comply with WW3 architecture. This work is done by Toulany (BIO), Auclair (BIO/ Dalhousie), Resio (USACE), Long (USACE), Perrie (BIO),.

WORK COMPLETED

Funding delays have occurred because policies were unclear regarding collaborative agreements that would be needed between Bedford Institute of Oceanography (Government of Canada) and ONR. These difficulties are now largely resolved. The project will move ahead on schedule, because work was completed using leveraged funds from a complementary Canadian Government project funded by the Panel on Energy Research and Development which is ending on 31 March 2011.

1) **Reference spectra and FBI.** The pioneering work of Zakharov and Filonenko (1966) showed that nonlinear wave-wave interactions produce stationary solutions related to constant energy flux through the equilibrium range when a deep-water spectrum follows an f^{-4} form, as verified in numerical studies in which the directional spectra follows a constant angular spreading distribution. In *Resio et al.* (2010) we show that, although energy fluxes through such spectra remain essentially constant, momentum fluxes do not. Moreover, if the angular distribution of the spectrum is allowed to behave in a manner consistent with observations, both the energy fluxes and the momentum fluxes appear to remain constant through a major portion of the spectrum. Thus, it appears that the directional distribution of energy within wind wave spectra has adjusted to a form with non-

divergent nonlinear fluxes, suggesting that these fluxes likely play a very prominent role in the evolution of directional spectra during wave generation.

2) **Reference spectra for TSA.** A preliminary set of computations were completed showing how TSA performs for directionally varying (sheared) spectra, in rapidly veering winds, and in swell-wave interaction situations, compared to fundamental properties of the FBI code. This activity extends basic cases considered by Perrie and Resio (2009) in using observed wave data from hurricane Wilma. We are able to show that TSA has ability to reproduce basic results suggested by FBI, even in very extreme cases. We will continue to test different spectral cases, in order to determine areas where TSA improvements are needed.

3) **TSA put into WW3.** We have made a preliminary implementation of TSA in the latest WW3 version (3.14). This activity has involved construction of the diagonal term (WAMDIG, 1988) needed for the implicit integration used by WW3. Preliminary results are shown in Figure 1 below. These results are encouraging, in that we can generate wave grow curves that act reasonably, although the other source terms for wind input and dissipation have not been tuned to TSA. Additional work needs to address outstanding issues.

RESULTS

a) In *Resio et al.* (2010) we examine nonlinear fluxes of energy and momentum through wave spectra via an exact integration of the full Boltzmann integral (the WRT method). Conclusions are:

   i. The bimodal structure observed in studies of the directional distributions of wind-wave spectra (Wang and Hwang, 2001; Long and Resio, 2007; Toffoli *et al.*, 2010) is relatively consistent with the $\cos^{2n}$ angular distributions, at least in a bulk sense, as derived in earlier field studies.

   ii. Spectra with a bimodal distribution of energy consistent with recent observations give relatively constant fluxes of both energy and momentum through the equilibrium range which suggests that the role of nonlinear interactions is quite critical to the directional evolution of wave spectral.

   iii. Nonlinear momentum fluxes from the spectral peak region through the equilibrium range, from a numerical solution to the Boltzmann integral, agree well with the expected momentum balance.

b) In studies of reference spectra and TSA, we showed that for directionally varying (sheared) spectra, in rapidly veering winds, and in swell-wave interaction situations, compared to fundamental properties of the FBI code, TSA has ability to reproduce basic results suggested by FBI, even in very extreme cases. We will continue to test different spectral cases.

IMPACT/APPLICATIONS

This project is concerned with TSA. The rationale for this project is that nonlinear 4-wave interactions, represented by FBI, have been shown to be central to wave forecast models since Hasselmann (1962) and Zakharov and Filonenko (1966), and accurate numerical formulations have been demonstrated, by Resio and Perrie (2008), and Resio *et al.* (2001), for finite depths. However, these formulations for the FBI are too slow for operational wave forecasting. The discrete interaction approximation, or DIA (WAMDIG, 1988) is the basis for operational wave models, such as WW3 and SWAN. Although DIA

is calibrated to agree with the FBI for the forward face of the spectrum, e.g. with peakedness $\gamma = 3.3$, it deviates substantially elsewhere within the spectrum. On the other hand TSA offers a new approach to this problem. TSA is presented by Resio and Perrie (2008), and Perrie and Resio (2009). It outperforms DIA in accuracy, with respect to exact FBI results, and it has run times that are on the scale of run times for DIA; therefore TSA is a candidate for implementation in WW3 and SWAN.

RELATED PROJECTS

A related project is funded by the Canadian Panel on Energy Research and Development entitled "Waves and Winds in Extreme Storms". It's focus is development of a) new wave model physics, b) improved wind and waves estimates from better atmosphere-ocean coupling, c) improved models for wave-current interactions, d) development of a versatile prototype wave forecast system, e) estimates of biases in wind and wave climatologies. This project is ending on 31 March 2011.

REFERENCES

Hasselmann, K., 1962: On the non-linear energy transfer in a gravity wave spectrum, part 1, General theory, *J. Fluid Mech.*, *12*, 481-500.

Long, C.E, and D. Resio, 2007: Wind wave spectral observations in Currituck Sound, North Carolina, *J. Geophys. Res.* 112, CO5001.

Perrie, W., and D. Resio, 2009: A Two-Scale Approximation for Efficient Representation of Nonlinear Energy Transfers in a Wind Wave Spectrum. Part II: Application to Observed Wave Spectra. *J. Physical Oceanography*. Vol. 39, pages 2451 – 2476. DOI: 10.1175/2009JPO3947.1

Resio, D., and Perrie, W. A., 2008: two-scale approximation for efficient representation of nonlinear energy transfers in a wind wave spectrum. Part 1: Theoretical Development. *J. Phys. Oceanogr.* 38: 2801-2816.

Resio, D. T., C. Long, and W. Perrie, 2010, The Effect of Nonlinear Fluxes on Spectral Shape and Energy Source-Sink Balances in Wave Generation. Submitted to *J. Phys. Oceanogr*.

Resio, D. T., J. H. Pihl, B. A. Tracy, and C. L. Vincent, 2001: Nonlinear energy fluxes and the finite depth equilibrium range in wave spectra, *J. Geophys. Res.*, *106*, 6985-7000.

Toffoli, A., Onorato, M., Bitner-Gregersen, E.M. and J. Monbaliu, 2010: Development of a bimodal structure in ocean wave spectra, *J. Geophys. Res.*, 115.

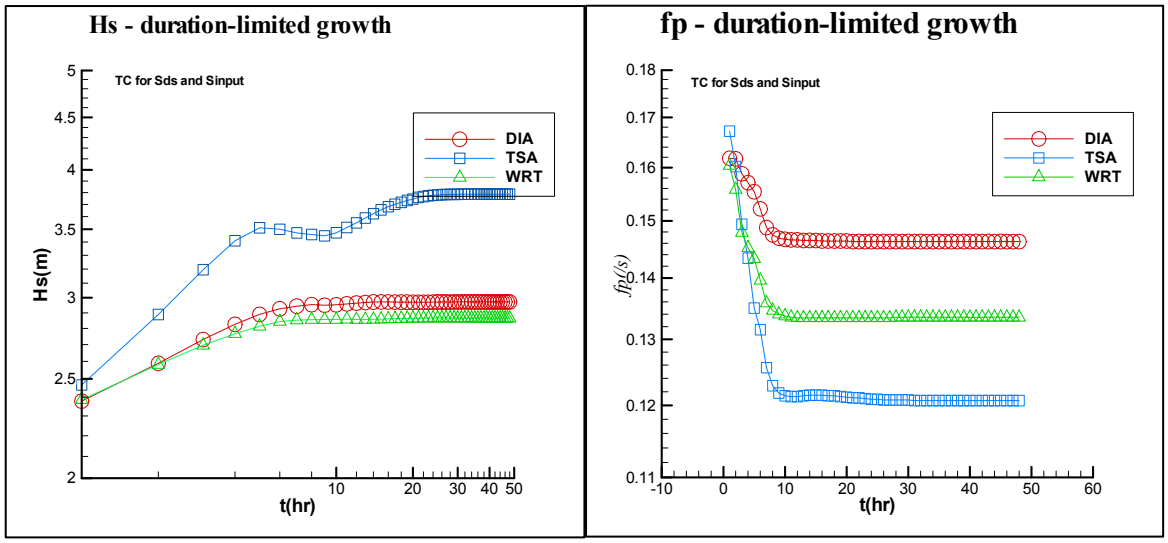
WAMDI Group (1988). The WAM model – a third generation ocean wave prediction model. *J. Phys. Oceanogr., 18*, 1775-1809.

Wang, D. W., and P. A. Hwang, 2001: Evolution of the bimodal directional distribution of ocean waves, *J. Phys. Oceanogr.*, *31*, 1200-1221.

Zakharov, V. E., and N. N. Filonenko, 1966: The energy spectrum for stochastic oscillation of a fluid's surface, *Dokl. Akad. Nauk.*, *170*, 1992-1995.

PUBLICATIONS

Resio, D. T., C. Long, and W. Perrie, 2010: The Effect of Nonlinear Fluxes on Spectral Shape and Energy Source-Sink Balances in Wave Generation. Under review for *J. Phys. Oceanogr.*



(a) (b)

Figure 1. Variation in (a) significant wave height Hs, and (b) peak frequency fp, as a function of time t, for an integration of TSA implemented in WW3 version 3.14, implemented in a square-ocean SWAMP test, compared to results using DIA and WRT for the nonlinear interactions.