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) Optimize the implementation of TSA in WAVEWATCHIII (WW3), using a recent WW3 model version, maximizing the efficiency, with verification tests of TSA codes using accepted source terms for wind input and dissipation (S_{in} and S_{ds}).

2) Derive new formulations for S_{in} and S_{ds}, based on first principles, theoretical, numerical and field studies, from recent published model studies and experiments, and make comparisons with source terms currently in use in the waves community, using WW3 as a template.

3) Conduct tests and verification studies using TSA and applying accepted S_{in} and S_{ds} formulations,

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as new formulations, implemented in WW3, using high-quality field data, fetch- and duration-limited tests, turning winds, marine storms, etc.

APPROACH

1) **TSA implemented in WW3.** Optimize and make the implementation of TSA in the operational model WW3 efficient, without loss of accuracy. Fully test the implementation of TSA in WW3. We will use the most recent available WW3 version, and make verification tests with accepted standard source terms S_{in} and S_{ds}. This activity is done by Perrie (BIO), Toulany (BIO), in consultation with Resio (UNF).

2) **New S_{in} and S_{ds} parameterizations.** Develop parameterizations for wind input and dissipation, S_{in} and S_{ds}, respectively. Do tests to compare with standard state-of-the-art S_{in} and S_{ds} formulations within WW3, and also use a relatively simple modern wave model, in comparisons with high-quality field data. The approach will build on first principles, as well as results from the waves community, in conjunction with recent theoretical, field, and numerical studies. This activity is done by Perrie (BIO), Toulany (BIO), and with collaboration with Resio (UNF).

3) **Tests with new S_{in} and S_{ds}.** In conjunction with the new formulation for TSA implemented in WW3, tests and verification studies will apply source terms for wind input S_{in} and wave dissipation S_{ds} formulations. Candidate formulations for S_{in} and S_{ds} include those newly developed here, and also those suggested by the NOPP partnership, and recent literature, as long as these formulations have progressed sufficiently so that they can fit the parameterization requirements for modern wave forecast models. Tests will use high-quality field data, fetch- and duration-limited tests, turning winds, etc., storm data. This activity is done by Perrie (BIO), Toulany (BIO), and with collaboration with Resio (UNF).

WORK COMPLETED

1) **TSA implemented in WW3.** Completion of this task required numerous test and innovative re-programming of TSA, in order to fit the architecture of WW3. This task has proven challenging. However, once completed, the same methodology can be repeated to implement TSA in other models such as SWAN and WAM, which have similar wave model architectures.

   a. A major challenge is that implementation of TSA within WW3 involved construction of the diagonal term for nonlinear wave-wave interactions for TSA (motivated by WAMDIG, 1988), which is required for the implicit integration which is used by WW3.

   b. Once TSA was implemented within WW3, there followed extensive testing. Tests included simple 1-point simulations, tests with simple square-box oceans, and real-storm cases, with actual winds, and comparisons with field data.

   c. Tests included simple duration-limited and fetch-limited growth curves, with orthogonal uniform constant wind fields. These simulations assume the WW3 default formulations for S_{in} and S_{ds}. TSA results are shown to compare well with observed data (e.g. JONSWAP, etc. and from the NOPP project). Results for fetch-limited growth comparisons are shown in Figure 1.

   d. Tests also involved turning winds, over a square-box ('SWAMP') ocean. This is a particularly difficult problem, motivated by examples such as the passage of a front or waves generated by a passing cyclone. This is important because the wind often turns in actual ocean situations, resulting in multiple peaked wave spectra. The problem is that TSA assumes a broad –scale term and a local – term, or perturbation term. Thus, with turning winds, the TSA formulation is not able to quickly respond to the new wind situation, and tends to persist in transferring energy to the previous wind direction. Thus, the response time can be too long.

e. To obtain reasonable results for turning wind conditions, we had to revise and re-organize TSA, to allow the initial "broad-scale term" to be applied more than one time, in order to handle double peaks in frequency spectra, and to let TSA downshift, appropriately. Thus, the required modification is to allow two or more broad-scale terms in the TSA formulation. In practice, we found that only two broad-scale terms in TSA is sufficient, and that additional terms did not provide significant benefit. This formulation has become denoted as the double broad-scale version of TSA, or 'dTSA'. In this manner dTSA is able to respond to changing wind situations. Results were shown to compare well with 'exact' FBI calculations.

2) **New S_{in} and S_{ds} parameterizations.** Development of new wind input and dissipation formulations, S_{in} and S_{ds}, is ongoing. Continuing tests are comparing model simulations and characteristics with baseline results and characteristics for well-known WW3 formulations for S_{in} and S_{ds}, such as WAM cycle3, Tolman/Chalikov physics, etc.

3) **Tests with S_{in} and S_{ds} in WW3, using TSA.** We showed that WW3 tested well with TSA implemented, compared to exact calculations of wave-wave interactions, using standard formulations for S_{in} and S_{ds}, using the WW3 model architecture:

a. We also implemented the revised version of TSA, denoted 'dTSA', in WW3 for tests with a storm case, hurricane Juan, which made landfall as a category 2 hurricane in 2003, causing wide-spread damage. Comparisons were made with the standard operational formulation of WW3 (using 'DIA' the discrete interaction approximation), as well as the 'exact' full Boltzmann integral (FBI) method to calculate the nonlinear wave –wave interactions, and also included buoy measurements of waves, collected along the storm track. Results from TSA were shown to compare favorably with buoy results, relative to results from implementations of either DIA or FBI. Results comparing wave spectra simulations are shown in Figures 2 and 3.

4) **Implementation of TSA in simple modern models.** To ensure that TSA is computationally efficient it must be re-formulated so that much of the computation occurs prior to the main time-stepping loops of the wave model code. This is an ongoing challenge, which is presently being pursued. This is meant to be the basis for development of simple numerically efficient operational wave forecast models using TSA.

RESULTS

a) We completed the study *Resio et al.* (2011) where we examine nonlinear fluxes of energy and momentum through wave spectra via an exact integration of the Full Boltzmann Integral, and show:

i. Bimodal spectra structures, as observed in studies of wind-wave spectra (Wang and Hwang, 2001; Long and Resio, 2007; Toffoli *et al.*, 2010), are consistent with exact calculations of nonlinear wave-wave interactions. These bimodal spectral features are consistent with the $\cos^{2n}$ angular distributions, as derived in earlier field studies.

ii. Energy spectra with a bimodal distribution that are consistent with observations give relatively constant fluxes of both energy and momentum through the equilibrium range which suggests that the role of the nonlinear interactions is critical to the spectrum's directional evolution.

b) In *Perrie et al.* (2012a), we implemented TSA into WW3 and completed a number of tests for fetch- and duration-limited wave growth, as well as real storm – wave comparisons with field data collected during hurricane Juan. Results compare well with observed data, and with simulations using the 'exact' FBI code in WW3. The real challenge has been turning winds, such as generated by a moving cyclone or hurricane, and the generalization of WW3 to accommodate spectral evolution in turning wind cases. This challenge was met by generalizing the manner in which the broad-scale of TSA was defined, developing 'dTSA' as described above, so that in complicated rapidly changing wave spectra cases, a second broad-scale term could be defined, in order to handle double peaks, and to let TSA downshift appropriately.

c) A testbed for further tests is presented in *Perrie et al.* (2012b), following model studies from the operational oceanography community. This study also gives further tests of 'dTSA' using data from a December 2012 nor'easter, showing further evidence (and weaknesses) of TSA's performance in simulation of actual storm-generated wave simulations. This testbed approach to inter-comparisons builds on related wave model studies, such as *Mulligan et al.* (2011), and *Xu et al.* (2012a).

d) In *Xu et al.* (2012b), we investigate modifications to standard formulations for shallow water wave dissiptaiton S_{ds}, in comparisons with shallow water wave data collected of the Mackenzie Delta during International Polar Year. Results suggest improvements for the standard S_{ds} formulation in these conditions.

IMPACT/APPLICATIONS

Nonlinear 4-wave interactions, represented by FBI (Full Boltzmann Integral) have been shown to be central to wave forecast models in studies since pioneering work by Hasselmann (1962) and Zakharov and Filonenko (1966). The accuracy of the TSA numerical formulation has been demonstrated by Resio and Perrie (2008), and Perrie and Resio (2009). Here, the impact and applications for this project is that, unlike FBI ('exact' full Boltzmann integrations) formulations, which are far too slow for operational wave forecasting, we are building versions of TSA that are relatively accurate compared to the present operational formulation for 4-wave interactions, DIA, and potentially can be made fast enough to be operational, to a much greater extent than is possible for FBI. Thus, TSA does offer a new potential approach to outperform and replace DIA, in accuracy and efficiency. With completion of the successful implementation of 'dTSA' in WW3, and run tests on hypothetical and real field tests showing success, this method is a candidate for further tests, and potentially increasing role in operational wave forecast models.

RELATED PROJECTS

A related project is funded by the Canadian Panel on Energy Research and Development entitled "Waves and Winds in Extreme Storms". Its focus is development of a) new wave model physics, b) improved wind and waves estimates using coupled atmosphere-ocean forecast models, c) improved models for wave-current interactions, d) development of a versatile prototype wave forecast system, e) estimates of biases in wind and wave climate studies. This project is ending on 31 March 2013.

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PUBLICATIONS

a. Articles in refereed publications

1. Mulligan, R.P., Perrie, W., Toulany, B., Smith, P. Hay, A.E., and Bowen, A.J., 2011: Performance of nowcast and forecast wave models for Lunenburg Bay, NS. *Atmosphere-Ocean*, 49(1), doi:10.1080/07055900.2011.558468. [published, refereed]
2. Resio, D., Long, C. and Perrie, W., 2011: The effect of nonlinear fluxes on spectral shape and energy source-sink balances in wave generation. *J. Phys. Oceanography*. 41, 781-801. DOI: 10.1175/2010JPO4545.1 [published, refereed]
3. Perrie, W., Toulany, B., Resio, D., and Auclair, J.-P., 2012a: A two-scale approximation for wave-wave interactions: Application in an operational wave model. Under review by *Ocean Modelling.* [refereed]
4. Perrie, W., Toulany, B., Chen, C. S., Beardsley, R., Roland, A., 2012b: Comparison of next generation model performance for waves generated by mid-latitude nor'easters. Submitted to *J. Geophys. Res.* [refereed]

5. Xu, F., Perrie, W., 2012a: Extreme Waves and Wave Runup in Halifax Harbour under Climate Change Scenarios. In press in *Atmosphere-Ocean.* DOI:10.1080/07055900.2012.707610. 14 pages. [published, refereed]
6. Xu, F., Perrie, W. and Solomon, S., 2012b: Shallow water dissipation processes for wind-waves off the Mackenzie Delta. Submitted to *Atmosphere-Ocean.* [refereed]

b. Conference Proceedings

1. Perrie, W., Toulany, B., Resio, D. and Long, C., 2011: Two-Scale Approximation for Full Boltzmann Integral in Turning Winds. *12th Internat. Waves Workshop*, Hawaii, 11p. [published]
2. Perrie, W., Guo, L., Long, Z. and Toulany, B., 2011: Impacts of Climate Change on Autumn North Atlantic Wave Climate. *12th International Waves Workshop*, Kohala Coast, Hawaii, 10 pages. [published]
3. Resio, D., Long, C. and Perrie, W., 2011: New source terms and the details of 'Detailed Balance', *12th International Waves Workshop*, Hawaii. Abstract only. [published].
4. Toulany, B. and Perrie, W., 2011: A super-regional test-bed to improve wave models Abstract only. *Canadian Meteorological and Oceanographic Society Congress*. Ottawa. [published].

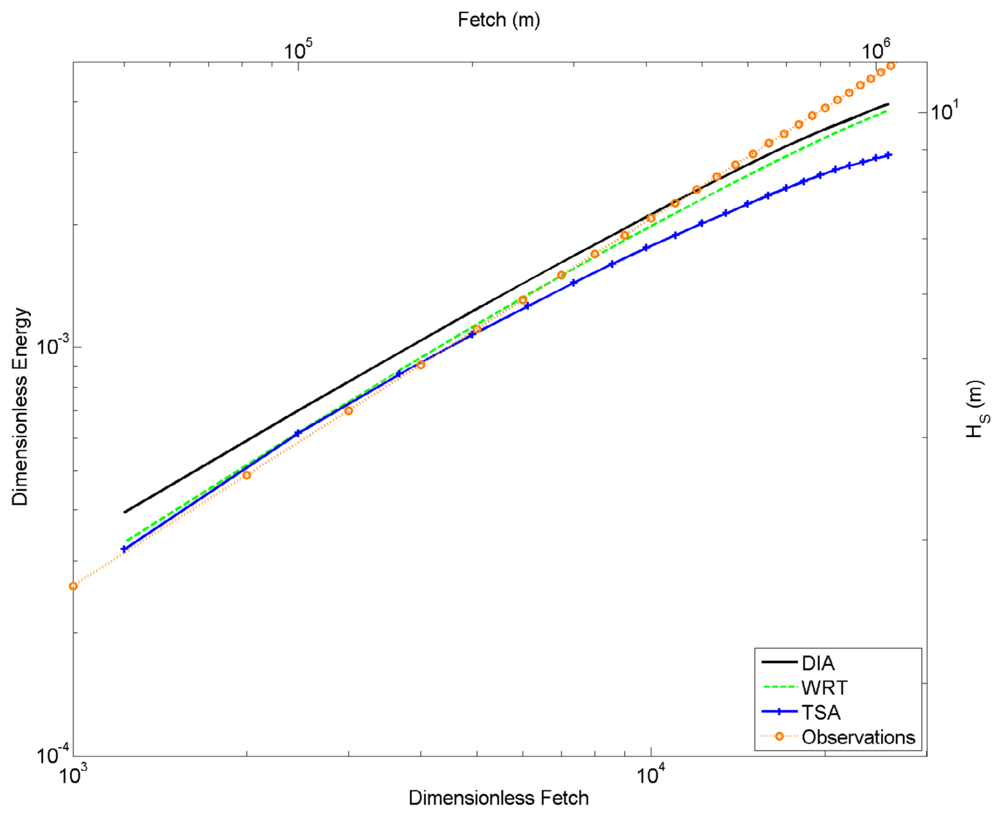
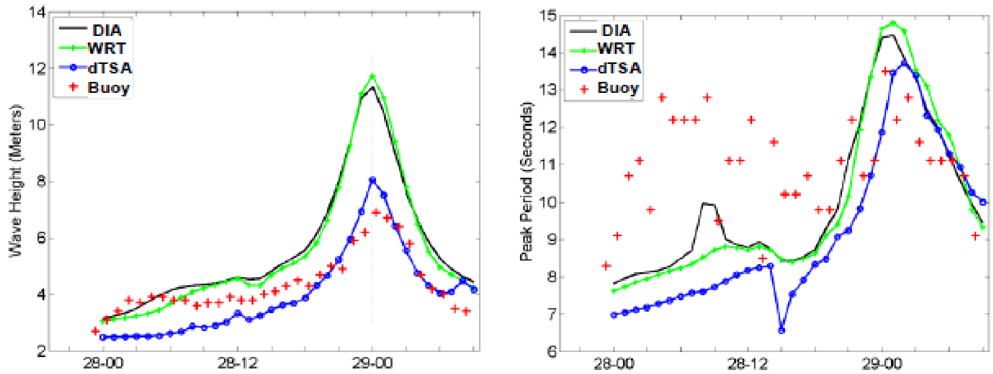
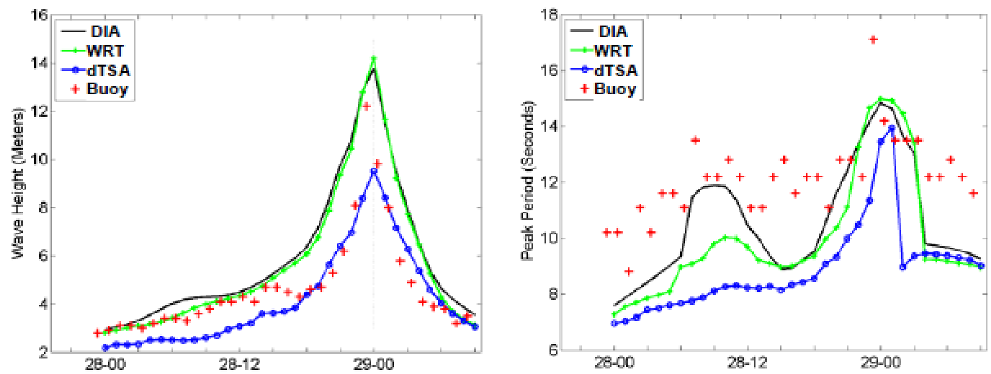


Figure 1. Growth curves for dimensionless energy $\tilde{E} = Eg^2/U_{10}^4$ as a function of dimensionless fetch $\tilde{x} = xg/U_{10}^2$, comparing results from formulations for S_{nl} given by: WRT, DIA, and TSA. Observations are the revised JONSWAP relations presented by Holthuijsen (2007).



(a) Buoy 44137



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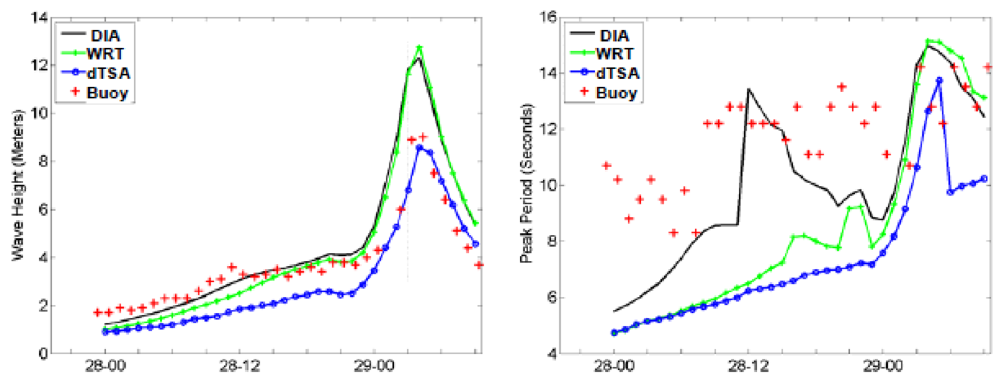
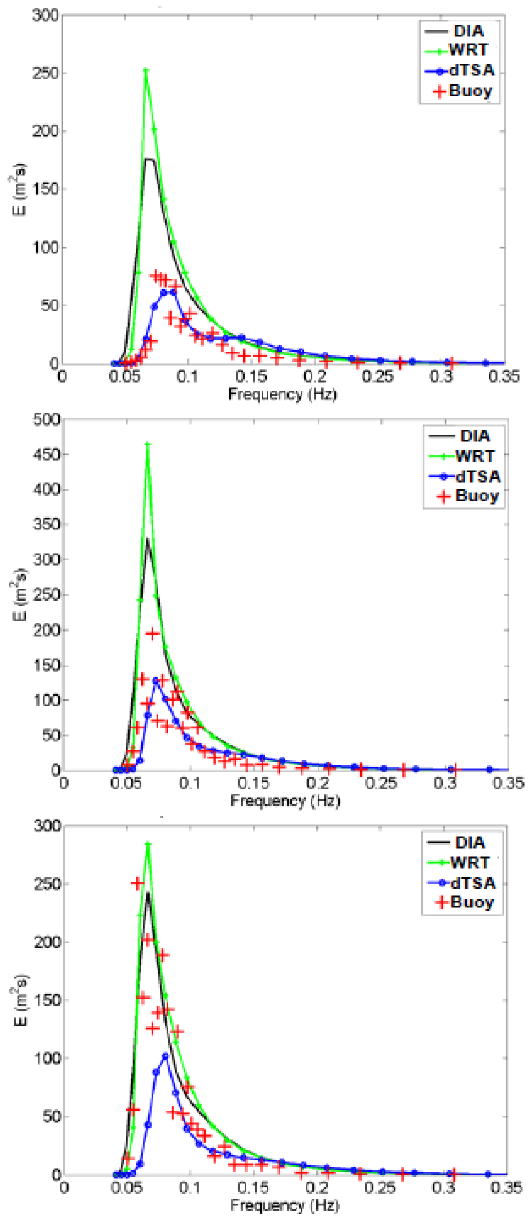


(c) Buoy 44258

Figure 2. Comparison of results from three formulations for S_{nl} with observed Hs and Tp data at three buoys along the track of hurricane Juan. The new formulation dTSA is used.



(a) Buoy 44137

(b) Buoy 44142

(c) Buoy 44258

Figure 3. As in Figure 2, comparison of results from three S_{nl} formulations, namely DIA, WRT also known as FBI, and the double TSA formulation, dTSA, to observed 1-d data at three buoys, at the peak of hurricane Juan, 0300 UTC on 29 Sept 2003.