

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. WAVEWATCHTM (WW3) and SWAN for extensive tests on important, realistic wave conditions.
- (e) Derive, adapt and implement new formulations for source terms, wind input S_{in} , and dissipation 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) Complete implementation of TSA in operational WAVEWATCHIII (WW3), with comparisons in terms of simulations with Full Boltzmann Integral (FBI) for wave-wave interactions.
- 2) Conduct standard tests including duration- and fetch-limited wave growth tests for TSA and FBI, using standard S_{in} and S_{ds} , as coded in WW3, e.g. WAMcycle3, Tolman/ Chalicov physics etc.
- 3) Begin the implementation of TSA in a simple reliable modern operational wave model, for example as developed in USACE, suitable for tests and development of new formulations for wind input and dissipation parameterizations.

APPROACH AND WORK PLAN

We need to do basic tests and comparisons. Thus, we need to exercise the TSA code in duration- and fetch-limited cases, and begin to address the issues related to S_{in} and S_{ds}

- 1) ***TSA put into WW3.*** Complete the implementation of TSA in WW3. This is essential in order to later perform a large set of tests (accelerating or veering winds, and combined sea/swell with varying separations of peak frequencies, etc., storm-generated waves; SWAMP, 1985) so that we can test TSA's behavior, with standard source terms S_{in} and S_{ds} available in WW3, and new formulations determined in this project, and compare results with implementations of TSA in a reliable modern relatively simple operational model, e.g. in USACE wave model (see below). This activity is done by Perrie (BIO), Toulany (BIO), and Resio (UNF).
- 2) ***TSA and duration- and fetch-limited growth.*** TSA will be tested against the FBI code and observed data (e.g. JONSWAP, etc.) for duration-limited and fetch-limited wave growth properties. For these tests, the model set-up would assume standard operational formulations for S_{in} and S_{ds} , for example as implemented in WW3, until new formulations for S_{in} and S_{ds} are available in the NOPP project. This test provides numerical estimates for TSA's abilities, providing guidance to understand TSA limitations, and areas where improvements need to be made. This activity is done by Perrie (BIO), Toulany (BIO), and Resio (UNF).
- 3) ***Numerical downshifting for TSA.*** Initial indications from Perrie and Resio (2009) are that TSA downshifting is similar to that of FBI, because TSA compares well to FBI in the forward face region of the spectrum. Further tests are needed. Duration-limited tests reveal TSA downscaling properties. Are accepted self-similar laws of spectral peak downshift evident for TSA in both swell and wind-wave cases? It is important that TSA give an accurate spectral downshift for wind-driven waves and swell, because this property is a key to determining spectral development and spectral energy growth relations in time. This activity is done by Perrie (BIO), Toulany (BIO), and Resio (UNF).
- 4) ***Implementation of TSA in modern simple models.*** We will put TSA in a reliable modern relatively simple operational (USACE) wave model. These types of models are much easier to work with than WW3, because of its operational parallelized architecture, but they are comparable in standard comparison tests. This implementation allows TSA to be tested thoroughly against a large set of important, realistic conditions (accelerating or veering winds, and combined sea/swell with varying separations of peak frequencies, etc.). This activity is done by Resio (UNF), Long (USACE), and Perrie (BIO).
- 5) ***New S_{in} and S_{ds} parameterizations.*** Preliminary development of new wind input and dissipation formulations, S_{in} and S_{ds} , will involve numerical simulations and tests, including USACE data. The approach will consider first principles, starting from Miles (1957) but develop applicable codes for actual random sea, in conjunction with recent theoretical results and observational data, for wind –waves and swell. Tests include comparisons with S_{in} and S_{ds} . This work is done by Resio (UNF), Perrie (BIO), and Long (USACE).

WORK COMPLETED

The project is moving ahead on schedule.

- 1) ***TSA put into WW3.*** This required innovative re-programming of TSA, in order to fit the architecture of WW3. However, now that this was completed, the same approach can be repeated from other models such as SWAN and WAM, having the similar wave model structure. This work activity has involved construction of the diagonal term for nonlinear wave-wave interactions (WAMDIG, 1988) needed for the implicit integration used by WW3.
- 2) ***TSA and duration- and fetch-limited growth.*** TSA tested well compared to FBI and DIA codes for nonlinear wave-wave interactions, in terms of simple duration-limited and fetch-limited growth curves, for cases of simple 1-point wave models, as well-as square-box SWAMP-type oceans,

with orthogonal constant wind fields. These simulations assume the WW3 default formulations for S_{in} and S_{ds} , which are the Tolman / Chalikov physics. Results compared well with observed data (e.g. JONSWAP, etc.) for duration-limited and fetch-limited wave growth.

- 3) **Numerical downshifting for TSA.** In simple cases, with constant winds, whether 1-point oceans, or square-box oceans with constant orthogonal winds blowing straight to the coast, results from TSA in WW3 are good. Initial results for more complicated results were less good, for example for turning winds, or the case of a cyclone moving across the ocean. To obtain reasonable results we had to generalize 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. Once these changes were made TSA results were found to compare well to FBI, and to observations. See Figure 1, as illustration.
- 4) **Implementation of TSA in modern simple 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 any wave model code. A preliminary version of this formulation has been coded and is presently being checked and tested. This is meant to be the basis for development of numerically efficient operational versions of TSA for implementation in forecast waver models.
- 5) **New S_{in} and S_{ds} parameterizations.** Preliminary development of new wind input and dissipation formulations, S_{in} and S_{ds} , has also been completed. Ongoing tests are underway, comparing model simulations and characteristics with baseline results and characteristics for well-known formulations, such as WAMcycle3, Tolman/Chalikov physics, etc.

RESULTS

The meaningful technical results achieved in this fiscal year are:

- a) In *Resio et al.* (2011) we examine nonlinear fluxes of energy and momentum through wave spectra via an exact integration of the Full Boltzmann Integral. 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) We implemented TSA into WW3 and completed a number of tests for fetch- and duration-limited wave growth. Results are acceptable and compare well with observed data, and runs, 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, so that in complicated rapidly changing wave spectra cases, a second broad scale could be defined, in order to handle double peaks, and to let TSA downshift appropriately.

IMPACT AND APPLICATIONS

National Security

Landfalling severe storms and hurricanes, like Katrina (2005) or Sandy (2012) generate large waves that cover the coastal and nearshore areas, causing significant damage and sometimes loss of life. Better understanding and forecasting of these storms and the ocean waves that they can generate, can serve to potentially reduce some of these problems. This project focuses on the task of obtaining better science-based parameterizations for ocean wave models, suitable for operational marine forecasting.

Economic Development

The coastal zone involves significant potential future economic development, e.g., residences, recreation, fisheries, aquaculture, coastal transportation. Better forecast, with longer lead-time, and better accuracy can help reduce potential risk to these economic developments, due to ocean waves.

Quality of Life

Development of the coastal zone involves residences, recreation, fisheries, aquaculture, coastal transportation. Ocean waves are a risk to these developments both from the possibility of storm – related damage, and also of anthropogenic factors, such as transport of pollutants, and lastly, future potential issues such as changing wave climate and wave impacts on these environments. All represent potential future impacts on Quality of Life, e.g., public and ecosystem health, resource management.

TRANSITIONS

The new parameterization, TSA, is being implemented and tested within WW3, the operational forecast wave model, in close cooperation with NOAA / NCEP colleagues. Tests include the latest formulations for the wind input S_{in} , and S_{ds} parameterizations, with hypothetical test cases, as well as real storm cases. Thus, the result should ultimately be easily useable in the operational forecast model in routine use by NOAA/NCEP.

RELATED PROJECTS

A related project is supported by the Canadian Panel on Energy Research and Development (PERD) on ‘Waves and Winds in Extreme Storms’. Its 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. It benefits from the basic core work done in this NOPP project to improve the nonlinear wave-wave interactions for S_{nl} . This NOPP project benefits from the broader ranging activities coupling operational forecast models to the ocean currents and the atmospheric drivers. Another notable PERD project, also supported by related Canadian Space Agency funding, is ‘All-weather remote sensing of waves, winds, surface currents and oil’, and looks at high resolution (~ 1km) SAR (synthetic aperture radar) from RADARSAT-2 to retrieve marine winds and waves. This data can be used in wave model tests and validation.

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PUBLICATIONS

a. Articles in refereed publications

1. Kuang, H., W. Perrie, T. Xie, B. Zhang, W. Chen, 2012: Retrievals of sea surface temperature fronts from SAR imagery. *Geophys. Res. Lett.*, **39**, L10607, doi:10.1029/2012GL051288. [refereed]
2. Long, Z., W. Perrie: Air-sea interactions during an Arctic storm. In press *J. Geophys. Res.* [refereed]
3. 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]
4. 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]
5. 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]
6. Perrie W. + 12 others, 2012: Selected topics in Arctic atmosphere etc. In press *Clim. Change*. [refereed]
7. 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]
8. 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]
9. Xu, F., and W. Perrie, 2012: Extreme Waves and Wave Runup in Halifax Harbour under Climate Change Scenarios. In press in *Atmosphere-Ocean*. [refereed]
10. Xu, F., W. Perrie, W. and S. Solomon, 2012: Shallow water dissipation processes for wind-

waves off the Mackenzie Delta. In revision for *Atmosphere-Ocean*. [refereed]

11. Zhang, B. and W. Perrie, 2012: Cross-Polarized Synthetic Aperture Radar: A New Potential Technique for Hurricanes. *Bull. Amer. Meteorol. Soc.*, vol. 93, no. 4, pp. 531-541. [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].

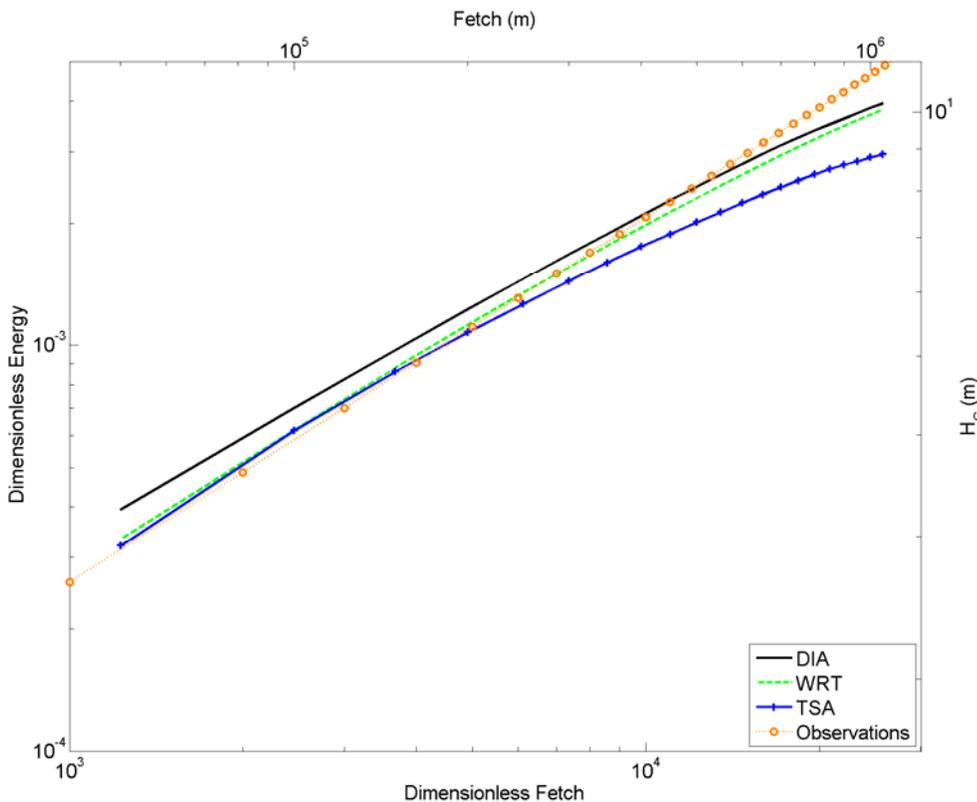


Figure 1. Growth curves for dimensionless energy $\tilde{E} = Eg^2/U_{10}^4$ as a function of dimensionless fetch $\tilde{x} = xg/U_{10}^2$, comparing results from formulations for S_{nl} given by: WRT, DIA, and TSA. Observations are the revised JONSWAP relations presented by Holthuijsen (2007).

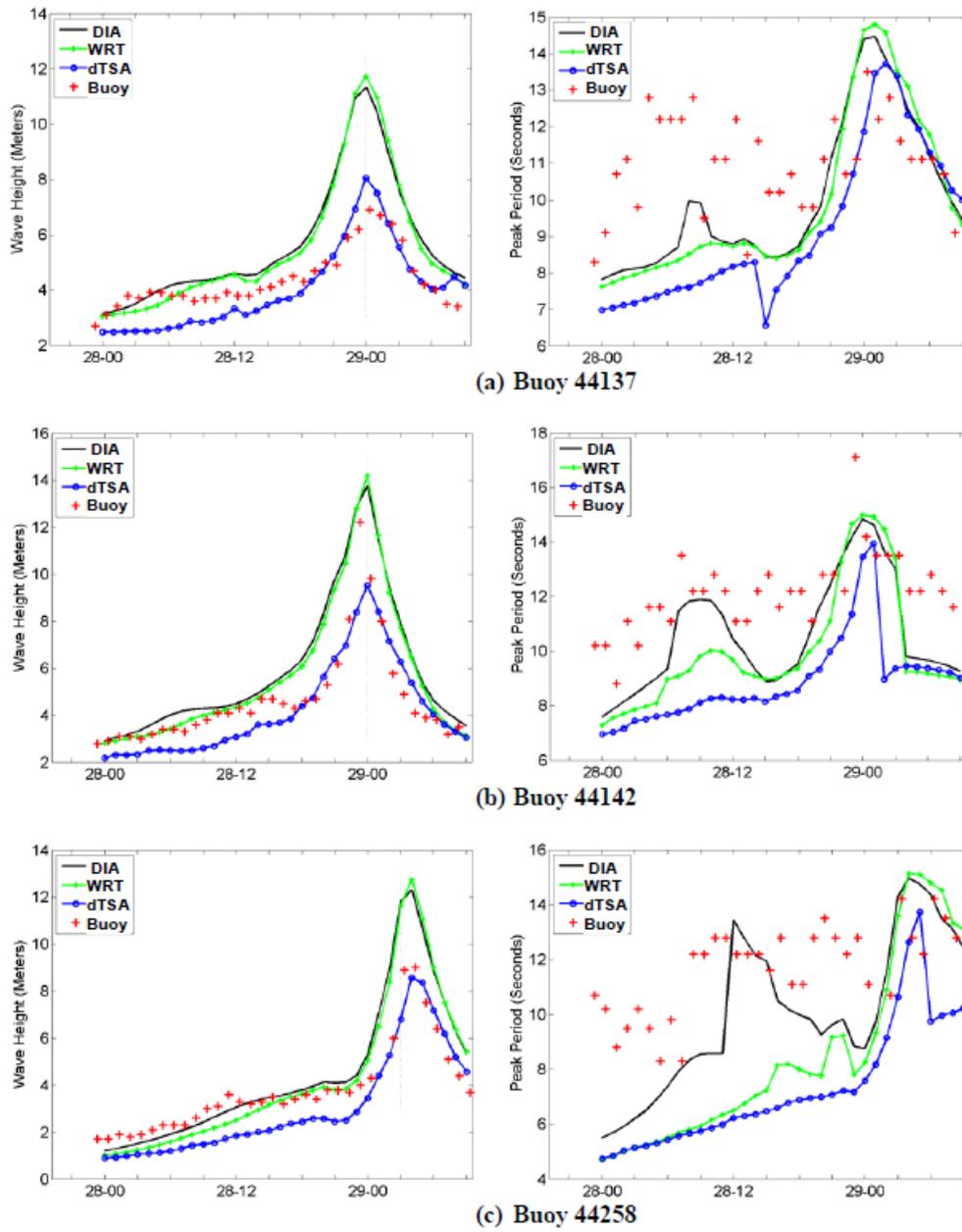


Figure 2. Comparison of results from three formulations for S_{nl} with observed H_s and T_p data at three buoys along the track of hurricane Juan. The new formulation dTSA is used.

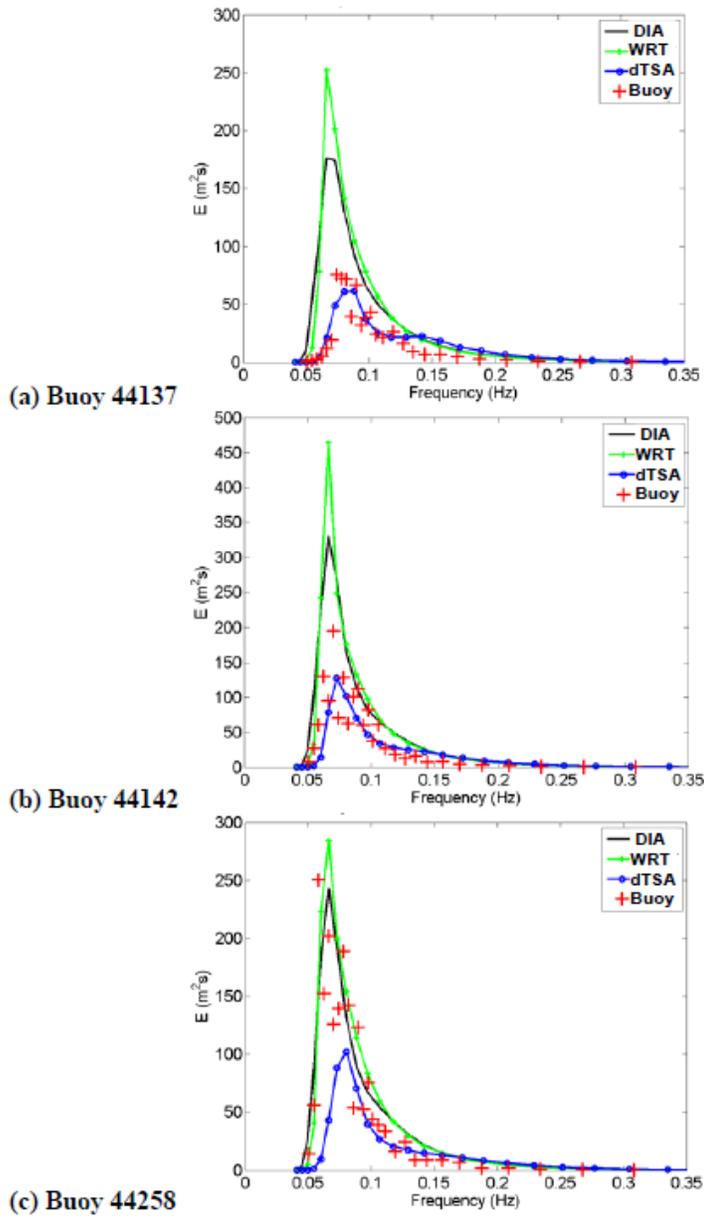


Figure 3. As in Figure 2, comparison of results from three S_{nl} formulations, namely DIA, WRT also known as FBI, and the double TSA formulation, dTSA, to observed 1-d data at three buoys, at the peak of hurricane Juan, 0300 UTC on 29 Sept 2003.