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, 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) Enhance the formulation of TSA, for computational efficiency, and also to consider complicated situations, such as turning winds, and real storms, implemented in WAVEWATCHIII (WW3).
2) Complete tests with storm-generated waves for TSA, using new S_{in} and S_{ds} parameterizations, in WW3, for real storms, as well as hypothetical fetch- and duration-limited wave growth situations.
3) Compare TSA implemented in WW3, including tests with relatively simple parameterizations for S_{in} and S_{ds} forms for wave models. Include tests for SWAN for shallow water waves cases.
4) Finalize the TSA formulation in terms of computational efficiency and accuracy.

APPROACH

We will clarify the limitations and properties of the finalized TSA implemented in modern operational wave models, with consistent source/sink terms, S_{in} and S_{ds}.

1) **Enhanced versions of TSA**. We will complete tests and derivations of new optimized versions of TSA, aiming to reduce execution times, maintain or improve accuracy, and address areas where TSA has been shown to be deficient, compared to FBI (full Boltzmann integral), e.g. accelerating or veering winds, combined sea/swell conditions, etc. This activity must address any TSA deficiencies that have become evident, in this project.
2) **TSA tests with new S_{in} and S_{ds}.** New parameterizations for S_{in} and S_{ds} and modifications to TSA necessitate the need to redo basic tests for duration-limited, fetch-limited, turning winds, and additional tests, using TSA in WW3, as are always needed to ensure that the model is reliable.
3) **TSA model-model comparisons.** We will compare selected cases for TSA implemented in both WW3 and SWAN with corresponding model estimates, using the variety of accepted formulations for S_{in} and S_{ds}, including new forms as in item 2), and older parameterizations, for storm cases, comparing model results with observed data.
4) **Finalized TSA and source terms.** The TSA formulation derived in this project, will be finalized, optimized in terms of run time and efficiency, and implemented in recent WW3 and SWAN versions. This includes additional testing and optimization of TSA for the new formulations of S_{in} and S_{ds} to get acceptable results compared to observed data. Shallow water tests are included. Tests for reliable modern relatively simple operational wave models are completed by Resio, separately.

WORK COMPLETED

The project has completed the objectives that were originally proposed.

1) ***Enhanced versions of TSA*.** In evolving wind and wave conditions, the TSA formulation works well for simple fetch-limited or duration-limited wave growth. However, when the wind direction continuously changes, the TSA formulation needs to be modified to allow the broad-scale term to respond properly. If there is a misalignment of TSA's broad-scale term with respect to the change in wind direction, and TSA is not able to provide a reliable representation of the nonlinear transfer due to wave-wave interactions in this changing situation. The multiple-TSA approach allows generalization of the broad-scale term, allowing more than one broad-scale parametric terms, corresponding to multi –peaked spectra. It can be shown that this modification of TSA (denoted 'double TSA', or dTSA) allows the TSA approach to respond as the wind direction veers, and is important for situations which result with swell- windsea interactions. Thus, model accuracy is improved, for waves generated by storms simulations. For additional details see *Perrie et al.* (2013a; 2013b; 2014), and Figure 1 below.
2) ***TSA tests with new S_{in} and S_{ds} parameterizations***. We have completed comparisons with modern source terms (*Ardhuin et al.*, 2010), so-called 'ST4', in comparison with older WAM cycle physics, from WAM model (WAMD1, 1988), and alternate formulations, by Tolman and Chalikov (1996), and others, and to investigate the response of TSA to these source terms, in storm conditions in the North Atlantic. Without any parameter tuning for ST4 (that is S_{in} *and* S_{ds}), we show that wave model results from the implementation of TSA in WW3 are better than results obtained by earlier source term formulations for S_{in} *and* S_{ds}, or runs using DIA – the discrete interaction approximation. See *Perrie et al.* (2013a; b; 2014).

3) ***TSA model-model comparisons.*** TSA was implemented in recent versions of WW3 (4.10 and 4.18), and SWAN, and tests were made to compare model skill, using modern source terms of *Ardhuin et al.* (2010), denoted 'ST4', as well as simpler source terms, like ST1 (WAMD1, 1988). Tests include simple hypothetical cases, as well as storms such as hurricane Juan (2003), and mid-latitude *nor'easters*. We show in these model studies that TSA works well with modern source terms like ST4, and that model skill is improved, compared to older versions of these source terms. Results are shown in *Perrie et al.,* (2013a; 2013b; 2014).

4) **Finalized TSA and source terms.** The derived TSA formulation was optimized in terms of run time and efficiency, and implemented in WW3 and SWAN. This involves an optimized selection of grids and computation loops over which the computation is carried out. The SWAN model tests use an unstructured grid allowing high accuracy for coastal areas with shallow water. Shallow water tests are included in tests with unstructured SWAN, including hurricane Juan (2003). Results are reported by *Sun et al*., (2014). Additional tests using a reliable modern simple operational wave model were completed as part of a separate project led by Resio.

RESULTS

The meaningful technical results achieved in this fiscal year are:

a) We have developed an *enhanced version of TSA* which is a generalization of the standard TSA formulation, originated by Resio and Perrie (2008), and Perrie and Resio (2009) in the sense that it is able to not only simulate evolving wind and wave conditions, for simple fetch-limited or duration-limited wave growth, but also conditions where the wind direction continuously changes. This generalization of TSA can be considered a multiple-TSA approach, whereby more than one broad-scale parametric term is allowed, corresponding to multi –peaked spectra. Thus, this modified TSA can handle situations where the wind direction veers, or in swell- windsea interactions cases. Model accuracy is improved, for waves generated in turning winds, or by rapidly developing storms.

b) We have completed a variety of tests and model implementations with the new *generalized* TSA, involving standard modern formulations for the source terms for wind input energy, and wave dissipation (S_{in} *and* S_{ds}) parameterizations, including state-of-the-art so-called 'ST4'(*Ardhuin et al.,* 2010). Comparisons were made with more historical versions of these source terms, for example 'ST1', dating from the original WAM code. We have shown that, without any tuning of ST4 source term coefficients, accurate waves simulations are possible with TSA implemented in WW3, giving the best overall performance. In model inter-comparisons, implementations were made in the most recent versions of WW3 (4.10 and 4.18), and SWAN (unstructured grid, and shallow water waves), and tests were conducted to simulate waves generated in storm conditions, again showing that ST4 source terms and TSA can demonstrate the best overall model skill.

c) Optimized versions of TSA have been formulated, in terms of computer run time, efficiency, and model accuracy, and implemented in very recent versions of WW3 and SWAN. This involves an optimized selection of grids and computation loops over which the computation is carried out, Thus far, for implementations in WW3, TSA has achieved a speed that is approximately 20× slower than a standard DIA formulation for the nonlinear wave-wave interactions. Tests have included waves generated by hurricane Juan (2003), as well as several mid-latitude *nor'easters*.

IMPACT / APPLICATIONS

The value of this project, to the scientific community and to society, is that a more physically based wave models will be developed, compared to the present state-of-the-art, which is DIA, for the nonlinear wave-wave interactions, at the heart of operational wave forecast models. TSA has been established as a viable (more accurate) alternative to DIA. Thus, where inaccuracies in DIA were hidden in tuning coefficients, for example embedded in S_{in} and S_{ds}, it is now be possible to better simulate and model the processes, previously hidden by tuned coefficients. Wave forecasts should improve, for global, basin, regional and coastal scale studies, with application of TSA as the key part of the forecast wave model. The success of this project can lead the way for TSA being implemented in operational wave forecast models, such as WW3 and SWAN, defining a new state-of-the-art.

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 forecasts, 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 and activities, both from 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 implemented and tested in WW3, which is the operational forecast wave model, for NOAA / NCEP and several other marine forecast offices, internationally. Thus, when tests are completed, which is scheduled to occur imminently, the resulting model will be easily useable as the operational forecast model for these marine forecast offices.

RELATED PROJECTS

A related project is supported by the Marine Environmental Observation Prediction and Response Network (MEOPAR; http://meopar.ca/) a team of outstanding, Canadian natural and social scientists, working to better understand and *predict the impact of marine hazards* on human activities and ecosystems…*and improve response*. Perrie’s MEOPAR project focuses on improved wave forecasts for waters off the coast of Atlantic Canada, with particular focus for Halifax Harbor and approaches.

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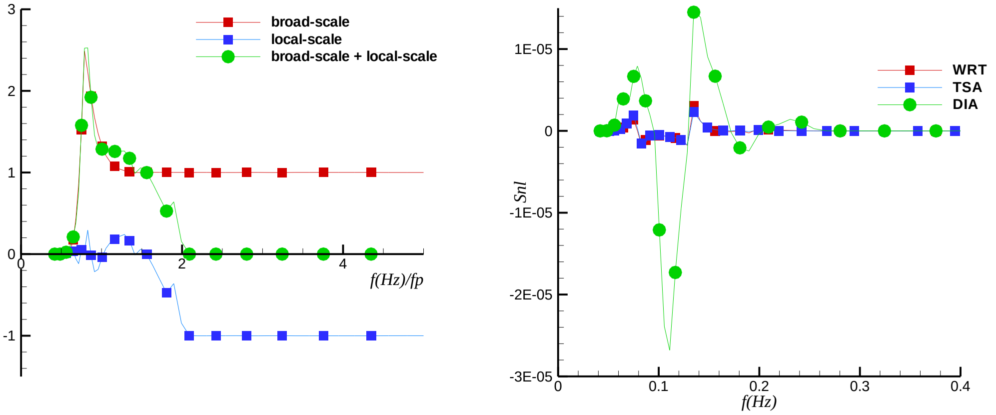
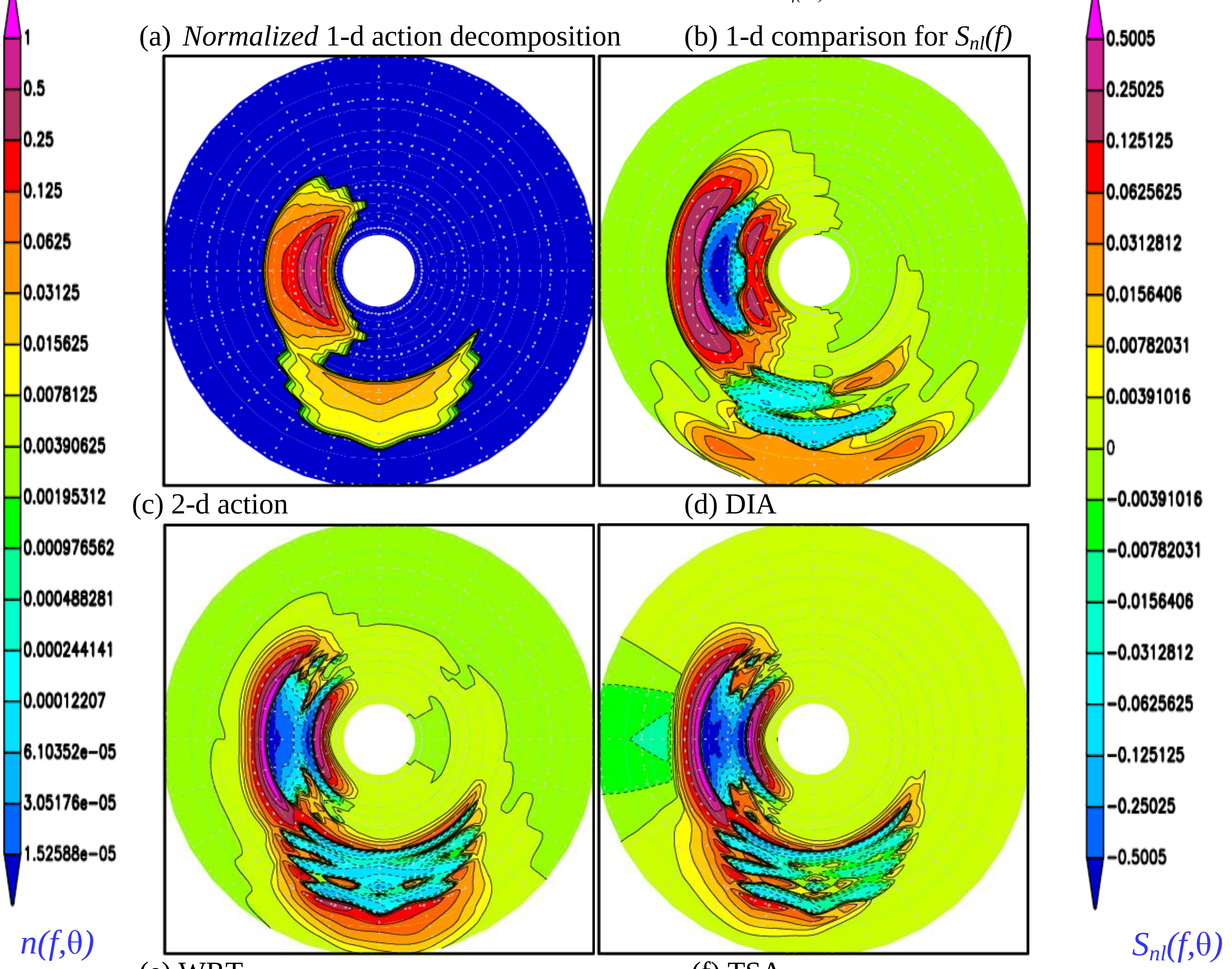


(a) *Normalized* 1-d action decomposition (b) 1-d comparison for $S_{nl}(f)$



(c) 2-d action (d) DIA

(e) WRT (f) TSA

Figure 1. (a) Decomposition in terms of broad-scale and local-scale terms normalized by the f^{-4}, (b) 1-d comparison of DIA, WRT and TSA, (units: m^2), (c) 2-d action density n_i, (d) $S_{nl}(f,\theta)$ from DIA, (e) WRT, and (f) TSA. Color-bar for DIA, WRT, TSA scales to $\pm 3.36\times10^{-5}$, $\pm 3.13\times10^{-6}$, and $\pm 2.64\times10^{-6}$, respectively. Color-bar for $n(f,\theta)$ scales to × 10.1. The 1st peak is at 0.0788 Hz, the 2nd at 0.135 Hz, shifted 90° with respect to 1st peak. Both distributions are JONSWAP: γ=3.3. From *Perrie et al* (2013).