Complex wave propagation patterns near shipping channels -Phase-averaged or phase-resolving wave model ?

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Complex wave propagation patterns near shipping channels - Phase-averaged or phase-resolving wave model?

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Abstract

The presence of navigation channels often results in sharp spatial bathymetric gradients (i.e. depth difference) which can significantly modify the propagation of incoming waves and in turn the wave conditions both outside and inside ports.

The fate of waves in intermediate to shallow water depths encountering a deeper navigation channel is largely dependent on the angle of approach relative to the channel axis. Wave transmission occurs when the angle of approach is large (e.g. near perpendicular to channel axis). In that case, we can expect a “reverse” refraction whereby waves bend away from the bathymetric contours when reaching the deeper channel water. When waves approach the channel with incidence closer to its axis, waves are subject to sharp refraction over the channel edge and effectively “reflect” at the same angle as the incident waves but in the landward direction. The superimposition of the incident and “reflected” waves can lead to wave interference patterns that can significantly modulate the resulting wave energy distribution in the lee area.

In this paper, we explore differences between phase-resolving (SWASH) and phase-averaged (SWAN) wave modelling results for waves propagating over the Port of Townsville shipping channel. It is found that the modelling approach can largely affect the predicted wave conditions statistics (based on a 10 year hindcast) typically required for coastal structure design, which suggests the importance to account for possible wave interference that can develop around shipping channel.

Keywords: Wave modelling, shipping channel, phase-averaged model, phase resolving model.

1. Introduction

The study was undertaken in the context of the Port of Townsville’s Channel Upgrade (CU) Project which includes deepening and widening of the existing channel to the design depth of 12.5m LAT, a realignment of the western entrance breakwater and land reclamation (see Figures 1 and 3).

The wave modelling objectives were to evaluate the existing wave processes in the vicinity of the existing channel (i.e. wave “reflection” / sharp refraction) and investigate the potential impact of the proposed CU channel widening/deepening and reclamation on operational wave conditions throughout port approach and within the inner harbour.

The primary wave modelling approach included a dynamic downscaling of the offshore wave climate offshore of the Port using a nested suite of Simulating WAves Nearshore (SWAN) domains, and a high-resolution, phase-resolving, SWASH domain for the Port of Townsville approach and basin to specifically investigate wave propagation over the entrance channel as well as wave interactions with structures (i.e. wave reflection/transmission and diffraction).

The Simulating WAves till SHore (SWASH) model was first compared with physical model results by [6] to ensure key wave patterns were correctly reproduced, and a wave transformation technique was then applied to downscale the hindcast offshore wave conditions (from SWAN) to local wave climates at several sites outside and inside the port basin (see Figure 3).

As a retrospective exploration step, in part motivated by the reduced computational effort involved to downscale the wave climate with SWAN, the feasibility of using a high resolution SWAN (phase-averaged) domain instead of SWASH (phase resolving) for the last downscaling step was explored and difference in predictions in the lee of the channel, outside (i.e. near reclamation) and inside of the port basin, were evaluated.

The paper is structured as follows. The wave modelling methodology including SWAN wave climate hindcasting and SWASH wave transformation approach is provided in section 2. Key wave processes and main study findings are outlined in section 3. A comparison with SWAN results is discussed in section 4 and main conclusions are provided in section 5.

2. Methods

2.1 SWAN hindcast

Wave modelling was undertaken using a modified version of Simulating WAves Nearshore (SWAN)

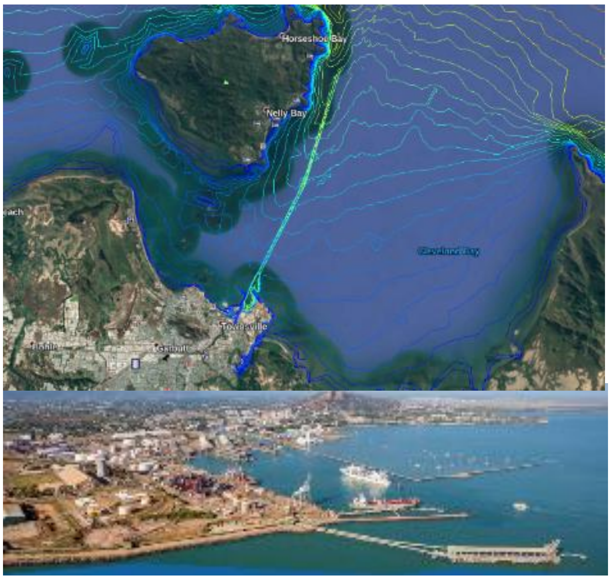


Figure 1. Port of Townsville. Note the long shipping channel and variety of port structures.

[4]. A suite of four nested domains (resolution 5 km to 50 m) was implemented to provide a 10-year high-resolution wave hindcast of the Cleveland Bay region spanning 2009 to 2019.The model suite used the new source terms parametrisation ST6 and included a non spatially-constant bottom friction to reproduce areas of the Great Barrier Reef. The model was validated against available observations.

The SWAN hindcast data provided long term spectral wave climate which was used as boundary conditions for the local SWASH modelling. Joint probabilities of wave parameters were established at the offshore boundary of SWASH domain and all non-empty bin wave conditions were considered for the wave transformation runs.

2.2 SWASH wave modelling

High-resolution nearshore wave modelling of the port of Townsville approach and basin was undertaken using the non-linear wave propagation model Simulating WAves till SHore (SWASH).

SWASH is an open-source non-hydrostatic wave-flow model solving the non-linear shallow water equations including non-hydrostatic pressure. It is notably intended to be used for predicting transformation of dispersive surface waves from offshore to the beach, for studying the surf zone and swash zone dynamics, wave propagation and agitation in ports and harbours. A complete description of the numerical algorithms used in the code and capabilities is provided in [11]

The model simulates individual waves as they propagate over the bathymetry towards the shore, i.e. phase-resolving model, accounting for all relevant nearshore processes, including shoaling, refraction, diffraction, reflection, non-linearity, and is therefore suitable to study wind seas (wave periods < 10 sec), swell (wave periods 10-22 sec) wave propagation and infragravity (wave periods 22-250 sec) wave generation and propagation.

A first phase of the SWASH modelling exercise consisted in a comparison with available 3D physical modelling results by [6] to ensure key wave processed were correctly reproduced. The physical model represented the Port of Townsville approaches at a 1:100 scale including the channel widening, as well as the bund wall of the proposed reclamation east of Berth 11 (see Figure 3). The SWASH domain reproduced the physical model configuration as closely as possible to allow consistent comparison between wave conditions measured within the physical model (using probes) and corresponding modelled wave conditions.

After the initial validation phase, a larger SWASH domain was implemented encompassing the full Port of Townsville approach, berths, reclamation and harbour basins. The simulations used a rectangular domain of 1602 by 1815 cells rotated to 33 degT North, with a spatial resolution of 2 m (Figure 2). The offshore wave boundary was chosen to coincide with Location P8 where wave conditions are available from the long-term SWAN hindcast. Two wave-dissipating sponge layers were included along the western and southern domain boundaries to allow waves to propagate out of the domain freely (200 and 70 meters wide respectively). The model was run in depth-averaged mode. A constant Manning friction of 0.019 $m^{-1/3}$.s (default) was used throughout the domain with local elevations to 0.1 $m^{-1/3}$.s over the rubble mound and rock revetments to account for the increased roughness.

To further simulate reflection and transmission of porous structures such as rubble mound revetments, SWASH also allows the use of so-called porosity layers in addition to, or in place of,

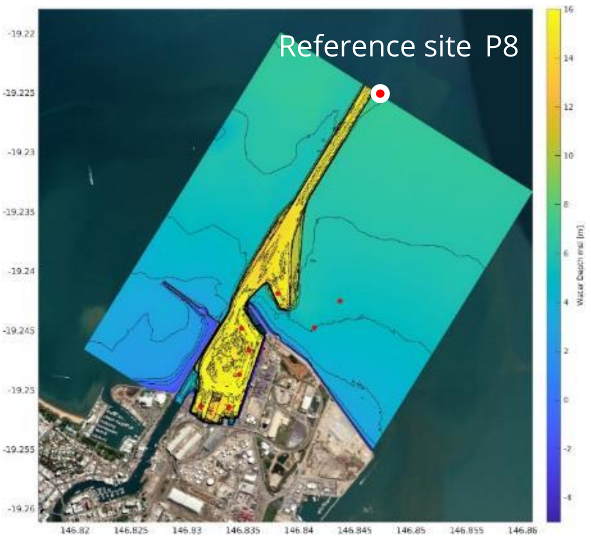


Figure 2. Port of Townsville model domain bathymetry used for SWASH and SWAN.

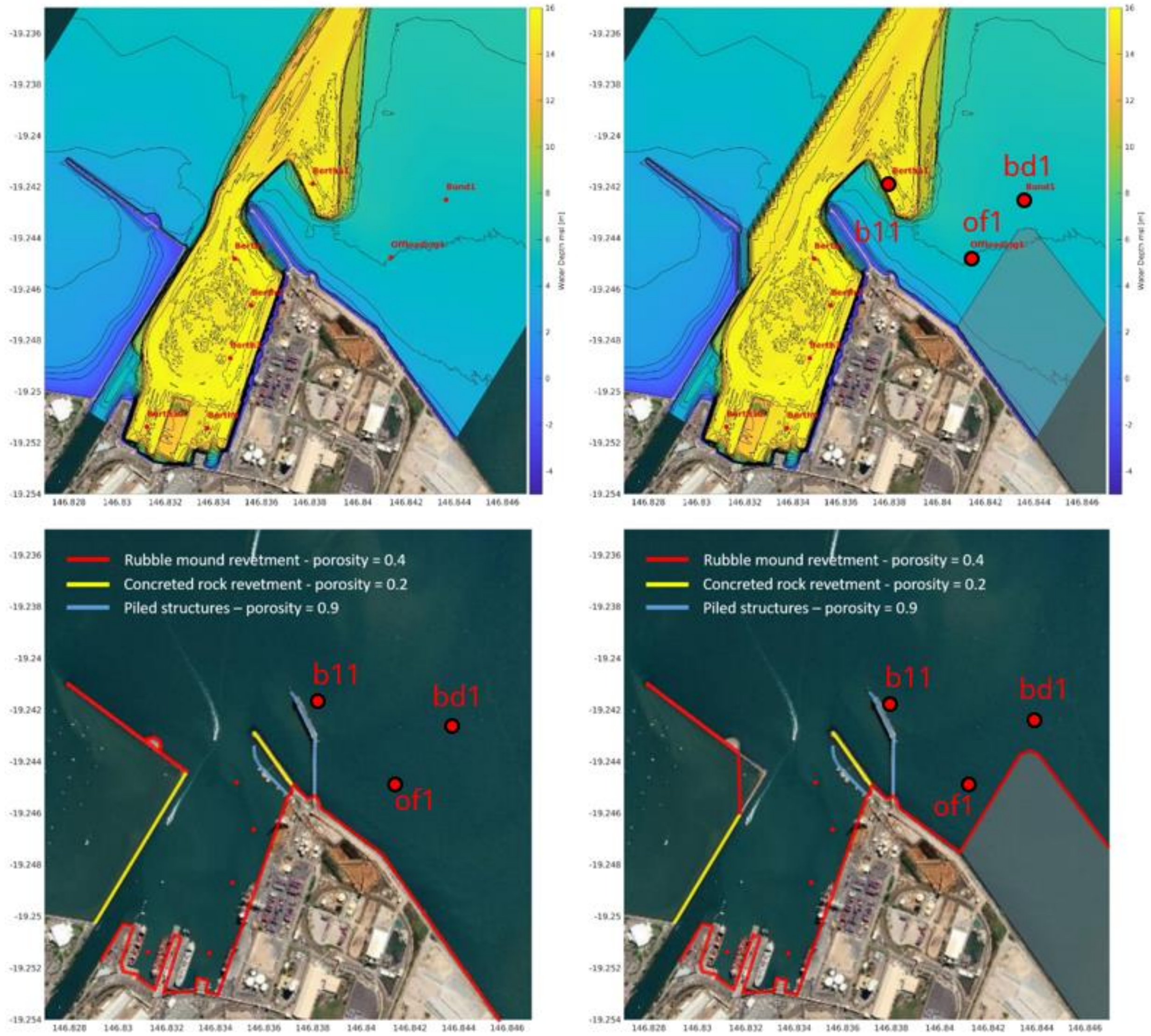


Figure 3. Zoomed-in view of SWASH model bathymetries for the existing (top left) and Channel Upgrade (CU) (top right) configurations and corresponding porosity layers included in the SWASH model domain. The CU reclamation area is shown as a shaded polygon (bottom right panel). Red dots are output locations.

representing the structures in the bathymetry. A porosity layer uses a porous flow model with equations by [10] to obtain the amount of wave/flow transmitted past an obstacle. In that context, the porosity is defined as the volumetric porosity of the structure, with value between 0.0 and 1.0. A porosity value of 0.0 reproduces an impermeable wall (i.e. land, no wave transmission, full reflection) while a porosity of 1.0 allows full wave transmission (i.e. “wet” point). In the present study, several porosity layers were defined over the existing and proposed port structures based on their revetment types. The existing and proposed bathymetries and corresponding porosity layers are illustrated in Figure 3.

Simulations were run over 1500 seconds and spatial maps of averaged wave parameters were computed on the last 900 seconds of the simulations. Timeseries of sea-surface elevations were extracted at the locations of sites of interest inside and outside of the port basin (see Figure 3) and wave parameters were determined using 1D spectral analysis.

2.3 Wave Transformation Technique

Although the SWASH model provides a very comprehensive modelling solution, its computational cost prevents its use for dynamic downscaling (i.e time-domain simulation). The objective of a wave transformation technique is to predict wave conditions at one or several nearshore locations, i.e. “forecast” sites, based on known conditions at an offshore position i.e. “reference” site (available from measurements, hindcast or forecast data). The technique involves generating a database of a large number of stationary wave model runs that transform wave conditions from the “reference” site to the “forecast” sites, for any wave condition that can be experienced at the “reference” site. The database is then used to transform known conditions at the “reference” site to the “forecast” sites without having to re-run any model simulation.

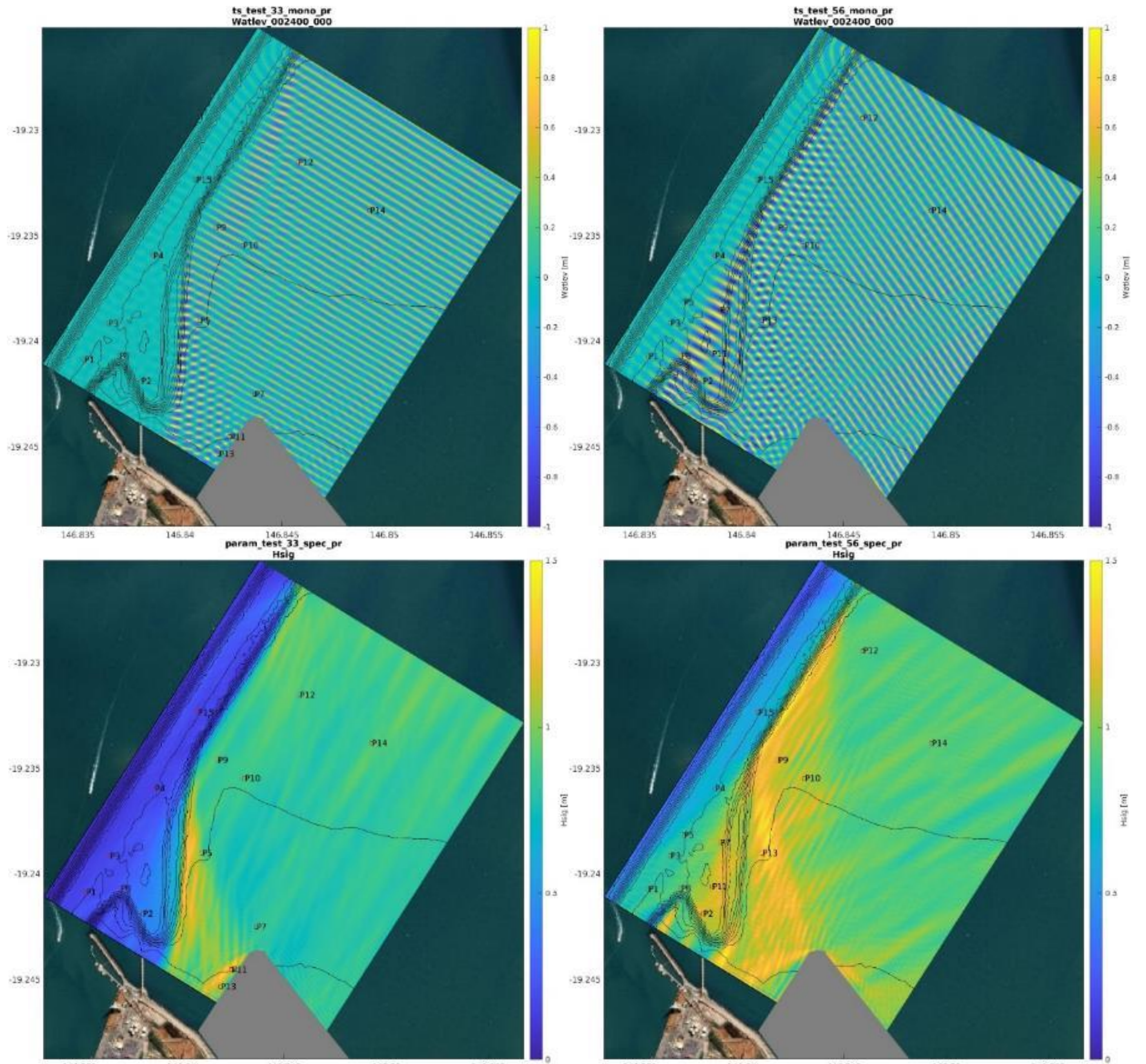


Figure 4. Snapshots of sea surface elevations for monochromatic conditions with normal (top left) and oblique wave incidence (top right). The bottom panels show significant wave height fields for spectral wave conditions with normal (left) and oblique wave incidence (right). Note the clear “diamond pattern” in the wave fields along the edges the channel and berth pocket, signature of wave “reflection” (or sharp refraction) when waves approach bathymetric gradients obliquely. This reduced domain reproduced the physical model against which SWASH was validated.

In the present study, the representative wave events at the site were simulated using the SWASH model and resulting wave transformation table were applied to the 10-year wave climate available from the SWAN hindcast at the model boundary to produce 10-year timeseries of wave conditions at nearshore sites.

3. Results

The comparison of the SWASH modelling with the physical modelling results provided a clear illustration of wave processes developing in the vicinity of a shipping channel, which in that case combined with subsequent interaction with port structure and proposed reclamation (Figure 4).

For obliquely approaching waves, sharp wave refraction from the channel edge and incident waves combine in cross-wave or “diamond” patterns along the eastern channel edge, typical signature of channel “reflection” processes (e.g. [3,7]). This feature combines with a similar wave “reflection” process and diamond pattern, albeit with different orientation, along the edge of the berth pocket. Another feature of interest is the clear wave focusing, and redirection of incoming waves along the channel and berth pocket edges. The focusing is more significant along the channel edge for the oblique wave incidence, while more significant along the berth pocket edge for the normal wave incidence. These processes produce bands of increased significant wave heights along the channel and berth pocket bathymetric edges (Figure 4. bottom panels). In contrast, wave heights within the channel remain relatively small indicating limited wave transmission.

For the oblique event, the wave focusing along the channel edge transmits a clear band of focused wave crests following the channel axis which then

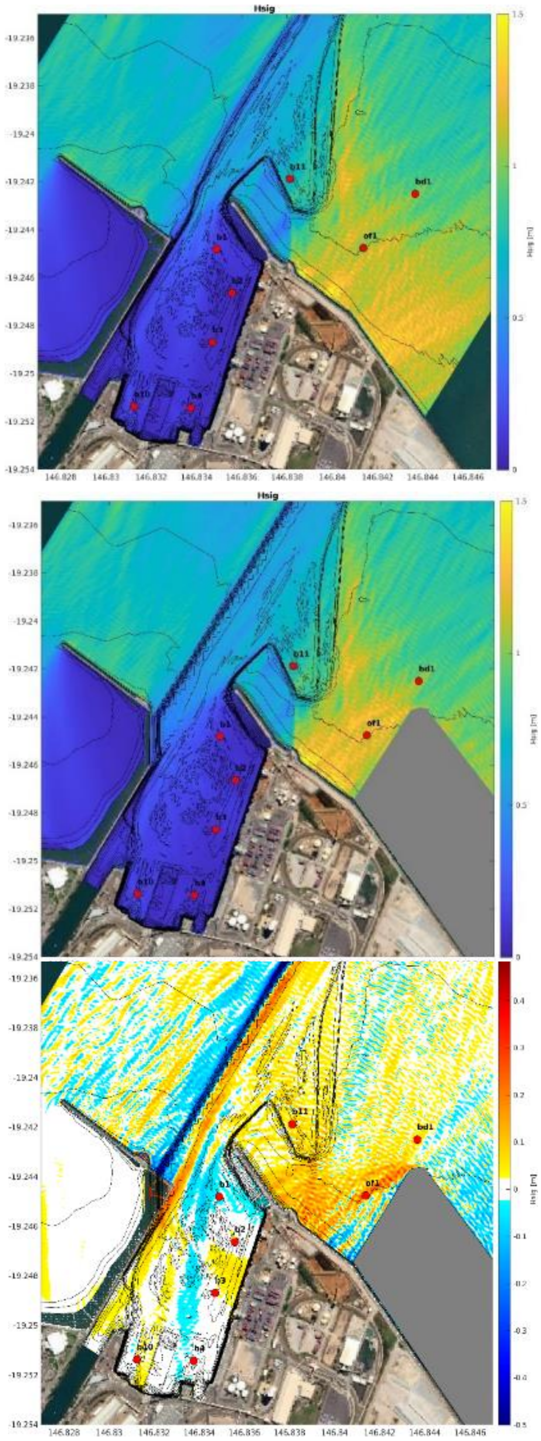


Figure 5. Significant wave height fields for offshore wave conditions at P8 Hs=0.75m, Tp=5 sec, Dpm =[20-40 degT] for the existing (top) and proposed (middle) CU configurations. Wave height difference are shown the bottom panel. A positive wave height change indicates larger wave heights on the proposed configuration relative to existing.

are further focused by the shallower wedge formed by the berth pocket, before reaching the landward end of physical domain but in reality would be reaching the eastern entrance breakwater.

Overall, the combination of wave concentration *over*, and wave reflection *from* channel and berth pocket edges results in relatively large wave heights towards the west-facing reclamation bund wall (~1.5 m versus 1.0 m offshore i.e. ~ 50% larger). This was consistent with observation by [6] which noted larger waves in that area relative to what would be experience with incident waves alone (i.e. no channel).

The extended SWASH domain used for final simulations included the full port layout and reproduced both existing and proposed port configurations (Figure 5). We note the presence of the reclamation in the proposed CU configuration locally reflects some of the incoming enhanced wave energy beam, which results in a further local increase wave height relative to the existing configuration.

In the proposed CU configuration, the channel widening and deepening as well as removal of the corner between the offshore and western breakwaters effectively widen the port entrance. For waves approaching from the 20-40 degT range, relatively more wave energy reaches the western side of the basin (+5-15cm), while the eastern side of the entrance area becomes more sheltered (- 5-10 cm). Some of the incident wave energy appears to bounce off the new junction between the offshore and western breakwater and redirects to the centre of the eastern wharves. Similar patterns were reproduced for wave from the 40-60degT window though with smaller magnitude of changes.

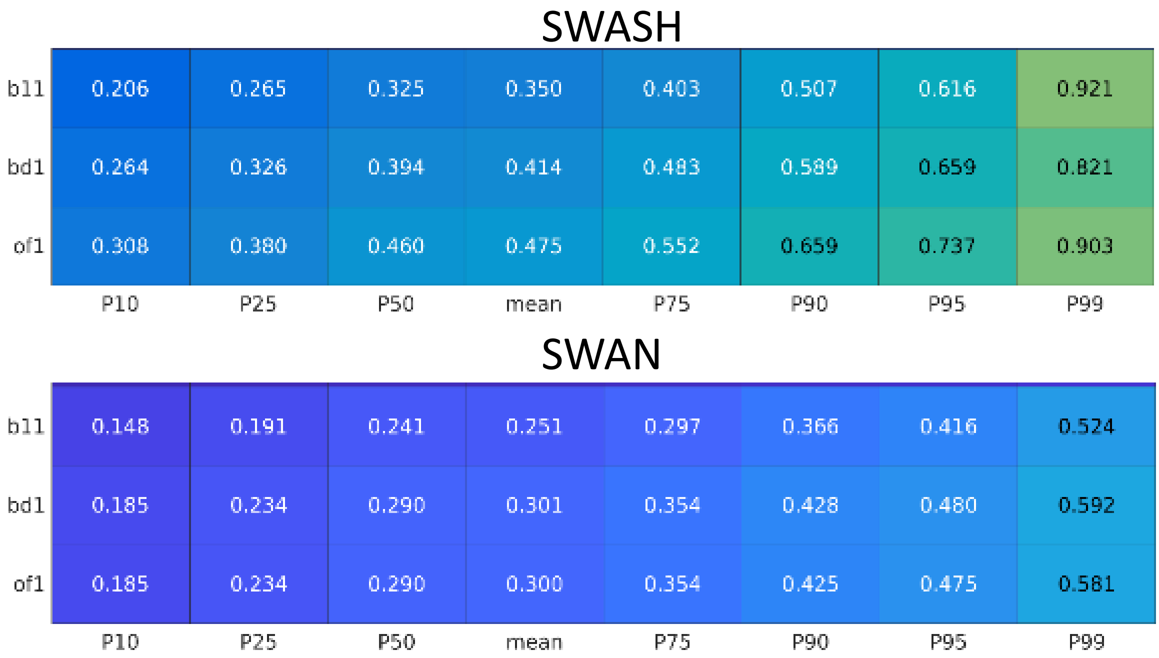
The application of the wave transformation technique produced long-term timeseries of wave conditions at several location inside and outside of the port which formed the basis to evaluate impact of proposed development on port operability.

4. Comparison with SWAN

The SWASH modelling indicated complex wave propagation patterns and interactions with structures which indeed motivated the choice for SWASH as main modelling tool for the study in the first place.

However, given the good interoperability of model inputs between SWASH and SWAN and much reduced computational cost of SWAN simulations, a comparative assessment was considered as a retrospective exploratory step, notably to evaluate the feasibility of a “lighter” approach which may allow a dynamic downscaling and/or domain implementation in an operational forecasting context.

Using the same high-resolution model domain (2m resolution), the wave transformation approach was applied, this time using SWAN instead of SWASH



SWASH

	P10	P25	P50	mean	P75	P90	P95	P99
b11	0.206	0.265	0.325	0.350	0.403	0.507	0.616	0.921
bd1	0.264	0.326	0.394	0.414	0.483	0.589	0.659	0.821
of1	0.308	0.380	0.460	0.475	0.552	0.659	0.737	0.903

SWAN

	P10	P25	P50	mean	P75	P90	P95	P99
b11	0.148	0.191	0.241	0.251	0.297	0.366	0.416	0.524
bd1	0.185	0.234	0.290	0.301	0.354	0.428	0.480	0.592
of1	0.185	0.234	0.290	0.300	0.354	0.425	0.475	0.581

Figure 6. Comparison of significant wave height statistics derived from 10-year timeseries predicted at sites of1, bd1, b11, outside of the port (see Figure 3, bottom panels) by SWAN and SWASH.

for the simulations of the discrete wave events. Diffraction in SWAN was also activated.

A comparison of statistics at some sites of interest outside of the port near the reclamation (see Figure 3, bottom panels) is shown in Figure 6. At these sites, SWASH predictions are 25 to 40 % higher than SWAN. Comparison at other sites including inside the basin (not shown) yielded SWASH wave height 15 to 50% larger than SWAN.

The reason for these large differences in wave height predictions are illustrated in Figure 7 that compares significant wave height fields predicted by SWASH and SWAN for the same generic offshore conditions. In SWASH results, more intense wave height amplification develops east of the port entrance where waves reflected and focused by the channel converge with ambient incoming waves. We also note a more efficient wave shadowing of the western side of the shipping channel due to the more intense reflection (or sharp refraction) from the channel in SWASH than in SWAN.

Although the processes of refraction, focusing, and shadowing features are accounted for in SWAN and the resulting patterns can be seen to some extent, they do not reach the magnitude of SWASH-predicted features, and resulting wave energy distributions are quite different for two models. Here, it is important to note that SWASH solves the nonlinear shallow water equations including non-hydrostatic pressure and can simulate the rapid changes of wave propagation taking into account nonlinear effects. It is thus much more accurate than in SWAN, where linear refraction is obtained from the kinematics of a wave packet (wave ray theory).

The sharp variations of wave height statistics that occur through the port approach in SWASH results suggest the importance to consider coherent wave effects at the site, and more widely around navigation channels. These coherent wave effects develop when incoming waves are scattered across multiple directions for example by sharp depth variations (or current) which can form focal zones and give rise to wave interference patterns ([1,2,8,9]). These effects can lead to rapid variations of the wave energy spatial distribution and corresponding wave statistics. Non-linear effects could also play a role in producing larger wave heights (e.g. [5]).

These processes are not accounted for in SWAN and other typical phase-averaged wave models based on the radiative transfer equation (RTE) that assume waves propagating at angles are mutually independent and that the wave field change slowly over several wavelengths ([1]). We note however that [8,9] have proposed an additional source term for the action balance that allows reproducing wave interference patterns (Quasi Coherent Model). This could be an interesting alternative for future experiments on wave propagation around shipping channels.

We also note some difference with respect to diffraction around port structures. This is more easily noticeable in the entrance and western

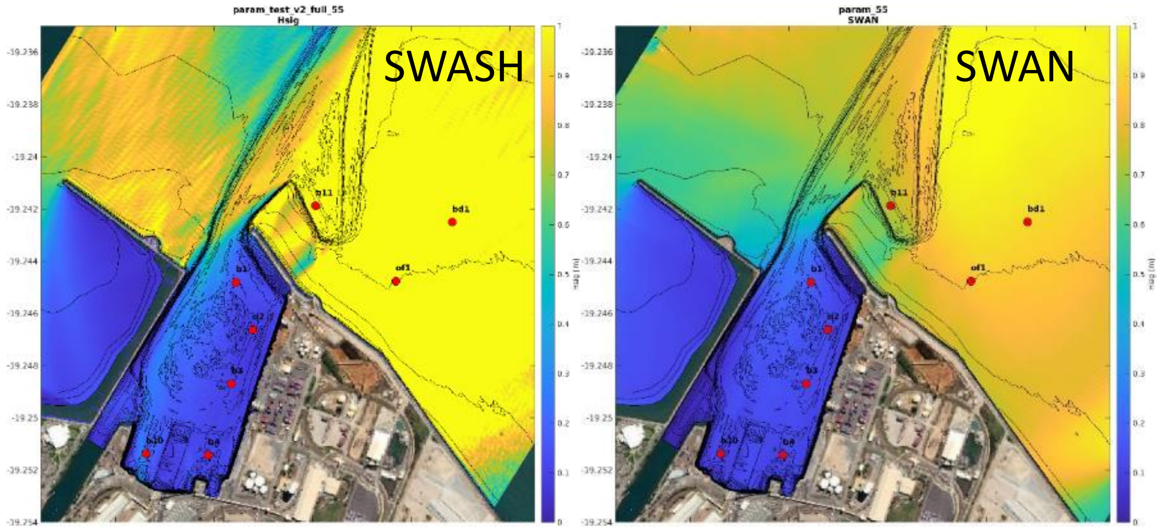


Figure 7. Comparison of predicted significant wave height for generic spectral wave conditions Hs=1.0m, Tp=5sec. Dp=55 degT (JONSWAP).

breakwater port area. There is a difference in wave height gradient in the alongshore direction between both models whereby SWASH fills more of the energy gap in the sheltered entrance area. This is expected given the more empirical treatment of diffraction in SWAN whose applicability in complex port configurations is debatable [e.g. 4].

Another point of difference between the models which was briefly explored was the inclusion of reflective obstacles in the SWAN domain. Treatment of wave interaction with land and structures are significantly different in SWASH and SWAN. SWAN requires reflection/transmission coefficients, possibly frequency-direction dependent along obstacle lines and assume full wave dissipation at land point. In contrast, SWASH employs porosity layers specified on structures themselves which allows more realistic modelling of wave interactions with structures. Full wave reflection occurs at land point unless specified otherwise (i.e. porosity > 0). SWAN obstacles need to be surrounded by water which complicates the definition of shoreface reflectivity, and this was also found to introduce stability issues in simulations which prevented running the full set of wave transformation events, notably when varying water levels.

An example of the net effects of reflective obstacles is shown in Figure 8. We note the local increase in wave height in the vicinity of structures and shorefaces would contribute to increase the SWAN-derived statistics presented in Figure 6 and thus reduce relative difference SWAN/SWASH, however magnitude of changes would most likely be too small to reach SWASH levels.

We note that that SWASH was not calibrated against in-situ measurements, but it is expected to be the best available guidance/reference in our comparison given its validation against the physical modelling results and more comprehensive model physics including wave refraction, diffraction, reflection and non-linear effects.

5. Conclusions

In the context of the Port of Townsville Channel upgrade (channel widening and deepening), the paper explores the impact of shipping channel on nearshore wave propagation and compares predictions obtained with two different wave models: SWASH (non-linear, phase-resolving) and SWAN (phase-averaged based on action balance equation).

We find the combination of wave concentration *over*, and wave reflection *from* channel and berth pocket edges results in wave heights transmitted in the lee zone that are significantly larger than what would be experienced with incident waves alone (i.e. no channel). These larger waves can further interact and reflect with port and/or reclamation structures driving further wave energy increase.

The model comparison indicates that SWAN does not reproduce the same intensity of wave focusing and wave convergence as SWASH, with predicted wave height smaller by 25 to 40 %. This suggests the importance of coherent wave effects around sharp bathymetric gradients such as shipping channel which can form focal zone and interference patterns that have the potential to significantly modulate the spatial distribution of wave energy in their lee. The fact that these effects cannot be accounted for in SWAN, along with a less realistic treatment of the wave interaction with structures, makes the SWASH model a preferred option over SWAN, even with a high spatial resolution, for our study site and likely others.

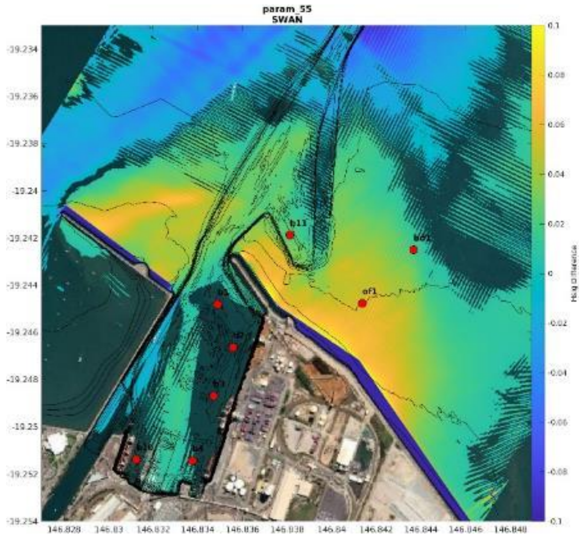


Figure 8. Significant wave height difference between SWAN simulations with and without reflective obstacles. A positive difference means larger wave height on configuration with reflective obstacles.

6. Acknowledgments

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