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Long-wave isentropic ocean-atmosphere dynamics:

providing faster-than-real-time, predictive modelling of the 2022 Hunga Tonga event

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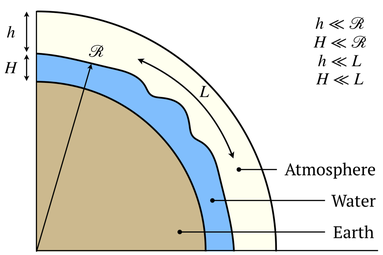
Motivation

The 2022 Hunga Tonga-Hunga Ha'apai eruption provoked worldwide confusion within tsunami warning systems and highlighted the need for predictive forecasting tools for coupled atmosphere-ocean events. Current one-way coupled forced shallow water equation (SWE) models provide unsatisfactory results motivating the present research which incorporates additional physics resulting in a two-way coupled (TWC) model .

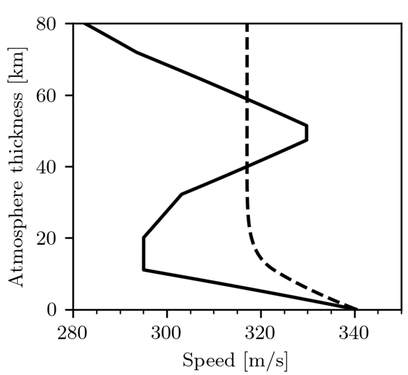
Thin layers, long waves and two-way coupling

To derive the TWC model, long waves are considered to propagate in both the atmosphere and the ocean, which are comparatively thin relative to the wavelength of the waves, governed by the 3D compressible Euler equations.



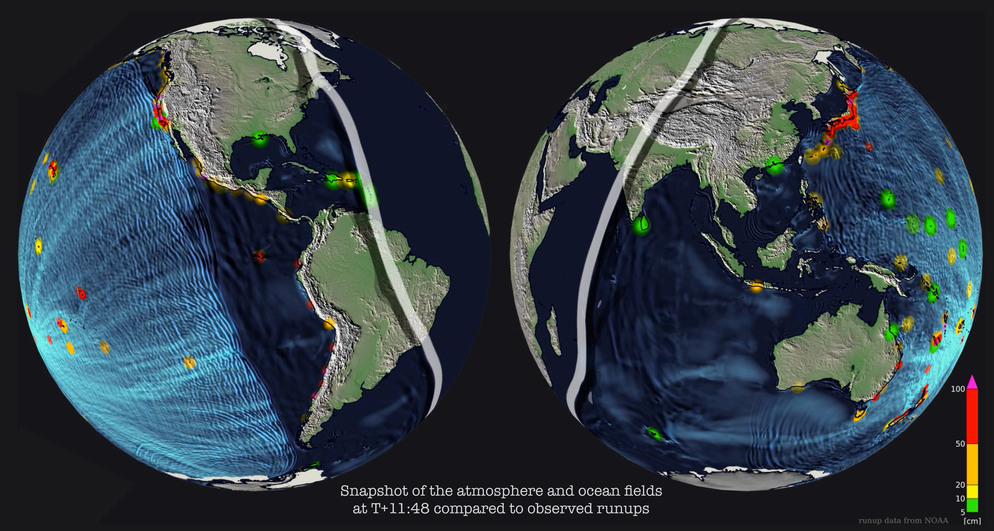
Overview of the length scale comparisons considered in this two-layer model

An expansion of the equations based on the length-ratio parameters and a density-weighted vertical averaging yield equations governing the flow on 2D spherical shells. This systems solves the flow in both the atmosphere and the ocean allowing dynamic two-directional energy transfer. The density weighting yields layer-averaged atmospheric properties that converge to observed values once a sufficient atmospheric thickness is considered.



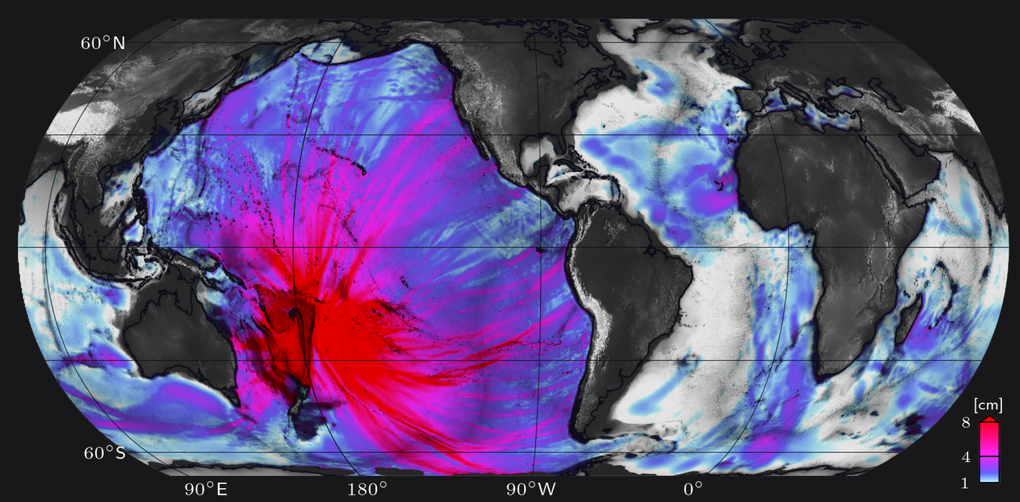
Local speed of sound (solid) and speed based on Favre-averaged temperature (dashed) versus atmospheric thickness using International Standard Atmosphere profiles

Two-way coupling is essential to providing **predictive** simulation tools for ocean-atmosphere interaction and understanding the **physical mechanisms** leading to large waves around the world.



Snapshot of the atmosphere and ocean fields at T+11:48 compared to observed runups

runup data from NOAA



Historical maximum sea height change at T+18hrs

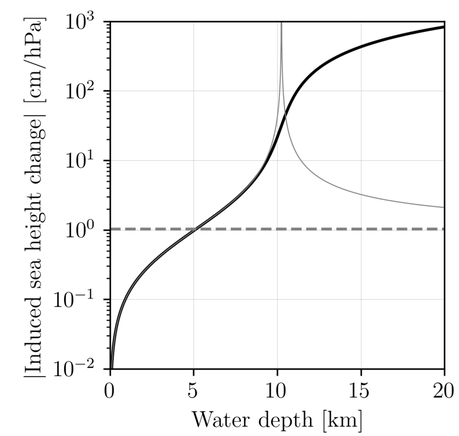
← Link to **paper** and **open-source** high-performance numerical **code**

No more Proudman resonance

The linear analysis of the TWC system reveals two pairs of gravito-acoustic eigenmodes, termed $\mathscr{A}$ and $\mathscr{G}$, which are respectively representative of the fast-traveling atmospheric wave (Lamb wave) and the slower-travelling gravity waves in the ocean.

Finite $\mathscr{A}$-mode induced sea height change

Unlike the forced SWE approach, which contains a singularity when atmospheric and gravity wave speeds match, referred to as the 'Proudman resonance', the sea height change induced by the $\mathscr{A}$ mode remains finite for all ocean depths on Earth.



Forced SWE (light grey), TWC (black) and pure hydrostatic (dashed grey) sea height change in response to a ground pressure change over a range of water depths

Refraction: $\mathscr{A} \leftrightarrow \mathscr{G}$ mode energy transfer

Energy transfer via refraction at steep changes in bathymetry is found to be significantly modified by the two-way coupling and is key to explaining unexpected early-arriving large waves around the world notably in the farfield region from the volcano (e.g. Atlantic ocean).

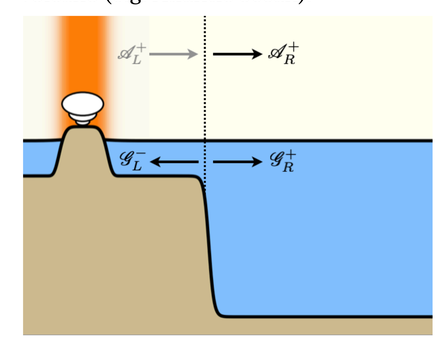


Illustration of the refraction problem: as the atmospheric wave (orange) spreads away from the volcano, it encounters steep changes in water depth where energy can be transfer from $\mathscr{A} \rightarrow \mathscr{G}$ which then propagates as would a regular tsunami.

Simulation inputs

To perform predictive ~24h timescale simulations, the following inputs are required:

- State of the atmosphere (e.g. ERA5 fields on pressure levels)
- Global bathymetry (e.g. GEBCO charts)
- Polar ice coverage (e.g. NSIDC sea ice index)
- Initial energy injection into water/atmosphere layers