Long-wave isentropic ocean-atmosphere dynamics: addressing a blind spot in tsunami warning systems

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On the 15th of January 2022, the powerful explosion of the Hunga Tonga-Hunga Ha'apai volcano injected a large amount of energy into the ocean and atmosphere. This was the first event of its kind to be captured in such detail by modern instruments, e.g. worldwide network of pressure sensors, IR spectral bands of Earth-observing satellites, providing a view of the coherent vertical structure of the generated atmospheric wave. Likened to the 1883 Krakatoa explosion, the event triggered unexpected worldwide tsunamis revealing blind-spots in tsunami warning systems which highlighted the need for a better understanding of global ocean-atmosphere interactions. Starting from the fully-compressible Euler equations, a two-way-coupled system governing the long-wave behaviour of thin layers (with respect to the radius of Earth) representing the ocean and atmosphere, under an isentropic constraint, was derived [1]. This approach incorporates bathymetry and topographic features as well as three-dimensional atmospheric non-uniformities through their depth-average over a spherical shell. Linear analysis of the obtained system yields two pairs of gravito-acoustic waves which are found to be representative of the fast-travelling atmospheric wave (with a propagation speed mainly governed by the atmospheric-layer-averaged speed of sound) and the slower-travelling gravity waves in the ocean (with a propagation speed mainly governed by local water depth). Remarkably, the 'Proudman resonance', observed in the forced shallow-water equation framework and invoked to justify, in part, observed large wave-heights, vanishes in favour of a continuous transition past the critical water depth, occurring when the two wave propagation speeds are closest. Two-dimensional non-linear global simulations were performed, using atmospheric conditions on the day, showcasing the predictive ability of the model (see Figure 1) [2]. Local maxima of water-height disturbance in the farfield from the volcano, linked to the atmospheric wave deformation, are observed, emphasising the importance of the atmospheric-layer modelling and two-way coupling for any daylong predictions. Future work would see the strategy extended to incorporate additional layers and physics e.g. ocean and atmosphere stratification, interaction with the upper atmosphere.

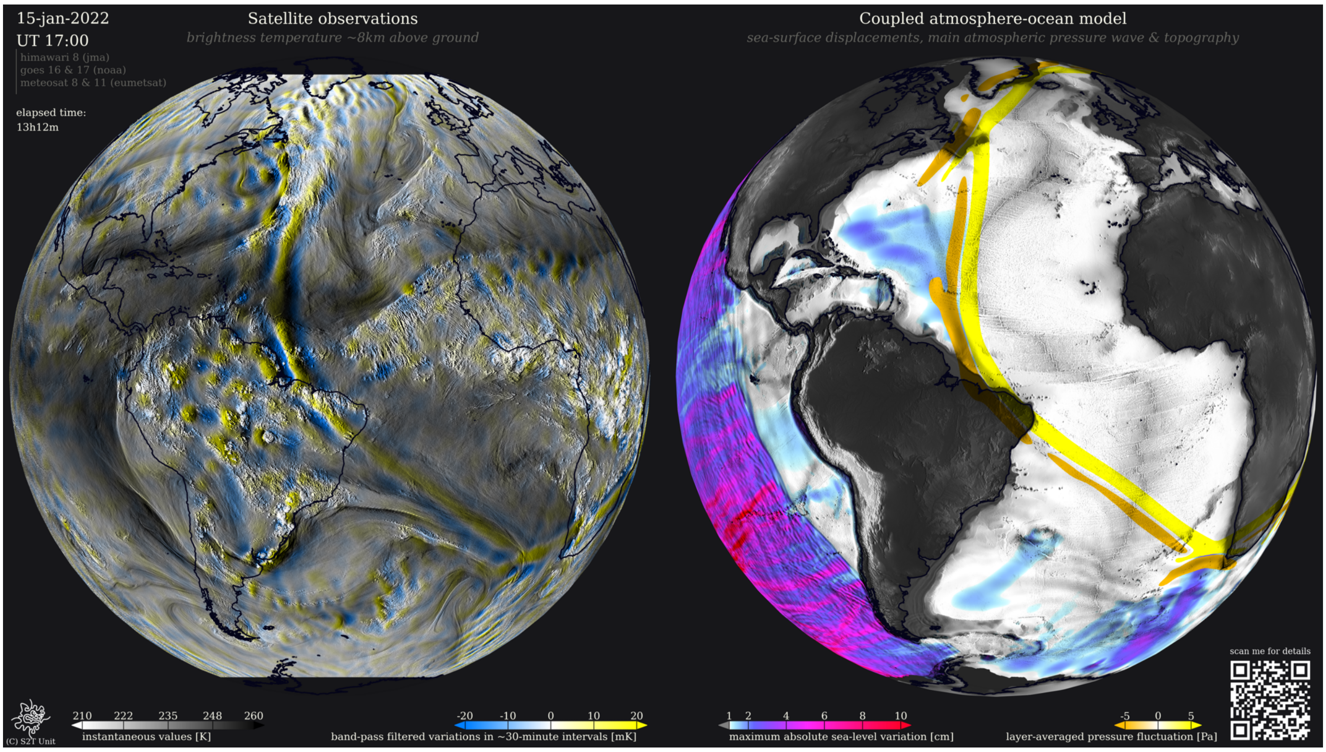

Figure 1: Instantaneous comparison between infra-red satellite data (left) and the two-way coupled model simulations (right, using `dNami` [3]) illustrating the wave deformation over time and its ability to locally inject energy into the water layer due to the wave pinching. Full video: `https://youtu.be/PaGtq5KBqJg`

References

[1] Winn, S.D. et al. (2023) Journal of Fluid Mechanics, 959, A22 `https://doi.org/doi:10.1017/jfm.2023.131`
[2] Winn, S.D. et al. (2022) Zenodo `https://doi.org/10.5281/zenodo.7691202`
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