High-frequency global seismic wave modelling with realistic ocean layers and bathymetry

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Abstract

Oceans are known to have complex and nuanced effects on seismic wave propagation; changing the behaviour of phases which propagate in the solid Earth, supporting the propagation of new classes of hydroacoustic waves, and acting as the source of the dominant ambient noise, the ocean microseism. Simulations with realistic ocean layers have historically been challenging, due to the need to explicitly mesh the low-sound-speed ocean and the challenge in implementing bathymetry with a conformal mesh. This has led to a number of simplifications becoming commonplace, including modelling the ocean as a 'weight load', and restriction to purely axisymmetric or local-scale domains. Such approximations are not appropriate in a high-frequency global seismology context, motivating us to develop a code capable of supporting realistic ocean layers with accurate bathymetry. Here, we present such an implementation of AxiSEM3D which should provide useful modelling output for comparison with new and exciting datasets from OBSs and Mermaids. We use this method to perform a high-frequency evaluation of the oft-used 'ocean loading' formulation, and find that it breaks down well above the 5-10 seconds period routinely suggested. Bathymetry is found to have a particularly substantial impact on surface-reflected phases (e.g. PP), and on the generation of ocean microseismic noise. We also consider the use of this method for interpreting observed water depth phases, and intend to work toward direct comparison to data.

– The Ocean Matters –

High-frequency seismic modelling with realistic ocean layers

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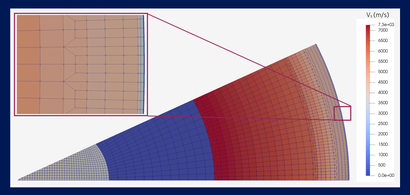
1. Motivation

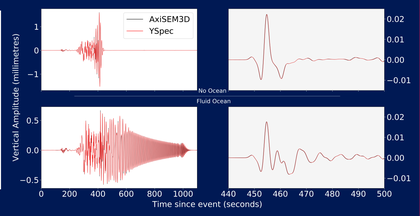
- Oceans cover most of our planet, but are challenging to model seismically.
- Nonetheless they are interesting and significant (e.g. in microseism generation).
- Previous approximations include 'ocean loading'[1] or localised formulations[2,3].
- These are of limited applicability - new methods must be developed.

This method enables computation of global, high-frequency synthetics in a 3D model with realistic oceans.

2. Implementation & Validation

- AxiSEM3D[4] is an efficient spectral element method for generation of synthetics which exploits wavefield smoothness by using an azimuthal Fourier expansion.
- Hence, we require only a 2D axisymmetric mesh (Fig. 1), even for fully 3D calculations. 1D Model: PREM. Where used, fluid ocean is 3km deep.





LEFT: Fig. 1 - Mesh section (10s resolution, with explicitly meshed ocean layer).

RIGHT: Fig. 2 - A 1D benchmark[5], at 2s. Left column: 20˚ distance, right column: P wave detail at 50˚. Top row: without ocean, bottom row: with ocean.

We implement and benchmark a global fluid ocean in AxiSEM3D, and enable inclusion of seafloor topography.

3. Results

3.1 Effects of a fluid ocean (1D Models)

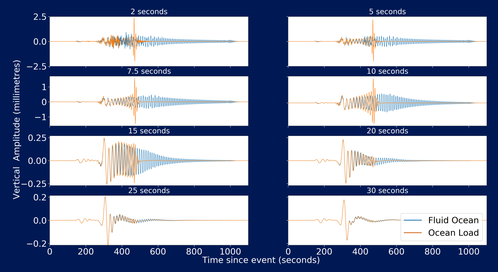


Fig. 3 - 1D Realistic ocean/ocean load approximation comparison at 20˚ distance. Decrease in misfit is non-linear (steepest between ~8s and ~15s).

Body waves (Fig. 2):

P waves become trapped in the water column

Surface waves (Fig. 2):

Lengthened by ocean, dispersion modified

Ocean Loading (Fig. 3):

Discrepancies small at ~20s, significant at ~15s. Agrees with Zhou (2016)[6], but not Komatitsch (2002)[1]

3.2 Effects of bathymetry (3D Models)

ANIMATION

Test source: *2015 April 30 New Guinea Earthquake (Mw = 6.6, 38km depth).*

3D Models: *Crust 1.0[7], SEMUCB-WM1[8]. Fourier order: 1500 in upper mantle.*

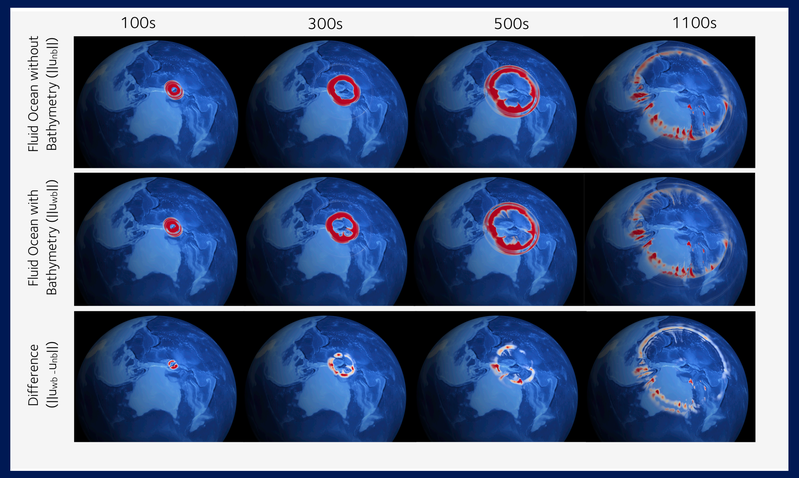
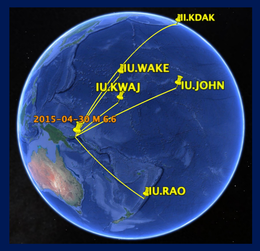
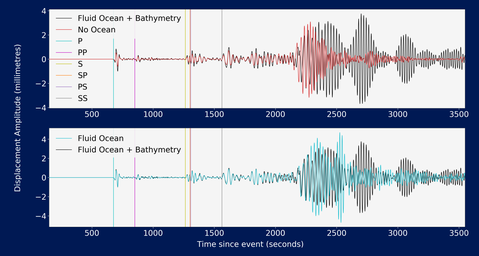


Fig. 4 - 3D synthetic wavefields. Top/Middle: without/with bathymetry; bottom: difference.





LEFT: Fig. 5 - Station Locations. Google Earth Pro[9]

RIGHT: Fig. 6 - Synthetics for station II.KDAK, log-gabor filtered (25s)

Bathymetry has less of an effect on synthetics than a fluid ocean. Differences greatest for surface waves.

3.3 Comparison to Data

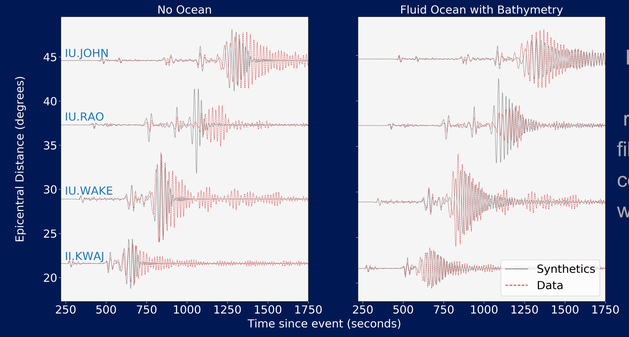


Fig. 7 - Comparison to data. 10s resolution, log-gabor filtered at 25s, vertical component convolved with the SCARDEC[10] STF.

Inclusion of a bathymetry gives a better fit to observed island data.

4. Discussion & Outlook

- 30 min global simulation at 10s (e.g Fig 6):
  - PREM + 3D model: 6000 processor-hours (p-h).
  - Add ocean: 90% increase. Add bathymetry: further 120% increase.
- Cut cost by shrinking mesh and optimising Fourier order:
  - 15 min at 5s with bathymetry: 33,500p-h; optimise for P-waves and save 80%.
- Possible developments: localised oceans, microseism generation.

– The seismic effects of the oceans and their bathymetry are significant –

Natural Environment Research Council

1. Komatitsch & Tromp, GJI 150(1), 2002 || **2. Cristini & Komatitsch**, J. Acoust. Soc. Am. 131(1), 2012 || **3. Bottero et al.**, J. Acoust. Soc. Am. 140, 2016 || **4. Leng et al.**, GJI 217(3), 2019 **5. Al-Attar & Woodhouse**, GJI 205(1), 2008 || **6. Zhou et al.**, GJI 206, 2016 || **7. Laske et al.**, EGU Abstract, 2013 || **8. French & Romanowicz**, GJI 199(3), 2014 || **9.** Landsat/Copernicus/IBCAO images &. SIO/NOAA/ US Navy/NGA/GEBCO data ||**10. Vallée & Douet**, Phys. Earth Planet. In. 257, 2016

CO_2 emissions

Per 10s, 30 minute global run with full bathymetry: ~170kWh = 70kg CO_2

Or 1/40th a return flight to AGU (from London)