Exo-oceanography and the Search for Life in Uncharted Waters

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Earth's ocean has been the site of several critical transitions in the evolution of our biosphere and the interplay between oceanography and biology has shaped the biological, chemical, and climatic histories of our planet. Nonetheless, existing models for exoplanet habitability and atmospheric biosignatures generally neglect ocean dynamics (e.g., by using a slab ocean) or exclusively consider the role of ocean circulation for heat transport and climate regulation (Hu & Yang, 2014; Yang et al., 2019).

The significance of ocean dynamics for exoplanet life detection studies extends far beyond heat transport. For example, wind-driven upwelling recycles nutrients lost to the deep ocean back to the surface environment where they may stimulate photosynthesis, which provides energy in the form of chemical disequilibrium that sustains life more broadly on our planet. Ocean circulation is thus a first-order control on the productivity and distribution of life on Earth. Moreover, ocean circulation patterns, sea ice coverage, and sea-air exchange kinetics modulate the extent to which biological activity within the ocean is expressed in the composition of Earth's atmosphere. Indeed, the chemical evolution of Earth's atmosphere is an imperfect reflection of the evolution of Earth's marine biosphere as the result of oceanographic phenomena (Reinhard et al., 2017; Olson et al., 2018). It is thus essential to understand how ocean dynamics may manifest on habitable exoplanets differing from Earth.

We address this issue using ROCKE-3D (Way et al., 2017), a fully coupled ocean-atmosphere general circulation model (GCM) with a thermodynamic-dynamic model for sea ice formation and advection. We spun up an Earth-like scenario that compares favorably with the modern Earth and provides a baseline for comparing marine habitats in our subsequent sensitivity analyses. We then systematically changed individual planetary parameters with respect to the baseline scenario, including insolation, planet mass and radius (and thus surface gravity), rotation period, orbital obliquity, surface pressure, and ocean salinity in isolation.

Our analysis focuses on three oceanographic metrics of biogeochemical significance:

1. depth of the mixed layer,
2. upwelling at the base of the mixed layer, and
3. sea-air gas exchange coefficients for O_2 and CH_4.

Together these metrics provide a framework for understanding limits on biospheric productivity and biosphere-atmosphere communication on a diversity of exoplanets.

We find that habitable planets are likely to differ in their capacity to support large biospheres—and that these planets will further differ in the efficiency of biosignature export from their biospheres to the overlying atmosphere. Such differences will be important considerations for prioritizing targets for detailed characterization and for interpreting ambiguous non-detections of biosignatures.

This presentation will (1) summarize the sensitivity of ocean circulation to key planetary parameters, (2) link unobservable oceanographic phenomena to potentially observable planetary and atmospheric observables, (3) discuss the biological constraints imposed by differing ocean habitats on other worlds, and (4) offer suggestions regarding the most favorable targets for exoplanet life detection studies.

References:

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