Development of a 2D Circulation Model for Rapid Exploration of Exoplanet Atmospheres

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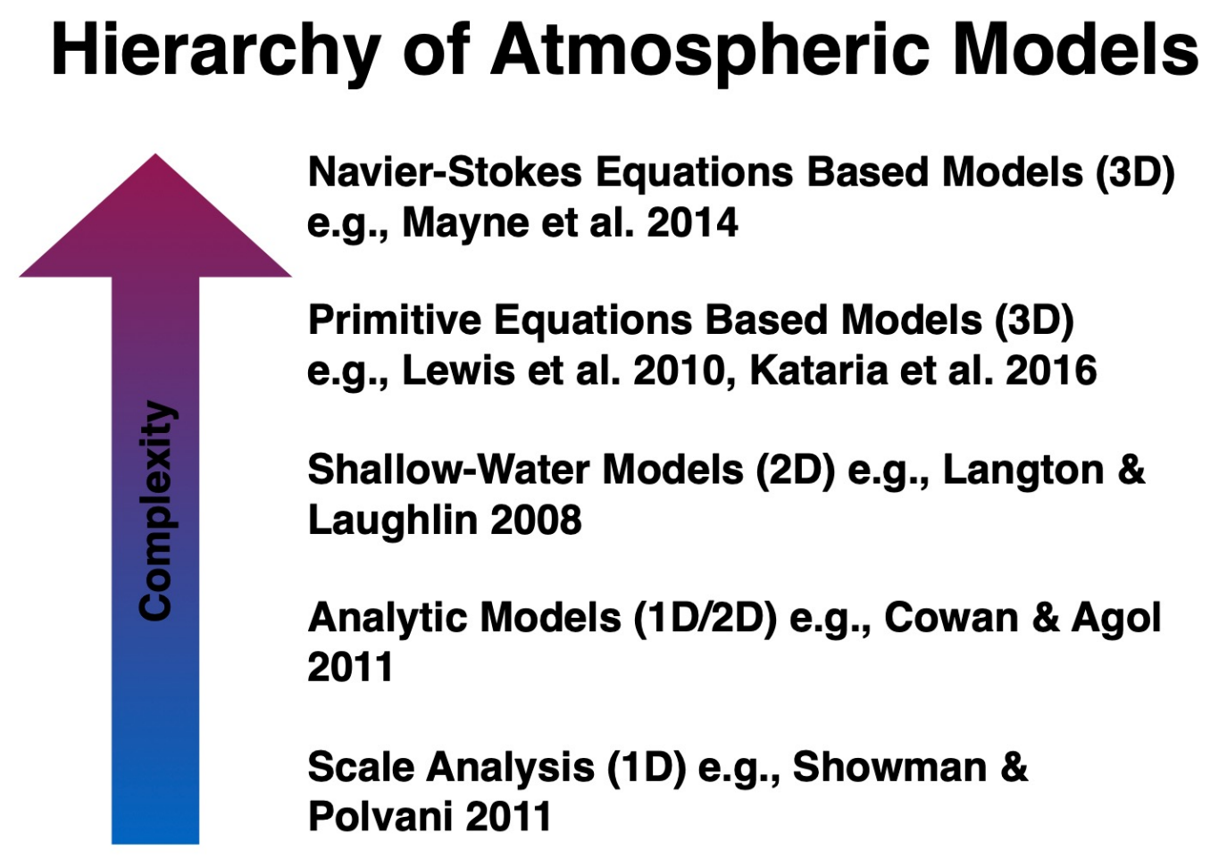
Objectives

- Develop a **two-dimensional (2D) atmospheric modeling framework** that is designed to capture the key physical processes in the atmospheres of **Mini-Neptune and Super-Earth exoplanets**, planets 1.6-6 times the radius of Earth
- These models, which employ the ‘shallow water’ equations along with specialized parameterizations for radiative transfer, clouds and chemistry, will be the first of its kind to identify dynamical mechanisms for this population of planets.

Background

- Current state-of-the-art exoplanet theoretical models generally fall into two categories (**Fig 1**):
  - **1D models** have ability to account for complex processes (e.g., cloud formation, chemistry) and rapidly explore relevant phase space, but largely ignore presence of horizontal gradients in an exoplanet atmosphere
  - Conversely, **3D models** capture spatial variations but cannot incorporate complex processes or rapidly conduct phase space studies due to computation requirements.
  - **2D models** provide a useful compromise in their relative speed and complexity, but to-date have only been applied to solar system planets (e.g.,[1]) and hot-Jupiter exoplanets (e.g., [2]).
- **Why Mini-Neptunes/Super-Earths?**
  - **Small planets most common**
  - **Readily characterized with current/future telescopes**
- Our 2D models of Mini-Neptunes/Super-Earths, and simulated observations derived from these models, can be readily applied to interpret ground- and space-based observations of their atmospheres
  - **Near-term applications**: observations with the Hubble Space Telescope (HST)
  - **Longer-term applications**: Make predictions for Mini-Neptunes/Super-Earths observed with James Webb Space Telescope (JWST), ARIEL, and Extremely Large Telescopes (ELTs)



Hierarchy of Atmospheric Models

- Navier-Stokes Equations Based Models (3D) e.g., Mayne et al. 2014
- Primitive Equations Based Models (3D) e.g., Lewis et al. 2010, Kataria et al. 2016
- Shallow-Water Models (2D) e.g., Langton & Laughlin 2008
- Analytic Models (1D/2D) e.g., Cowan & Agol 2011
- Scale Analysis (1D) e.g., Showman & Polvani 2011

Fig 1: Hierarchical list of atmospheric models for calculating atmospheric dynamics. As described above, most models used are 1D are 3D, and are therefore either low or high in complexity. In this work, we bridge this level of complexity with 2D shallow-water models of Mini-Neptunes/Super-Earths. Using these results, we will make observational predictions for a population of planets whose atmospheres will be readily characterized with current and future telescopes.

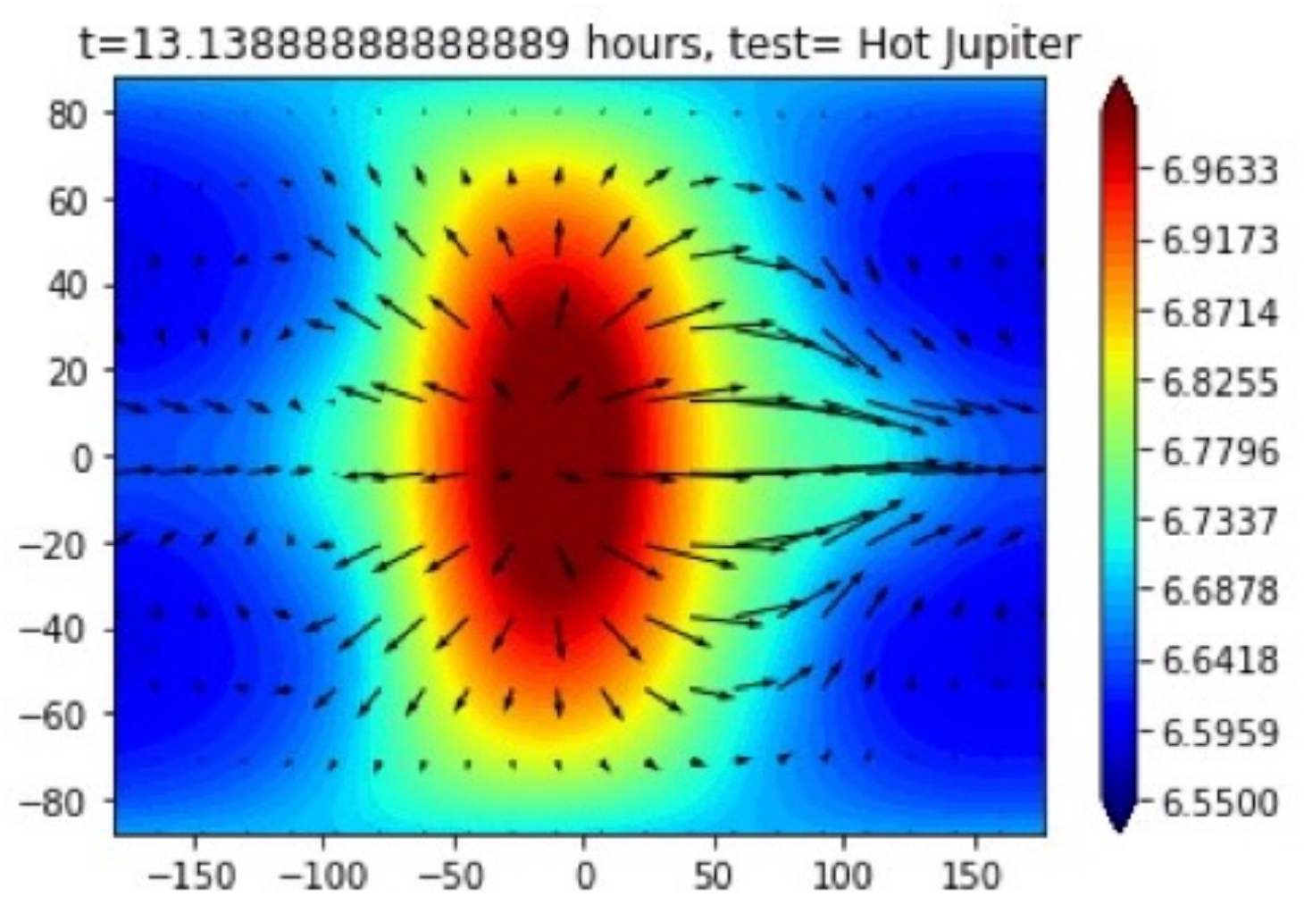


Fig 3: Map of the geopotential height (gh) from a SWAMP-E simulation of a hot Jupiter, replicating results from [2]. Overplotted are vector fields of steady state winds. This simulation assumes a radiative time constant, tau_rad of 1 Earth day, and drag timescale, tau_drag of 10 Earth days.

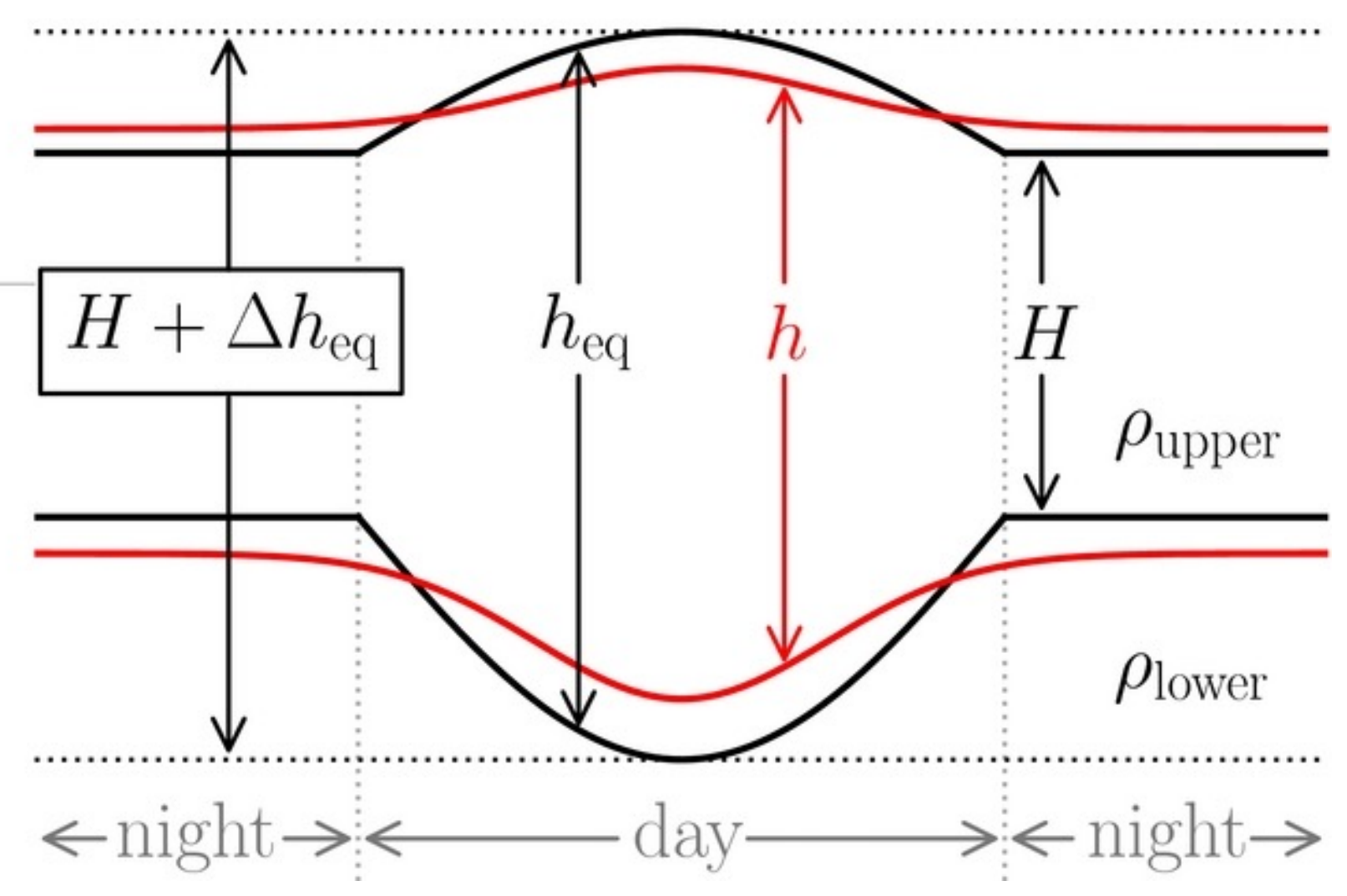


Fig 2: Illustration of a two-layer shallow-water model as applied to a tidally-locked giant exoplanet, from [2]. The upper layer with density rho_upper and thickness h overlies a lower layer with density rho_lower. The model will radiatively relax to a height heq over timescale tau_rad. This profile is set to have thickness H on the nightside and H+delta heq on the dayside. We employ a similar framework for modeling the atmospheric dynamics of Mini- Neptunes/Super-Earths.

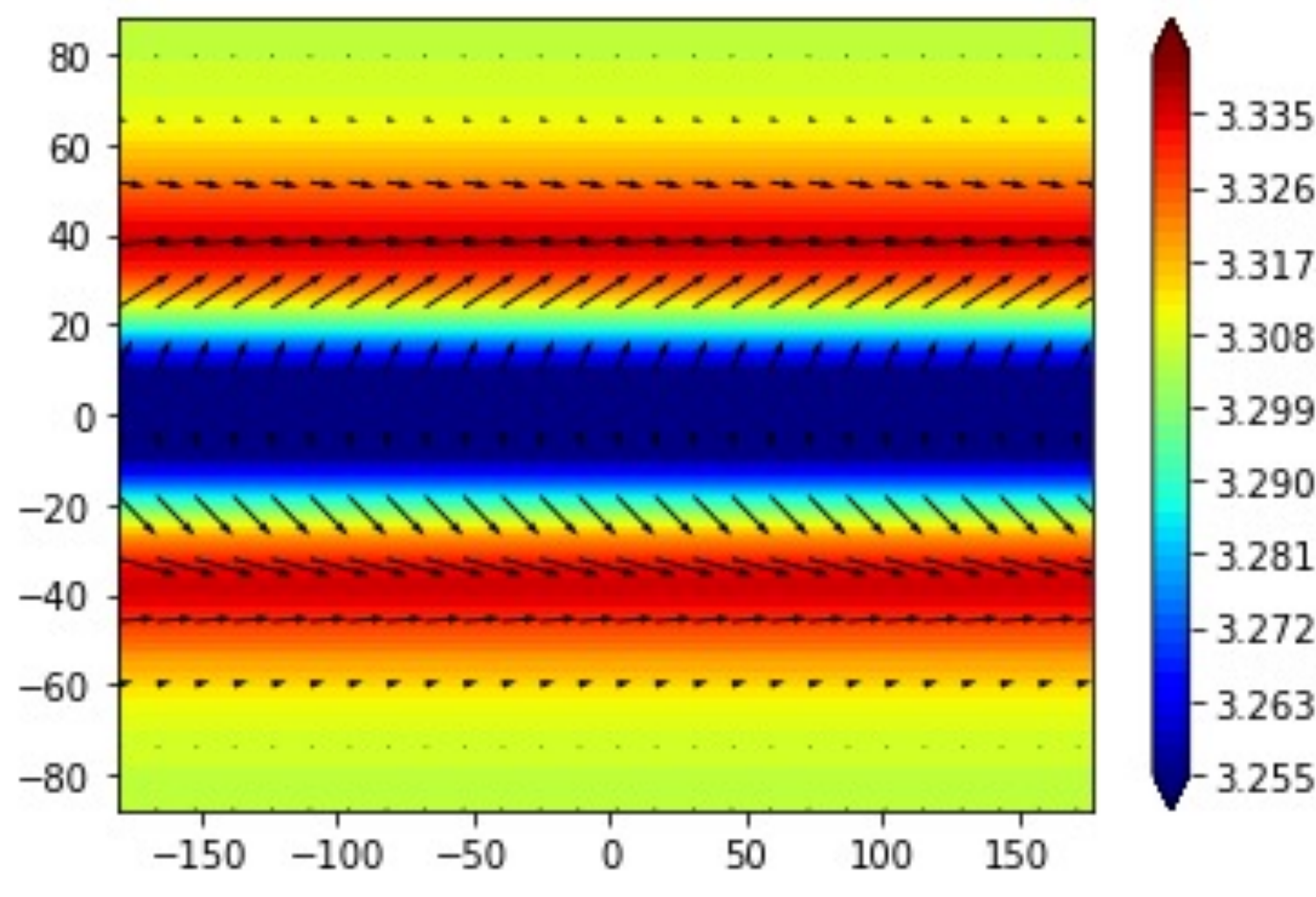


Fig 4: Geopotential (on a log10 color scale corresponding to the interval of 1800-2200 m^2/s^2) from a SWAMP-E simulation of Earth's troposphere with underlying topography corresponding to Earth's equinoctial state. The topography is a sine wave with a peak of 15000 m^2/s^2 at the equator. Two tropical eastward jets form symmetrically in mid-latitudes. Maximal wind speeds are approximately 35 m/s. We adopt a modified Euler's method as out time-stepping scheme and use a time step of 200 s.

Approach and Results

- Graduate student Ekaterina (Kath) Landgren has successfully built 2D code called Shallow-Water Atmospheric Model in Python for Exoplanets (**SWAMP-E**)
  - **Code features**:
    - Built from scratch in Python
    - Spectral dynamical core and optimized time-stepping routines
  - **SWAMP-E has been validated** against the test-suite presented in [3] and the hot Jupiter atmospheric simulations presented in [2] (**Fig. 3**)
- Moving from hot Jupiters to small planets
  - Taking a “meet in the middle” approach to exploring super-Earth and mini-Neptune atmospheres
  - We have begun exploration of weaker forcing conditions and broader assumption of planetary rotation rates
  - We also began efforts to validate SWAMP-E in “earth-like” planetary regimes presented in [4] and [5] then move into regimes of stronger forcing and slower rotation rates (**Fig. 4**)
- Final year objectives:
  - Focus on the **public release of SWAMP-E** via the Journal of Open Source Software (JOSS)
  - First of its kind exploration of the interplay between forcing strength and rotation rate for exoplanet atmospheres
    - Apply forcing specifications intermediate to the “earth-like” and hot Jupiter regimes and explore rotation rates across the full range expected for tidally-locked exoplanets
    - Provide critical constraints on the expected scale of atmospheric features on such planets, wind speeds, and thermal contrasts that can be easily folded into interpretation efforts of near-term observations from the James Webb Space Telescope
    - Graduate Student Kath Langren will present initial results at the upcoming AGU meeting
    - Paper planned for submission in Spring 2022

Significance/Benefits to JPL and NASA

- Project leads to the development of the first-of-its-kind 2D circulation models applied to Mini-Neptunes and Super- Earths
- Remarkable progress has been made to build and validate these models, especially in the midst of a pandemic
- Our model results, particularly transit/eclipse/reflection spectra derived from these models, will provide a framework for future “pseudo-retrieval” exploration of phase space relevant to understanding atmospheric dynamics, radiation, and chemistry in Mini-Neptunes/Super-Earths
- Our 2D models can also be used to identify interesting phase space for more detailed 3D modeling
- SWAMP-E can also be extended to other regimes, including brown dwarfs and terrestrial, potentially habitable exoplanets, which can guide the development of Astro2020 Decadal Concepts or future ELT efforts to identify biosignatures from the ground

References
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