National Aeronautics and Space Administration

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

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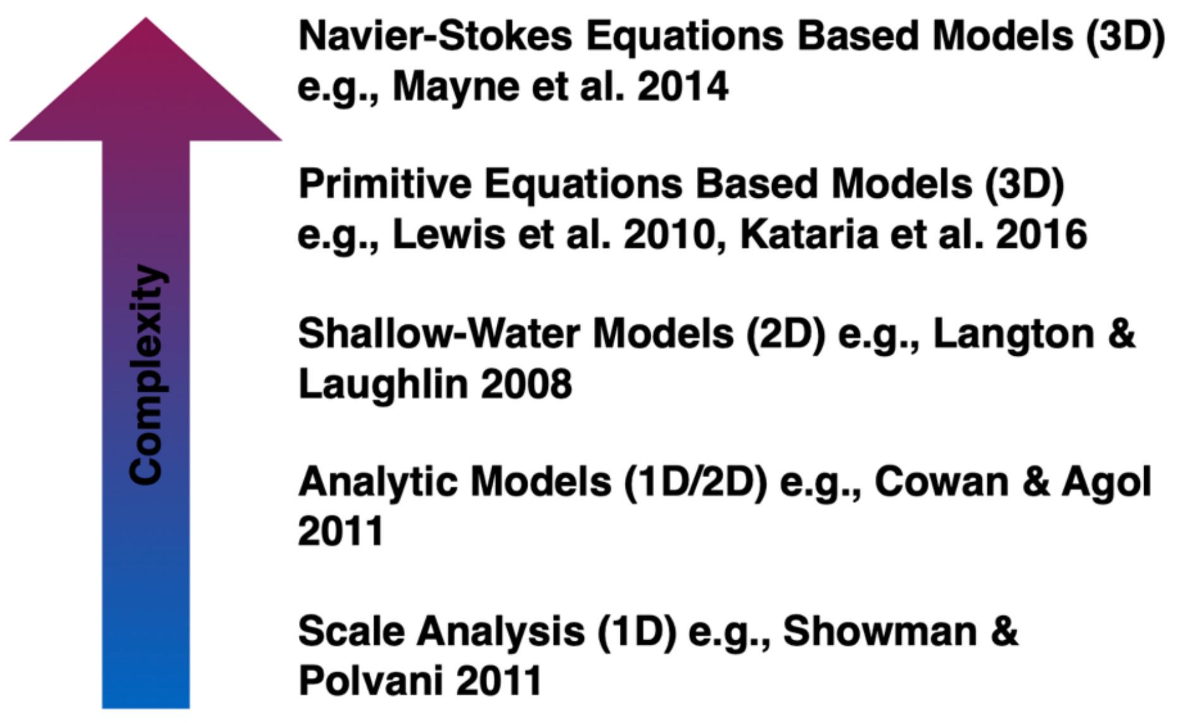
Program: FY22 SURP
Strategic Focus Area: Extra-solar planets and star and planetary formation

Objectives

- Develop a **two-dimensional (2D) atmospheric modeling framework** that is designed to capture the key physical processes in the atmospheres of **sub-Neptunes**, 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.

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

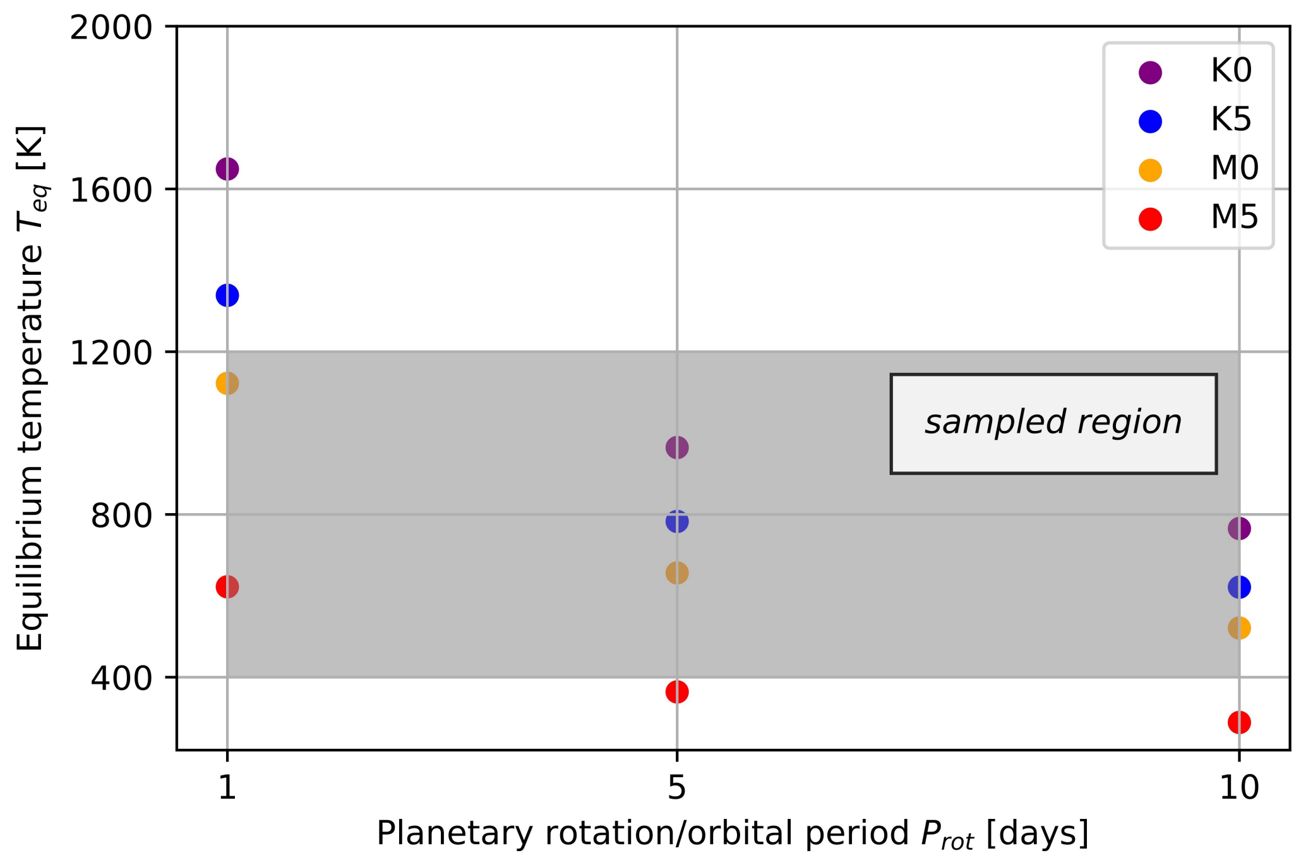
Shallow-Water Models (2D) e.g., Langton & Laughlin 2008

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. 2: Our model grid of sub-Neptune simulations using SWAMPE. The plot shows planetary equilibrium temperature as a function of rotation period for planets around K0, K5, M0, and M5 stars. Our sample region is highlighted in grey: we produce SWAMPE simulations at rotation periods of 1, 5, and 10 days and at planetary equilibrium temperatures of 400, 800, and 1200 K.



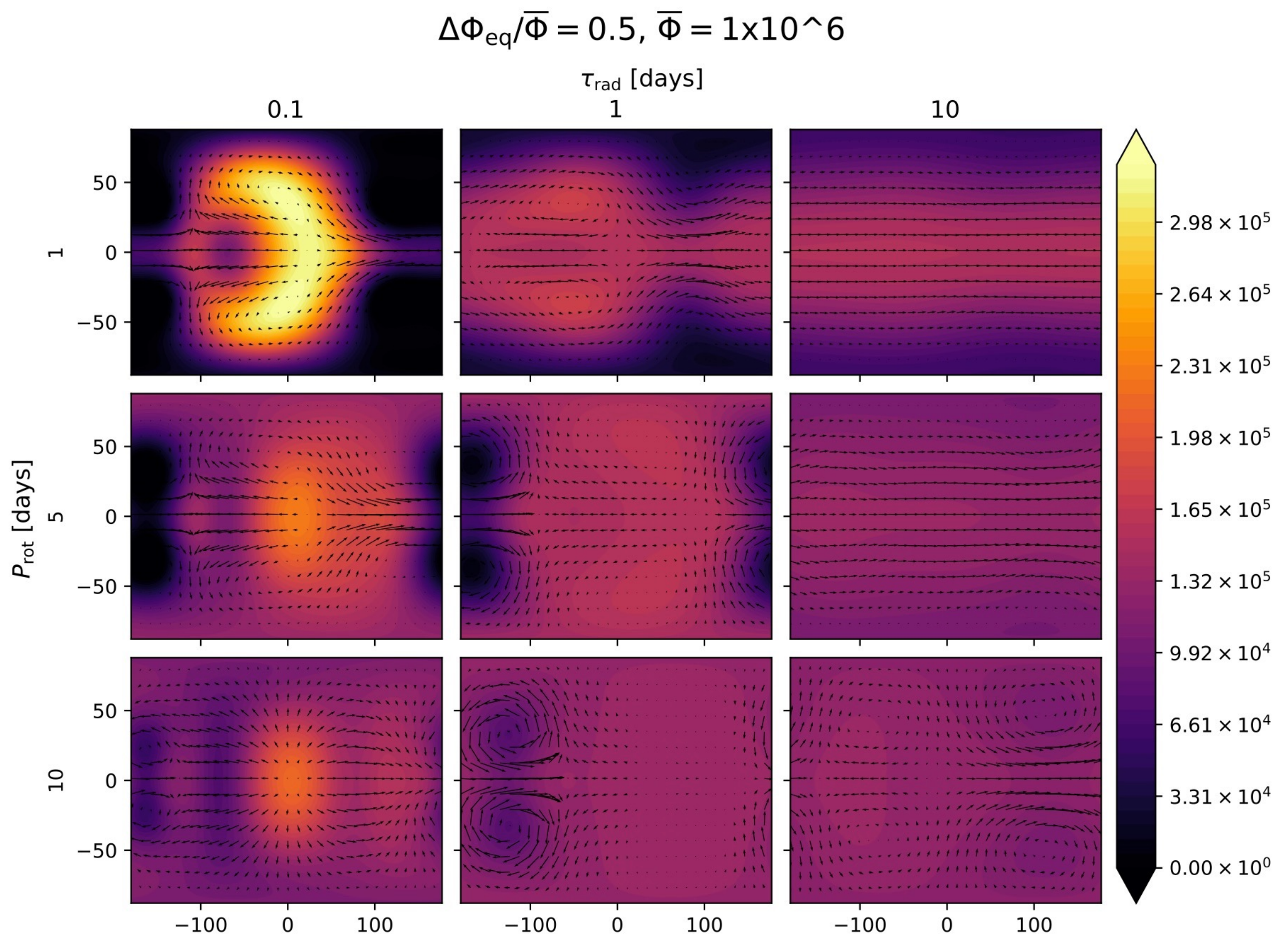


Fig. 3: The geopotential and wind fields for a synchronously rotating sub-Neptune with a forcing amplitude equal to half of scale height and geopotential at scale height equal to 10^6 m^2/s^2. The panels show combinations of radiative constant values of 0.1, 1, and 10 Earth days, and rotation period values of 1, 5, and 10 Earth days.

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 sub-Neptunes?**
  - **Small planets most common**
  - **Readily characterized with current/future telescopes**
- Our 2D models of sub-Neptunes, 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)

Results/Relevance

- Graduate student Ekaterina (Kath) Landgren has successfully built 2D code called Shallow-Water Atmospheric Model in Python for Exoplanets (SWAMPE)
- Code features:
  - Built from scratch in Python
  - Spectral dynamical core and optimized time-stepping routines
  - Validated against the test-suite presented in [3] and the hot Jupiter atmospheric simulations presented in [2]
- SWAMPE and Sub-Neptunes
  - SWAMPE has been used to model tidally-locked, sub-Neptune exoplanets as a function of day-night forcing and rotation period (1, 5, and 10 Earth days; **Fig 2-3**) (Landgren et al., in prep, ApJ)
  - Dynamical features
    - Geopotential exhibits smaller contrasts from dayside to nightside as compared to hot Jupiters, even at equivalent radiative forcing
    - Varying the radiative timescale, τrad, from 0.1 days to 10 days, leads to a transition from day-night flow with a visible hot spot to jet-dominated flow.
    - The low-forcing regime (not shown here) exhibits more temporal variability due to oscillations driven by the emergent Rossby waves.
  - Results to be presented at Fall AGU meeting
- PhD Student Landgren defending Oct 2022, and will be beginning a postdoctoral fellowship at CIRES in Jan 2023

Significance/Benefits to JPL and NASA

- Results from SWAMPE, particularly the 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. SWAMPE models can also be used to identify interesting phase space for more detailed 3D modeling
- SWAMPE can also be extended to other regimes, including brown dwarfs and terrestrial, potentially habitable exoplanets, which can guide the development of telescopes recommended by the Astro2020 Decadal.

Publications:
Landgren et al., in prep, JOSS
Landgren et al., in prep, ApJ

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