




# SWAMPE: A Shallow-Water Atmospheric Model in Python for Exoplanets

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## Software

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## Summary

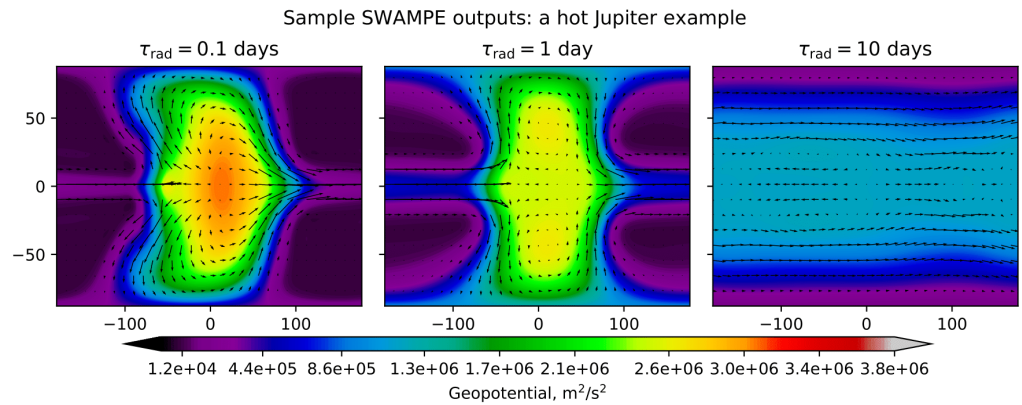
In order to answer questions about potential habitability of exoplanets, it is important to develop a robust understanding of a variety of dynamic processes that can take place in exoplanetary atmospheres. While many exoplanets are readily characterized with current facilities like Hubble and James Webb Space Telescope, exoplanet scientists work with indirect and limited observations of the planets that they study. To form hypotheses about their climate, weather, and atmospheric composition, astronomers need robust models that demonstrate how atmospheres act under different conditions. One-dimensional energy-balance models can capture complex mechanisms such as cloud formation and can rapidly explore the parameter ranges, but they fail to account for variations with longitude. In contrast, three-dimensional models capture the variation in latitude, longitude, and altitude, but they are computationally expensive, sometimes taking months to explore the parameter regimes. Their complexity can also obscure the mechanisms that govern atmospheric phenomena. This leaves a natural gap for two-dimensional models, which can capture the spatial variability as well as rapidly explore the parameter space and study the dynamical mechanisms.

SWAMPE is a Python package for modeling the dynamics of exoplanetary atmospheres. SWAMPE is an intermediate-complexity, two-dimensional shallow-water general circulation model. Benchmarked for synchronously rotating hot Jupiters and sub-Neptunes, the code is modular and could be easily modified to model dissimilar space objects, from Brown Dwarfs to terrestrial, potentially habitable exoplanets.

## Modeling Exoplanet Atmospheres with SWAMPE

Exoplanets exist in a vast range of orbital and planetary parameters. SWAMPE is designed to be adaptable to a variety of possible regimes. The user can specify physical parameters such as radius, surface gravity, rotation rate, stellar radiation, and scale height.

SWAMPE solves the shallow-water equations using the spectral method ([Hack & Jakob, 1992](#)), with a modified Euler's method time-stepping scheme ([Langton, 2008](#)). To ensure numerical stability, two filters are applied: the modal-splitting filter ([Hack & Jakob, 1992](#)) and a sixth-degree hyperviscosity filter ([Gelb & Gleeson, 2001](#)). SWAMPE can save simulation data at any user-specified frequency. The model outputs geopotential maps and the associated wind fields, which can be used to make inferences about the temperature profiles of exoplanet atmospheres and the dynamical mechanisms behind them. Sample SWAMPE outputs are illustrated in [figure 1](#).



**Figure 1:** Sample SWAMPE output: geopotential maps for a hot Jupiter exoplanet at three values of radiative timescale  $\tau_{\text{rad}}$ : 0.1 days, 1 day, and 10 days. This is a replication of the results in Perez-Becker & Showman (2013) for a high insolation, no-drag regime.

## Statement of need

Current efforts to model exoplanet atmospheres primarily focus on minimal-complexity one-dimensional and high-complexity three-dimensional models. One-dimensional (1D) energy-balance models can capture complex mechanisms (e.g., Bell & Cowan, 2018) and can rapidly explore the parameter space, but they fail to account for longitudinal variation. Furthermore, recent observations of giant exoplanets have shown that one-dimensional models cannot completely describe some of the key atmospheric processes (e.g., Feng et al., 2016). On the other hand, complex three-dimensional (3D) models can capture variation in the physical space. They are frequently based on primitive equations (Kataria et al., 2016; e.g., Menou & Rauscher, 2009; Parmentier et al., 2013) or on the Navier-Stokes equations (e.g., Cooper & Showman, 2006; Dobbs-Dixon & Agol, 2013) and can be used to understand a variety of radiative, chemical, and dynamical processes. 3D models such as ROCKE-3D (Way et al., 2017) can be tuned to a variety of exoplanets. However, 3D models tend to be computationally expensive, sometimes taking months to explore the parameter space.

The difference in capability between 1D and 3D models leaves a natural gap for two-dimensional shallow-water models, which can capture the spatial variability as well as run fast enough to rapidly explore the parameter space and study the dynamical mechanisms. In particular, shallow-water models have been used to study solar system planets, including Earth (Brueshaber et al., 2019; e.g., Ferrari & Ferreira, 2011). Outside the solar system, shallow-water models have been used to understand a variety of atmospheric phenomena of hot Jupiters, such as atmospheric variability (Menou et al., 2003) and superrotation (Showman & Polvani, 2011). They have also been used to make observational predictions for hot Jupiters (e.g., Langton & Laughlin, 2008; Perez-Becker & Showman, 2013). However, many of these models are written in Fortran, which makes them difficult to adapt to the varied needs of exoplanetary science.

SWAMPE offers a fully Python, open-source implementation of the 2D shallow-water system. This package does not require multiple cores, and is flexible and modular. SWAMPE is designed to be easily modified to model dissimilar space objects, from Brown Dwarfs to terrestrial, potentially habitable exoplanets. SWAMPE provides the capability to conduct wide parameter sweeps and to produce maps of the thermal and wind properties of the planets in latitude and longitude, which can be used to help constrain and make predictions for observations of their atmospheres.

## Documentation

Documentation for SWAMPE, with step-by-step tutorials for research applications, is available at <https://swampe.readthedocs.io/en/latest/>.

## Similar tools

Bell EBM (Bell & Cowan, 2018) is an energy-balance model. MITgcm (Marshall et al., 1997) is an open-source, Fortran-based 3D global circulation model which includes a shallow-water mode. GFDL FMS (Dunne et al., 2020) is also a 3D GCM that supports a shallow-water mode. Dedalus (Burns et al., 2020) is a framework for solving partial differential equations using spectral methods, including on a sphere.

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