Demarcating Circulation Regimes of Synchronously Rotating Habitable Planets

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We investigate the atmospheric dynamics of terrestrial planets in synchronous rotation within the habitable zone of low-mass stars using the Community Atmosphere Model (CAM). We define three dynamical regimes in terms of the equatorial Rossby deformation radius and the Rhines length.

The **Rossby deformation radius** is the ratio of buoyancy to rotational forces and tends to be larger for slowly rotating planets.

The **Rhines length** is the scale at which turbulent flow organizes into zonal jets, calculated as the ratio of wind velocity to rotation rate.

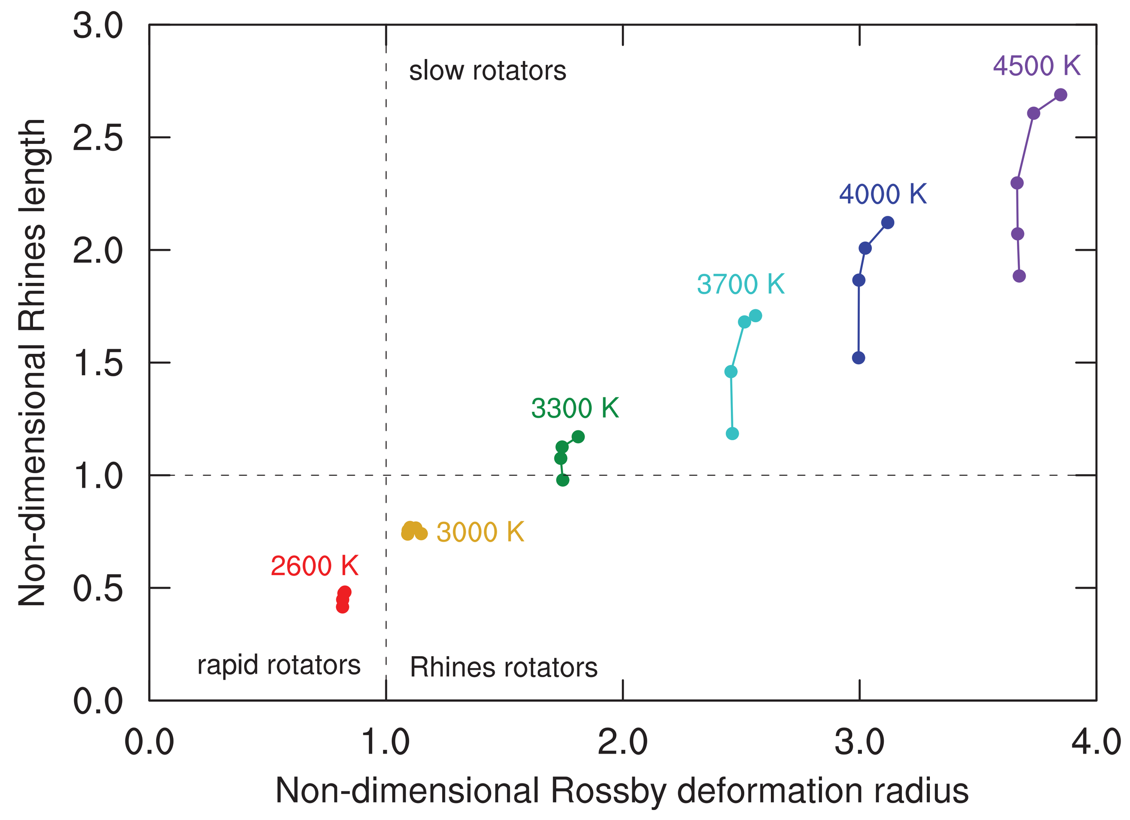
GCM calculations shown in the figure to the right are performed for stars of different stellar effective temperatures (labels) at increasing stellar flux up to the inner edge of the habitable zone, where the model atmosphere becomes unstable with the initiation of a runaway greenhouse. (Note that the Rossby radius and Rhines length have been scaled by planetary radius in our figures.)

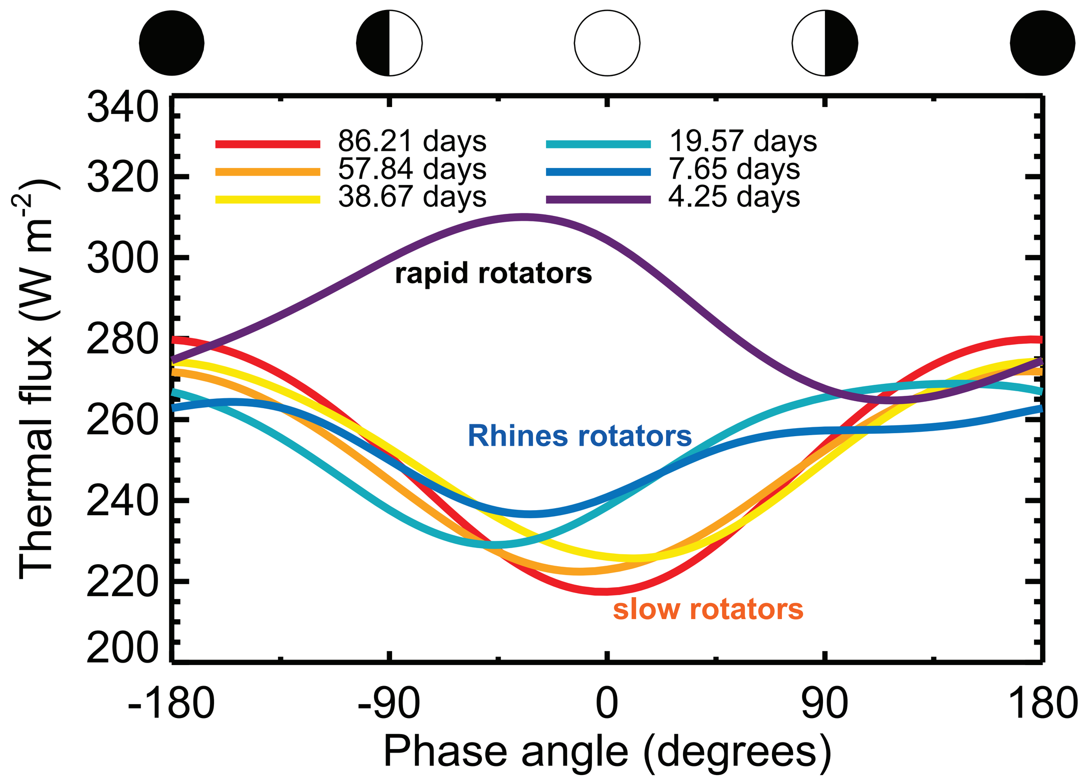
The **slow rotation** regime is characterized by a mean zonal circulation that spans from the day to night side. Slow rotation requires that both the Rossby deformation radius and the Rhines length exceed planetary radius, which occurs for planets around stars with effective temperatures of 3300 K to 4500 K (rotation period > 20 days).

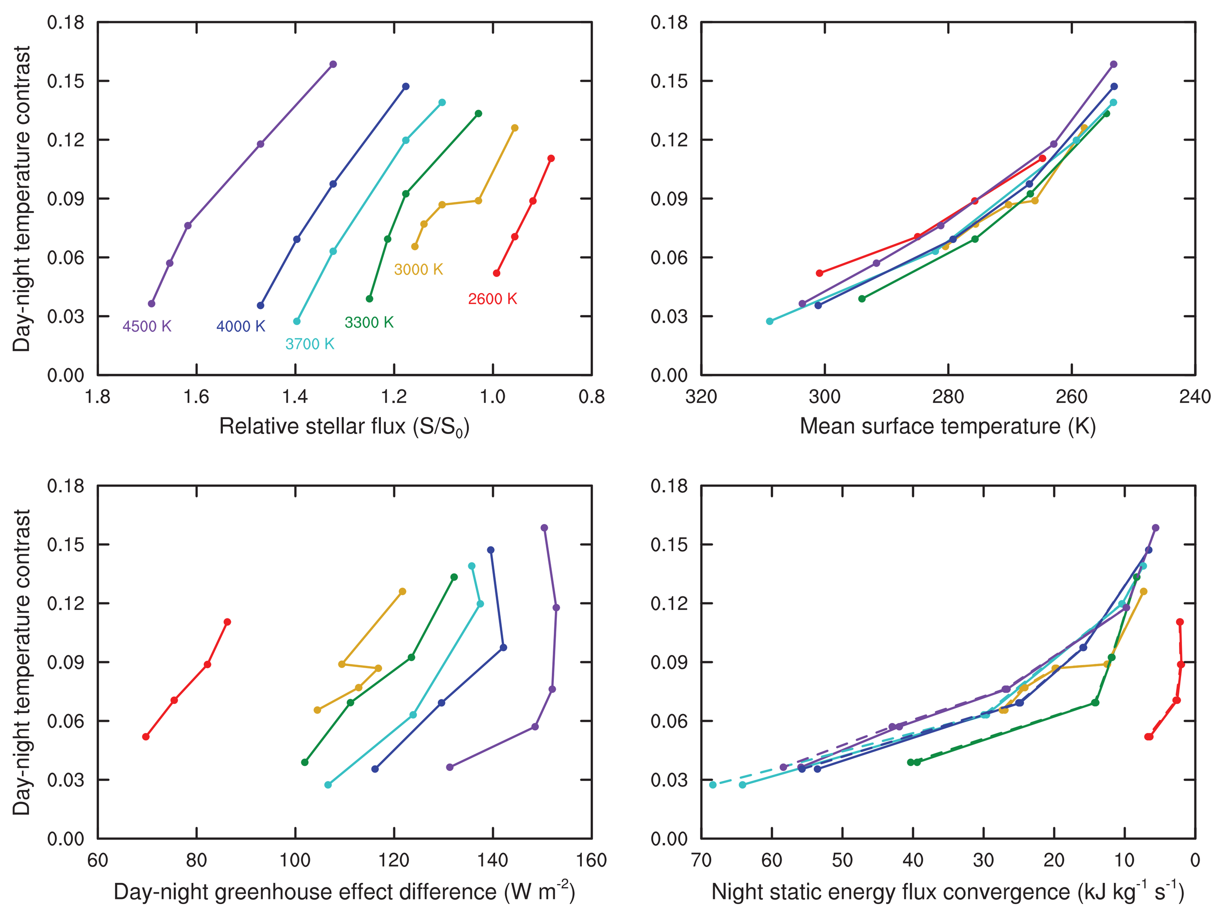
The **rapid rotation** regime shows a mean zonal circulation that only partially spans a hemisphere, with banded cloud formation beneath the substellar point. The rapid rotation regime is defined by the Rossby deformation radius being less than planetary radius, which occurs for planets orbiting stars with effective temperatures of less than 3000 K (rotation period < 5 days).

The **Rhines rotation** regime retains a thermally-direct circulation from day to night side but also features midlatitude turbulence-driven zonal jets. Rhines rotators are expected for planets around stars with effective temperatures in the range of 3000 K to 3300 K (rotation period ~5 to 20 days), where the Rhines length is greater than planetary radius but the Rossby deformation radius is less than planetary radius.

The dynamical state can be inferred from observations of orbital period and spectral type of the host star as well as from comparing the morphology of the thermal emission phase curves of synchronously rotating planets. **Thermal phase curves** (shown to the right) can identify synchronously rotating habitable zone planets as slow rotators (minimum thermal flux near 0°), Rhines rotators (minimum thermal flux near −45°), and rapid rotators (maximum thermal flux near −45°).



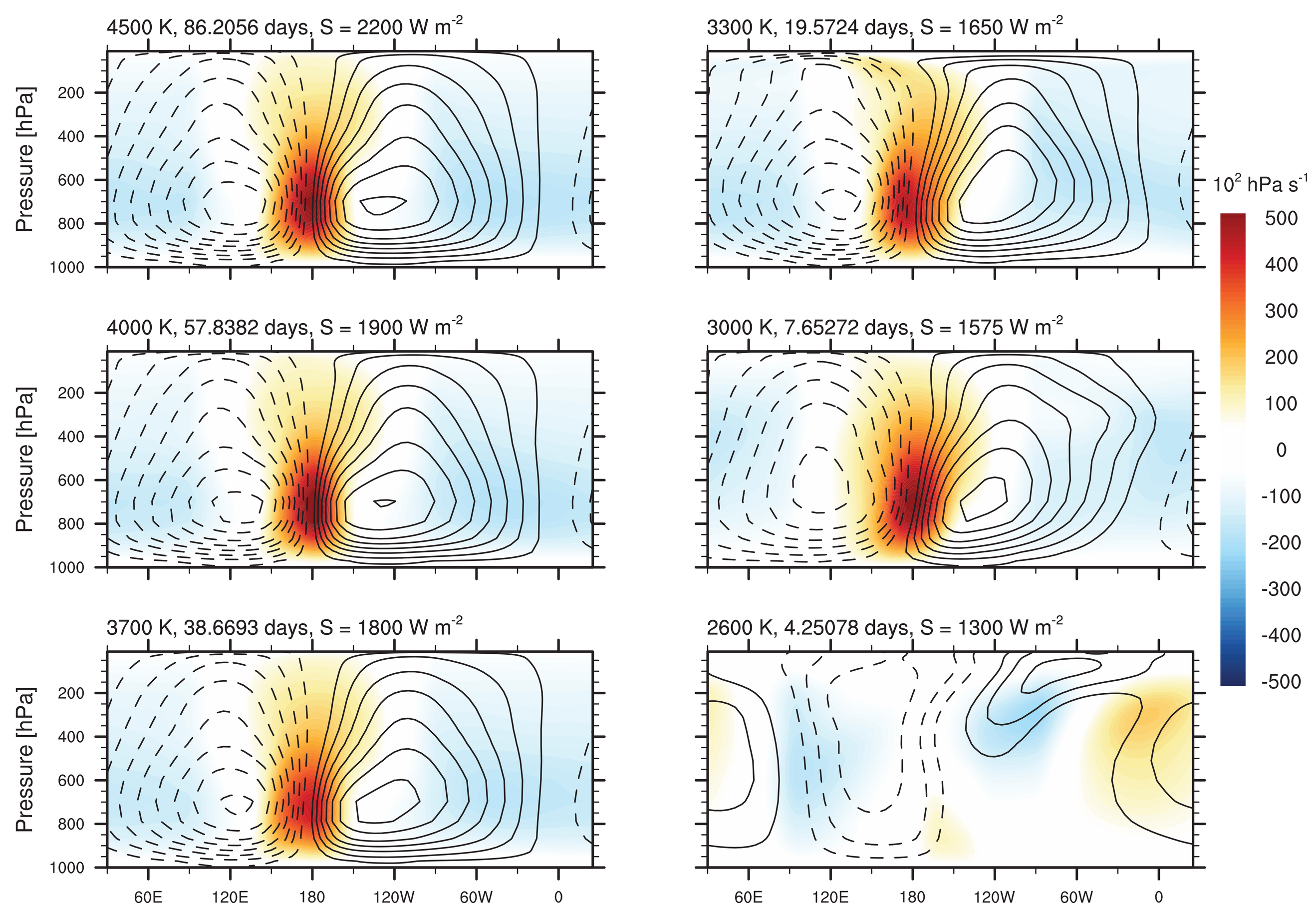




The full set of simulations is shown as scaled day-night temperature contrast, (mean day minus night temperature divided by equilibrium temperature) , versus relative stellar flux, with warmer stars at the left side of the panel (top left). These simulations all show a correlation between scaled day-night temperature contrast and mean surface temperature (top right).

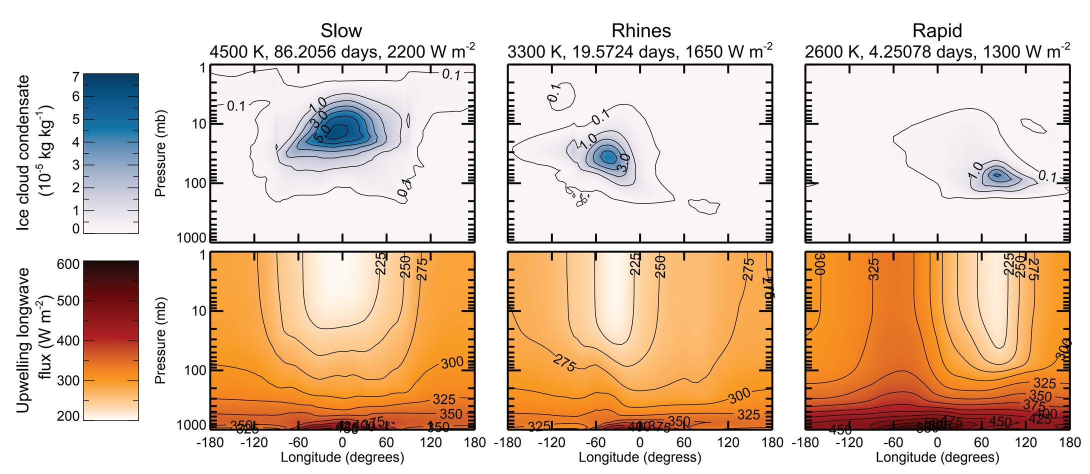
This decrease in day-night temperature contrast as the planet warms corresponds to a decrease in the day-night greenhouse effect difference (bottom left), which occurs as a result of an increase in the the dry static energy flux convergence on the night side (bottom right, solid lines). Static energy is the sum of an air parcel's internal energy, potential energy due to gravity, and latent energy due to moisture. The static energy flux represents the change in static energy due to wind, while the static energy flux convergence describes the inward flow of static energy. An increase in static energy flux convergence on the night side will lead to an increase in internal energy, which, causes the greenhouse effect to increase. The total static energy, with the moist latent energy component included, is also shown (bottom right, dashed lines), but the contribution of this latent energy is small.

The top left panel shows that at a fixed value of relative stellar flux, planets around hotter stars have a larger value of day-night temperature contrast. This increased day-night temperature contrast occurs due to changes in both rotation period and the spectral energy distribution.

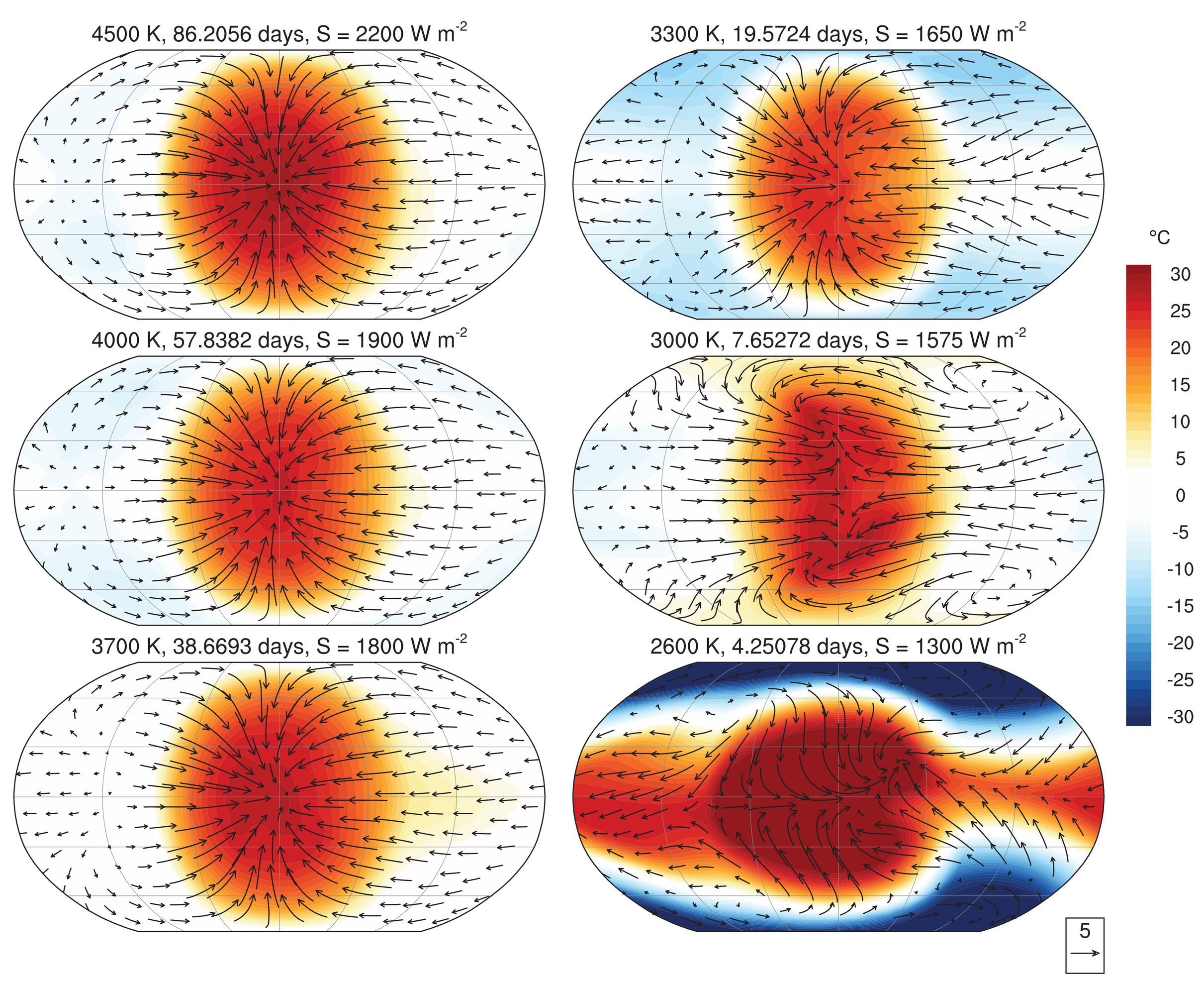


The Walker circulation and meridionally-averaged vertical wind for synchronously rotating planets around 4500 K, 4000 K, 3700 K, 3300 K, and 3000 K stars all show a thermally direct zonal circulation that spans day to night side. The 2600 K case shows rapid rotation with a Walker circulation that spans less than a full hemisphere.

The contour interval for the Walker circulation is 30×10^{11} kg s^{-1} , with solid contours indicating clockwise circulation and dashed contours indicating counterclockwise circulation. Shading indicates pressure tendency, which corresponds to rising (warm colors) or sinking (cool colors) motion. This particular set of simulations was chosen because they all have an approximately constant value of day-night contrast.



The maximum in ice cloud condensate mass mixing ratio (top row) corresponds to the minimum in upwelling longwave flux (bottom row), which is closely tied to the location of cirrus clouds. Slow rotators show this cirrus cloud maximum at the substellar point, while this cloud absorption is shifted westward of the substellar point for Rhines rotators and eastward of the substellar point for rapid rotators.



Surface temperature and surface wind vectors show a nearly symmetric pattern of substellar heating and flow toward the substellar point for planets in the slow rotation regime around 4500 K, 4000 K, 3700 K, and 3300 K stars. The 2600 K case in the rapid rotation regime shows asymmetric warming flow patterns that extend in an equatorial band from day to night side. In between is the Rhines regime, which shows departure from symmetry particularly at midlatitudes for the 3000 K cases. This particular set of simulations was chosen because they all have an approximately constant value of day-night contrast.