Annular Modes of Climate Variability Across the Solar System and Implications for Exoplanets

Barotropic annular modes appear from zonal-mean zonal wind.

**Earth**

- Pressure (hPa)
- Latitude
- 30.6%

**Mars**

- Pressure (Pa)
- Latitude
- 39.1%

Right: “Barotropic” annular modes regress onto the zonal-mean zonal wind (contours) and eddy momentum fluxes (shading). This mode signifies N-S shifts of the jet. Percentages indicate amount of variance explained.

Baroclinic annular modes emerge from zonal-mean eddy (wave) kinetic energy.

**Earth**

- Pressure (hPa)
- Latitude
- 30.9%

**Mars**

- Pressure (Pa)
- Latitude
- 46.8%

**Titan**

- Pressure (Pa)
- Latitude
- Percentages indicate amount of variance explained.

“Baroclinic” modes regress onto the zonal-mean EKE (contours) and eddy heat fluxes (shading). Mars’s modes signify pulsing of the storm track, like Earth’s. Despite similarities between Mars and Earth, there are differences. The relationship between Mars’s baroclinic modes and barotropic processes may be due to the mixed barotropic/baroclinic nature of Mars’s waves and the barotropically unstable annular polar vortex. Percentages as in Panel 1.

All modes are truly annular, including those that describe eddies.

**Earth**

- 150,000 storms
- 8 Years

**Mars**

- Pressure (Pa)
- Latitude

**Titan**

- Pressure (Pa)
- Latitude

There is remarkable similarity in the horizontal structure in all four modes on each planet. Regressing the baroclinic mode onto the vertically integrated EKE pinpoints transient storm tracks (top). The amplitude of the barotropic mode in surface pressure maximizes at the poles (bottom). Perhaps annular modes are ubiquitous throughout the solar system and beyond on exoplanets.

Annular mode timescales may influence exoplanet wind observations.

**Mars, EKE-AM**

- Normalized Power
- Cycles/sol

**Mars, U-AM**

- Normalized Power
- Cycles/sol

**Titan, U-AM**

- Normalized Power
- Cycles/day

The EKE-AMs have timescales of around 25 days for both Mars and Earth. The U-AMs have timescales around 10–100 days for Mars, Earth, and Titan. Doppler measurements of zonal winds will have this timescale imprinted into the observations. Further, these timescales could impact observations of seasonality of the exoplanets.