# How does knowledge of Venus' atmospheric dynamics contribute to studies of exoplanets (and astrobiology)?

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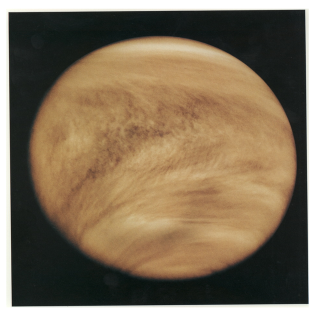
## Abstract

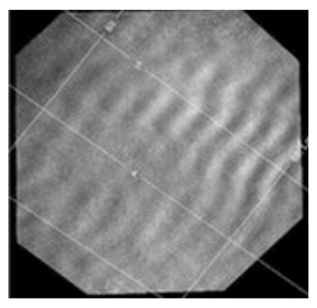
The region in our solar system between Venus and Mars broadly defines the boundaries of a habitable zone in our own solar system, where water can exist in a liquid state and conditions have the potential to support life. Since the transit method has a strong bias toward the detection of planets relatively close to their host star we may expect to find a significant number of Venus analogues amongst exoplanets. Measurements of general bulk properties from exoplanet observations are not enough to constrain atmospheric dynamics, since planetary atmospheres are highly variable in both space and time. To understand and interpret observations of exoplanet atmospheres in the Venus zone, we need to understand the dynamics of Venus' atmosphere, especially at cloud levels, since the cloud-level atmosphere corresponds to what would most likely be seen in observations of Venus-like exoplanets. Venus' clouds, unlike those on the Earth, display significant morphological differences at different wavelengths, i.e. at different altitudes in the cloud deck. Venus' clouds also show a wide range of wave-related features, which include Kelvin waves, Rossby waves, small-scale and global-scale gravity waves, vortices, and large streak-like structures. The irregular and variable dark regions in Venus' clouds have also been suggested as potential locations for some kind of microscopic life (e.g. Limaye et al., 2018a). The phase curves of exoplanets can give some information on atmospheric structure. In particular, longitudinal brightness variations may point to longitudinal variations caused by day-night differences, variations in chemical composition, inhomogeneous cloud coverage, or the effects of atmospheric waves which could displace the thermal phase curve relative to the substellar point. To understand and interpret observations of Venus' cloud-level atmosphere and hence observations of exoplanet atmospheres in the Venus zone, we perform simulations using a Venus middle atmosphere general circulation model. In this investigation, we study the influence of propagating waves on the atmosphere at cloud altitudes. We validate results by comparison with observations, including measurements from Venus probes, and from the Akatsuki and Venus Express missions.

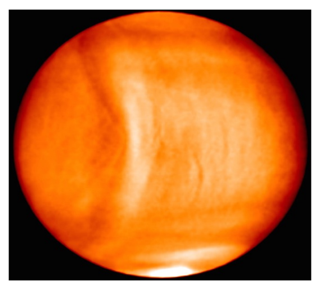
## Background

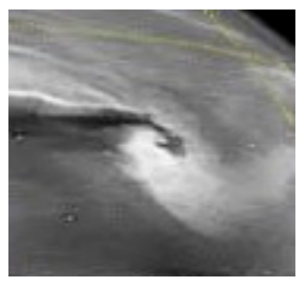
- Waves of *many types and scale sizes* observed in Venus' cloud-level atmosphere
- Wave activity may influence *observed phase curves* of Venus-like exoplanets

- Dark features in Venus clouds *not well understood*. May be related to *dynamics, chemistry, or possibly some kind of cloud level microorganisms* (Limaye et al., 2018a, Grinspoon and Bullock, 2007; Cockell, 1999; Morowitz and Sagan, 1967)


Global scale planetary waves (Pioneer Venus)


Smaller scale gravity waves (Venus Express) (Piccialli et al. 2014)


Global scale gravity wave (Fukuhara et al., 2017)


Interesting features, possibly wave-related (Akatsuki) (Limaye et al., 2018b)

## Motivation

- To determine which processes shape the observed structure at cloud altitudes, *in Venus' atmosphere and potentially in the atmospheres of Venus-like exoplanets*.
- In particular we investigate the *role that propagating waves play in generating the observed cloud-level wind and temperature structure*.
- We investigate the influence of *Kelvin and Rossby waves*, long believed to be present in Venus' atmosphere (e.g. Del Genio and Rossow, 1990).
- We *validate simulated results* in comparison with probe measurements and observations from the Venus Express and Akatsuki missions.

## Venus Middle Atmosphere Model

- We have performed investigations using a version of the *FMS (Flexible Modeling System)* model (Gordon and Stern, 1982), modified for Venus' atmosphere (*Parish and Mitchell, 2018*).
- ***Model components and setup include***
  - Spectral dynamical core, hydrostatic primitive equations.
  - Physical constants adjusted to values appropriate for Venus.
  - Initial T21L31 resolution: 64 longitudes, 32 latitudes and 31 height levels.
  - Vertical levels from 4 x $10^5$ Pa (~ 40 km altitude) at lowest level to around 3 Pa (~ 95 km altitude) at top.
  - Initialized with winds at rest.
  - Simplified Newtonian cooling radiation scheme, for relaxation of temperature to a specified radiative equilibrium.
  - Since the lower atmosphere is not simulated directly in this model ***a simple linear friction is introduced within the first ~2km from the lower boundary*** to maintain zonal and meridional winds within observed values.

## Forcing of Atmospheric Waves

- In the simulations described here, we discuss the possible influence of two types of equatorial wave: Kelvin waves and Rossby waves long suggested to be present in Venus' cloud-level atmosphere (e.g. Del Genio and Rossow, 1990).
- Waves are assumed to be excited in the lower atmosphere, and are represented in our middle atmosphere model by lower boundary forcing.

### I). Forcing of Kelvin-like Waves

- The horizontal wave structure is approximated as a temperature variation with a maximum at the equator, and a Gaussian latitude structure, with periodic variations in longitude and time (see e.g. Andrews et al., 1987, Holton, 1992, Imamura, 2006):

$$T = T_K \ \exp\left(-\frac{y^2}{2{L_K}^2}\right)\cos(s\phi - \omega_K t)$$

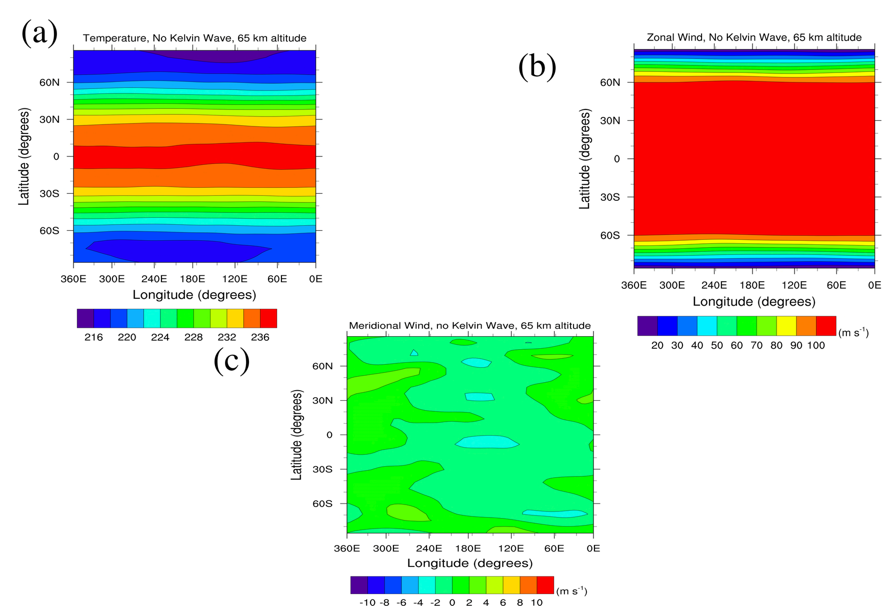
[where T = temperature, $T_K$ = amplitude of oscillation = 1.0 K, y = distance from equator, $L_K$ = latitudinal scale length (chosen to be = 2500 km), ø = longitude, s = longitudinal wave number (chosen to be 1 ), $2\pi/\omega_K$ = wave period in inertial frame (chosen to be 4 (Earth) days for Kelvin wave), t = time]

- The forcing was introduced with an approximate ***Gaussian structure in the vertical***, with vertical extent between around 41 and 48 km altitude. Simulations were performed with this forcing for ***two (Earth) years*** from a quasi equilibrium background state.

### Results of Simulations

**1) No Kelvin Wave Forcing**

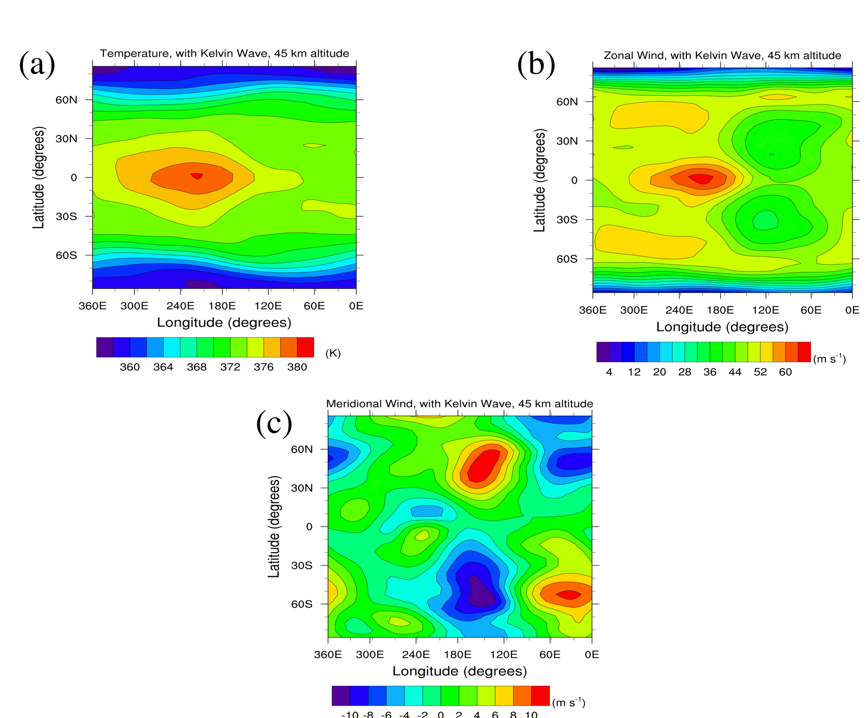
- Response at cloud altitudes without Kelvin wave forcing. (Zonal winds are positive westward, meridional winds are positive northward).
- (a) **Temperatures** and (b) **Zonal winds** display maximum values at the equator at all longitudes. (c) **Meridional winds** are small.



**2) With Kelvin Wave forcing**

**(i) Response just above forcing region**

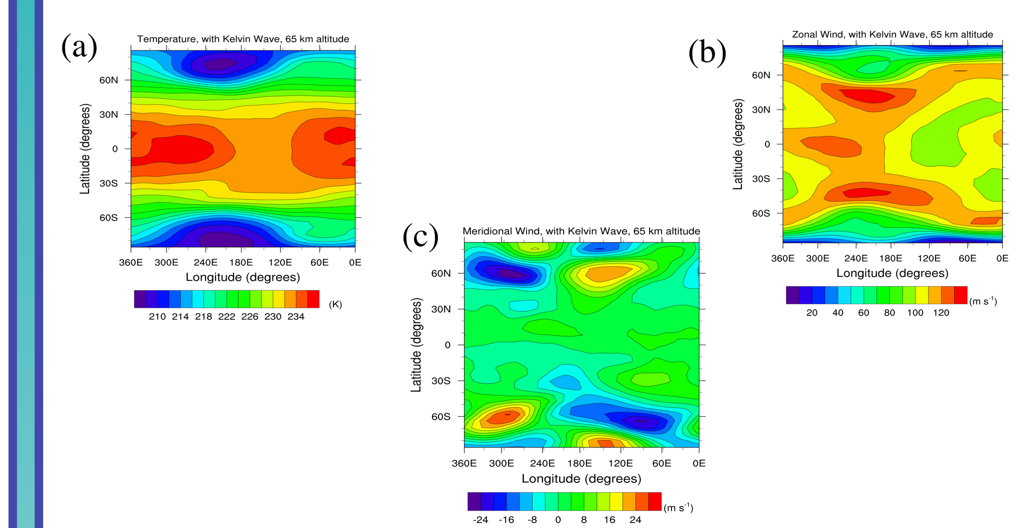
(a) **Temperature** shows wave number 1 structure. Maximum at equator. Response largely confined to low latitudes.
(b) **Zonal wind** also shows wave number 1 structure. Peaks at low latitudes. Smaller maxima around $50^0$ to $60^0$ latitude.
(c) **Meridional wind** much smaller in magnitude than zonal wind. Anti-symmetric around equator.



**(ii) Response at cloud top altitudes**

(a) **Temperature** shows diurnal variation and peaks at equator. Temperature range has increased by a few degrees relative to that without Kelvin wave forcing.
Changes in the temperature response are also seen at higher latitudes.

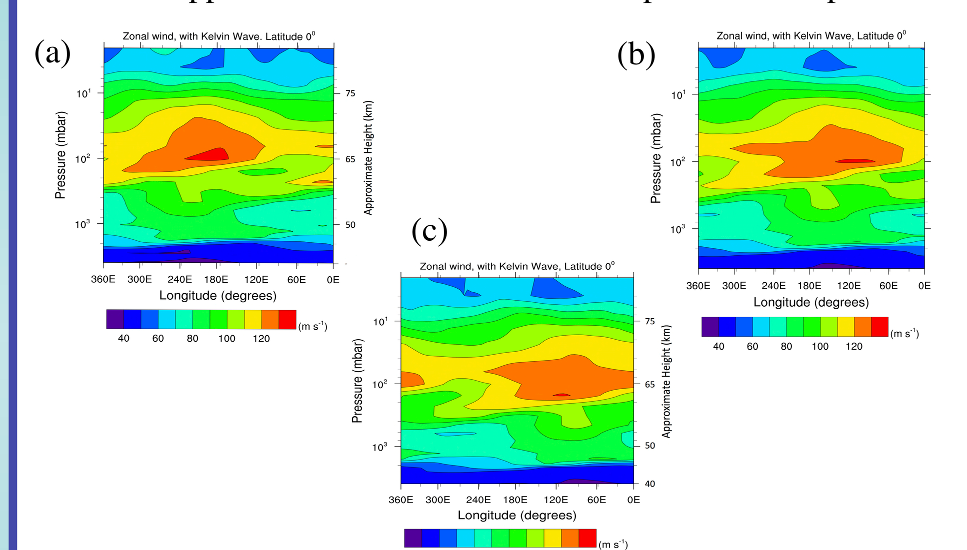
**Response at cloud top altitudes** (continued)



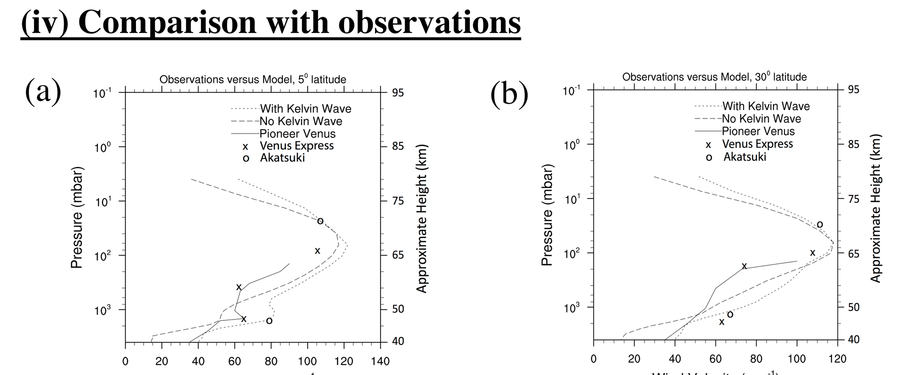
(b) **Zonal winds** have maximum at the equator and diurnal variation
Responses also seen at higher latitudes
Maximum zonal wind has increased by ~20 m/s
(c) **Meridional winds** are small in magnitude relative to the zonal winds, and anti-symmetric around the equator. Larger at high latitudes

**(iii) Longitudinal variations**

- Zonal wind at equator versus longitude, pressure and approximate height.
- Successive plots (a), (b), (c) separated by one (Earth) day
- Longitudinal wave number 1 variation above ~45 km altitude.
- Wind maximum moves westward (i.e. to the right) over time with a period close to 4 days, consistent with westward propagation of Kelvin wave on Venus.
- Westward slope of the wind maxima with altitude suggests upward propagation
- Wave appears evanescent above cloud top zonal wind peak



**(iv) Comparison with observations**

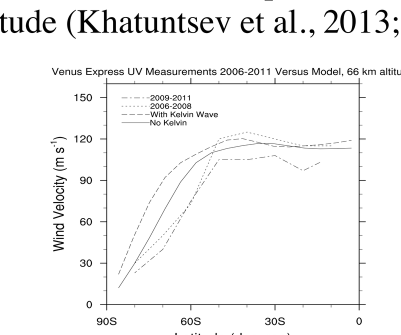


***Vertical Structure***

- Simulated zonal winds at $5^0$ and $30^0$ latitude, versus measurements from Pioneer Venus (Schubert et al., 1980), Akatsuki (Horinouchi et al., 2017), Venus Express (Sanchez-Lavega et al., 2008)
- Wave forcing increases the maximum zonal winds
- Breaking of Kelvin-like waves around the cloud tops may enhance superrotation at this altitude

***Latitudinal Structure***

- Simulated zonal winds compared with Venus Express measurements at ~66 km altitude (Khatuntsev et al., 2013; Hueso et al., 2015).
- Magnitudes generally similar to measured values
- Overestimated at latitudes >$50^0$, perhaps due to high latitude waves or polar vortex.



### II). Forcing of Rossby-like Waves

- Assume the gravest Rossby mode, with latitudinal node number n = 1. The horizontal wave structure is approximated as a temperature variation with a maximum at the equator, a Gaussian latitude structure, and periodic variations in longitude and time (based on Andrews et al., 1987, Holton, 1992, updated from Imamura, 2006):

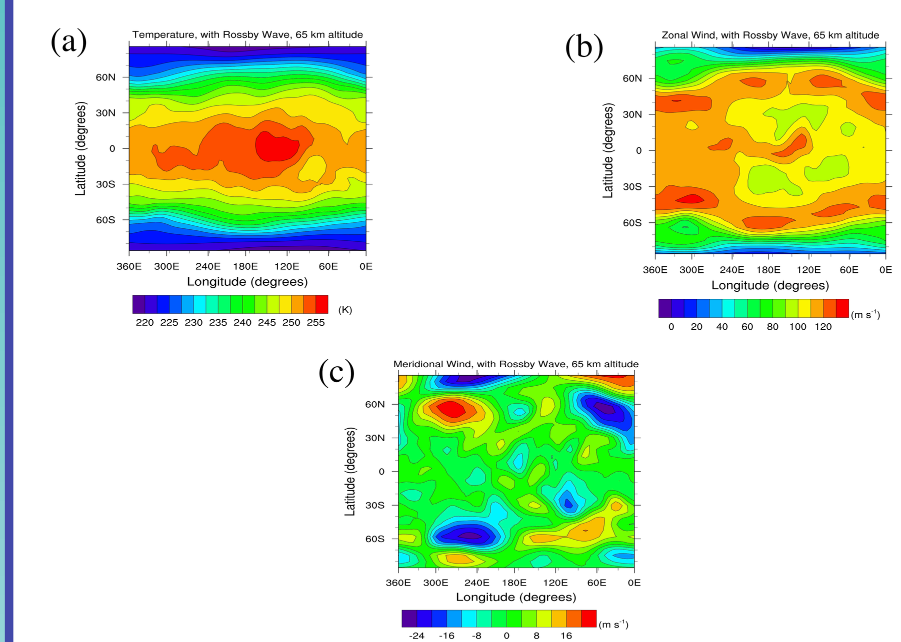
$$T = T_R\left[\frac{\omega^*}{\beta {L_R}^2 k}\left(1-\frac{y^2}{{L_R}^2}\right)-\frac{y^2}{{L_R}^2}\right]\exp\left(-\frac{y^2}{2{L_R}^2}\right)\cos(s\phi - \omega_R t)$$

[where T = temperature, $T_R$ = amplitude of oscillation = 1K, y = northward distance from equator, $L_R$ = equatorial deformation radius (2500 km here), ø = longitude, s = 1 = longitudinal wave number, $\omega^* = \omega_R - k\bar{u}$ = intrinsic wave frequency, k = zonal wavenumber, ū = zonal mean zonal wind velocity, β = Rossby parameter, $2\pi/\omega_R$ = wave period in inertial frame (chosen to be 6 (Earth) days for Rossby wave), t = time]

### Results of simulations

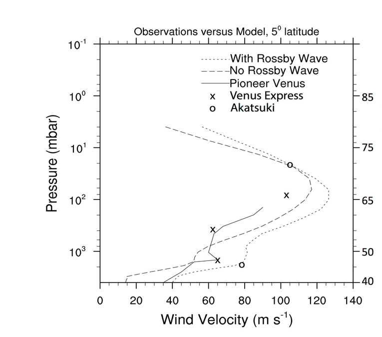
**(i) Response at cloud top altitudes**

- **Temperature** peaks at equator. Smaller response at higher latitudes.
- **Zonal winds** show a symmetric structure with maxima at the equator and at higher latitudes around $50^0$ to $60^0$.
- **Meridional winds** are small in magnitude relative to the zonal winds, with an anti-symmetric structure around the equator. Larger at high latitudes.



**(ii) Comparison with observations**

- Simulated zonal winds at $5^0$ latitude with and without wave forcing, compared with measurements from Pioneer Venus, Akatsuki and Venus Express (Schubert et al., 1980; Horinouchi et al., 2017; Sanchez-Lavega et al., 2008).
- Wind magnitudes increased around zonal wind maximum when wave forcing is included, suggesting that Rossby-like waves are enhancing superrotation
- Wind magnitudes are increased above the zonal wind maximum



## Conclusions

1) Forcing close to the lower boundary with the characteristics of Kelvin or Rossby waves, produces *upward propagating variations which reach cloud top altitudes*.
2) Simulations with and without wave forcing show general *agreement with Akatsuki, Venus Express, and Pioneer Venus measurements*, within the range of variability of the observations.
3) These results show the potential of the model to investigate and interpret *which processes shape the structure at cloud altitudes on Venus and possibly on Venus-like exoplanets*.
4) Venus' cloud level atmosphere exhibits significant morphological changes as a function of altitude / measured wavelength. This model has the potential to simulate and *interpret these structural differences as a function of altitude*.
5) The source of the variable dark features observed at Venus' cloud tops (unknown absorber) is currently not well known, and may be generated via atmospheric dynamics, chemical processes or, as some have suggested, by some kind of microscopic organisms. If the latter hypothesis is determined to be correct, Venus-like exoplanets displaying similar features *might also be considered potential astrobiology targets*.

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