Understanding the Dynamics of the Cloud-Level Atmosphere on Venus and Venus Analog Exoplanets Using a Middle Atmosphere General Circulation Model

Helen Parish[1]

[1]University of California Los Angeles

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Abstract

Venus is comparable to the Earth in size and overall distance from the Sun, but is outside of a defined "habitable zone" in which water can exist in liquid form. The deep atmosphere of Venus provides a hostile environment for life. However, recent work suggests that the atmosphere at cloud altitudes, which includes regions with temperatures and pressures similar to those at the Earth's surface, could provide possible locations for microscopic life. Since the transit method strongly favors observations of planets close to their host stars, Venus analogs may be common in exoplanet observations. With over 100 Earth-sized exoplanets observed to date, it is important to be able to identify the characteristics of Venus analogs. Thick layers of clouds, such as those which enshroud Venus, are the regions most likely to be observed on a Venus-like exoplanet. The cloud layers on Venus display a wide range of wave-related features including global scale and smaller scale gravity waves, Rossby and Kelvin waves, streak-like structures, irregular dark regions, and vortices, and show considerable variations with altitude. It is important to characterize these temporal and spatial variations to understand the dynamics of the cloud-level atmosphere on Venus or Venus-like exoplanets. Observed thermal phase curves of exoplanets may show longitudinal variations, which could indicate inhomogeneities in cloud cover, day-night differences, variations in composition, or the influence of atmospheric waves, which may shift the phase curve relative to the substellar point. To understand and interpret observations of Venus or Venus-like exoplanets at cloud altitudes, simulations have been performed using a Venus middle atmosphere general circulation model. In this investigation we simulate Rossby and Kelvin waves and modify forcing parameters, including the resolution and dissipation, and compare the results with observations from Venus probes, Venus Express and the Akatsuki mission.

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Helen F. Parish

Department of Earth, Planetary and Space Sciences,
University of California
Los Angeles, Los Angeles CA 90095

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Abstract

Venus is comparable to the Earth in size and overall distance from the Sun, but is outside of a defined "habitable zone" in which water can exist in liquid form. The deep atmosphere of Venus provides a hostile environment for life. However, recent work suggests that the atmosphere at cloud altitudes, which includes regions with temperatures and pressures similar to those at the Earth's surface, could provide possible locations for microscopic life. Since the transit method strongly favors observations of planets close to their host stars, Venus analogs may be common in exoplanet observations. With over 100 Earth-sized exoplanets observed to date, it is important to be able to identify the characteristics of Venus analogs. Thick layers of clouds, such as those which enshroud Venus, are the regions most likely to be observed on a Venus-like exoplanet. The cloud layers on Venus display a wide range of wave-related features including global scale and smaller scale gravity waves, Rossby and Kelvin waves, streak-like structures, irregular dark regions, and vortices, and show considerable variations with altitude. It is important to characterize these temporal and spatial variations to understand the dynamics of the cloud-level atmosphere on Venus or Venus-like exoplanets. Observed thermal phase curves of exoplanets may show longitudinal variations, which could indicate inhomogeneities in cloud cover, day-night differences, variations in composition, or the influence of atmospheric waves, which may shift the phase curve relative to the substellar point. To understand and interpret observations of Venus or Venus-like exoplanets at cloud altitudes, simulations have been performed using a Venus middle atmosphere general circulation model. In this investigation we simulate Rossby and Kelvin waves and modify forcing parameters, including the resolution and dissipation, and compare the results with observations from Venus probes, Venus Express and the Akatsuki mission.

Motivation

- We aim to determine the role that waves of different scale sizes play in generating winds and temperatures at cloud altitudes on Venus, and potentially on Venus-like exoplanets, using model simulations.
- Small scale eddies are believed to be important in maintaining the low latitude superrotation at cloud altitudes on Venus (Gierasch, 1975). Larger planetary scale waves such as Kelvin and Rossby waves are characteristic features of the larger scale structure (e.g. Del Genio and Rossow, 1990), and may be excited by small scale eddies and instabilities.
- These eddies and instabilities may occur on sub grid scales, and the effects of sub grid scale processes are frequently approximated in models using horizontal dissipation.
- In this work, the timescale for horizontal dissipation and the horizontal resolution have been varied, with the aim of determining the influence of smaller scale variations on simulated cloud-level characteristics and superrotation.
- Here we examine the winds and temperature structures that occur in the model spontaneously, without any direct wave forcing.

Venus Middle Atmosphere Model

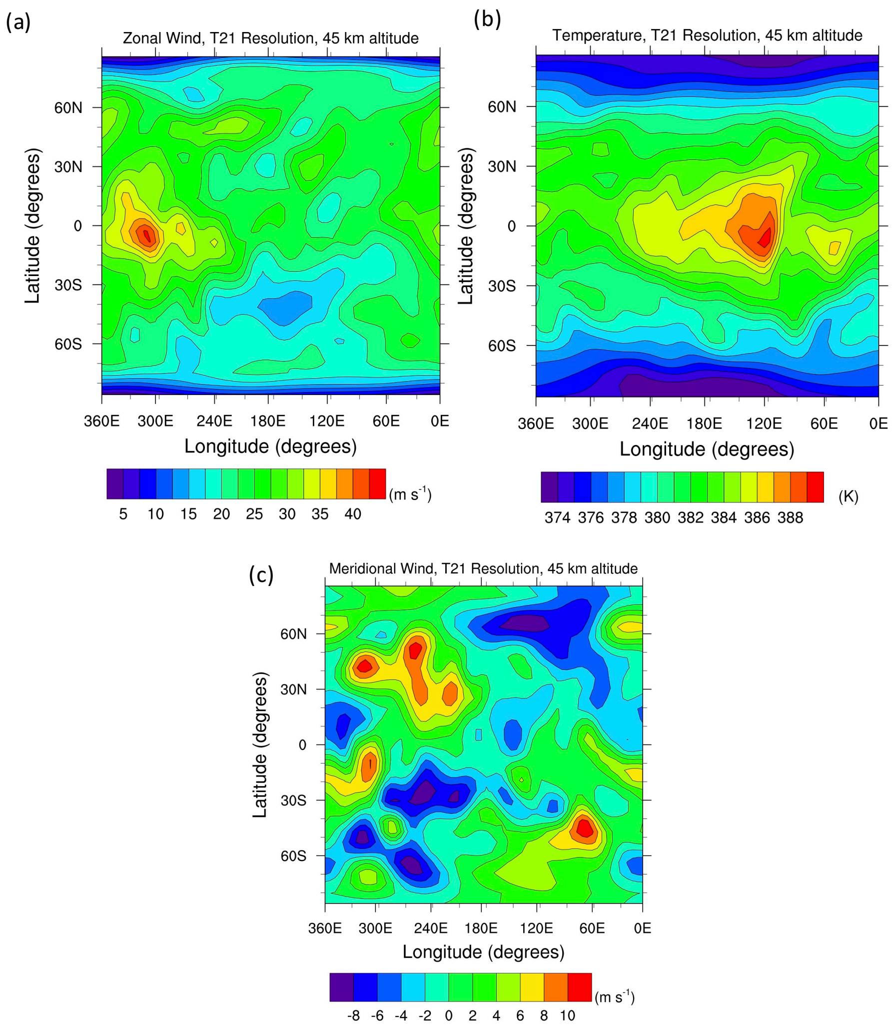
- We have performed investigations using a version of the FMS (Flexible Modeling System) model (Gordon and Stern, 1982), modified for Venus' atmosphere (Parish and Mitchell, 2018).

Model components and setup include

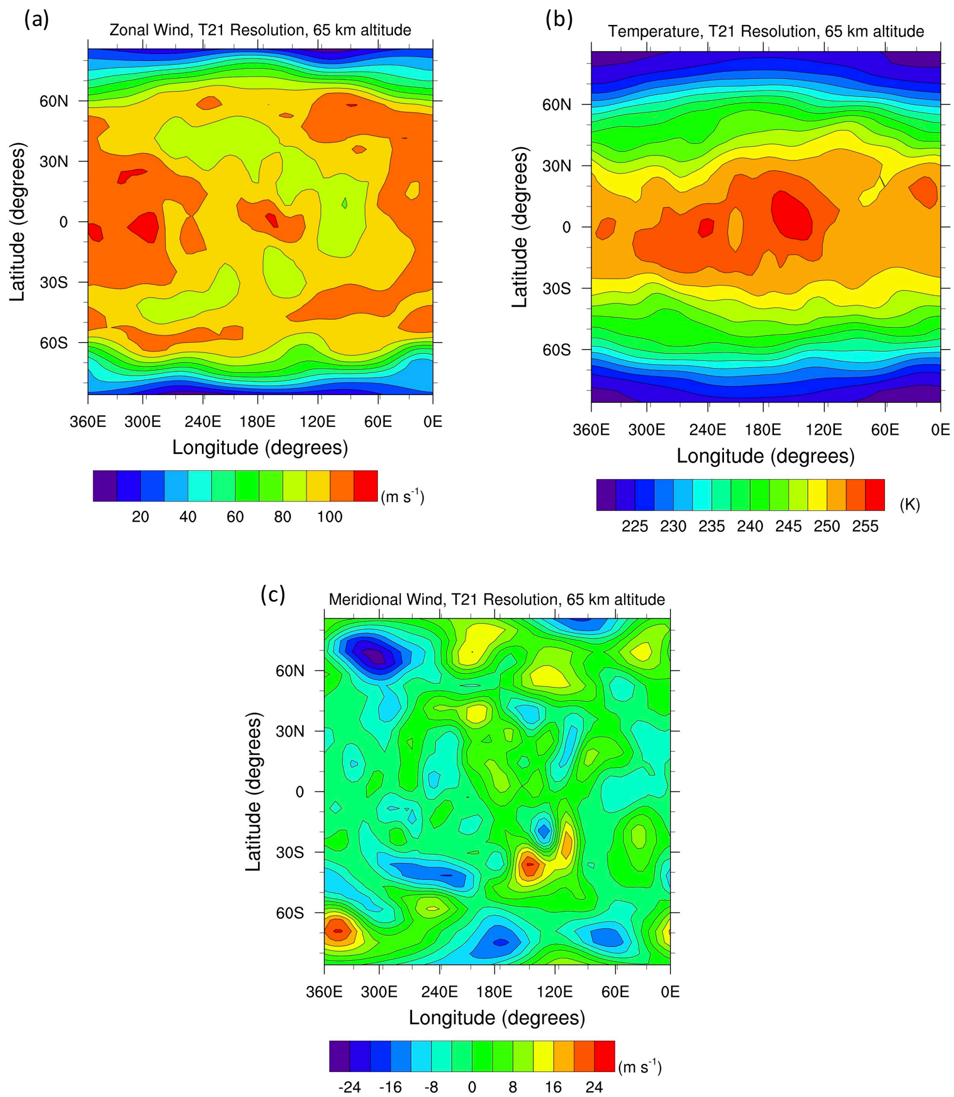
- Spectral dynamical core, hydrostatic primitive equations.
- Physical constants adjusted to values appropriate for Venus.
- Initial T21L31 resolution: 64 longitudes, 32 latitudes and 31 height levels.
- Vertical levels from 4 x 105 Pa (~ 40 km altitude) at lowest level to around 3 Pa (~ 95 km altitude) 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.

Effects of Changes in Resolution

In these simulations the resolution was varied between low T21 resolution (64 longitudes, 32 latitudes) to high T42 resolution (128 longitudes, 64 latitudes). Each simulation was run for ~20 simulated (Earth) years to quasi equilibrium. In these simulations, no wave forcing was applied.

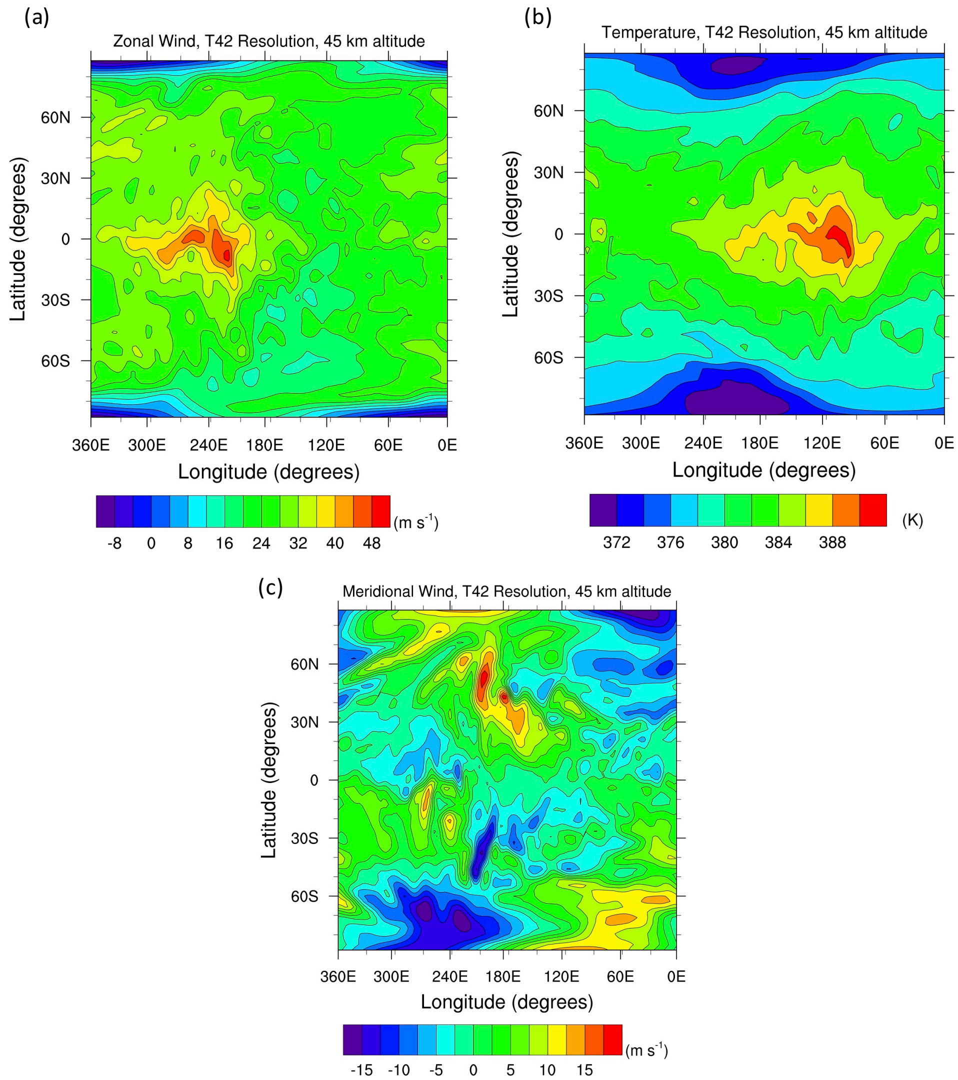


- Figure 1 shows the zonal wind, temperature and meridional wind as a function of latitude and longitude at Venus' lower cloud altitudes at ~45 km altitude
- Lower resolution i.e. T21 (64 longitudes, 32 latitudes)
- Simulations run for ~20 (Earth) years from rest to quasi equilibrium state
- Disturbances appear in the equatorial region up to ~ 30 degrees latitude in each hemisphere, without any applied wave forcing.
- Dominant latitudinally-symmetric wave number 1 disturbance. Smaller disturbance at high latitudes ~50 – 60 degrees latitude
- Smaller anti-symmetric disturbances in meridional wind at mid to high latitudes



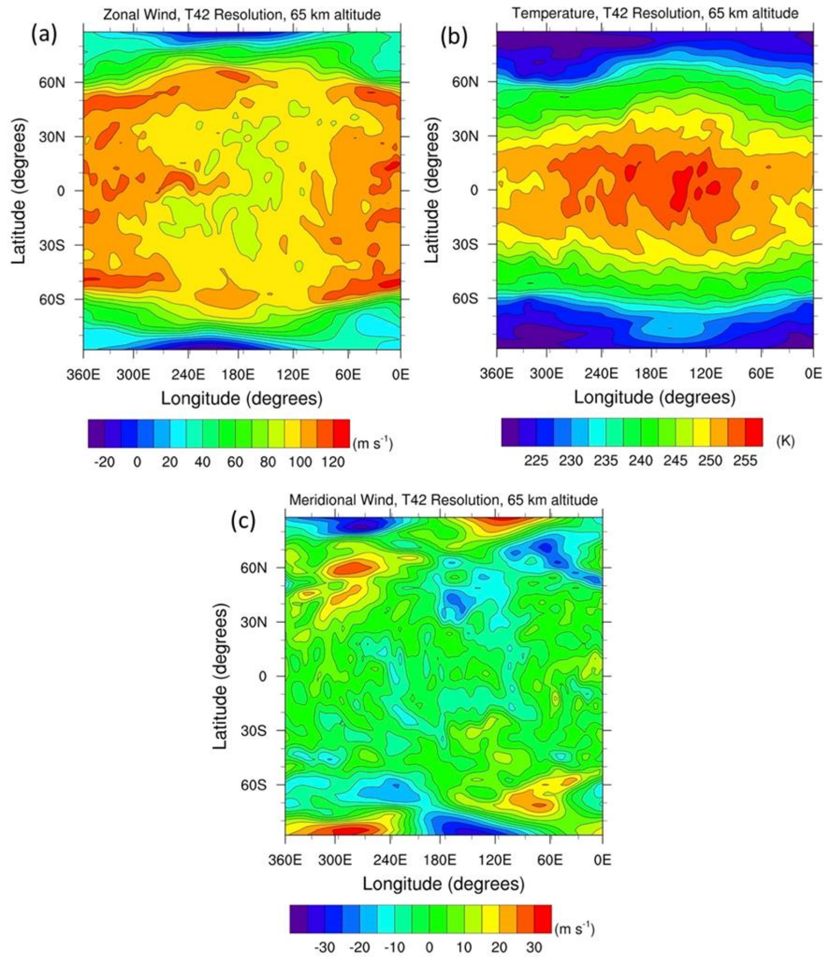
- Same as Figure 1, but near height of cloud tops at ~65 km altitude. Also T21 resolution.
- Strong superrotation with magnitudes up to ~110 to 120 m/s
- Dominant wave number 1 structure in zonal winds and temperatures
- Zonal wind shows significant wave variations at low latitudes and also at higher latitudes ~ 50 – 60 degrees latitude
- Meridional winds are relatively small and have largest magnitudes at mid to high latitudes

Figure 3



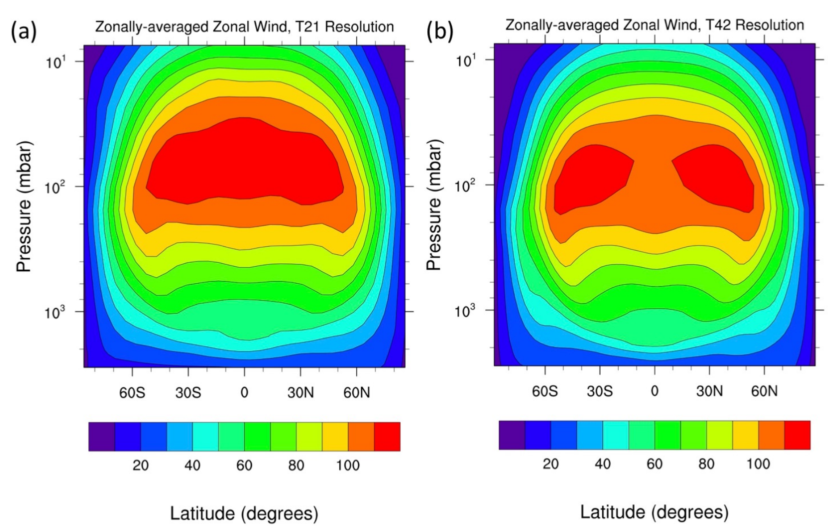
- As Figure 1, at lower cloud region ~45 km altitude, but with high T42 resolution (128 longitudes, 64 latitudes)
- Compared with T21 results, shows finer scale structure and slightly larger peak magnitudes
- Similar to wave number 1 longitudinal structure for T21 resolution, in zonal winds and temperatures, but smaller scale structure is seen in the wave
- Disturbance mostly confined to the equatorial zone, but smaller periodic variations are also seen at higher latitudes ~40 to 60 degrees latitude
- Meridional wind shows generally smaller magnitudes than the zonal winds, and shows a basically anti-symmetric and complex structure

Figure 4



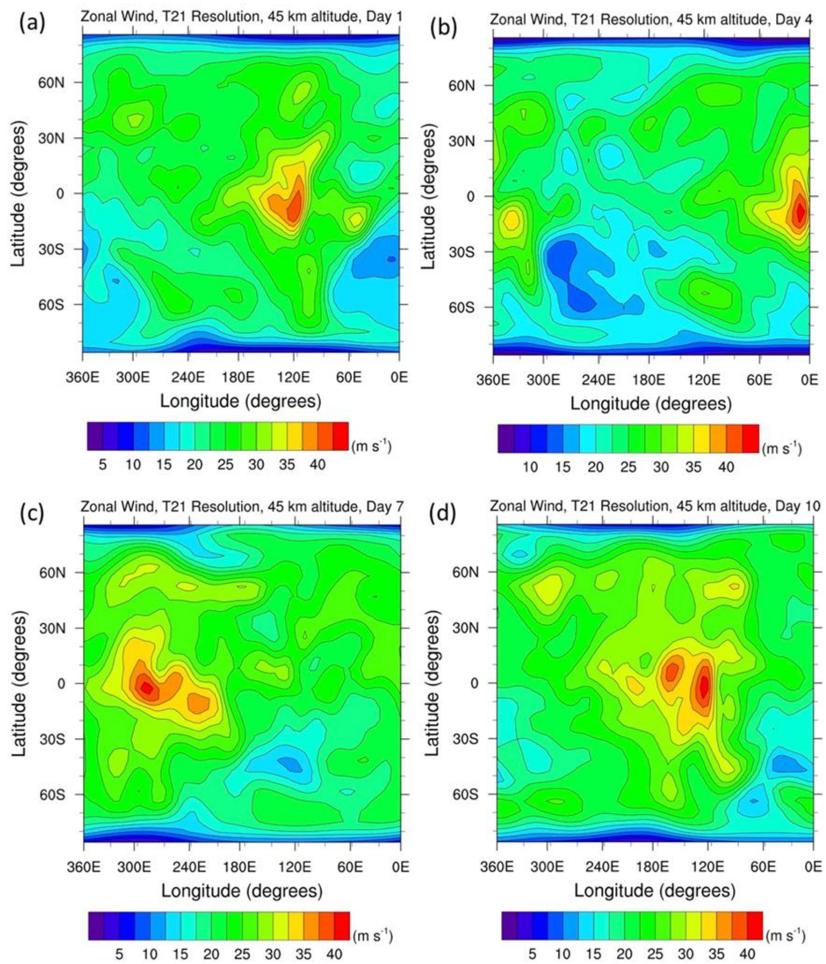
- As Figure 2, near the cloud tops, with higher T42 resolution
- Similar overall structure to T21 results, but with finer resolution features visible and slightly higher peak magnitudes
- Zonal winds and temperatures show a dominant wave number 1 variation, with more smaller scale variations present
- Largest magnitudes in equatorial region with smaller variations at higher latitudes ~50 – 65 degrees latitude
- Meridional winds small compared with zonal winds, largest at higher latitude, and show an anti-symmetric latitudinal structure

Figure 5



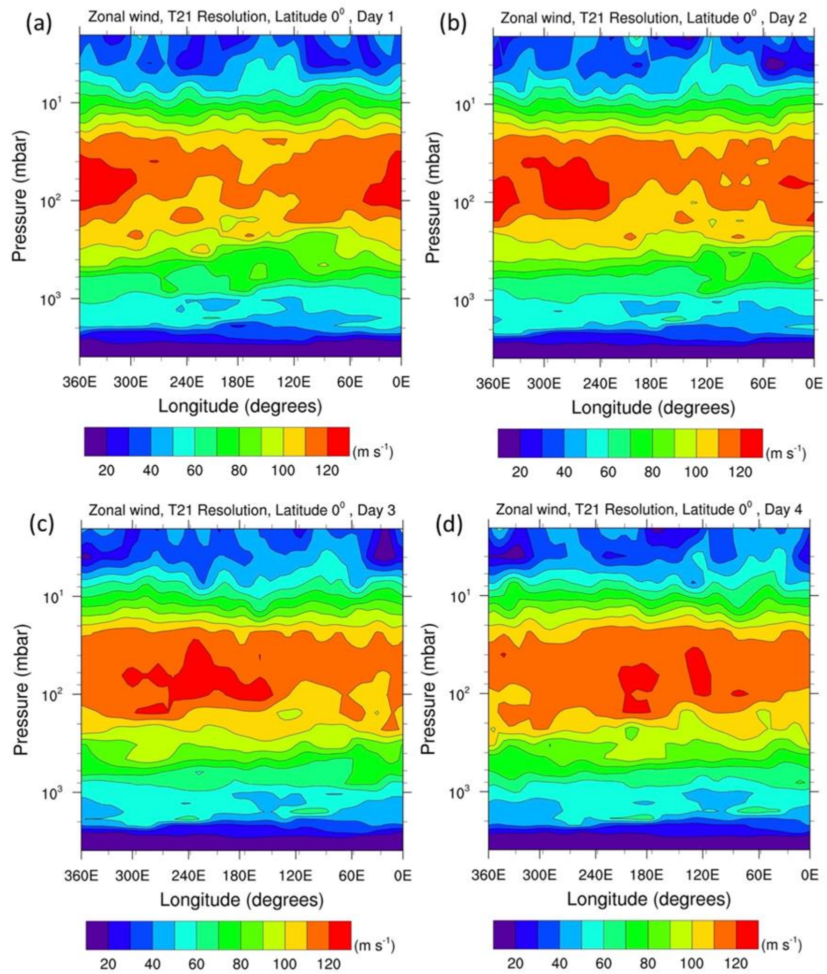
- Figure 5 shows the zonal wind as a function of latitude and altitude (pressure) for (a) T21 and (b) T42 resolution, to the same scale
- Results for T21 and T42 resolutions have similar overall structures
- High resolution T42 results have comparable magnitudes to the T21 results around the 102 mbar (~65 km) altitude region, but peak at slightly lower altitudes where the atmosphere is denser where more energy is required to move the atmosphere
- T42 resolution simulation shows clear mid-latitude zonal wind jets between ~15 to 50 degrees latitude, centered around 30 degrees latitude, which are not seen for T21 simulations

Figure 6



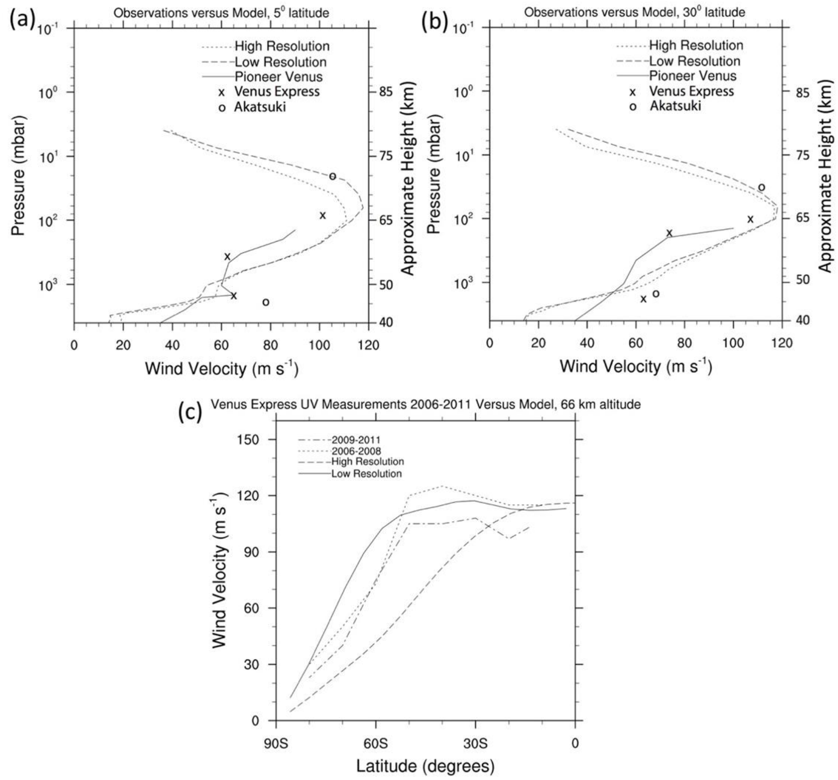
- Figure 6 shows changes over a 10 (Earth) day time interval in the zonal winds at ~45 km altitude for T21 resolution. (a) Day 1, (b) Day 4, (c) Day 7, (d) Day 10
- Westwards propagating disturbances seen. Moving with the approximate speed of the background flow at this altitude, which has an ~10 day revolution period
- Wave number 1 is dominant close to the equator, perhaps consistent with a Kelvin wave. However, smaller magnitude periodic structures are seen at ~50 - 60 degrees latitude, suggesting a possibly connection with Rossby waves.

Figure 7



- Figure 7 shows changes of the zonal winds over a 4 day time interval as a function of longitude and height (pressure), for T21 resolution results. (a) Day 1, (b) Day 2, (c) Day 3, (d) Day 4.
- Dominant wave number 1 variation seen as well as smaller scale structures
- Peak of disturbance moves westward in the direction of the background flow which revolves in ~4 days at this altitude, but the disturbance takes around 5 to 6 days to return to its original location i.e. the disturbance is moving slightly retrograde relative to the background flow
- May be consistent with a Rossby wave disturbance which would move slightly retrograde relative to the background flow on the Earth. Other disturbances may also contribute to the simulated variations.

Figure 8

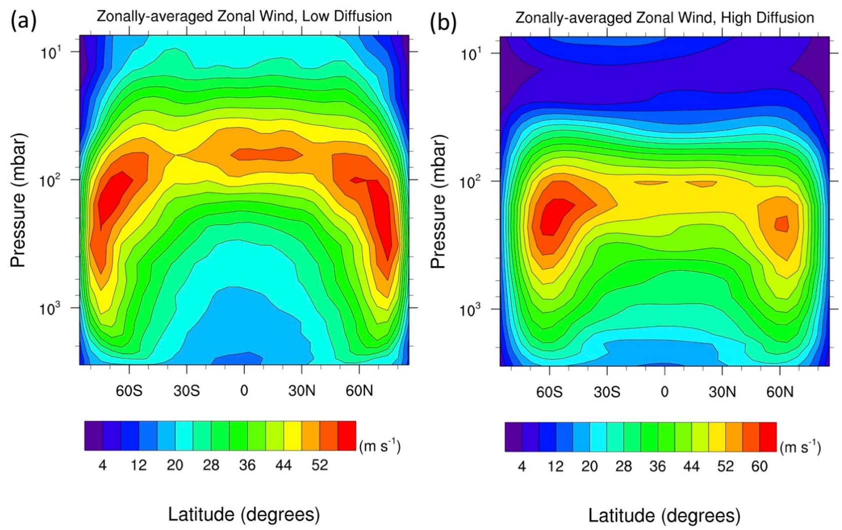


- Figure 8 shows vertical profiles of the zonal winds for T21 and T42 resolutions at (a) 5 degrees latitude and (b) 30 degrees latitude, compared with measurements at the same latitudes from Pioneer Venus (Schubert et al., 1980), from Akatsuki (Horinouchi et al., 2017), and from Venus Express (measured in ultraviolet, visible and near infrared, at ~66 km, 61 km and 47 km altitude respectively) (Sanchez-Lavega et al., 2008).. (c) latitudinal profiles for T21 and T42 resolutions compared with Venus Express measurements at ~66 km altitude. (Venus Express average winds between 2006 to 2008 and 2009 to 2011 show a long term increase at latitudes < ~ 500 , Khatuntsev et al., 2013; Hueso et al., 2015).
- Simulated results at both low and high resolutions show magnitudes in the vertical profile that are within the range of variability of observations
- High resolution T42 results show slightly larger magnitudes around 50 km altitude, where the atmosphere is relatively dense, at both 4 degrees and 30 degrees latitude. The T42 results reproduce the observed small zonal wind maximum just below 50 km altitude at 5 degrees latitude better than the T21 results.
- The T42 response is lower in magnitude than the T21 response above ~65 km altitude
- Peak magnitudes in the T42 response are slightly smaller and occur at a lower altitude that those in the T21 response.
- Latitudinal structure shows magnitudes larger than those observed by Venus Express at high latitudes for T21 resolution and lower than those observed at T42 resolution, consistent with the T42 response showing a larger magnitudes at lower latitudes than the T21 results.
- Additional inputs may be required at high latitudes to realistically simulate the observed structure

Effects of Changes in Horizontal Diffusion

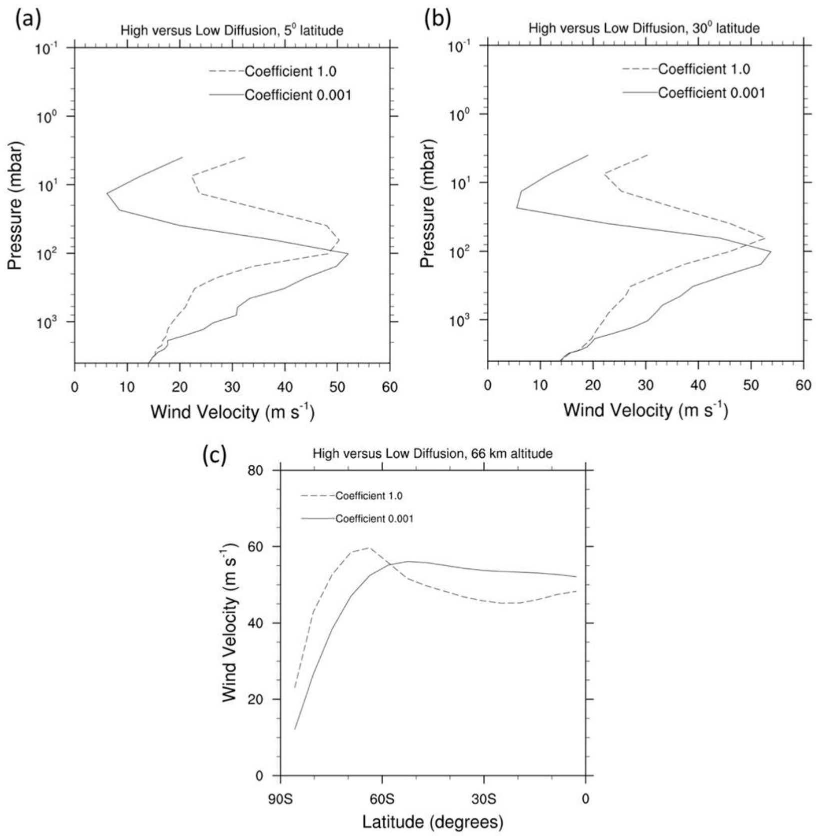
- The timescale for 4th order horizontal numerical diffusion included in model simulations was varied to determine the effects on the cloud level dynamics.
- The default timescale for horizontal diffusion in the model is 0.1 days. The timescale was varied. Results are shown here for timescales of 0.001 days (high diffusion) and 1.0 days (low diffusion). These sets of simulations were run for 2-3 (Earth) years from rest. The simulated response may not have reached a full quasi equilibrium state, but provides useful insights into the influence of horizontal diffusion on the simulations.

Figure 9



- Figure 9 shows the zonal wind as a function of altitude (pressure) and latitude for low diffusion (timescale 1.0 days) and high diffusion (timescale 0.001 days)
- Zonal superrotation at low latitudes at cloud top altitudes is believed to be influenced by the effects of small scale eddies (Gierasch,1975) which are likely of subgrid scales in the model. Horizontal numerical diffusion in the model helps to simulate the effects of these eddies.
- An increase in horizontal diffusion moves the zonal wind jets to lower latitudes. An increase in diffusion also produces peak zonal wind magnitudes at lower altitudes where the atmosphere is denser.
- Peak magnitudes are also a little larger for higher diffusion

Figure 10



- Figure 10 shows vertical profiles of zonal winds for high and low diffusion at (a) 5 degrees latitude (b) 30 degrees latitude. (c) latitudinal profiles of zonal winds for high and low diffusion at 65 km altitude
- In the vertical profiles, the peak magnitudes are larger and at lower altitudes for high diffusion.
- Larger magnitudes are produced in the denser atmosphere below ~65 km (102 mbar) altitude for higher diffusion, and lower magnitudes above 65 km altitude for higher diffusion.
- The response at high latitudes is reduced for higher diffusion, consistent with the production of a larger response at lower latitudes due to the influence of eddies (Gierasch, 1975).
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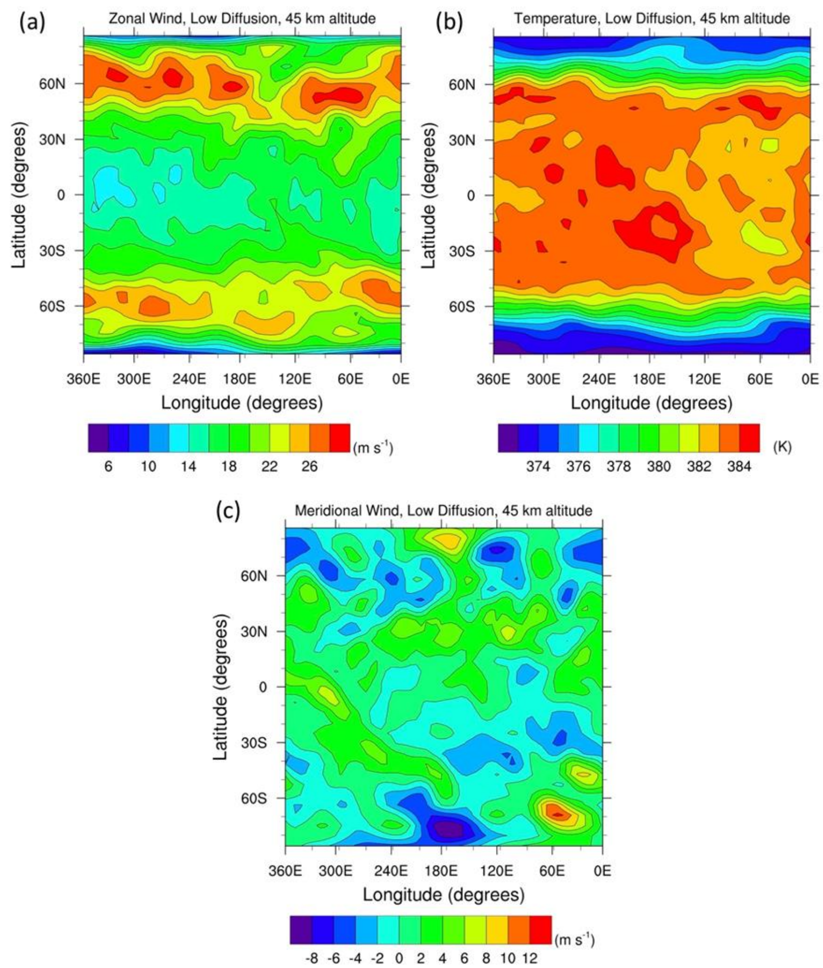
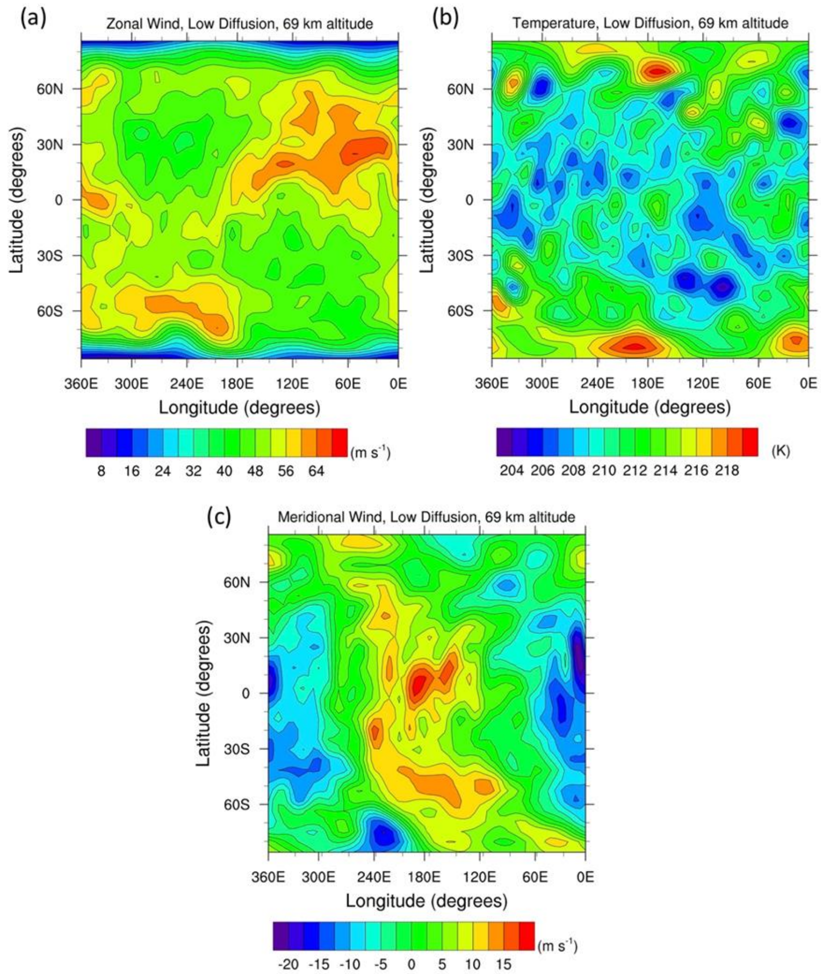
Figure 11



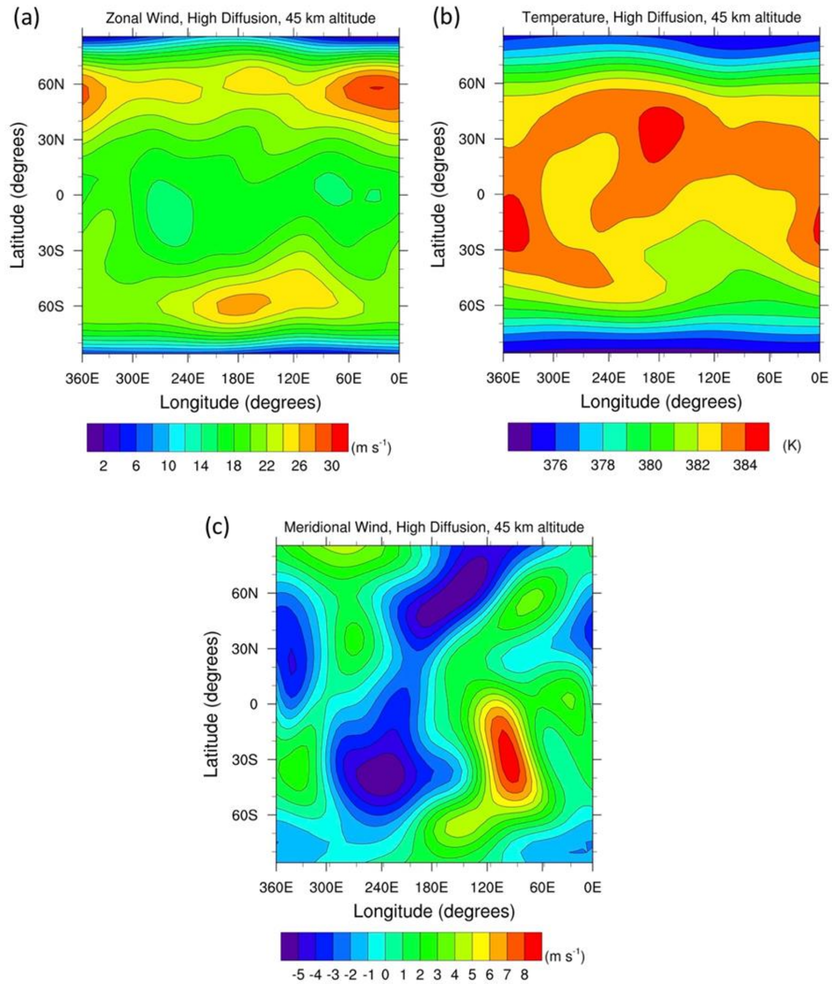
- Figure 11 shows the zonal wind, temperature and meridional wind for lower diffusion as a function of latitude and longitude in the lower cloud region at ~45 km altitude

Figure 12



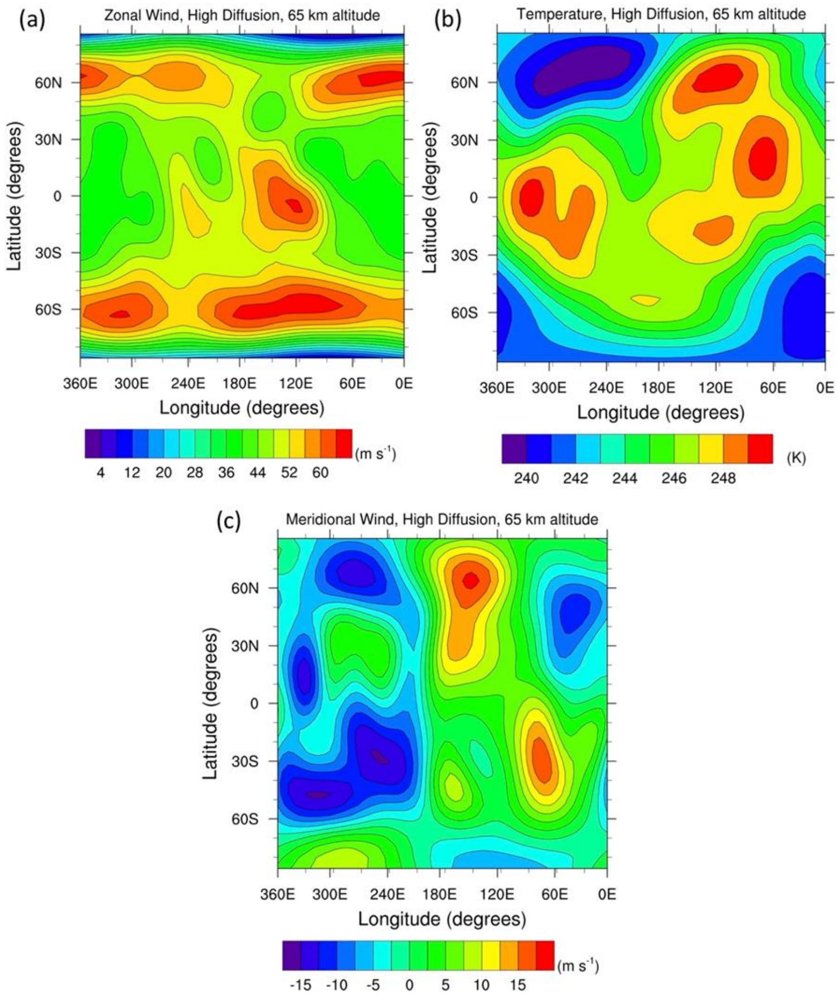
- Same as Figure 11 for the upper cloud regions at ~65 km altitude

Figure 13



- Same as Figure 11, for higher diffusion

Figure 14



- Same as Figure 12, for higher diffusion

- In Figures 11 to 14, for higher diffusion there is a clearer development of wave-like variations at lower latitudes
- At the upper cloud altitudes, lower diffusion produces variations at higher latitudes with anti-symmetric structures in the zonal winds and symmetric structures in the meridional winds.
- For higher diffusion, there is a clearer development of waves in the zonal winds at the equator as well as at higher latitudes, which is generally symmetric at low latitude in the zonal winds and antisymmetric in the meridional winds. The temperature shows more of a response at low latitude for high diffusion.
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Discussion and Conclusions

1) Large and smaller scale oscillations are generated in the model without the need for direct wave forcing

2) Some of the large scale waves show characteristics consistent with Rossby or Kelvin waves. Oscillations have a dominant longitudinal wave number 1 structure. The oscillations appear at the equator and mid to high latitudes. In the upper cloud region (~65 km altitude) they show periods around 5-6 days, i.e. retrograde relative to the ~4 day westward rotation of the background flow. In the lower cloud (~45 km altitude), there are oscillations with ~10 day periods, comparable to the rotation rate of the background flow at that altitude. The dominant oscillations show zonally -symmetric structure in the zonal winds and temperature and anti-symmetric structure in the meridional winds.

3) When the resolution is increased from T21 to T42 resolution, the zonal wind at low to mid latitudes increases slightly (~5 m/s) at the lower cloud level (~ 45-50 km altitude) and decreases slightly (~5-10 m/s) at the upper cloud level (~65-70 km altitude). The general magnitude of the zonal wind profile with height for t21 or T42 resolution is within the range of variability of measurements from the Akatsuki and Venus Express missions. When the resolution in increased from T21 to T42 resolution, the response at high latitudes is decreased in magnitude, from values which are larger than those observed by Venus Express, to values which are a little smaller than those observed. The zonally-averaged response of the zonal wind as a function of latitude for T42 resolution shows the presence of zonal jets in the 20 to 50 degrees latitude range on both hemispheres, which are not seen for T21 resolution.

4) The zonal superrotation at cloud altitudes is believed to be maintained by small scale instabilities, which may be too small to be resolved by model grids. These small scale processes are parameterized by using horizontal diffusion in the model. The effects of varying the timescale of this diffusion were investigated. The default diffusion timescale used in simulations is 0.1 days. Results shown here are for values of 1 day and 0.001 days. For the lower rate of diffusion (longer timescale), the zonal wind jets are generated at higher latitudes and significant magnitudes at lower latitudes are seen at higher altitudes where the atmospheric density is lower. Larger diffusion (shorter timescale) produces high latitude jets at lower latitudes and generates superrotation at lower altitudes where the atmosphere is denser. Planetary scale oscillations are generated for low and high diffusion, but are larger in magnitude and more well defined and larger in magnitude for higher diffusion.

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