



## Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes

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[1] Some dynamical and morphological similarities exist between the vortex organization of the atmosphere in the northern and southern hemispheres of Venus and the tropical cyclones/hurricanes on Earth. An S-shape feature detected in the center of the vortices on Venus from Pioneer Venus Orbiter and Venus Express observations has also been seen in tropical cyclones. This feature can be simulated with an idealized nonlinear and non-divergent barotropic model and, like in the vortices on Venus and in tropical cyclones, it is found to be transient. Given the challenges in measuring the deep, atmospheric circulation of Venus, the morphological similarities provide clues toward understanding the processes involved in the maintenance of Venus' atmospheric super rotation. **Citation:** Limaye, S. S., J. P. Kossin, C. Rozoff, G. Piccioni, D. V. Titov, and W. J. Markiewicz (2009), Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes, *Geophys. Res. Lett.*, *36*, L04204, doi:10.1029/2008GL036093.

[2] Organization of the Venus atmospheric circulation into two circumpolar vortices, one centred on each pole, was first deduced more than 30 years ago from Mariner 10 ultraviolet images [Suomi and Limaye, 1978; Limaye, 1977]. An S-shape was seen from Pioneer Venus Orbiter Infrared data around the northern pole [Taylor et al., 1979] during its two month observing period. An inverted S-shape has been observed near the southern pole [Piccioni et al., 2007] and also is observed to be transient. Here we explore the dynamic stability of the flow and Venus south polar features in an idealized nondivergent barotropic framework. Numerical calculations with a nonlinear, barotropic model show the evolving flow generates an S-shape that is qualitatively very similar to the S-shaped feature seen in recent VIRTIS images from Venus Express, and has analogues to terrestrial tropical cyclones.

[3] Recent Venus Express observations indicate the presence of a hemispheric vortex in the south hemisphere of Venus [Piccioni et al., 2007; Markiewicz et al., 2007; Limaye, 2007] that occasionally exhibits an S-shape (previously referred to as a dipole). Although much smaller in scale, similar features have been observed in terrestrial tropical cyclones (Figure 1). Dynamic instability of the tropical cyclone inner-core winds has been shown to play

a fundamental role in the appearance of such features [Schubert et al., 1999; Kossin and Schubert, 2001; Kossin and Eastin, 2001; Kossin et al., 2002; Montgomery et al., 2002; Knaff et al., 2003; Kossin and Schubert, 2004]. Here we report on a nondivergent barotropic numerical simulation initialized with the observed circumpolar flow on Venus. The results show that instability in an ideal analogue of the observed flow can generate transient features in the core of the Venus vortex with its morphology and evolution depending on the latitudinal profile of ambient vorticity.

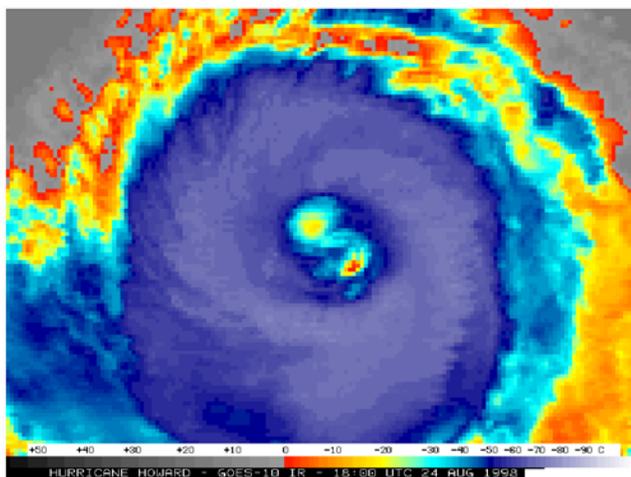
[4] The oft-observed transient features in both the Venus polar vortex and terrestrial tropical cyclones may be partly explored in the simplified framework of two-dimensional nondivergent barotropic flow. In this framework, height-dependent variations are ignored. In terms of Venus, the evolution of an initial zonally-symmetric basic state flow can be described in terms of Rossby waves propagating in the east-west direction within a meridional gradient of absolute vorticity [Platzman, 1968]. If the meridional gradient of vorticity changes sign anywhere in the flow, then the flow satisfies Rayleigh's necessary condition for exponential barotropic instability. This instability can be manifested through phase-locking of Rossby waves that counter-propagate zonally within the positive and negative absolute vorticity gradients [e.g., Schubert et al., 1999]. In terrestrial tropical cyclones, barotropic instability is realized in a barotropically unstable ring of elevated vorticity resulting from persistent latent heating in a convective eyewall. On Venus solar heating occurs near the top of the main cloud layer during the day and some heating occurs near the bottom of the elevated cloud layer from absorption of emission in near infrared from the hot surface and lower atmosphere.

[5] Similar to tropical cyclones, the cloud-level flow on Venus determined from Mariner 10 images has also been found to be barotropically unstable [Limaye and Suomi, 1981; Travis, 1978; Michelangeli et al., 1987]. Using a linearized nondivergent barotropic model and the thermal structure determined from Pioneer Venus Orbiter Infrared Radiometer data, Elson [1982] also found that the associated, idealized high latitude jet on Venus is barotropically unstable, with the most unstable barotropic mode of zonal wavenumber 2. Such waves were centred near 70° latitude and possessed a 3.2-day rotational period. Using a more general linear barotropic model, Dobrovolskis and Diner [1990] showed that Elson's [1982] results are robust even when divergent flow is permitted. They suggested that nonlinear evolution is likely essential in the evolution of the observed polar dipoles on Venus. However, previous research has not closely examined the nonlinear evolution of barotropic instabilities leading to mature dipole structures in the polar regions of Venus.

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**Figure 1.** An infrared satellite image of Hurricane Howard [1998], showing an S-shaped pattern in the low (warm) clouds in the tropical cyclone’s eye. The blue annular region comprises high (cold) cloud tops that result from deep, convective clouds in the tropical cyclone eyewall. The enhanced convective heating within the eyewall produces a barotropically unstable annulus of enhanced vorticity via vortex stretching. In the case of Hurricane Howard, the instability was manifested in wavenumber two. Higher wavenumber instabilities have also been observed in many tropical cyclones (e.g., Hurricane Isabel [2003] [see *Kossin and Schubert*, 2004]). Howard’s reversed S-shaped pattern in the warm eye may have resulted from filamentation associated with two cyclonic vortices that may have been located in the northeast and southwest sectors of the eyewall. Note that terrestrial tropical cyclones in the Northern Hemisphere rotate anti-clockwise and the S-shaped feature on Venus straddling the southern Venus pole also rotates counter-clockwise.

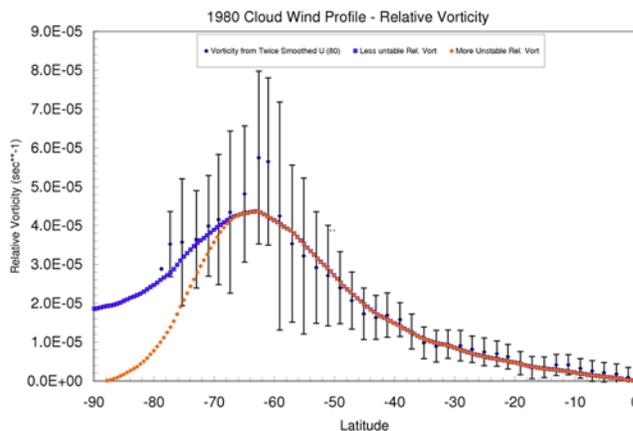
[6] Here we examine the barotropic instability and both the linear and nonlinear evolution of observed polar flows on Venus and, in distinction from the earlier studies, we directly incorporate recently re-analyzed Pioneer Venus (1980) cloud-tracked winds at high latitudes [*Limaye*, 2007]. At the cloud top level,  $\sim 65$  km, the atmosphere is known to be very stably stratified and has a temperature inversion layer at  $\sim \pm 60^\circ$  latitude. Figure 2 shows the latitudinal profile of the cloud level relative vorticity determined from the zonal flow on Venus. While vorticity is depressed near the centre of the vortex, the magnitude of vorticity increases equatorward with a maximum around  $60^\circ$  latitude. Thus, the meridional vorticity gradient changes sign and the flow can potentially support exponential instability.

[7] To explore the stability of the Pioneer Venus data presented in Figure 2, we incorporate a smoothed version of the data (also shown in Figure 2) and assume the vorticity decays to (i) zero at the pole, a region where data is missing, and (ii) where it reaches a non-zero value. The result of assuming plausibly higher vorticity in the center is briefly described later. An eigensolver based on the linearized nondivergent barotropic framework [e.g., *Reasor et al.*, 2000] indicates that both profiles (i) and (ii) are unstable at zonal wavenumber two, in agreement with previous studies [*Dobrovolskis and Diner*, 1990; *Elson*, 1982;

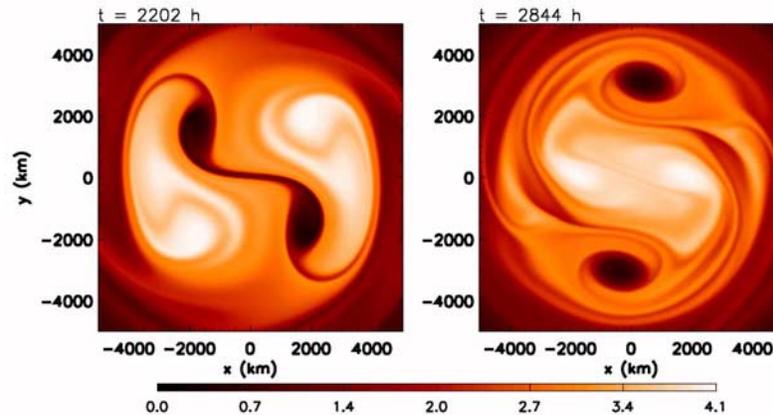
1989; *Michelangeli et al.*, 1987]. The corresponding  $e$ -folding instability growth rates are 7.7 days and 16.9 days respectively.

[8] Utilizing a double Fourier pseudo-spectral nondivergent barotropic model on the  $f$ -plane [*Schubert et al.*, 1999], we separately investigate the high-resolution, nonlinear evolution of vorticity initialized as the smoothed vorticity profiles shown in Figure 2. This numerical simulation is unforced although ordinary diffusion acts on the smallest resolvable scales to account for spectral blocking associated with the enstrophy cascade. Solutions are obtained using  $512 \times 512$  equally spaced collocation points on a doubly periodic domain size of  $15,000 \text{ km} \times 15,000 \text{ km}$ . The model used a de-aliased calculation of quadratic nonlinear terms, resulting in  $170 \times 170$  Fourier modes, yielding an effective resolution of  $88.2 \text{ km}$ . The diffusion coefficient is  $1.7 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ , yielding a  $1/e$  damping time of about 4.2 days for all modes having total wavenumber 170.

[9] A small sample of results from the numerical integration for the more unstable profile are shown in Figures 3 (left) and 3 (right). After 800 h, the small random perturbations had grown to finite amplitude and the wavenumber-two instability stretched and deformed the flow into an ellipse. In fact, this shape and existence of wave number two was also identified from the ultraviolet cloud morphology by *Suomi and Limaye* [1978]. The low vorticity centred on the pole is distorted into an S-shaped pattern (rotating with a period of about 4 days) by 2202 h (Figure 3 (left)). As the high, mid-latitude vorticity subsequently mixes inward, an inverted S-shaped pattern appears in the centre of the vortex as well, which is seen in Figure 3 (right). This is similar to the pattern seen from VIRTIS in April 2006



**Figure 2.** Relative vorticity profile at the cloud level determined from the zonal flow 1980 dayside zonal flow profile. The associated error bars represent formal uncertainty based on the standard error in each latitude bin average of the zonal component profile of the cloud motions. Blue and orange curves show the profiles used for model simulation by using a linear inverse weighted-average centred at each point of latitude. The ultraviolet cloud morphology prevents obtaining reliable measurements beyond  $\sim 60^\circ$  latitudes on Venus and hence vorticity profile is extrapolated towards the pole. The profile corresponding to the blue curve is less unstable (longer instability growth time) compared to the orange one.



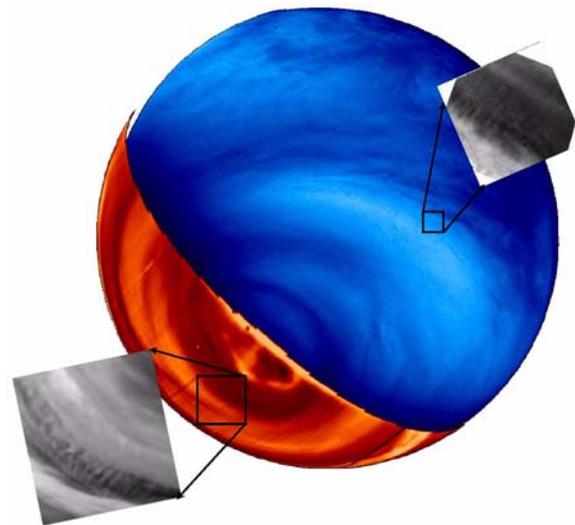
**Figure 3.** Plan view of vorticity (in units of  $10^{-5} \text{ s}^{-1}$ ) in the nondivergent barotropic model simulation after 2202 and 2844 hours elapsed time in the numerical integration. The darker shading represents lower vorticity originating over the pole and the brighter shading represents elevated vorticity that originated in an annulus surrounding the pole. The flow supports barotropic instability with azimuthal wavenumber two as the most unstable mode. Wavenumber two patterns within the vorticity field emerge throughout the simulation. Growth of the instability within the ambient shearing deformation produces an S-shaped feature in a central area of weaker vorticity by 2202 h (see auxiliary material). Eventually, inverted S-shaped features appear in the central enhanced vorticity after high vorticity begins mixing into the centre of the vortex. These features rotate with a period of about 4 days (cf. observed rates of 2.8 – 3.2 days). The difference between the observed rotation rate and the model rate could be due to several reasons – one is the actual flow profile when VIRTIS observations were made and the Pioneer Venus observations. Due to low resolution of the data, a good vorticity profile cannot yet be obtained from Venus Express data.

[Piccioni *et al.*, 2007] (see also auxiliary material).<sup>1</sup> The lighter regions correspond to regions of higher brightness temperatures that define the S-shape and may arise through sinking motion, although the advection of colder (higher) clouds by the vortex motions may help give rise to the observed pattern. The rotation period of the simulated S-shape is about 4 days, somewhat slower than the 2.5 days exhibited in the VIRTIS data. Additionally, the scale of the modeled S-shaped pattern is larger than observed. The Pioneer Venus Orbiter Infrared Radiometer also observed a similar but inverted pattern at the northern pole in 1978 which also rotated about the pole at rates from 2.8 to 3.2 days [Schofield and Diner, 1983; Taylor *et al.*, 1980].

[10] It is worth noting that a slight modification of the initial condition depicted in Figure 2 within the uncertainty bars can lead to significantly different results. For example, as shown in the auxiliary material, increasing the core vorticity in the zonal region between  $-80^\circ$  to  $-90^\circ$  latitude to above  $2 \times 10^{-5} \text{ s}^{-1}$  can lead to a less unstable vortex in that it takes a much longer time to break into two finite amplitude waves. Regardless, distinct wavenumber two patterns emerge under this assumption as well. In passing, it likely would prove both exciting and critical to our understanding of the general circulation to quantify the amount of time that the polar vortices on Venus exist in a more barotropically neutral state versus a more unstable configuration. Current Venus Express observations are relevant in this context, providing an ability to observe the evolution of the instabilities, and also the zonal flow profile at two levels, with some limitations.

[11] The barotropic instability and flow patterns deduced from the cloud data of the polar vortex on Venus have also

been noted in numerical simulations and observations of terrestrial tropical cyclone flow fields [Schubert *et al.*, 1999; Kossin and Schubert, 2001; Kossin and Eastin, 2001; Kossin *et al.*, 2002; Montgomery *et al.*, 2002; Knaff *et al.*, 2003; Kossin and Schubert, 2004]. Hurricane Howard



**Figure 4.** Vortices on Venus and Earth show other similarities, such as the waves on the spiral arms of the Venus vortex seen in this composite image from VIRTIS at  $1.74 \mu$  depicting night side of at  $\sim 45\text{--}50 \text{ km}$  level (red), and the day side ultraviolet view from VMC ultraviolet image at  $\sim 67 \text{ km}$  (blue). Transverse gravity waves (seemingly orthogonal to the spiral bands) similar to those seen in tropical cyclones (auxiliary material) can often be seen in a VIRTIS images and also VMC high resolution images (insets).

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2008GL036093.

(1998) formed S-shaped patterns within the low (warm) clouds in the eye during a vorticity rearrangement associated with barotropic instability of the eyewall wind field [Knaff *et al.*, 2003] (Figure 1). Here, the S-shape comprises two regions of weak vorticity that rotate in a retrograde sense relative to the ambient anti-clockwise rotation, and the S-shape is consequently not inverted. Comparatively, the feature observed near the Venus South pole comprises two regions of strong vorticity that rotate in the same direction as the ambient anticlockwise flow. Analogous patterns are seen in the weaker (dark) and stronger (light) vorticity simulated in the numerical model (Figure 3). In both observations and numerical simulations, the dipole features within the polar vortices of Venus (and in the eyes of terrestrial tropical cyclones) are relatively transient and variable in shape. In a relatively rare instance, one S-shaped feature seen in the VIRTIS data has been observed to last a few weeks [Piccioni *et al.*, 2007]. VIRTIS observed the S-shaped structure during the initial orbit and on a few later orbits (Orbit 38) about five weeks later. In most cases the vortex feature exhibits changing shapes consistent with the unforced vortex simulation.

[12] The differences between the polar vortices of Venus and terrestrial tropical cyclones include physical scale, lifetime and nature of heating that forces the flow. From the presumed origin of inflow at the cloud level near the equator to the centre of the vortex on Venus, the vortex has a radial size of about 12,000 km. Among the largest tropical cyclones observed on Earth, the radius of inflow is generally less than 1000 km. Tropical cyclones often last about one to two weeks in their mature phase. This timescale is relatively short in comparison to the vortex on Venus, which has been observed since 1974 and has likely existed for a much longer time. Tropical cyclones are migratory systems that move under synoptic control. On the day side of Venus, a significant fraction of the incident solar energy is deposited in the cloud layer from low to high latitudes. It is likely that an additional small energy deposition occurs globally due to the opacity presented by the cloud layer to the thermal emission from the hot lower atmosphere and surface of Venus (day and night), but especially in the polar region [Titov *et al.*, 2007] where the incident solar energy is much lower. Another similarity between the observed features in the vortex circulations of Venus and in terrestrial hurricanes is the presence of transverse waves extending radially outward from the vortex centres (Figure 4). The lack of observations of such features in Earth's polar vortices is suggestive that the dynamics of the Venus polar vortices may have more in common with hurricanes than their more direct terrestrial counterparts. Given the difficulties of reliably obtaining the required dynamical observations on Venus, we expect to gain more insight into Venus through the similarities in observed morphology.

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