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WIND CIRCULATION REGIMES AT VENUS' CLOUD TOPS : GROUND-BASED DOPPLER VELOCIMETRY USING CFHT/ESPADONS AND COMPARISON WITH SIMULTANEOUS CLOUD TRACKING MEASUREMENTS USING VEX/VIRTIS

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Abstract. We present new results based on ground-based Doppler spectroscopic measurements, obtained with the ESPaDOnS spectrograph at Canada-France-Hawaii telescope (CFHT) and simultaneous observations of velocity fields, obtained from space by the VIRTIS-M instrument on board the Venus Express spacecraft. These measurements are based on high-resolution spectra of Fraunhofer lines in the visible to NIR range (0.37-1.05 μm) acquired on Feb. 19-21, 2011 at a resolution of about 80,000, measuring Venus' winds at 70 km, using incoming solar radiation scattered by cloud top particles in the observer's direction (Widemann et al., 2007, 2008). The zonal wind field has been characterized by latitudinal bands, at a phase angle $\Phi = (68.7 \pm 0.3)^{\circ}$, between $+10^{\circ}$N and 60°S, by steps of 10°, and from $[\phi - \phi_E] = -50^{\circ}$ to sub-Earth longitude $\phi_E = 0^{\circ}$, by steps of 12°. From space, VIRTIS-M UV (0.38 μm) imaging exposures on the dayside were acquired simultaneously in orbit 1786, providing the first simultaneous cloud-tracking measurements with Doppler velocimetry. From the ground, we measured a zonal mean background velocity of $\overline{v}_z$ = (117.3 $\pm$ 18.0) m s^{-1} on Feb. 19, and $\overline{v}_z$ = (117.5 $\pm$ 14.5) m s^{-1} on Feb. 21. We detect an unambiguous poleward meridional flow on the morning dayside hemisphere of (18.8 $\pm$ 12.3) m s^{-1} on Feb. 19/21. Latitudinal variations of the zonal and meridional winds are further compared with the simultaneous VIRTIS data. We discuss temporal variability as well as its statistical significance (Machado et al., 2014).

Keywords: Venus, atmosphere; Atmospheres, dynamics; Spectroscopy.

1 Introduction

In a first approach Venus and Earth are similar planets: they accreted in the same proto-solar region and evolved out of the same initial densities, size, mass and bulk chemical composition (Svedhem et al. 2007); they both outgassed a thick initial atmosphere, allowing important cloud systems to develop (Bengtsson and Grinspoon 2013). A closer look, however, clearly evidences the drastic present differences between them.

The atmosphere of Venus in the upper cloud layer and lower mesosphere (65-85 km) is driven mainly by retrograde zonal circulation in cyclostrophic balance with the pressure gradient (Schubert et al. 1980). It is the site of significant variability of the flow, directly measured at both long and short timescales (Machado et al. 2012, 2014; Khatuntsev et al. 2013). This variability is likely coupled with variable horizontal distributions of dynamical tracers of the flow, such as water vapor, carbon monoxide and sulphur dioxide, for which different, and sometimes conflicting mixing ratios have been measured (de Bergh et al. 2006; Marcq et al. 2008; Bézard et al. 2009; Encrenaz et al. 2012; Chamberlain et al. 2013).

2 Observations and results

Background zonal wind circulation - We present in Table 1 the mean zonal wind velocities retrieved, under the assumption of a pure zonal one-wind system to data points acquired during sequences [1-6] (Feb. 19, 2011) and

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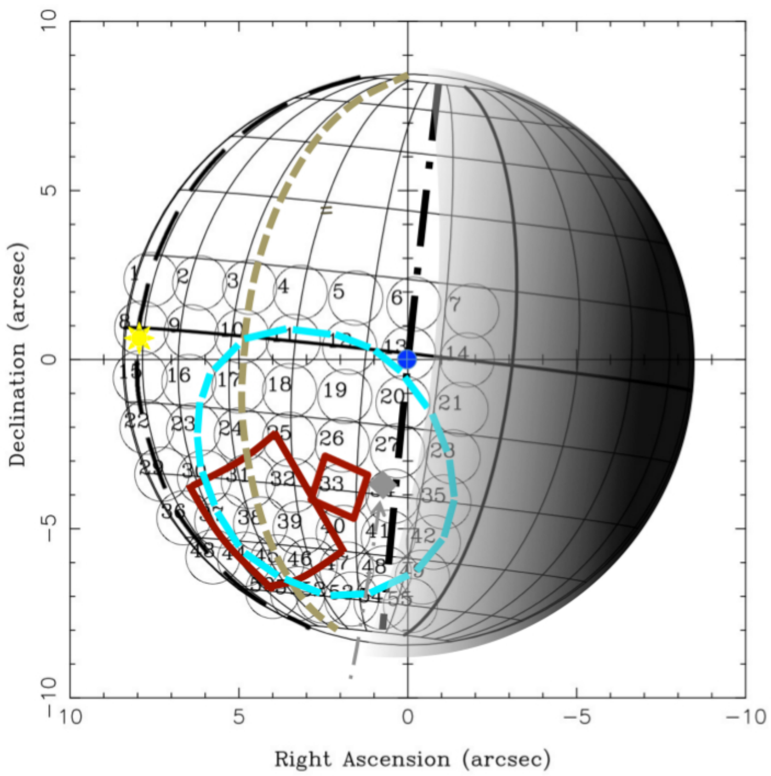

Fig. 1. Aspect and angular size of Venus as seen from Earth on Feb. 20, 2011 21h UTC, with superimposed Venus-Express instruments FOVs.

Date	Mean zonal wind (m s^{-1}) $\overline{v}_z$	reduced χ^2	2σ m s^{-1}	3σ m s^{-1}
19 Feb. 2011	117.3	1.16	± 18.0	±27.0
21 Feb. 2011	117.5	2.12	± 14.5	± 21.5

Date	Meridional velocity (m s^{-1}) $\overline{v}_m$	reduced χ^2	2σ m s^{-1}	3σ m s^{-1}
19/21 Feb. 2011	18.8	1.38	±12.3	±19.6

Table 1. CFHT/ESPaDOnS mean zonal and mean meridional flow results. - (a) Mean zonal velocity $\overline{v}_z$ on Feb. 19 and Feb. 21, 2011 data. The 1-wind regime fit is applied to the entire probed region $v_{z,i}$ data points at latitudes 30° and 40° S (Feb. 19) and between latitudes 10° and 50° S (Feb. 21). Best-fit reduced χ^2 is indicated at 2σ and 3σ confidence. (b) Mean meridional wind velocity $\overline{v}_m$ fit along HPA meridian ($[\phi - \phi_E] = \Phi/2 \simeq$ -36°), obtained at 2σ and 3σ confidence level.

sequences [14-20] (Feb. 21, 2011), with the exception of points at the dayside limb facing east-sky and points with SZA $> \Phi = 68°$. The best-fit results for the two days of observations are self-consistent, with $\overline{v}_z$ = (117.3 ± 18.0) m s^{-1} on Feb. 19, and $\overline{v}_z$ = (117.5 ± 14.5) m s^{-1} on Feb. 21, respectively, with a good quality of fit (S$_{min}$ = 1.16). Figures 2a,b present 1-parameter fit results for a pure zonal wind on Feb. 19, Feb. 21 observing sequences. The ESPaDOnS field-of-view (FOV) is represented to scale over the apparent Venus disk, and its projected size at disk center is indicated in Table 1. Zonal velocities retrieved at each offset position are weighed means of individual exposures.

Figure 3a shows all measurements for the zonal velocity at cloud tops as a function of latitude. The variability of $v_{z,i}$ in local time and $[\phi - \phi_E]$ longitude reflects the scatter of ESPaDOnS zonal velocities at each latitude of reference, as well as the time variability for data points acquired more than once during the day, *i.e.* at 40°

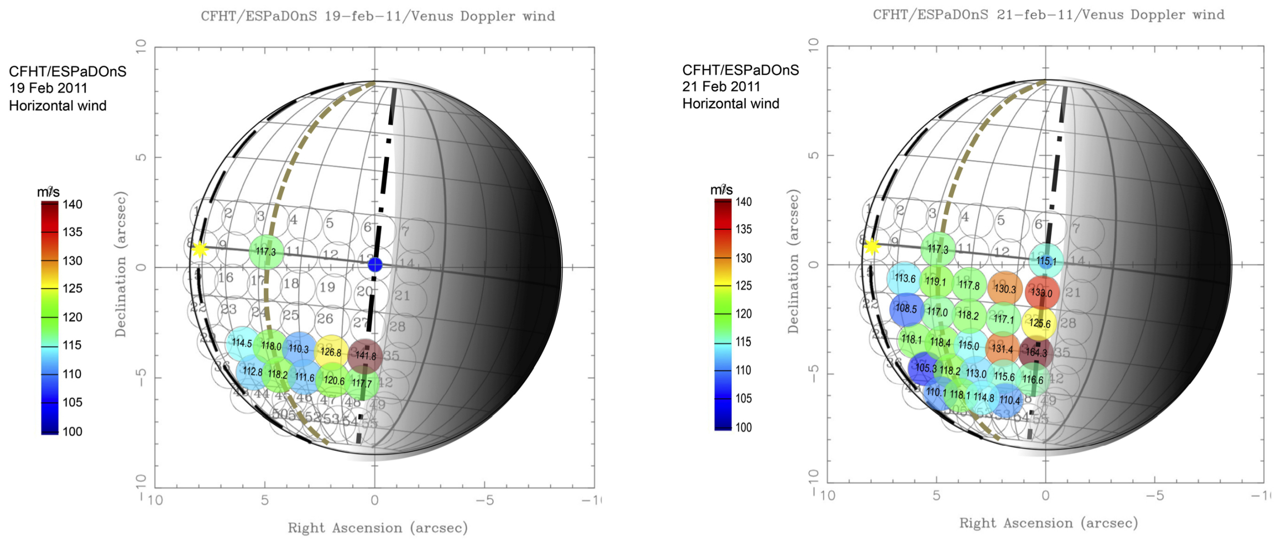

Fig. 2. Left: Results for day-averaged wind velocity $\overline{v}_{z,i}$ for observing sequences [1-6] (Feb. 19). $\overline{v}_{z,i}$ is the day-averaged zonal component at point i deprojected from line-of-sight day-averaged measurements $\overline{v}'_i$. Values are in m/s. Each point has a projected field of view of 574 km at Venus. **Right:** Results for Feb. 21, 2011 (sequences [14-21]). FOV is 582 km at Venus. Sub-solar, HPA, sub-terrestrial and morning terminator meridians are indicated as in Fig. 1.

and 50°S. Our mean zonal latitudinal profile is in general agreement with simultaneous as well as previous CT data. In the overlapping region between S lat. 20° and 50° we note an excellent agreement between $v_{z,i}$ and $v_{z,CT}$. Equatorward of 30°S we note a general excess of 10−15 m s^{-1} of the Doppler velocimetry results with respect to VIRTIS-M.

Figure 3b shows the comparison for the meridional circulation component. Results for cloud-tracking $v_{m,CT}$ of VIRTIS-M are compared to simultaneous $\overline{v}_m$ in CFHT/ESPaDOnS with a 1-wind fit to a pure meridional flow peaking at $\overline{v}_m = (18.8 \pm 12.3)$ m s^{-1} in Feb. 21 data. We note a good agreement between the two techniques at all latitudes where simultaneous measurements were performed. The meridional circulation found by Snchez-Lavega et al. (2008) and Moissl et al. (2009) displayed positive meridional velocities that increase from 0 m s^{-1} at the South pole to about 10 m s^{-1} at 55° S and then decrease to 0 m s^{-1} at low latitudes (Hueso et al. 2012). We observe a similar latitudinal profile for the pure meridional flow $\overline{v}_m = (18.8 \pm 12.3)$ m s^{-1} in Feb. 21 data. The upper cloud velocimetry in our data is therefore consistent with the poleward branch of a Hadley cell expected in global meridional circulation models. Our model flow $\overline{v}_m$ is assumed to vary sinusoidally with latitude through its de-projection coefficients (c_z), having zero velocity at equator and the poles, and a maximum velocity v$_m$ (positive for poleward motion) at lat 45°. The comparison between simultaneous velocity measurements with CFHT/ESPaDOnS ($\overline{v}_{z,i}$, $\overline{v}_m$) and VEx/VIRTIS ($v_{z,CT}$, $v_{m,CT}$) shows excellent agreement for both the zonal and meridional components of the global circulation, with minor differences equatorward of 30° S and significant temporal variations $v_{z,i} - \overline{v}_z$ to the mean zonal wind at 30° S.

ESPaDOnS measurements (green triangles) and simultaneous VIRTIS-M zonal velocity measurements the (red circles) show a good general agreement between the two methods. VIRTIS-M data have an uncertainty on individual motions of the tracked clouds of about 5 m s^{-1}, while ESPaDOnS individual measurement uncertainties $v_{z,i}$, due to additional on-sky calibration and data reduction have a final value of 10−12 m s^{-1}. The general latitudinal variation of the zonal wind field at cloud tops is in excellent agreement with previously published results of Snchez-Lavega et al. (2008); Moissl et al. (2009); Hueso et al. (2012), with zonal wind speed in the upper clouds at nearly constant speed from the equator down to 65°S followed by a steady decrease toward zero velocities at the pole. In our data the meridional shear of the wind between 60° and 80°S is -0.03 m s^{-1} km^{-1}.

Comparison between Cloud tracking (VIRTIS) and Doppler (ESPaDOnS)

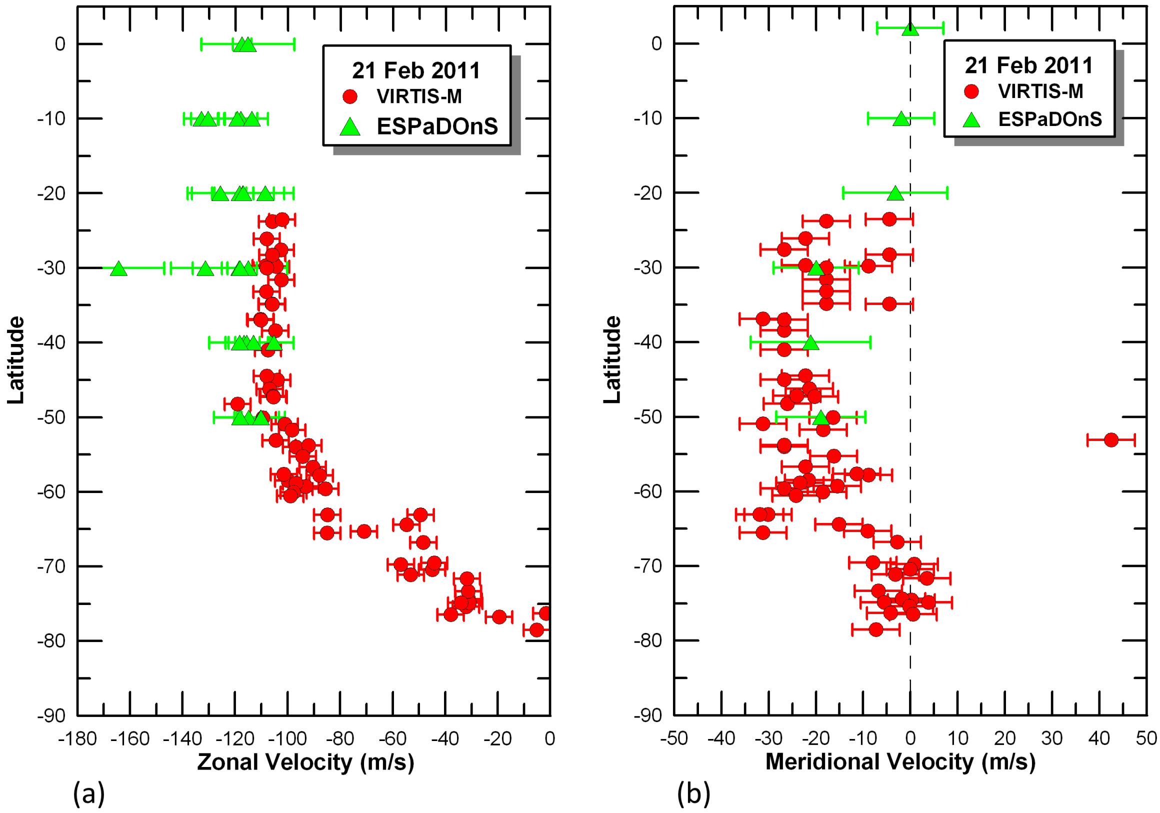

Fig. 3. Simultaneous cloud-tracking wind velocity measurements of VEx/VIRTIS-M (red dots) and CFHT/ESPaDOnS instantaneous Doppler winds (triangles, green in the online version) on February 21, 2011. For the two techniques horizontal velocity (x-axis) is plotted vs. latitude (y-axis) in m s^{-1}. (a) Cloud-tracking zonal component $v_{z,CT}$ plotted with Doppler zonal component $\overline{v}_{z,i}$. (b) Cloud tracking meridional component $v_{m,CT}$ plotted with Doppler meridional component $\overline{v}_{m,lat}$. CFHT/ESPaDOnS $\overline{v}_{z,i}$.

3 Conclusions

Winds can be measured from Venus Express orbit using cloud tracking at 45 and 70 km by both VIRTIS-M and VMC instruments (Markiewicz et al., 2007 ; Sanchez-Lavega et al., 2008 ; Hueso et al., 2012). However, winds derived in this manner are usually averaged over several days of observations and do not reflect instantaneous wind velocity and its significant variability at shorter time scales. In addition, cloud tracking is not able to measure wind fields above cloud level, where wind inferences have to rely on indirect hypothesis such as cyclostrophic balance.

The ground-based velocimetry technique has proven its reliability in constraining global wind circulation models, complementary of space-based measurements. Doppler retrievals in the visible are in good agreement with Venus-Express cloud tracking measurements within our confidence intervals, as was previously suggested (Widemann 2008, Machado 2012, Machado 2014). For the first time, simultaneous measurements were carried out and self-consistent results were obtained from space and ground-based observations. An unambiguous detection of poleward meridional circulation is reported on the morning dayside hemisphere, using optical Doppler velocimetry from the ground at CFHT.

In addition, we assessed the feasibility of day-to-day monitoring of short time-scale variability from the ground (although its significance remains essentially marginal at the 2-σ level). Establishing a reliable model of the circulation of Venus requires long-term as well as short-term averages to constrain both the mean circulation and eddy motions. Time-scale variations are expected to bring new constraints on Venus General Circulation Models at cloud top level, and we hope to develop further the technique's capability to track short-term variations in future observations. The present study also highlights the added value of coordinated studies from ground-based observatories and from spacecraft (Witasse et al. 2006; Lellouch and Witasse 2008; Machado et al. 2014).

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