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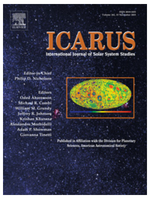

Variations of water vapor and cloud top altitude in the Venus' mesosphere from SPICAV/VEx observations

A. Fedorova[a,*], E. Marcq[b], M. Luginin[c,a], O. Korablev[a], J.-L. Bertaux[b], F. Montmessin[b]

[a] *Space Research Institute (IKI), Profsoyuznaya 84/32, 117997 Moscow, Russia*
[b] *LATMOS, CNRS/INSU - IPSL - Univ. Pierre & Marie Curie - Univ. Versailles Saint-Quentin, Université Paris-Saclay, 11 Boulevard d'Alembert F-78280 Guyancourt, France*
[c] *Moscow Institute of Physics and Technology (MIPT), Dolgoprudny, Russia*

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ABSTRACT

SPICAV VIS-IR spectrometer on-board the *Venus Express* mission measured the H_2O abundance above Venus' clouds in the 1.38 µm band, and provided an estimation of the cloud top altitude based on CO_2 bands in the range of 1.4–1.6 µm. The H_2O content and the cloud top altitude have been retrieved for the complete *Venus Express* dataset from 2006 to 2014 taking into account multiple scattering in the cloudy atmosphere. The cloud top altitude, corresponding to unit nadir aerosol optical depth at 1.48 µm, varies from 68 to 73 km at latitudes from 40°S to 40°N with an average of 70.2 ± 0.8 km assuming the aerosol scale height of 4 km. In high northern latitudes, the cloud top decreases to 62–68 km. The altitude of formation of water lines ranges from 59 to 66 km. The H_2O mixing ratio at low latitudes (20°S-20°N) is equal to 6.1 ± 1.2 ppm with variations from 4 to 11 ppm and the effective altitude of 61.9 ± 0.5 km. Between 30° and 50° of latitude in both hemispheres, a local minimum was observed with a value of 5.4 ± 1 ppm corresponding to the effective altitude of 62.1 ± 0.6 km and variations from 3 to 8 ppm. At high latitudes in both hemispheres, the water content varies from 4 to 12 ppm with an average of 7.2 ± 1.4 ppm which corresponds to 60.6 ± 0.5 km. Observed variations of water vapor within a factor of 2-3 on the short timescale appreciably exceed individual measurement errors and could be explained as a real variation of the mixing ratio or/and possible variations of the cloud opacity within the clouds. The maximum of water at lower latitudes supports a possible convection and injection of water from lower atmospheric layers. The vertical gradient of water vapor inside the clouds explains well the increase of water near the poles correlating with the decrease of the cloud top altitude and the H_2O effective altitude. On the contrary, the depletion of water in middle latitudes does not correlate with the H_2O effective altitude and cannot be completely explained by the vertical gradient of water vapor within the clouds. Retrieved H_2O mixing ratio is higher than those obtained in 2.56 µm from *VIRTIS-H* data (Cottini et al., [2015] Planet. Space Sci., 113, 219–225) at altitudes of 68–70 km which is well consistent with the lower altitudes of water mixing ratio from the 1.38 µm band. Observations for different solar and emission angles allowed to constrain also the average vertical distribution of H_2O mixing ratio in the clouds with 2 ppm at 66 km and 7–7.5 ppm at 59–61 km. The water vapor latitudinal-longitudinal distribution does not show any direct correlation with the cloud tops. Yet a strong asymmetry of H_2O longitudinal distribution has been observed with a maximum of 7–7.5 ppm from −120° to 30° of longitude and shifted to the southern hemisphere (20°S-10°N). To the east, the minimum is observed with values not in excess of 6 ppm and over a wide range of longitudes from 30° to 160°. Bertaux et al. (2015) announced a correlation between the zonal wind pattern in the equatorial region and underlying topography of Aphrodite Terra as the result of stationary gravity waves produced at the ground level near the mountains. The water minimum corresponds to the Aphrodite Terra highlands and can be also associated with the influence of Venus topography. No prominent long-term on the time scale of 8.5 years nor local time variations of water vapor and the cloud top altitude were detected.

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[*] Corresponding author. Tel.: +7 495 3331067.
E-mail address: fedorova@iki.rssi.ru (A. Fedorova).

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1. Introduction

Although water vapor is only a minor component, it is one of the most important gases in the Venus' atmosphere. The question why Venus is so much drier than Earth is crucial for understanding the evolution of the Venus atmosphere. H_2O plays a significant role in the chemistry of the lower and middle atmosphere of Venus and cloud formation owing to its involvement in sulfur oxidation cycle that produces H_2SO_4, and in active photochemistry above the clouds. Water vapor also participates in the thermal balance of the atmosphere. Based on the simple cloud model, Hashimoto and Abe (2001) showed that the increase in H_2O abundance raises the cloud albedo and cools the surface environment.

During several decades of Venus' exploration numerous ground-based, orbital and in-situ measurements of water vapor have provided a consistent picture of H_2O distribution from the surface to the upper mesosphere. Below the clouds the water vapor was measured by Venera-11-14 descent modules and by observing in night-side spectral windows from ground-based telescopes and since 2006 by *Venus Express* spectrometers. Most of observations from the surface to the lower cloud level ~30–40 km are consistent with the 30 ± 10 ppm abundance (where ppm is parts per million by volume) (Ignatiev et al., 1997; Bézard and de Bergh, 2007; Marcq et al., 2008; Bézard et al., 2011, Chamberlain et al., 2013; Arney et al., 2014; Fedorova et al., 2015). The microwave and IR observations of water vapor in the mesosphere and low thermosphere (70–120 km) (Encrenaz et al., 1995; Sandor and Clancy, 2005; Gurwell et al., 2007; Fedorova et al., 2008; Krasnopolsky, 2010; Krasnopolsky et al., 2013) are characterized by a lower mixing ratio of 0–5 ppm with about constant vertical distribution.

Within the clouds the water abundance was measured mostly in the thermal IR range. The *Pioneer Venus Orbiter Infrared Radiometer* (PV OIR) (Taylor et al., 1979) and *Venera 15 Fourier Transform Spectrometer* (FTS) (Moroz et al., 1986) observations of thermal emission from Venus middle atmosphere provided global maps of water vapor abundance using the 45 μm fundamental rotational water band. The cloud top H_2O abundance observed by the PV OIR instrument varied from 10 ± 5 ppm at night up to 90 ± 15 ppm in the equatorial cloud-top region early afternoon at 55–60 km (Schofield et al., 1982; Koukouli et al., 2005). The water vapor abundance from Venera 15 was within 5–15 ppm at altitudes of 58–62 km (Ignatiev et al., 1999; Koukouli et al., 2005).

In April 2006 the European Space Agency's *Venus Express* (VEx) spacecraft (Titov et al., 2006, Svedhem et al., 2009) delivered to Venus' orbit several spectrometers capable to measure water vapor in the middle atmosphere on the nightside and the dayside. The *Planetary Fourier Spectrometer* (PFS) on VEx was intended to measure H_2O based on several IR bands including the fundamental thermal 20–40 μm (Formisano et al., 2006). Unfortunately, a scanner mechanism of the instrument was blocked in the initial position, pointing toward a blackbody target, making the measurements impossible (Svedhem et al., 2009). A high-resolution infrared (1.8–5.0 μm) spectrometer *VIRTIS-H*, a channel of *Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)* (Drossart et al., 2007) provided long-term observations of H_2O above clouds in 2.56 μm band from 2006 to 2011 (Cottini et al., 2012, 2015). The measured water vapor abundance equals to 3 ± 1 ppm at low latitudes that corresponds to the cloud top altitude of 69 km and increases to a maximum of 5 ± 2 ppm with cloud top altitudes of 62–64 km at 70–80° of latitude in both hemispheres with sharp polar decreases.

Despite numerous observations, the vertical distribution, variations and transport of water vapor within and above the clouds is still poorly understood. As we know, the Venus' clouds are composed of H_2SO_4-H_2O droplets, the sulfuric acid is produced photochemically through hydration of SO_3 above 60 km, where SO_2 is photooxidized (Krasnopolsky and Pollack, 1994, Hashimoto and Abe, 2001). The H_2SO_4 gas condenses into droplets, which grow and move downward by diffusion and sedimentation. At about 48 km, the cloud particles evaporate due to high temperature. The H_2SO_4 is thermally decomposed to H_2O and SO_3 at about 38 km. H_2O and other reaction products diffuse then upward. Below 45 km, the water vapor is uniformly mixed. Above, similarly to SO_2, the water vapor vanishes in the thin layer where the sulfur acid forms. The photochemical model of Krasnopolsky (2012) gives this layer at 66 km, and above the H_2O mixing ratio is steeply decreasing to 70 km and almost constant above this altitude. The model of Krasnopolsky (2012) predicted the H_2O abundance above 70 km is sensitive to changes in eddy diffusion and the SO_2 content at the lower boundary.

High variability of water observed by PV OIR near 60 km is not supported by *VIRTIS* results, which haven't shown any maximum of water vapor near the sub-solar point (Cottini et al., 2015). On the other hand, VIRTIS observations are mostly related to 65–70 km, which may explain the disagreement. In any case the near-sub-solar region is of special interest due to high convective activity and possible uplift of H_2O and SO_2 from deeper layers (Schofield et al., 1982; Marcq et al., 2013).

Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Venus/Solar Occultation in the Infrared (SPICAV/SOIR) instrument (Bertaux et al., 2007) on the *Venus Express* spacecraft is a set of three spectrometers optimized for measuring the density and composition of the upper atmosphere by observations in stellar and solar occultation mode. It is also used in nadir mode, together with other instruments. During more than eight years of *Venus Express* operations, the instrument provided measurements of the water vapor abundance mapped near the cloud-top on the day-side in the 1.38 μm band. It is the longest middle atmosphere H_2O dataset to date.

In this paper, we present spatial and temporal variations of water vapor for the full set of *SPICAV* observations. In Section 2 we describe the instrument, observations and data calibrations related to H_2O observations. In Section 3 the direct atmospheric model and data inversion technique is explained. Section 4 is dedicated to results for the cloud top altitude and the H_2O mixing ratio. Comparison with previous observations and sensitivity of the results to the vertical gradient of H_2O are also discussed.

2. SPICAV IR observations

2.1. Description of the spectrometer

The *SPICAV/SOIR* instrument on-board the *Venus Express* spacecraft consists of three spectrometers: UV (118–320 nm) spectrometer, VIS-IR (0.65–1.7 μm) Acousto-Optical Tunable Filter (AOTF) spectrometer and high-resolution mid-infrared echelle-AOTF spectrometer *SOIR* (Bertaux et al., 2007). The VEx spacecraft operates in a polar 24 h orbit with an apocenter at an altitude of about 60,000 km above the South Pole and a pericenter at an altitude of about 250 km. In this paper, we consider results of the VIS-IR spectrometer which is an AOTF pencil-beam spectrometer for the spectral range of 0.65–1.7 μm (Korablev et al., 2012). This spectral range is divided into two sub-ranges, the short wavelength (SW) (0.65–1.1 μm) with a spectral resolution of 7.8 cm^{-1}, and the long wavelength (LW) (1–1.7 μm) with spectral resolution of 5.2 cm^{-1}. Resulting resolving power is ~1400 at 1.4 μm. There is one AOTF with two different acoustic transducers, and two different types of detectors. Hereafter the sub-ranges are designated as SW and LW channels. Both the SW and LW spectra are obtained in two orthogonal polarizations. The instrument measures a spectrum of solar radiation reflected from Venus on the day side, and the emitted Venus radiation in spectral “windows” on the night side. The field