Icarus 272 (2016) 178–205

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Radiative energy balance of Venus based on improved models of the middle and lower atmosphere

R. Haus [a,*], D. Kappel [b], S. Tellmann [c], G. Arnold [b], G. Piccioni [d], P. Drossart [e], B. Häusler [f]

[a] University of Münster (WWU), Institute for Planetology, Wilhelm-Klemm-Str.10, 48149 Münster, Germany
[b] German Aerospace Center (DLR), Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany
[c] Rhenish Institute for Environmental Research at the University of Cologne, Department for Planetary Research, Aachener Str. 209, 50931 Köln, Germany
[d] Istituto Nazionale di Astrofisica, (INAF-IAPS), Via Fosso del Cavaliere 100, 00133 Roma, Italy
[e] Observatoire de Paris, Section de Meudon, Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique (LESIA), 5 place Jules Janssen, 92195 Meudon Cedex, France
[f] Bundeswehr University Munich, Institute of Space Technology and Space Applications, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany

ARTICLE INFO

Article history:
Received 4 December 2015
Revised 11 February 2016
Accepted 23 February 2016
Available online 4 March 2016

Keywords:
Venus
Atmospheres, structure
Radiative transfer
Infrared observations
Radio observations

ABSTRACT

The distribution of sources and sinks of radiative energy forces the atmospheric dynamics. The radiative transfer simulation model described by Haus et al. (2015b) is applied to calculate fluxes and temperature change rates in the middle and lower atmosphere of Venus (0–100 km) covering the energetic significant spectral range 0.125–1000 μm. The calculations rely on improved models of atmospheric parameters (temperature profiles, cloud parameters, trace gas abundances) retrieved from Venus Express (VEX) data (mainly VIRTIS-M-IR, but also VeRa and SPICAV/SOIR with respect to temperature results). The earlier observed pronounced sensitivity of the radiative energy balance of Venus to atmospheric parameter variations is confirmed, but present detailed comparative analyses of possible influence quantities ensure unprecedented insights into radiative forcing on Venus by contrast with former studies.

Thermal radiation induced atmospheric cooling rates strongly depend on temperature structure and cloud composition, while heating rates are mainly sensitive to insolation conditions and UV absorber distribution. Cooling and heating rate responses to trace gas variations and cloud mode 1 abundance changes are small, but observed variations of cloud mode 2 abundances and altitude profiles reduce cooling at altitudes 65–80 km poleward of 50°S by up to 30% compared to the neglect of cloud parameter changes. Cooling rate variations with local time below 80 km are in the same order of magnitude.

Radiative effects of the unknown UV absorber are modeled considering a proxy that is based on a suitable parameterization of optical properties, not on a specific chemical composition, and that is independent of the used cloud model. The UV absorber doubles equatorial heating near 68 km. Global average radiative equilibrium at the top of atmosphere (TOA) is characterized by the net flux balance of 156 W/m^2, the Bond albedo of 0.76, and the effective planetary emission temperature of 228.5 K in accordance with earlier results. TOA radiative equilibrium can be achieved by slight adjustments of either UV absorber or cloud mode abundances. Ratios of synthetic spectral albedo values at 0.36 μm calculated for different abundance factors of the UV absorber are suggested to provide a possible tool to interpret observed VMC/VEX brightness variations with respect to actual absorber abundances.

Atmospheric net heating dominates the low and mid latitudes above 82 km, while net cooling prevails at high latitudes at all mesospheric altitudes (60–100 km). This radiative forcing field has to be balanced by dynamical processes to maintain the observed thermal structure. A similar but much smaller meridional gradient is also observed at altitudes between 62 and 72 km where the unknown UV absorber provides additional heating. At these altitudes, equatorial net heating dominates net cooling from

* Corresponding author. Tel.: +49 3053011092.
E-mail addresses: rainer.haus@gmx.de (R. Haus), dkappel@gmx.net, gabriele.arnold@dlr.de (D. Kappel), silvia.tellmann@uni-koeln.de (S. Tellmann), giuseppe.piccioni@iaps.inaf.it (G. Piccioni), pierre.drossart@obspm.fr (P. Drossart), b.haeusler@unibw.de (B. Häusler).

http://dx.doi.org/10.1016/j.icarus.2016.02.048

about 07:30 h until 16:30 h local time. Intermediate altitudes (72–82 km) are characterized by net cooling at all latitudes in case of VIRTIS temperature data. This planet-wide net cooling region is not observed when calculations are based on VeRa temperatures, and low latitudes are then characterized by small net heating. When a warm atmospheric layer as detected by SPICAV/SOIR around 100 km is considered, strong global average net cooling occurs above 90 km that is far away from radiative equilibrium. A weak net cooling layer (1–2 K/day) exists at altitudes between 55 and 60 km, while very weak net heating (0.1–0.5 K/day) takes place near the cloud base (48 km). Almost zero net heating prevails in the deep atmosphere below 44 km. On global average, the entire atmosphere of Venus at altitudes between 0 and 90 km is not far away from radiative equilibrium (usually within± 2 K/day).

Maximum temperature change rate deviations from mean values at each altitude and latitude are defined based on retrieved atmospheric parameter single standard deviations using VIRTIS data. This is an important prerequisite to investigate parameterization approaches for the calculation of atmospheric temperature change rates that can be used in Global Circulation Models. This will be a major topic of future studies on radiative energy balance of Venus' atmosphere.

1. Introduction

Physical processes in a planetary atmosphere are based on three fundamental influence quantities, the input of solar energy including spatial and temporal variations due to both the planet's movement around its sun and its axial rotation, the release of energy by heated bodies, and the forces that result from planetary gravitation and rotation. Radiative energy conversion stimulates dynamical processes at all atmospheric levels and determines climate and weather in the lower atmosphere via a number of coupling effects. One of the main mysteries in our Solar System is the atmospheric superrotation that is present on Venus and on Saturn's Moon Titan. The origin of this phenomenon and the driving forces for the winds that blow faster than the bodies rotate are not well understood yet. To improve insights into atmospheric dynamics especially on Venus, detailed radiative energy balance studies are necessary. They will provide input parameters for General Circulation Models (GCMs) that are used to simulate and explain observed dynamical properties (e.g. Lebonnois et al., 2010). Calculation of the radiative budget at each level of the atmosphere that is determined by absorption and scattering of solar radiation as well as thermal emissions requires precise knowledge of the thermal state, gaseous and particulate constituent distributions, and specific interaction processes between radiation and matter considering spatial and temporal variations of atmospheric parameters.

Early orbital and lander missions to Venus (Mariner 2, 5, 10; Venera 4–16; Pioneer Venus 1+2; Vega 1+2; Magellan) and space experiments during the Venus flybys of Galileo/NIMS and Cassini/VIMS revealed basic information about pressure and temperature conditions on the surface, chemical composition, thermal structure and cloud composition of the atmosphere, large-scale atmospheric circulation features as well as surface topography (Arnold et al., 2012). But in spite of the many successful measurements, some fundamental problems in the physics of the planet remained unsolved. In particular, a systematic and long-term survey of the atmosphere was missing (Titov et al., 2008a).

Former analyses of radiative processes in the atmosphere of Venus were mainly based on Pioneer Venus and Venera-15 data (e.g. Pollack et al., 1980; Schofield and Taylor, 1982, 1983; Tomasko et al., 1985; Crisp, 1986, 1989; Haus and Goering, 1990; Titov, 1995). Summaries of knowledge about the planetary energy balance characteristics and of open issues were given by Crisp and Titov (1997), Taylor (2006), and Titov et al. (2006, 2007, 2013). These investigations already revealed a strong sensitivity of radiative energy balance to atmospheric parameter variations like changes of temperature structure, cloud microphysical properties, and vertical distributions of individual cloud mode abundances. However, all these parameters were not strongly constrained by measurements before Venus Express with its great planetary mapping potential. Moreover, early analyses were hampered by computational constraints during that time, and the use of band models for gaseous absorbers was mostly unavoidable.

The latest mission to Venus (ESA's Venus Express, VEX) has carried the most powerful remote sensing suite of instruments ever flown to Earth's sister planet. Together with the other instruments (VMC, SPICAV/SOIR, VeRa, ASPERA, MAG), the Visible and Infrared Thermal Imaging Spectrometer VIRTIS has enabled for the first time a long-time study of the structure, composition, chemistry, and dynamics of the atmosphere and the cloud system, as well as investigations of the thermal and compositional characteristics of the planetary surface. VIRTIS (Piccioni et al., 2007a; Drossart et al., 2007; Arnold et al., 2012) provided an enormous amount of new data and a four-dimensional picture of the planet Venus (2D imaging, spectral dimension, temporal variations) on global scales. The spectral dimension permits a sounding of atmospheric properties at different altitude levels. VIRTIS-M-IR measurements during eight Venus solar days between April 2006 and October 2008 have been used by Haus et al. (2013, 2014, 2015a) to retrieve information on mesospheric nightside thermal structure and cloud features and on trace gas distributions in the lower atmosphere using new methodical approaches. Resulting maps for the southern hemisphere have covered parameter variations with altitude, latitude, local time, and mission time.

Temperature profile and cloud top altitude retrieval results using VIRTIS-M-IR spectra were also reported by Grassi et al. (2010, 2014). Tellmann et al. (2009) used VeRa data to determine temperature profiles at altitudes between 45 and 90 km, while SPICAV/SOIR occultation measurements provided profiles at 90–140/80–170 km (Piccialli et al., 2014; Mahieux et al., 2012). Altimetry of the Venus cloud top based on VIRTIS, VMC, and VeRa data was also investigated by Titov et al. (2008b), Ignatiev et al. (2009), and Lee et al. (2012). Trace gas distributions below the cloud bottom based on VIRTIS-M-IR and -H measurements were studied by Tsang et al. (2008, 2009, 2010), Marcq et al. (2008), Bézard et al. (2009). The only recent two-dimensional analysis (altitude-latitude) of both radiative cooling and radiative heating in the atmosphere of Venus that considers atmospheric parameters retrieved from VEX instrument data (VeRa temperatures, VIRTIS-M-IR cloud parameters) was performed by Lee et al. (2015).

It is the main goal of the present paper to investigate atmospheric radiation fluxes (F) and temperature change rates (Q) in the middle and lower atmosphere of Venus (0–100 km) that are mainly based on improved three-dimensional atmospheric models (altitude-latitude-local time) retrieved from VIRTIS-M-IR data. An additional focus is the response of Q to the replacement of VIRTIS temperature profiles by VeRa data. The used approach is premised