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Radiative energy balance of Venus: An approach to parameterize thermal cooling and solar heating rates

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ABSTRACT

Thermal cooling rates Q^C and solar heating rates Q^H in the atmosphere of Venus at altitudes between 0 and 100 km are investigated using the radiative transfer and radiative balance simulation techniques described by Haus et al. (2015b, 2016). Q^C strongly responds to temperature profile and cloud parameter changes, while Q^H is less sensitive to these parameters. The latter mainly depends on solar insolation conditions and the unknown UV absorber distribution.

A parameterization approach is developed that permits a fast and reliable calculation of temperature change rates Q for different atmospheric model parameters and that can be applied in General Circulation Models to investigate atmospheric dynamics. A separation of temperature, cloud parameter, and unknown UV absorber influences is performed. The temperature response parameterization relies on a specific altitude and latitude-dependent cloud model. It is based on an algorithm that characterizes Q responses to a broad range of temperature perturbations at each level of the atmosphere using the Venus International Reference Atmosphere (VIRA) as basis temperature model. The cloud response parameterization considers different temperature conditions and a range of individual cloud mode factors that additionally change cloud optical depths as determined by the initial latitude-dependent model. A Q^H response parameterization for abundance changes of the unknown UV absorber is also included. Deviations between accurate calculation and parameterization results are in the order of a few tenths of K/day at altitudes below 90 km.

The parameterization approach is used to investigate atmospheric radiative equilibrium (RE) conditions. Polar mesospheric RE temperatures above the cloud top are up to 70 K lower and equatorial temperatures up to 10 K higher than observed values. This radiative forcing field is balanced by dynamical processes that maintain the observed thermal structure.

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1. Introduction

The conversion of radiative energy in a planetary atmosphere stimulates dynamical processes at all altitudes and forces climate and weather phenomena via a number of coupling effects. The general processes being responsible to maintain the zonal super-rotation in the troposphere and mesosphere of Venus (where the winds blow up to four times faster than the solid body rotates) and its transition to the sub-solar to anti-solar circulation in the thermosphere are still poorly understood (Schubert et al., 2007). Different General Circulation Models (GCMs) for Venus' atmosphere have been developed during the past years and are currently under further development. They intend to simulate atmospheric circulation processes and observed dynamical properties (e.g. Lee and Richardson, 2010; Lebonnois et al., 2010; Rodin et al., 2013). GCMs have to rely on parameterized descriptions of radiative heating and cooling processes due to limited overall numerical resources.

Calculations of accurate quasi-monochromatic downward and upward directed radiation fluxes inside the atmosphere that consider both gaseous and particulate atmospheric absorption, emission, and multiple scattering processes are only possible on the basis of very time consuming numerical procedures. The overall broad spectral range from 0.1 to 1000 µm has to be addressed where the individual contributions of atmospheric constituents at ultraviolet (0.1–0.4 µm), visible (0.4–0.7 µm), and infrared (0.7–1000 µm) wavelengths are very different. Calculations can be separately performed for thermal (1.67–1000 µm, 10–6000 cm^{-1}) and solar (0.125–1000 µm, 10–80,000 cm^{-1}) flux components. Wavelength-integrated quantities and diurnal averages of resulting net fluxes and their altitude divergences are then used

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to determine temperature change rates in terms of thermal cooling rates and solar heating rates at each altitude, latitude and for different local times. The results strongly depend on the used atmospheric models both with respect to thermal structure and cloud composition. It is impossible to incorporate accurate radiative balance calculations that take several hours on current computer hardware into GCMs, and the use of time efficient parameterization approaches is urgently required.

The main methodical aspects to investigate the radiative energy balance in the middle and lower atmosphere of Venus (0–100 km) were described by Haus et al. (2015b). Variations of initial atmospheric model data sets (also denoted as 'standard' in the following) were used to calculate responses of radiative fluxes and temperature change rates to atmospheric and spectroscopic parameter variations. A second paper (Haus et al., 2016) has then investigated atmospheric radiation fluxes (F) and temperature change rates (Q) that are based on improved three-dimensional atmospheric models (altitude-latitude-local time) mainly retrieved from VIRTIS-M-IR data. An additional focus of that paper was the response of Q to the replacement of VIRTIS temperature profiles by those obtained from VeRa data. VIRTIS (Visible and Infrared Thermal Imaging Spectrometer; Piccioni et al., 2007; Drossart et al., 2007; Arnold et al., 2012) and VeRa (Venus Express Radio science experiment; Häusler et al., 2006) were two of the experiments aboard ESA's Venus Express (VEX) mission. Retrieval results from VIRTIS-M-IR measurements during eight Venus solar days between April 2006 and October 2008 were extensively described by Haus et al. (2013, 2014, 2015a). They comprised new information on mesospheric nightside thermal structure and cloud features and on trace gas distributions in the lower atmosphere. Resulting maps for the southern hemisphere covered parameter variations with altitude, latitude, local time, and mission time. The most important retrieval results have been summarized in the recently published paper by Haus et al. (2016).

Only few information on radiative transfer parameterization approaches can be found in the literature. The only recent papers that describe a success in this direction are those of Mendonca et al. (2015) and Lebonnois et al. (2015). Lebonnois et al. applied the NER (Net Exchange Rate) formalism developed by Eymet et al. (2009). This method only allows a user to consider infrared radiative transfer, that is, a parameterization of thermal cooling rates. Moreover, the radiative budget analysis of Lebonnois et al. is a one-dimensional global average approach. The impact of latitudinal variations of atmospheric parameters was not considered so far. Globally averaged solar heating rates were taken from other literature sources (e.g. Crisp, 1986). Mendonca et al. also applied a layer exchange radiative transfer code for thermal radiation that is based on an absorptivity/emissivity formulation (neglecting scattering) and the diffusivity approximation for emission angle integration. Solar radiation fluxes were calculated using a two-stream solution whereby incorporating the δ-Eddington approximation and a layer-adding method. Several averaging steps (e.g. over gaseous absorption features originally determined by a k-distribution method) permit a fast recalculation of atmospheric radiation fluxes. A latitudinal uniform cloud distribution was assumed based on the equatorial model developed by Crisp (1986).

It is the main goal of the present paper to utilize the comprehensive results of radiative energy balance analyses recently performed by Haus et al. (2016) and to investigate possible approaches to parameterize the calculation of both thermal cooling rates Q^C and solar heating rates Q^H. Section 2 gives an overview of Q results obtained by Haus et al. (2016) for different sets of temperature profiles, cloud parameters, and abundances of the unknown UV absorber (UVA). Section 3 describes the newly developed parameterization technique used to calculate Q^C and Q^H for changing atmospheric thermal conditions. Section 4 presents parameterized Q results for cloud parameter and UVA variations. Section 5 provides a discussion that is related to an atmosphere being in full radiative equilibrium. The main results are summarized in Section 6.

2. Accurate calculation results of temperature change rates for different atmospheric models

The terminology 'accurate' is used here and in the following to characterize methods and results that are based on quasi-monochromatic calculations of radiation fluxes and temperature change rates. In contrast, the approximative method described in Sections 3 and 4 is denoted as 'parameterization'.

2.1. Thermal structure

Fig. 1 shows a comparison of zonally averaged mean VIRTIS, VeRa, VIRA-2, and VIRA-1 atmospheric model temperature profiles at 20 and 65° (displays A-B) as well as resulting altitude profiles of zonally averaged mean thermal cooling rates (Q^C, displays C and D) and solar heating rates (Q^H, displays E and F). VIRTIS temperatures (that is, atmospheric temperatures retrieved from VIRTIS data) are primarily valid for the southern hemisphere, while VIRA (Venus International Reference Atmosphere) and VeRa temperatures result from observations over both hemispheres. High similarities between northern and southern hemisphere temperature fields as retrieved by Haus et al. (2013) indicate global N-S axial symmetry of atmospheric temperature structure, however. The notation 'mean' accentuates the fact that depicted profiles correspond to the mean state of the atmosphere obtained from VIRTIS and VeRa retrievals and VIRA-2 averages over local time.

VIRA-1 (Seiff et al., 1985) is the model that will be used as initial or 'basis' model of Venus' atmospheric thermal structure in the following assuming identical thermal regimes on the nightside (N) and dayside (D) of the planet up to 95 km. Corresponding pressure profiles for each temperature model are always determined by integrating the hydrostatic equation and using the ideal gas law and a mean surface pressure of 92.1 bar at zero elevation, taking into account the altitude dependence of the gravity acceleration. VIRA-1 considers data from early US and USSR Venus missions and (for that time) latest results from the Pioneer Venus mission 1978. VIRA-2 (Zasova et al., 2006) summarizes temperature results obtained from missions that had been completed after the earlier work on VIRA-1. It includes results from infrared thermal soundings performed by Venera-15 (1983), the Vega 2 entry probes (1985), and Galileo NIMS (1990) as well as radio occultation profiles from Venera-15/16 and Magellan (1990) data. The notation VIRA-2 was originally introduced by Moroz and Zasova (1997) and is also used here. VIRA-2 provides latitude and solar longitude-dependent temperature profiles at altitudes between 50 and 100 km. To construct a pure latitude-dependent model, these data have been averaged over solar longitude (local time) here. Below 40 km, VIRA-2 corresponds to VIRA-1 where all profiles are local time-independent models from the outset. VIRA-2 profiles between 40 and 50 km are obtained by linear interpolation between both models. VIRA-1 and -2 profiles above 90 km (horizontal broken lines in displays A and B of Fig. 1 marked by 'a') result from a linear interpolation between the latitude-dependent temperatures at 90 km and a fixed value of 165 K at 100 km. A latitude-independent linear nightside profile then extends to 140 K at 140 km altitude.

The temperatures on the day- and nightside of Venus start to diverge at altitudes above 95 km. At this altitude, VIRA-1 and VIRA-2 profiles below 95 km converge to about 170 K. For present flux calculations, the top of the atmosphere (TOA) is set to an altitude of 140 km to avoid discontinuities at 100 km (the assumed upper boundary of Venus' mesosphere). A latitude-independent

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