# VENUS AFES LETKF DATA ASSIMILATION SYSTEM (VALEDAS)

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**Introduction:** The data assimilation has become an effective tool in the planetary atmospheric science. However, it has not been applied to the Venusian atmosphere so far. One of the reasons might be the limitation of meteorological observations, and another one would be the immaturity of Venusian general circulation models (GCMs); any GCMs could not reproduce a realistic structure of the Venusian atmosphere. Recently, we have developed a Venusian GCM named AFES-Venus[1] on the basis of Atmospheric GCM For the Earth Simulator (AFES)[2], which enables us to reproduce the realistic structure of the Venusian atmosphere, such as planetary scale waves[3], cold collar[4], polar vortex[5], and thermal tide[6]. Comparison between the AFES-Venus simulations and Akatsuki observations suggests that AFES-Venus could be used for the data assimilation at this moment. In the present study, we have developed a new data assimilation system for the Venusian atmosphere, VALEDAS (Venus AFES LETKF Data Assimilation System), based on AFES-Venus and the local ensemble transform Kalman filter (LETKF)[7] which is one of the most powerful and efficient schemes for the data assimilation, and tested the system with idealized and real observation data.

**Experimental settings:** In a data assimilation scheme, an improved estimate (called analysis) is derived by combining observations and short time forecasts. The LETKF is a kind of the Kalman filter and seeks the analysis with minimum error variance. In VALEDAS, uncertainty of the model forecast is characterized by a 31-member ensemble of AFES-Venus runs. A minimal interval of the data assimilation cycle is 6 hours. The four-dimensional LETKF has 7 hourly time slots at each analysis, then observations can be assimilated every hour if they are available.

As test cases, we prepare two observations of the horizontal winds at 70 km altitude (approximately at the cloud top) only: one is a synthesized observation data produced by an AFES-Venus run forced with the solar heating with the diurnal component (Case Qt; the thermal tide is included) with different time-intervals: 1, 6, and 24 hours (Cases H1, H6, and H24), and the other is a real observation data based on the UV images taken by the Venus Monitoring Camera (VMC) onboard the Venus Express[8], which includes the horizontal winds at the cloud top only in a narrow dayside region from approximately 60°S to 30°N between 80°W (~7:00 local time; LT) and 80°E (~17:00 LT) where the sub-solar point is assumed to 0°E (12:00 LT) longitude. Time-intervals of the VMC horizontal wind data are approximately an Earth day. We use 73 observations of the horizontal winds derived by the cloud tracking in a period from 28 Jan. 2008 to 26 Apr. 2008 (Case Vmc).

The AFES-Venus forecasts are performed by an AFES-Venus run forced with the solar heating excluding the diurnal component (Qz). This indicates that the thermal tide is *not* included in the basic forecasts run. Therefore, if the VALEDAS works, the thermal tide will be reproduced in the data assimilation with both the test observations. Our main goal is to demonstrate that the VALEDAS works well and can be useful for future observations.

In addition, we perform a free run forecast (Case Frf) to produce background, in which we have a 31-ensemble of Case Qz runs without observations, i.e., without the data assimilation. In all runs the resolution is fixed to T42L60, 128 times 64 grids horizontally with 60 layers vertically extending from the flat ground to 120 km. To spin up, we performed numerical integrations from an idealized superrotating state for Cases Qz and Qt for four Earth years. The model atmospheres reached quasi-steady states within approximately an Earth year, which could be maintained for more than ten Earth years[3]. Results shown for Cases H1, H6, H24, Vmc, and Frf are the 31-member ensemble mean of each case.

**Results:** Figure 1 shows that the VALEDAS quickly reduces the analysis and subsequent forecast root-mean-square (RMS) error at every grid points at 70 km both for the zonal and meridional winds except for Case Frf (background). For Case H24, the cycle of data assimilation, i.e., once a day, is clearly seen.

Though the observation data are given at 70 km only, Figures 2 and 3 show that the three-dimensional structure associated with the thermal tide, which propagates upward above 70 km, appears clearly even for Case Vmc. Note that the RMS errors for the zonal and meridional winds for Case H24 do not converge; they are considerably reduced only at the timing of the observations. Nevertheless, the thermal tide structure with a zonal wavenumber of 1, which is similar to that obtained for Case Qt (not shown) in which the thermal tide is excited by the solar heating directly, can be found in the temperature field, even though the temperature is not included in the observation data. Compared with Case Qt, amplitude of the thermal tide found in Case Vmc is much smaller than that in Case Qt.

It should be emphasized that the VALEDAS successfully reproduced the three-dimensional structure of thermal tide not only in the horizontal winds but also in the temperature field by assimilating the temporally sparse observation data without the temperature only given at 70 km altitude in the dayside of the southern hemisphere with a time interval of approximately 24 hours for Case Vmc. Wind and temperature components antisymmetric about the equator are also induced by meridional winds which go across the equator included in the VMC data[8].

The thermal tide and its vertical propagation are not present for Case Qz (not shown) in which the thermal tide is ruled out by excluding the diurnal component from the solar heating. These results clearly show that the data assimilation with the horizontal winds including the thermal tide component produces the temperature deviations associated with the thermal tide as a dynamically balanced state. Since the vertical shear of the zonal-mean zonal wind are different between Cases Vmc and Qt, the inclinations of the phase of the thermal tide differ from each other.

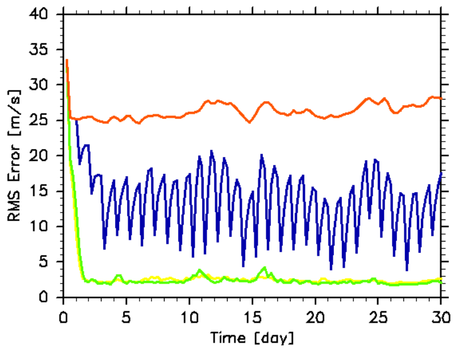


Figure 1. Time evolutions of the root-mean-square (RMS) errors from idealized observations at 70 km in zonal wind (m s$^{-1}$) for Cases H1 (1-hourly observations; yellow), H6 (6-hourly observations; green), H24 (24-hourly observations; blue), and Frf (background; red).

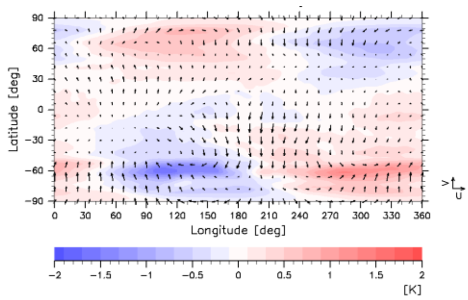


Figure 2. Horizontal distribution of temperature deviation from zonally averaged temperature (color shades; K) associated with the thermal tide for Case Vmc at day 87 midnight noon. Slowly varying components (thermal tide) are extracted by a low-pass filter with a cut-off period longer than 4 Earth days. A horizontal distribution of horizontal winds at 70 km is also depicted (black vectors; units 25 m s$^{-1}$, zonal wind is a deviation from its zonal mean).

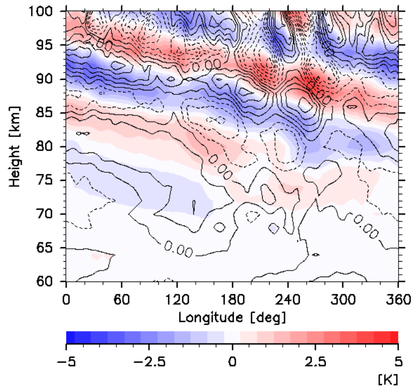


Figure 3. Vertical distributions of temperature deviation from zonally averaged temperature (color shades; K) associated with the thermal tide for Case Vmc at day 87 midnight noon. Slowly varying components (thermal tide) are extracted by a low-pass filter with a cut-off period longer than 4 Earth days. A vertical distribution of zonal wind deviation from its zonal mean at the equator is depicted (black contours; intervals are 1 m s$^{-1}$).

**Summary:** A new data assimilation system for the Venusian atmosphere, VALEDAS (Venus AFES LETKF Data Assimilation System), has been developed[9] on the basis of AFES-Venus and LETKF to make full use of the observational data. VALEDAS rapidly reduced the errors between the analysis and forecasts. In addition, it successfully reproduced the thermal tide excited by the diurnal component of solar heating, even though the real observation datasets included horizontal winds only at the cloud top (~70 km) in the dayside with a long time-intervals of approximately one Earth day (Case Vmc).

Very recently, Ensemble Forecast Sensitivity to Observations (EFSO) technique has been implemented[10] to quantify how much each observation would improve the AFES-Venus forecasts. The system would be useful to produce reanalysis from the Venus Climate Orbiter 'Akatsuki'.

**References:**

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