

DATA ARTICLE OPEN ACCESS

ALERA-V Version 1.0: An Objective Analysis Dataset of the Venus Atmosphere

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ABSTRACT

An objective analysis dataset of the Venus atmosphere, ALERA-V version 1.0, has been released. This objective analysis provides the best estimate of the state of the Venus atmosphere produced by combining observations and a forecast model weighted according to their respective levels of uncertainty. The accumulation of frequent observations by the Venus Climate Orbiter ‘Akatsuki’ has, for the first time, enabled an objective analysis of the Venus atmosphere. ALERA-V stands for AFES-LETKF experimental ensemble objective (re)analysis of the Venus atmosphere, and is generated by ALEDAS-V, the AFES-LETKF data assimilation system for the Venus atmosphere. ALEDAS-V uses AFES-Venus (Atmospheric General Circulation Model for the Earth Simulator for Venus) as a forecast model and the LETKF (Local Ensemble Transform Kalman Filter) for data assimilation. The observations of the zonal and meridional winds obtained by a cloud tracking technique from images taken by Akatsuki’s UVI (Ultraviolet Imager) are assimilated to produce ALERA-V version 1.0. The dataset consists of atmospheric variables defined on a grid of 128 longitude and 64 latitude points, and 60 vertical levels, with output every 6 Earth hours from September to December 2018, including the intensive observation period of November. ALERA-V is expected to be useful for both scientific and engineering research, such as understanding the dynamical mechanisms of various atmospheric phenomena and planning for future satellite missions, with appropriate consideration of its quality and limitations.

1 | Introduction

Objective analysis has advanced in Earth meteorology as a technique for recognizing the current state of the atmosphere from observations and providing improved initial conditions for numerical weather prediction. Numerical weather prediction and general circulation models (GCMs) have been developed and refined since the mid-20th century, and data assimilation

methods that combine observations and numerical models have become an essential component of modern weather prediction systems (e.g., Kalnay 2003). Since then, major climate simulation centres and weather bureaus have produced more accurate reconstructions of past atmospheric conditions by using improved prediction models and data assimilation systems that incorporate additional observations not available in earlier forecasting systems. This type of objective analysis is called

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'reanalysis', and the resulting datasets have been widely used as the basis for Earth's meteorological and climatological research (Bosilovich et al. 2013).

Objective analysis of planetary atmospheres, obtained by assimilating spacecraft observations into numerical models, has the potential to compensate for the shortcomings of both observations and models, such as the spatial and temporal scarcity of observations and the physical and dynamical uncertainties of numerical models. So far, advances in the objective analysis of planetary atmospheres have only been achieved in the studies of the atmosphere of Mars. Data assimilation of the global Martian atmosphere was first attempted in the late 1990s (Houben 1999). Since then, several objective analyses such as MACDA (Montabone et al. 2014), EMARS (Greybush et al. 2019), and OpenMARS (Holmes et al. 2020) have become available. The MACDA (Mars Analysis Correction Data Assimilation) dataset is the first objective analysis of the planetary atmospheres other than Earth's. It implements the AC (Analysis Correction) method which is a relatively simple data assimilation technique. OpenMARS (Open access to Mars Assimilated Remote Soundings) builds upon MACDA by the use of an improved version of the simulation model and the reinforced observational data, and provides a longer-term dataset. EMARS (Ensemble Mars Atmosphere Reanalysis System) uses the LETKF (local ensemble transform Kalman filter; Hunt et al. 2004, 2007) for the data assimilation method, and provides data spanning multiple years across the observations of multiple spacecraft instruments. The LETKF is a data assimilation method based on the EnKF (ensemble Kalman filter; Evensen 1994) that offers excellent parallel computing efficiency and is highly practical.

Observations of Venus are not as extensive as those of Mars. Its thick cloud layers make it particularly difficult to observe the atmospheric states beneath them. Therefore, the general characteristics of Venus's atmospheric circulation remain poorly understood, and the development of numerical models and data assimilation is more challenging than for Mars. Recent advances in Venus GCMs have enabled more realistic and stable representations of key atmospheric phenomena. In particular, models have become capable of dynamically reproducing characteristic phenomena such as super-rotation and thermal tides (e.g., Lebonnois et al. 2010; Yamamoto and Takahashi 2006; Takagi et al. 2018). These advances provide an essential foundation for meaningful comparisons with observations and for the application of data assimilation techniques. The first attempt of data assimilation was made by Sugimoto et al. (2017), who developed a data assimilation system for the Venus atmosphere named ALEDAS-V (ALEDAS for Venus). This system, following ALEDAS (the AFES-LETKF Data Assimilation System for Earth; Enomoto et al. 2009; Enomoto et al. 2013; Yamazaki et al. 2021), is based on the LETKF and the atmospheric GCM for Venus, AFES-Venus (See Section 2.2). Using ALEDAS-V, Sugimoto, Kouyama, and Takagi (2019) demonstrated an improvement in the spatial structure of thermal tides by assimilating cloud-top horizontal winds derived from ultraviolet images obtained by the VMC (Venus Monitoring Camera) on board the ESA's (European Space Agency) Venus Express spacecraft. In addition, OSSEs (Observing System Simulation Experiments) using ALEDAS-V have been conducted, confirming that various atmospheric phenomena on Venus, such as the cold

collar (Sugimoto, Abe, et al. 2019; Fujisawa et al. 2023), thermal tides (Sugimoto, Fujisawa, Komori, et al. 2022), and Kelvin waves (Sugimoto, Fujisawa, Shirasaka, et al. 2021, 2022), can be reproduced within the data assimilation system.

Since December 2015, the Venus orbiter 'Akatsuki' has been observing Venus (Nakamura et al. 2011, 2016). Its data provide new insights into various atmospheric phenomena. Fujisawa et al. (2022) performed data assimilation using Akatsuki UVI (Ultraviolet Imager) cloud tracking data with ALEDAS-V, producing an objective analysis that successfully improved the phase of thermal tides and modified the speed of super-rotation globally. This objective analysis was made possible by the long-term accumulation of Akatsuki's frequent observation data, in addition to the advances in GCMs and assimilation technology mentioned above, and the high-performance computer environment of the Earth Simulator provided by the JAMSTEC (Japan Marine Science and Technology Centre).

The objective analysis dataset generated by F2022 was named ALERA-V (AFES-LETKF experimental ensemble objective (re)analysis for the Venus atmosphere). This name comes from ALERA (AFES-LETKF experimental ensemble reanalysis), the preceding Earth reanalysis dataset produced by ALEDAS (Miyoshi and Yamane 2007; Miyoshi et al. 2007a, 2007b; Yamazaki et al. 2017). This paper focuses on the ALERA-V dataset itself, while F2022 focused on its scientific analysis. Here, we provide detailed information on the data generation process, dataset format, data quality, and potential applications, which were not described in previous studies. The aim of this paper is to facilitate the use of the ALERA-V dataset and to contribute to research on the Venusian atmosphere. Section 2 describes the observational data, the GCM, and the data assimilation system. Section 3 provides a detailed description of the dataset and its format. Section 4 covers how to access the dataset. Section 5 highlights the quality and limitations of the dataset. Section 6 outlines potential uses of the dataset. Section 7 describes expected future developments for the dataset.

2 | Data Production Methods

2.1 | Observation Data

The observation data used for the present data assimilation are the zonal and meridional winds obtained by a cloud tracking technique from images taken by UVI with a 365nm filter of Akatsuki from September to December 2018 (Horinouchi et al. 2018, 2024). The utilized dataset version is v1.3, and the file is 'uvi_20190903_201512-201,812/concat_365_eps10_pphvlen2.nc', which is available from AKATSUKI Science Data Archive (https://darts.isas.jaxa.jp/missions/akatsuki/index_en.html) in DARTS (Data ARchives and Transmission System) by ISAS (Institute of Space and Astronautical Science) / JAXA (Japan Aerospace Exploration Agency) (<https://darts.isas.jaxa.jp/en>).

The spatial resolution of the dataset is 120×60 horizontal grids (longitude $\times$ latitude), corresponding to a global grid with 120 points in longitude (0° – 360°) and 60 points in latitude (-90° – 90°), with an approximate horizontal resolution of $3 \times 3^\circ$.

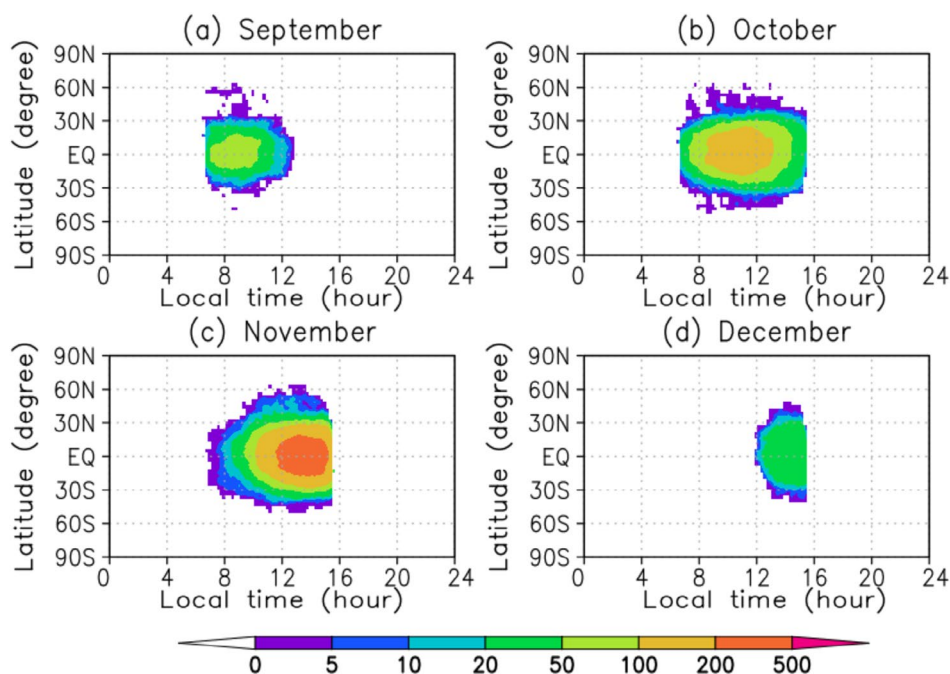


FIGURE 1 | Local time and latitudinal distributions of the number of observations: (a) September, (b) October, (c) November, and (d) December 2018. This figure is the same as figure 6 in F2022 and is reproduced from F2022 under the CC BY 4.0 licence.

This is close to the resolution of AFES-Venus described below (Section 2.2). To facilitate assimilation, the observation times are rounded to the nearest hourly time (e.g., 01:00, 02:00). These hourly observations are then used within the 6-h assimilation window (Section 2.3). The actual spatial and temporal coverage of the wind data is influenced by the relative positions of Akatsuki and Venus, and by technical factors including UVI imaging and satellite communication conditions. The spatial coverage of the wind observations is shown in Figure 1. These winds are only obtained in the dayside region from 60°S to 60°N, and the coverage is the widest in November 2018, available from 7 to 15 LT. Most winds in September 2018 are derived from morning images, whereas those in early December 2018 are mostly from the afternoon. The temporal coverage of the wind observations is shown in Figure 2. The objective analysis assimilates the winds from September 1 to December 7, 2018. This period includes the intensive observation campaign conducted in November 2018, characterized by relatively continuous data availability. The UVI images are typically obtained every 2 Earth hours, although the actual temporal sampling is not uniform due to observational constraints such as spacecraft geometry and communication periods. The number of wind data per day generally ranges from 6 to 13. Note that for details on the cloud tracking algorithm used in Akatsuki, please refer to Ikegawa and Horinouchi (2016) and Horinouchi et al. (2017).

These wind data are assimilated in ALEDAS-V at the altitude of 70 km, which is considered to be near the cloud top. The observation error of the wind speeds is assumed to be 4.0 ms^{-1} . Sato et al. (2020) estimated that the cloud top altitude is about 70 km at latitudes below 30 degrees and decreases with increasing latitude, reaching about 62 km at latitude 60 degrees. Horinouchi et al. (2020) estimated the uncertainty in cloud tracking and found that the standard deviation of zonal wind errors was below 4.0 ms^{-1} at latitudes below 30 degrees and 2.5 ms^{-1} near

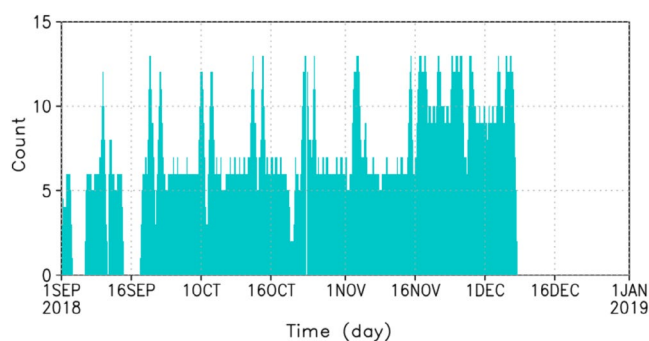


FIGURE 2 | Time variation of observation frequency. Each count represents the total number of observations performed within 12 Earth hours preceding and after. This figure is the same as figure 5 in F2022 and is reproduced from F2022 under the CC BY 4.0 licence.

the equator. In contrast, at mid- and high latitudes, it exceeded 4.0 ms^{-1} , peaking at 7.0 ms^{-1} . The standard deviation of meridional wind errors was generally around 3.0 ms^{-1} across all regions. In this objective analysis, mainly low-latitude observational data are assimilated. Therefore, for simplicity, uniform values for the observation altitude and the error are adopted without considering their latitudinal dependences.

2.2 | Atmospheric General Circulation Model

The GCM, AFES-Venus, was used for ensemble forecasting to produce the objective analysis. AFES-Venus was developed by Sugimoto et al. (2014a) based on AFES (Atmospheric GCM For the Earth Simulator). AFES is a GCM for the Earth's atmosphere that has been optimized for the Earth Simulator, which is a high-performance vector computer, and allows calculations with high spatial resolution (Ohfuchi et al. 2004; Enomoto

et al. 2008). AFES-Venus of Sugimoto et al. (2014a) uses the dynamical core of AFES implemented with simplified physical processes to mimic the characteristics of the Venus atmosphere. The experimental setup for the present data assimilation is essentially the same as Sugimoto et al. (2014a, 2014b) as detailed in the subsequent paragraphs.

The dynamical core is given by the primitive (hydrostatic with shallow atmosphere assumption) equations of a dry ideal gas, and is numerically solved with the spectral transformation method. The horizontal resolution is a spherical harmonic truncation wavenumber of 42 (T42), with 128 grid points in longitude and 64 in latitude at each vertical level, corresponding to a grid cell size of about 300 km at the equator. The vertical sigma coordinate is used. Sigma is defined as atmospheric pressure divided by surface pressure. The vertical direction is divided into 60 layers. The model levels are designed such that the vertical spacing corresponds approximately to 2 km in geometric height from the ground to 120 km. No topography is taken into account.

The following physical parameters have been selected to represent the atmosphere of Venus: planetary radius (6050 km), gravity acceleration (8.87 ms^{-2}), rotation period (243 Earth days), solar day (117 Earth days), and mean surface pressure ($9.2 \times 10^4 \text{ hPa}$). Seasonal variation due to planetary revolution and axial tilt is not considered; therefore, the solar forcing is fixed in time. For simplicity in this GCM, the specific heat, C_p , is fixed at a constant value of $1000 \text{ J kg}^{-1} \text{ K}^{-1}$, though it depends on temperature with the range from 700 to $1200 \text{ J kg}^{-1} \text{ K}^{-1}$ in the real Venus atmosphere (Seiff et al. 1985). It should be noted that this simplification may affect the temperature and dynamic structures (Takahashi et al. 2024).

The turbulent mixing processes are represented simply by vertical and horizontal eddy viscosity and heat diffusion. The coefficients of the vertical eddy viscosity and heat diffusion are set to a constant value of $0.15 \text{ m}^2 \text{ s}^{-1}$. Horizontal eddy viscosity and heat diffusion are represented by second-order hyperviscosity and hyperdiffusion (Laplacian squared, $\Delta^2 = \nabla^4$). The decay time for the maximum wave number adopted in the present model corresponds to approximately 0.1 Earth days, preventing numerical instability (Sugimoto et al. 2023). Rayleigh friction is employed at the lowest level to mimic surface friction. We assume that the damping time of Rayleigh friction at the lowest level is 1.0 Earth days. Additionally, a dry convective adjustment scheme is employed to restore the temperature lapse rate to neutral when an atmospheric layer becomes statically unstable.

A sponge layer is introduced at altitudes over 80 km to prevent numerical instability, where eddy components of the horizontal wind are damped in order to prevent disturbances from reflecting artificially at the upper boundary of the model atmosphere. Note, however, the sponge layer does not act on the zonal-mean ($k=0$) component of the zonal wind. The coefficient of Rayleigh friction $K_R(\sigma)$ is given by

$$K_R(\sigma) = K_R^0 \left[1 + \tanh \left(\frac{z_R \log \sigma - z_R \log \sigma_R}{H_R} \right) \right]. \quad (1)$$

where $K_R^0 = (0.1 \text{ Earth days})^{-1}$, $H_R = 40 \text{ km}$, $z_R = 80 \text{ km}$, and $\sigma_R = 5.0 \times 10^{-8}$ representing the relaxation time, width, height

and sigma level of sponge layer, respectively. Using these values, the sponge layer acts effectively only greater than $\sim 100 \text{ km}$ and at 120 km a relaxation time is 0.05 Earth days.

Solar heating is the same as that adopted by Sugimoto et al. (2014b), given based on the vertical profile of solar flux determined from observations by Tomasko et al. (1980) and the horizontal structure proposed by Crisp (1986). The amount of solar flux absorbed by the ground surface is redistributed directly in the lowest 10 km layer above the surface for simplicity. The heating maximum is located at $\sim 60 \text{ km}$ altitudes. Above 80 km, heating is neglected for numerical stability. The infrared radiative process is simplified by a Newtonian cooling approximation, with the cooling coefficients based on Crisp (1986). The relaxation time decreases almost exponentially from the surface to 120 km, ranging from approximately 2.5×10^4 at the surface to 0.1 Earth days at 120 km (see figure 1a in Sugimoto et al. 2014a). Temperature relaxes to a prescribed horizontally uniform temperature distribution on each geometric altitude based on the Venus International Reference Atmosphere (VIRA) (Seiff et al. 1985). While temperature relaxes to the horizontally uniform field, the latitudinal gradient of temperature is maintained by the solar heating in this model.

As an initial state, an idealized super-rotation in a solid-body rotation at each pressure level is given (see figure 2 in Sugimoto et al. 2014a). The zonal wind increases linearly with altitude. Above 70 km, the maximum velocity is 100 ms^{-1} at the equator. Temperature is in gradient wind balance with the super-rotation. Note that the direction of the planetary rotation is set to be eastward, following the conventional direction of rotation used in geophysical fluid dynamics, and consistently, the zonal mean flow and the movement of the Sun are all opposite to the real Venus. This is a setting convenient for those familiar with the Earth's atmospheric dynamics. This convention is applied consistently to both the model and the reanalysis dataset. Therefore, users should be aware that the direction of the flow in this dataset is reversed relative to that on real Venus. Non-linear numerical simulations of around four Earth years are performed for spin-up. After the spin-up integration, the model maintains a super-rotating state. The zonal-mean zonal wind is about 150 ms^{-1} at its maximum at altitudes of 70–75 km, which deviates from UVI observations showing maximum zonal winds of about $80\text{--}110 \text{ ms}^{-1}$ in the low-latitude dayside region (F2022). Data assimilation reduces this discrepancy and produces a more realistic atmospheric circulation. Finally, the eight-hourly outputs (in Earth time) are used for the initial conditions for each member of the ensemble forecast.

2.3 | Data Assimilation System

The objective analysis here was generated by using the Venus data assimilation system, ALEDAS-V. The settings are the same as those in Sugimoto et al. (2017); Sugimoto, Kouyama, and Takagi (2019) as detailed in the subsequent paragraphs.

Data assimilation is performed every 6 Earth hours (Figure 3). The assimilation window is also 6 Earth hours, 3 Earth hours before and after the analysis time. For example, to obtain the analysis at time $t=6$, a 9-h ensemble forecast is performed starting

from $t=0$, providing seven Earth hourly forecasts for times $t=3, 4, 5, 6, 7, 8$, and 9 , which can then be compared with the observations taken at the same times. In the current design, observations at the edges of the assimilation window may be used in multiple analysis cycles. This issue is expected to be improved in future work. However, temporal localization with a scale of 3 Earth hours is applied, so that the influence of observations decreases with increasing temporal distance from the analysis time. As a result, their impact is considered to be limited.

The data processing workflow in ALEDAS-V consists of two stages: the forecast stage and the analysis stage (Figure 4). The

forecast stage is performed as an ensemble forecast using AFES-Venus, which is detailed in the previous section. The number of ensemble members is 31. This generates ‘background’, a set of state vectors x^b consisting of zonal wind, meridional wind, temperature, and surface pressure and a corresponding error covariance, implicitly represented by the ensemble perturbations (denoted here as P^b), at each forecast time. In the analysis stage, the LETKF is performed using these seven sets of background (x^b, P^b), and the observation vectors y^o given at each forecast time and their error covariance matrix R described in Section 2.1 to produce ‘analysis’, a set of assimilated state vectors x^a and their error covariance matrix, P^a . Additionally, an

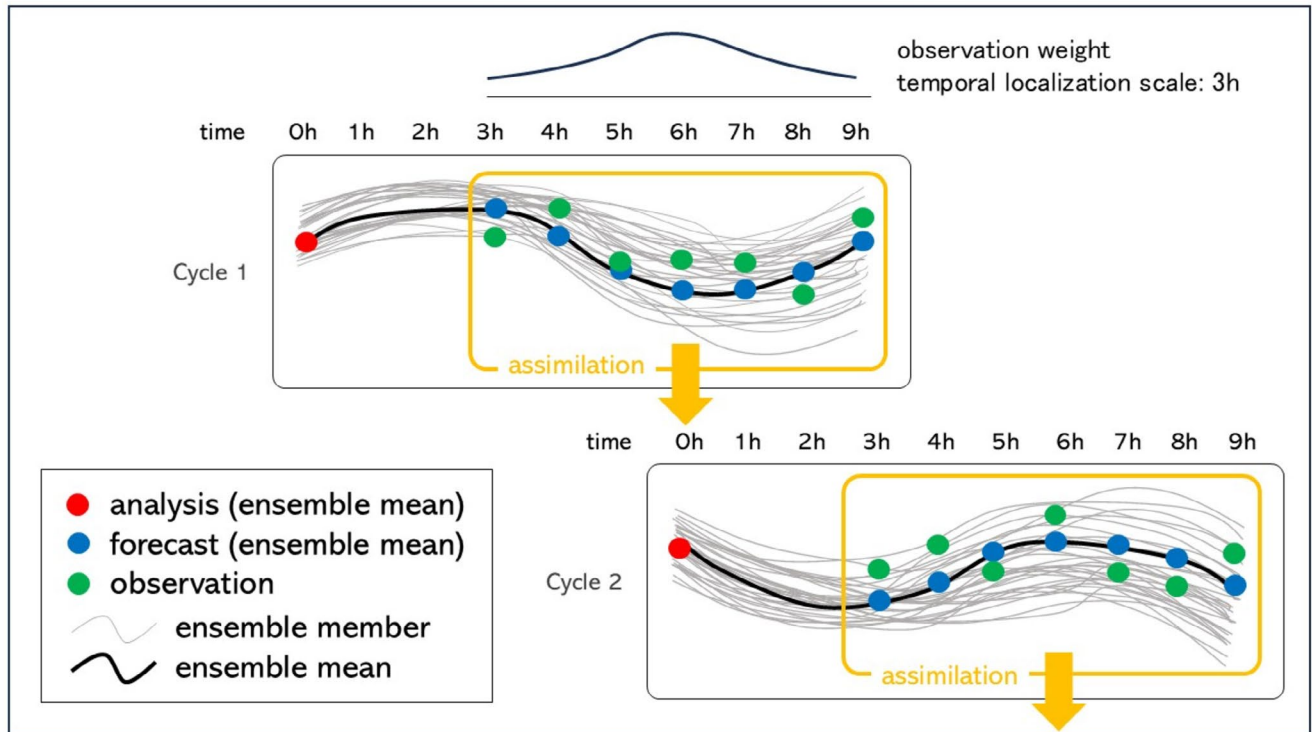


FIGURE 3 | Schematic diagram of the 4D data assimilation cycle in ALEDAS-V.

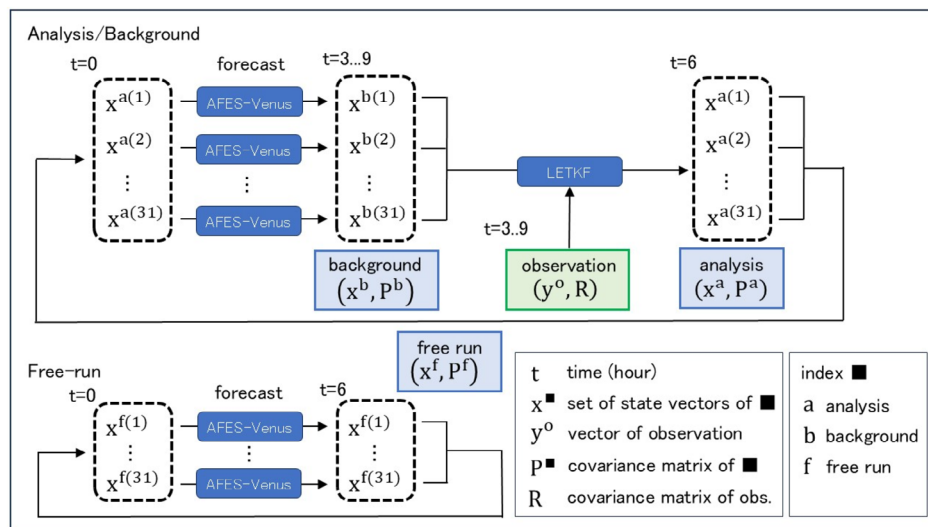


FIGURE 4 | The data processing workflow in ALEDAS-V.

AFES-Venus ensemble integration without LETKF data assimilation, termed ‘free run’, is performed with its output state vectors and error correlation matrix denoted as (x^f , P^f).

The values of the parameters related to localization and inflation are adopted following the settings of the LETKF in ALEDAS (Miyoshi and Yamane 2007; Miyoshi et al. 2007a, 2007b). For the covariance localization, Gaussian weights are applied in all of the horizontal, vertical and temporal directions. The localization scales (one standard deviation) are set to 400 km in the horizontal direction, 0.4 in the vertical direction measured by $\log P$ where P represents pressure, and 3 Earth hours in the temporal direction. It should be noted that spatial localization scales are roughly around the grid widths of the forecast model used for this objective analysis; the horizontal grid width near the equator is approximately 300 km, and the vertical grid width at the altitude of 70 km is about 0.2 measured by $\log P$. Covariance inflation in the EnKF helps to prevent the insufficient incorporation of observational data caused by underestimation of forecast errors due to model imperfections, nonlinearities and so on. We apply the multiplicative inflation at a spread inflation rate of 10%.

3 | Dataset Description and Format

ALERA-V version 1.0 provides the objective analysis 6 hourly dataset (in Earth time) of the Venus atmosphere from September to December 2018 in the netCDF format. Tools for reading and writing data in the netCDF format are maintained primarily by the atmospheric science communities and are available online from <https://www.unidata.ucar.edu/software/netcdf> (NSF Unidata 2023).

The dataset provides the following files. Table 1 shows three experimental types of the data: ‘analysis’ (anal), ‘background’ (back), and ‘free run’ (free). Table 2 lists the labels for the handling types in each experiment, namely, 31 ensemble members (mb01, mb02, mb031), the ensemble mean (mean), and the ensemble spread (sprd). Each netCDF file corresponds to a unique combination of experimental type and handling type. The file naming convention is shown in Figure 5.

The variables contained in each netCDF file are zonal wind (u), meridional wind (v), temperature (temp), vertical velocity (omg), geopotential height (gph), and surface pressure (ps). The dimensions and variables contained in each file are summarized in Table 3. Although the original variables of ALEDAS-V outputs utilize the vertical sigma coordinate, we converted them

to the pressure coordinate in ALERA-V version 1.0 for ease of use. The pressure levels are defined to correspond to the original sigma levels, resulting in 60 vertical levels. The model levels are designed such that the vertical spacing corresponds approximately to 2 km in geometric height from the surface to 120 km. We added a file, ‘QSOL’, that includes the solar heating rate as a variable to help our study (Figure 5). It is necessary for analysing phenomena based on local time. Here, ‘local time’ refers to the solar local time, defined by the position of the Sun relative to longitude. On Venus, solar heating plays an important role in atmospheric phenomena (e.g., Horinouchi et al. 2020), and analyses based on local time are therefore useful.

There are 3 experimental types and 33 handling types. In addition, one supplementary file is included, resulting in a total of $3 \times 33 + 1 = 100$ netCDF files being provided. Each file is approximately 9.6 GB in size, and the total data volume is about 1 TB.

4 | Dataset Access

ALERA-V version 1.0 is available from the AKATSUKI Data Assimilation (DA) Data Archive within DARTS (https://darts.isas.jaxa.jp/missions/akatsuki/da_en.html). This page includes links to the websites where the data are actually hosted. One of them is the research data repository Zenodo, where only the ensemble mean data are archived and assigned a DOI (<https://doi.org/10.5281/zenodo.14799183>), allowing the dataset to be cited. Another is in the CPS (Centre for Planetary Science) server at Kobe University/Hokkaido University, where the complete dataset, including data for each ensemble member, their variances, and the programs used to generate the ensemble mean data, is available (<https://www.cps-jp.org/~akatsuki/pub/dataassim/al-erav/index.html.en>).

TABLE 2 | List of handling types.

Handling type code	Description
mean	Ensemble mean
sprd	Ensemble spread
mb01	Ensemble member 01
mb02	Ensemble member 02
...	...
mb31	Ensemble member 31

TABLE 1 | List of experimental types.

Experimental type code	Experimental type	Description
Anal	Analysis	Analysis by data assimilation
Back	Background	Output from forecast model
Free	Free run	Output without assimilation

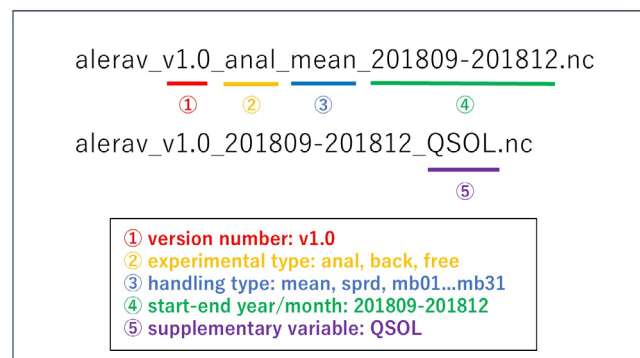


FIGURE 5 | The file naming convention in ALERA-V version 1.0.

TABLE 3 | List of variables contained in each netCDF file.

Variable	Dimension	Units	Description
lon	lon	degrees_east	Longitude
lat	lat	degrees_north	Latitude
plev	plev	Pa	Pressure
time	time	hours since 2000-01-01 12:00:00 (Earth time)	Time
u	time, plev, lat, lon	ms ⁻¹	Zonal wind
v	time, plev, lat, lon	ms ⁻¹	Meridional wind
temp	time, plev, lat, lon	K	Temperature
omg	time, plev, lat, lon	Pas ⁻¹	Vertical p-velocity
gph	time, plev, lat, lon	m	Geopotential height
ps	time, lat, lon	Pa	Surface pressure
qsol	time, plev, lat, lon	Ks ⁻¹	Solar heating

Note: The zonal wind (u) is defined in the model coordinate system and is reversed relative to that on real Venus (Section 2.2).

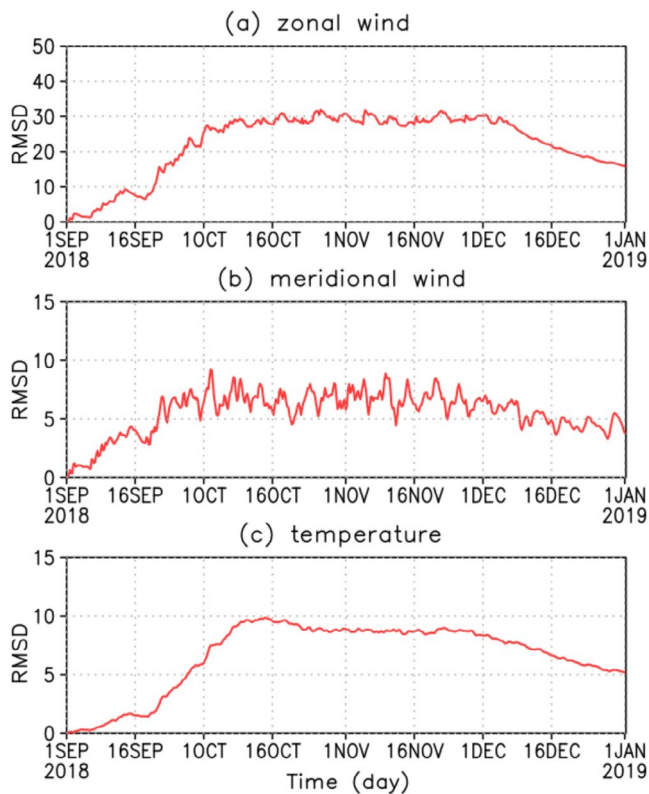


FIGURE 6 | RMSD at 70 km altitude: (a) zonal wind, (b) meridional wind and (c) temperature. This figure is the same as figure 7 in F2022 and is reproduced from F2022 under the CC BY 4.0 licence.

5 | Quality and Limitations

The verification of the objective analysis is presented in F2022. To check if the assimilation is properly functioning, RMSD is calculated at a certain altitude as follows:

$$RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - x_i)^2}, \quad (2)$$

where X_i and x_i are physical values in the FR and analysis for each case, respectively, and N is the total number of horizontal grid points. Thus, RMSD shows the difference between the FR and assimilation result; large RMSD indicates that the data assimilation significantly modified the model result. Figure 6 shows that the RMSD (root-mean-square-deviation) values remain stable roughly from the end of September to the beginning of December, when observations become more frequent. This indicates that assimilation is functioning properly during this period. Figure 7 shows the altitude distributions of the RMSD and the differences between the analysis and the free run for zonal wind, confirming that the assimilation has an effect at altitudes of about 65–90 km. Figure 8a,c,d shows that the ensemble spreads in the analysis, i.e., the diagonal elements of the error covariance matrix, are reduced globally compared to those in the free run. This indicates that data assimilation reduces the uncertainty of the analysis not only around local noon in the low-latitude region, where observations are assimilated, but also in the mid-latitude region where baroclinic waves are dominant. Figure 8c,f shows that the distributions of the ensemble increments (differences between the background and the analysis) for zonal and meridional winds. This indicates that the assimilation correction amounts are maximum on the morning side near the equator for zonal wind, and at noon around 30° latitude for meridional wind. The ensemble spread in these regions is on the order of 5–10 ms⁻¹, which is comparable to or larger than the prescribed observation error (~4 ms⁻¹). This suggests that data assimilation contributes to adjusting the model state in regions where sufficient observational data are available and where the forecast error is comparable to or larger than the observation error.

This dataset uses only cloud-top horizontal wind observations on the dayside, and the observational constraints for data assimilation are limited. As a result, the dynamical circulation structure of the Venus atmosphere represented in this dataset is largely determined by the GCM. AFES-Venus includes several simplifications, including assuming a constant C_p and applying an idealized radiative process (see Section 2.2), and these

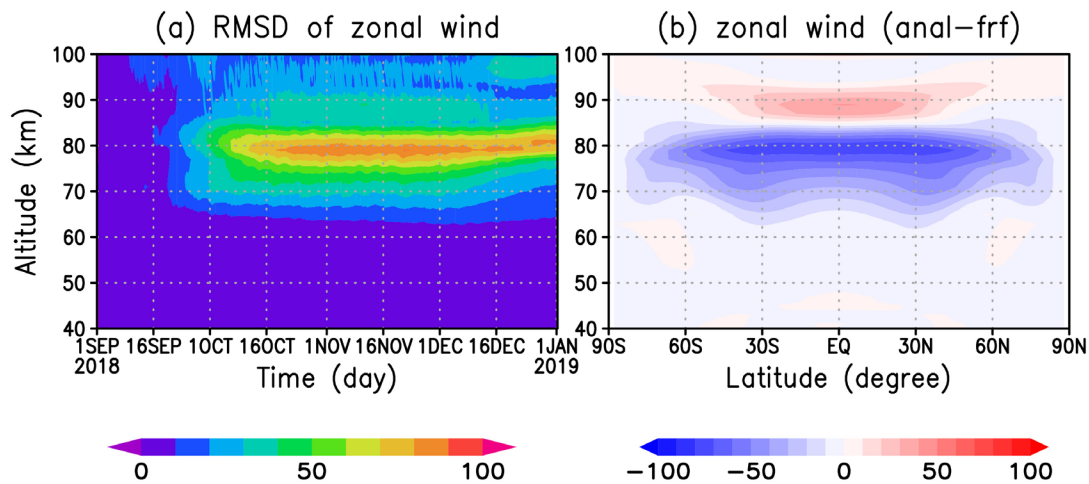


FIGURE 7 | (a) Altitude–time plot of RMSD of zonal wind (m s^{-1}). (b) Latitude–altitude cross sections of zonal mean zonal wind (m s^{-1}), representing the differences between the analysis and the free-run forecast. The values are averaged over the two Earth months from 1 October to 30 November 2018.

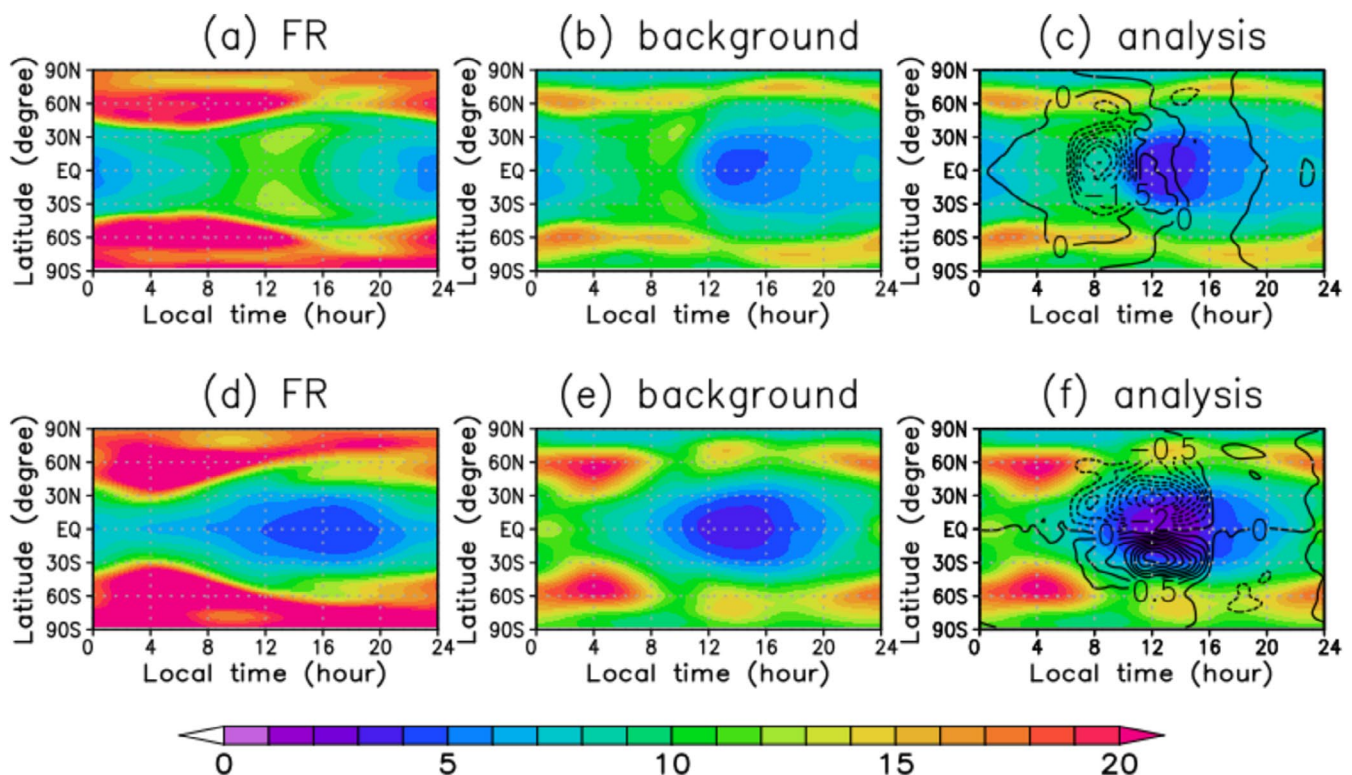


FIGURE 8 | Local time and latitudinal distributions of ensemble spread (colour, m s^{-1}) and ensemble increment (contour, m s^{-1}) for (a, b, c) zonal winds and (d, e, f) meridional winds (m s^{-1}) associated with thermal tides at the cloud-top ($\sim 70 \text{ km}$) level. (a, d) FR spreads, (b, e) background spreads and (c, f) analysis spreads and increments. The contour intervals of ensemble increment are 0.5 m s^{-1} . These distributions are averaged for the two Earth months from 1 October to 30 November 2018 in a reference frame moving with the Sun to extract the structures associated with thermal tides. This figure is the same as figure 6 in F2022 and is reproduced from F2022 under the CC BY 4.0 licence.

choices are likely to have a significant influence on the results. Users of this dataset should be aware that discrepancies may exist between the dataset and the actual Venus atmosphere.

6 | Usefulness of the Dataset

Objective analysis data of the Venus atmosphere will have applications for both scientific and engineering research. In scientific

research, F2022 investigated the fluid dynamical structure of thermal tides in the equatorial region using ALERA-V version 1.0, and Ando et al. (2023) studied the maintenance mechanism of the ‘cold collar’, which is a cold latitudinal band surrounding the warm polar vortex at about 65 km altitude and 60° – 80° latitudes. These results exemplify that the objective analysis dataset is expected to contribute to studies on the dynamical structures and generation mechanisms of these phenomena and ALERA-V version 1.0 is useful in the scientific research on the Venus atmosphere.

For engineering research, it can be used to characterize atmospheric conditions that affect spacecraft trajectory and are referred to in designing manoeuvres such as aerobraking, aerocapture and so on for orbital injection, descent, and landing. In fact, ALERA-V version 1.0 has been provided to the VCD (Venus Climate Database) (<http://www-venus.lmd.jussieu.fr/>), a project led by LMD (Laboratoire de Météorologie Dynamique) in France, which will be used for the consideration of the EnVision mission by ESA.

7 | Future Versions

ALERA-V version 1.0 only assimilates wind data obtained from UVI with 365 nm observations. Akatsuki observations also include wind data obtained from UVI through 283 nm observations and temperature data obtained from LIR (Longwave Infrared Camera) observations. We are now trying to produce several assimilation experiments with some or all of those data. Winds obtained from UVI observations represent cloud-top winds, although the 283 nm winds are likely to sample slightly higher altitudes than the 365 nm winds (Horinouchi et al. 2018). Temperatures derived from LIR represent a weighted infrared radiance from the cloud-top region, with an effective observation altitude of approximately 65 km (Kouyama et al. 2019). Assimilating observations at different altitudes may be useful for elucidating the three-dimensional structure of atmospheric phenomena. In the future, we will compare and evaluate the assimilation experiments with these different types of observational data. F2022 showed that AFES-Venus itself is unable to accurately and faithfully reproduce observed thermal tides without data assimilation. To reproduce thermal tides and zonal mean zonal winds accurately, it is important to improve the GCM itself, which may require improved stability as in Suzuki et al. (2022), introduction of temperature dependent specific heat of the atmosphere or implementation of a realistic radiative transfer code. Furthermore, we have yet to utilize whole of the information obtained by Akatsuki. The present objective analysis covers only for a specific 4 Earth months period; there are many dense observation periods of about 4 Earth months during the entire 8 years of Akatsuki observation. Analysis using those remaining observation periods will help us understand the reasons for long-term variations in the super-rotation due to momentum transport of long- or short-period disturbances.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.14799183>.

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