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Observing system simulation experiment for radio occultation measurements of the Venus atmosphere among small satellites

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We have developed the Venus AFES (atmospheric GCM (general circulation model) for the Earth Simulator) LETKF (local ensemble transform Kalman filter) data assimilation system (VALEDAS) to make full use of observations. In this study, radio occultation measurements among small satellites are evaluated by the observing system simulation experiment (OSSE) of VALEDAS. Idealized observations are prepared by a French Venus Atmospheric GCM in which the cold collar is realistically reproduced. Reproducibility of the cold collar in VALEDAS is tested by several types of observations. The results show that the cold collar is successfully reproduced by assimilating at least 2 or 3 vertical temperature profiles in the polar region every 4 or 6 hours. Therefore, the radio occultation measurements among three satellites in polar orbits would be promising to improve the polar atmospheric structures at about 40–90 km altitudes.

Key Words : *Venus atmosphere, Cold collar, General circulation model, Data assimilation, Local ensemble transform Kalman filter, Radio occultation, Observing system simulation experiment*

1. INTRODUCTION

Venus is similar to the Earth in its size and density (gravitational acceleration), and is often called the Earth's sister planet. However, the Venus atmosphere consists mostly of CO_2 and its surface pressure is about 90 times higher than that of the Earth, so its surface temperature is high; about 730 K. The Venus rotation period is very long, ~243 Earth days; the Venus solar day is ~117 Earth days. Understanding the difference between the Earth and Venus is quite important for studies of the habitable zone and the formation of the Earth climate. At cloud top levels (~70 km), the Venus atmosphere is in "super rotation", which rotates much faster than the solid part of Venus, flowing around Venus at ~4 Earth days. On the Earth, westerlies and jet streams (strong westerlies located in upper troposphere), which appear only in mid-latitudes, are one fourth times (~100 m/s) faster than its solid part at most. However, on Venus, the super rotation is ~60 times faster than its solid part globally. It is one of the big mysteries in the planetary atmospheres. In addition, the Venus atmosphere has a unique structure called cold collar, which is a latitudinal band encircling the warm polar region at 60°-80° latitudes around ~65 km altitude[1]. The structure has been almost permanently observed, but its formation mechanism and vertical structure (including statically stable or unstable around the cold collar) have not been fully understood.

We have developed AFES-Venus[2,3], which is based on AFES (Atmospheric GCM For the Earth Simulator) optimized for the Earth simulator, and succeeded in the generation and maintenance of realistic super rotation[4], the reproduction of the baroclinic wave[3]; an instability wave produced by latitudinal temperature gradient, the cold collar[5], the polar vortex[6]; a planetary-scale vortex around the poles, and the thermal tide[7]; a planetary-scale wave forced by solar heating. Recently, we have also reproduced the thermal structure in the equatorial upper atmosphere[8], the planetary-scale streak structure[9]; global cloud streaks observed in both hemispheres with equatorial symmetry, and the super rotation from a motionless state driven only by the mean meridional circulation[10]; a horizontal convection generated by latitudinal temperature gradient.

Nowadays data assimilation has been conducted not only for the Earth atmosphere but also for the Mars one. It is one of the ways to reduce error between model and observation. So far, the first data assimilation system for the Venus atmosphere named VALEDAS (Venus AFES LETKF Data Assimilation System) has been successfully developed[11] using Local Ensemble Transform Kalman Filter[12] (LETKF; the details are explained in Section 2) based on AFES-Venus, because AFES-Venus has enabled us to reproduce many kinds of phenomena in the Venus atmosphere as mentioned above. The phase distributions of the thermal tide have been successfully improved by VALEDAS with the wind velocity derived from the Venus Monitoring Camera onboard Venus Express (VMC/VEX)[13]. From 2016, the Japanese Venus Climate Orbiter "Akatsuki" has been observing the Venus atmosphere and many observation data has been accumulated so far. The first analysis of the Venus atmosphere using VALEDAS and Akatsuki's data is in progress. It is noted, however, that the thermal structures in global scale cannot be observed accurately by Akatsuki. Temperature distributions as well as wind vectors are quite important to constrain the Venus atmospheric dynamics.

In order to reproduce more realistic Venus atmospheric structures by the data assimilation, we propose "radio occultation measurements among small satellites". Radio occultation is a method to observe atmospheric states by transmitting and receiving radio waves through the atmosphere[14]. Although Venus is covered by a thick cloud located at 48–70 km altitudes, radio occultation technique enables us to observe vertical temperature profiles between 40–90 km levels. Radio occultation measurements have been performed in some Venus missions, such as Pioneer Venus Orbiter, Venus Express and Akatsuki[15]. However, one of the problems is the limited frequency and coverage of the observations. In the case of Akatsuki, the frequency is less than once a week. In addition, observational area is limited to some fixed latitudinal band due to the orbit of the satellites. It is expected that the measurements opportunity (and thus the coverage) would be significantly improved by transmitting and receiving radio waves among small satellites orbiting around Venus. On the Earth, such kind of observations have already been conducted by small GNSS (Global Navigation Satellite System) satellites. Another advantage to use small satellites is that we can reduce the costs drastically compared with previous large satellite missions.

In this study, we assimilate idealized observations simulating radio occultation measurements among small satellites by VALEDAS and examine how the reproduced atmospheric structure depends on frequency and coverage of the observations. Idealized observations are provided from French Laboratoire de Météorologie Dynamique / Institut Pierre Simon Laplace Venus atmospheric GCM (IPSL Venus GCM), in which the cold collar has been realistically reproduced[16]. In order to propose an effective mission, we investigate how many observations and satellites are needed to reproduce the cold collar. Namely, we will evaluate idealized observations by the reproducibility of the cold collar.

2. EXPERIMENTAL SETTING

AFES-Venus uses 3-D primitive equation on sphere (assuming hydrostatic balance; gravity is balanced by a pressure-gradient force) without moist processes nor topography. The physical parameters are chosen for Venus. For example, the planetary radius is 6052 km, the rotation cycle is 243 Earth days (1.8 m/s), the gravity acceleration is 8.87 m/s^2, the atmospheric composition is CO_2 with 92 bar at the surface and the specific heat is constant (1000 J/kgK). The resolution is T42L60 (T denotes the truncation number for spherical harmonics and L indicates the number of layers), namely, 128×64×60 total grids are used. Solar heating is prescribed[17] and radiative cooling is simplified by the Newtonian cooling; the heating/cooling rate of the temperature is directly proportional to difference from the reference temperatures, whose relaxation time is based on the previous study[18]. Additionally, a dry convective adjustment scheme is used to restore the temperature lapse rate to neutral when an atmospheric layer becomes statically unstable.

Starting from a given initial value of zonal wind assuming solid body super rotation, AFES-Venus spins up for 4 Earth years. The obtained zonal winds are in good agreement with previous observations19). Details are shown in our previous works3,4).

Although AFES-Venus is a simple dynamical model without complicated physical processes, such as radiative transfer, cloud micro-physics, topography and small-scale turbulences, it has succeeded in reproducing many atmospheric phenomena similar to observations above the cloud level as mentioned. The super rotation has been also generated from a motionless state10). Therefore, it is considered that at least AFES-Venus has a sufficient ability to study atmospheric dynamics near the cloud layer.

LETKF is one of the ways of the data assimilation used for the Earth atmosphere12). It is a useful tool to obtain an analysis (an atmospheric state) which is dynamically consistent using a statistical method that combines observations and short-term ensemble forecasts. The ensemble member used here is 31. The inflation is fixed to 10 %. The time interval of the data assimilation cycle is set to 6 hours. The four-dimensional LETKF comprised 7-hour time slots at each analysis, and the observations are assimilated every hour depending on their availability.

Idealized observation data are provided from IPSL Venus GCM16) with 96×96×50 total grids; the resolution differs from AFES-Venus's, in which vertical temperature distributions at fixed points (longitudes and latitudes) are given at 40–90 km altitudes on the northern hemisphere for assuming radio occultation measurements among stationary satellites around the northern hemisphere. Observations are prepared for two Earth months. The observation error is set to 3 K for simplicity. The temperature measurement error of radio occultation observation is basically determined by the stability of the oscillator. It is expected from the oscillators installed in Akatsuki and Venus Express that the temperature measurement errors are ~ 0.1 K15). On the other hand, in the present study, in order to prevent the forecasts from getting too close to the observations, random errors of 3 K are added to each observation to give some variability. In the previous works11), we have conducted experiments with different observation errors (6 K) and confirmed that there was almost no effect on the results. We have assimilated these observations for two Earth months.

Twenty-four experiments are conducted in the present study, in which observation conditions are changed as shown in **Table 1**. We have assumed ideal situations that observations were concentrated near the north pole for the purpose of reproducing the cold collar. The center position of warm polar region (hot polar vortex) with the cold collar can be regarded as 90° latitude, but we set observation points at a little distance from 90°N latitude in order to prepare the pattern in which the number of observation points was changed in the same latitude band. If there are multiple observation points in the same latitude, they were set to have the same distance from 90°N latitude. For example, "l85x1h2" is the case in which one fixed vertical profile (at 180° longitude) of temperature observation at 85°N latitude every 2 hours. "l85x2h4" is the case in which two fixed vertical profiles (at 90° and 270° longitudes) of temperature observations are given at 85°N latitude every 4 hours. "l85x3h6" is the case in which three fixed vertical profiles (at 60°, 180°, and 300° longitudes) of temperature observations are given at 85°N latitude every 6 hours. "l6x12h1" is the case in which 72 vertical profiles of temperature observations at 6 fixed latitudes (60°, 65°, 70°, 75°, 80°, and 85°N latitudes) and 12 fixed longitudes (15°, 45°, 75°, 105°, 135°, 165°, 195°, 225°, 255°, 285°, 315°, and 345° longitudes) are given at every hour. We have also prepared the case without data assimilation named "frf" (free run forecast).

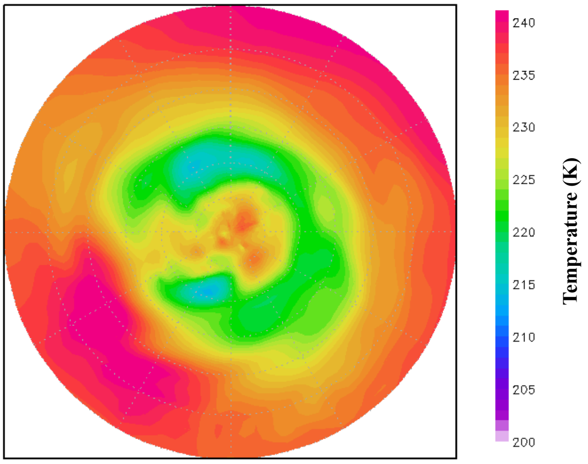
Table 1. 24 experiments in which observation conditions are changed.

l85x1	**h1**	**h2**	**h4**	**h6**	**h12**	**h24**
l85x2	**h1**	**h2**	**h4**	**h6**	**h12**	**h24**
l85x3	**h1**	**h2**	**h4**	**h6**	**h12**	**h24**
l6x12	**h1**	**h2**	**h4**	**h6**	**h12**	**h24**

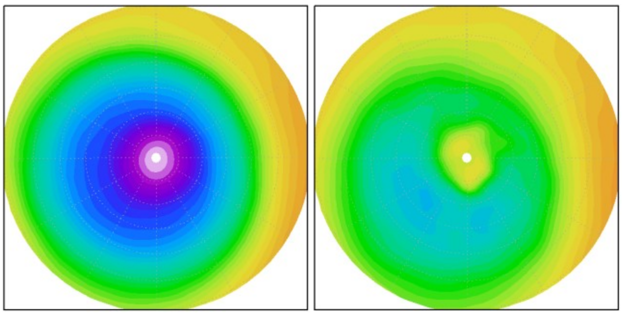
3. RESULTS

In this section, we will focus on several interesting cases selected from **Table 1**. **Fig.1** shows temperature at ~66 km altitude on the northern hemisphere for the cases with 12 observations per day, original observations (truth) and without observations (frf): (a) IPSL Venus GCM (truth), (b) AFES-Venus free run forecast (frf), (c) l85x1h2, (d) l85x2h4, and (e) l85x3h6. It is clearly seen that the cold collar, the cold latitudinal band surrounding the hot polar vortex, is reproduced in both (d) and (e), in which 2 and 3 vertical profiles of temperature observations at 85°N latitude are given every 4 and 6 hours, respectively. Temperature difference between the hot polar vortex and the cold collar is ~23 K, which is similar to that for (a). However, hot polar vortex is relatively small and weak in (c), where only one vertical profile of temperature observation at 85°N latitude is given every 2 hours. Temperature difference between the polar vortex and the cold collar is less than 15 K for (c). Therefore, it is suggested that at least 2 or 3 vertical profiles are required to reproduce the cold collar even though they are obtained every 4 or 6 hours. Note that the observation frequency of (c), which is 2 hours, is higher than those of (d) and (e), which are 4 and 6 hours, respectively. Therefore, the present result suggests that the number of observation points would be more important than the frequency, at least, in reproducing the cold collar.

(a) IPSL Venus GCM



(b) frf (c) l85x1h2



(d) l85x2h4 (e) l85x3h6

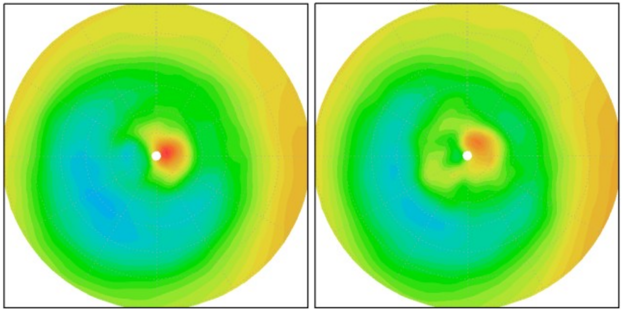
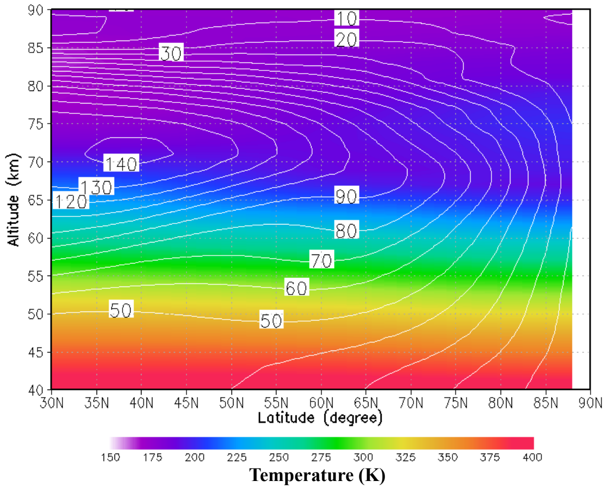


Fig.1 Temperature at 66 km altitude on the northern hemisphere (30°–90°N latitudes) for (a) IPSL Venus GCM (truth), (b) AFES-Venus without data assimilation (frf) and the cases with 12 observations per day: (c) l85x1h2 (1 vertical profile of temperature observation at 85°N latitude every 2 hours), (d) l85x2h4 (two profiles every 4 hours) and (e) l85x3h6 (three profiles every 6 hours). Results are shown for the final day of the data assimilation (March 1st).

Fig.2 shows latitude-height cross sections of zonal mean zonal wind (contour) and temperature (color). The low temperature region, e.g. the cold collar is produced at 65–70 km altitudes and 70°–75°N latitudes for (b) l85x3h6. It should be emphasized that, although we conducted data assimilation only for the temperature in this study, the zonal winds (contour) are also changed especially in the area around the polar vortex. These results clearly show that the temperature observations would improve the zonal winds significantly by using the data assimilation.

On the Earth, it is expected that wind fields are connected with temperature gradients, because Coriolis force acting them is balanced with pressure gradient force produced by latitudinal temperature gradient. On the other hand, the rotation of Venus is so slow that Coriolis force would be neglected. Furthermore, idealized observations of vertical profiles of temperature are given only a few limited points. Therefore, it is not obvious how wind fields are changed by temperature observations.

(a) frf



(b) l85x3h6

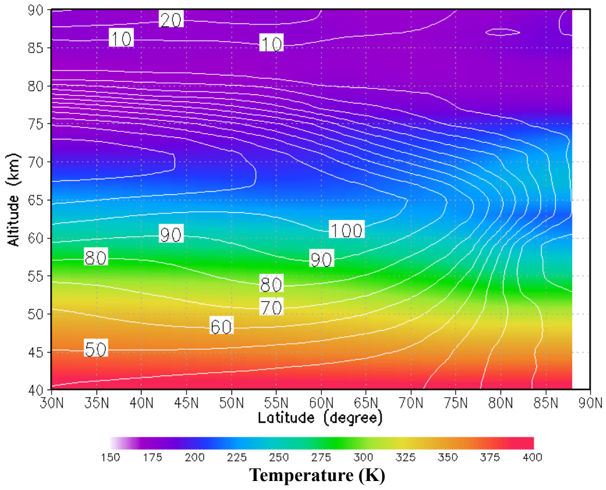


Fig.2 Latitude-height cross sections of zonal mean zonal wind (m/s; contour) and temperature (color) at 40–90 km altitudes and 30°–90°N latitudes. (a) frf (without data assimilation) and (b) l85x3h6 (three vertical profiles of temperature observations with every 6 hours). Results are shown for the final day of the assimilation (March 1st).

To quantify impact of the observations, root-mean-square-deviation (RMSD) expressed in the following equation (1) is calculated at a fixed altitude:

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

where X_i are original values (frf) and x_i are assimilated values (analysis) for each case. N is a total number of horizontal grid points. Therefore, RMSD are differences between analysis and frf. Then, large values of RMSD indicate that the model is considerably modified by the data assimilation. However, large RMSD doesn't necessarily indicate that the model gets closer to true value. We will discuss it later.

Fig.3 shows RMSD of temperature at 66 km altitude for three cases with 12 observations per day, l85x3h6, l85x2h4, and l85x1h2 (black, red, blue) and l6x12h1 (green) on the northern hemisphere. The cases with fewer observations; l85x3h24 (dotted black), l85x2h12 (dotted red), and l85x1h6 (dotted blue) are also shown in addition to the case of l6x12h1 on the southern hemisphere (purple). l6x12h1 is the case with the most frequent observations with the maximum number of points (72 observation points) in this study. It is clearly shown that the temperature fields are more modified as the number of observation points increases in the order of l85x1h2, l85x2h4, l85x3h6, and l6x12h1.

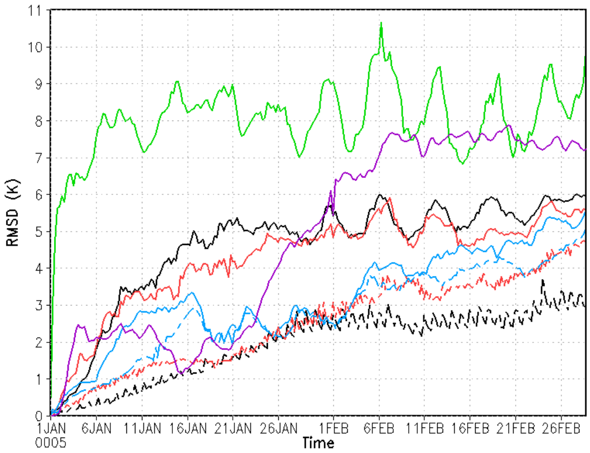


Fig.3 Root-mean-square-deviation (RMSD) of temperature on the northern hemisphere at 66 km altitude for l85x3h6 (black), l85x2h4 (red), l85x1h2 (blue), l85x3h24 (dotted black), l85x2h12 (dotted red), l85x1h6 (dotted blue), and l6x12h1 (green). RMSD on the southern hemisphere is also shown for l6x12h1 (purple).

According to **Fig.1** and **Fig.3**, in the cases with 12 observations per day, the cold collar is well reproduced in the both cases of l85x2h4 and l85x3h6 that have the larger values of RMSD compared with l85x1h2. Therefore, it is suggested again that the number of observation points would be more important than the frequency to improve the model states, at least, to reproduce the cold collar.

On the other hand, for the cases with less frequency observations, the temperature fields are more modified as the frequencies of observations increase in the order of l85x3h24, l85x2h12, l85x1h6. In the original setup of VALEDAS, the cycle of data assimilation is set to every 6 hours. Therefore, observations are not available three fourths and half per day for l85x3h24 and l85x2h12, respectively, though they are always available for l85x1h6.

In this study, we conduct data assimilation of temperature only on the northern hemisphere. Nevertheless, RMSD on the southern hemisphere also increases gradually, showing that the assimilation impact extends globally.

4. DISCUSSION

In the previous section, the cold collar was reproduced for the case in which 2 or 3 vertical profiles are assimilated every 4 or 6 hours (**Fig. 1** (d) and (e)). To check the robustness of the results for the case of l85x3h6, we have also performed data assimilation with different initial values from April 1st (l85x3h6-s1) and July 1st (l85x3h6-s2) for one month, after 3 and 6 months AFES-Venus time integrations, respectively. Even starting from different initial values, the results are almost the same (**Fig. 4**). Temperature differences between the hot polar vortex and the cold collar are ~25 K, which are similar to those for **Fig. 1**.

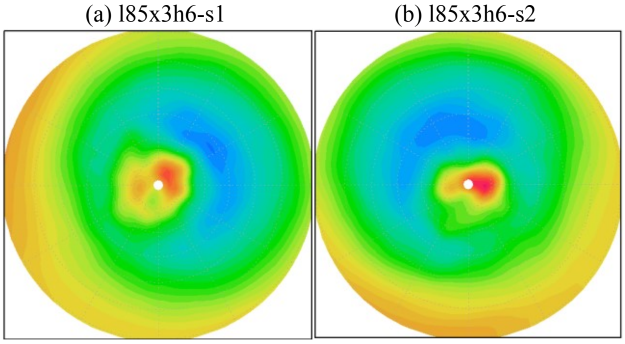

(a) l85x3h6-s1
(b) l85x3h6-s2

Fig.4 Temperature at 66 km altitude on the northern hemisphere (30°–90°N latitudes) for the cases with different initial values; (a) l85x3h6-s1 (started from April 1st) and (b) l85x3h6-s2 (started from July 1st). Color scale is the same as that used for Fig.1 (a). Results are shown for the final day of the data assimilation ((a) May and (b) August 1st).

In addition, we have also performed data assimilation with different observational latitudes; 65°N (l65x3h6), 70°N (l70x3h6), 75°N (l75x3h6), and 80°N (l80x3h6) latitudes. Although the reproducibility of the cold color is weaker than that for l85x3h6, it is reproduced if observation latitudes are higher than 75°N latitude (**Fig.5**).

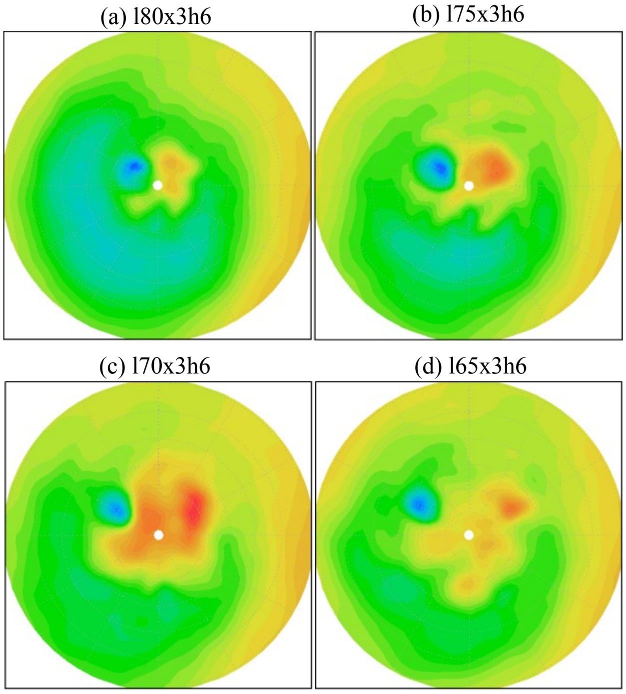


Fig.5 Temperature at 66 km altitude on the northern hemisphere (30°–90°N latitudes) for (a) l80x3h6 (at 80°N), (b) l75x3h6 (at 75°N), (c) l70x3h6 (at 70°N) and (d) l65x3h6 (at 65°N). Color scale is the same as that used for Fig.1 (a). Results are shown for the final day of the data assimilation (March 1st).

Finally, for the cases with less frequency observations, l85x3h24, l85x2h12, and l85x1h6, we have checked the reproducibility of the cold collar (**Fig.6**). For the cases of l85x2h12 and l85x1h6 relatively weak the cold collar appears, though almost no hot polar vortex appears l85x3h24. As mentioned above, since the cycle of data assimilation is set to every 6 hours, observations are not available three fourths and half per day for l85x3h24 and l85x2h12, respectively. Therefore, observations would be almost forgotten at the time of 18:00 for the case of l85x3h24.

It is possible to observe two or three vertical points every 2 or 4 hours by the radio occultation measurements among only 3 satellites. Therefore, the radio occultation measurements among small satellites would be promising, at least, to improve the Venus atmospheric structures in the polar region by the data assimilation. In our experiment, the cold collar is reproduced ~7 days after data assimilation starts for the cases of l85x2h4 and l85x3h6. Then, it would be highly expected that we can reproduce the cold collar by continuous observations for a week. On the other hand, if we do not have any observations, the hot polar vortex (with the cold collar) immediately weakens and totally disappears about 2 weeks. Meanwhile, continuous observations would be necessary to reproduce and maintain the cold collar.

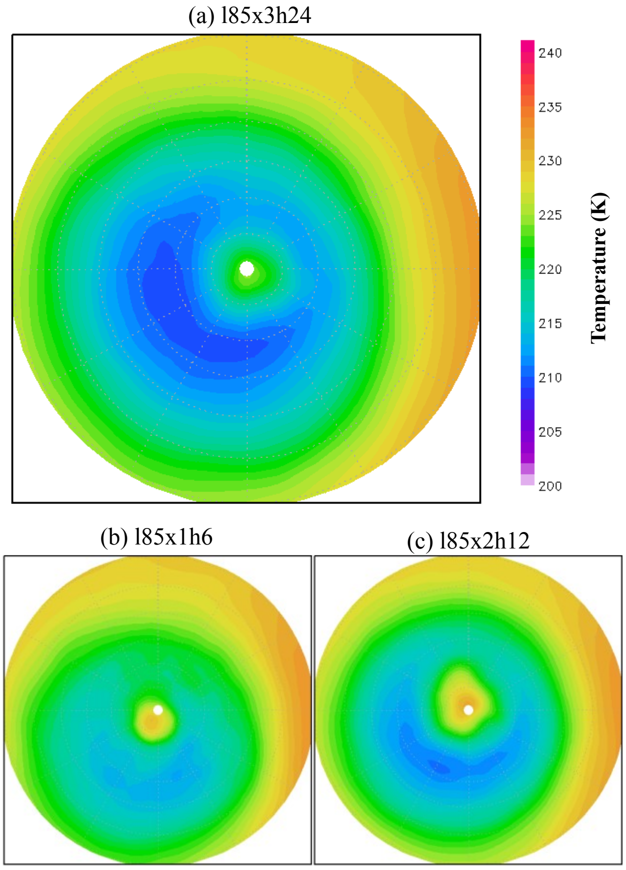


Fig.6 Temperature at 66 km altitude on the northern hemisphere (30°–90°N latitudes) for (a) l85x3h24 (three profiles every 24 hours), (b) l85x1h6 (one profile every 6 hours), and (c) l85x2h12 (two profiles every 12 hours). Results are shown for February 28th 18:00.

In the original setup of VALEDAS, the cycle of data assimilation is set to every 6 hours. Thus, we can get only one analysis even if more frequent observations are available within 6 hours. Therefore, it is expected from the present results that even if highly frequent observations are available at 1 vertical profile, reproducibility of the cold collar would not be improved significantly. In addition, if we have 2 or more observations in the longitudinal direction, planetary scale waves with a zonal wavenumber of 1 could be captured, which may be advantageous for the reproduction of non-axisymmetric structure of the Venus polar atmosphere.

As shown in **Fig.2**, the assimilation of temperature also changed the wind fields. Here, we consider how the general circulation and disturbance fields are changed in association with the modification of temperature and wind fields. The spread is a useful index that indicates the magnitude of variation among members constituting the ensemble forecasts, and is obtained by the following equation (2):

$$SPRD = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(\boldsymbol{x}_j - \overline{\boldsymbol{x}}_j\right)^2} \qquad (2)$$

where M represents the number of ensemble member (in this case, $M = 31$). $\boldsymbol{x}_j$ ($j = 1, \dots, M$) are the state vectors of forecast which contain all of the model prognostic variables (such as temperature and winds). $\overline{\boldsymbol{x}}_j$ are those of the ensemble mean (analysis).

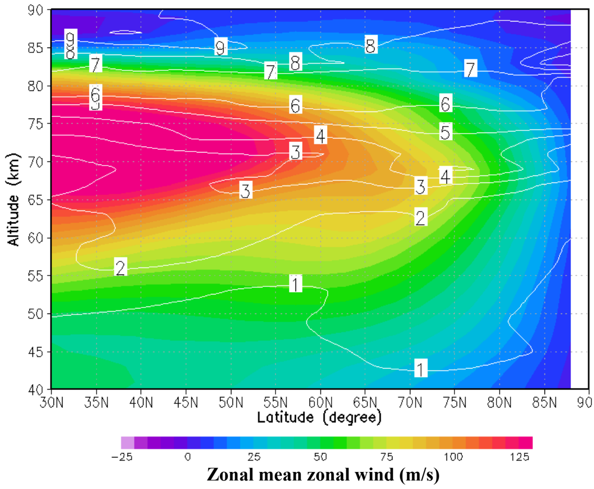
The structure of the spread shows the followings[20]: one is that the smaller the spread value becomes, the smaller the error among members would be. In other words, as the spread value decreases, the reliability of the forecast would increase. The other is that statistical properties of disturbance can be considered by comparing the spread obtained in each case with that in frf (without data assimilation).

Fig.7 shows the latitude-height cross sections of the temperature spread (contour) and the zonal mean zonal wind (color) at 40–90 km altitudes and 30°–90°N latitudes. Considering the former, the spread values obtained in (b) l6x12h1 are generally smaller than those in frf because the large number of observations (72 points) are assimilated with high frequency (hourly).

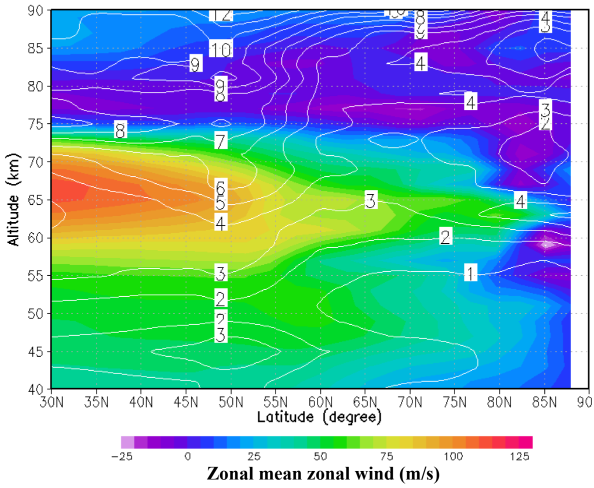
Next, we will consider the disturbance by comparing the spread obtained in each assimilated case with that in frf; larger difference from the spread of frf indicates that the disturbance would appear more actively. In (c) l85x3h6, there are 2 regions with the large temperature spread in 45–75 km altitudes and 70°–80°N latitudes. Comparison with the spread of (a) frf suggests that the active disturbances appear in these regions, which are characterized by strong horizontal and vertical shear of the wind velocity. Therefore, the disturbances would be caused by barotropic instability due to the horizontal shear of the zonal wind or baroclinic instability due to the latitudinal temperature gradient and the vertical shear of the zonal wind.

As mentioned in **Fig.3**, large RMSD doesn't necessarily indicate that the model gets closer to true value. **Fig.8** shows the temperature at 66 km altitude seen from the North Pole for the cases of (a) l6x12h24 and (b) l6x12h1, in which observations are assimilated at 72 observation points every 24 and 1 hours, respectively. As suggested by **Fig.1** and **Fig.3,** since the number of observation points is more important than the frequency, it is expected that the cold collar would be reproduced clearly if we prepare many observation points. However, the cold collar obtained for (b) l6x12h1 is not clearer than that for (a) l6x12h24 although the frequency of observation in (b) l6x12h1 is much higher than that in (a) l6x12h24. In addition, the temperature is higher in large area of the polar region for l6x12h1. The reason why the cold collar is unclear despite the frequent observations will be discussed below.

(a) frf



(b) l6x12h1



(c) l85x3h6

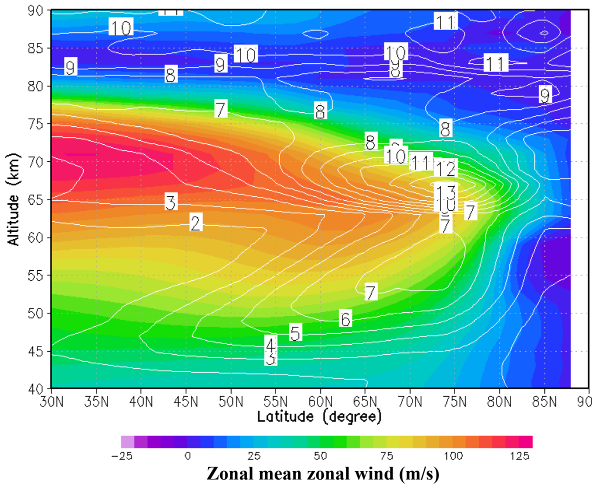


Fig.7 Latitude-height cross sections of spread at 40–90 km altitudes and 30°–90°N latitudes. Zonal mean zonal wind (color) and spread of temperature (K; contour) are shown for the cases (a) frf, (b) l6x12h1, and (c) l85x3h6. Results are shown for the final day of the data assimilation (March 1st).

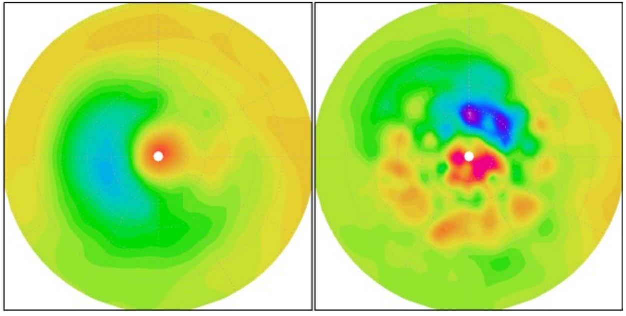

(a) l6x12h24
(b) l6x12h1

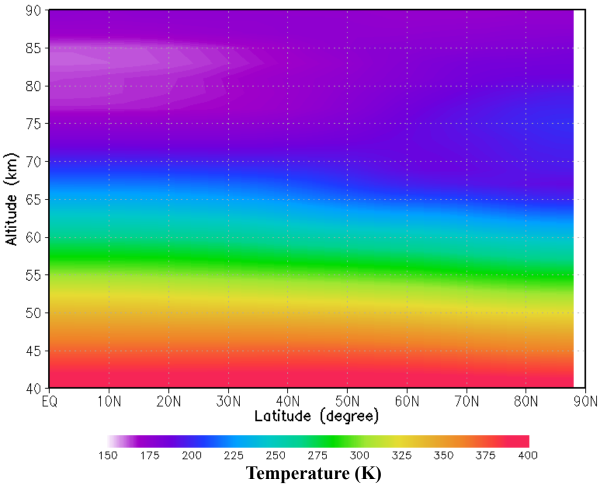
Fig.8 Temperature fields at 66 km altitude on the northern hemisphere (30°–90°N latitudes) for (a) l6x12h24 (12 vertical profiles of temperature observation every 24 hours) and (b) l6x12h1 (the same ones every 1 hour). Color scale is the same as that used for Fig.1 (a). Results are shown for February 28th 18:00.

Fig.9 displays latitude-height cross sections of zonal mean temperature for (a) AFES-Venus and (b) IPSL Venus GCM at 40–90 km altitudes and 0°–90°N latitudes. It is shown that there is a bias in the horizontal mean (globally averaged) temperature at the same altitude between these results; the temperature obtained in AFES-Venus is higher (lower) at lower (higher) altitudes than that in IPSL Venus GCM. This is partly because IPSL Venus GCM solves radiative transfer process. Because many observations are assimilated for the cases of l6x12 and the modification of temperature is larger than that in other cases (see **Fig.3**), it is expected that assimilation using many observations would correct the bias and improve the global mean temperature. This would be the reason why the cold collar is not reproduced in the case of l6x12 clearly (see **Fig.8**).

It should be discussed here how to assimilate temperature profiles with a bias in a real observation. If we focus on the reproduction of the cold collar only, it would be effective to perform a bias correction between observation and model. For example, the bias can be corrected by calculating horizontal mean temperature of observation and model and then subtracting its difference to extract the anomaly. On the other hand, it would be also important to improve a bias directly by the data assimilation. For future work, we will check how many observations are needed to correct a bias.

In this study, the position of observation was always fixed for simplicity, and the fixed observation points, e.g. the observation data obtained at the same points, are assimilated. In general, the actual observations will occur at different latitudes. This would be an important difference with respect to the experiments performed here. In the future, in order to simulate idealized observations more realistically, we plan to produce observation data assuming the actual orbit in which observation points move with time. It is expected, however, that the fundamental results obtained in the present study would not change significantly because the observation information is advected by the fast mean zonal wind in the Venus atmosphere. In addition, to reproduce the cold collar, we should design the orbits focusing on the polar region.

(a) AFES-Venus



(b) IPSL Venus GCM

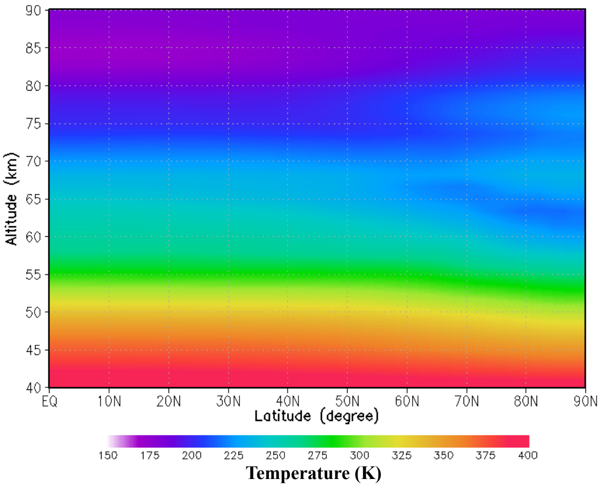


Fig.9 Latitude-height cross sections of zonal mean temperature for (a) AFES-Venus and (b) IPSL Venus GCM at 40–90 km altitudes and 0°–90°N latitudes.

5. CONCLUSION

In this study, the data assimilation with idealized temperature observations was conducted to evaluate radio occultation measurements among small satellites based on reproducibility of the cold collar. The present results can be summarized by the following three points.

First, the number of observation points is more important than the frequency. Second, the cold collar is reproduced if we can observe 2 or 3 vertical profiles every 4 or 6 hours. Third, even when only the temperature field is observed, the wind field is also improved.

It is possible to obtain vertical temperature profiles at 2 or 3 points every 2 or 4 hours by the radio occultation measurements among only three satellites. So, it is strongly expected that the wind and temperature fields associated with the cold collar would be improved by such observations. It is concluded, therefore, that the radio occultation measurements among small satellites would be useful and promising at least to improve the atmospheric structure around the cold collar.

VALEDAS enables us to conduct the observing system simulation experiment (OSSE) of the Venus atmosphere as demonstrated in this study. For example, wind velocity derived from cloud tracking of future observing mission could be assimilated. Such kind of studies would be quite useful for planning more effective future Venus missions.

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