HIGH RESOLUTION SIMULATIONS OF DUST DEVILS AND GLOBAL CIRCULATION OF THE MARTIAN ATMOSPHERE.

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Introduction

High resolution simulations of Martian atmosphere have been performed by the use of two models, a large-eddy simulation (LES) model and a general circulation model (GCM). One of purposes of our study is to investigate atmospheric disturbances whose horizontal scales are from that of dust devil to planetary scale on Mars. In addition, our study aims to give some insights into dust related process, too.

In order to investigate small scale disturbances including dust devils, high resolution LES have been performed (*Nishizawa et al.*, 2016) by the use of SCALE-LES (*Nishizawa et al.*, 2015; *Sato et al.*, 2015). The simulations have been performed with several resolutions up to 5 m grid size. On the other hand, high resolution general circulation simulations have been performed by the use of a model based on AFES (*Ohfuchi et al.*, 2004). The simulations have been performed with several resolutions up to about 11 km horizontal grid size. By using those two models, we try to cover a wide range of atmospheric disturbances appearing on Mars.

Models and experimental settings

LES model

An LESs are performed by SCALE-LES (*Nishizawa et al.*, 2015; *Sato et al.*, 2015) with assuming diurnally varying thermal forcing. The dynamics of the model is based on the fully compressive equations. The equation systems are numerically solved with a fully explicit temporal integration scheme. Sub-grid scale turbulence is parameterized by the Smagorinsky-type eddy viscosity model (*Brown et al.*, 1994; *Scotti et al.*, 1993). Surface fluxes are calculated using the Louis-type model (*Louis*, 1979; *Uno et al.*, 1995). Diurnally varying radiative heating is imposed by the use of pre-calculated tables given by the one-dimensional simulation conducted by *Odaka et al.* (2001). The one-dimensional simulation is performed with the condition of $L_s = 100^\circ$ at 20°N; the net shortwave flux at the surface is 485 W m^{-2} at noon. In addition, the surface temperature is also assumed based on the same one-dimensional simulation.

The simulation domain is a square of 19.2 km times 19.2 km in the horizontal, and and about 21 km in the vertical, and has double periodic boundary condition on lateral boundary. The horizontal grid size of simulations are 100, 50, 25, 10, and 5 m, and the simulation domain are the same for all simulations. The vertical grid size is the same as horizontal one below 15 km altitude for each simulation, but is stretched gradually above 15 km altitude.

Integrations are performed for one Martian day from the initial condition of the horizontally uniform steady state at midnight, except in the 5 m resolution run. The initial conditions of vertical temperature is obtained from the above-mentioned one-dimensional simulation. As for the 5 m run, integration is performed for one hour from the snapshot of the 10 m resolution run at 14:00 LST. Analyses are performed at 14:30 and 15:00 LST, at which time the PBL is almost at its deepest.

GCM

General circulation simulations are performed by a Mars GCM based on AFES (*Ohfuchi et al.*, 2004) and physical processes for Mars imported from another Mars GCM (*Takahashi et al.*, 2003, 2006). The dynamics of the model is based on the primitive equation system. The equation system is numerically solved with a spectral Eulerian method. Sub-grid scale turbulence is parameterized by a simplified *Mellor and Yamada* (1982) level 2.5 scheme, in which the advection of eddy kinetic energy is neglected. Surface fluxes are calculated using the Louis (1979) model.

The radiative transfer equation is solved numerically with considering absorption by CO_2 gas and absorption and scattering by dust. In the simulations presented in this study, a distribution of dust is assumed with surface dust optical depth of 0.2. The surface orographic height, albedo and thermal inertia variations are based on observations. But, in some experiments, uniform surface properties are used to investigate effects of surface property variations on disturbances.

The horizontal resolution of simulations are T79, T159, T319, and T639, which corresponds to about 89, 44, 22, and 11 km grid sizes, respectively. The number of vertical layers is 96 for all simulations.

Results

Figure 1 shows the horizontal distribution of vertical vorticity at 62.5 m height in the 5 m resolution run. Convective cells with hexagonal or quadrangular structures can be observed, as observed in previous studies (Michaels et al., 2004). There are strong upward motions in the narrow cell boundary and relatively weak downward motions in the entire cell region. The horizontal size of the cells is roughly 2 km at this height, but tends to be smaller at lower heights. The depth of the PBL is about 6 km at this time in the runs at all resolutions.

In the figure, some intense vortices are observed in upward motion regions, in particular, around the corners of the convection cells. Investigating results with different resolution, it is found that the intensity of vortices depends on the resolution. The higher the resolution is, the more intense the vortices are.

Statistical analysis is performed on the dust devils in the simulations. One of the example is shown in Figure 2, which shows histograms of maximum vorticity of isolated vortices in the 100, 50, 25, 10, and 5 m resolution runs. Number of vortices in the model changes drastically, and the slope of the histogram is slightly different with resolution.

On the other hand, general circulation simulations performed in this study show atmospheric disturbances whose horizontal scales from tens of kilometers to planetary scale. Figure 3 shows an example of vorticity at 4 hPa in a T639 simulation. The figure shows synoptic scale mid-latitude waves, many kinds of orographically induced circulations, and small scale vortices in low latitudes. The horizontal scales of low latitude vortices are around minimum resolvable scales of about 20 km, which roughly corresponds to the simulation domain size of LES in this study.

Other results of those simulations with two models will be given and discussed further in the presentation.

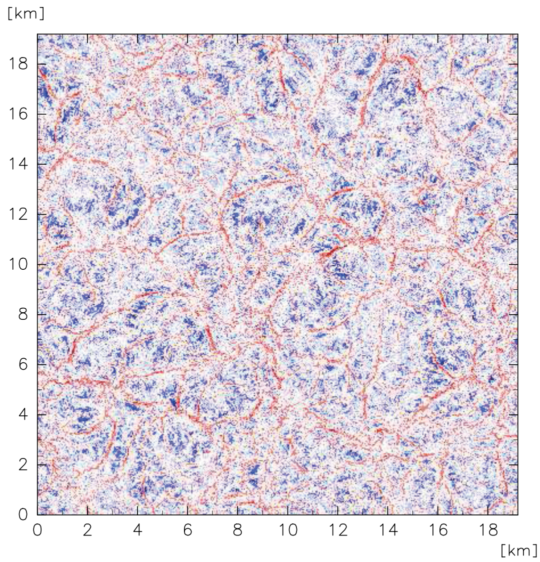

Figure 1: Distribution of vorticity at 5 m height obtained by 5 m LES.

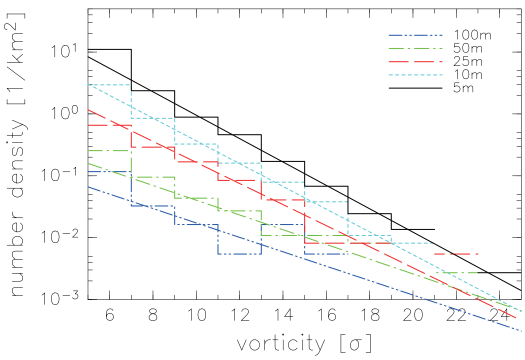

Figure 2: Histogram of isolated vortices obtained by LES with several horizontal grid sizes.

References

Brown, A. R., S. H. Derbyshire, and P. J. Mason (1994), Large-eddy simulation of stable atmospheric boundary layers with a revised stochastic subgrid model, *Q. J. Roy. Meteor. Soc.*, *120*, 1485–1512.

Louis, J.-F. (1979), A parametric model of vertical eddy fluxes in the atmosphere, *Bound.-Lay. Meteorol.*, *17*, 187–202.

Mellor, G. L., and T. Yamada (1982), Development of a Turbulent Closure Model for Geophysical Fluid Problems, *Rev. Geophys. Space Phys.*, *20*, 851–875.

Michaels, T. I., and S. C. R. Rafkin (2004), Large-eddy simulation of atmospheric convection on Mars, *Q. J. R. Meteorol. Soc.*, *130*, 1251–1274, doi:10.1256/qj.02.169.

Nishizawa, S., H. Yashiro, Y. Sato, Y. Miyamoto, and H. Tomita (2015), Influence of grid aspect ratio on planetary boundary layer turbulence in large-eddy simulations, *Geosci. Model Dev.*, *8*, 3393–3419, doi:10.5194/gmd-8-3393-2015.

Nishizawa, S., M. Odaka, Y. O. Takahashi, K. Sugiyama, K. Nakajima, M. Ishiwatari, S. Takehiro, H.

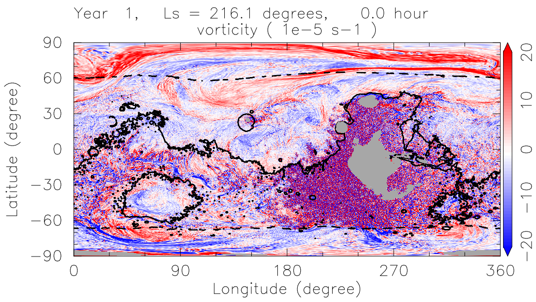

Figure 3: Distribution of vorticity at 4 hPa pressure level obtained by T639 GCM simulation at northern fall. Also shown are the areoid (solid line) and the location of polar cap edge (dashed line). Gray areas represent mountains at 4 hPa pressure level.

Yashiro, Y. Sato, H. Tomita, and Y.-Y. Hayashi (2016), Martian dust devil statistics from high-resolution large-eddy simulations, *Geophys. Res. Lett.*, *43*, 4180–4188, doi:10.1002/2016GL068896.

Odaka, M., K. Nakajima, M. Ishiwatari, and Y.-Y. Hayashi (2001), A numerical simulation of thermal convection in the Martian lower atmosphere with a two-dimensional anelastic model, *Nagare Multimedia*, http://www2.nagare.or.jp/mm/2001/odaka/index.htm.

Ohfuchi, W., H. Nakamura, M. K. Yoshioka, T. Enomoto, K. Takaya, X. Peng, S. Yamane, T. Nishimura, Y. Kurihara, and K. Ninomiya (2004), 10-km Mesh Meso-scale Resolving Simulations of the Global Atmosphere on the Earth Simulator – Preliminary Outcomes of AFES (AGCM for the Earth Simulator) –, *Journal of the Earth Simulator*, *1*, 8–34.

Sato, Y., S. Nishizawa, H. Yashiro, Y. Miyamoto, Y. Kajikawa, and H. Tomita (2015), Impacts of cloud microphysics on trade wind cumulus: which cloud microphysics processes contribute to the diversity in a large eddy simulation?, *Prog. Earth Planet. Sci.*, *2*, 23, doi:10.1186/s40645-015-0053-6.

Scotti, A., C. Meneveau, and D. K. Lilly (1993), Generalized Smagorinsky model for anisotropic grids, *Phys. Fluids A-Fluid*, *5*, 2306–2308.

Takahashi, Y. O., H. Fujiwara, H. Fukunishi, M. Odaka, Y.-Y. Hayashi, and S. Watanabe (2003), Topographically induced north-south asymmetry of the meridional circulation in the Martian atmosphere, *J. Geophys. Res.*, *108*, 5018, doi:10.1029/2001JE001638.

Takahashi, Y. O., H. Fujiwara, and H. Fukunishi (2006), Vertical and latitudinal structure of the migrating diurnal tide in the Martian atmosphere: numerical investigations, *J. Geophys. Res.*, *111*, E1003, doi:10.1029/2005JE002543.

Uno, I., X.-M. Cai, D. G. Steyn, and S. Emori (1995), A simple extension of the Louis method for rough surface layer modeling, *Bound. Lay. Meteorol.*, *76*, 395–409.