Development of a global non-hydrostatic Martian atmospheric model and its high-resolution simulation

*Hiroki Kashimura[1], Hisashi Yashiro[2], Seiya Nishizawa[2], Hirofumi Tomita[2], Kensuke Nakajima[3], Masaki Ishiwatari[4], Yoshiyuki O. Takahashi[1], Yoshi-Yuki Hayashi[1]

1. Kobe University/Center for Planetary Science, 2. RIKEN Center for Computational Science, 3. Kyushu University, 4. Hokkaido University

Scales of atmospheric motions in Earth range from a few meter scale to the planetary scale, and multi-scale phenomena interact with each other. This is a reason for promoting an atmospheric simulation with higher resolution. The situation must be the same in other planets such as Mars. In the Martian atmosphere, dust storms in various scales—from dust devils of tens to hundreds of meter scales, to local dust storm of several tens of kilometer scale, and to global dust storm—have been observed. However, interactions between these scales are unknown. In addition, since Mars has a thin atmosphere and no ocean, the temperature difference between day and night is large and vertical convection should play an essential role in the Martian meteorology, but it is also unknown. To investigate these mysteries, global atmospheric simulations with horizontal resolution as high as few kilometers are required. Additionally, in order to explicitly simulate vertical convection, it is necessary to solve the governing equations without assuming the hydrostatic balance.

We are developing a non-hydrostatic global Martian atmospheric model (Martian SCALE-GM) which is suitable for large-scale parallel computation, targeting to perform high-resolution simulations described above on the post-K computer. SCALE-GM (http://scale.aics.riken.jp/) is being developed by using the dynamical core of NICAM (Tomita and Satoh, 2005; Satoh et al., 2008; Satoh et al., 2014), a non-hydrostatic model using a finite volume method in the icosahedral grid systems (Tomita et al., 2001, 2002), that has been used for simulations of Earth atmosphere and climate, and by aiming at sharing of physical process modules with the regional model (SCALE-RM) and application to other planetary atmospheres. We are developing Martian SCALE-GM by incorporating constants and physical process modules of the Martian atmosphere. The Martian physical modules are taken from DCPAM (https://www.gfd-dennou.org/library/dcpam/), an existing pan-planetary atmospheric general circulation model (GCM). DCPAM is a traditional, hydrostatic GCM using a spectral method for horizontal discretization.

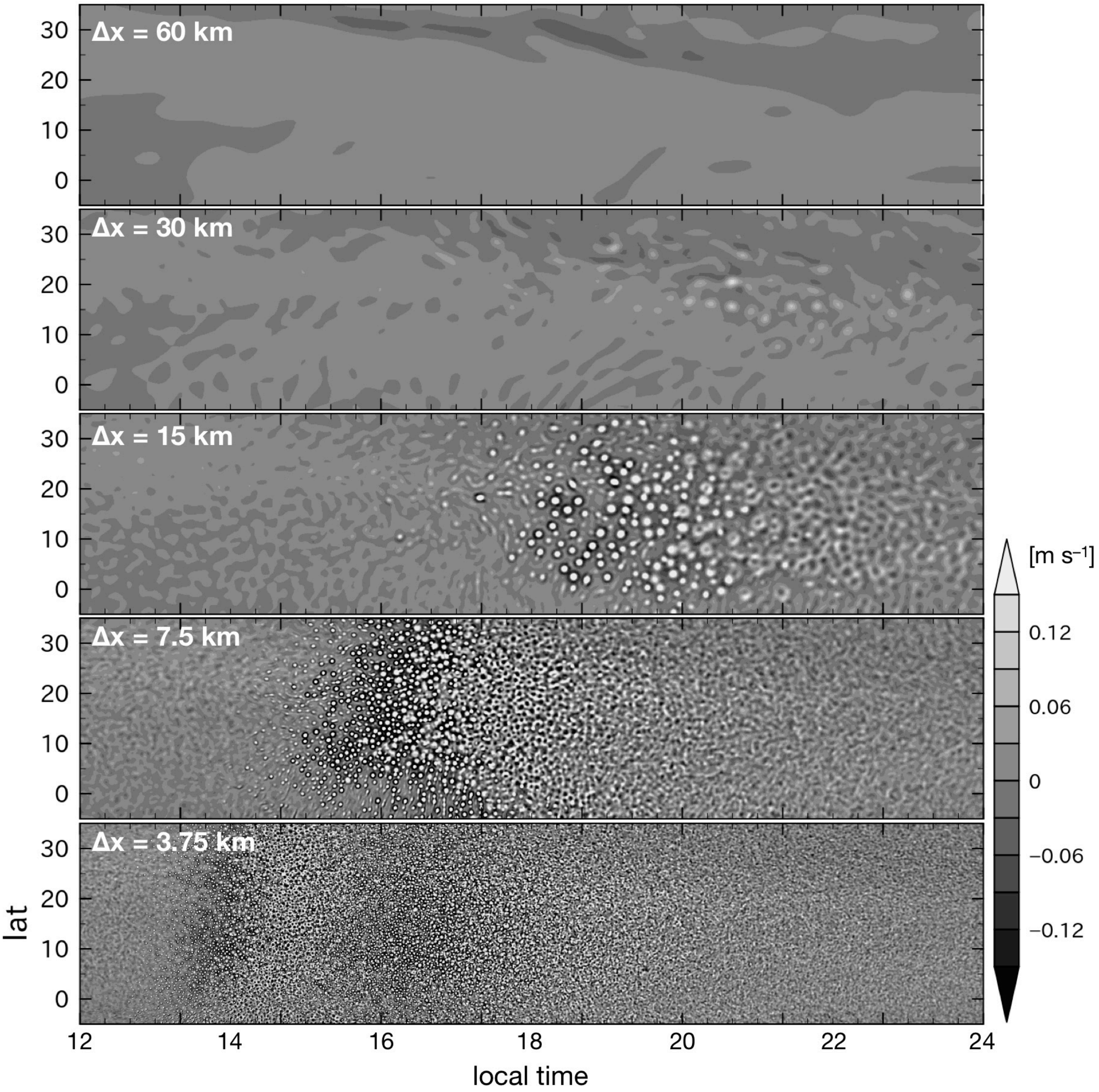
In this study, we ported a Martian atmospheric radiation model (Forget et al., 1999) and a soil model from DCPAM to SCALE-GM and performed a test of temperature evolution in a vertical 1D-atmosphere and soil. The atmosphere model has 100 layers (Δz = 1 km), and distribution of dust is fixed with 0.2 optical depth. The soil model has 18 layers. Soil's heat capacity and thermal conductivity are set to 9.7×10^5 [J K^{-1} kg^{-1}] and 0.076 [W m^{-1} K^{-1}], respectively. Surface albedo is fixed at 0.2. For the calculation of surface fluxes and vertical diffusion, BH91B95 (Beljaars & Holstang, 1991; Beljaars, 1995) and MY2.5 (Mellor & Yamada, 1982) are used, respectively. The initial condition is the 200 K constant temperature atmosphere and soil. We have confirmed that both models (SCALE-GM and DCPAM) show almost the same temperature evolution.

Next, we performed 3D calculations under a Mars-like condition in 7 different horizontal resolutions and checked the dependence of the numerical solutions on the horizontal resolution. Horizontal grid intervals are $240\times(1/2)^n$ [km] (n = 0, 1, 2, 3, 4, 5, 6); i.e., 3.75 km at minimum. The horizontal diffusion representing turbulent mixing in sub-grid scales is given in the 3rd order Laplacian with the relaxation time for the shortest scale given by $100\times(1/2)^n$ [s]. The atmosphere is divided into 36 layers, which are concentrated near the surface. To avoid wave reflections at the model top, a sponge layer represented by 1st order Laplacian is set above 40 km altitude; the relaxation time for the shortest scale is given by $3600\times(1/4)^n$ [s] except for the case of Δx = 3.75 km, in which 3 s is used. The 4th order Runge-Kutta method is used for time-integration with a time step of $360\times(1/2)^n$ [s]. The surface albedo is set to 0.5. Neither topography nor condensation processes are included.

Numerical solutions showed that vertical convections due to diurnal solar heating did not appear clearly in the cases with Δx larger than 15 km, whereas they appeared in higher resolution cases. Furthermore, it was confirmed that the horizontal scale and occurrence local-time of the vertical convection are highly dependent on the horizontal resolution at least in this range.

(Figure: Horizontal resolution dependence of vertical wind. Snapshots at 2 km altitude after 30 days from the spring equinox of the Northern hemisphere.)

Keywords: Mars, atmosphere, global, non-hydrostatic, high-resolution simulation, model development


Δx = 60 km
Δx = 30 km
Δx = 15 km
Δx = 7.5 km
Δx = 3.75 km
30
20
10
0
lat
12
14
16
18
20
22
24
local time
[m s⁻¹]
0.12
0.06
0
−0.06
−0.12