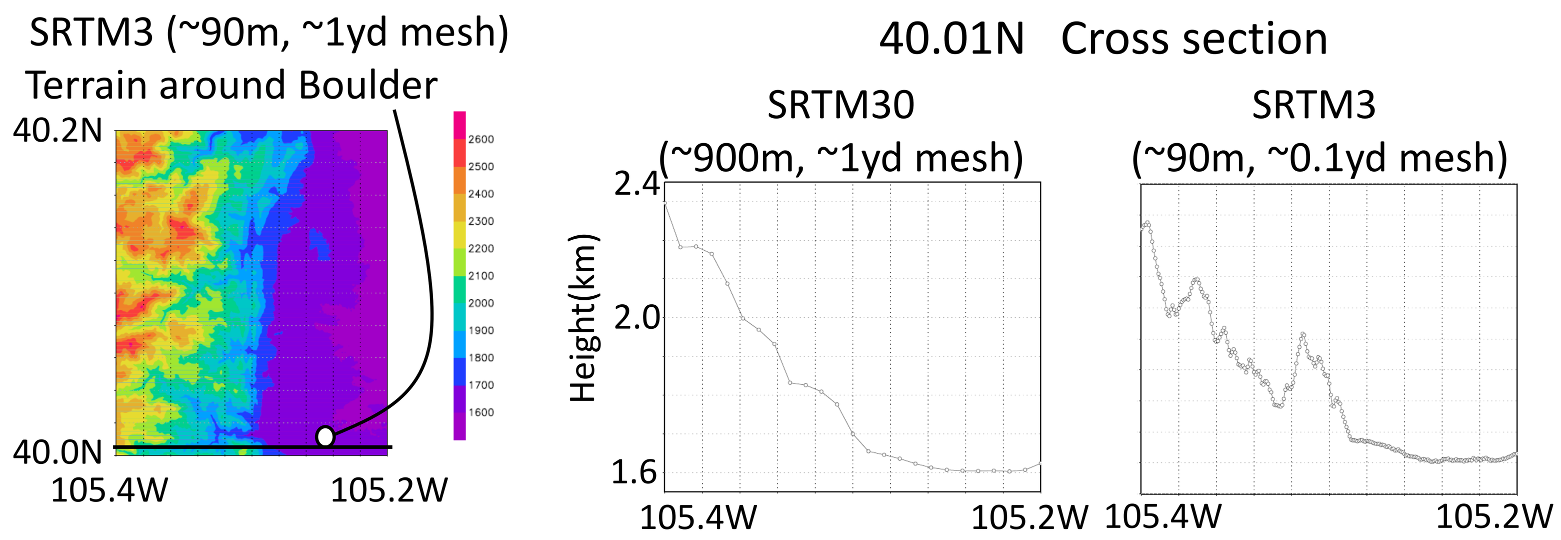
Development of a non-hydrostatic atmospheric model using the Chimera grid method for a steep terrain

*Kazushi Takemura, Keiichi Ishioka, Shoichi Shige
Graduate School of Science, Kyoto University

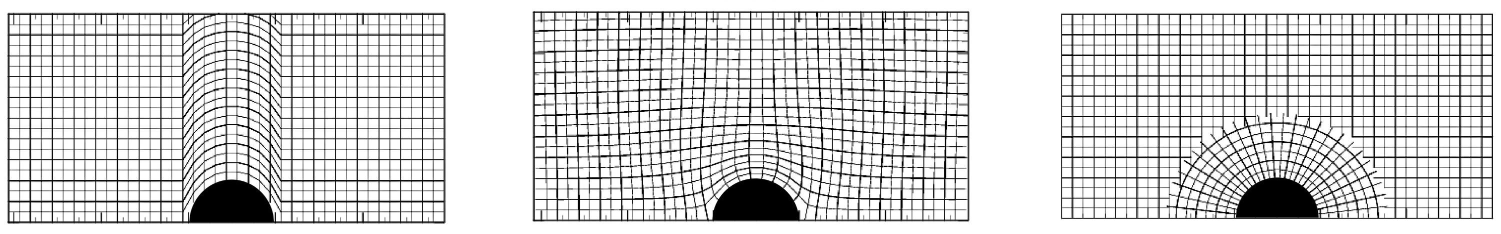
1. Background and Introduction

Recent developments in computing have rapidly increased atmospheric models' resolution. In high-resolution models, the terrain is resolved in more detail, and thus **steeper and more complex terrain can be resolved**.



The terrain-following coordinate, which is commonly used to represent the terrain, does not have orthogonality on the such steep terrain. It is known that **the less orthogonality induces serious errors**.
Satomura(1989) used **numerically generated coordinates,** which have high orthogonality, and succeeded in reducing this error. However, this system cannot be generated over complex terrain in which the slope angle changes abruptly: e.g. a cliff.

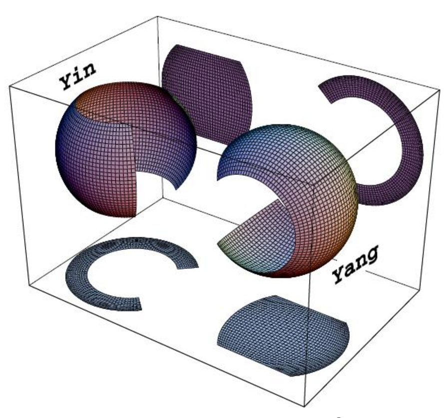
<u>In this paper, we present an non-hydrostatic model that uses **the Chimera grid method** to represent steep and complex terrain</u> (Takemura et al. 2015).



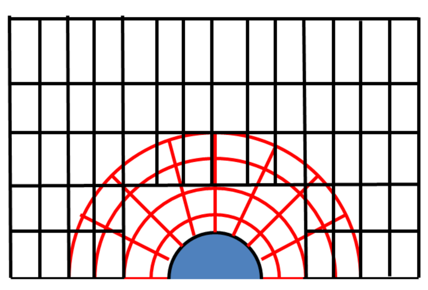
2. Chimera grid method

The chimera grid method is mainly used in the field of CFD **to represent complex topography** (Benek et al. 1986). In the filed of the earth science, the chimera grid method is used as **Yin-Yang grid** to represent the globe (Kageyama and Sato 2004).

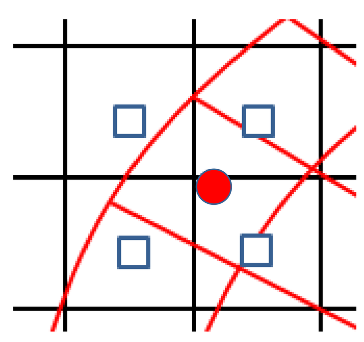
The computational region is represented by **a composite of overlapping grid**; a local grid and a global grid. Interaction between grids is accomplished by **interpolating boundary point values** each other.



Yin-Yang grid
(Kageyama and Sato,2004)



Local grid: terrain detail
Global grid: global region



Interpolation
from Global grid
to Local grid

Boundary Value :
Surrounding value :

3. Model description

- Governing equations

Momentum equation

$$\frac{\partial U^i}{\partial t} = -v^j\frac{\partial U^i}{\partial \xi^j} - \frac{1}{\rho}\frac{\partial p'}{\partial x^i} + \frac{\rho'}{\rho}g^i + \frac{\partial}{\partial \xi^k}\left(G^{jk}K_m\frac{\partial}{\partial \xi^j}U^i\right) + diff.U^i$$

Continuity equation

$$\frac{\partial \rho'}{\partial t} = -\frac{1}{J}\frac{\partial (J\rho v^i)}{\partial \xi^i} + diff.\rho'$$

Thermodynamic equation

$$\frac{\partial \theta'}{\partial t} = -v^i\frac{\partial \theta}{\partial \xi^i} + \frac{\partial}{\partial \xi^k}\left(G^{kl}K_h\frac{\partial}{\partial \xi^l}\theta\right) + diff.\theta'$$

State equation

$$p = \bar{p} + p' = \left(\rho R_d \theta p_0^{-\frac{R_d}{C_p}}\right)^{1-\frac{R_d}{C_p}}$$

U^i: physical velocity
v^j: contravariant velocity
p: pressure, ρ: density,
θ: potential temperature,
$\bar{p}, \bar{\theta}, \bar{\rho}$: basic component of each variables,
p', θ', ρ': perturbation component of each variables,
G: metric tensor, J: Jacobian,
$diff.\phi$: artifical diffusion term

- Time integration : 4th order runge kutta scheme
- Finite difference scheme : 2nd–order centered scheme
- Layout of variables : B grid
- Interpolation method : bi-linear interpolation, 3rd order Lagrange interpolation

4. Mountain wave simulation

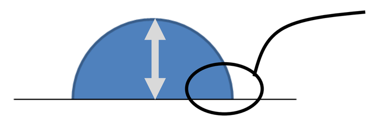
<u>Setting</u>

$\Delta x, \Delta z$		**250**m,**250**m
Time integration		**60** min
Boundary condition	Side	Periodic
	Top & Bottom	Free slip
Sponge layer		**18**km above

<u>Initial Condition</u>

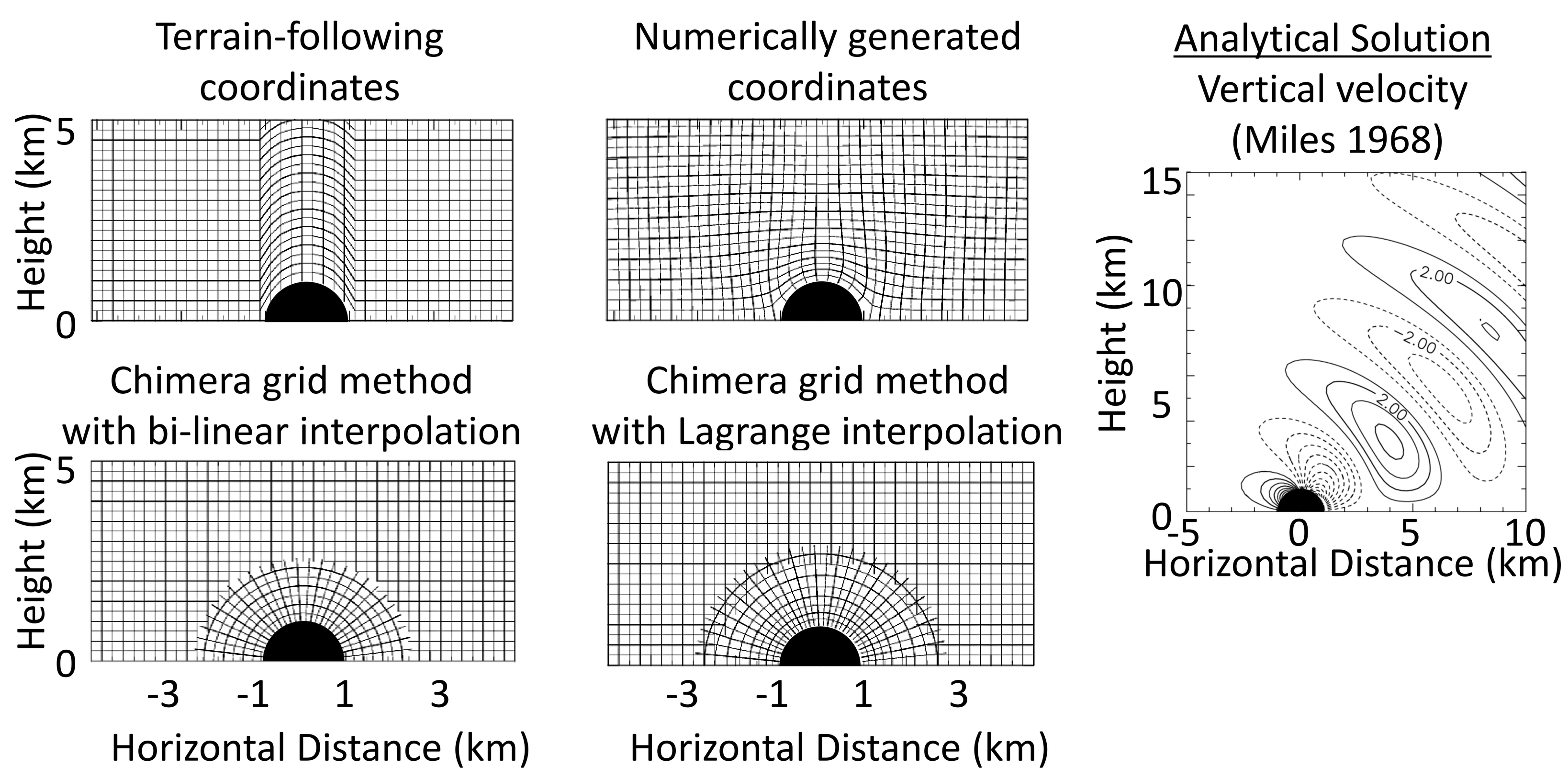
Horizontal velocity	**10** m/s
Brrant-vaissala frequency	**0.01** s^{-1}

<u>Terrain</u> Semi-circular mountain
Radius 1000m

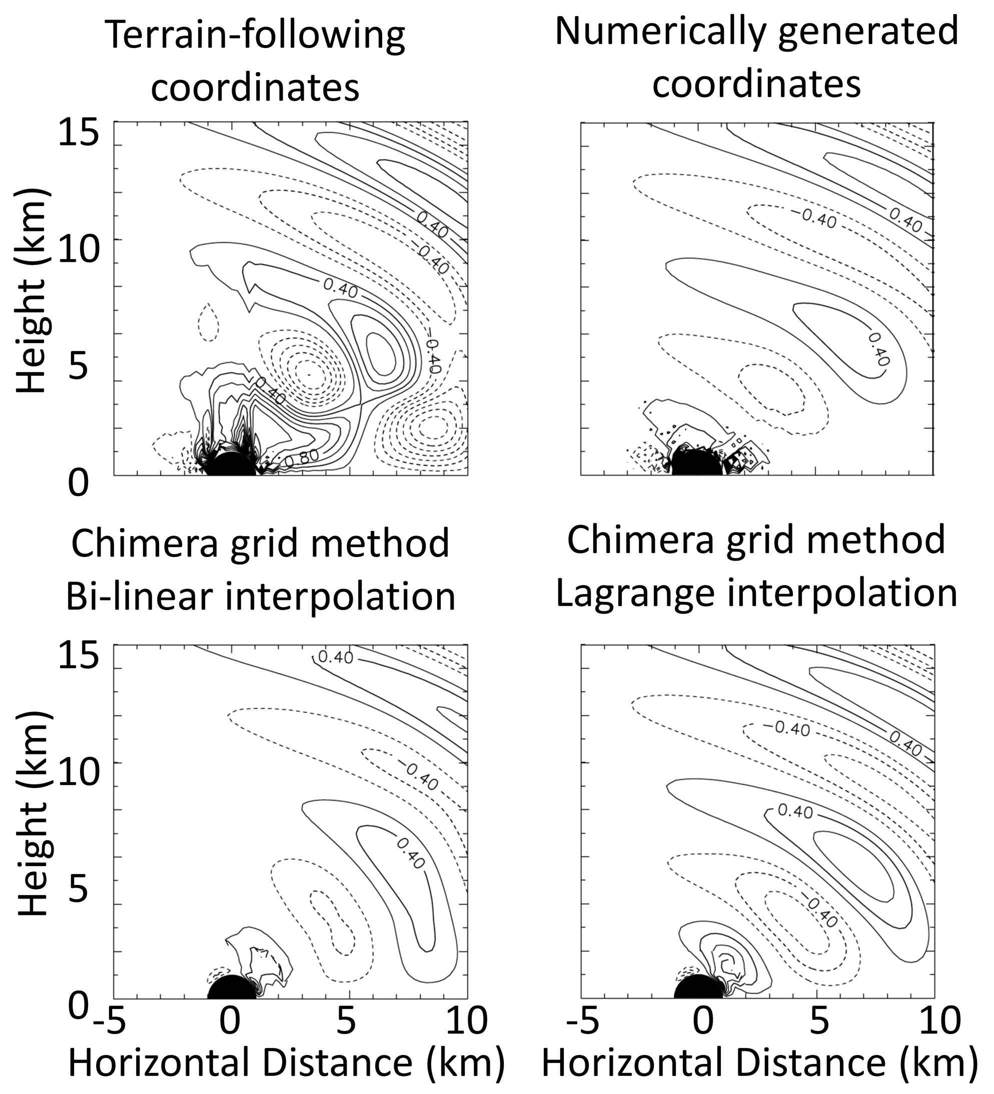


Very steep,
The slope angle change abruptly

<u>Grid</u>



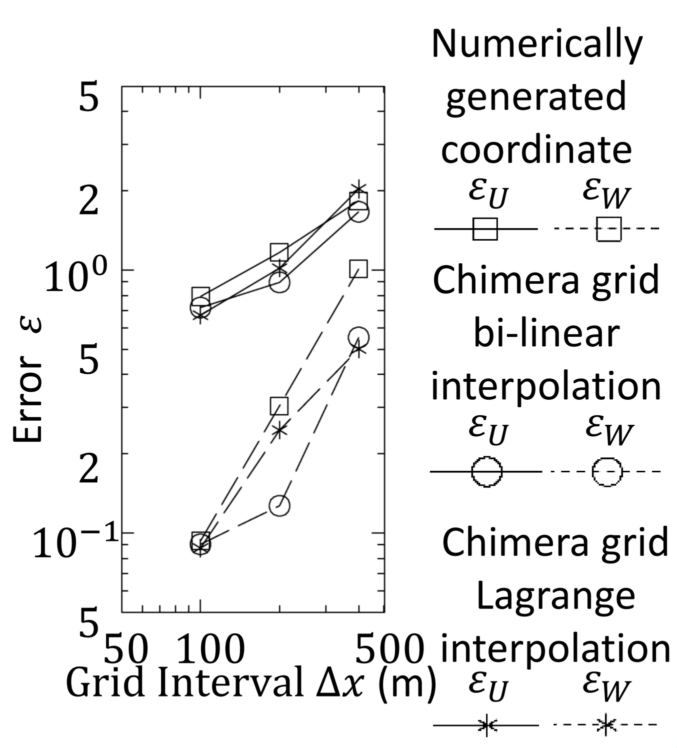
5. Result



<u>Horizontal velocity error ε_U</u>
<u>Vertical Velocity error ε_W</u>
<u>with grid interval Δx</u>

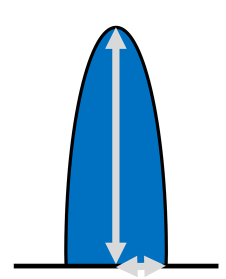
$$\varepsilon_U = \frac{1}{N_x N_z}\sum_{i,k=1}^{N_x,N_z}\left|U_{i,k}^c - U_{i,k}\right|$$

$$\varepsilon_W = \frac{1}{N_x N_z}\sum_{i,k=1}^{N_x,N_z}\left|W_{i,k}^c - W_{i,k}\right|$$



6. Tall semi-elliptical mountain

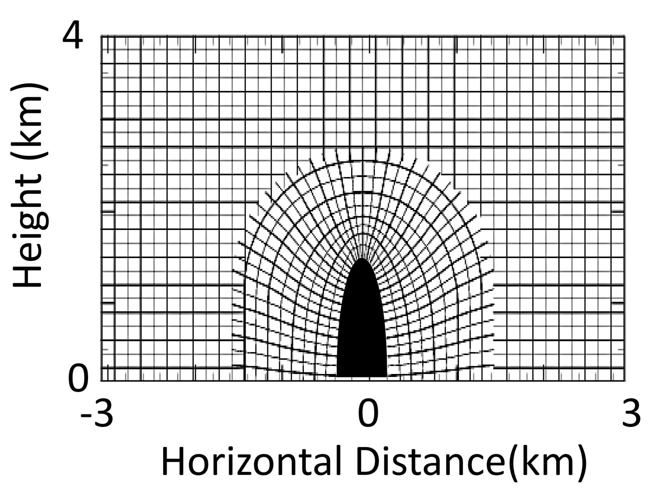
<u>Terrain</u>



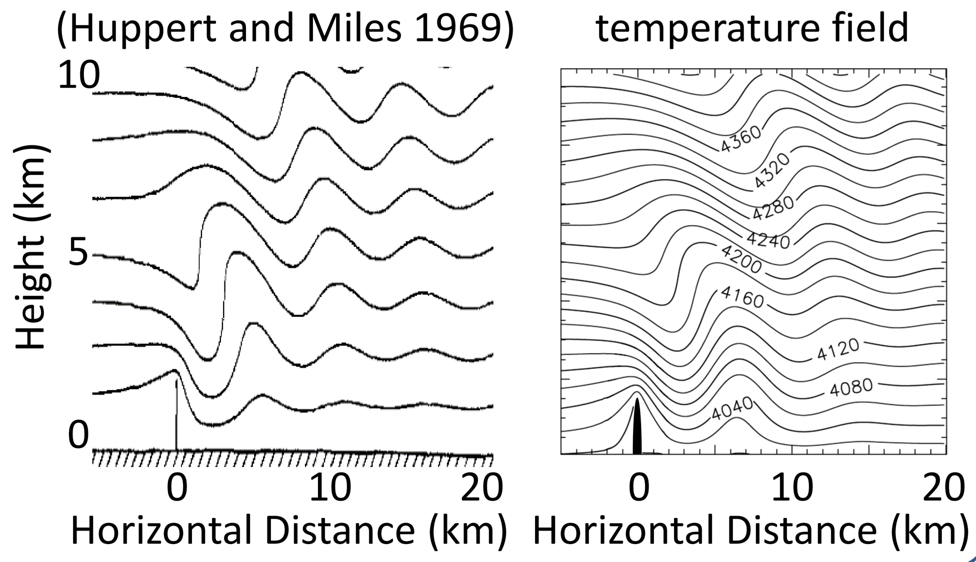
Height: 1500m
Width: 300m
Average slope of 80°

This mountain is very steep, and slope angle change abruptly like a cliff.
Thus, the numerically generated coordinate cannot represent.

<u>Grid</u> $\Delta x = \Delta z = 150$m



<u>Result</u>



7. Summary and Future work

We have developed an atmospheric model using the Chimera grid method and have performed a high-resolution simulation of air flow over steep and complex terrain. The results show that the Chimera grid can reduce the errors that are produced by using terrain-following coordinates for steep terrain, and can simulate the flow appropriately over a very steep mountain for which the numerical coordinates cannot be generated.

However, we did not consider the global conservation of physical quantities in this paper. To satisfy the global conservation, we should introduce a conservative interpolation, which interpolates fluxes of physical quantities. And now we are trying it as future work.

8. Reference

Satomura, T. (1989), *J. Meteor. Soc. Japan*, **67**, 473-482.
Takemura, K., K. Ishioka and S. Shige (2015), Development of a non-hydrostatic atmospheric model using the Chimera grid method for a steep terrain. *Atmos. Sci. Lett.*, **114**, 109-114.
Benek, J.A., Steger, J.L., F.C. Dougherty and Burning, P. (1986). AEDC-TR-85-64., 125pp
Kageyama, A. and T. Sato, (2004), *Geochem. Geophys. Geosyst.*, **5**(9), 15
Miles, J.W. (1968), *J. Fluid. Mech.*, **33**(4), 803-814
Huppert, H.E. and J.W. Miles (1969), *J. Fluid Mech.*, **35**(3), 481-496