2018/03/29
CPS/WTK Mini-Workshop on Planetary Atmospheres II

Wind fields in the Martian atmospheric boundary layer obtained by high-resolution large eddy simulations

*Kuriki Murahashi[1],

Kohei Suto[1], Seiya Nishizawa[2], Masaki Ishiwatari[1], Masatsugu Odaka[1], Kensuke Nakajima[3], Shin-ichi Takehiro[4], Ko-ichiro Sugiyama[5], Hirotaka Ogihara[1], Yoshiyuki O. Takahashi[6], Yoshi-Yuki Hayashi[6]

1. Hokkaido Univ., 2. RIKEN/AICS, 3. Kyushu Univ.,
4. Kyoto Univ., 5. National Institute of Tech. Matsue college,
6. Kobe Univ.

CPS, Kobe, Japan

Self introduction

- Doctor course student
  - This presentation shows planning of my doctor thesis
- Sorry for be late, because of business trip to Nayoro observatory

© OpenStreetMap contributers

- Dormitory leader of Keiteki-ryo dormitory (2012 – 2013)

It’s me!

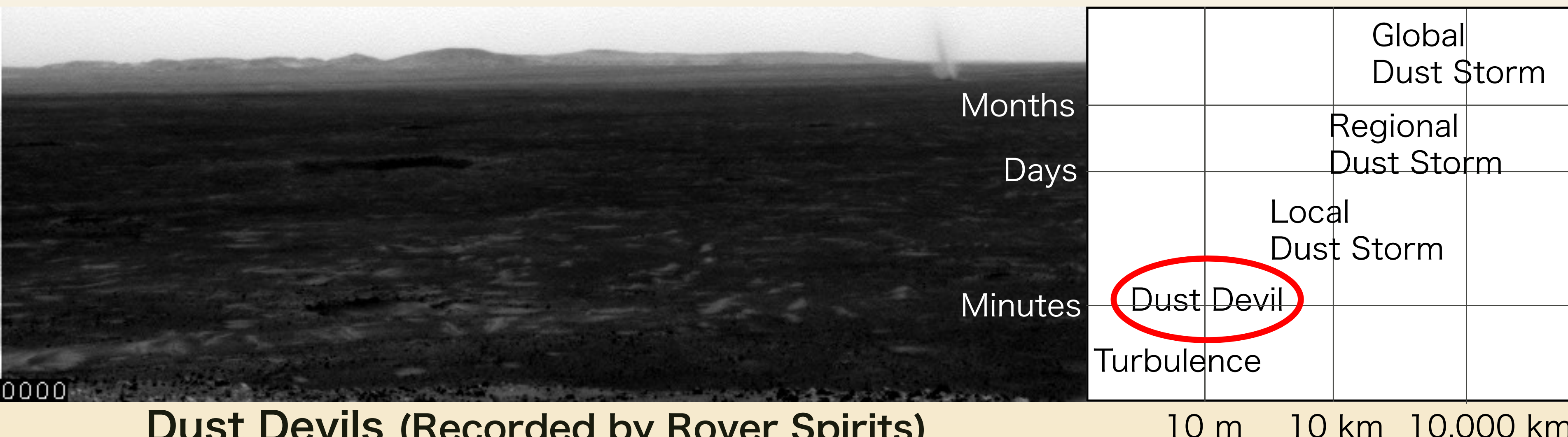
One third of Keiteki-ryo Dormitory residents (2013)

Outline

- Introduction
  - Dust in the Martian atmosphere
  - MGCM calculation including dust processes
  - Problems of dust lifting schemes used in MGCM
  - Purpose of this study
- LES Model / Data
- Results
  - Wind fields of the highest resolution results
  - Surface wind stress of various resolution results
  - Wind structures associated with the strongest wind stress
  - Dust flux distribution
- Summary

Dust in the Martian atmosphere

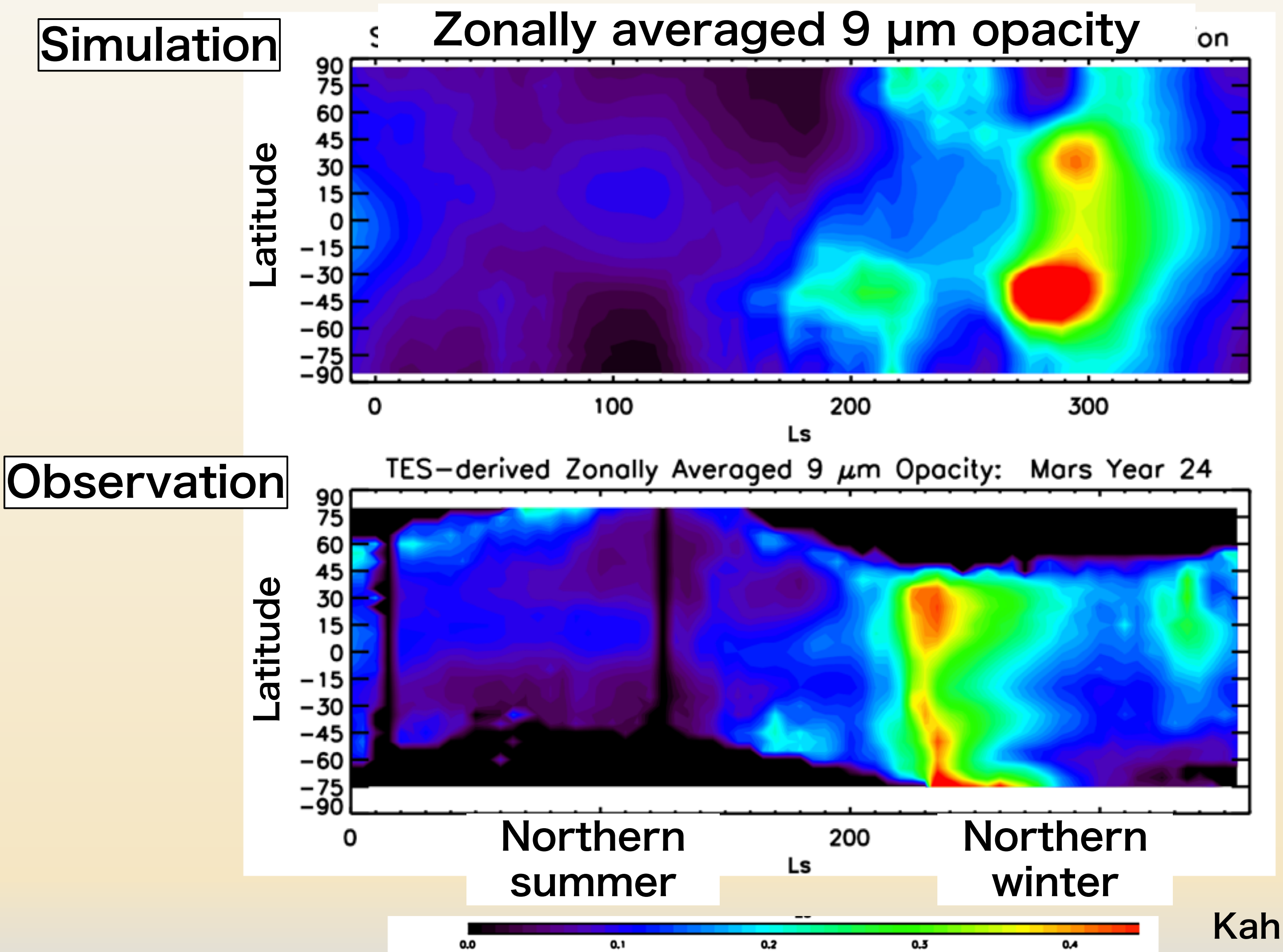
- Dust in the Martian atmosphere greatly influences optical depth and temperature structure. (Smith, 2009, etc.)
- Various space-time scale dust phenomena exist.



Dust Devils (Recorded by Rover Spirits)
http://mars.nasa.gov/mer/gallery/press/spirit/20050819a.html

MGCM calculation including dust processes

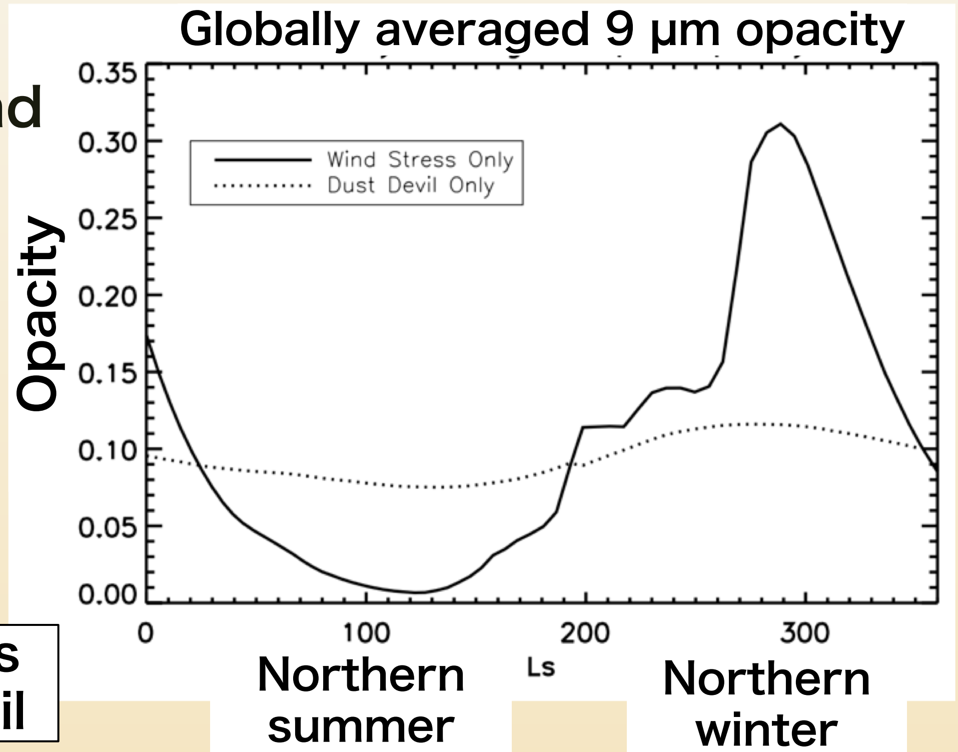
- Kahre et al. (2006) simulates seasonal variability of dust distribution.



Kahre et al. (2006)

Dust lifting schemes used in MGCM

- Kahre et al. (2006) uses 2 types of dust lifting parameterization schemes.
  - Wind stress lifting schemes
    - The seasonal variability of dust amount can be simulated.
  - Dust devil lifting schemes
    - An amount of background dust can be simulated.



Solid line : wind stress
Dotted line : dust devil

Kahre et al. (2006)

Wind stress lifting schemes

- KMH scheme (Kahre et al., 2006)

$$F_W = \alpha_W \times 2.3 \times 10^{-3} \tau^2 \left(\frac{\tau - \tau^*}{\tau^*} \right)$$

F_W : Dust flux [kg/(m² s)]

α_W : Efficiency factor

τ : Surface wind stress [N/m²]

τ^* : Threshold value [N/m²]

Parameters in Kahre et al. (2006)

τ^*	α_W
10×10^{-3}	0.02
22.5×10^{-3}	0.1
35×10^{-3}	0.45

- Based on observational results on the Earth (Sahara desert). (Westphal et al., 1987)
- Adjusting to the Martian conditions. (Kahre et al., 2006)
  - Atmospheric density, gravitational acceleration.

Dust devil lifting schemes

- DDA scheme (Newman et al., 2002)

$$F_D = \alpha_D F_s (1 - b)$$

$$b = \frac{p_s^{\chi+1} - p_{con}^{\chi+1}}{(p_s - p_{con})(\chi + 1) p_s^{\chi}}$$

$$\chi \equiv \frac{R}{c_p}$$

F_D : Dust flux [kg/(m² s)]

F_s : Sensible heat flux [W/m²]

α_D : Efficiency factor [kg/J]

p_s : Surface Pressure [Pa]

p_{con} : Pressure at the top of PBL [Pa]

R : Specific gas constant

c_p : Specific heat capacity

- Based on the thermodynamics of dust devils as a heat engine.
  (Rennò et al., 1998)
- Thermal efficiency is used for expressing dust flux.
  - With the higher sensible heat flux, kinetic energy of convection becomes larger.
  - With the higher PBL altitude, the conversion rate of kinetic energy from sensible heat flux becomes larger.
  - Therefore the amount of dust flux increases.

Problems of parameterization

- Adjusting parameters are necessary in order to simulate observational results.
  - Wind stress threshold value should be decreased compared to experimental value. (Greeley and Iversen, 1985)
- Schemes have been developed without considering details of wind structures.
- Wind stress schemes are suspected to include effects of dust devil schemes.

Purpose of this study

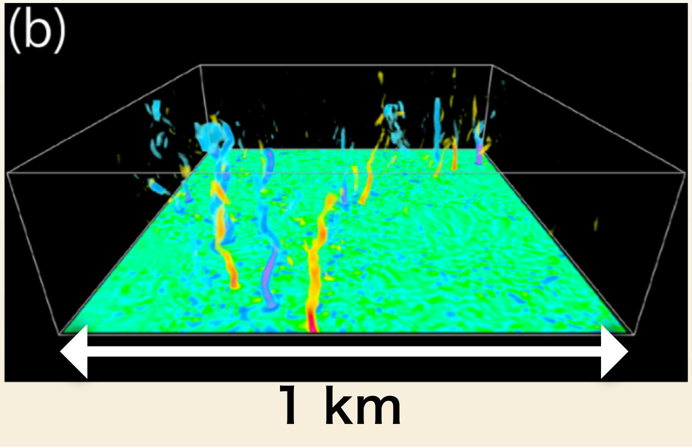
- Our purpose is to reconsider the schemes with examining relationship between wind microstructures such as dust devils and large scale convective structures.
  - What are characteristics of the wind field?
  - How much is the strength of the wind stress?

- In this study, we examine LES with several km domain.
  - Our results can be applied to MGCM.
  - The most high-resolution MGCM can resolved up to several km. (~ 11 km; Takahashi et al., 2011)

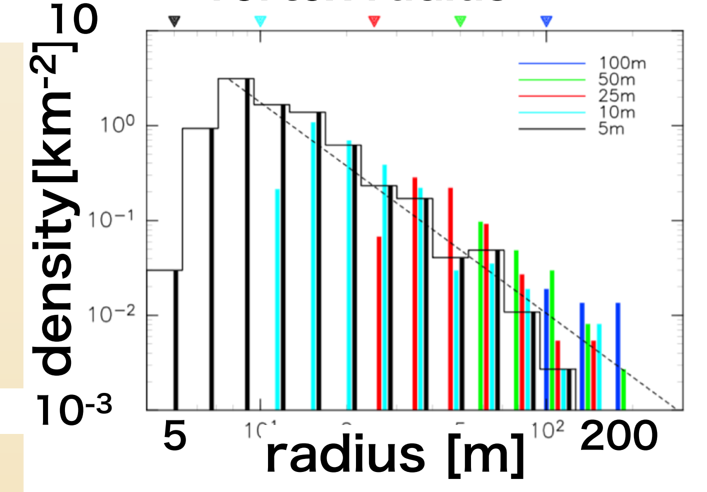
The highest resolution LES for the Mars

- Nishizawa et al. (2016)
  - Domain :
    Horizontal 19.2 km, Vertical 21 km
  - Horizontally periodic boundary conditions.
  - Resolution 5, 10, 25, 50, 100 m
    - About 4.8 x 10^{10} grid points in 5 m resolution.
      (1 time snapshot has 1.2 TB !)
- Statistics on vortices are investigated.
  - e.g. vortex radius distribution of 62.5 m height at LT = 14:30

Vorticity distribution



Frequency distribution of vortex radius



Nishizawa et al. (2016)

Model

- SCALE-LES (Nishizawa et al., 2015; Sato et al., 2015)
  - https://scale.aics.riken.jp/index.html
  - 3D fully compressible non-hydrostatic equations model.
  - Developed by RIKEN/AICS.
- Turbulence process
  - Smagorinsky-type eddy viscosity model (Brown et al., 1994; Scotti et al., 1993).
- Surface model
  - Louis-type bulk method (Louis 1979, Uno et al., 1995).

Settings

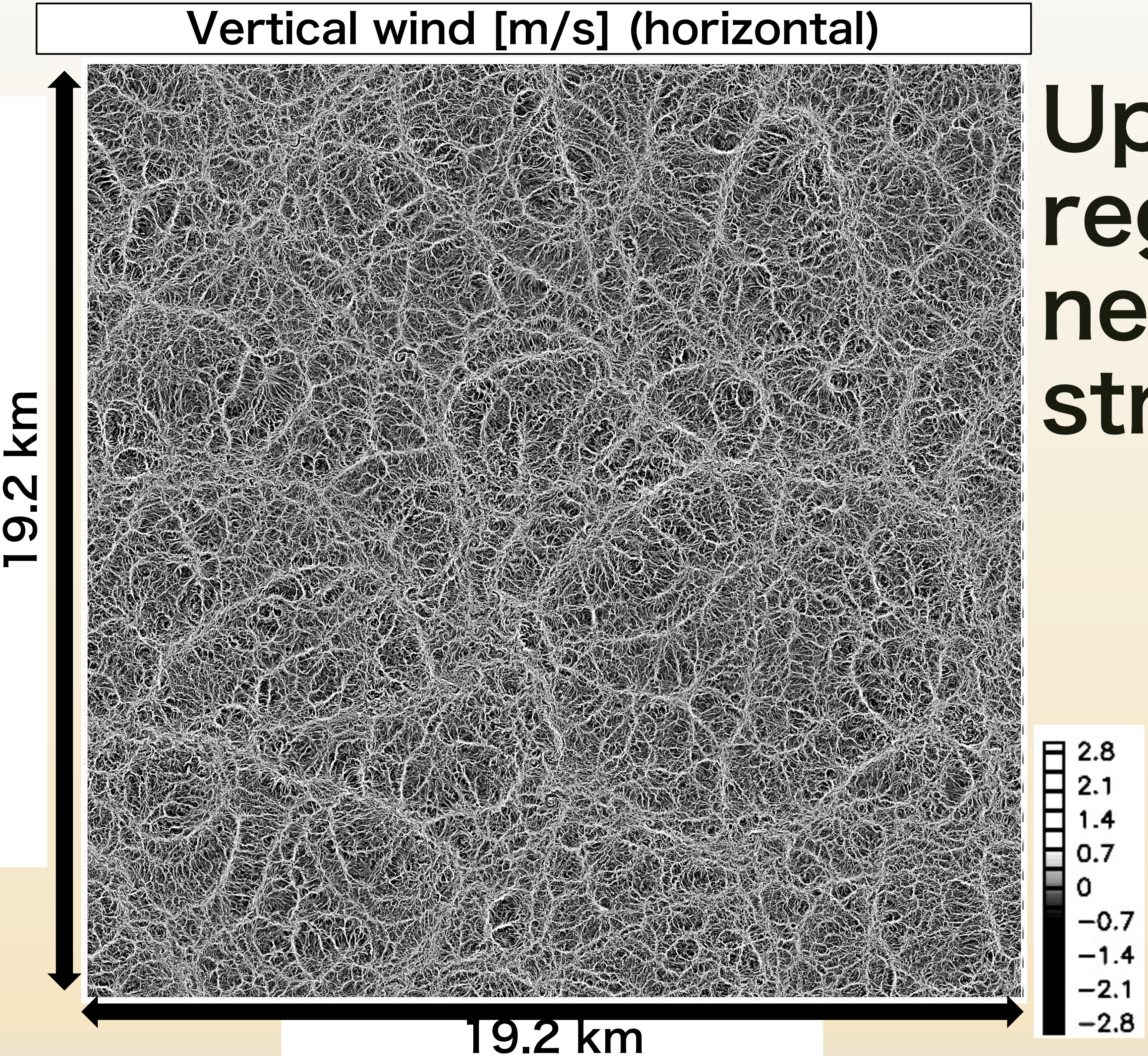
- Thermal forcing
  - The heating rate and surface temperature are given by one-dimensional simulation by Odaka et al. (2001)
- Initial State
  - 10 - 100 m resolution :
    Stable stratified stationary atmosphere
    with tiny random temperature perturbations.
  - 5 m resolution :
    interpolated 10 m result on LT = 14:00
- Integration period
  - 10 – 100 m resolution : from LT = 0:00 - 24:00
    (LT : Local Time)
  - 5 m resolution : from LT = 14:00 - 15:00

Analysis in this study

- In this analysis, using LT = 14 : 30 data.
  - The same as Nishizawa et al. (2016) analysis.

- Analysis procedure
  - Merging original data sets.
    - 5 m resolution original data files consist 7,200 files.
    - It takes a few hour.
    - Each data are about 240 MB.
    - Script language Ruby is used.
  - Making
    - Horizontal distribution
    - Vertical distribution
    - Histogram ...etc.

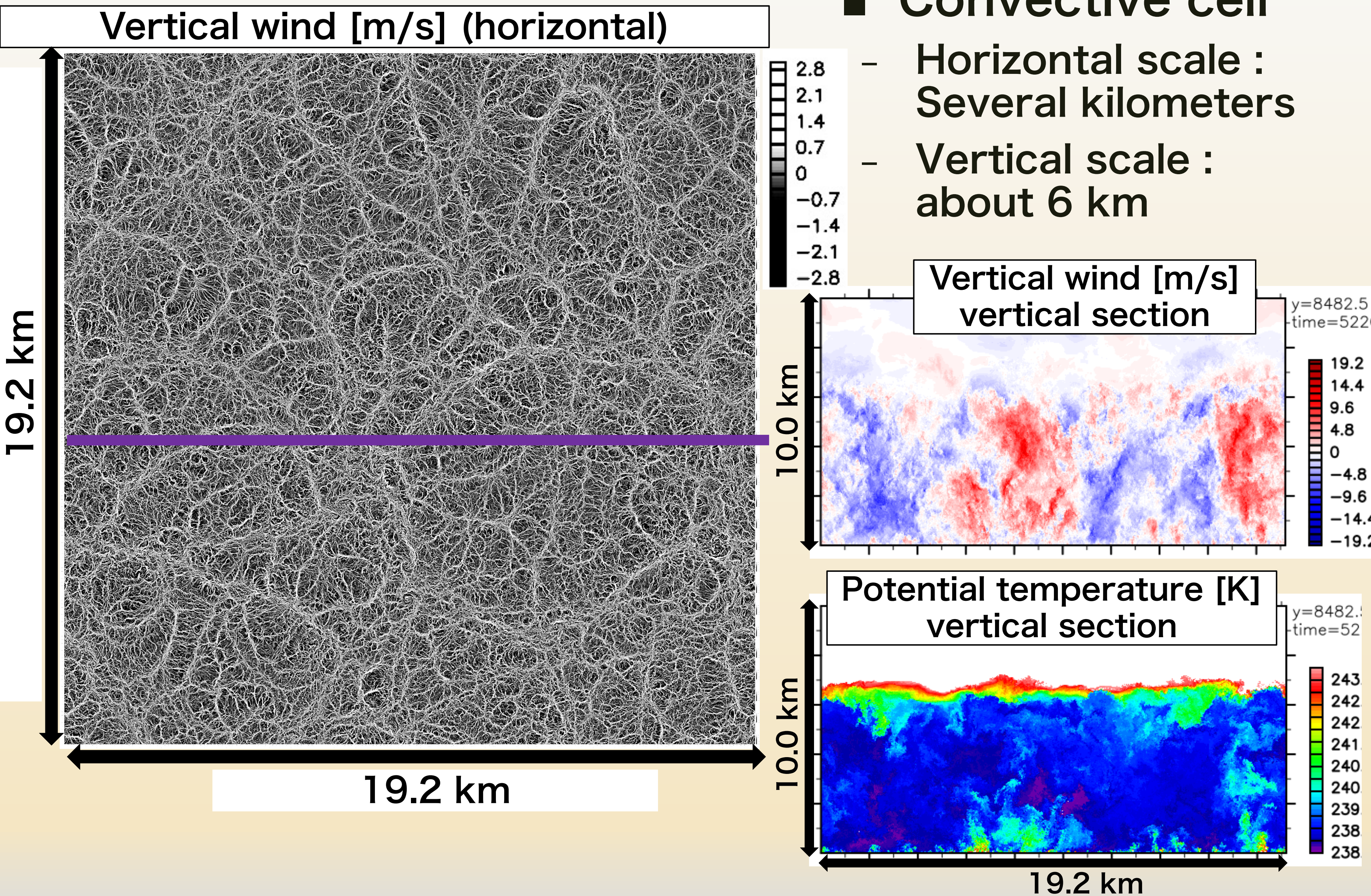
Vertical wind (bottom level z = 2.5 m)



Upward wind region forms network-like structures.

Convective cellular structures

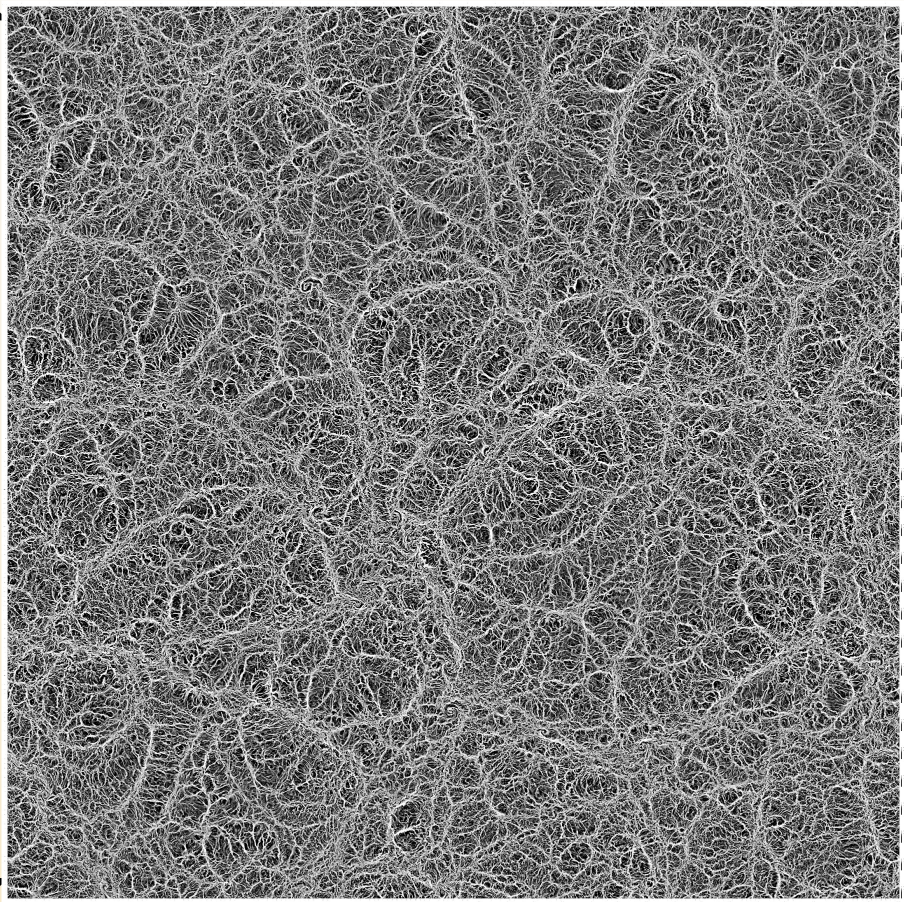
- Convective cell
  - Horizontal scale : Several kilometers
  - Vertical scale : about 6 km

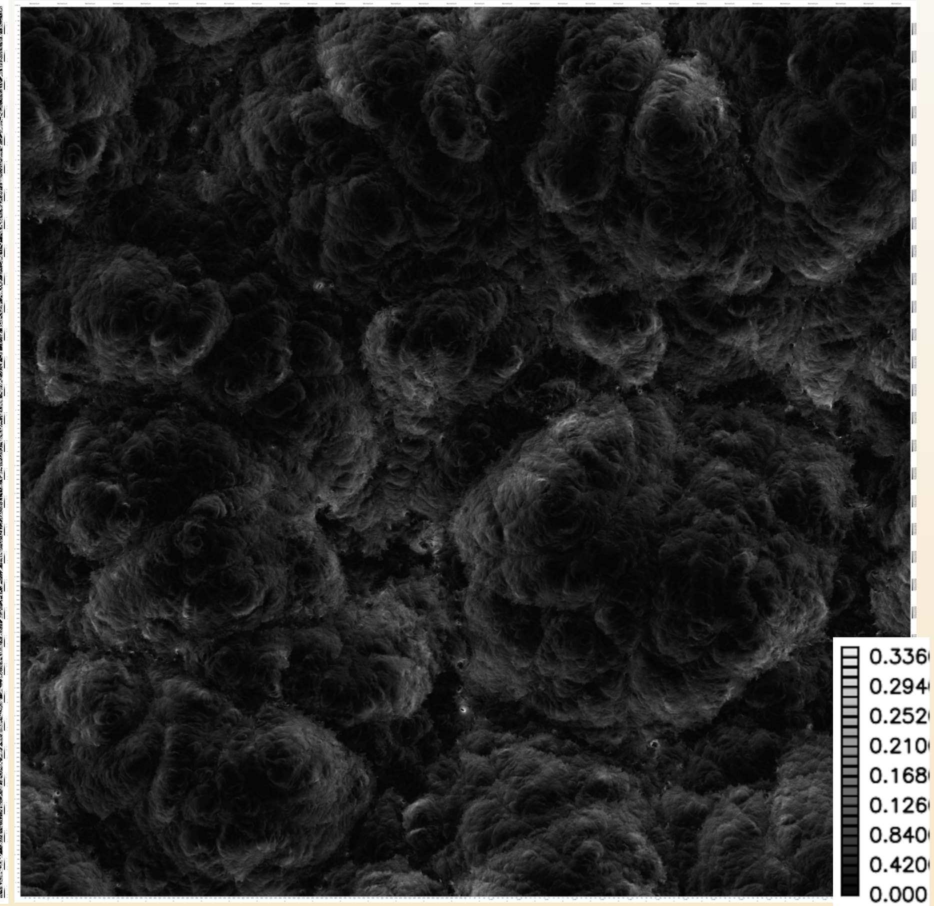


Surface wind stress

Vertical wind [m/s] (horizontal) | Surface wind stress [Pa] (horizontal)

19.2 km

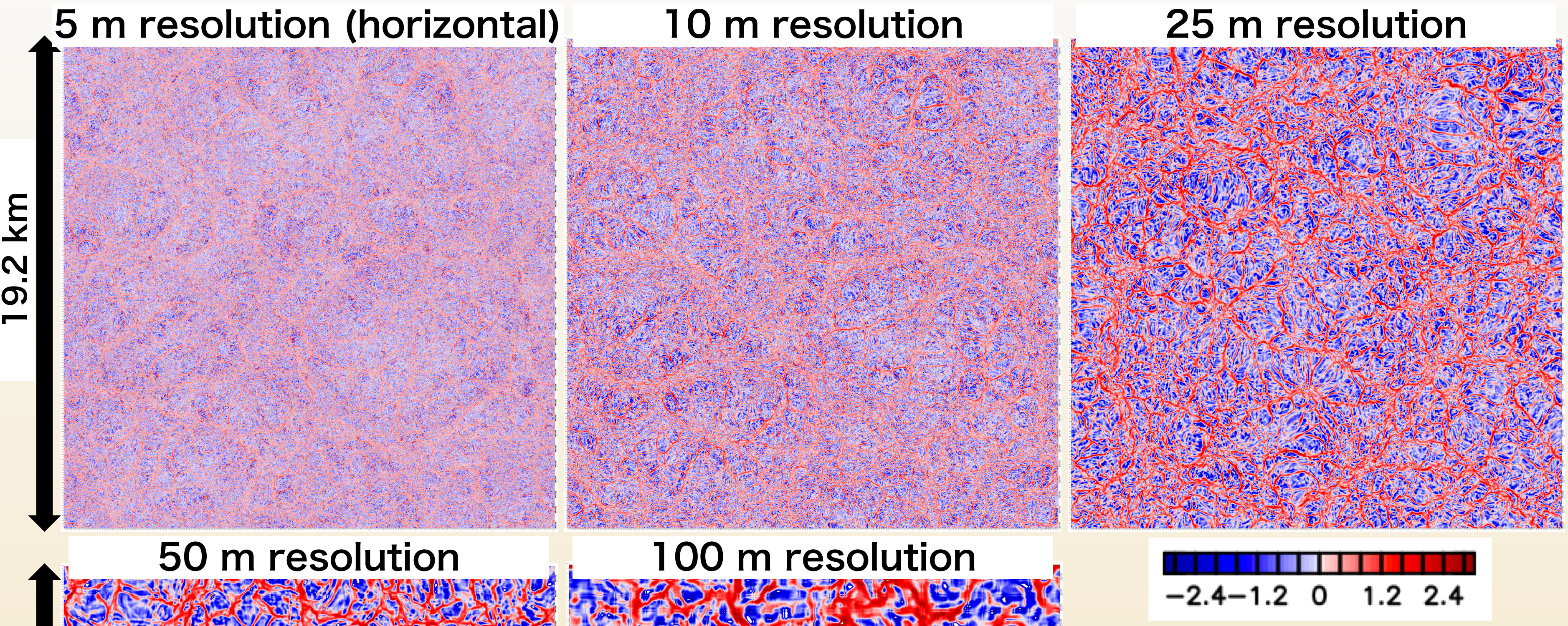


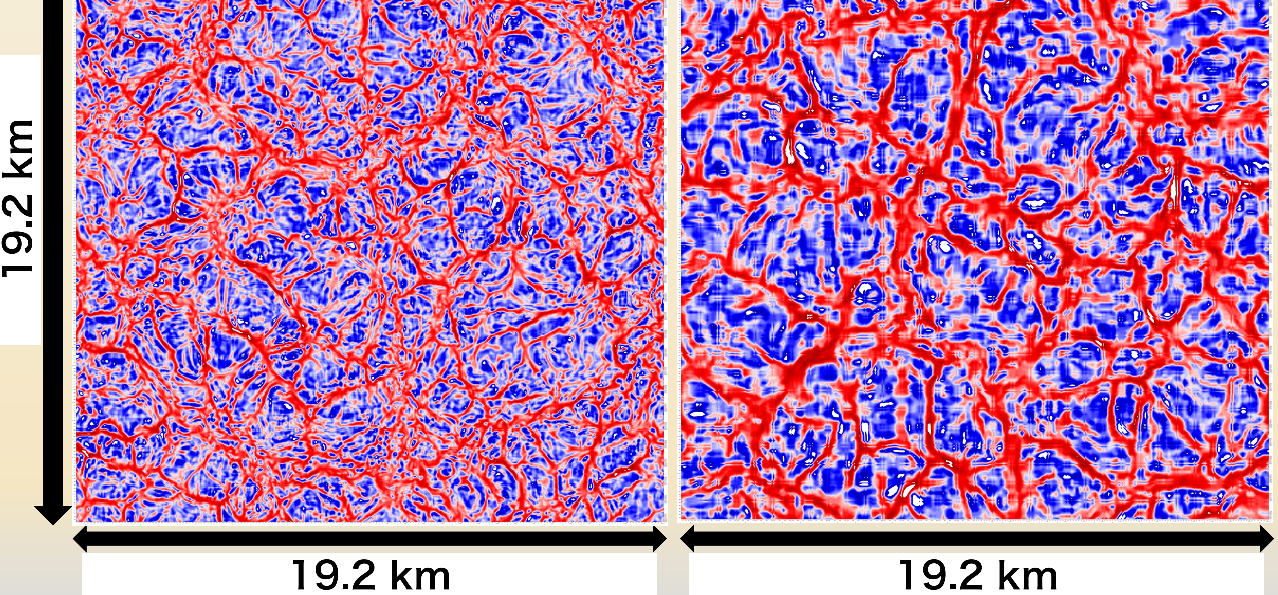


19.2 km | 19.2 km

Wind stress tends to be strong near the convective cell boundary

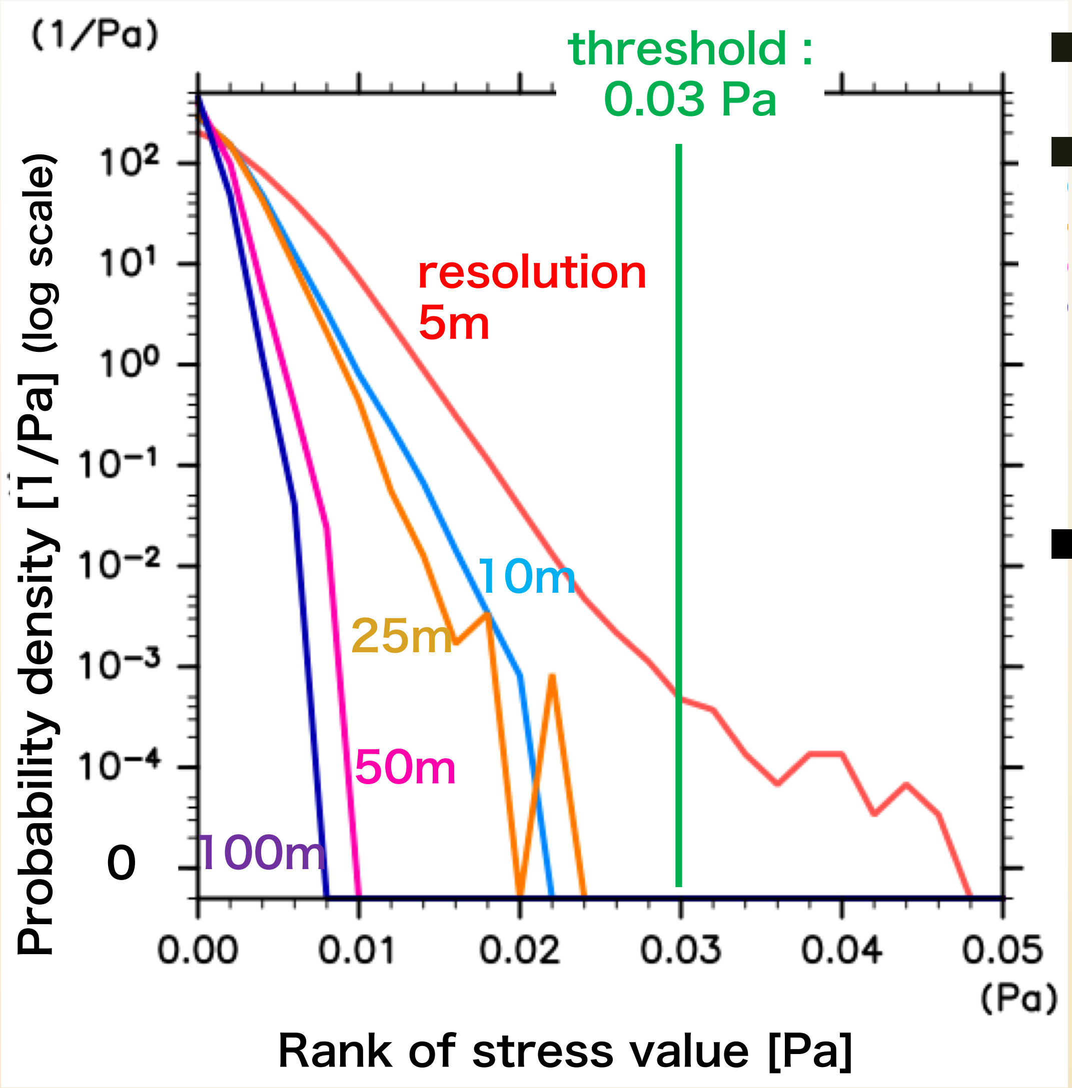
Vertical wind fields of each simulation





- Bottom level
- Network-like structures are similarly seen.

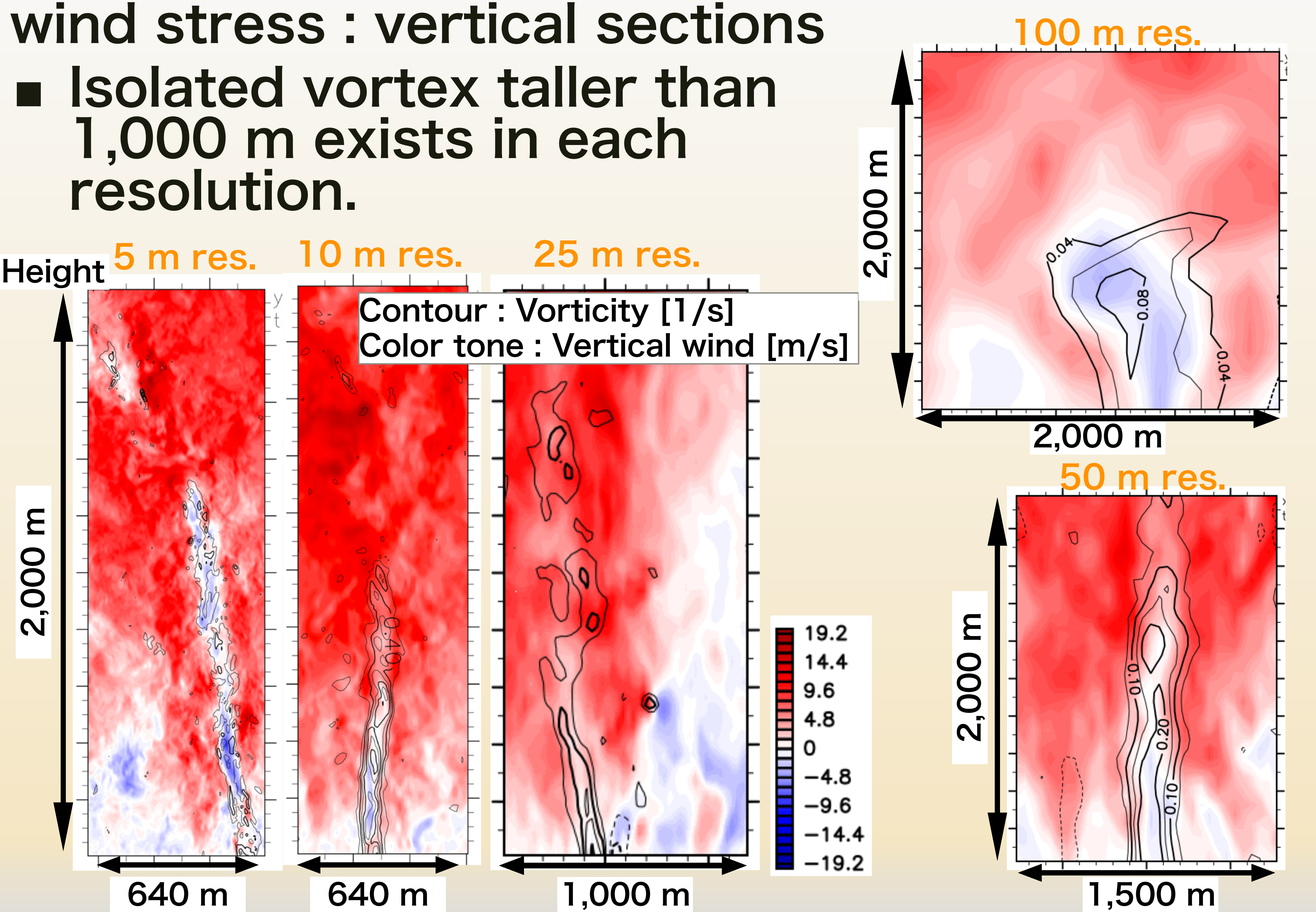
Surface stress probability density distribution



- Bin width : 0.002 Pa
- Result of 5 m resolution is greatly differs from those of more than 10 m resolution results.
- Only 5 m resolution result has the points exceeding threshold value.
  - Threshold value 0.03 Pa obtained by experimental results.
    (Greeley and Iversen, 1985)

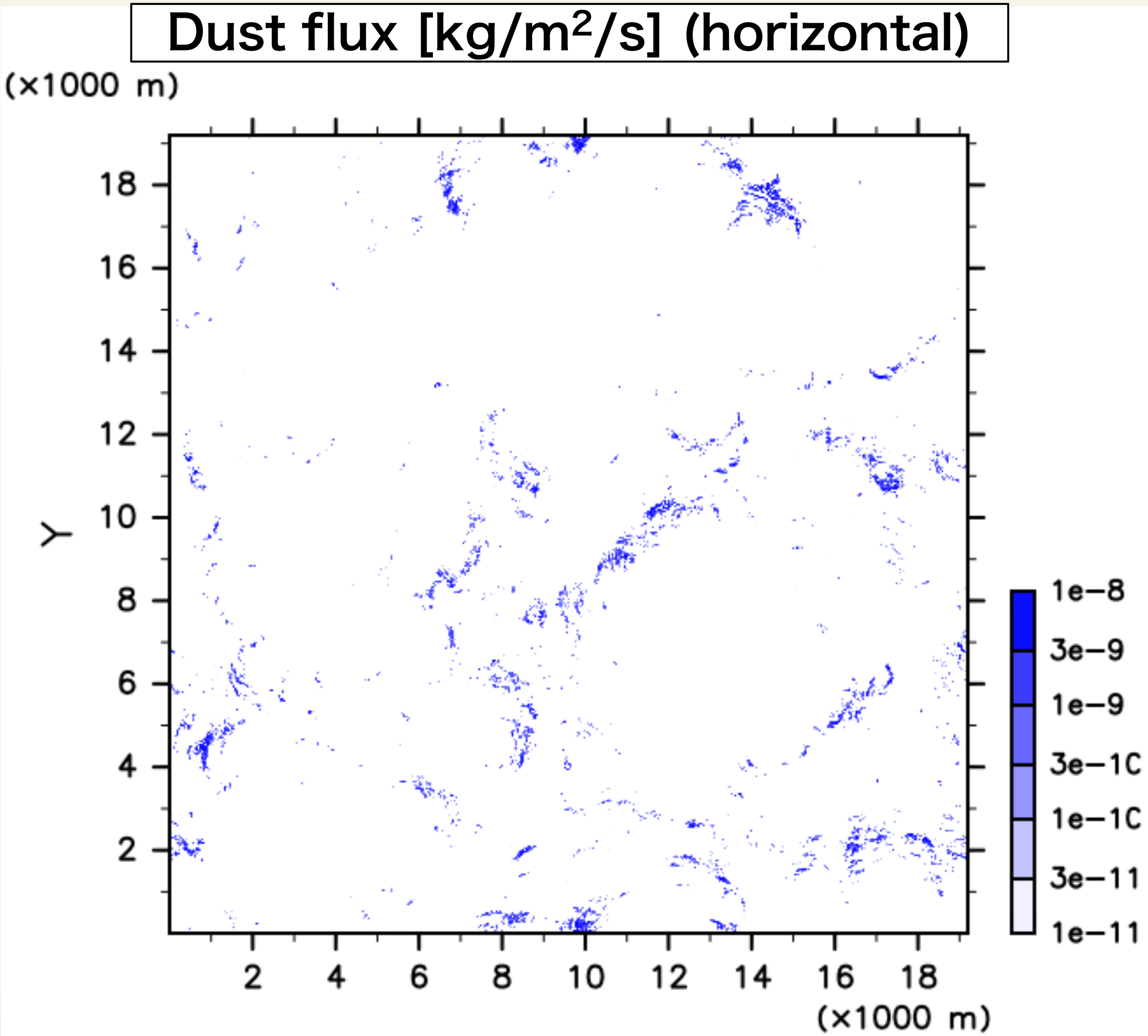
Wind structure associated with the strongest wind stress : vertical sections

- Isolated vortex taller than 1,000 m exists in each resolution.



Horizontal distribution of dust flux

- Dust flux is calculated using wind stress scheme (KMH scheme) of Kahre et al. (2006)



Horizontal averaged dust flux [10^{-13} kg/(m^2 s)]

Resolution	5 m	10 m	25 m
Dust flux	391	2.89	3.64

- Adopted parameters

τ^* : 0.001 Pa

α_W : 0.02

- 5 m result has extraordinaly large dust flux

Summary

- Dust lifting parameterization schemes in MGCM have problems.
  - Schemes have been developed without considering details of wind structures.

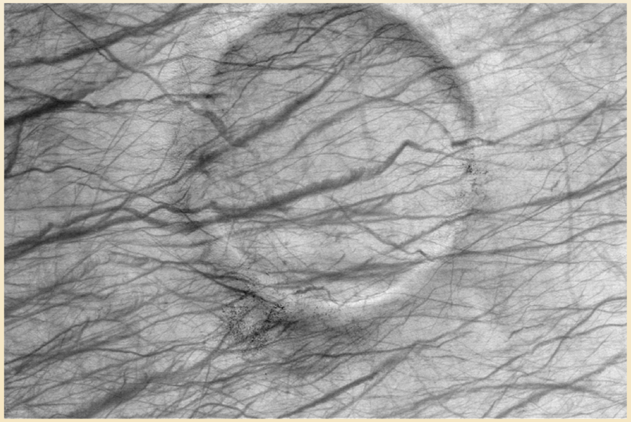
- Our purpose is to reconsider schemes with examining wind structures.
- We are investigating high-resolution LES for considering validity of parameterization.
  - An isolated vortex taller than 1,000 m exists at the point with the strongest wind stress in each resolution result.
  - Only 5 m resolution result has the points exceeding threshold value of surface wind stress.

References

- Greeley, R., and J. D. Iversen, 1985: Wind as a Geological Process on Earth, Mars, Venus, and Titan., Cambridge Univ. Press., 333 pp
- Kahre, M. K., et al., 2006: Modeling the Martian dust cycle and surface dustreservoirs with the NASA Ames general circulationmodel, J.G.R, 111, 25
- Louis, J.-F., 1979: A parametric model of vertical eddy fluxes in the atmosphere, Boundary Layer Meteorol., 17, 187–202.
- Mulholland, D. P., et al., 2013: Simulating the interannual variability of major dust storms on Marsusing variable lifting thresholds, Icarus, 223, 344-358
- Nishizawa, S., et al., 2016: Martian dust devil statistics from high-resolution large-eddy simulations, Geophys. Res. Lett., 43, 4180–4188
- Odaka M., 2001: A numerical simulation of Martian atmospheric convection with a two-dimensional anelastic model: A case of dust-free Mars, Geophys. Res. Lett., 28, 895-898
- Rennò, N. O., et al., 1998: A simple thermodynamical theory for dust devils, A.M.S., 55, 3244-3252
- Smith, M. D., 2009: THEMIS observations of Mars aerosol optical depth from 2002–2008, Icarus, 202, 444-452
- Westphal, D. L., et al., 1987: A two-dimensional numerical investigation of the dynamics and microphysics of saharan dust storms, J.G.R., 92, 3027-3049
- Wilson, R. J., and Hamilton, K., 1996: Comprehensive model simulation of thermal tides in the Martian atmosphere, J.A.S, 53, 9, 1290-1326

火星大気大循環モデル (MGCM) におけるダスト

- かつてはダスト分布を固定して火星の大気循環が調べられてきた (Wilson and Hamilton, 1996)
  - ダストストームが発生するのに十分な風速が得られなかった
  - MGCM の中でダストストームを起こすには, 小スケール (<~ 100 km) な風の揺らぎが重要であることを示唆
  - 細かい風の流れを考慮する何らかの仕組みが必要
- 領域モデルによる対流計算によって, 小スケールの流れを考慮すれば十分な風速が得られることがわかった (Odaka, 2001)
- Mars Global Surveyor によって数多くのダストデビルが見つかる (2000 年以降)
  - GCM で表現できない小さな風のゆらぎをもたらす現象としてダストデビルが注目されはじめた

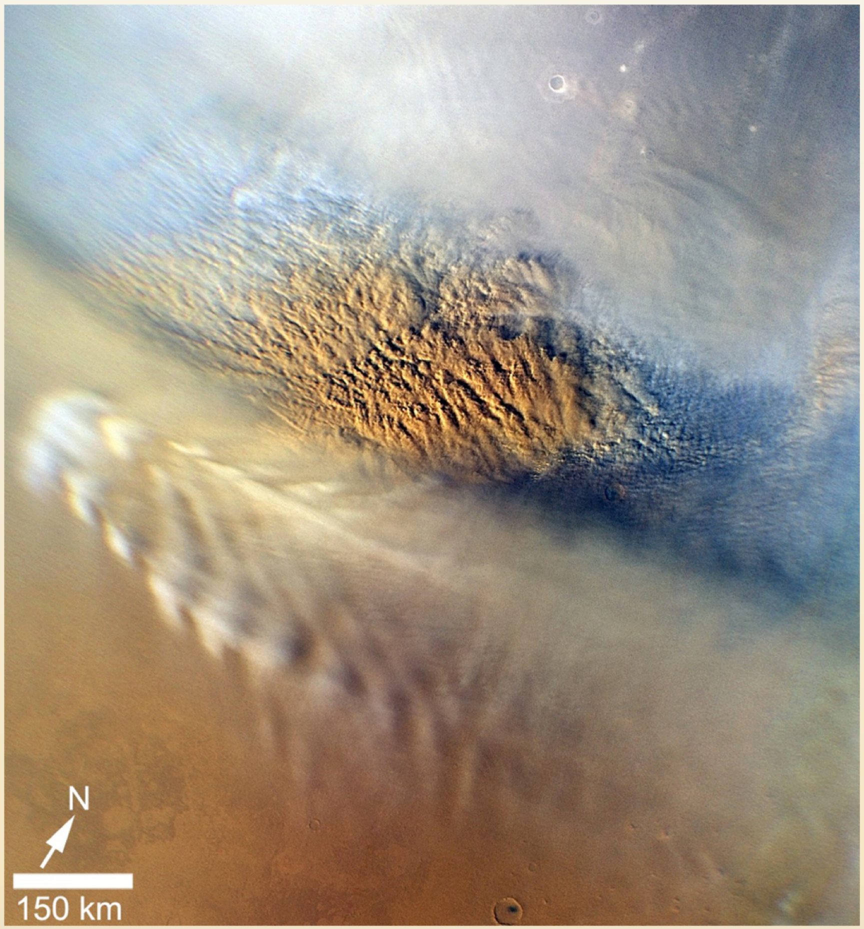


ダストデビルの通った跡

https://apod.nasa.gov/apod/ap031230.html

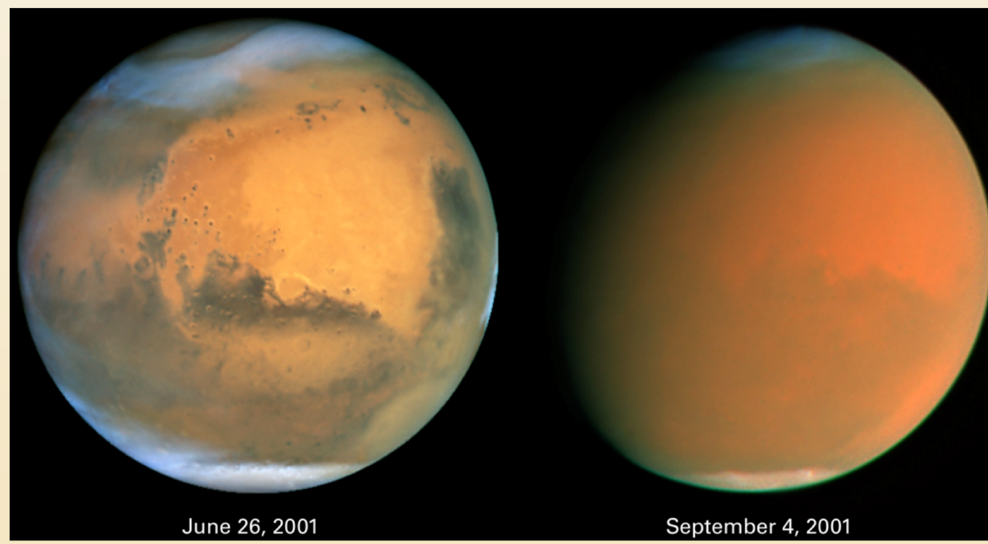
はじめに

ローカルダストストーム



https://www.jpl.nasa.gov/spaceimages/images/largesize/PIA15959_hires.jpg

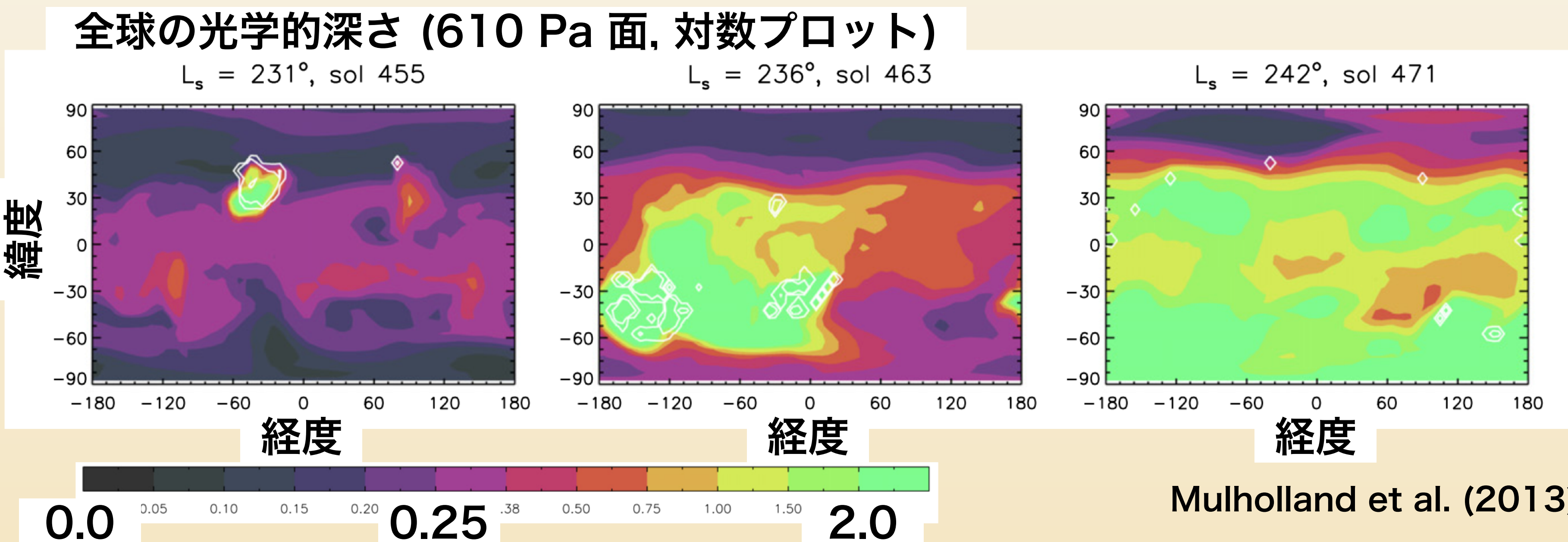
グローバルダストストーム



https://www.jpl.nasa.gov/

ダスト巻き上げを考慮した MGCM 計算

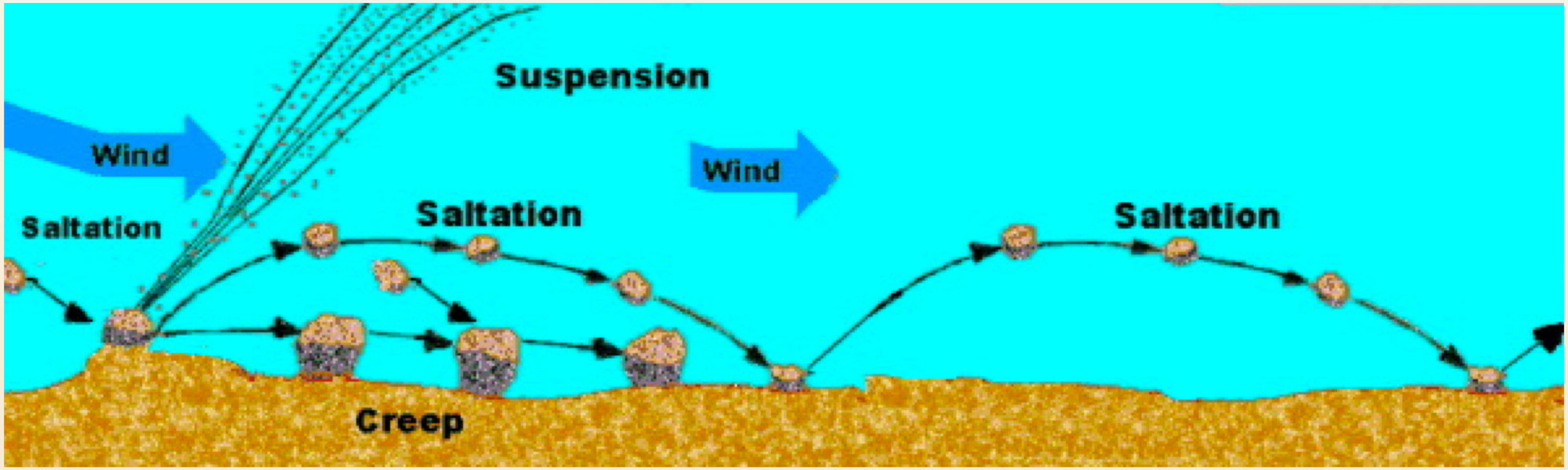
- Mulholland et al. (2013) : ダストストームにおける
  ダスト量の年々変動が再現できたと主張
  - グローバルダストストームの隔年変動を大雑把に再現 (4 ~ 7 年周期)
  - 平均風応力閾値をダスト量に合わせて変化することを仮定
  - 南半球から北半球へのダスト輸送を仮定



Mulholland et al. (2013)

Mulholland et al. (2013) における仮定

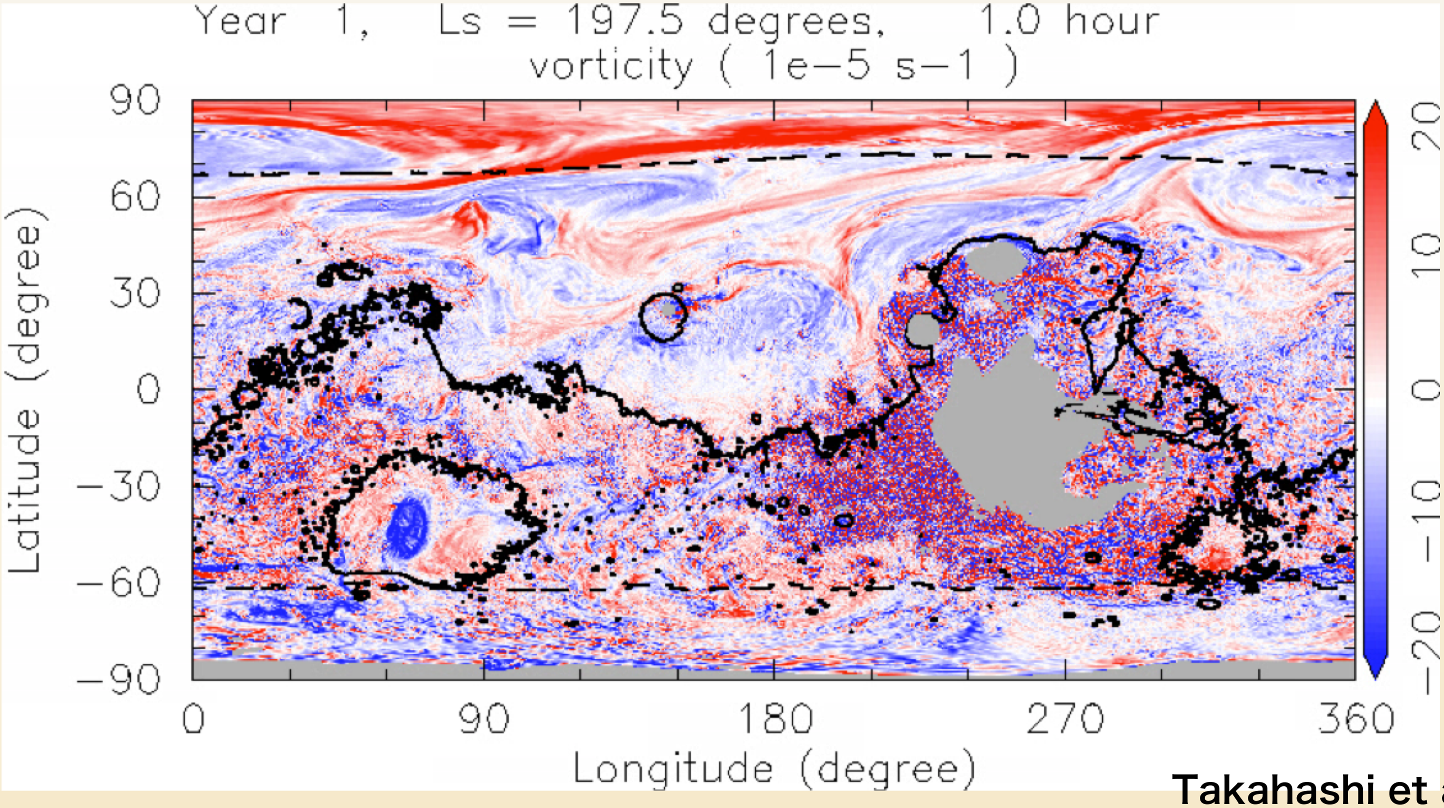
- 平均風応力閾値をダスト量に合わせて変化することを仮定
  - ダストが多く溜まると saltation が生じにくくなり, 巻き上げの風応力閾値を下げられると仮定



- 北半球から南半球へのダスト輸送を仮定
  - MGCM の計算では北半球へのダストの偏在化が進むので, ダストデビルなど何らかの小スケール現象によって南半球へダストの輸送が生じていることを仮定

To improve parameterization

- Most high-resolution MGCM can resolved up to several km. (~ 11 km; Takahashi et al., 2011)



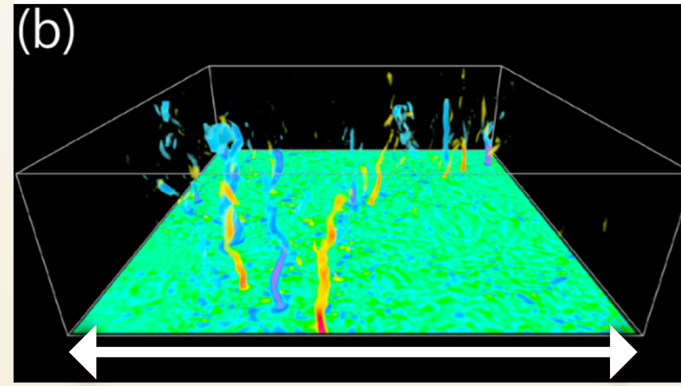
Takahashi et al. (2011)

- Most high-resolution LES can resolved isotropic 5 m, (Nishizawa et al., 2016)

Nishizawa et al でいったこと

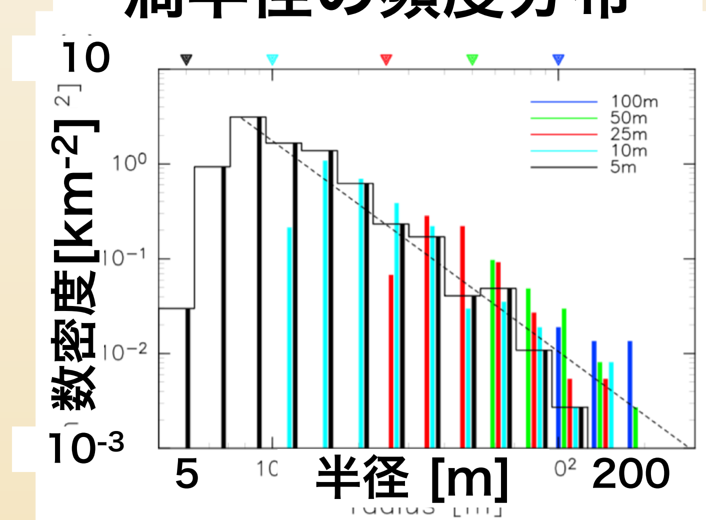
- Nishizawa et al. (2016)
  - 計算領域 水平 19.2 km, 鉛直 21 km
  - 空間解像度 5, 10, 25, 50, 100 m
  - 日変化する熱強制を外部から与える
  - LT = 0:00 から計算開始 (LT : 現地時刻)
- 渦に関する統計量を調べた
  - LT = 14:30 の高度 62.5 m 付近における渦のサイズ分布など
- しかし, 地表付近における速度場や応力場については未調査
  - ダストの巻き上げを考える上では地表付近を観察する必要がある

渦度空間分布



1 km

渦半径の頻度分布



Nishizawa et al. (2016)

地表面応力が強い場所の流れ場 (須藤, 2018)

- 応力が強い場所上位 10 箇所について, 孤立渦の有無を比較
  - dx = 5 m　: 5/10
  - dx = 10 m : 5/10
  - dx = 25 m : 6/10
  - dx = 50 m : 6/10
  - dx = 100 m : 5/10
- 渦を伴っているかどうかは
  およそ半々
  - 一番強い場所には渦が伴っている
- 応力が強い場所はダストデビル (渦) だけではない