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Analyses on dust lifting processes simulated by a high-resolution LES for the Martian atmospheric boundary layer

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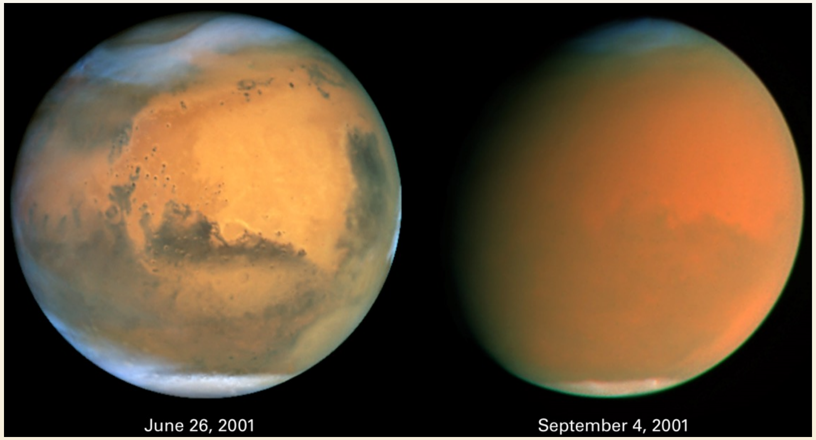
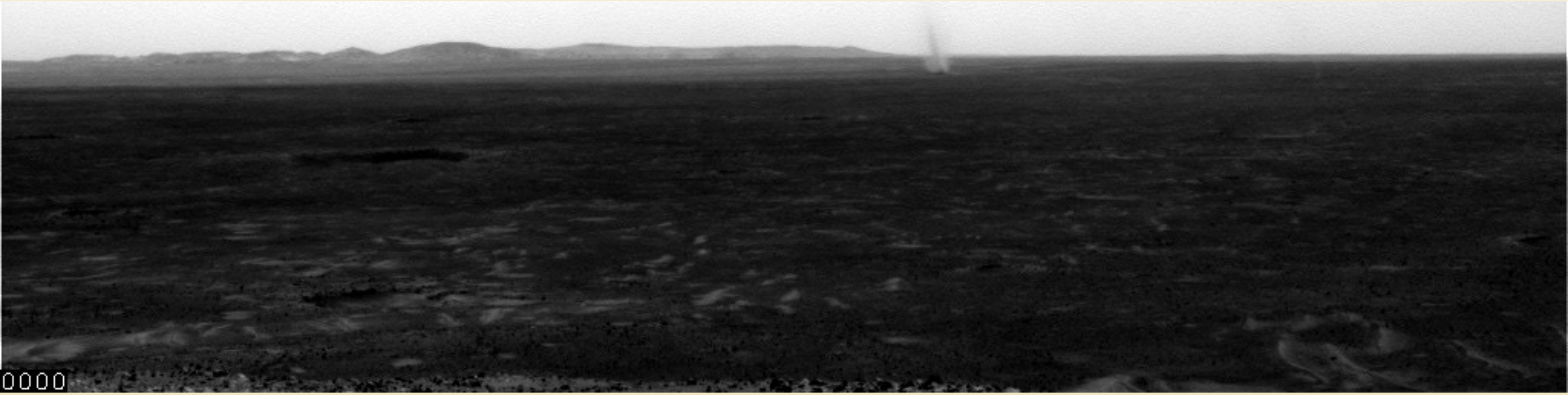
Dust in the Martian atmosphere

- Dust in the Martian atmosphere greatly influences optical depth and temperature structure. (Smith, 2009, etc.)



Global Dust Storm
https://www.jpl.nasa.gov/

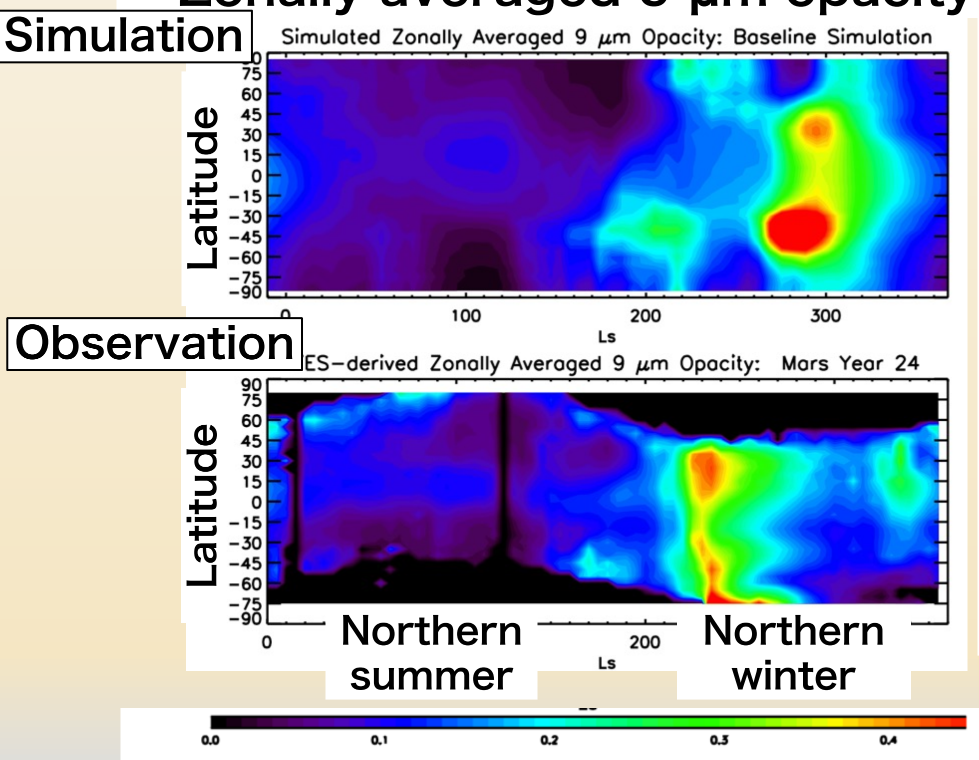


Dust Devils (Recorded by Rover Spirits)
http://mars.nasa.gov/mer/gallery/press/spirit/20050819a.html

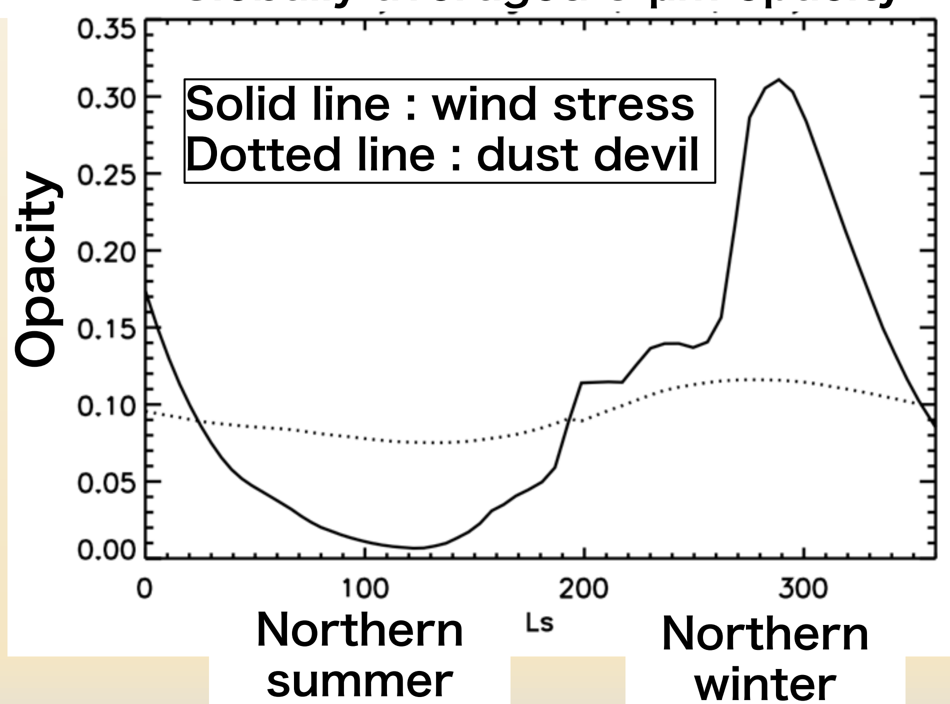
Dust in the Martian atmosphere

- Dust in the Martian atmosphere greatly influences optical depth and temperature structure. (Smith, 2009, etc.)
- Kahre et al. (2006) simulates seasonal variability of dust distribution on Mars General Circulation Model (MGCM).

Zonally averaged 9 μm opacity



Globally averaged 9 μm opacity



Kahre et al. (2006)

Dust lifting schemes

- Wind Stress (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]

- Based on observational results on the Earth (Sahara desert). (Westphal et al., 1987)

- Dust Devil (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]

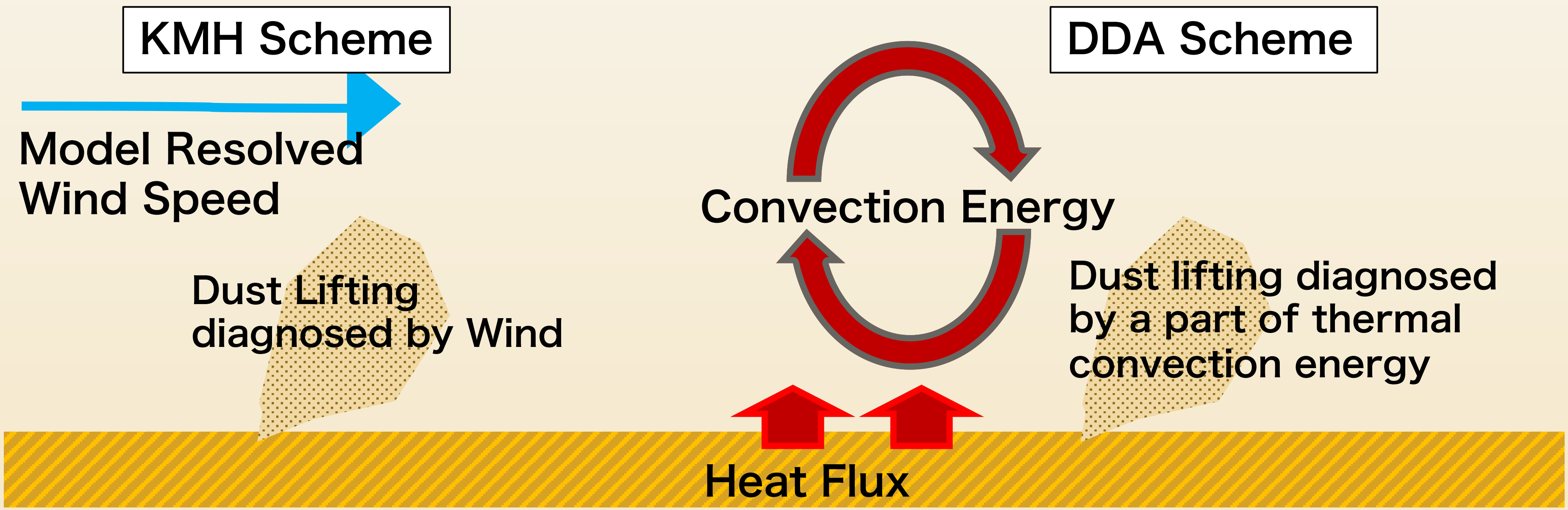
R : Specific gas constant

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.

Problems of parameterization

- Schemes have been developed without considering details of wind structures.
  - Wind stress schemes are suspected to include effects of dust devil schemes.

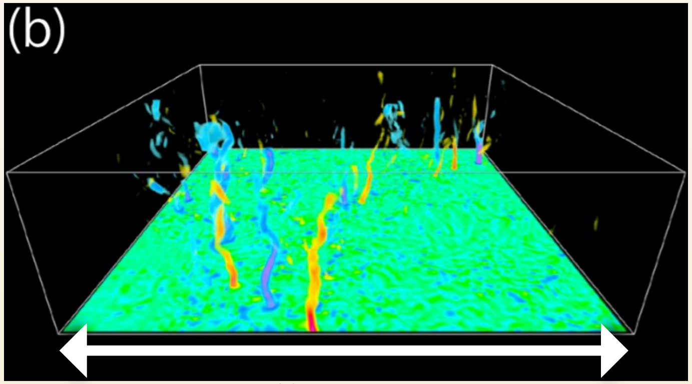


- Adjusting parameters are necessary in order to simulate observational results.
  - Wind stress threshold value should be decreased compared to experimental value. (Greeley and Iversen, 1985)

The highest resolution LES for the Mars

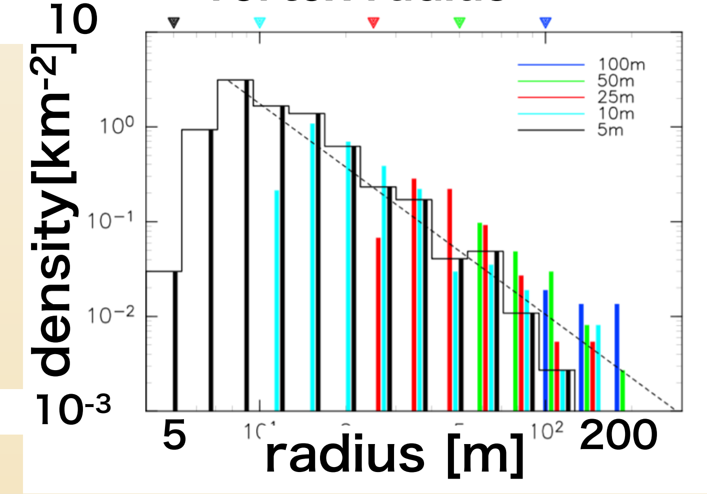
- Nishizawa et al. (2016)
  - Domain :
    Horizontal 19.2 km, Vertical 21 km
  - Horizontally periodic boundary conditions.
  - Resolution 5, 10, 25, 50, 100 m
    - About 4.8 x 10^{10} grid points in 5 m resolution.
      (1 time snapshot has 1.2 TB !)
- Statistics on vortices are investigated.
  -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

Vorticity distribution



1 km

Frequency distribution of vortex radius



Nishizawa et al. (2016)

Purpose of this study

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

- We make hypothesis that dust devils are very important phenomena to consider dust lifting.
  - In observational results, there are many dust devils on the Mars.
- In this study, we examine LES with several km domain.

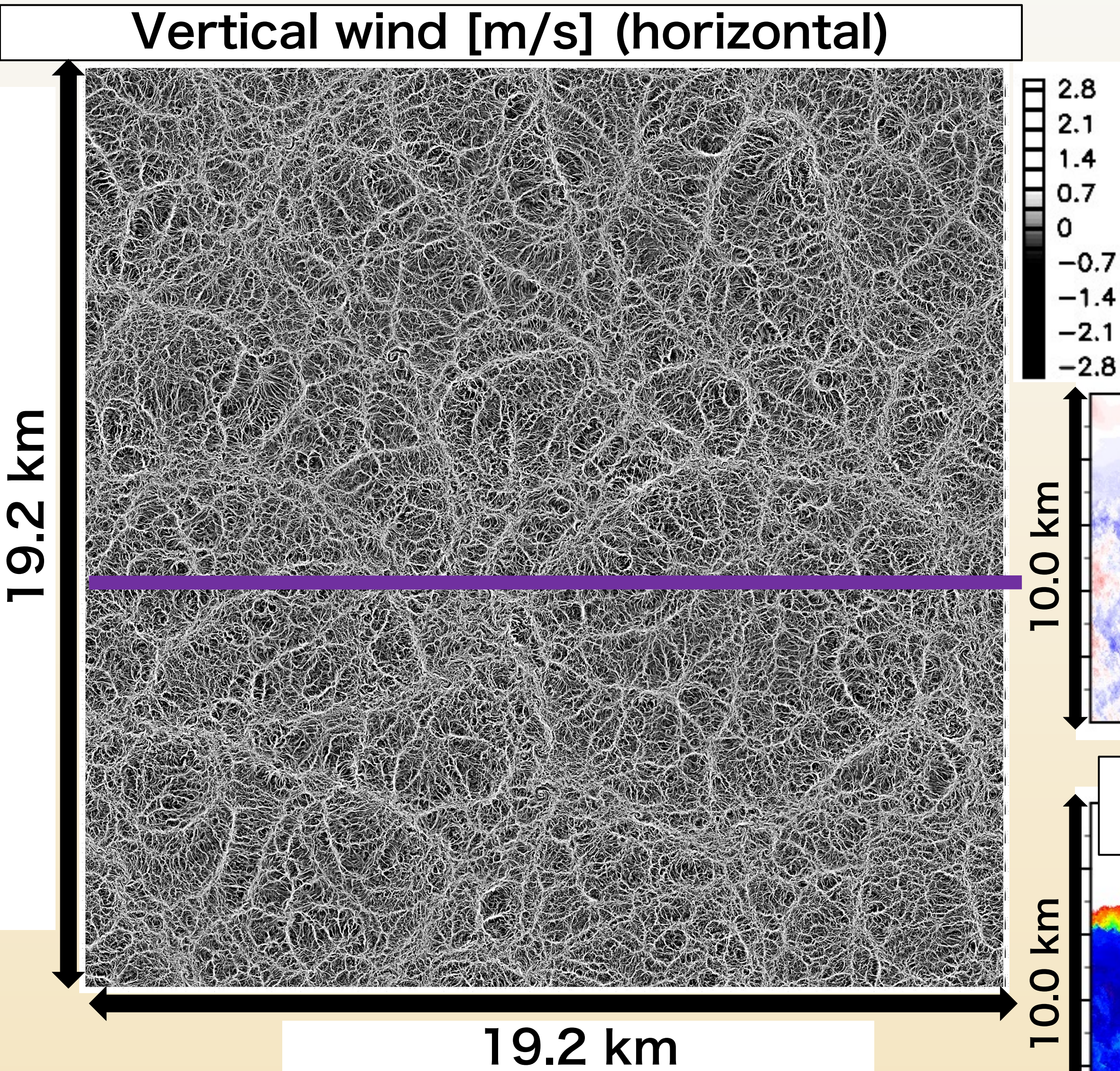
Model / Settings

- SCALE-LES ver.3 (Nishizawa et al., 2015; Sato et al., 2015)
  - http://r-ccs-climate.riken.jp/scale/
  - 3D fully compressible non-hydrostatic equations model.
  - Developed by RIKEN/R-CCS.
- Surface model
  - Louis-type bulk method (Louis 1979, Uno et al., 1995).
- 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 at LT = 0:00
  - 5 m resolution : interpolated 10 m result at LT = 14:00.

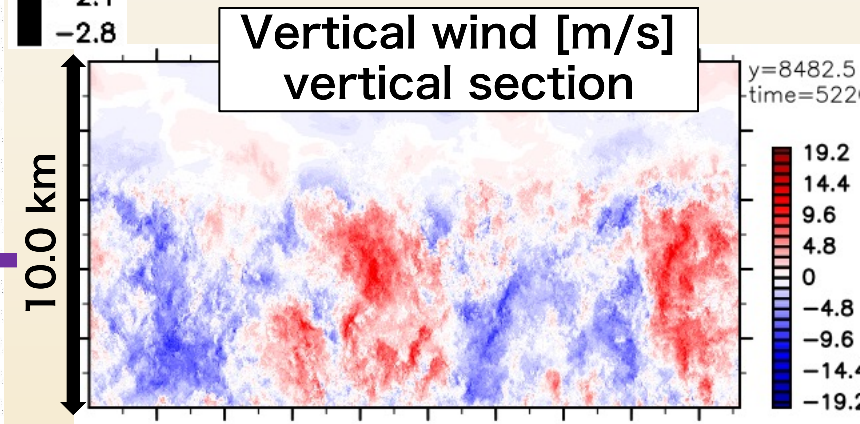
(LT = Local Time)

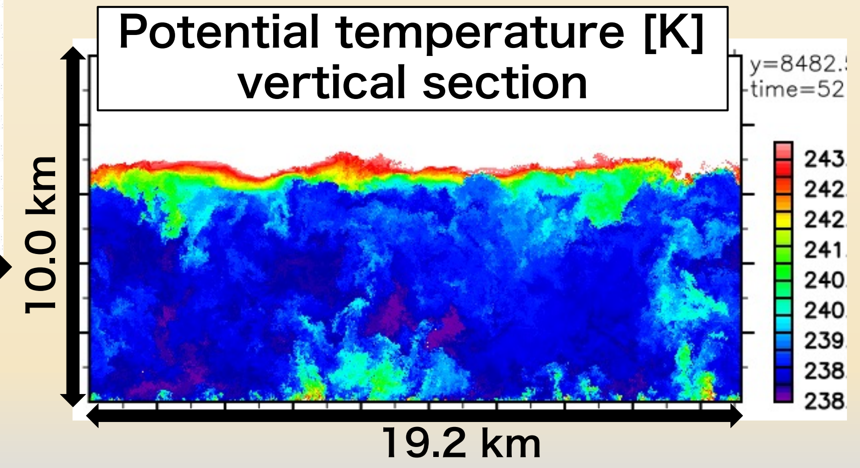
- Integration period
  - 5 m resolution : from LT = 14:00 - 15:00
    - The dataset is every 5 minutes.

Convective cellular structures (14:30)

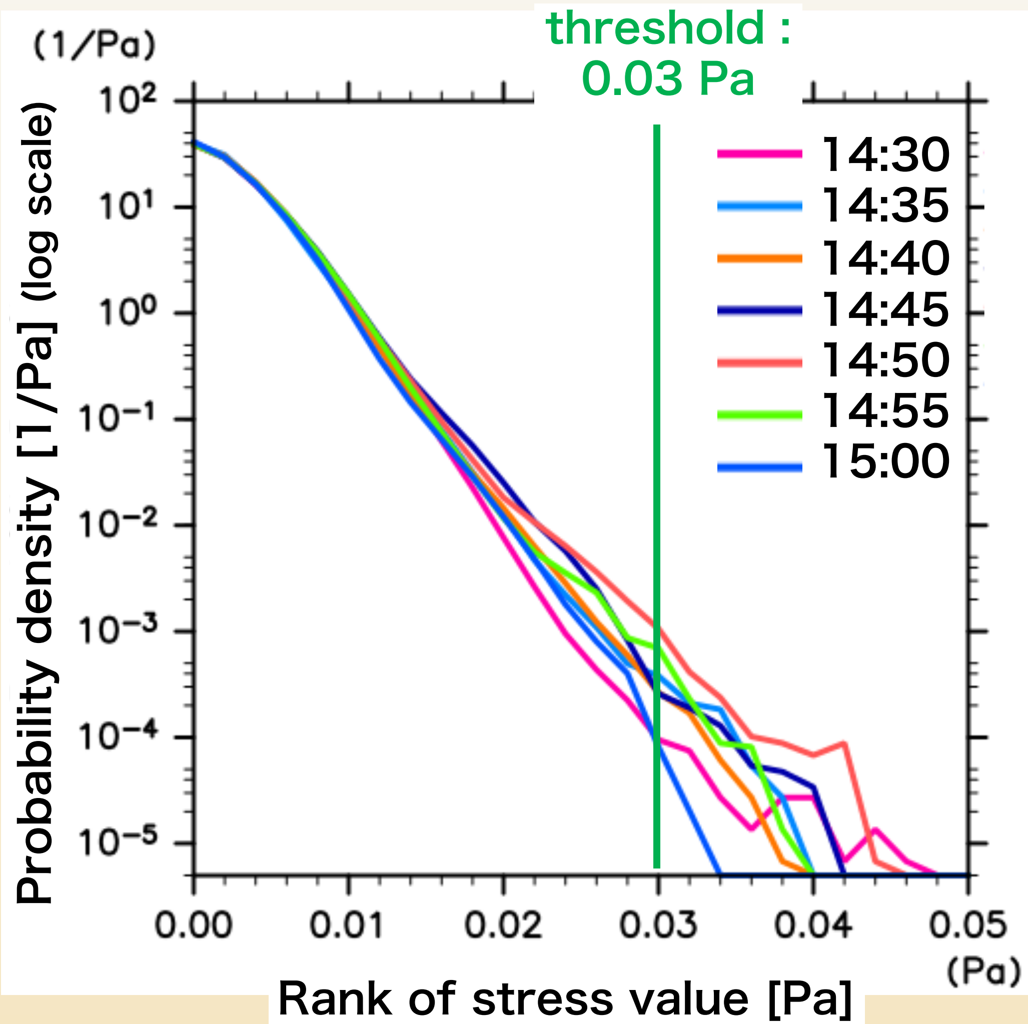


- **Convective cell**
  - Horizontal scale : Several kilometers
  - Vertical scale : about 6 km





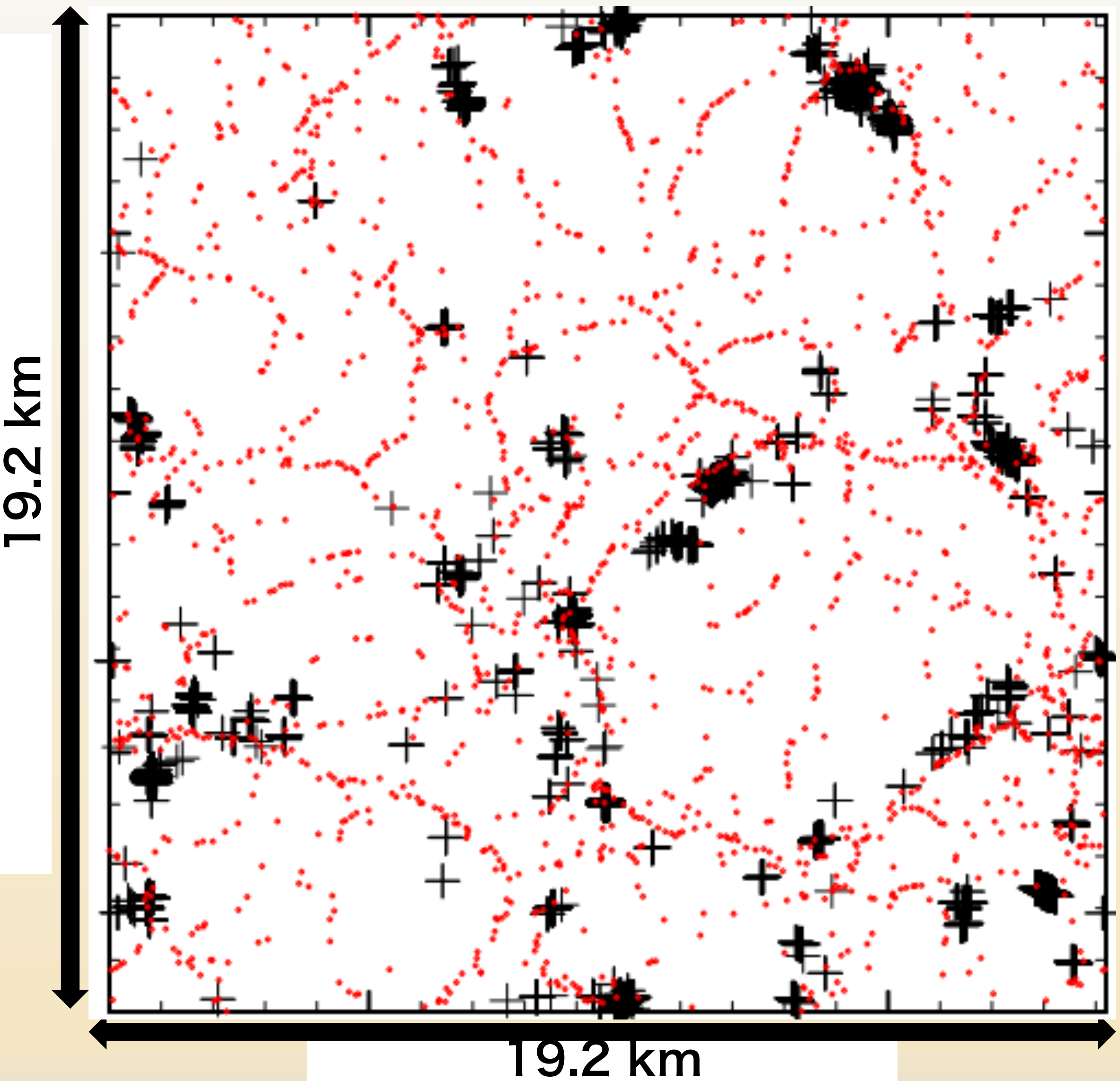
Surface stress probability density distribution



- Bin width : 0.002 Pa
- Surface stress exceeds threshold value of dust lifting in the analyzed period.
  - Threshold value 0.03 Pa obtained by experimental results.
    (Greeley and Iversen, 1985)

Horizontal distribution of vortices (14:30)

Red dot : Vortex, Cross mark : strong stress (> 0.017 Pa)

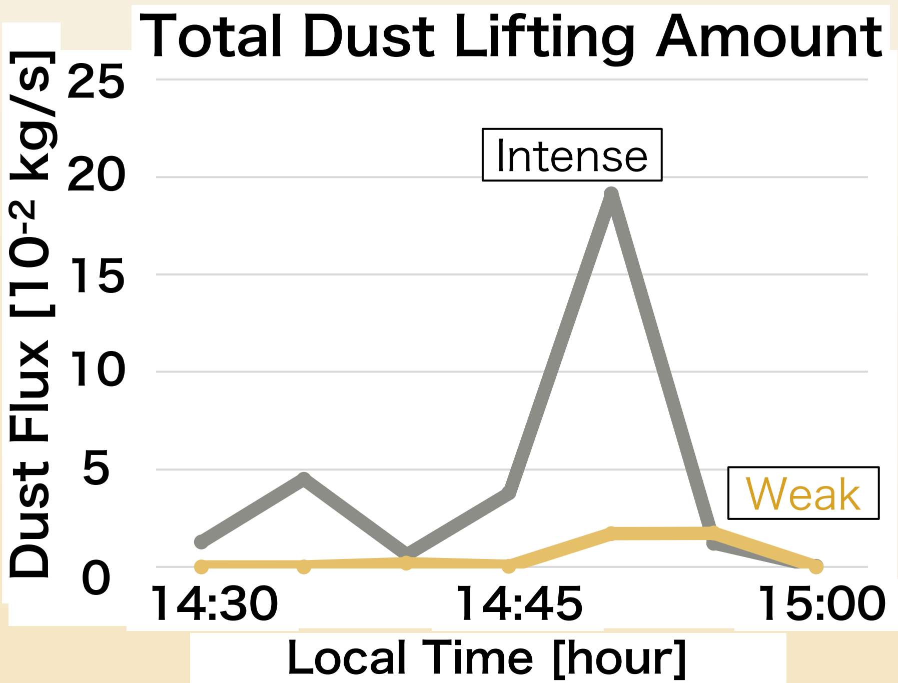


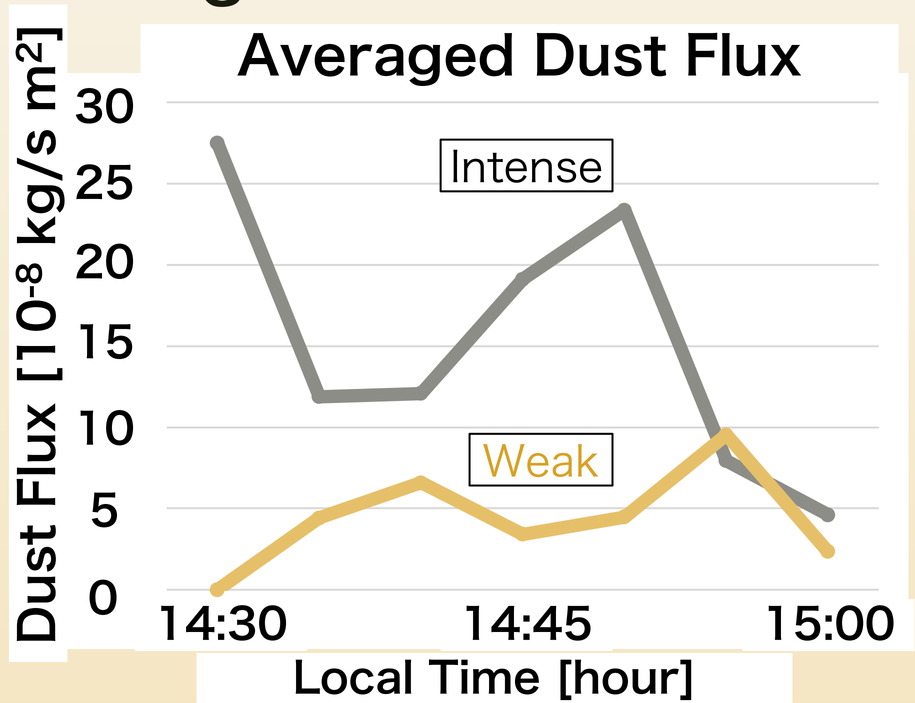
Vortices align along to convective cell boundaries.

We suppose that strong surface stress is produced by strong vortex.

Dust flux in intense/weak vorticity regions

- Dust flux estimated by KMH scheme
  - Threshold value τ^* : 0.03 Pa
- 2 kinds of regions are considered.
  - Intense vorticity region : inside 50 m from vortex centers with intensity over $15 \times \sigma$ (σ : Standard deviation)
  - Weak vorticity region : Other region





- Strong vortices are important for dust lifting.

Summary

- We are analyzing LES result for Martian atmospheric boundary layer aiming for reconsidering dust lifting parameterization schemes used in MGCM.
- Analysis of 5 m resolution results
  - Surface stress exceeds threshold value of dust lifting in the analyzed period (30 minutes).
  - Strong vortices are important for dust lifting.
    - In intense vorticity regions, total amount and average of dust flux is higher than other region.
- Considering strong vortices is important for reconsidering dust lifting parameterization scheme (future work).

References

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- Wilson, R. J., and Hamilton, K., 1996: Comprehensive model simulation of thermal tides in the Martian atmosphere, J.A.S, 53, 9, 1290-1326

How to detect vortex structures

- Rankine Vortex Fitting (Nishizawa et al., 2016)

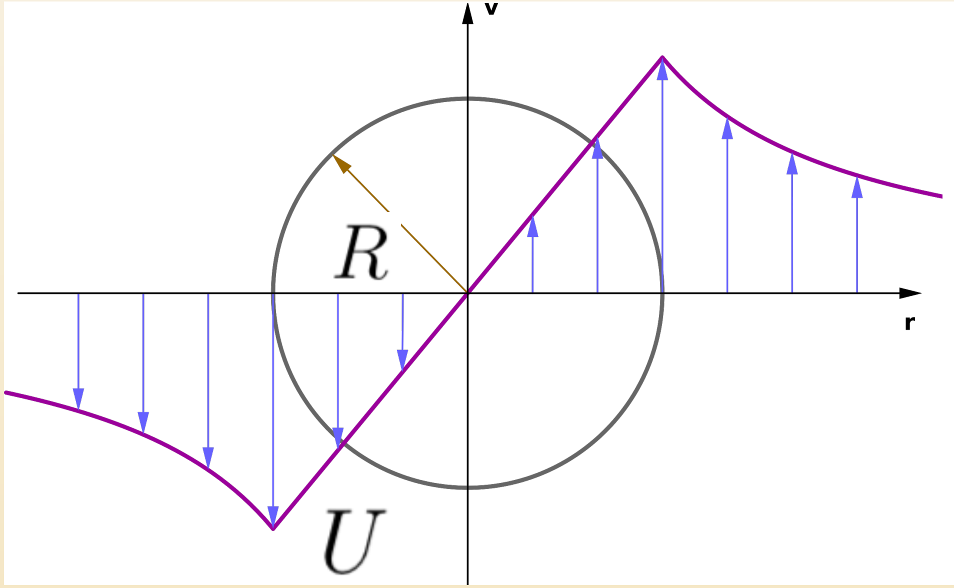
$$u(r) = \begin{cases} Ur/R & r < R \\ UR/r & r > R \end{cases}$$

u : Tangential wind speed [m/s]

r : Vortex radius [m]

U : Maximum tangential wind speed [m/s]

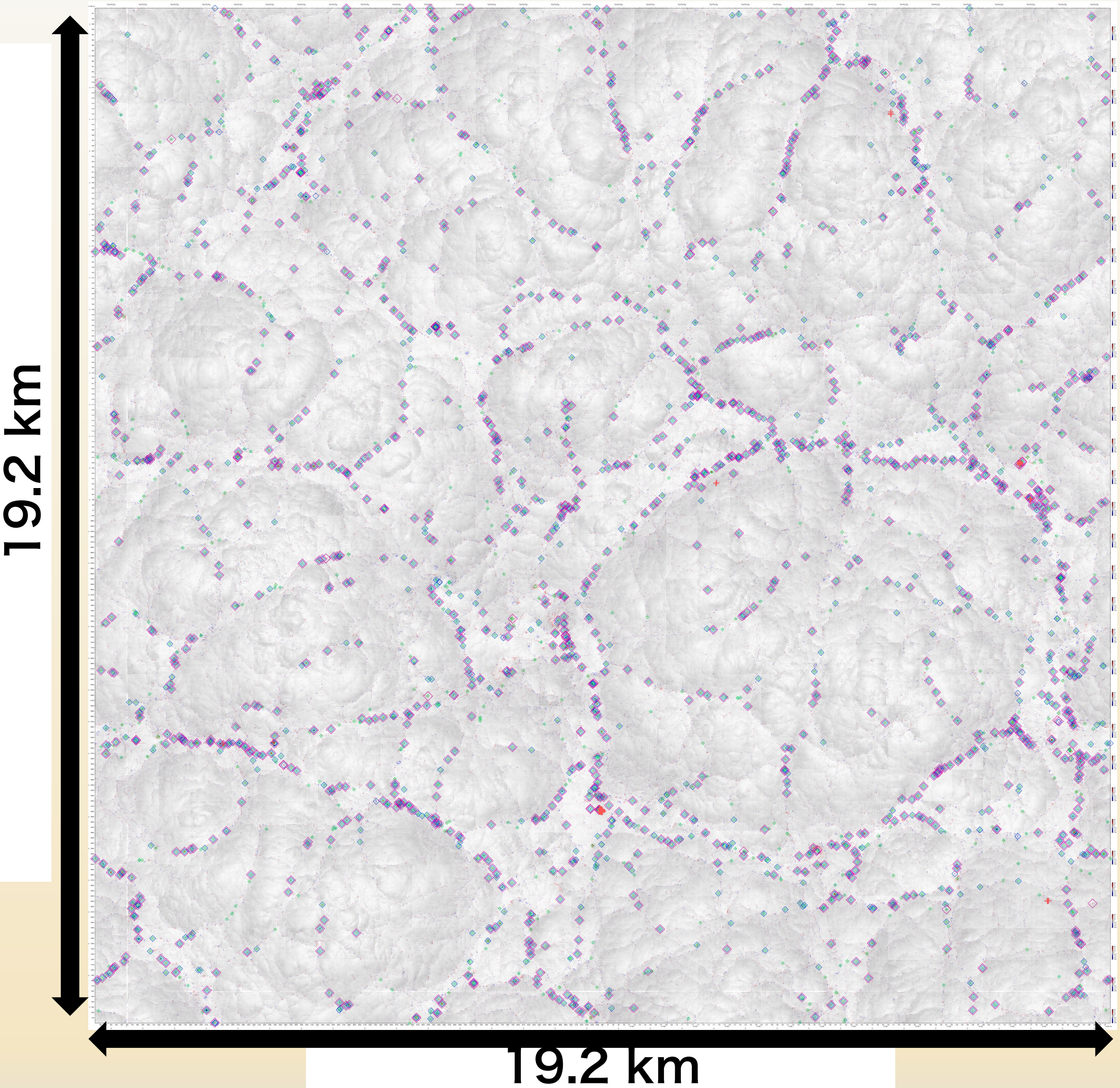
R : Radius at u = U [m]



- Before apply the fitting, we extract points by vorticity value which has over some level of standard deviation

Vortex Structures distribution

Vertical wind [m/s] (horizontal)



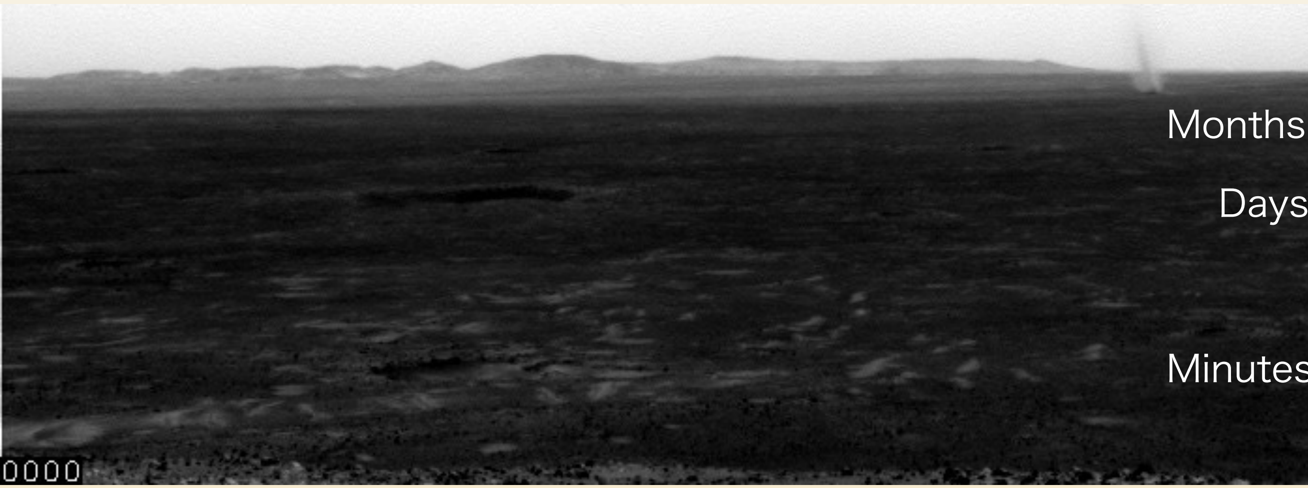
Vortex structures align along to convective cell boundary

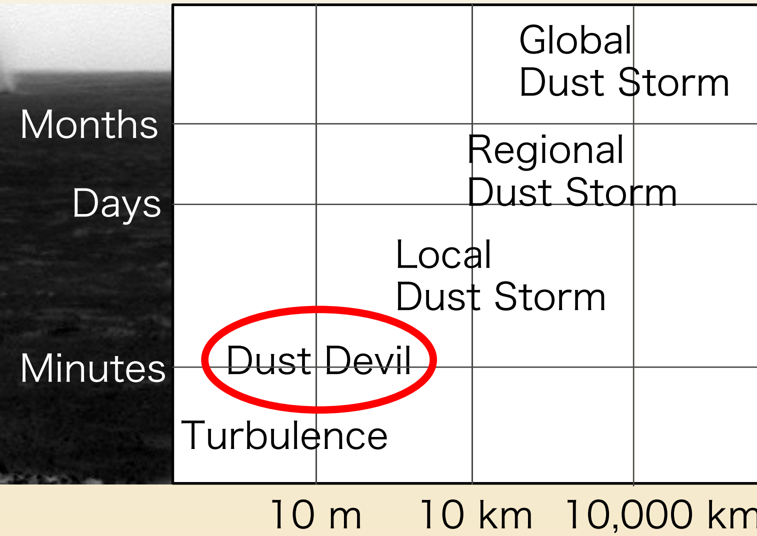
We suppose

応力が強いところは渦が伴うに違いないと思った

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.

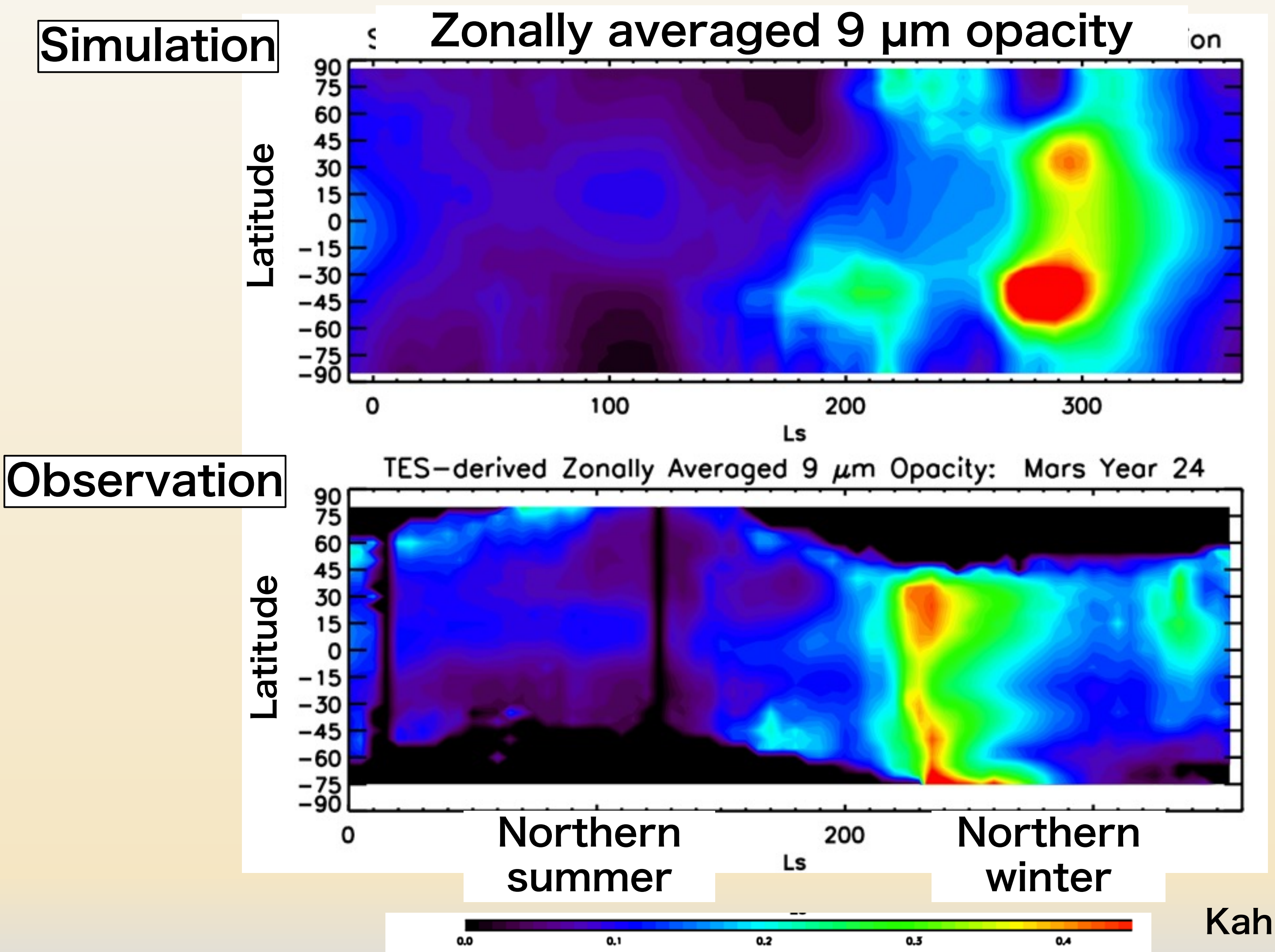




Dust Devils (Recorded by Rover Spirits)
http://mars.nasa.gov/mer/gallery/press/spirit/20050819a.html

MGCM calculation including dust processes

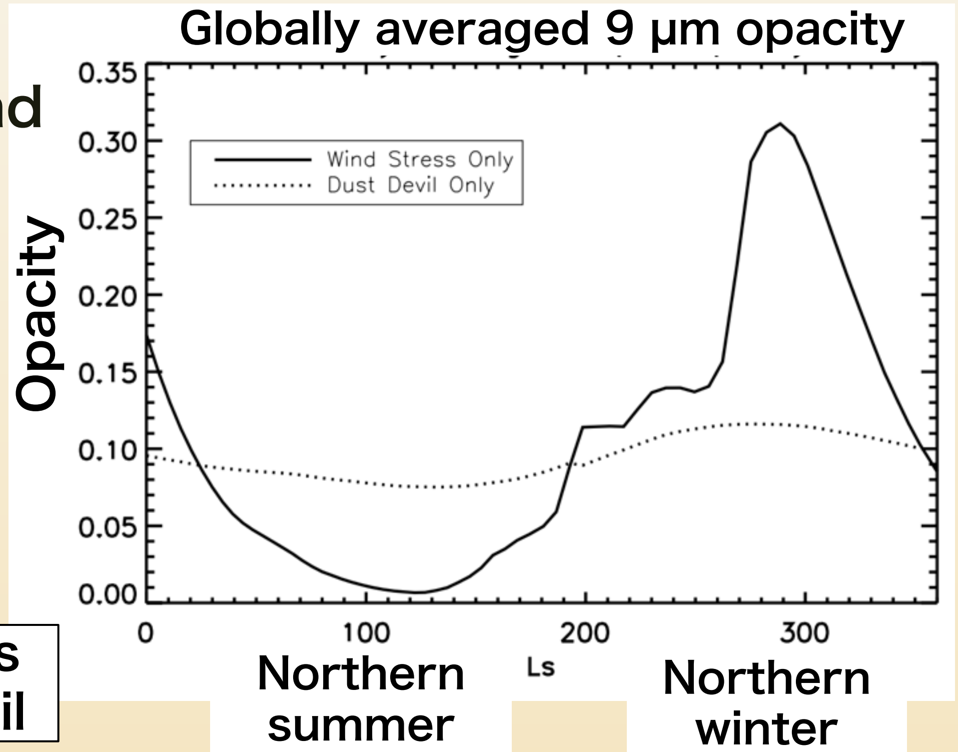
- Kahre et al. (2006) simulates seasonal variability of dust distribution.



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)

$$F_D = \alpha_D F_s (1 - b) \qquad b = \frac{p_s^{\chi+1} - p_{con}^{\chi+1}}{(p_s - p_{con})(\chi + 1) p_s^{\chi}} \qquad \chi \equiv \frac{R}{c_p}$$

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

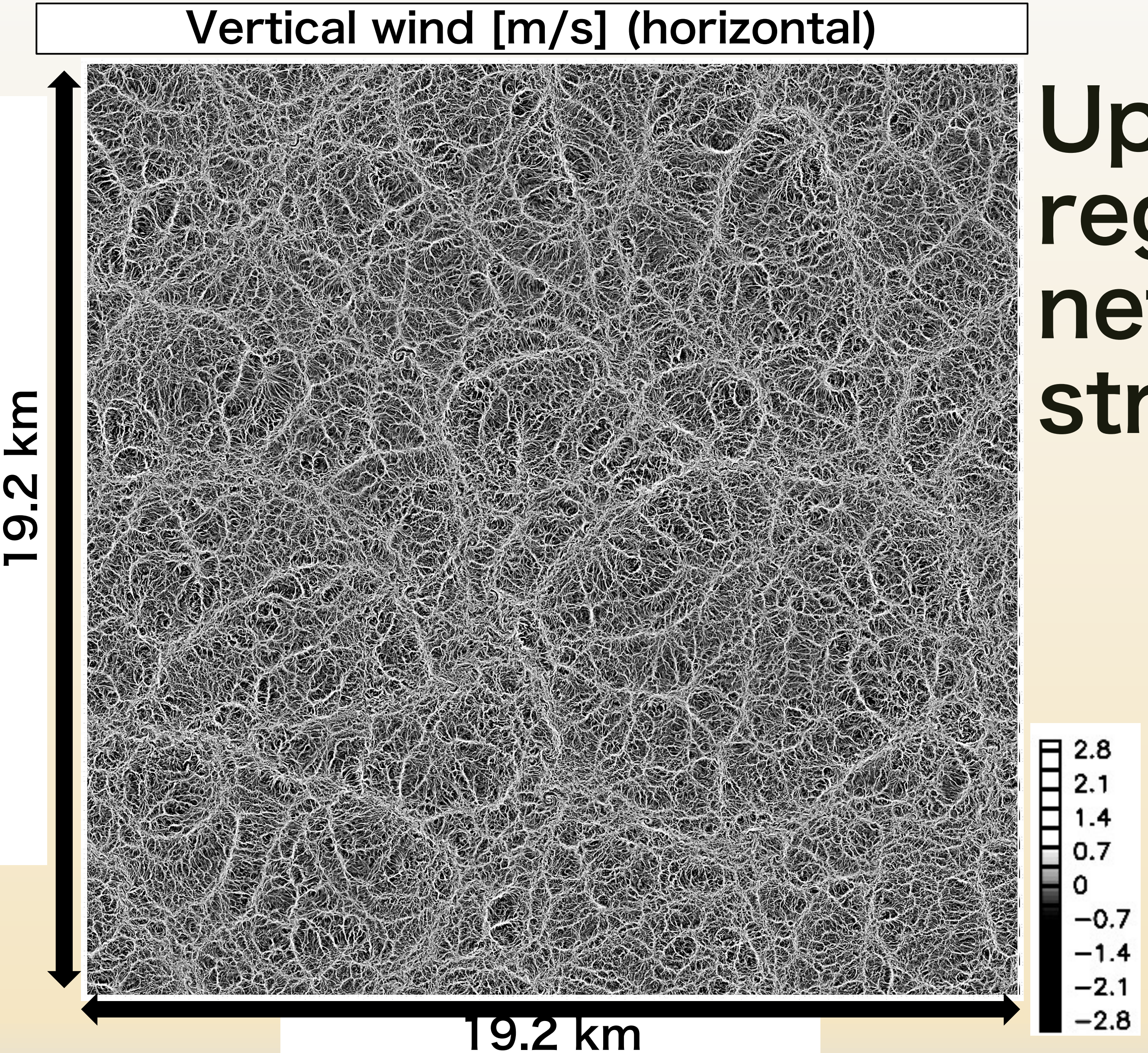
- Based on the thermodynamics of dust devils as a heat engine.
  (Rennò et al., 1998)
- Thermal efficiency is used for expressing dust flux.
  - With the higher sensible heat flux, kinetic energy of convection becomes larger.
  - With the higher PBL altitude, the conversion rate of kinetic energy from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

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?

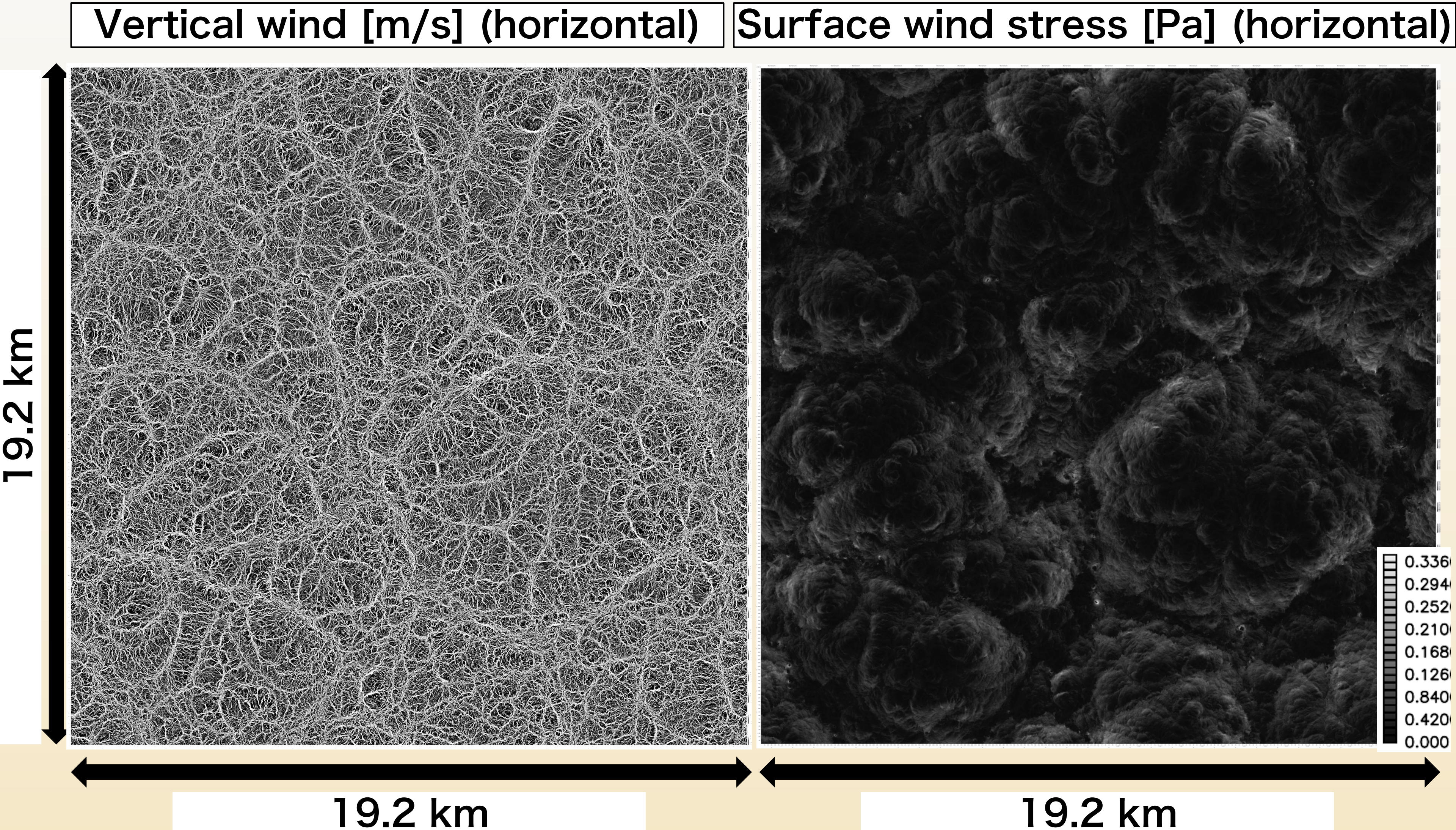
- We suppose that dust devils are very important
- In this study, we examine LES with several km domain.
  - Our results can be applied to MGCM.
  - The most high-resolution MGCM can resolved up to several km. (~ 11 km; Takahashi et al., 2011)

Vertical wind (bottom level z = 2.5 m)



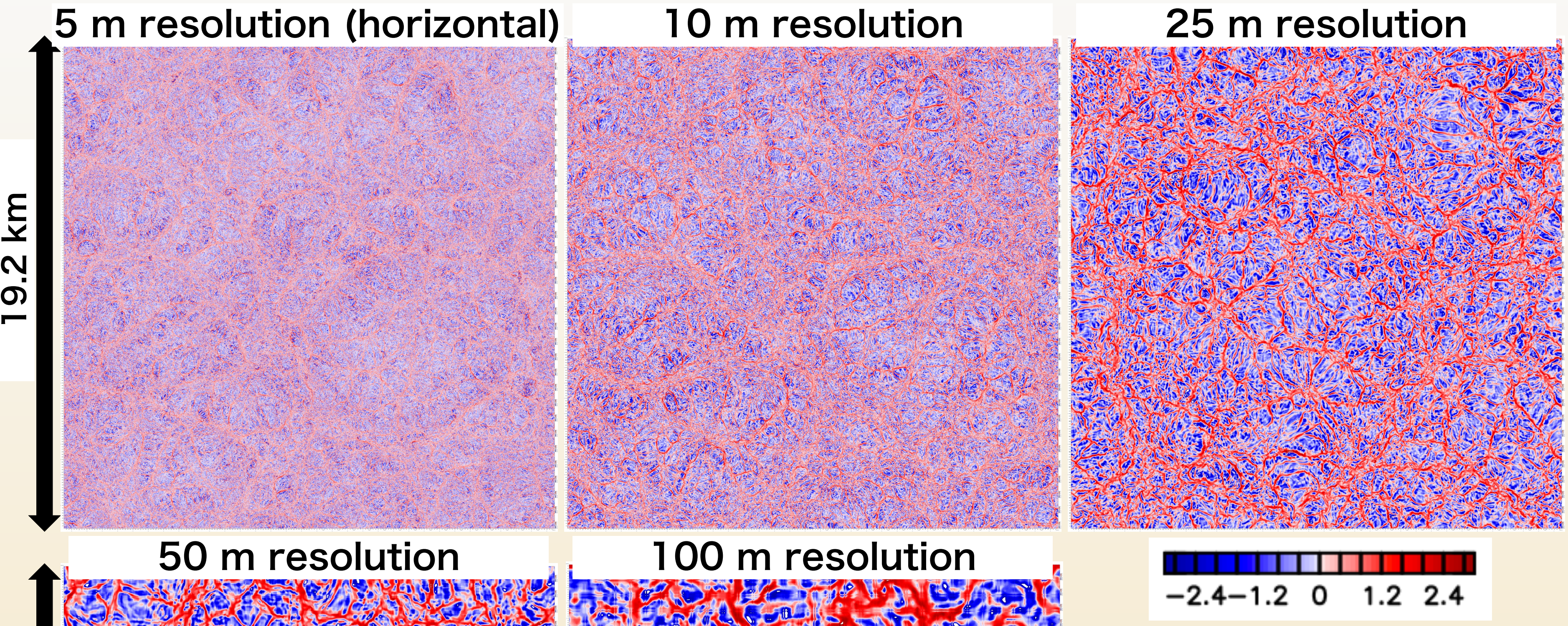
Upward wind region forms network-like structures.

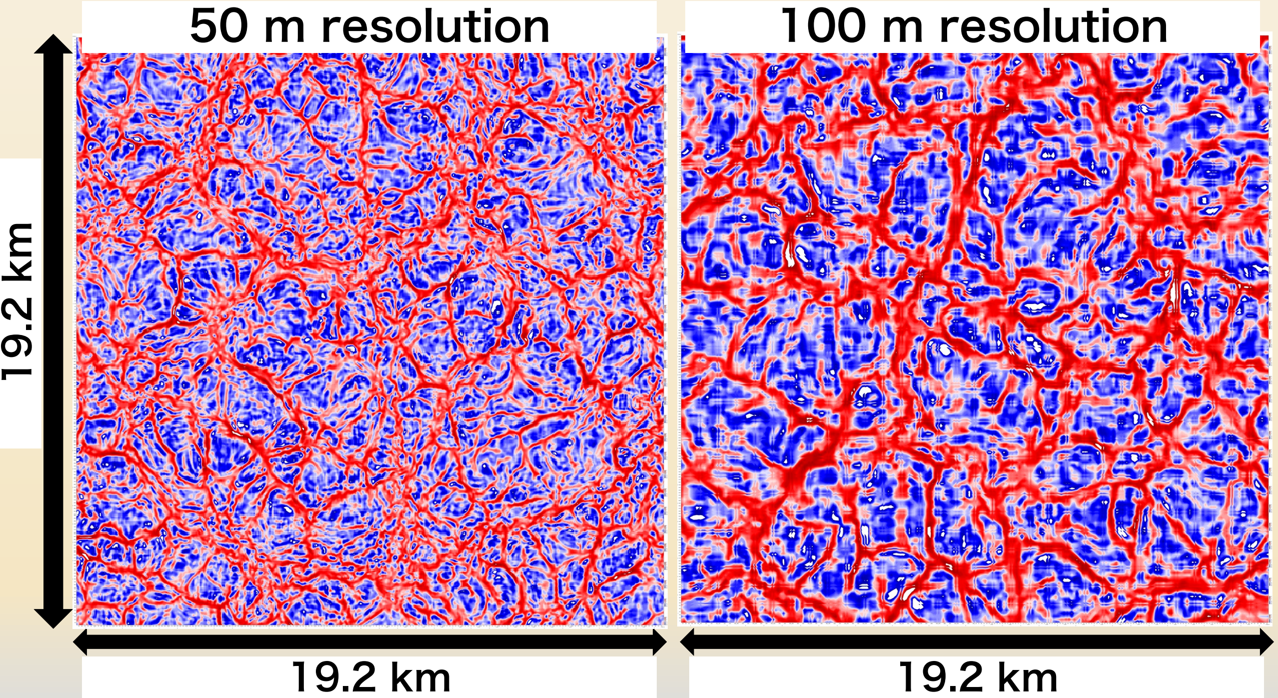
Surface wind stress



Wind stress tends to be strong near the convective cell boundary

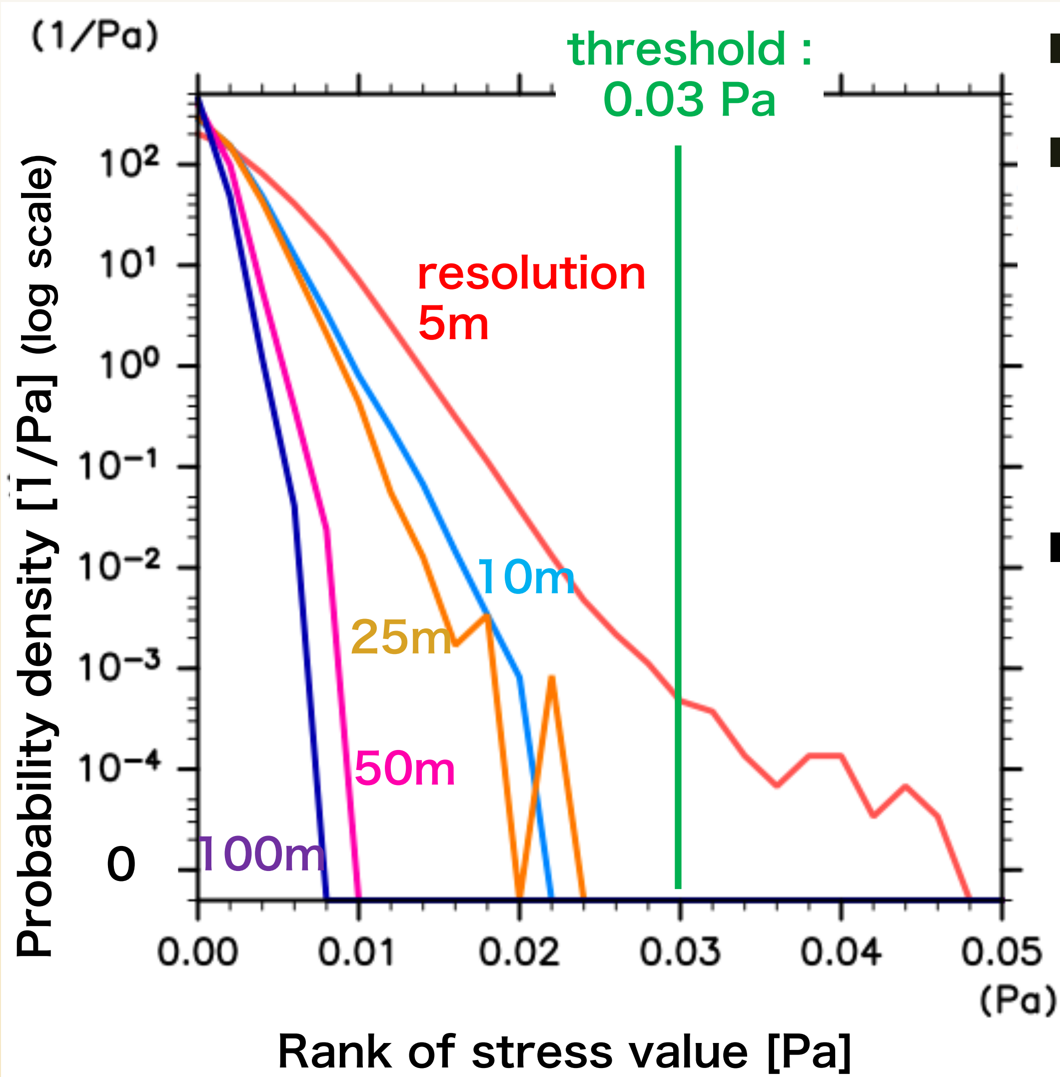
Vertical wind fields of each simulation





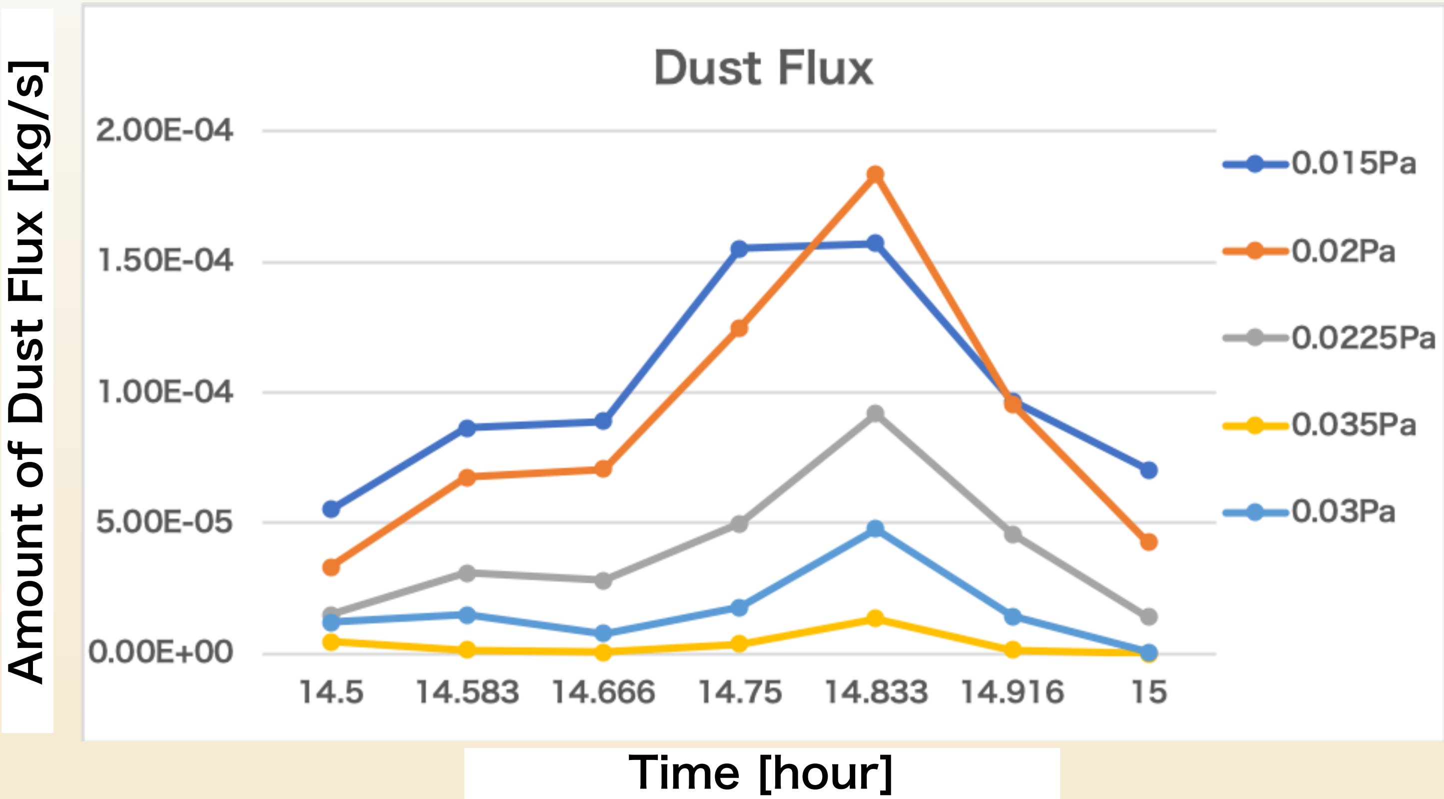
- Bottom level
- Network-like structures are similarly seen.

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)

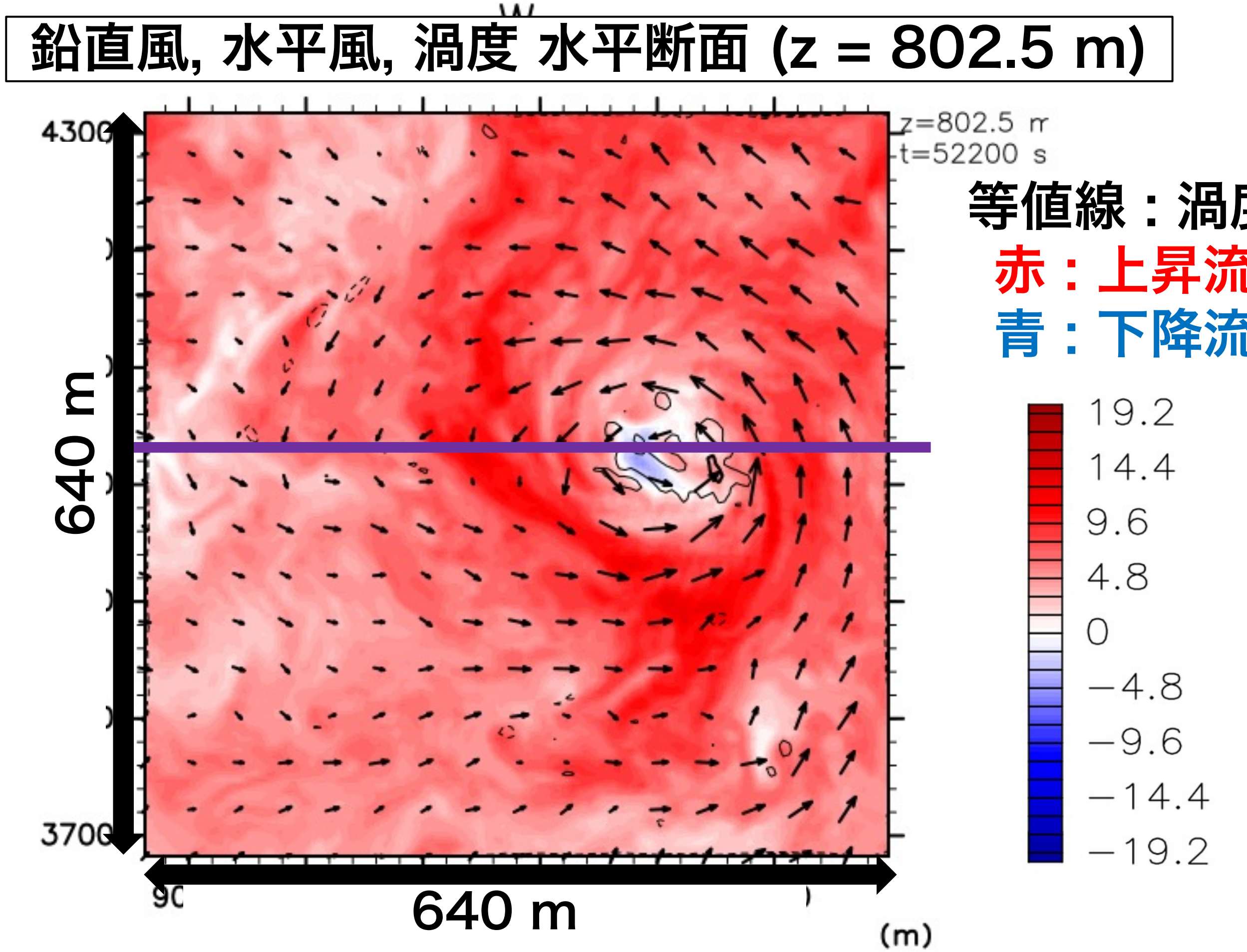
Amount of Dust Flux (Whole area)

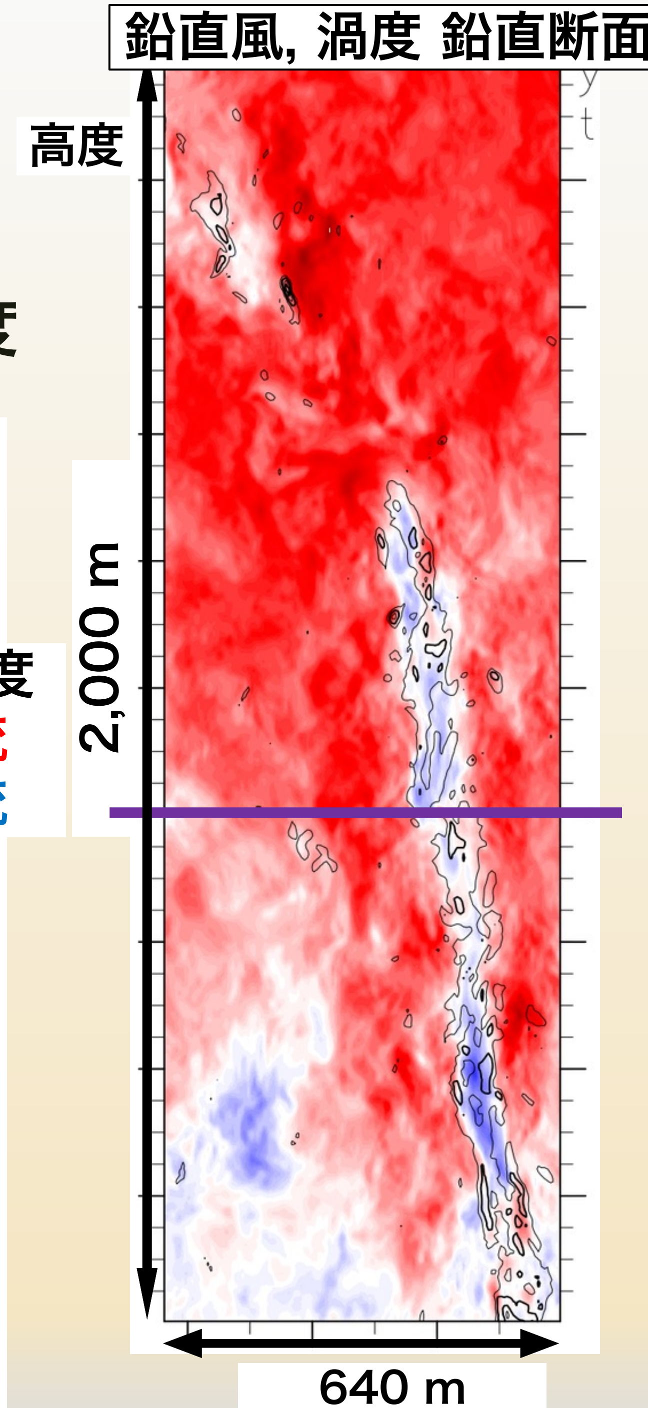


- Calculated by wind stress scheme in each threshold case
- Dust is lifted the most at 14:50
  - However difference of value is only a few times

応力が強い箇所の流れ場

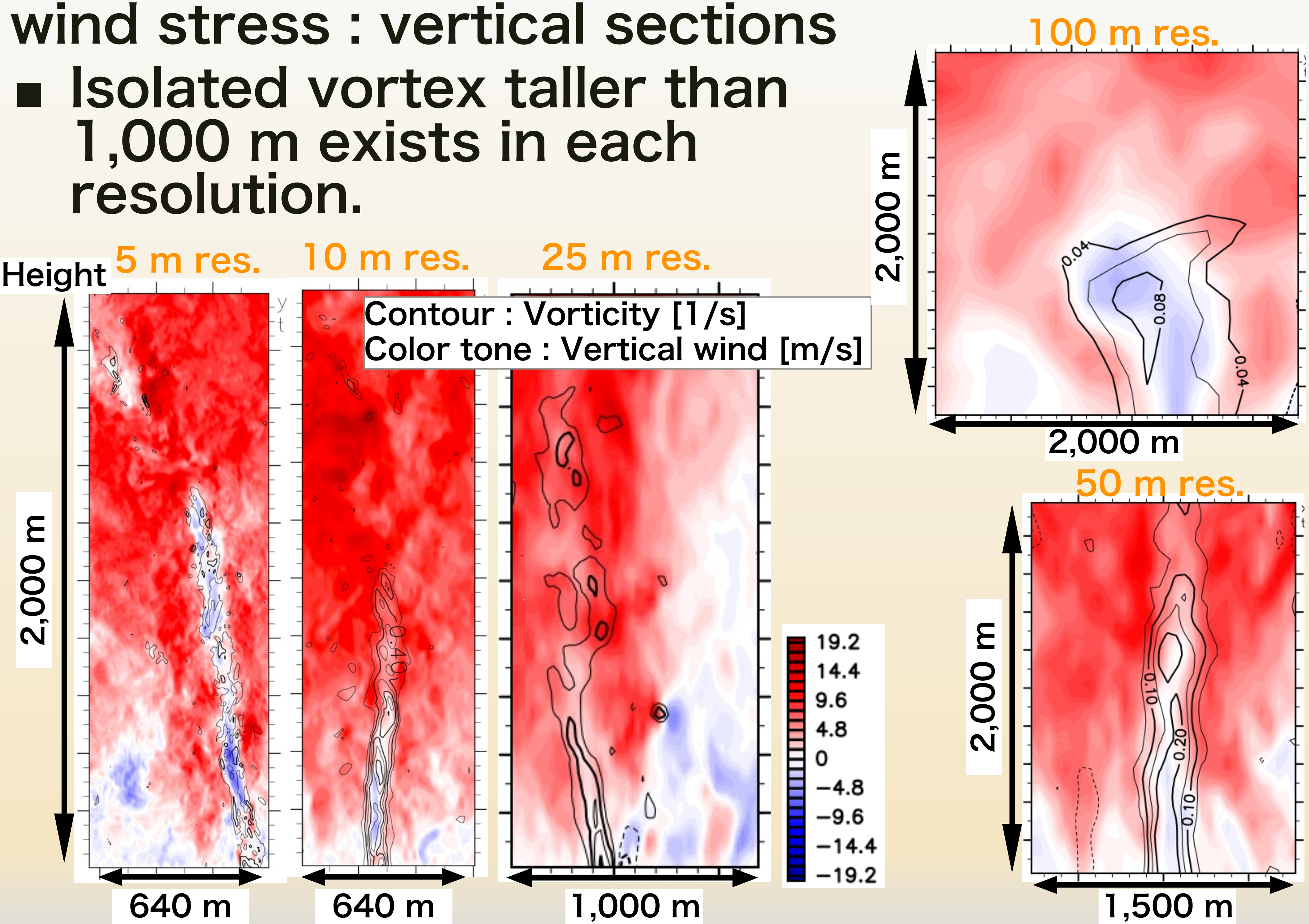
- 孤立渦があるように見える
  - 直径 120 m 程度, 高さ 1,500 m 程度





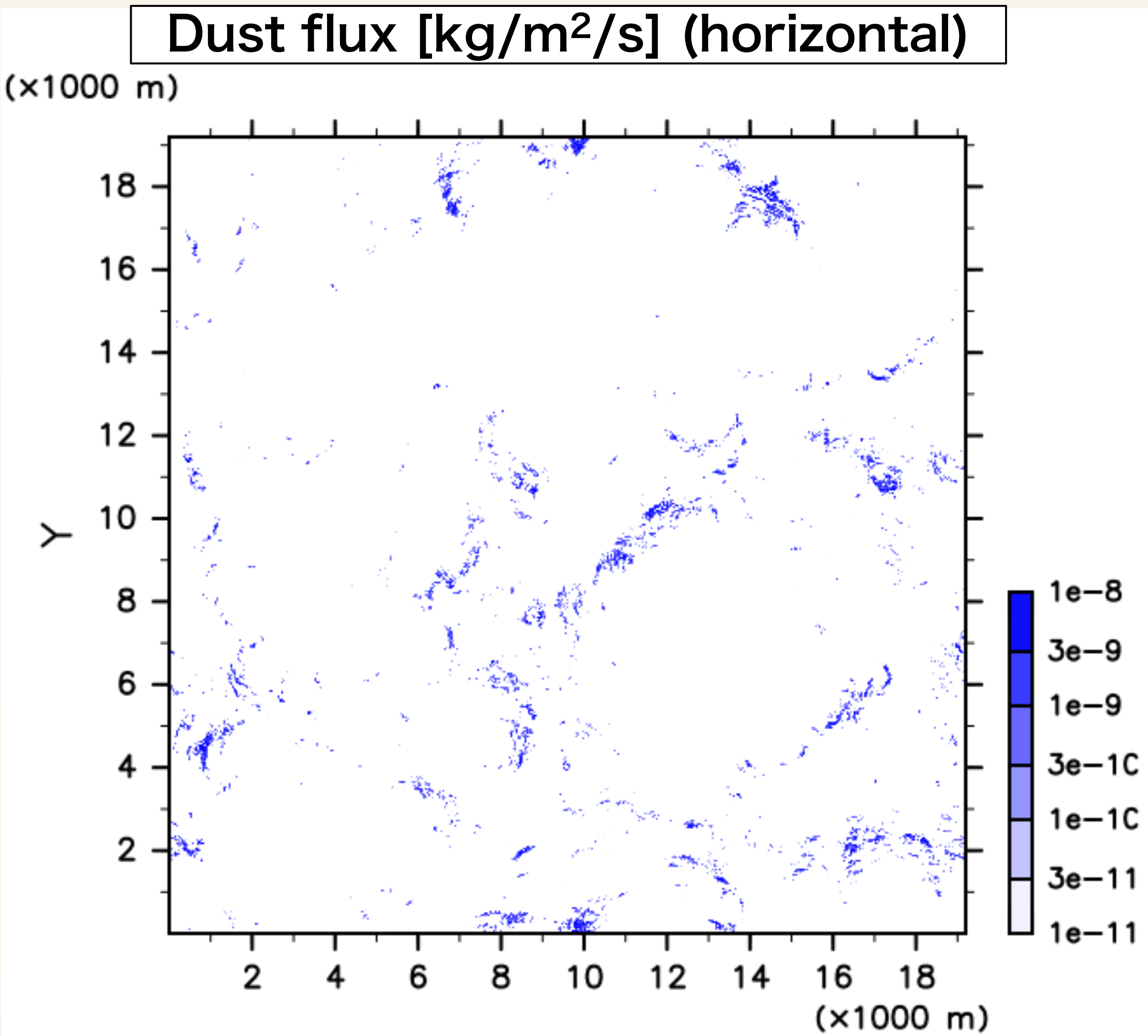
Wind structure associated with the strongest wind stress : vertical sections

- 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

火星大気大循環モデル (MGCM) におけるダスト

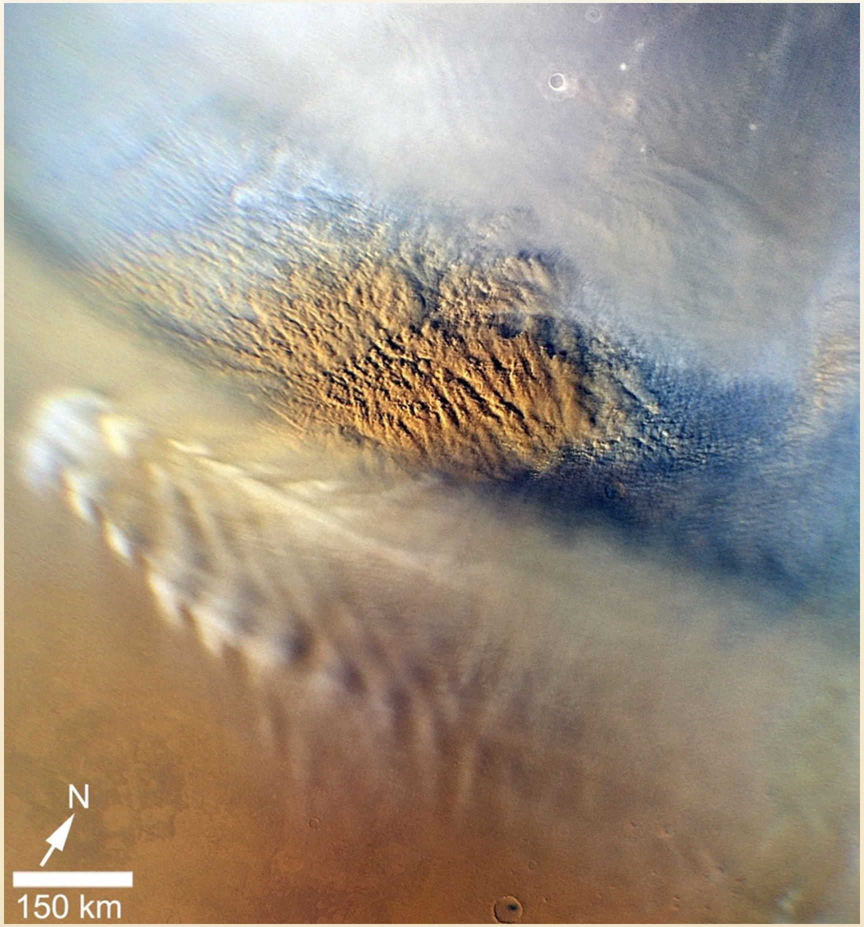
- かつてはダスト分布を固定して火星の大気循環が調べられてきた (Wilson and Hamilton, 1996)
  - ダストストームが発生するのに十分な風速が得られなかった
  - MGCM の中でダストストームを起こすには, 小スケール (<~ 100 km) な風の揺らぎが重要であることを示唆
  - 細かい風の流れを考慮する何らかの仕組みが必要
- 領域モデルによる対流計算によって, 小スケールの流れを考慮すれば十分な風速が得られることがわかった (Odaka, 2001)
- Mars Global Surveyor によって数多くのダストデビルが見つかる (2000 年以降)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

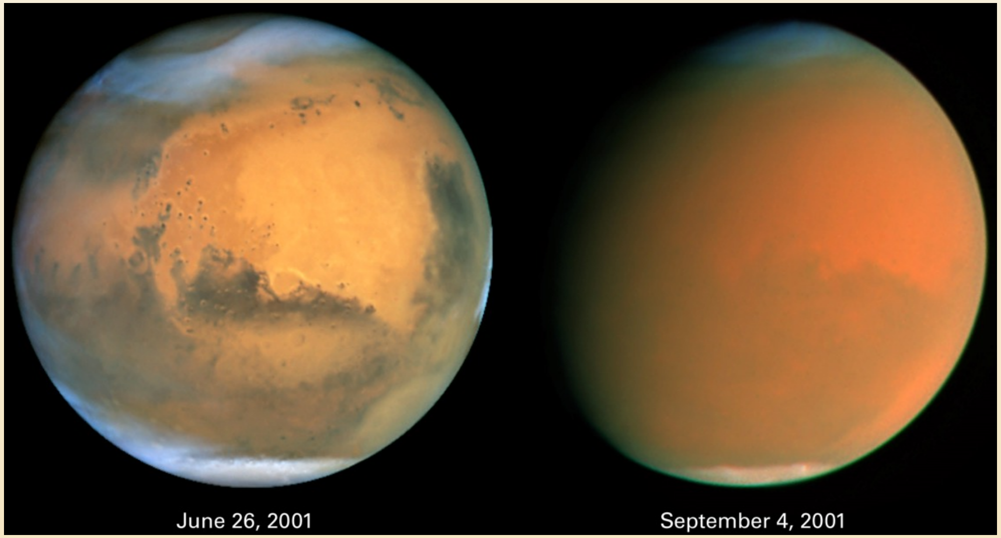
https://apod.nasa.gov/apod/ap031230.html

はじめに

ローカルダストストーム



グローバルダストストーム



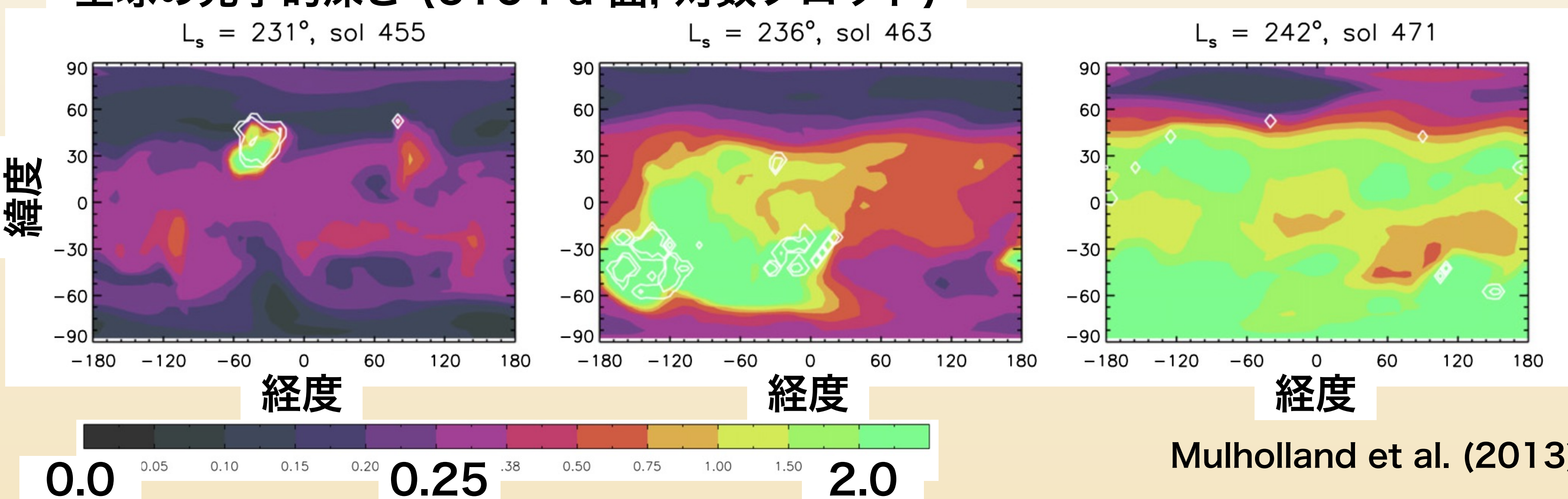
https://www.jpl.nasa.gov/

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

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

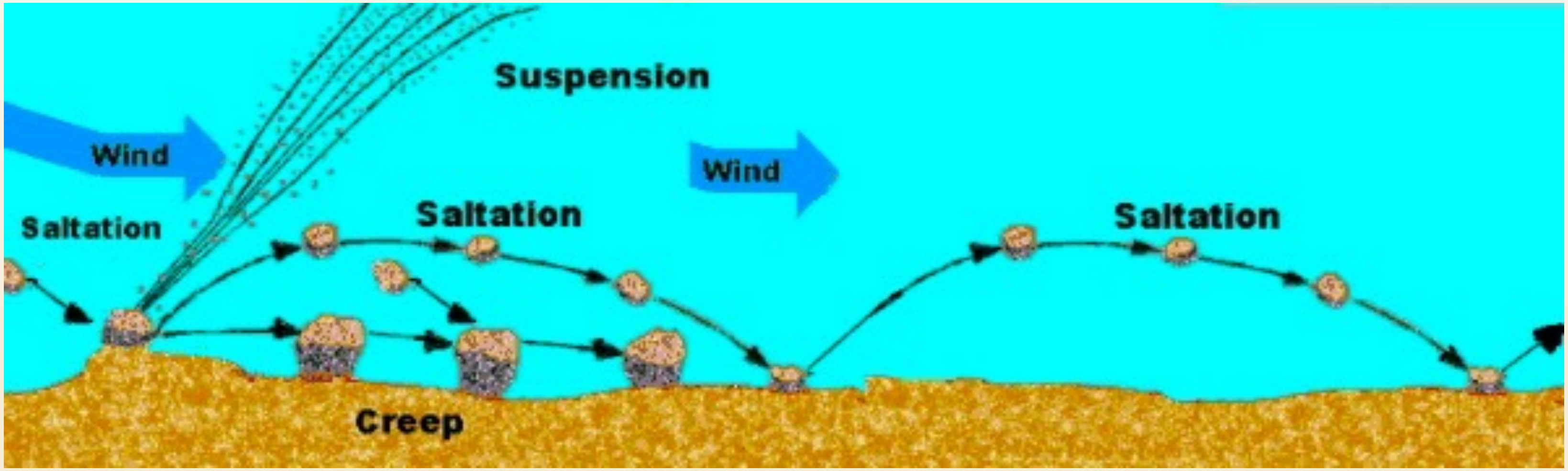
全球の光学的深さ (610 Pa 面, 対数プロット)



Mulholland et al. (2013)

Mulholland et al. (2013) における仮定

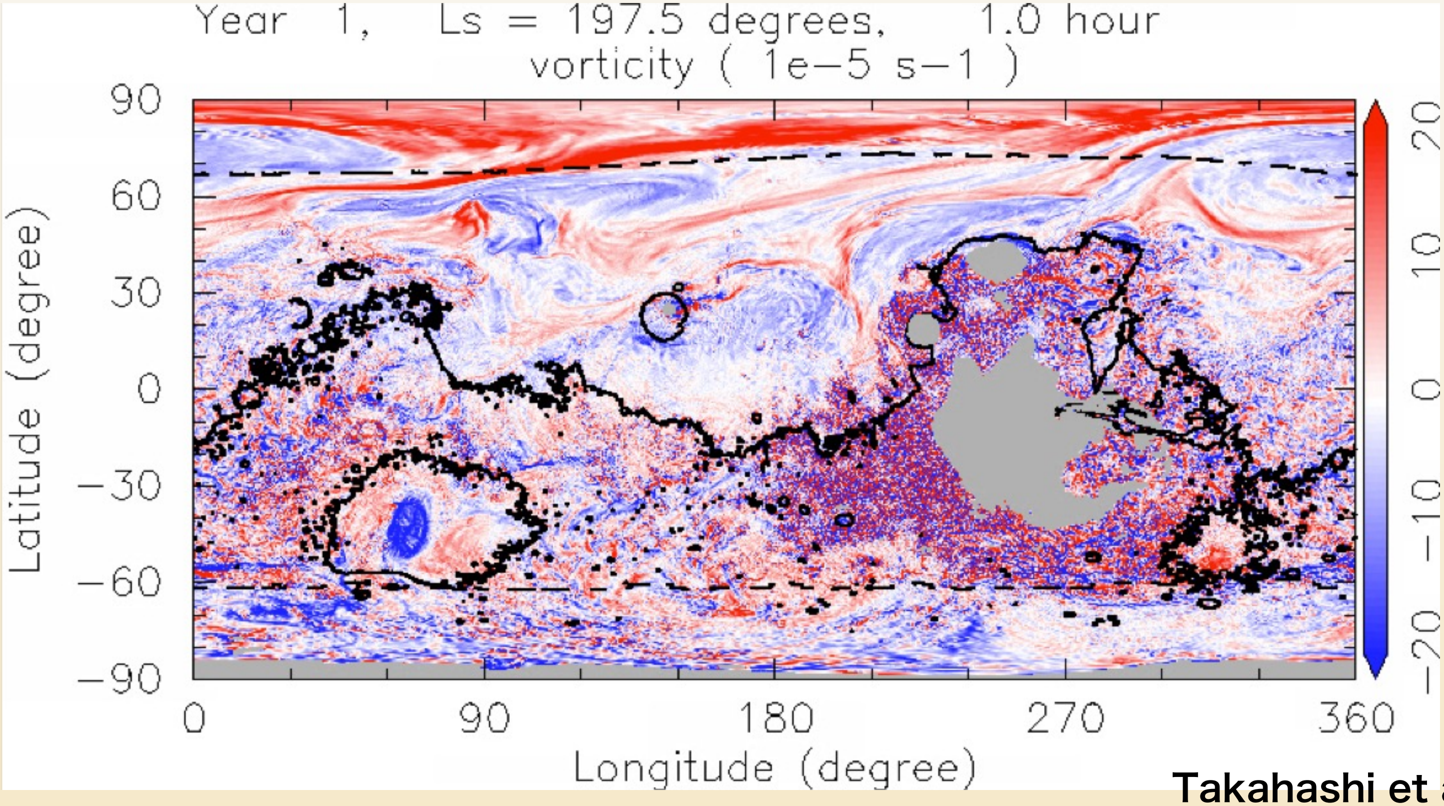
- 平均風応力閾値をダスト量に合わせて変化することを仮定
  - ダストが多く溜まると saltation が生じにくくなり, 巻き上げの風応力閾値を下げられると仮定



- 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)



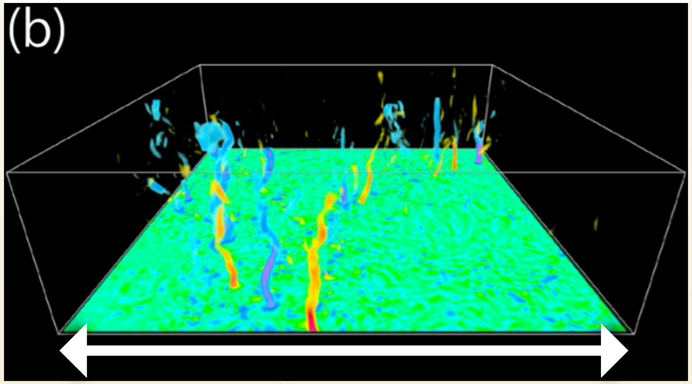
Takahashi et al. (2011)

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

Nishizawa et al でいったこと

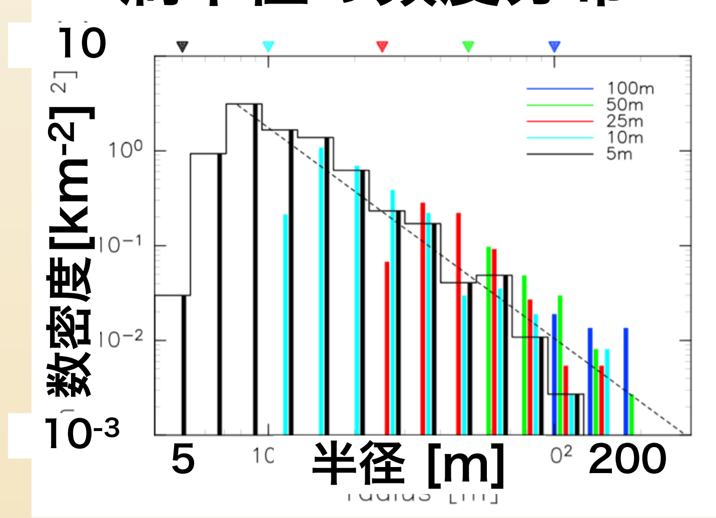
- Nishizawa et al. (2016)
  - 計算領域 水平 19.2 km, 鉛直 21 km
  - 空間解像度 5, 10, 25, 50, 100 m
  - 日変化する熱強制を外部から与える
  - LT = 0:00 から計算開始 (LT : 現地時刻)
- 渦に関する統計量を調べた
  - LT = 14:30 の高度 62.5 m 付近における渦のサイズ分布など
- しかし, 地表付近における速度場や応力場については未調査
  - ダストの巻き上げを考える上では地表付近を観察する必要がある

渦度空間分布



1 km

渦半径の頻度分布



Nishizawa et al. (2016)

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 to consider relationship between wind microstructures and large scale convective structures.
  - At all times, surface stress is sufficiently strong to dust lifting.
  - Strong vortices are important for dust lifting.