Large eddy simulations for terrestrial convective mixed layers

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Outline

LES studies:

1. Earth convection

– Tropical cyclone

2. Terrestrial convective mixed layer

2.1 Dust devil

2.2 Development of parameterization:

Horizontal eddy diffusivity for numerical weather prediction models

1. LES for entire tropical cyclone

- "Japan metrological agency's non-hydrostatic model" generally used for operational regional weather prediction

  → Used as LES with cloud physics

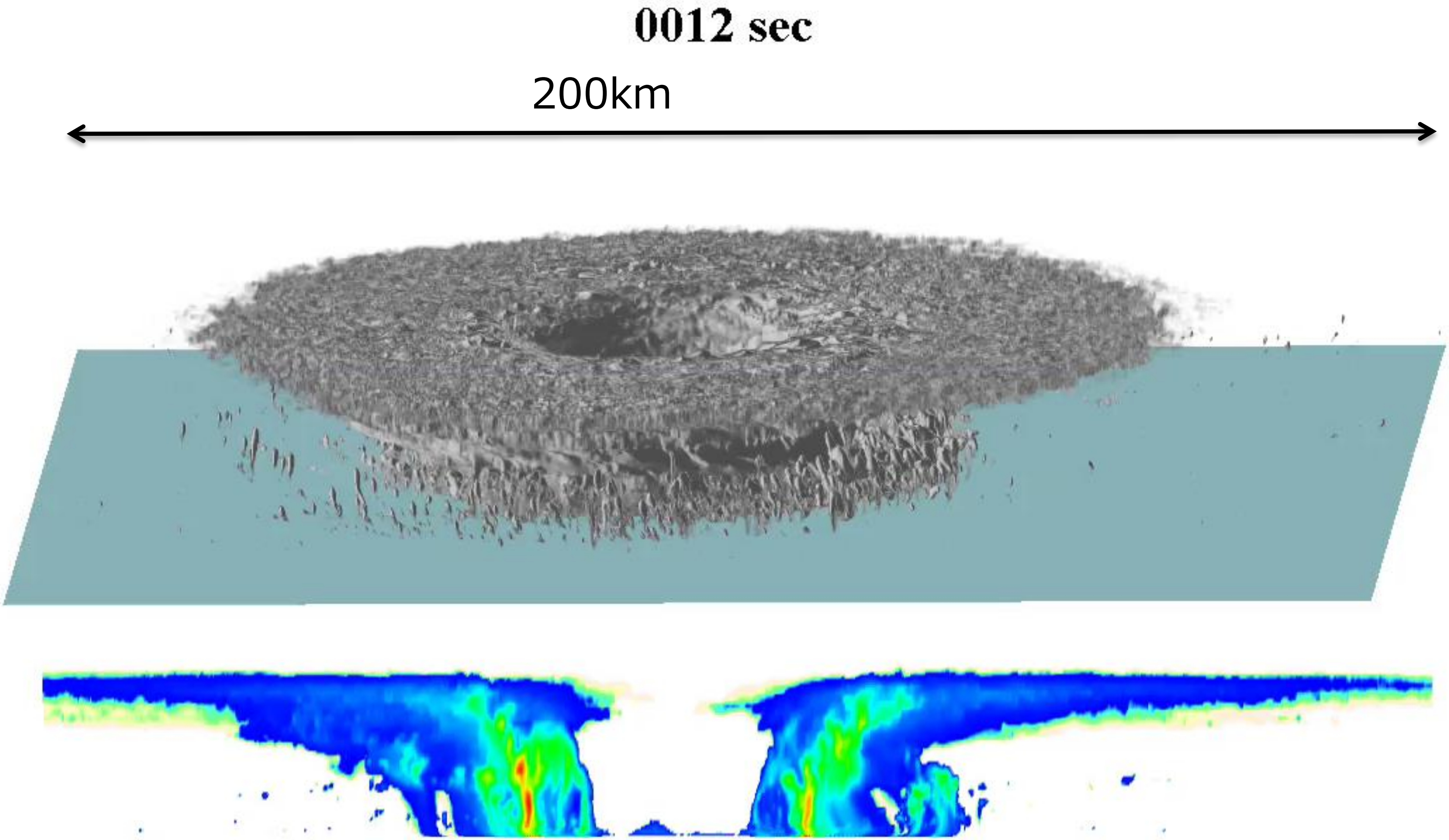
  - Horizontal resolution: dx=100 m
  - Domain: 2000km×2000km×27km
  - Grid number: 20000×20000×60
  - Doubly periodic horizontal boundaries
  - Horizontal homogenous surface (sea)
  - Initial condition: Tropical cyclone developed with dx=2 km is interpolated to dx=100 m

Idealize experiment

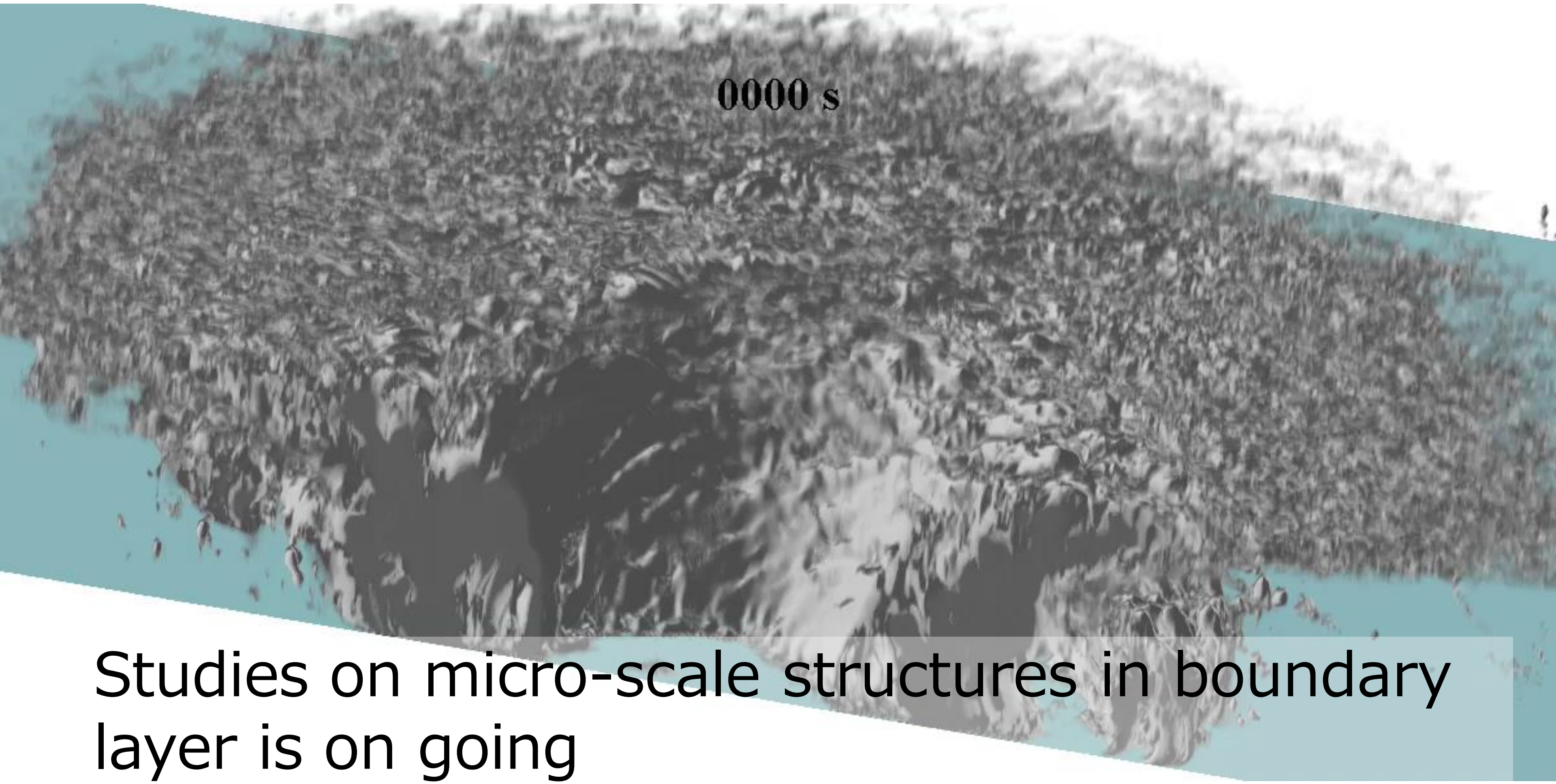
conducted by 1/8 nodes of K-computer

(～ 10000 nodes)

Result (Cloud water amount, 9→10 hr)



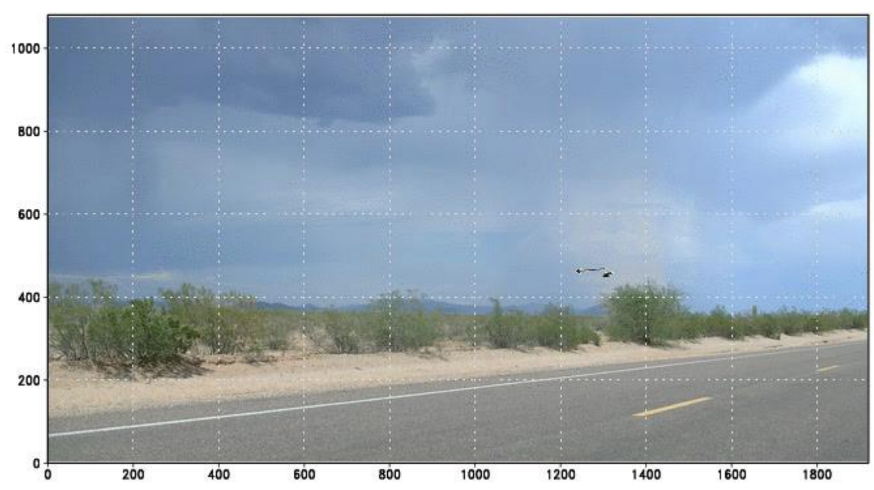
Result (Cloud water amount, 9→10 hr)



Studies on micro-scale structures in boundary layer is on going

2.1 LES for dust devil

a. Sensitivity test on diurnal variation, surface heat flux, and ambient wind (Ito et al., 2010)
b. Formation mechanism (Ito et al., 2011; Ito et al., 2013)
c. Population of simulated dust devils
d. Feedback between surface heat flux and dust devil wind



~~LES study~~

Ito (2011)
↓
PIV of dust devil (Ito and Niino 2014)

LES model

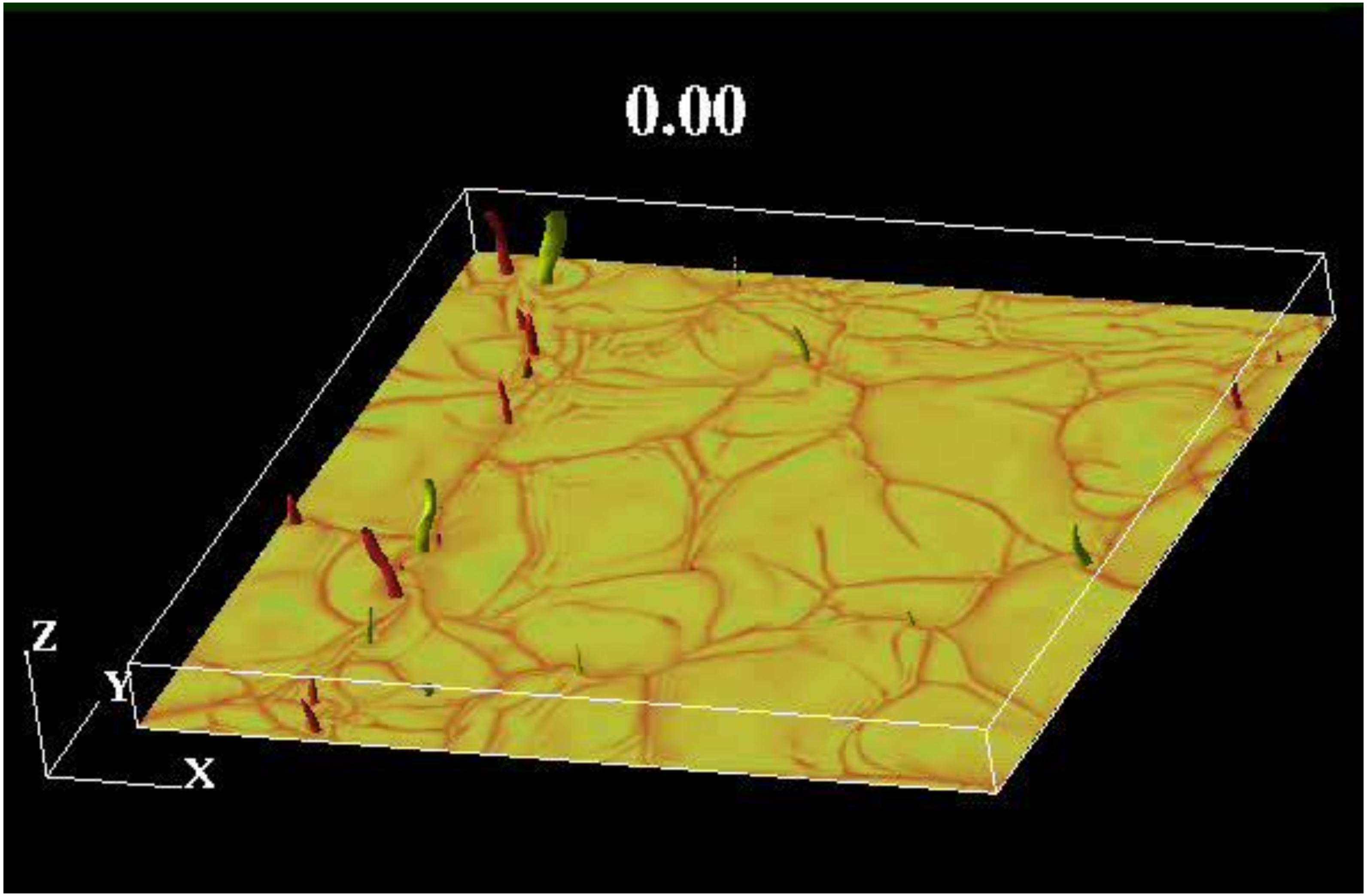
Assume typical convective mixed layer on the Earth

- Basic equations: 3D, Boussinesq approximation
- Sub-grid model: Smagorinsky model
- Grid interval: uniform Δ= 50 ～ 5 m
- Domain: e.g. 4.5 km×4.5 km×3.6 km (90×90×60 grids) for Δ=50 m
  1.8 km×1.8 km×1.6 km (360×360×320 grids) for Δ= 5 m
- Boundary conditions
  - Surface
    - Momentum: Bulk-method or Free-slip
    - Heat: Prescribe Horizontally uniform forcing with diurnal variation or constant
  - Lateral: Doubly-periodic
  - Top: Free-slip
- Initial conditions: Stable stratification Γ(＝4.0K/km)
- Time integration: 0.2s step

Simulated dust devils

12:00~12:30, Δ=5m, vertical vorticity $\zeta>0.25\mathrm{s}^{-1}$, $\zeta<-0.25\mathrm{s}^{-1}$

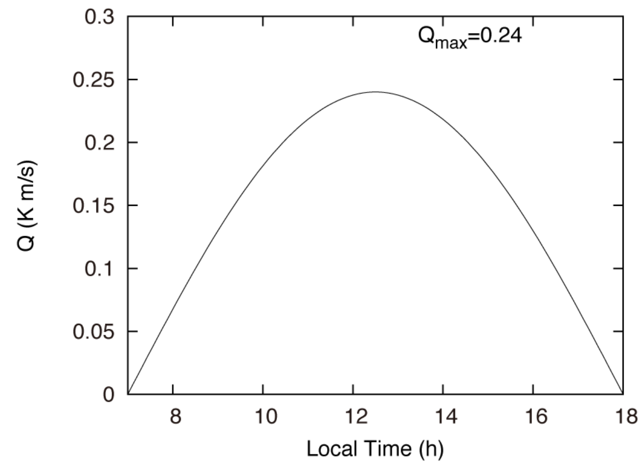
Thick yellow at the bottom: updraft regions



a. Sensitivity test on diurnal variation, surface heat flux, and ambient wind

- Impose diurnal-varying surface heat flux

$$Q = Q_{\max} \times \sin\left(\frac{t-7}{11}\right)$$



- Various sensitivity tests

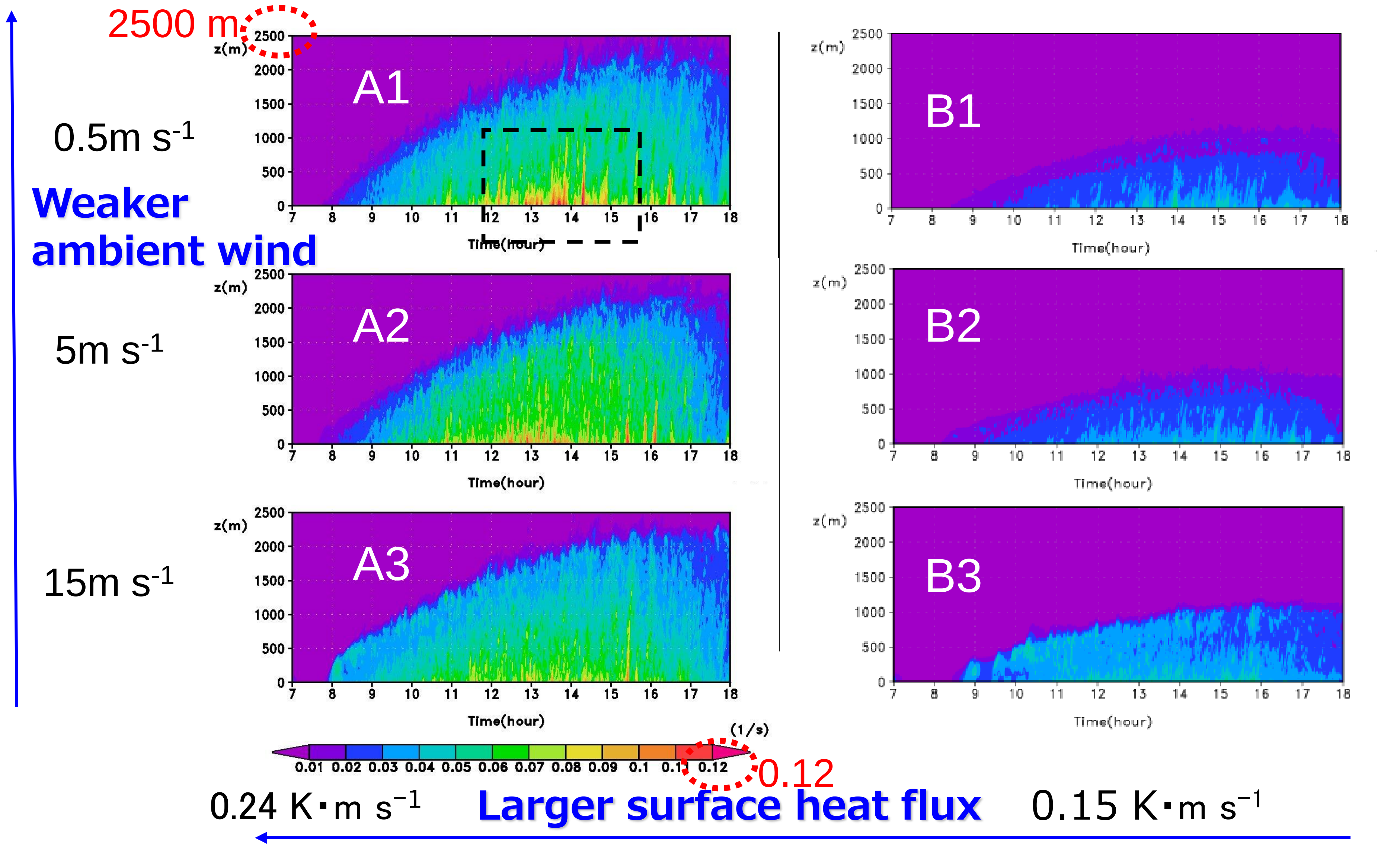
Maximum of surface heat flux Q_{max}

Ambient wind

	$0.24 \mathrm{K \cdot m\ s^{-1}}$	$0.15 \mathrm{K \cdot m\ s^{-1}}$
$0.5 \mathrm{m\ s^{-1}}$	A1	B1
$5 \mathrm{m\ s^{-1}}$	A2	B2
$15 \mathrm{m\ s^{-1}}$	A3	B3

Favorable environment

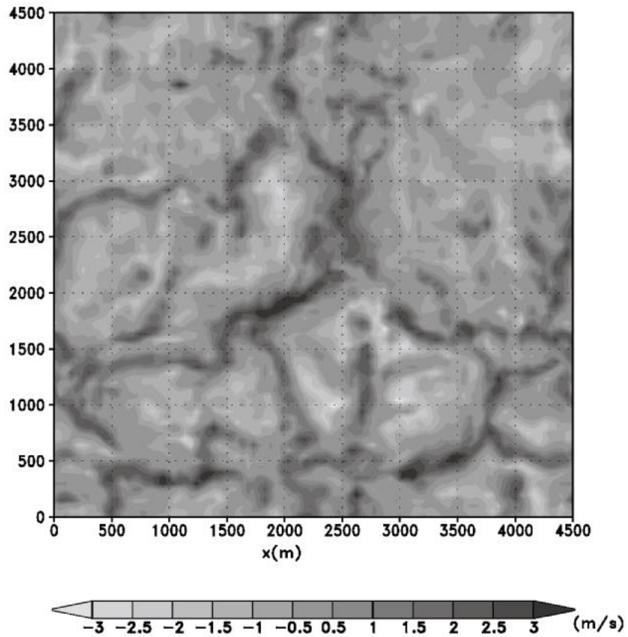
Maximum vertical vorticity ζ(s^{-1}) in horizontal sections at each height



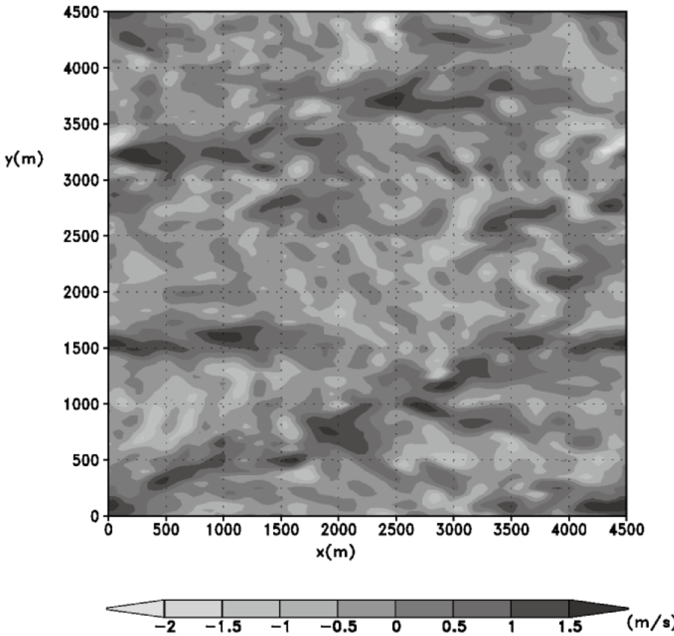
Structure in convective mixed layer

Vertical velocity in horizontal section @14:00, z=50m

A1: **Weaker** ambient wind, **larger** surface heat flux



B3: **Stronger** ambient wind, **smaller** surface heat flux



Cellular convection ⟷ **Roll convection**

Favorable for dust devils

Consistent with observation (Hess and Spillane, 1990)

b. Formation mechanism

LES (e.g. Kanak 2005) have shown dust devils can occur even in horizontally homogeneous convective mixed layer without ambient wind

→ **Formation mechanism?**

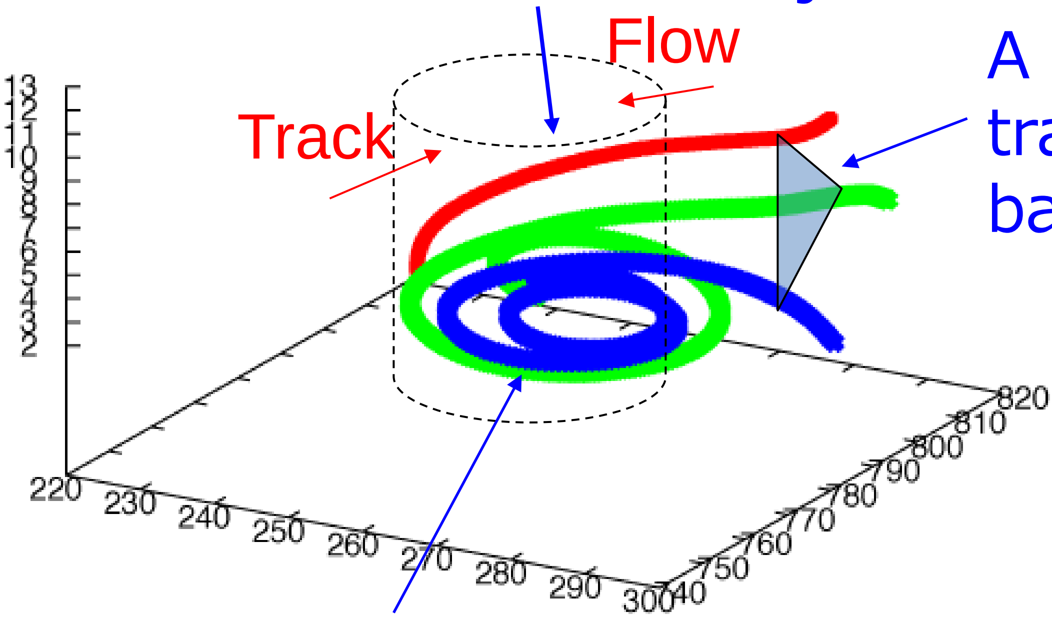
No quantitative study on formation mechanism has been presented

Vorticity analysis results in inconsistent between backward-trajectories due to active CBL turbulence...

→ **Circulation analysis** (Ito et al., 2013)

Circulation analysis

Backward-trajectories



A material surface (MS) is tracked with multiple backward-trajectories

Circulation in MS

$$\Gamma = \oint_S \vec{\omega}\cdot\vec{n}\,ds$$

Fluid particles are distributed at the core of dust devil

Change of the Γ: $\dfrac{d\Gamma}{dt} = F_d + B$

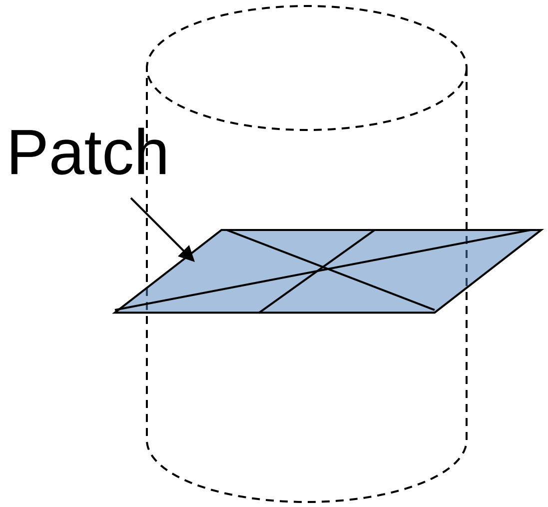
F_d : Turbulent mixing

B : Baroclinic production

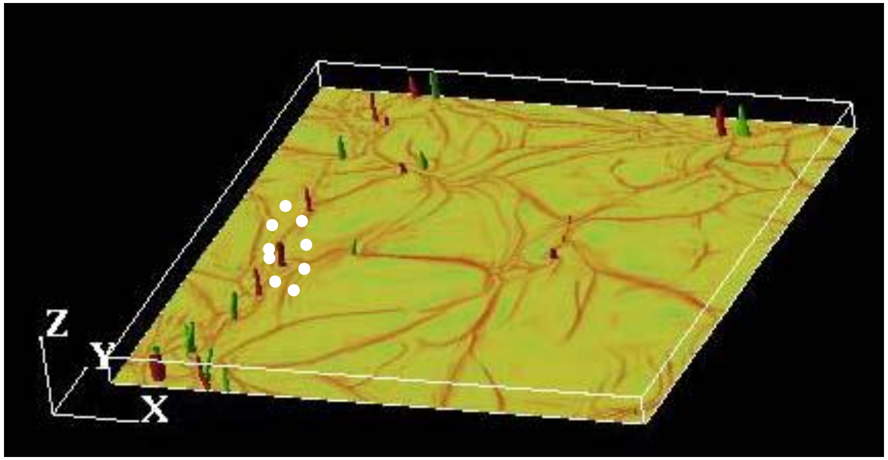
Shrink of MS ⇔ Stretching of vorticity

Tilting of MS ⇔ Tilting of vorticity

Material surface (MS) in a dust devil



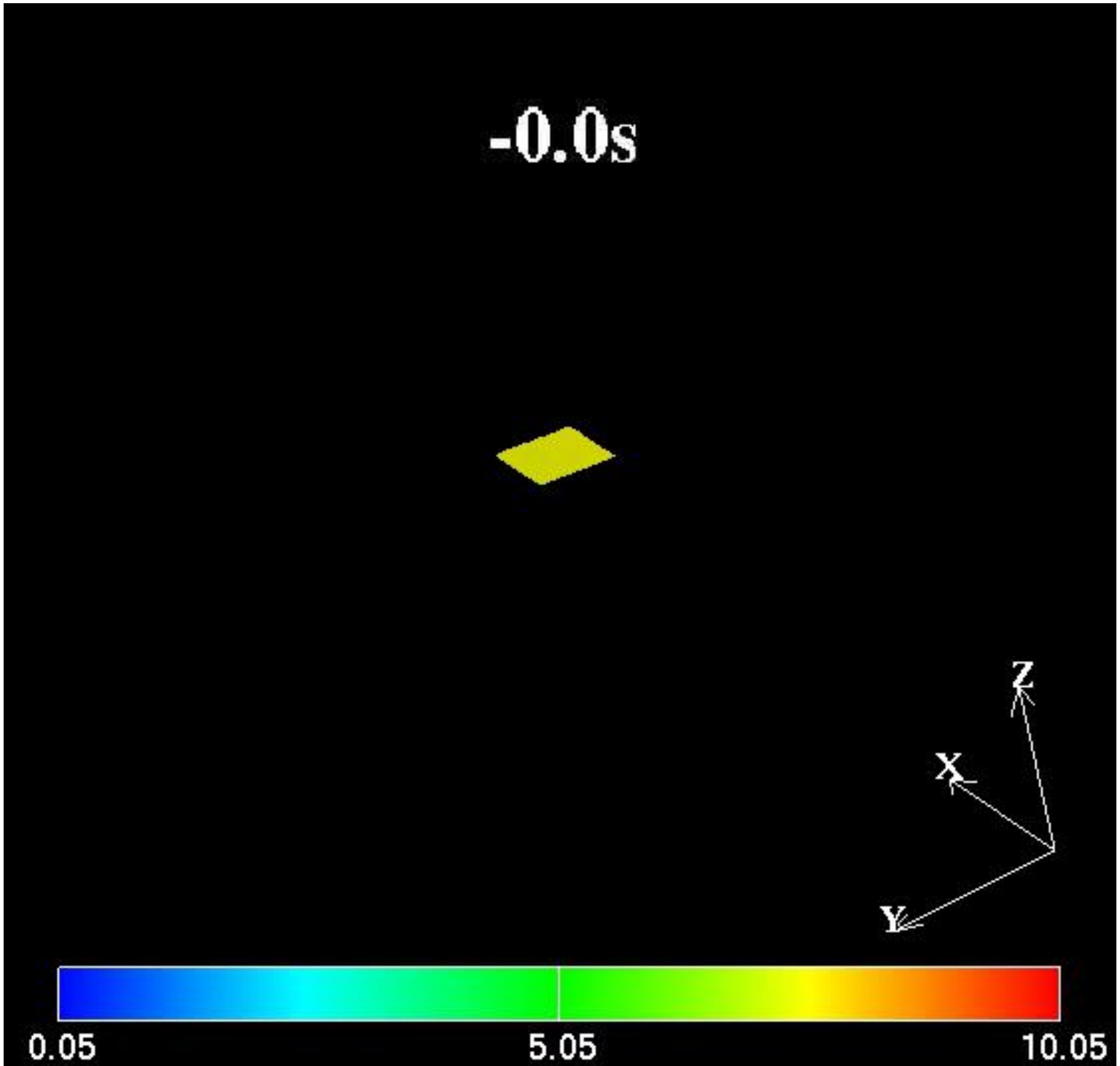
Focusing on the strongest dust devil in LES (dx=5m, Free-slip)



A MS of horizontal 20m×20m square at z=7.5m is placed in the dust devil

The MS consisting of 40,000 triangle patches is tracked with 20,000 backward-trajectories

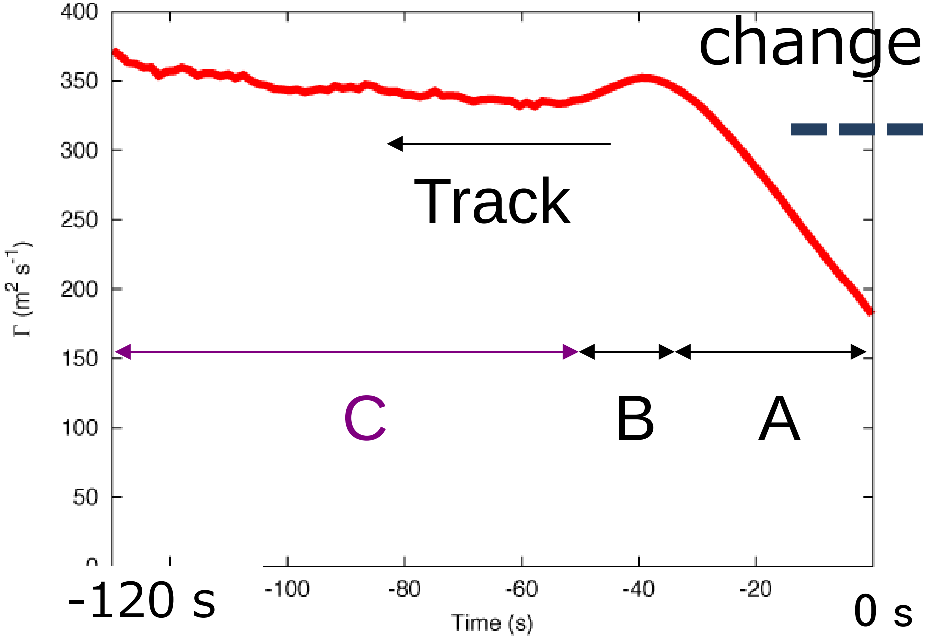
Tracking of Material Surface



Shading:
height (m)

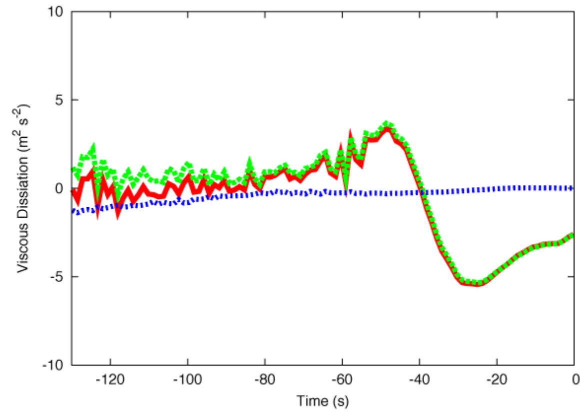
Results and discussion

Circulation Γ

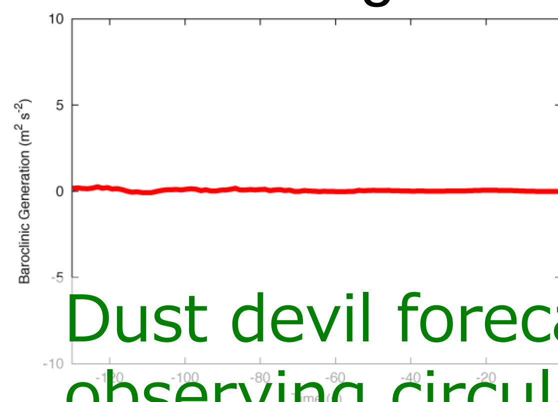


Factors to change of Γ

Turbulent mixing (horizontal, veritical)



Baroclinic generation



Due to turbulent mixing

A: Γ decrease

B: Γ Increase

C: Approximately constant

→ Vertical vorticity stretching in convergence from a wide horizontal area is significant

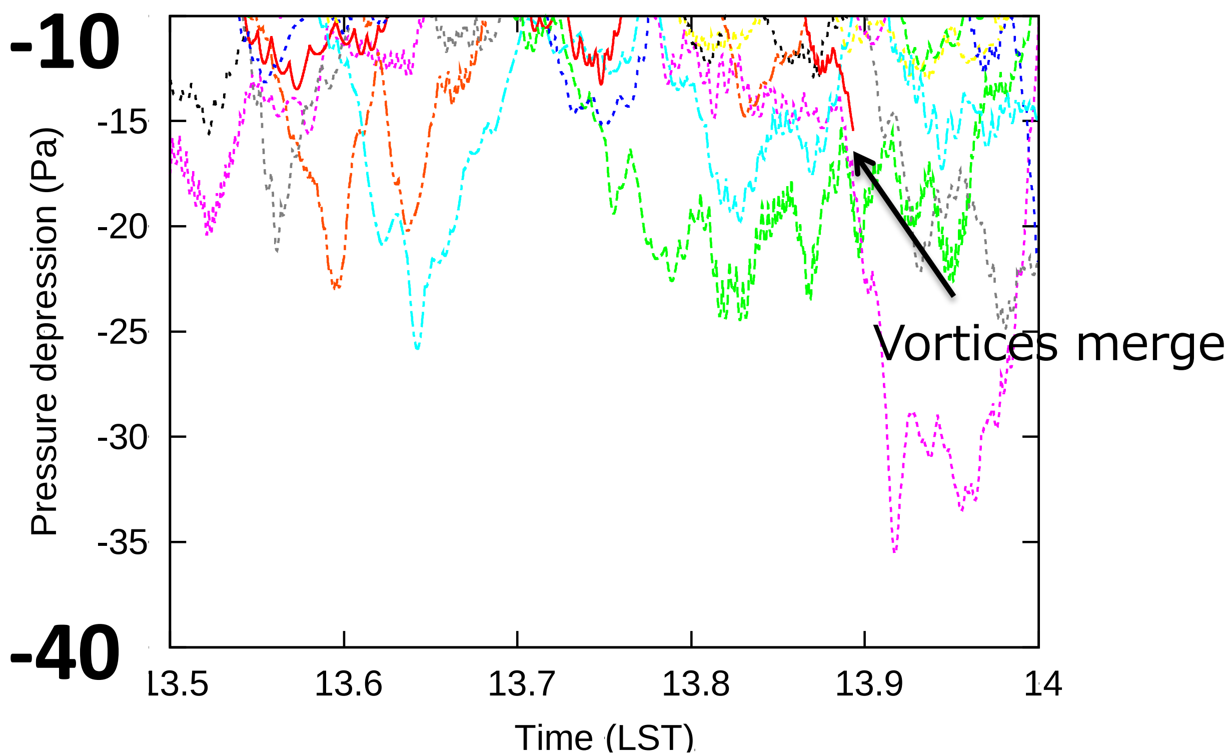
Dust devil forecast by observing circulation?

c. Population of simulated dust devils

LES → Output → Information of All pressure minima p′ < -5 Pa at every time step

→ Track all simulated vortices automatically through a day (0700−1700 LST); only p′ <-10 pa are presented

Example: time series of p′ of each tracked vortex between 1330 and 1400 LST



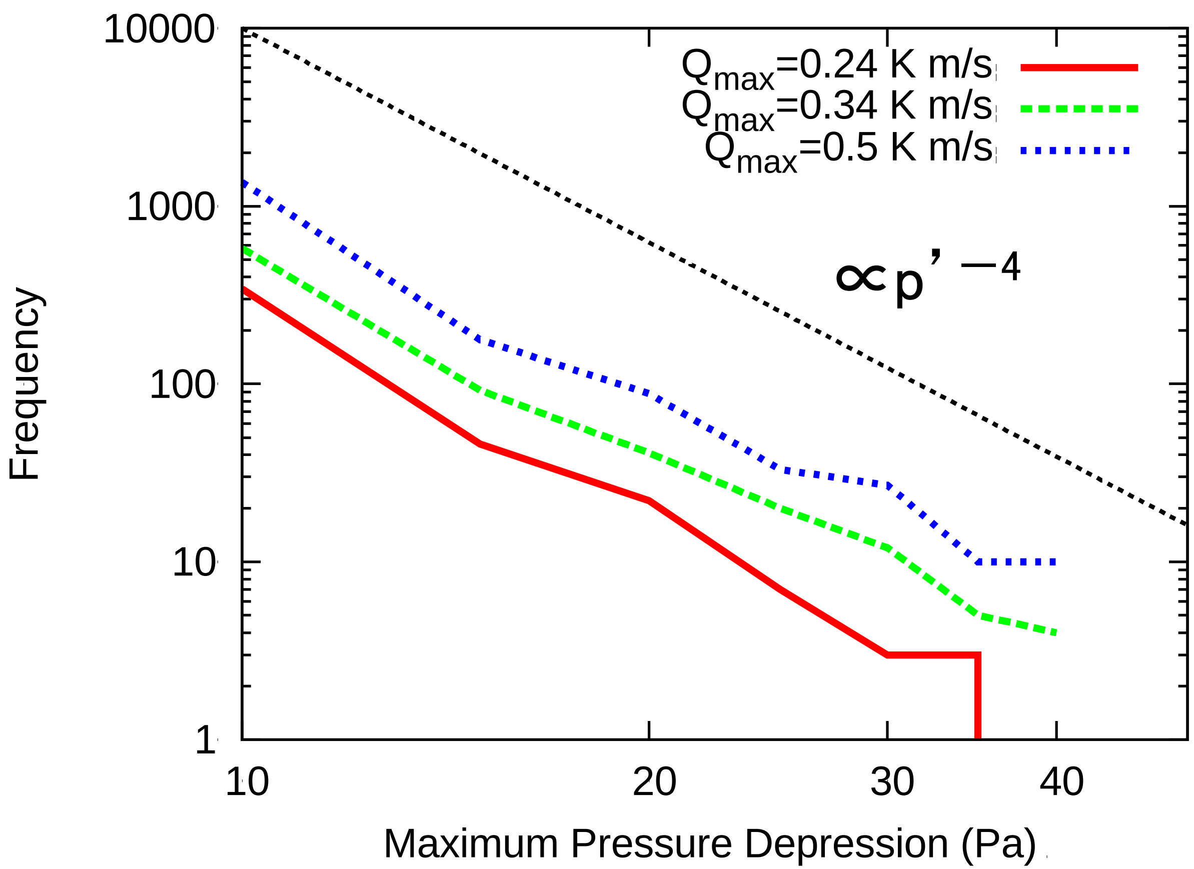
The number of Tracked vortices

LES: dx=20km, Domain: 4.2km×4.2km×4km

Maximum of diurnally varying surface heat flux	The number of vortices whose p' <-10 pa
0.24 K・ms^{-1}	423
0.34 K・ms^{-1}	757
0.5 K・ms^{-1}	1728

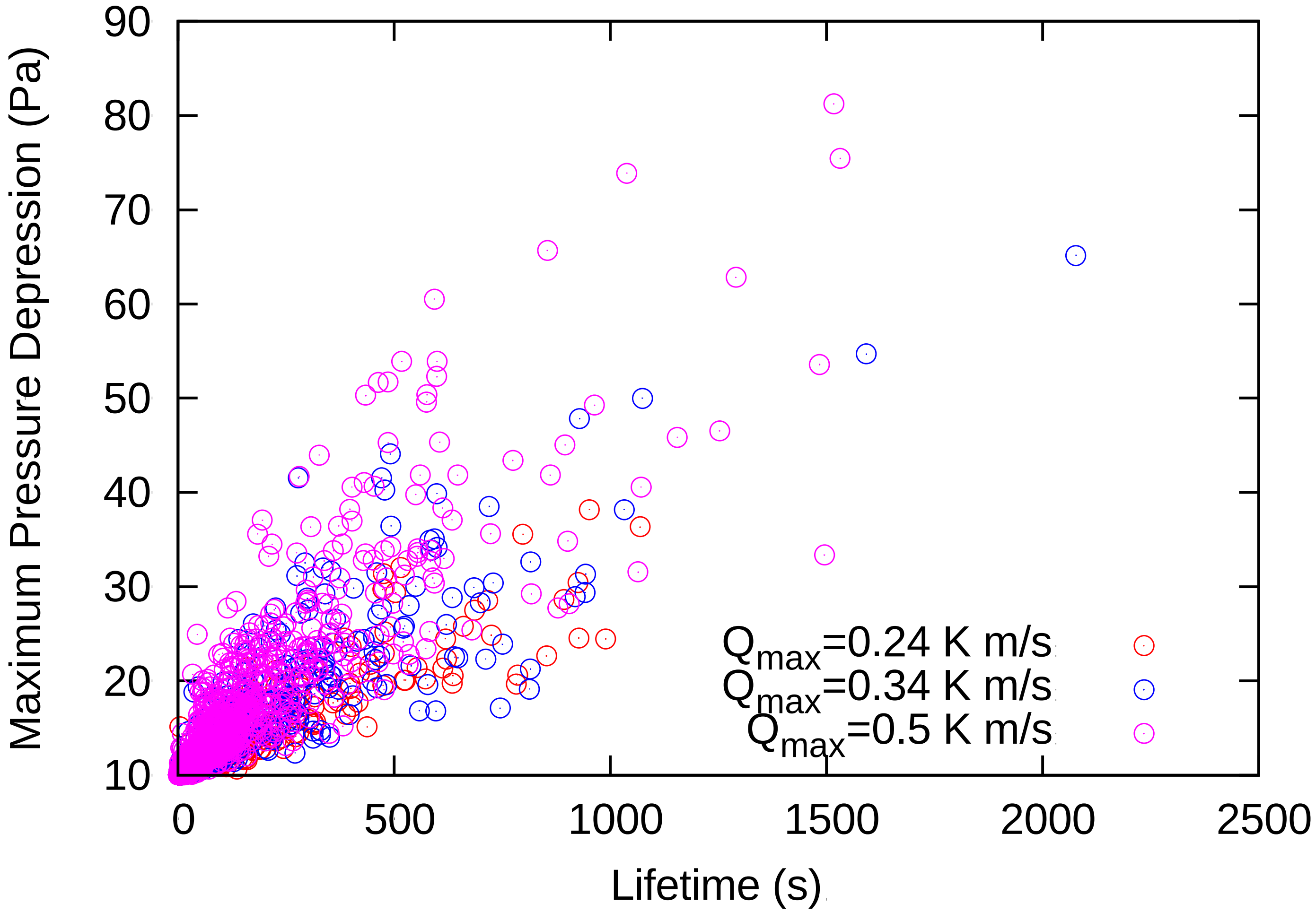
Frequency of Intensity

Based on maximum -p′ of thorough its lifetime



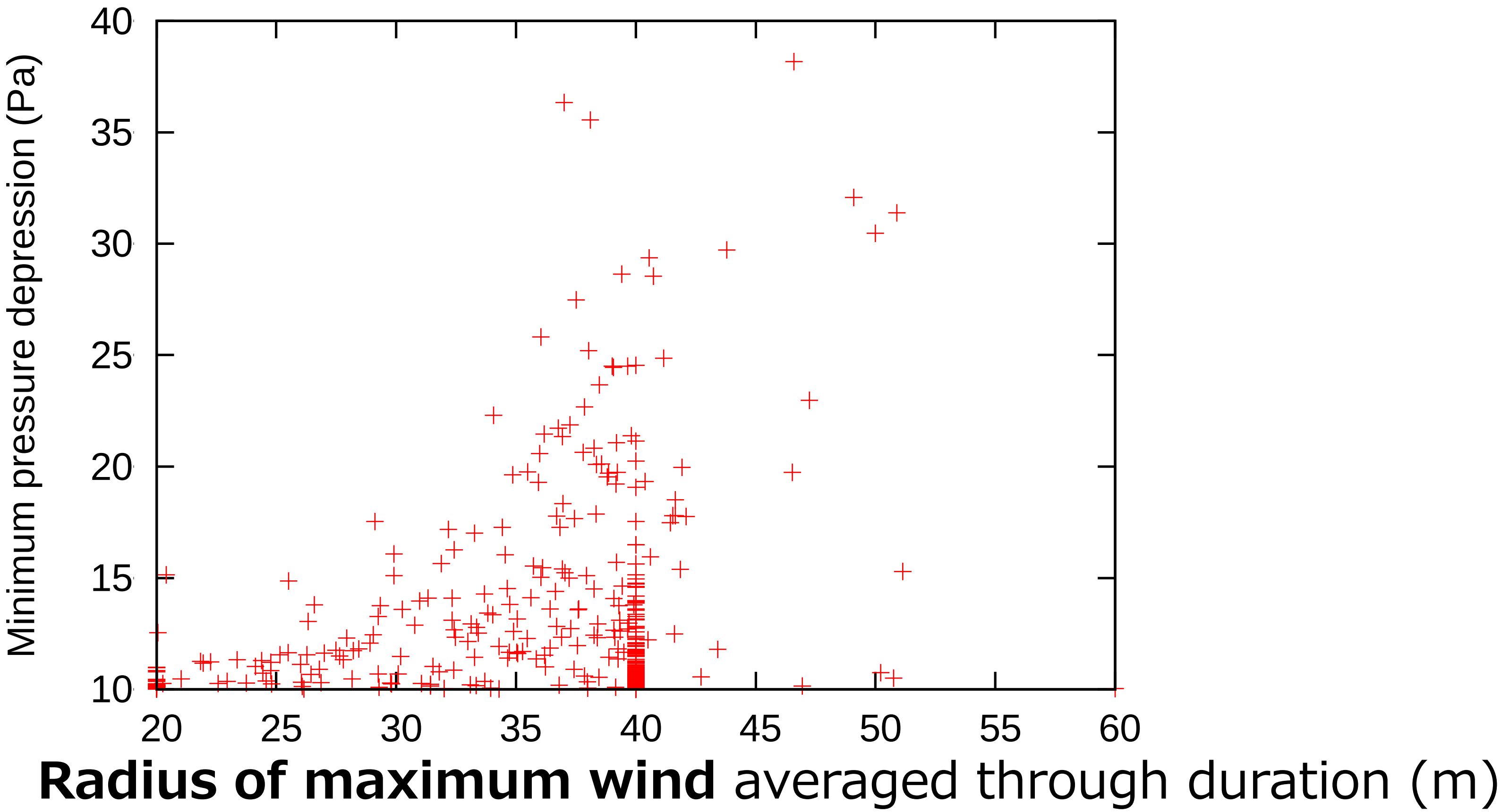
→ Distributions appear to obey a power law

Lifetime vs Intensity



Almost linear relationship: Lifetime $\propto -p'$

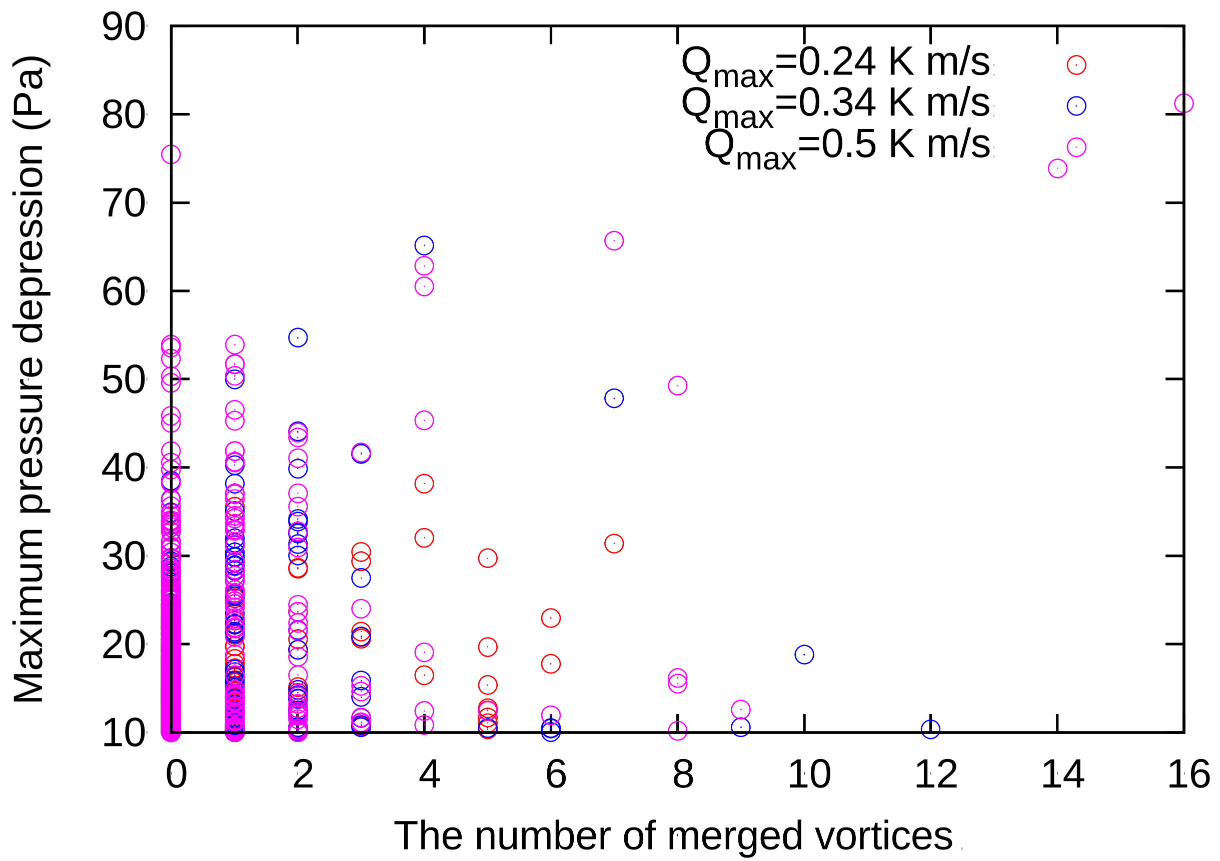
Radius vs Intensity



→ weak positive relationship between radius and intensity

Vortex merging vs Intensity

The number of merged tracked vortices (p’<−5 pa)



- Some vortices merge more than 10 other vortices

↔ Vortex merge is unnecessary for forming strong vortex

d. Feedback between surface heat flux and dust devil wind

Surface heat flux *Q*:

(LES so far) Horizontally homogeneous:

$$Q = Q_f \circ 0.5 \times \sin((t - 7)/11)$$

↕

(In reality) Depends on **near-surface wind speeds**

(i.e. Bulk method: $Q = C_H U \Delta\theta$)

U: Wind speed at lowest level

Possible positive feedback

Whirl wind induce locally large *Q* → Intensify dust devil → Stronger whirl wind → … (c.f. WISHE to develop Tropical cyclone)

Quasi-bulk method

$$Q = Q_f \times \frac{U}{\langle U \rangle}$$

Horizontal average remain the same

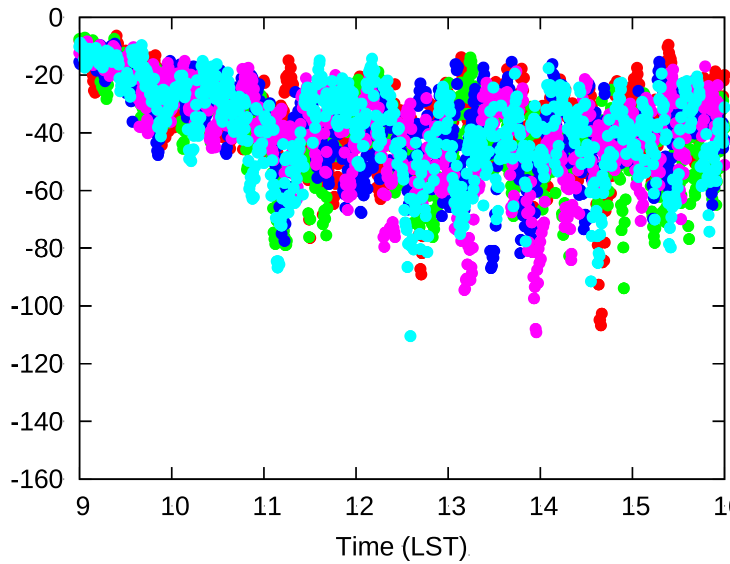
<*U*>: horizontal average of *U*

Comparison of pressure depression

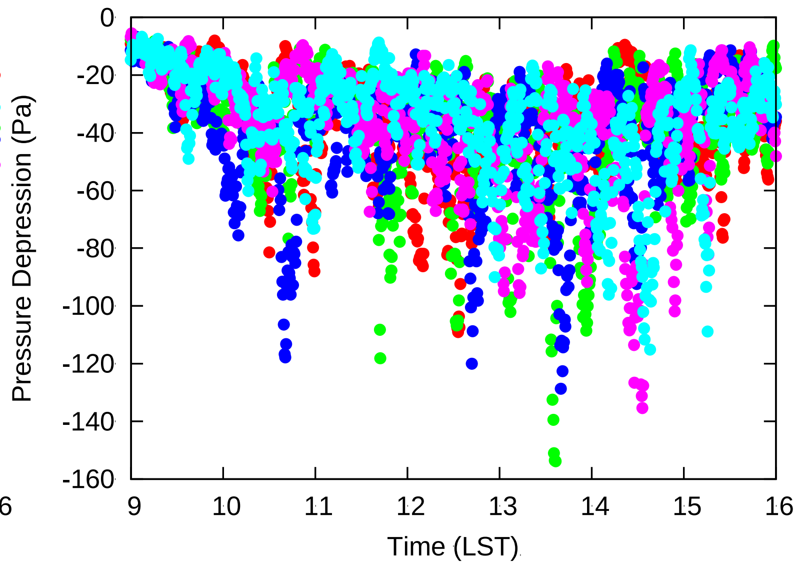
Time series of minimum pressure depression at each time

(Pa)

5 samples with usual LES **Homogenous Q**



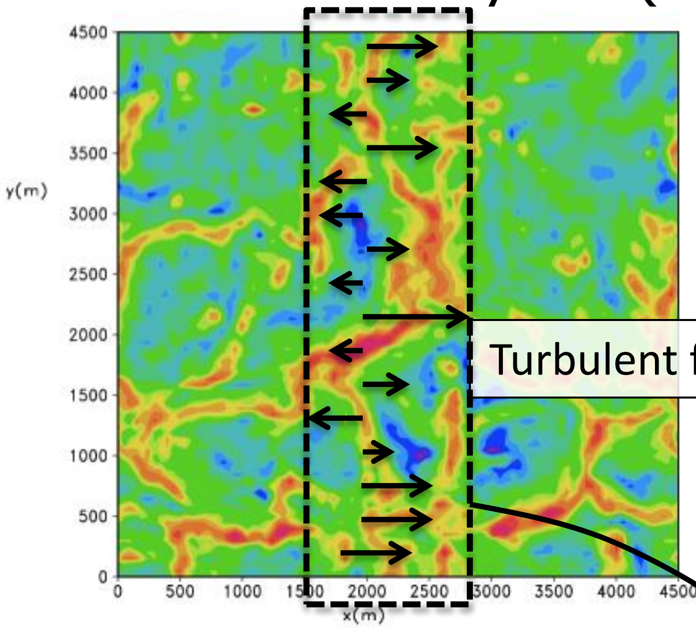
5 samples with **Quasi-bulk method**



The feedback between **surface heat flux** and **whirl wind** may form **stronger dust devils**

2.2 LES to develop parameterization

LES (Large Eddy Simulation) resolve turbulent eddies in convective mixed layers (CML)



Turbulent flux

Vertical velocity in horizontal cross-section at the middle of CML

Horizontal turbulent diffusivity K_h

↑ little investigated so far, but significant for high horizontal resolution

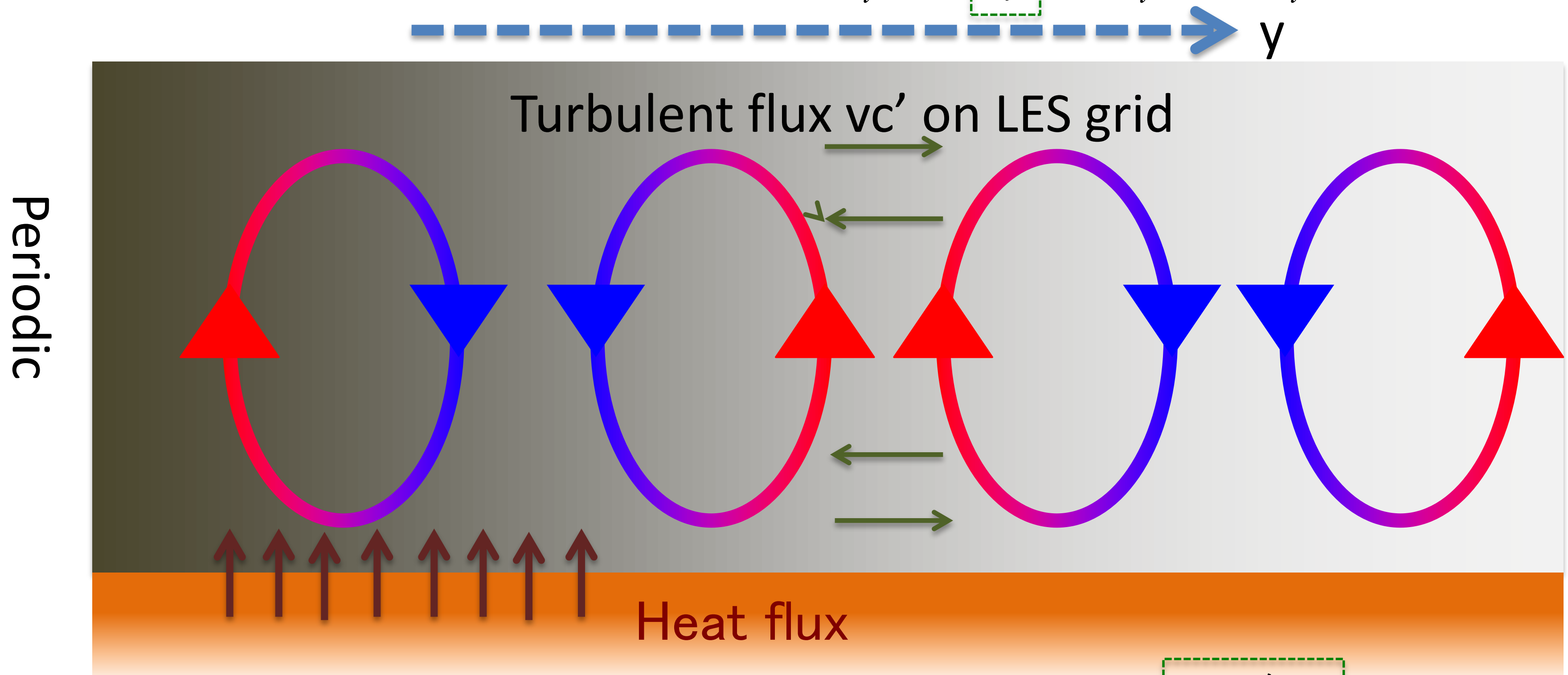
Given

<Horizontal turbulent flux> = - K_h × Gradient

Passive scalar to evaluate diffusivity

Passive scalar with uniform gradient $\boxed{\frac{\partial C}{\partial y} = -1}$ as **basic field**

Equation of perturbation : $\frac{\partial c'}{\partial t} = -u_i \frac{\partial c'}{\partial x_i} - u_y \boxed{\frac{\partial C}{\partial y}} + \frac{\partial}{\partial x_i}\left(u_q \frac{\partial c'}{\partial x_i} \right)$



<vc>=−<Horizontal turbulent diffusivity **K_h**> × $\boxed{\partial C/\partial y}$

< > : horizontal average over domain

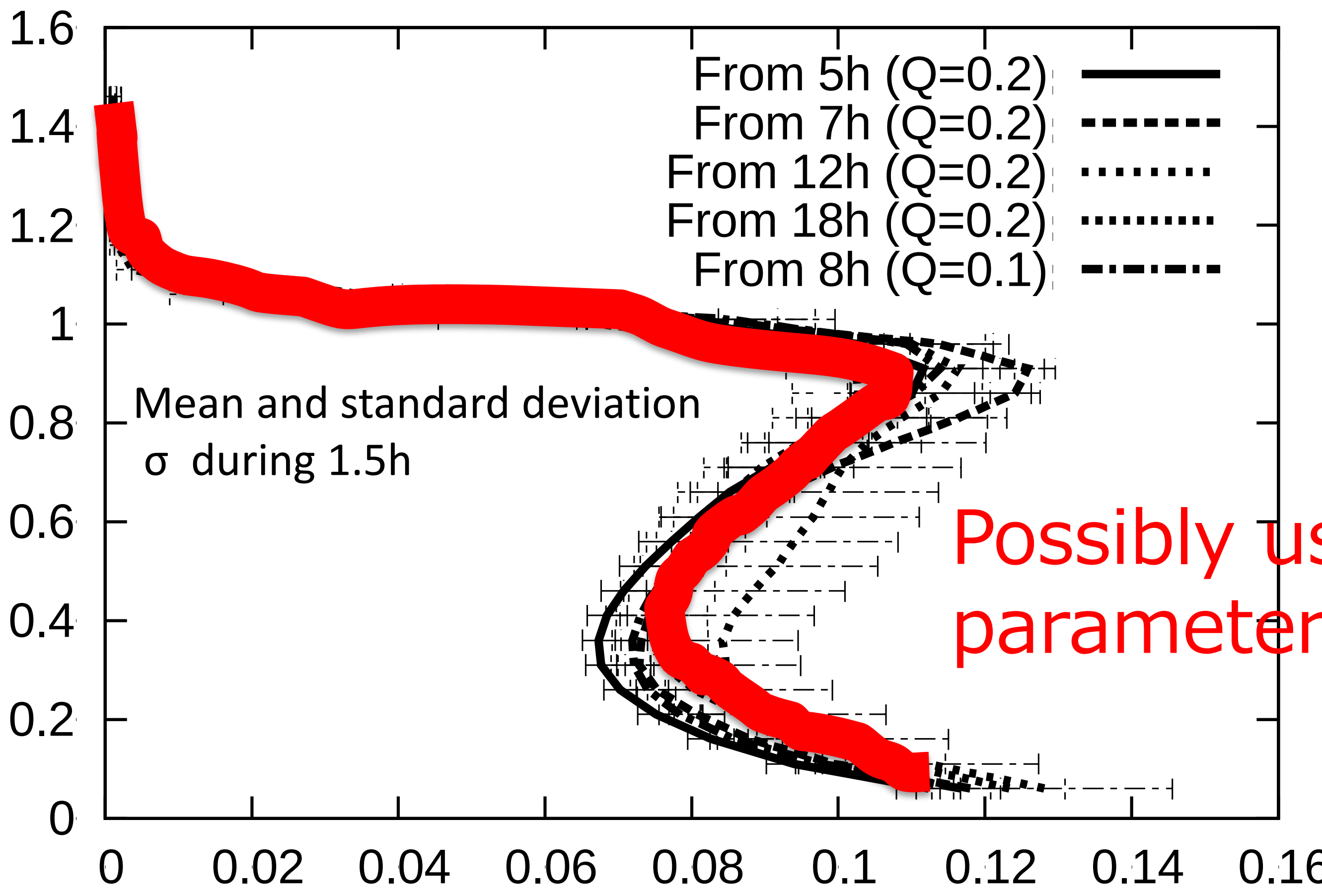
LES model (almost the same as that for dust devil)

Basic equation	3-D, dry, and Boussinesq approximation
Sub-grid	Smagorinsky-Lilly model
Resolution	25 m
Domain	18 km × 18 km × 5.0 km
Boundary conditions	Lateral: doubly periodic Bottom: Constant flux Q (Heat) + Friction given by bulk method (Momentum)
Initial conditions	U=0m/s, Stable stratification (Γ=4.0K/km)
Time step	0.2 s

Vertical profile of non-dimensional K_h

(Ito et al. 2014)

Scaled Height z/h



Possibly used for parameterization

Non-dimensional K_h ($\equiv K_h / w_* / h$)

Summary

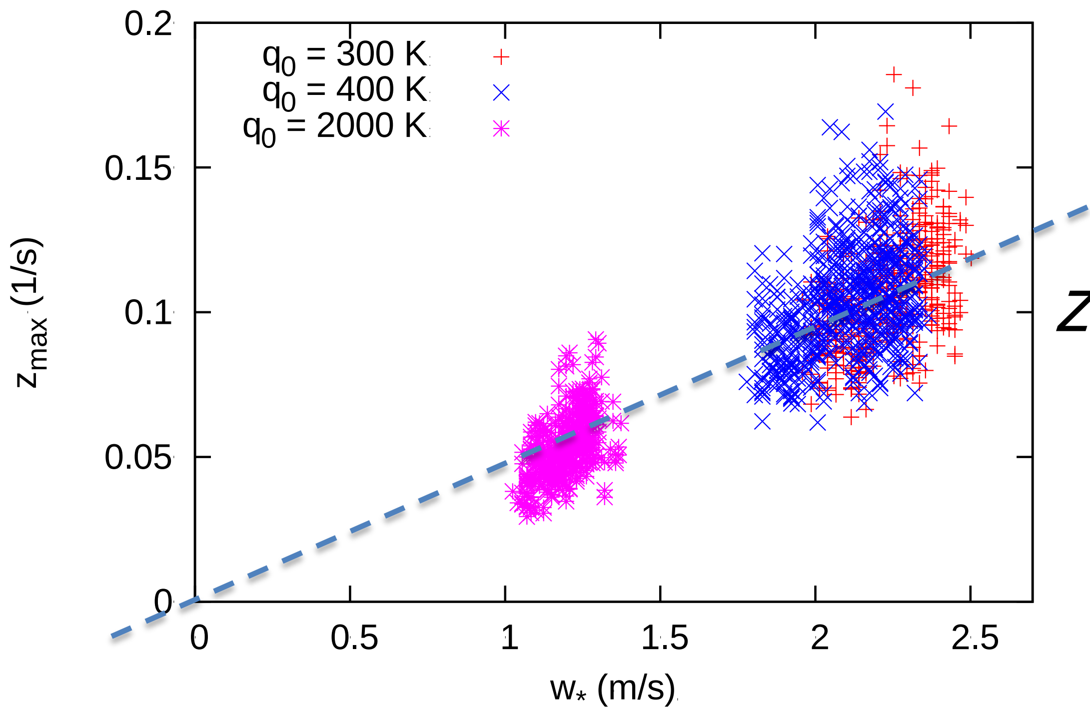
- **LES for Earth**: huge LES for entire tropical cyclone was conducted
- **LES for terrestrial convective mixed layers**
  - **Dust devil**
    - Favorable environment: weak ambient wind and strong surface heat flux
    - Formation Mechanism: Convergence of preexisted circulation over wide horizontal area
    - Population is evaluated
    - Positive feedback between surface flux and wind
  - **Horizontal eddy diffusivity**

    Non-dimensional horizontal diffusivity

    $K_h \sim 0.1$

Scaling by w_* for different standard potential temperature θ_0

Q=0.2Kms^{-1}, Γ=0.004K/km, dx=50m, θ_0=300K, 400K, and 2000K (Difference between planets?)



$w_* \text{ o } \left(gQh/q_0\right)^{1/3}$

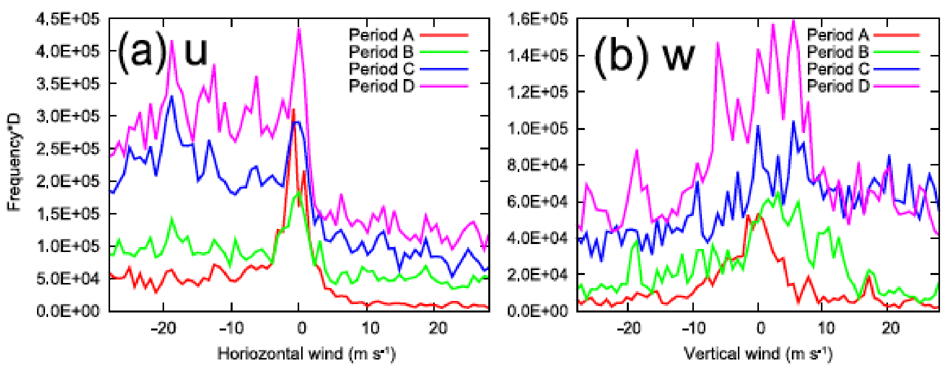
$z_{\max}\ \mu\ w_*$

Convective velocity w_* seems to be velocity scale

→ What is length scale that depend little on time?

Wind speed estimated by PIV (Ito et al. 2014)

- Particle Image Velocimetry (PIV) is performed
- RGB difference between two successive time steps at the front of the dust devil → Wind vectors in pixel/s
- Stereoscope of the dust devil by two cameras and height of observer → 1 pixel = 13 cm (physical unit)



0. PIV of a dust devil

- Tucson, Arizona, 19/7/2012

3. Scaling of dust devils

CBL has self-similarity → Scaled by CBL height h, convective velocity w_*, and so on (Deardroff 1970)

Vorticity of dust devil can be also scaled as

~(a velocity scale)/(a length scale)?

A natural choice:

- A velocity scale: Convective velocity w_* ?
- A length scale: CBL height h ?

→ Vorticity scale $\frac{w_*}{h} \propto h^{-3/2}$

Inconsistent because vorticity scale become small when CBL develop

$$w_* \propto (gQh/\theta_0)^{1/3}$$

g: gravitational constant

Q: surface heat flux

θ_0: standard temperature

LES for exploring scaling

Domain : 4.5km×4.5km×3km; no ambient wind

Parameters to be changed

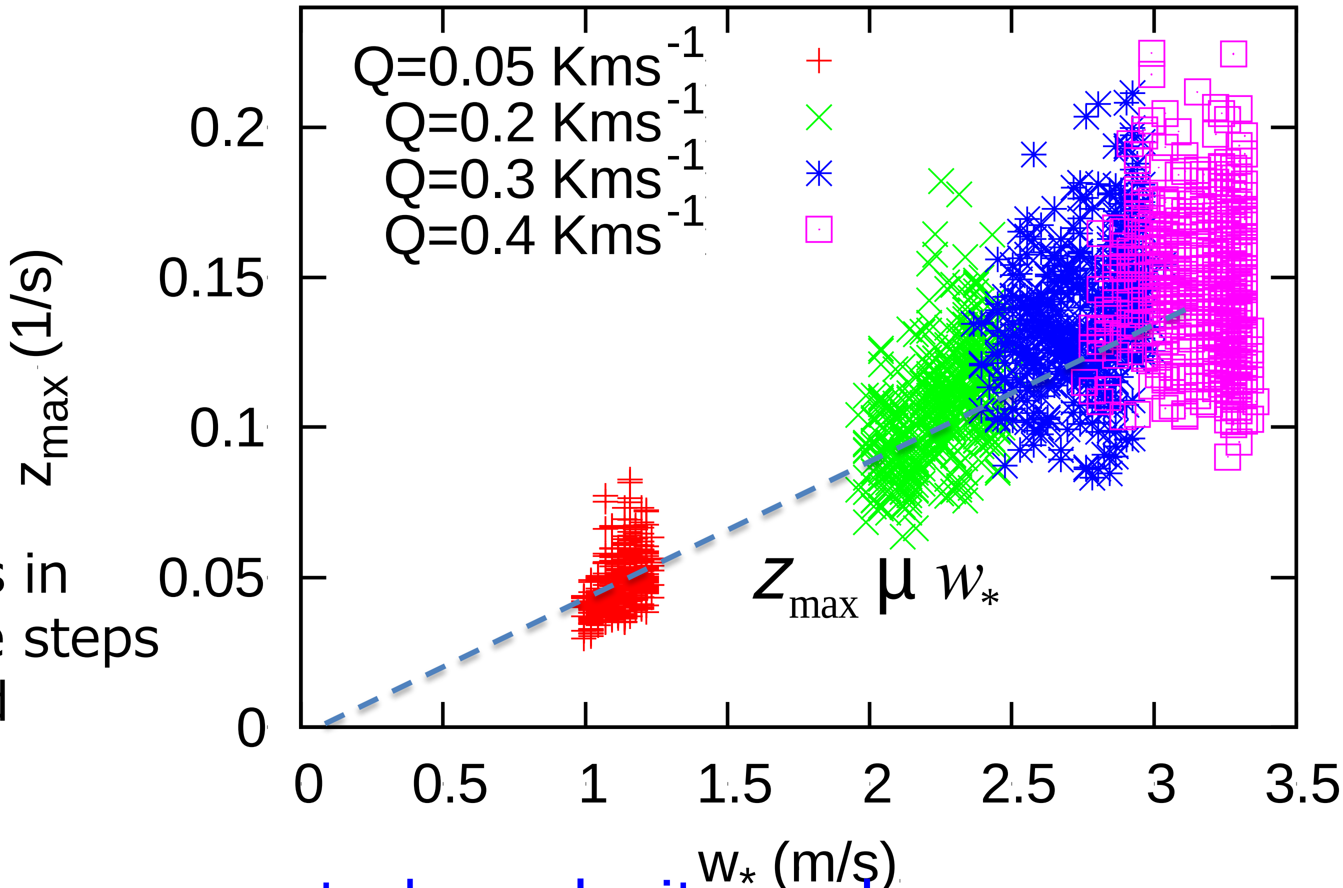
- Surface heat flux Q: Constant (0.005, 0.1, 0.2, or 0.3 K・m/s)
- Grid resolution Δ: (50 → 6.25m)
- Standard temperature θ_0
- Initial stratification Γ: 4, 8 K/m

CBL height h is also varied by time t; h increase as square root of t

$$h = \sqrt{\frac{2Qt}{G}}$$

Scaling by w_* for various Q

Correlation between w_* and maximum vertical vorticity ζ_{max} at z=75 m at each time



Data points in earlier time steps are omitted

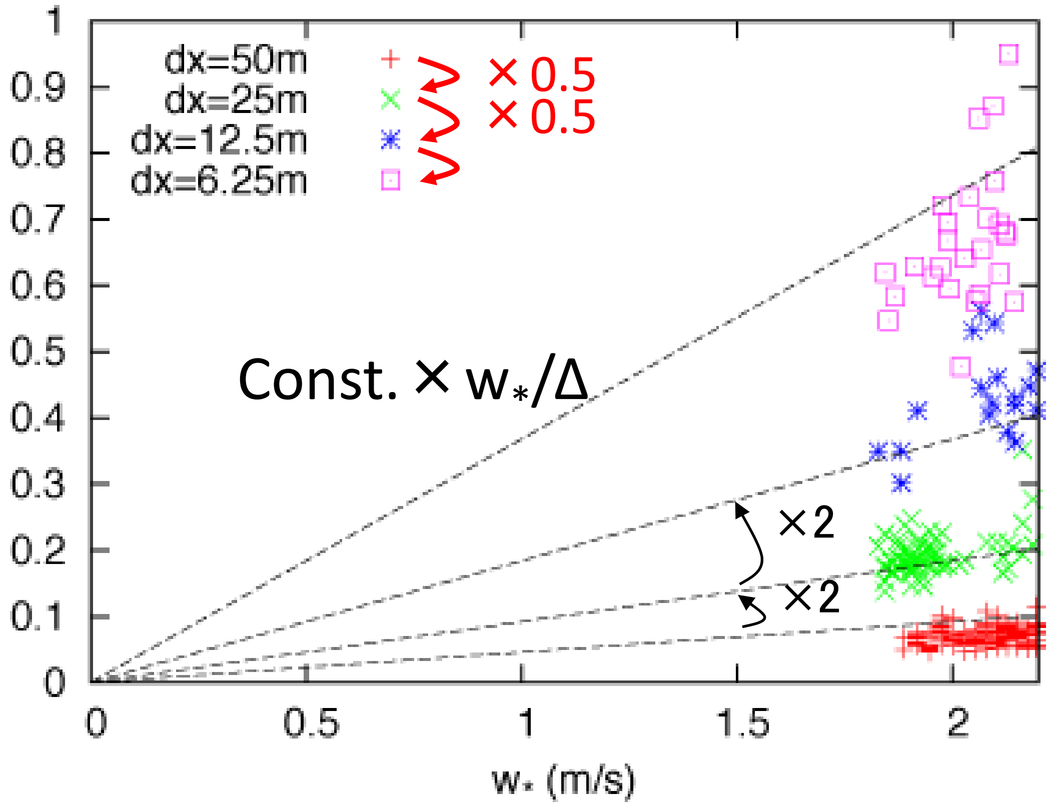
→ w_* seems to be velocity scale

Vorticity～Velocity/Length

→ What is length scale that depend little on time?

Dependence on dx

Correlation between w_* and ζ_{max}; Q=0.2K･m/s, Γ=0.004K/m, Various *dx*



ζ_{max}:

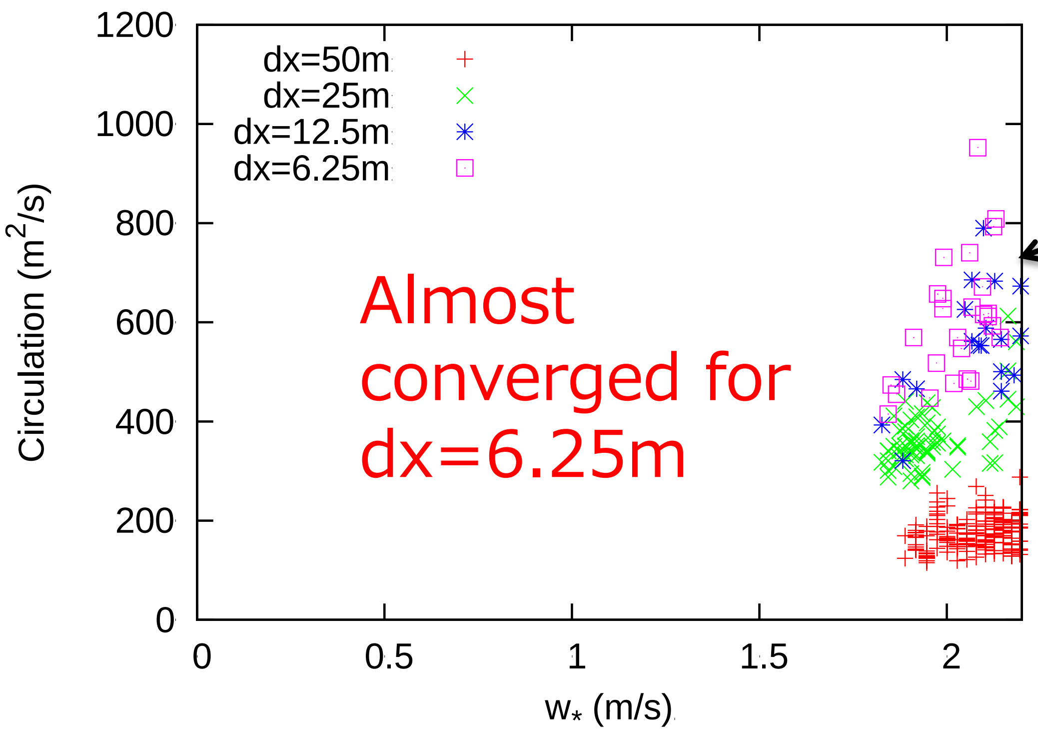
maximum vorticity at z=75m

dx=50 m→12.5 m: halving dx doubles vorticity

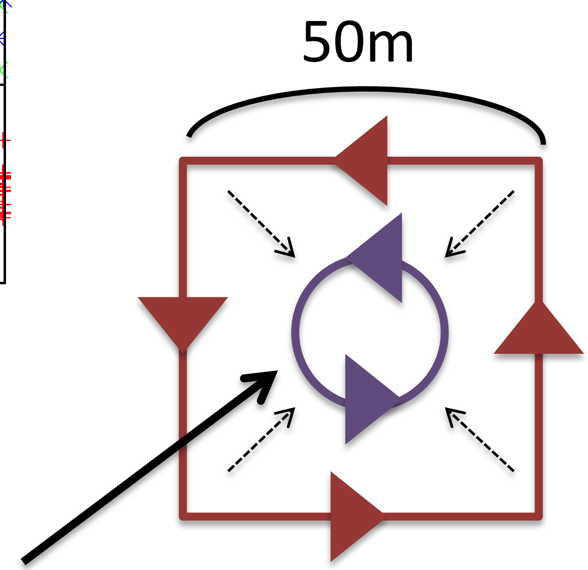
dx=12.5 m → 6.25 m: vertical vorticity increase more moderate

Scaling of *circulation*

Correlation between w* and circulation in the range of 50m by 50m horizontal plane at z=75 m



$\Gamma_{max} \propto h \times w_*$: circulation can be scaled
(Ito et al. 2013)

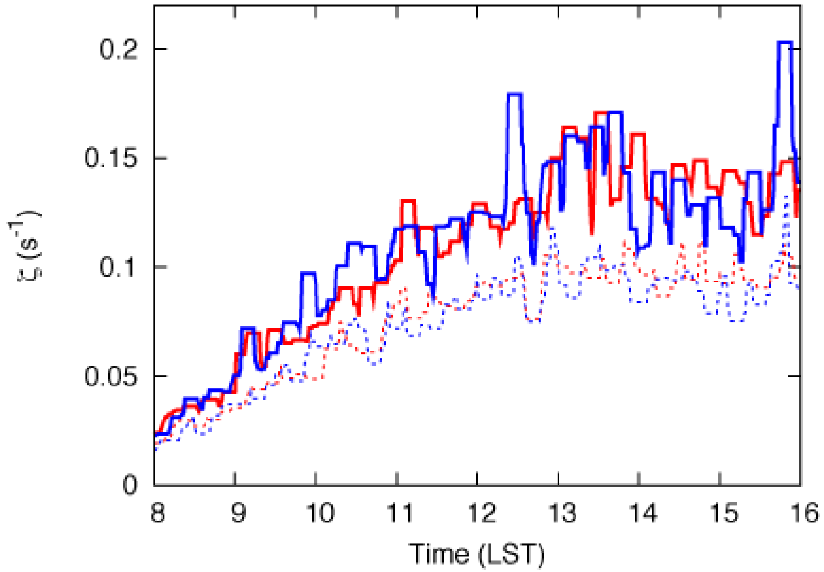


Simulated dust devil vorticity may strongly depend on resolution *dx*

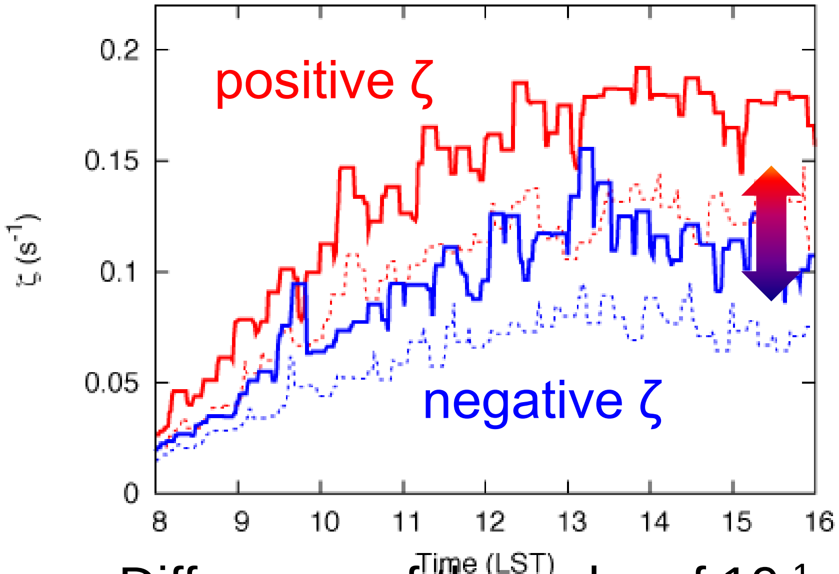
Effect of ambient rotation (Ito et al. 2012)

Time series of maximum Positive vertical vorticity and Negative vertical vorticity at z = 25 m with LES whose Δ = 50 m

LES without Coriolis effect



LES with Coriolis effect f~10^{-3} 1/s（10 times as large as one at mid-latitude ）



Littlie difference between ←→ Difference of the order of $10^{-1}s^{-1}$ between positive and negative ζ

Ambient rotation ～ 10^{-3} s^{-1} → Difference in vertical vorticity at dust devils ～ 10^{-1} s^{-1}

→ Convergence from wider horizontal area

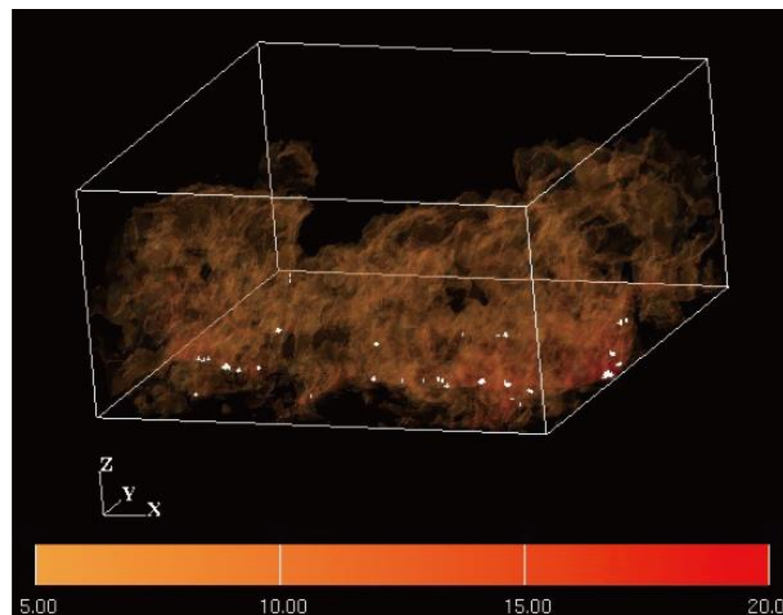
6. Dust suspension

- Include dust processes
  - Bulk formula for upward dust flux F_d at lowest level (Loosmore and Hunt, 2000)

  $F_d \equiv 3.6(u_*)^3$, u_*: frictional velocity
  - Gravitational settling
  - Prognostic equation of dust concentration c
- No ambient wind
- dx=25m

3D image of dust concentration c at 1500 LST

Shade: dust concentration
White circles: larger vertical vorticity



Dust amount in CBL

Horizontally averaged dust concentration

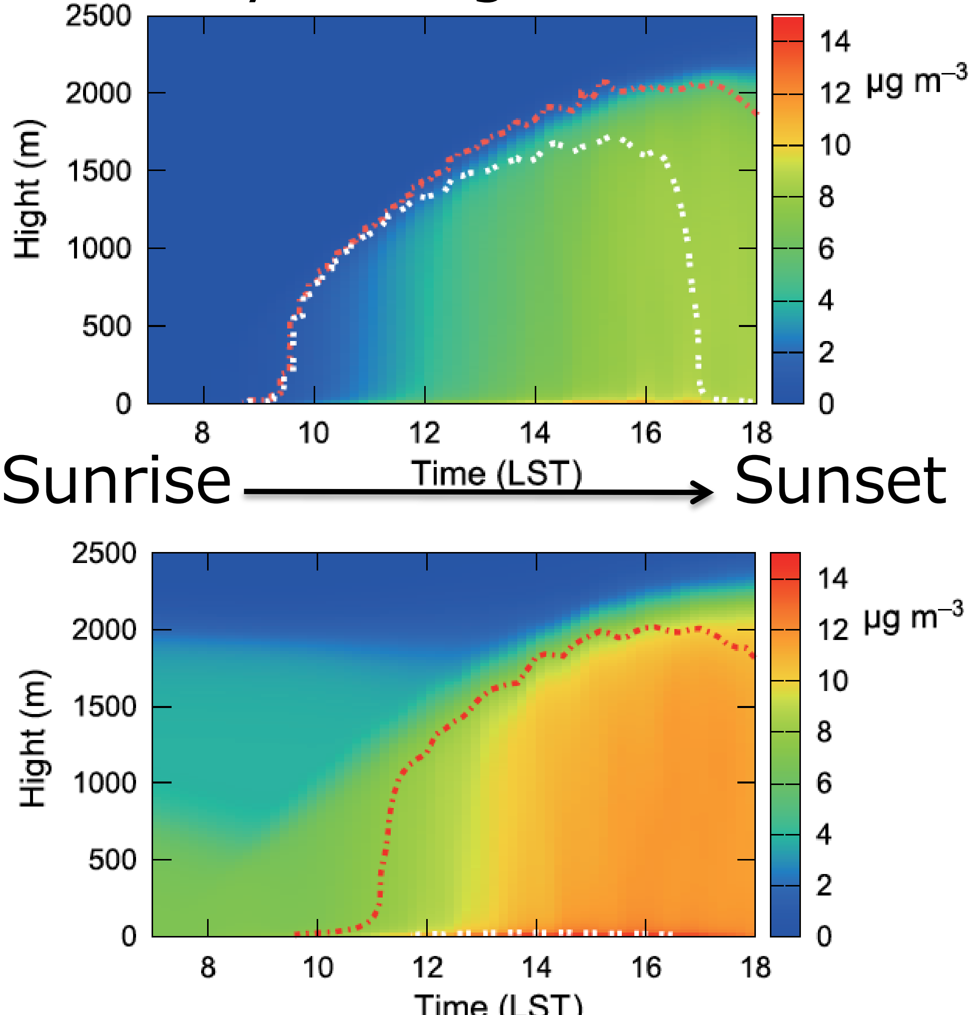
1st day

Assume gravitational settling at night

2nd day

1.86 times larger concentration

→ ∞ day



$$c_1+0.86c_1+0.86^2c_1+0.86^3c_1+\cdot\cdot\cdot+0.86^{\infty}c_1 \rightarrow 7.16c_1$$