Workshop on Japanese-French Model Studies of Planetary Atmospheres
CPS, Kobe University, Kobe, Japan, 11-15 May 2015

Numerical Experiments on Dust Devils, Atmospheric Vortices, and Dust Transport on Earth

Tetsuya Takemi

Disaster Prevention Research Institute
Kyoto University

DPRI-KU

京都大学
KYOTO UNIVERSITY

Collaborators: Hiroshi Ohno, Yuhei Hayashi, Yoshiaki Miyamoto

Atmospheric vortices: dust devils

(Balme and Greeley 2006)

(Gu et al. 2008)

Atmospheric vortices: tornadoes

Figure 1. Ellis County, OK tornado of May 4, 2007. Photos courtesy of Reed Timmer and Joel Taylor of TornadoVideos.net. Image (a) is from approximately 1 km away, a few minutes before the viewing at approximately 100 m in the (b) image. Suction vortices are evident at the base of the condensation funnel.

(Fiedler 2009)

Figure 4

An example of a multiple-vortex tornado. Photograph courtesy of H.B. Bluestein.

(Rotunno 2013)

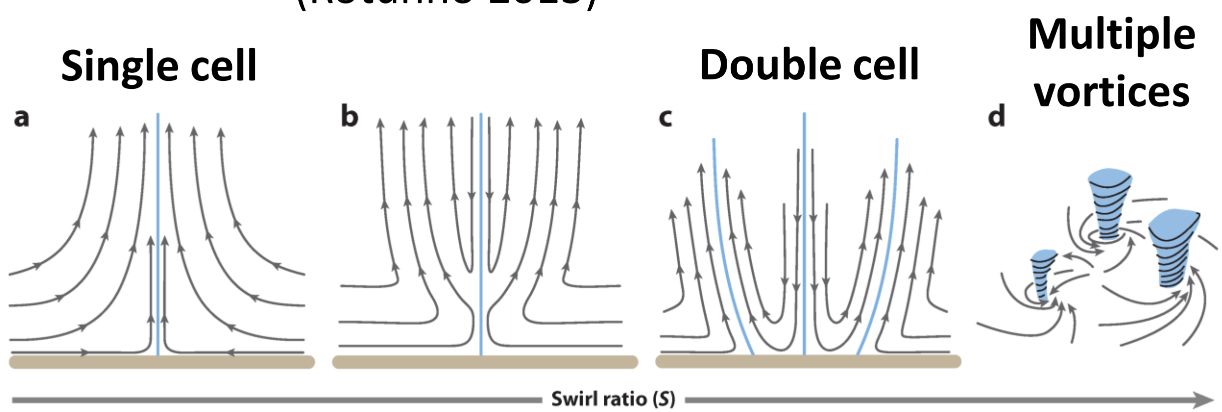


Figure 9

For increasing swirl ratio, S, Ward (1972) showed that the form of the vortex changes from (*a*) single-celled to (*b*) single-celled below and doubled-celled above to (*c*) doubled-celled to (*d*) multiple vortices. Figure adapted from Davies-Jones (1986).

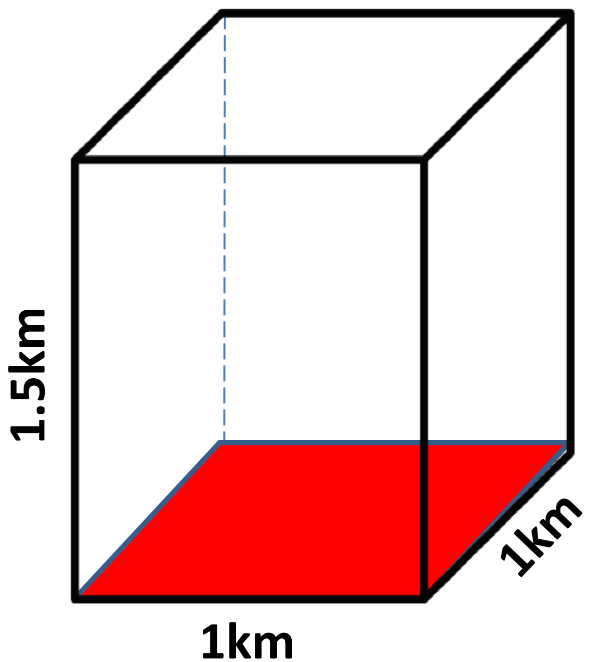
(Rotunno 2013 [Adapted from Davies-Jones(1986)])

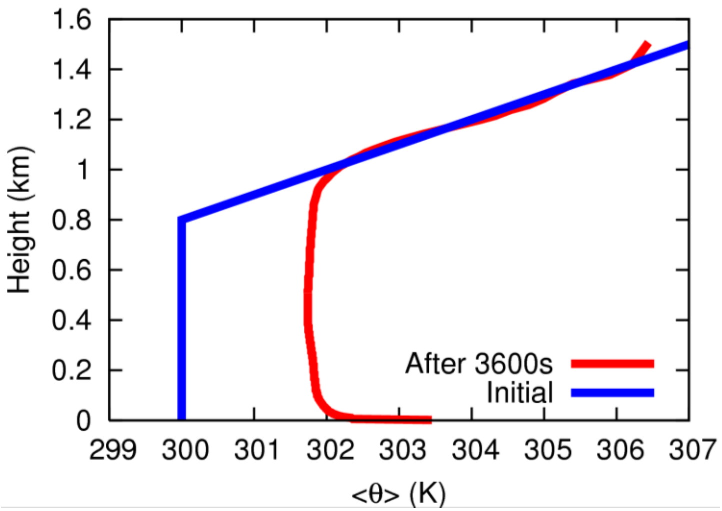
Motivation and purpose

- Dynamics of vortices has been investigated by laboratory experiments and numerical models.
- Numerical models are a useful tool to investigate the dynamics of vortices.
- Previous numerical models mostly are based on an incompressible fluid; however, this assumption is not valid in cases with very high wind speeds and density stratification.

- Therefore, we investigate the dynamics of vortices with non-hydrostatic, compressbile atmospheric models.

Large-eddy simulation of dust devils





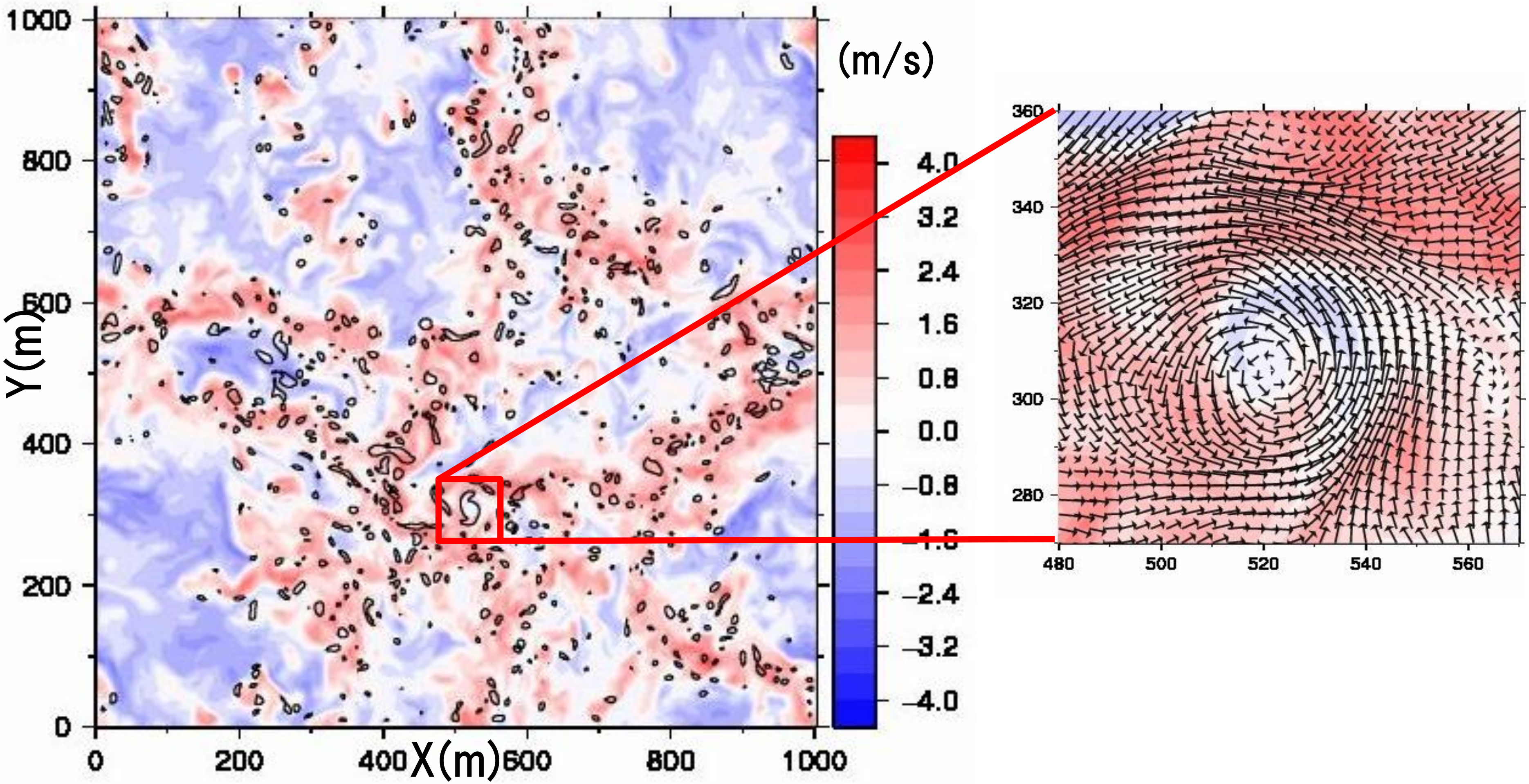
- Numerical model: WRF/ARW
- Domain: 1 km x 1 km x 1.5 km
- Resolution: 3 m (horizontal)
- Lateral boundaries: periodic
- Surface: momentum & heat fluxes
- SGS model: Smagorinky
- Base-state: initially at rest

Vertical profile of potential temperature at Initial and 3600 s times.

(Ohno and Takemi 2010a)

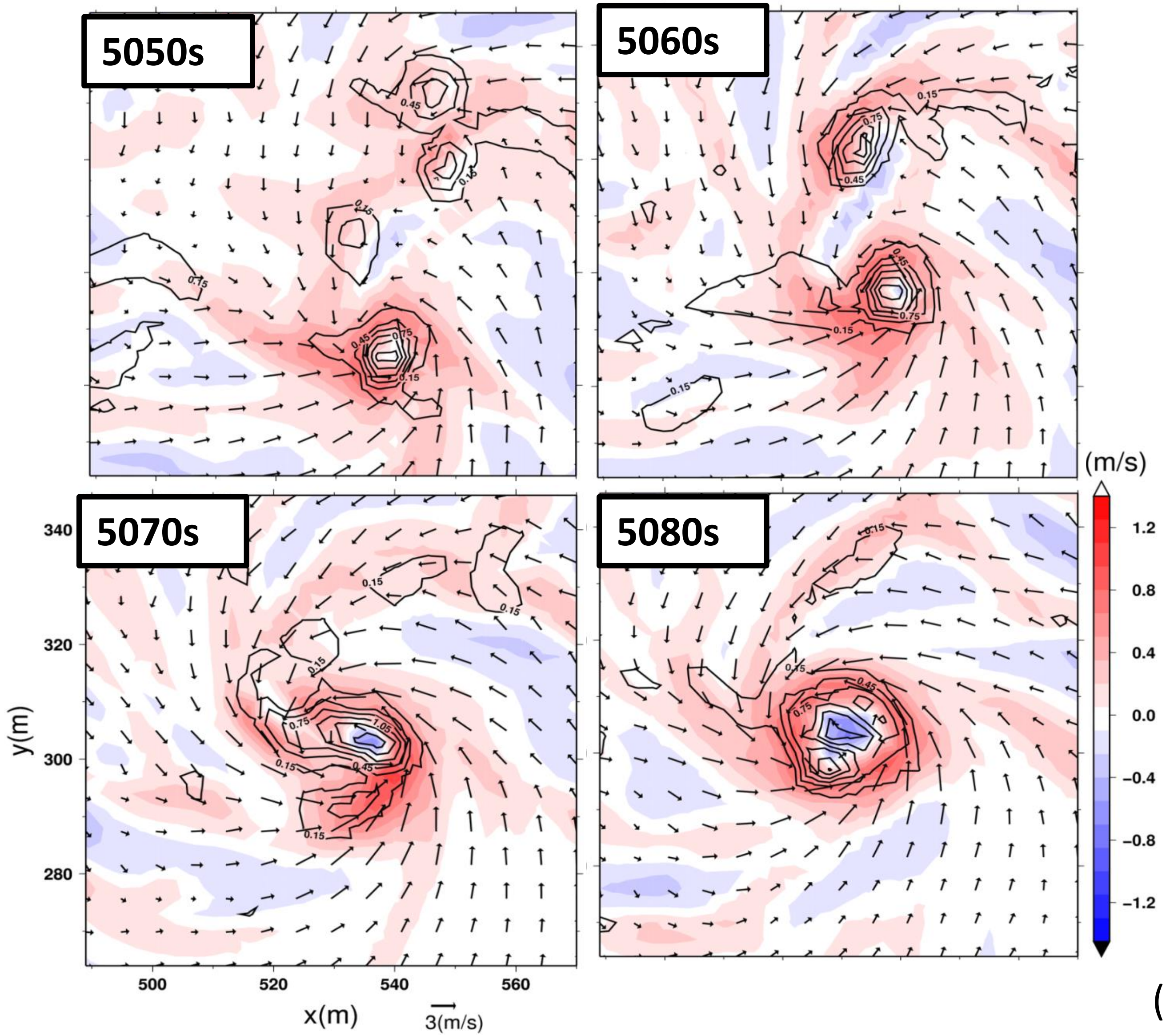
Convective cell and vortices

Horizontal cross section of vertical velocity and vertical vorticity at the 50-m height



(Ohno and Takemi 2010a)

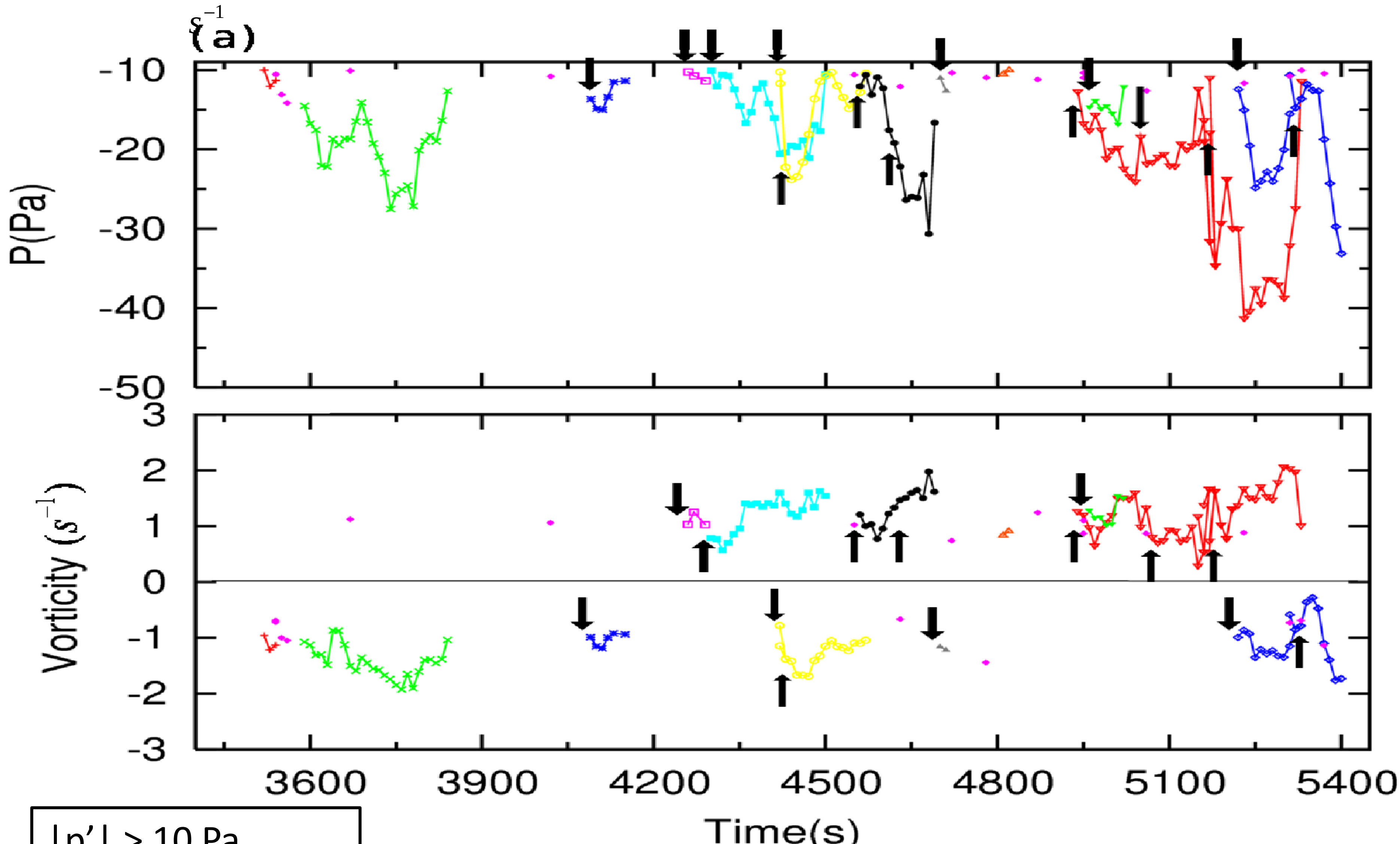
Intensification of vortices by merger



(Ohno and Takemi 2010a)

Merger + Tilting and Stretching = Intense dust devils

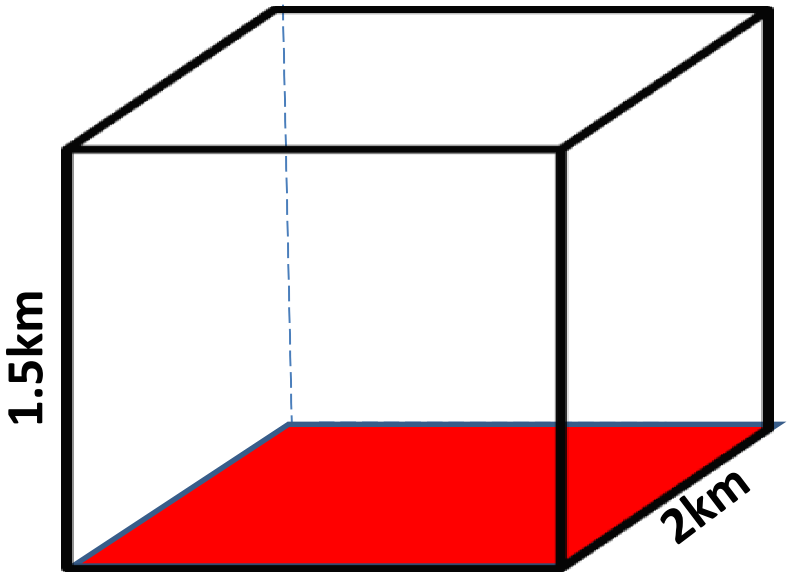
Temporal evolution of vortices



|p'| > 10 Pa
|ζ| > 0.15 s^{-1}

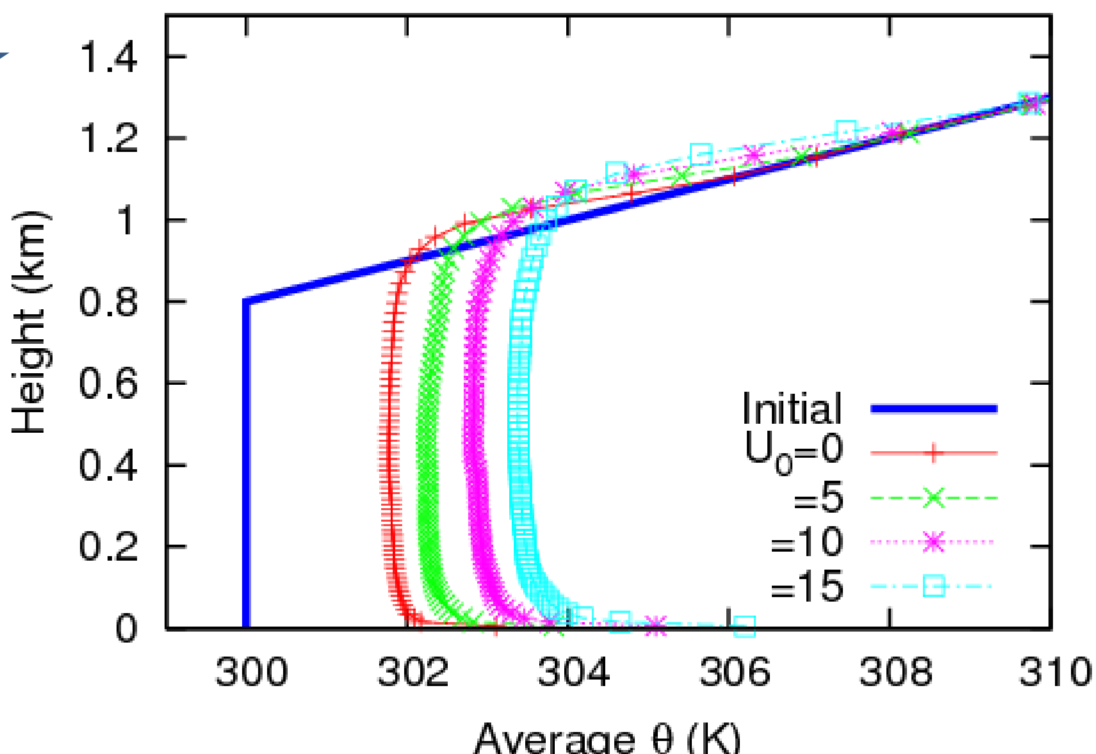
(Ohno and Takemi 2010a)

Sensitivity of dust devils to mean winds



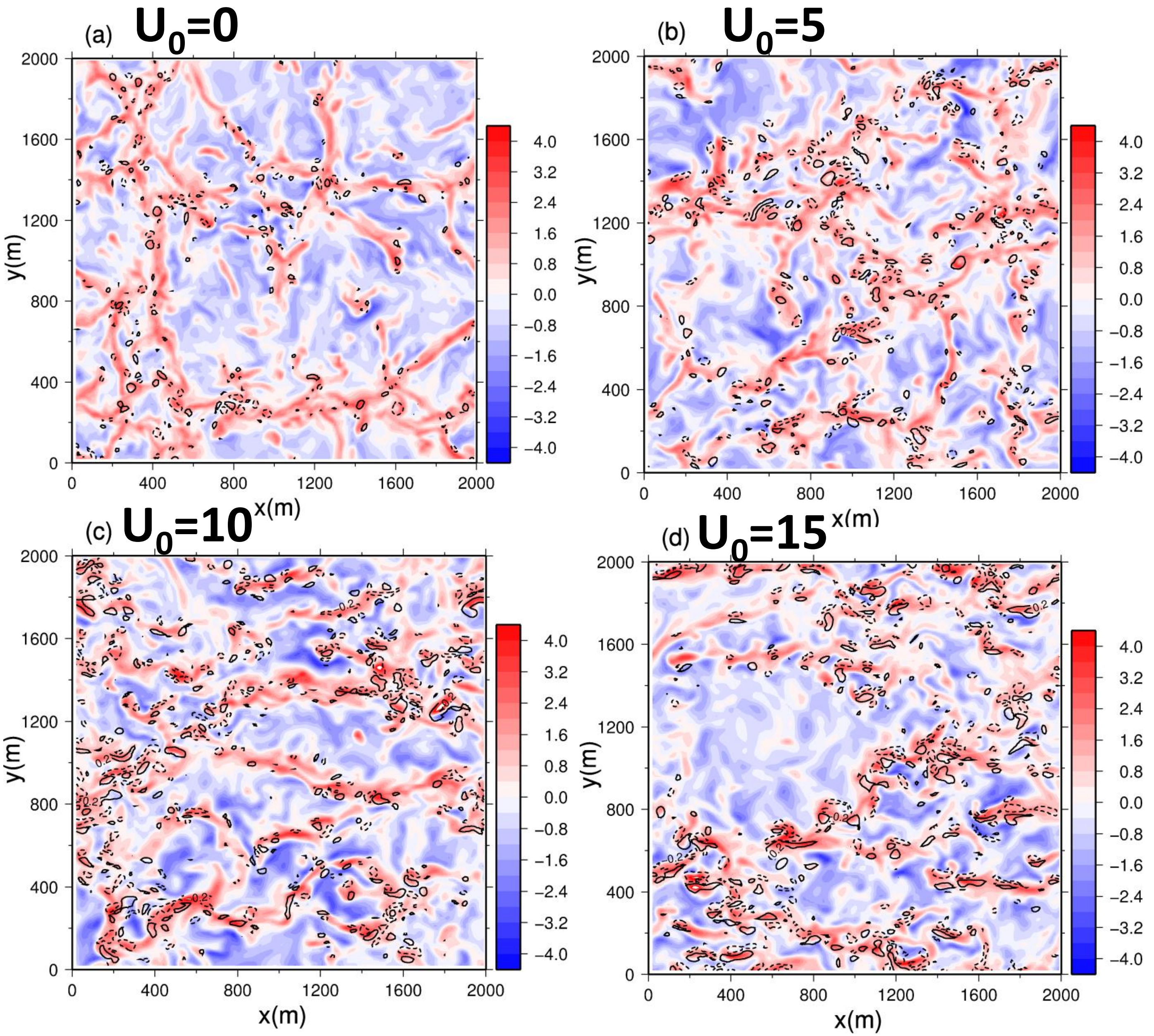
Mean wind: U_0=0, 5, 10, 15 (m/s)

Initial mean winds



(Ohno and Takemi 2010b)

Dependence of CBL structure on mean wind

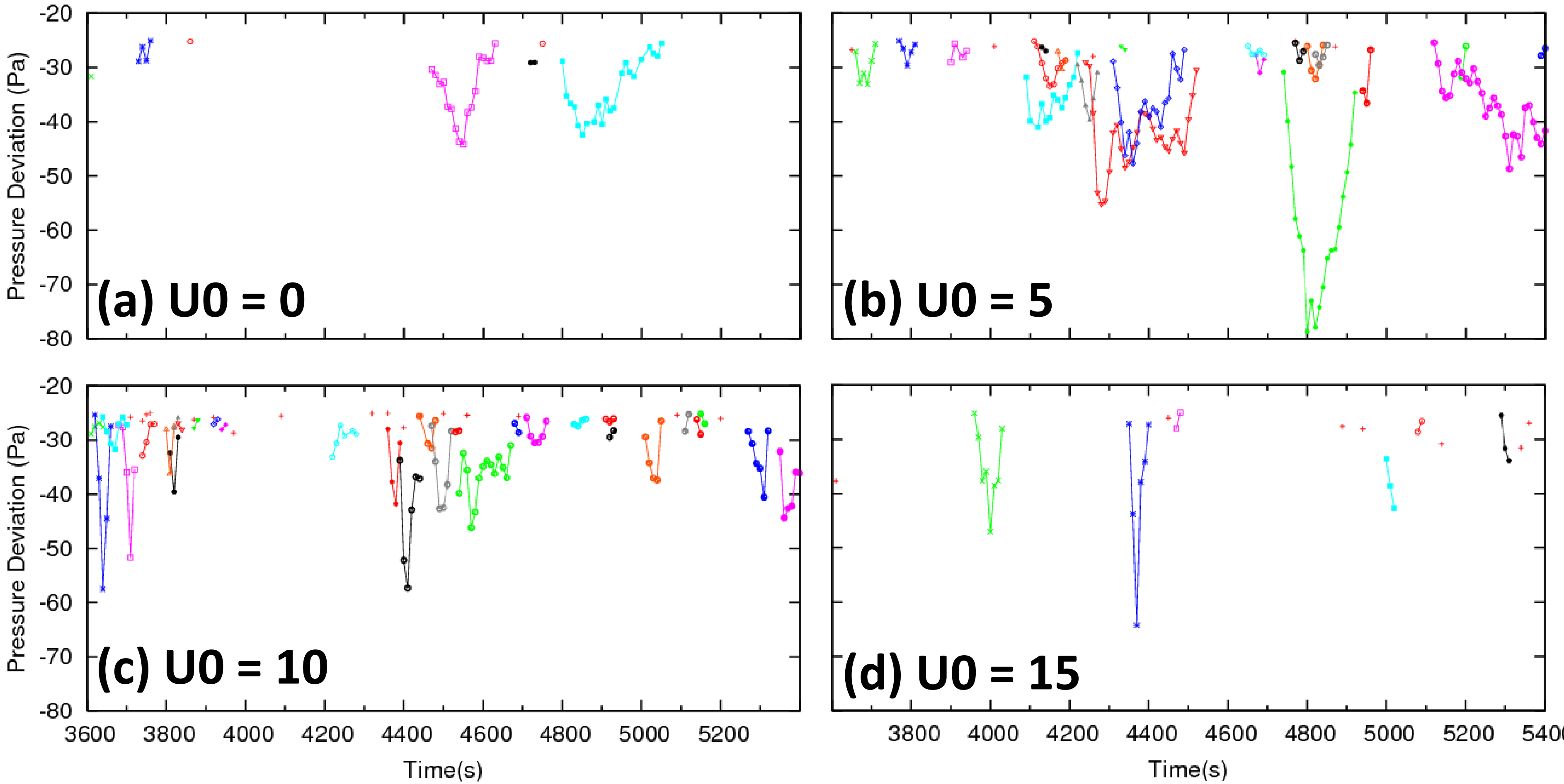


Vertical velocity at z=50 m (color) and vorticity (sold lines)

Temporal evolution of vortices

Definition of vortices:

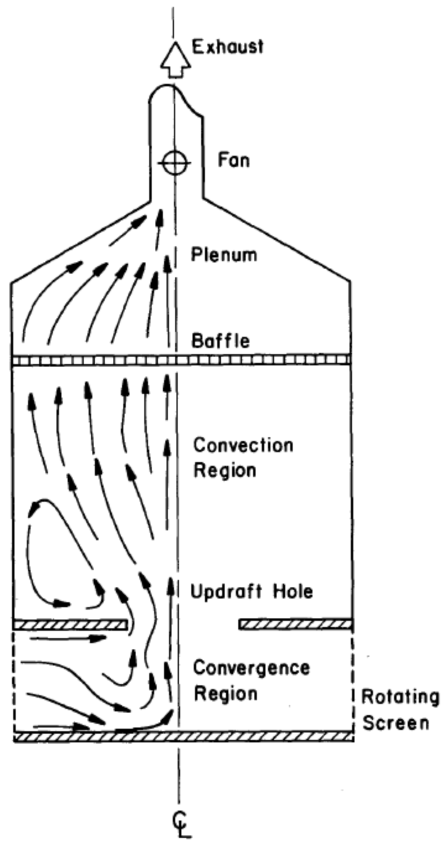
$|p'| > 25$ Pa, $|\zeta| > 0.15\ s^{-1}$



(Ohno and Takemi 2010b)

Vortex chambers in tornadoes studies

Ward (1972) type

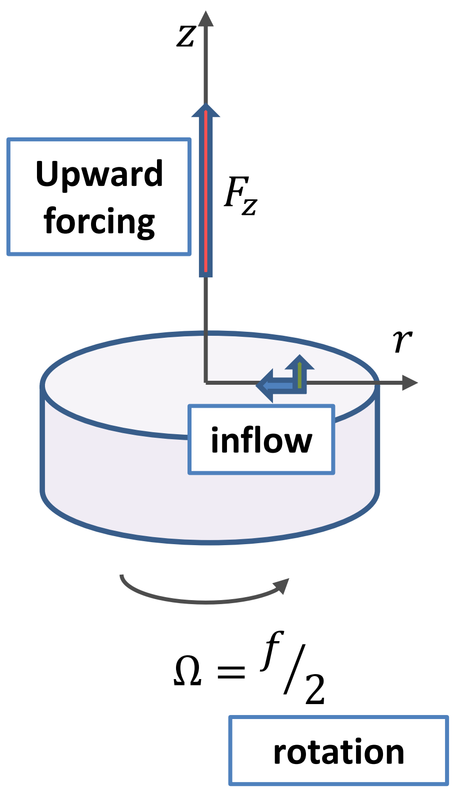


(Church et al., 1979)

Both for laboratory and numerical studies

Fiedler (1994) type

Circulation induced by rotating disk and prescribed updraft forcing



For numerical studies

Numerical models

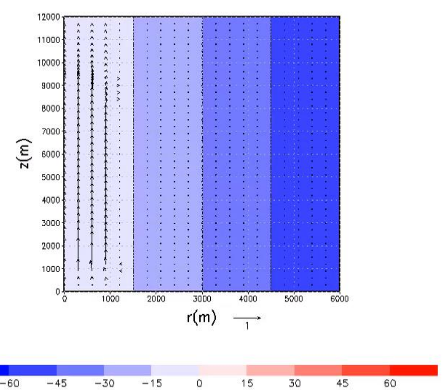
- 2D model: Nonhydrostatic axisymmetric model (Miyamoto and Takemi 2010, Miyamoto 2010)
- 3D model: Nonhydrostatic meteorological model, WRF/ARW (Skamarock et al. 2008)

  - Dry atmosphere
  - Turbulence: Smagorinsky-Lilly (Lilly 1962)
  - Surface friction: With friction (Garratt 1977) or None
  - Base state: Supercell-storm environment (Weisman and Klemp 1982)
  - Upward forcing at the vortex center
  - Computational domain size
    - † $R = 6000$ m, $H = 12000$ m (2D)
    - † $L_x = L_y = 6000$ m, $H = 15000$ m (3D)

Evolution and transition of vortex (2D & 3D)

Surface friction	Garratt (1977)
Rotation rate parameter	$f = 0.02$ (s^{-1})

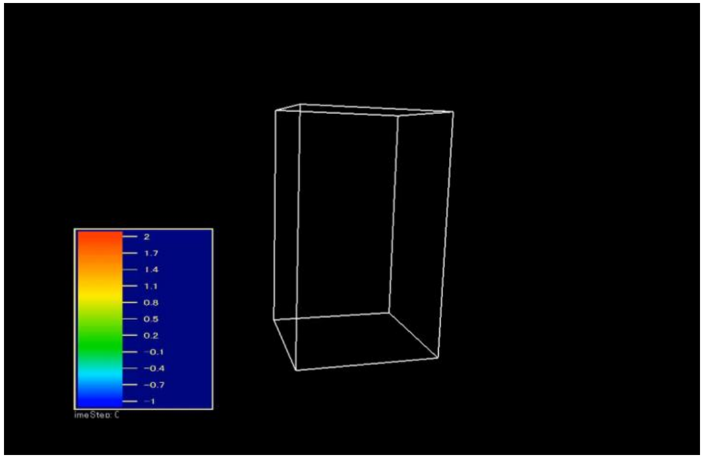
2D model (Axisymmetric model)



$\Delta r = 30$ m, $\Delta z = 5$ m

Vectors: velocity (m s^{-1})
color shading: tangential wind (m s^{-1})

3D model (WRF)



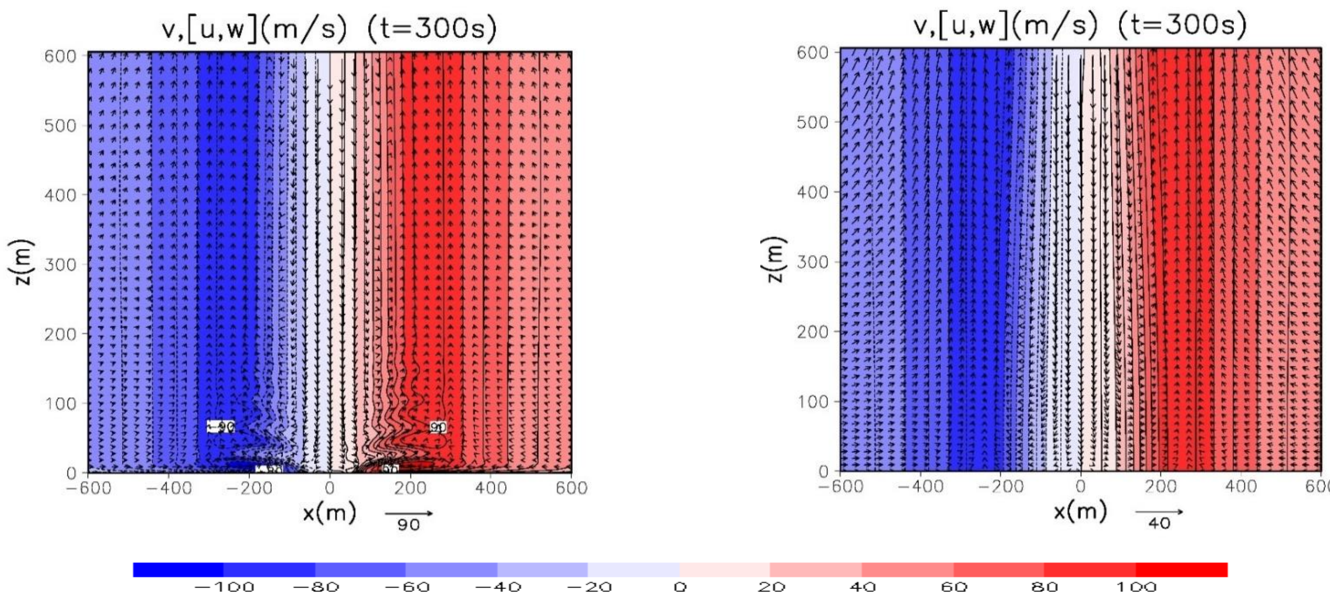
$\Delta x = \Delta y = 30$ m, $\Delta z = 4.5$ m

Vectors: surface winds (m s^{-1})
Color shagging: vorticity (s^{-1})

Dependence on surface friction (3D)

Resolution	$(\Delta x, \Delta y, \Delta z_{\mathrm{min}}) = (30, 30, 4.5)$ [m]
Rotation rate parameter	$f = 0.02$ (s^{-1})
Surface friction	With friction, No friction

Radial and vertical cross section



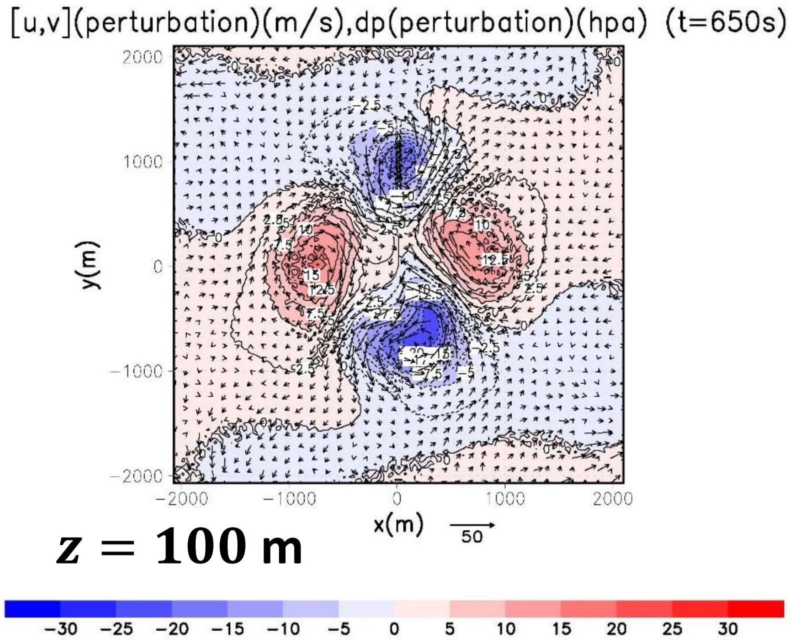
With surface friction **No friction**

Color shading & contours: tangential wind (m/s)
Vectors: radial and vertical wind (m/s)

Transition to multiple vortices

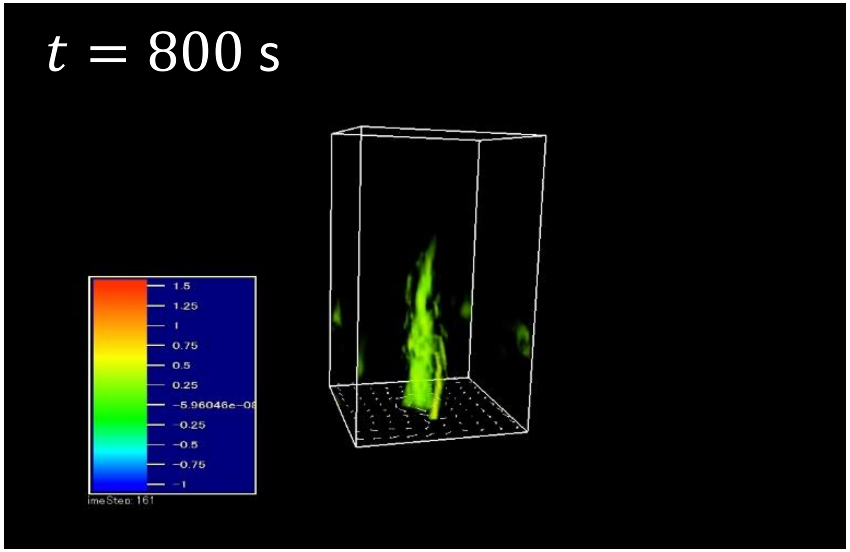
Resolution	$(\Delta x, \Delta y, \Delta z_{\text{min}}) = (30, 30, 4.5)$ [m]
Surface friction	With friction, No friction
Rotation rate parameter	f =0.10 (s^{-1})

Asymmetric component of near-surface vortex



Vector: asymmetric component of surface wind (m/s)
Color shading: asymmetric component of pressure perturbation (Pa)

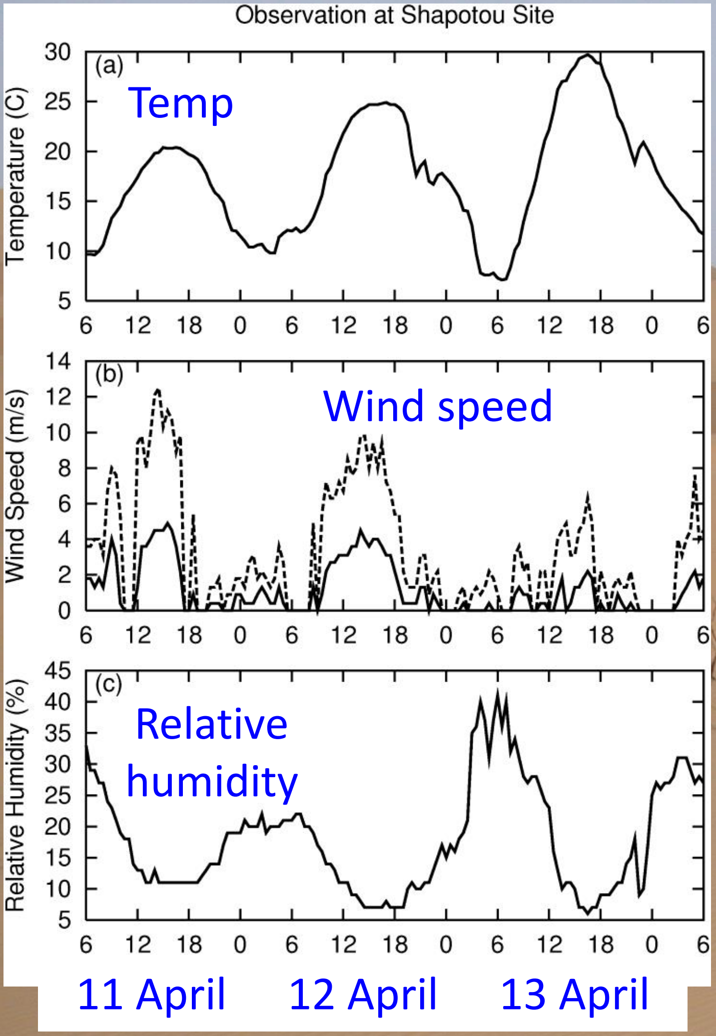
3D view of vorticity



Vector: surface wind (m/s)
Color shading: vorticity (s^{-1})

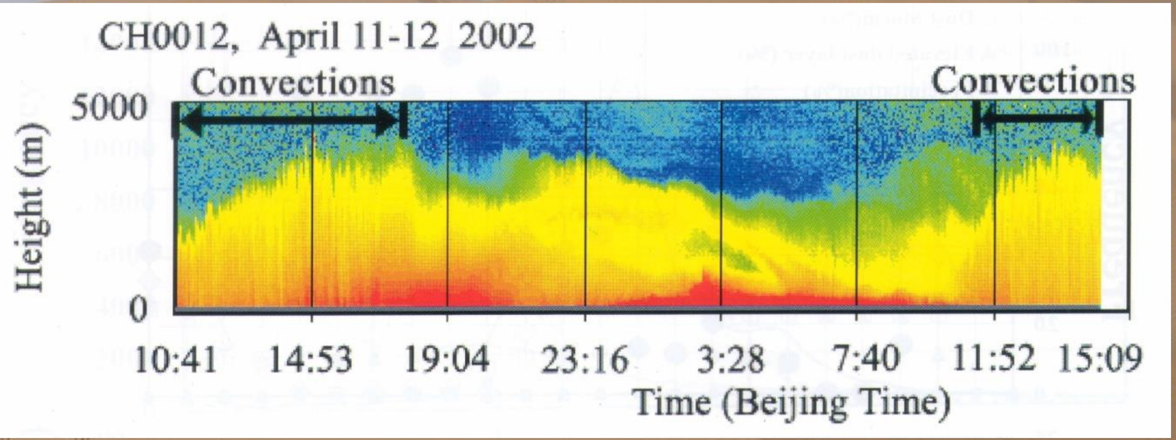
Diurnal variation of dust layer over Gobi Desert

Surface meteorology



(Takemi et al. 2005)

Temporal change of vertical profile of dust content observed by lidar during 11-12 April 2002 in ADEC IOP



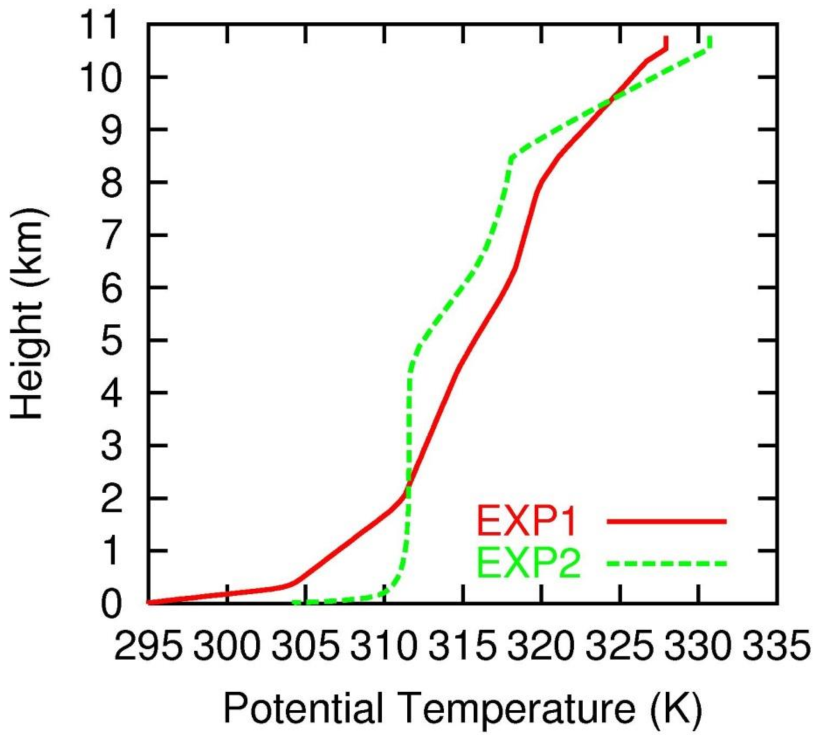
(Yasui et al. 2005)

ADEC: Asian Dust Experiment on Climate Impact (2000-2005)

(Picture by Dr. M. Yasui, NICT)

Initial stability profiles

- **EXP1**: 00 UTC (06 LT) 13 April 2002 sounding at a Gobi desert; w/strongly stable surface inversion capped by a stable PBL
- **EXP2**: created by 3-day spin-up run from EXP1 sounding; w/surface inversion layer capped by a residual neutral layer



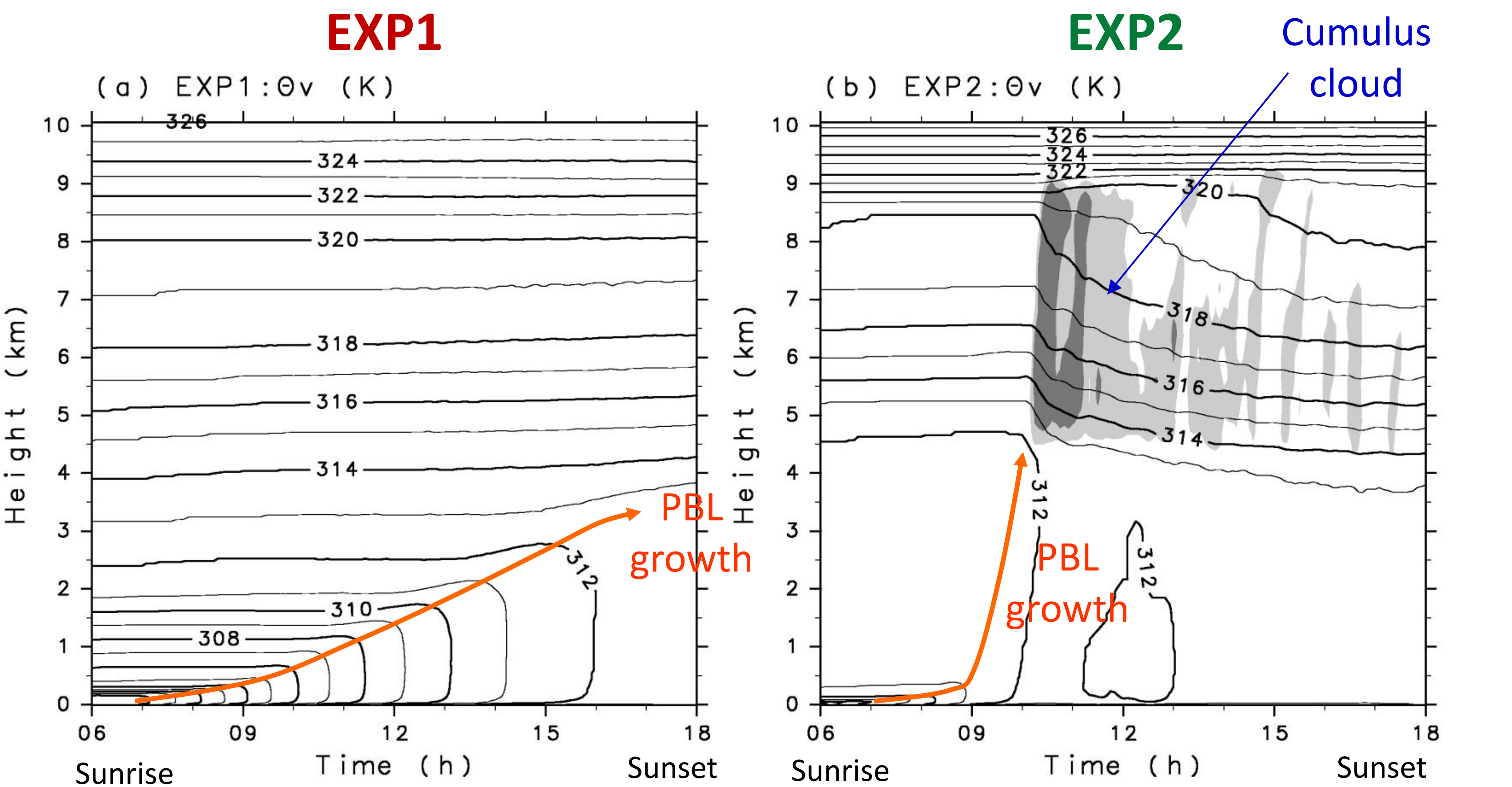
(Takemi 2008, 2012)

Diurnal variation of the atmosphere

Numerical experiments with a nonhydrostatic model, ARPS

Diurnal variation of the horizontally averaged virtual potential temperature & cloud mixing ratios;

no cloud formation in EXP1, while active cloud development in EXP2

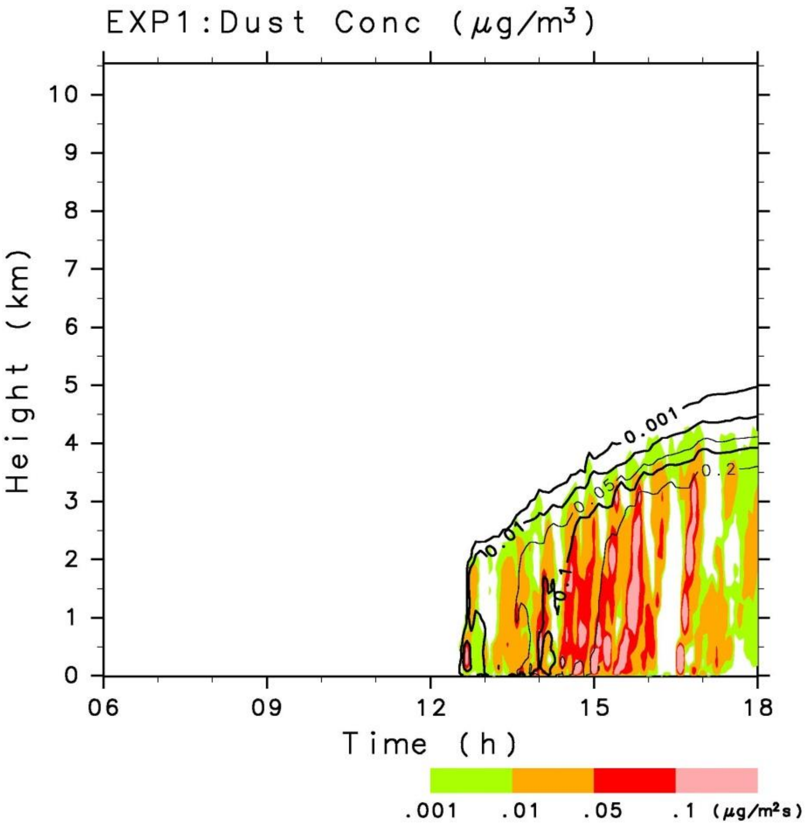


(Takemi 2008, 2012)

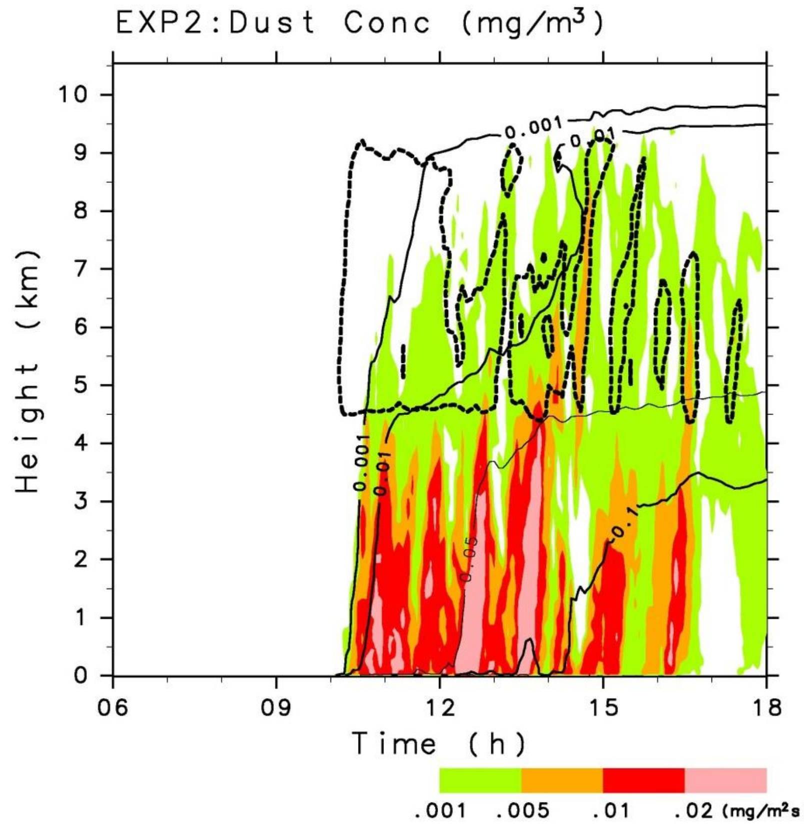
Diurnal variation of dust transport: 100-m grid

Numerical experiments with a nonhydrostatic model, ARPS

EXP1



EXP2



Column dust content - **EXP1**:1.2 μg/m²
- **EXP2**: 0.63 g/m²

Color: Upward dust flux (mg/m²/s)

Black contour: Dust conc (mg/m³)

Dotted contour: Cloud boundary

(Takemi et al. 2006; Takemi 2008, 2012)

Severe dust storm case

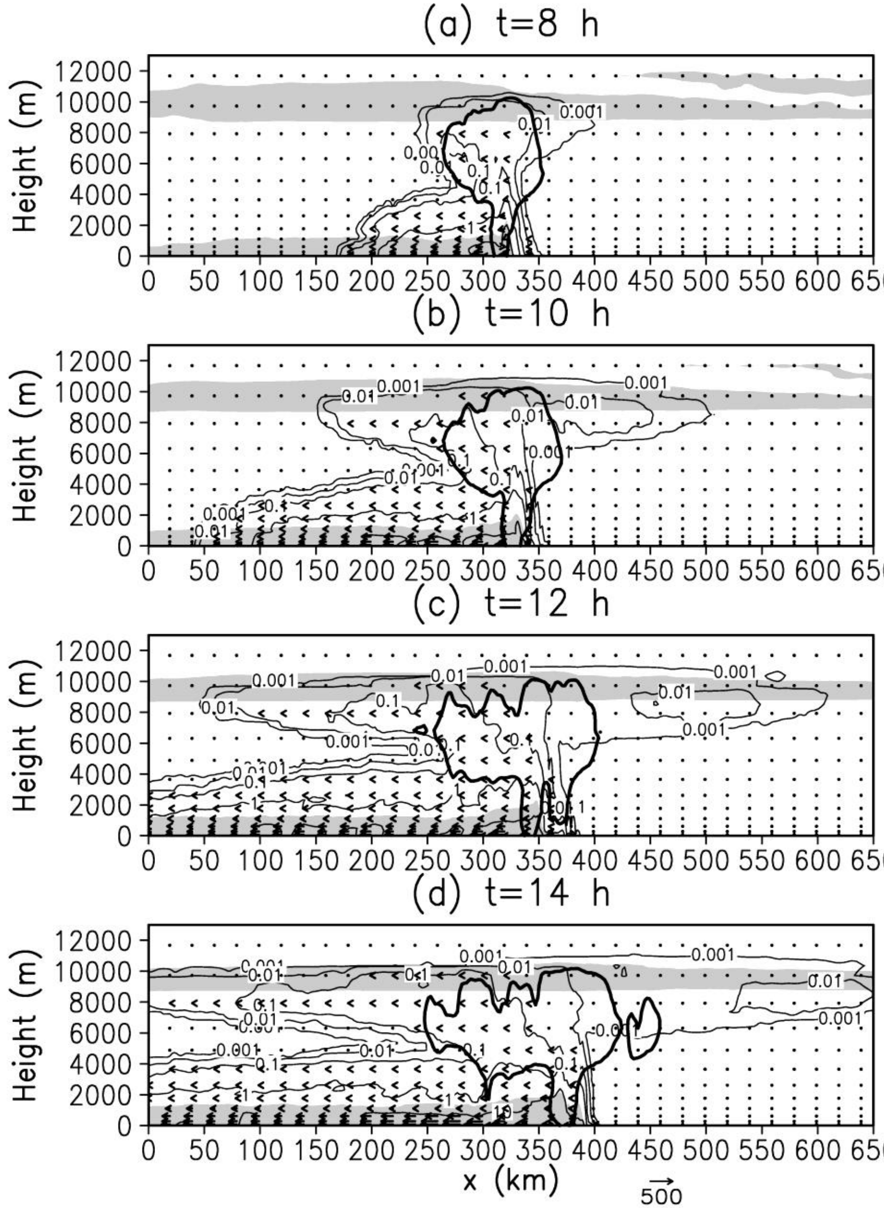
5 May 1993 Dust Storm over Gobi

(Mitsuta et al. 1995; Takemi 1999)

- Dust transport by squall line
- High concentration within surface cold-air pool
- Moderate concentration within updraft and system's rearward
- Low concentration at upper levels

(Takemi 2005)

Dust concentration



Column dust content

- Severe storm case: 12.5 g/m^2

- Fair-weather condition (with shallow surface stable layer): 0.63 g/m^2

- Fair-weather condition (with deep surface stable layer): 1.2 $\mu g/m^2$

Concluding remarks

- The intensification of vortices through mergers and the transition of vortex structure are successfully simulated with high-resolution simulations by non-hydrostatic meteorological models.
- A grid spacing of 100 m seems to capture the diurnal cycle of PBL and dust transport associated with not only shallow convection but also deep convection rooted in PBL.

- Nonhydrostatic modeling as a vortex chamber can be used for studies on dust devils on Earth and Mars.
- Dust transport associated with dust devils and its consequences on larger-scales under realistic meteorological conditions should be further investigated.