
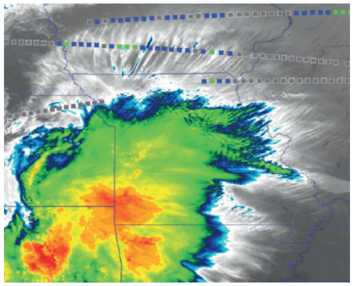

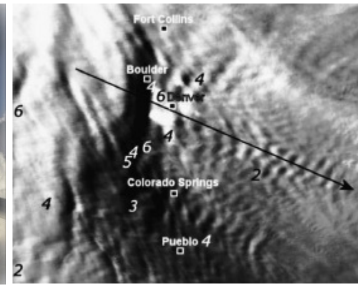


A Numerical Simulation of Convectively Induced Turbulence (CIT) above Deep Convection

Jung-Hoon Kim and Hye-Yeong Chun

Department of Atmospheric Sciences
Yonsei University, Seoul, Korea

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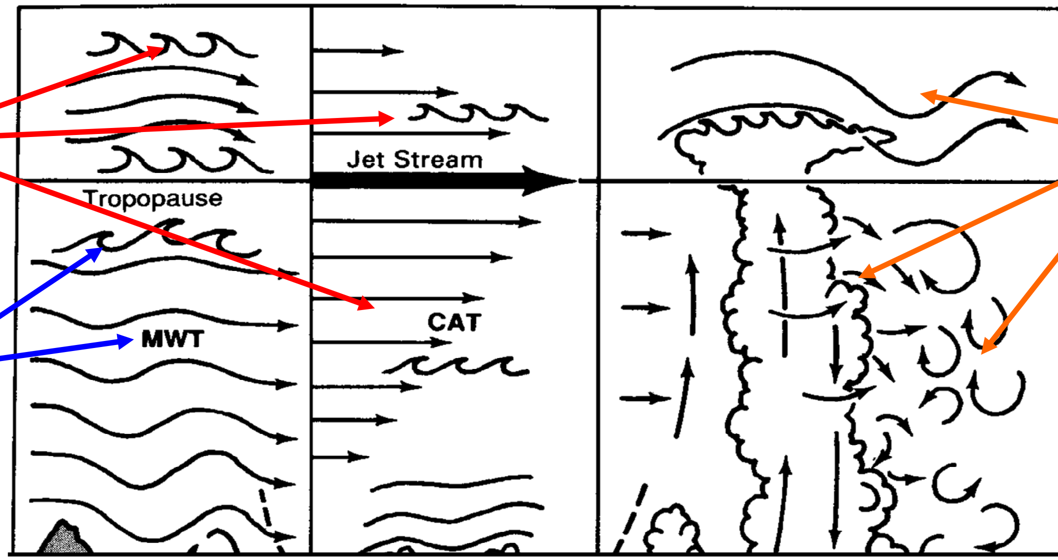
1. Introduction

CAT:
Clear-Air Turbulence

MWT:
Mountain Wave induced Turbulence



CIT:
Convectively Induced Turbulence

Lester (1994)

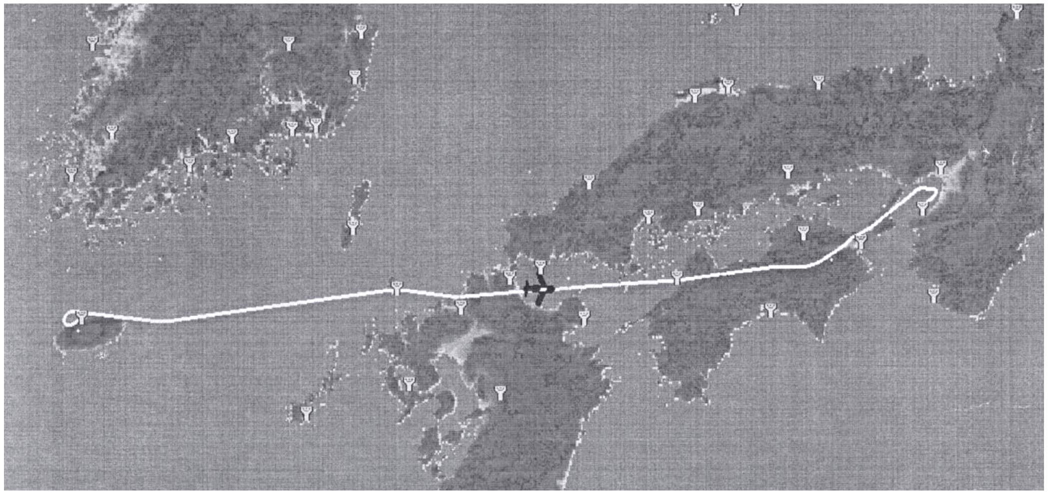
- **Convectively induced turbulence (CIT) :**

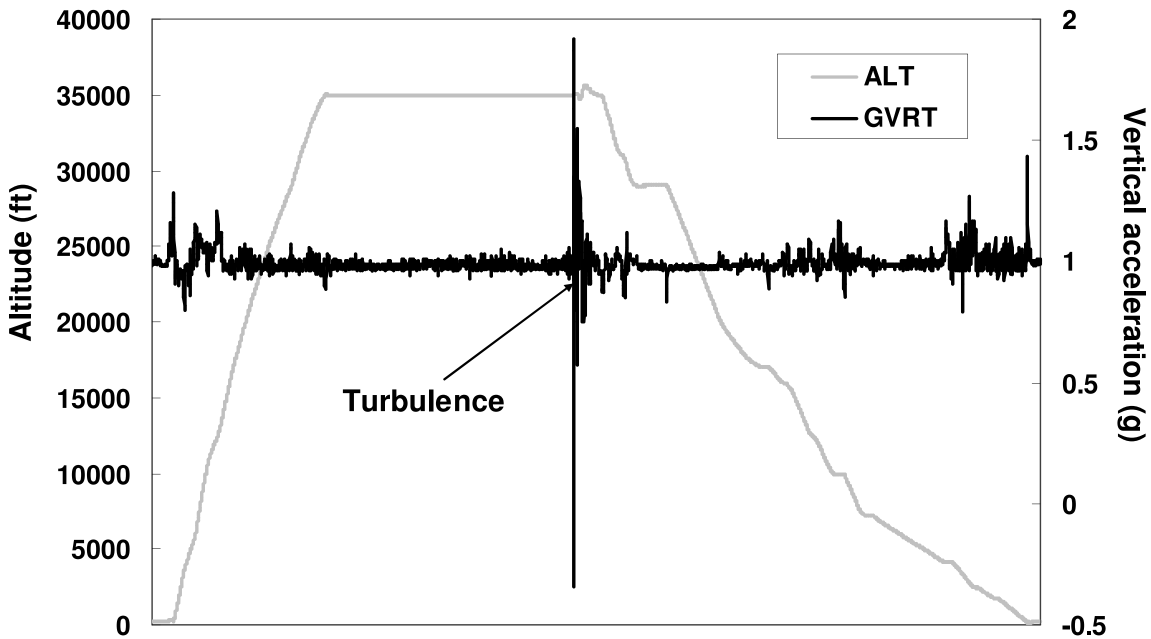
 * Classified into two categories such as in-cloud and out-of-cloud CIT.

 * Generation mechanisms of out-of cloud CIT (convectively induced CAT) include flow deformation on top of the convective cloud (Grabowski and Clark 1991) and convectively generated gravity waves and their subsequent breaking (Lane et al. 2003).

- Due to the potential severity of out-of cloud CIT, the FAA recommends that an aircraft flying over a developing and/or mature convection should avoid cloud top at least 1000 ft vertically for every 5 m s^{-1} of cloud-top wind speed (FAA 2008).

2. Investigation of the turbulence encounter





✓ **Case description**

Date : 2 September 2007 (1034 UTC)

En route : from Jeju to Osaka

Location : 33.679°N, 131.264°E

Level : about 11.2 km (35000 ft)

Perturbation acceleration :

+1.92 and -0.34 g's

(g : gravity acceleration; 9.8 ms^{-2})

✓ **Damages**

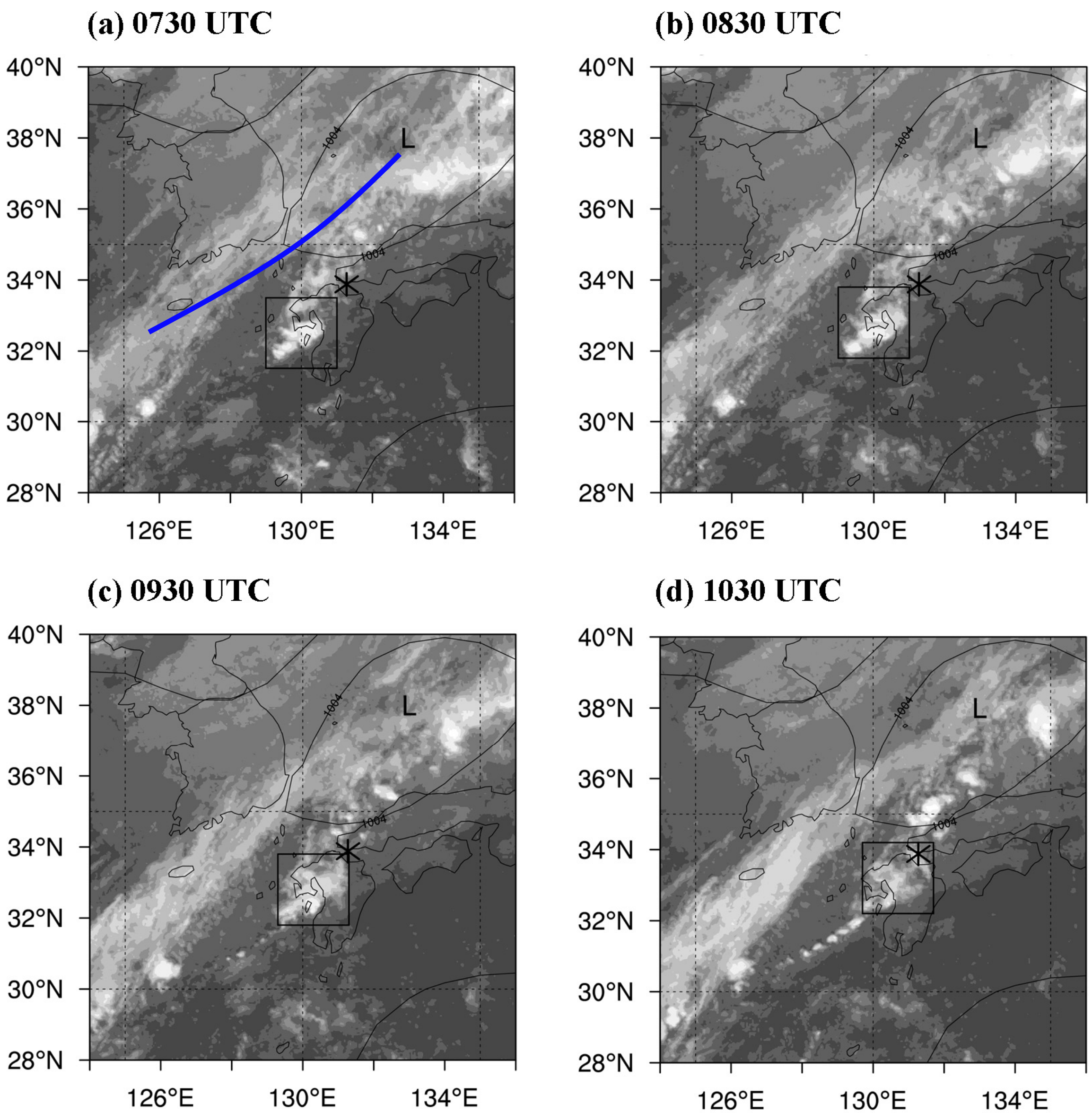
5 passengers and 6 crews suffered major or minor injuries

✓ **Pilot statements**

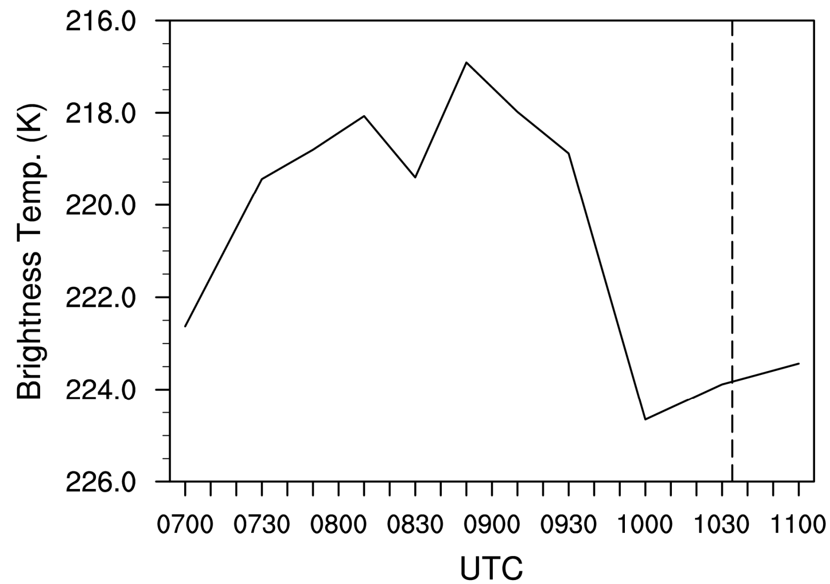
Weather : 220/15 kts, -44°C, CLR

Seat belt sign off, No turb. Warnings.

2. Investigation of the turbulence encounter



- ✓ A deep convection ahead of cold front developed in southwestern region of the turbulence location.
- ✓ As the convection moves toward the turbulence location, convection becomes in the dissipating stage.

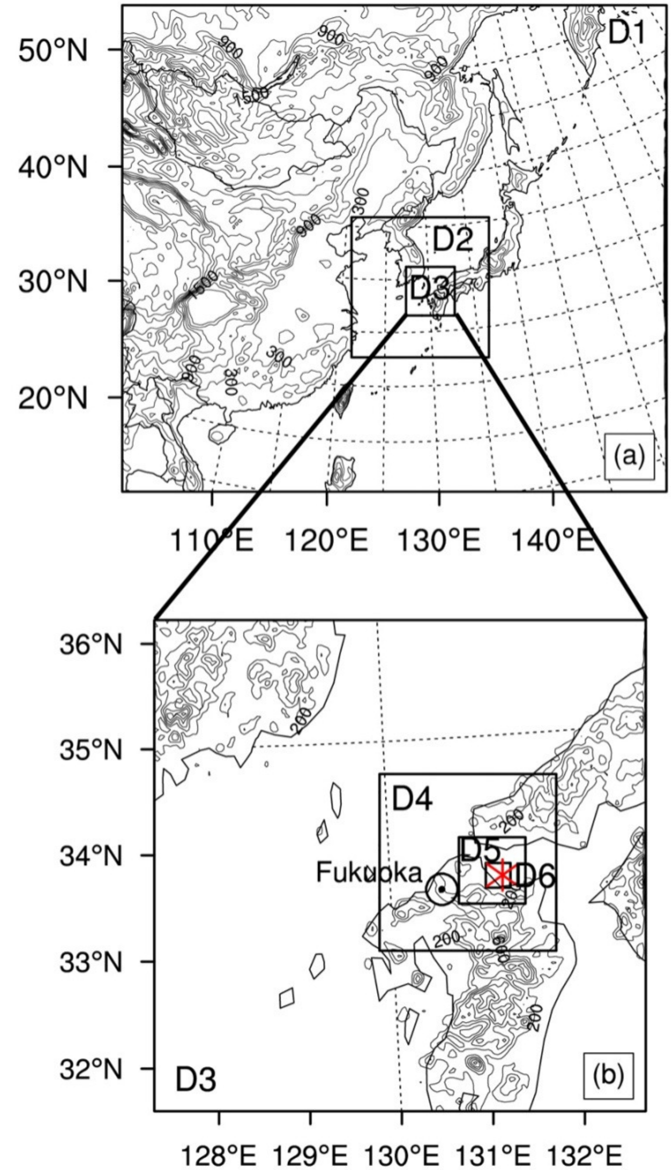


3. Experimental design of the model

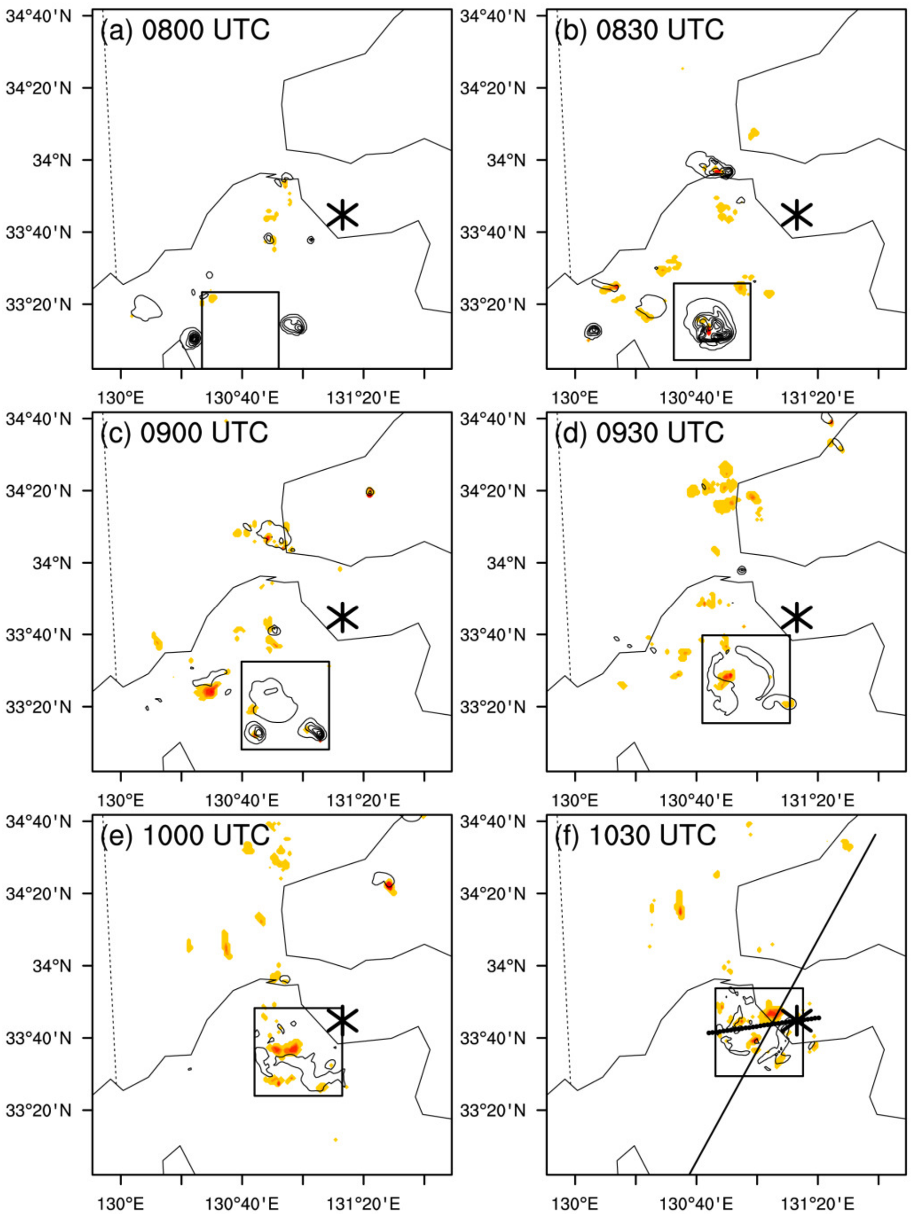
Model	ARW-WRF (Weather Research Forecast) Version 3.2					
Domain	1	2	3	4	5	6
Δx (km)	30	10	3.33	1.11	0.37	0.12
Δt (s)	Adaptive time steps (condition for CFL < 1.2)					
Dimension	191×171	145×148	154×154	166×166	187×187	208×208
Integrated time	00 UTC ~ 18 UTC 2 Sep. 2007 (18 hours) in D1~2 06 UTC ~ 15 UTC 2 Sep. 2007 (09 hours) in D3~6					
Cumulus	Kain-Fritsch scheme (Kain 2004) is used in D1 and 2					
MP	WSM 6-class graupel scheme (Hong et al. 2006)					
PBL	Mellow-Yamada-Janjic (MYJ) scheme (Janjic, 2002)					

- Outmost forcing : NCEP FNL 1°×1° DATA
- Upper BC: Rayleigh damping (uppermost 5 km, model top : 20 hPa)
- Lateral BC: 1 grid specified zone + 4 grid relaxation zone

- Vertical layers and resolution : 113 σ-levels, Δz = 100 m (9~13 km)
- 2-way nesting

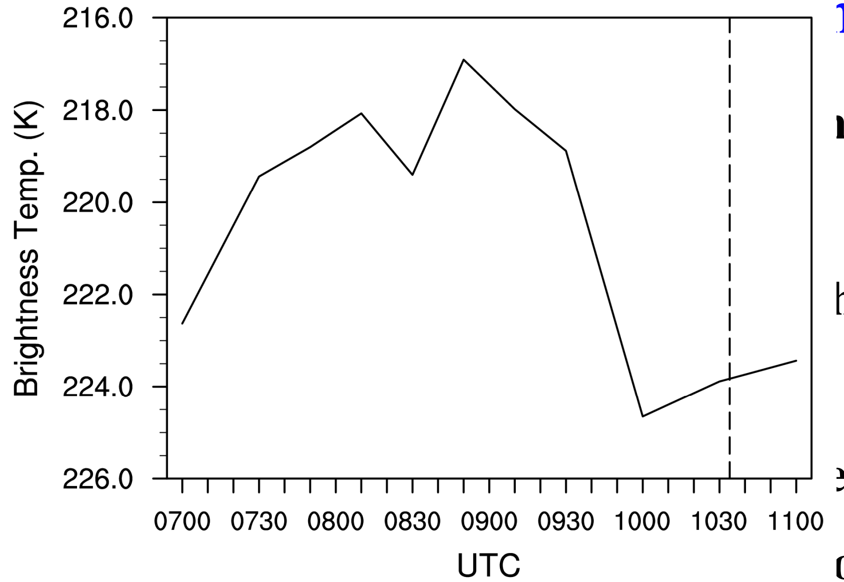


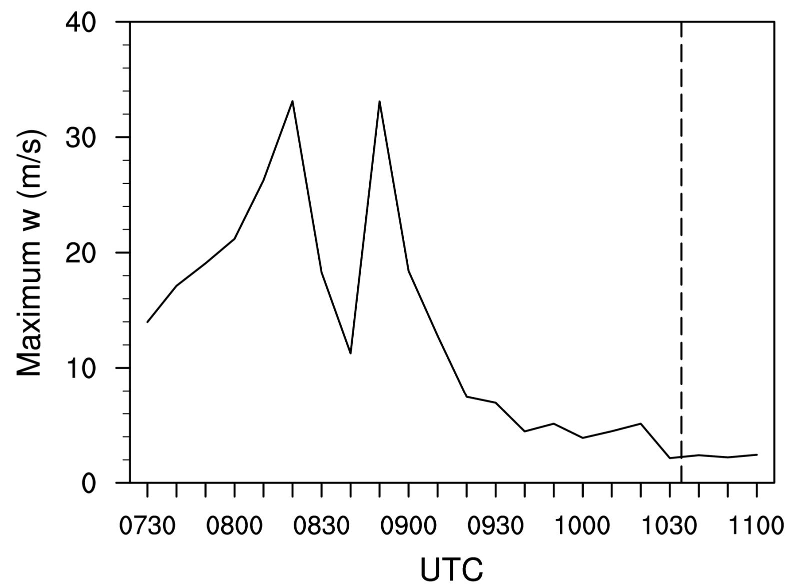
4. Model results in domain 4 (Δx = 1.1 km)



4.1 E ... n

- ✓ **At ... ass**
  of ... up
  to ... hind
  the
- ✓ **Af ... ed,**
  no ... oud.

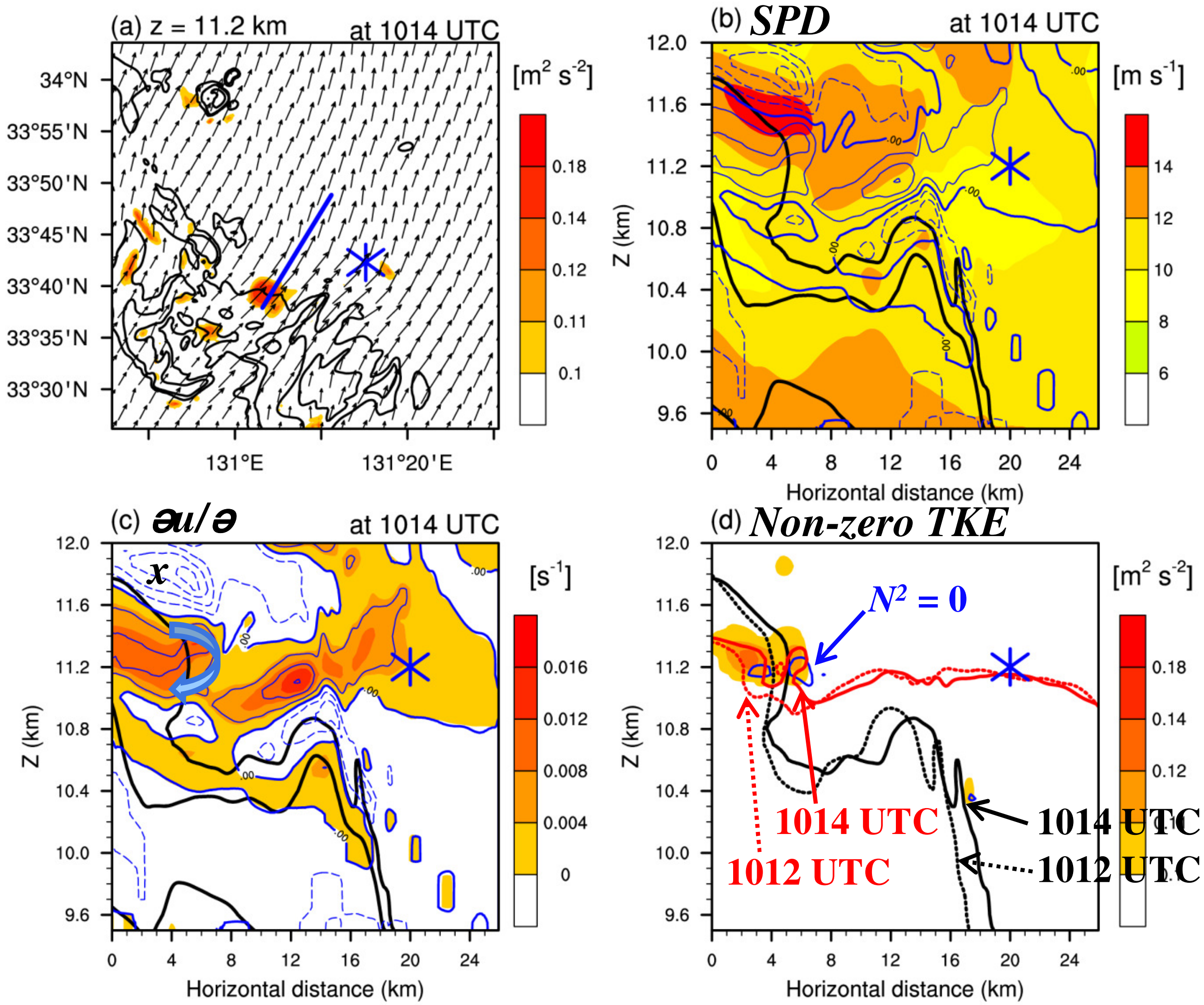




4.2. Generation mechanism of the out-of-cloud CIT

(a): Model results in domain 5 (Δx = 0.37 km)

(b), (c), and (d): Model results in domain 6 (Δx = 0.12 km)

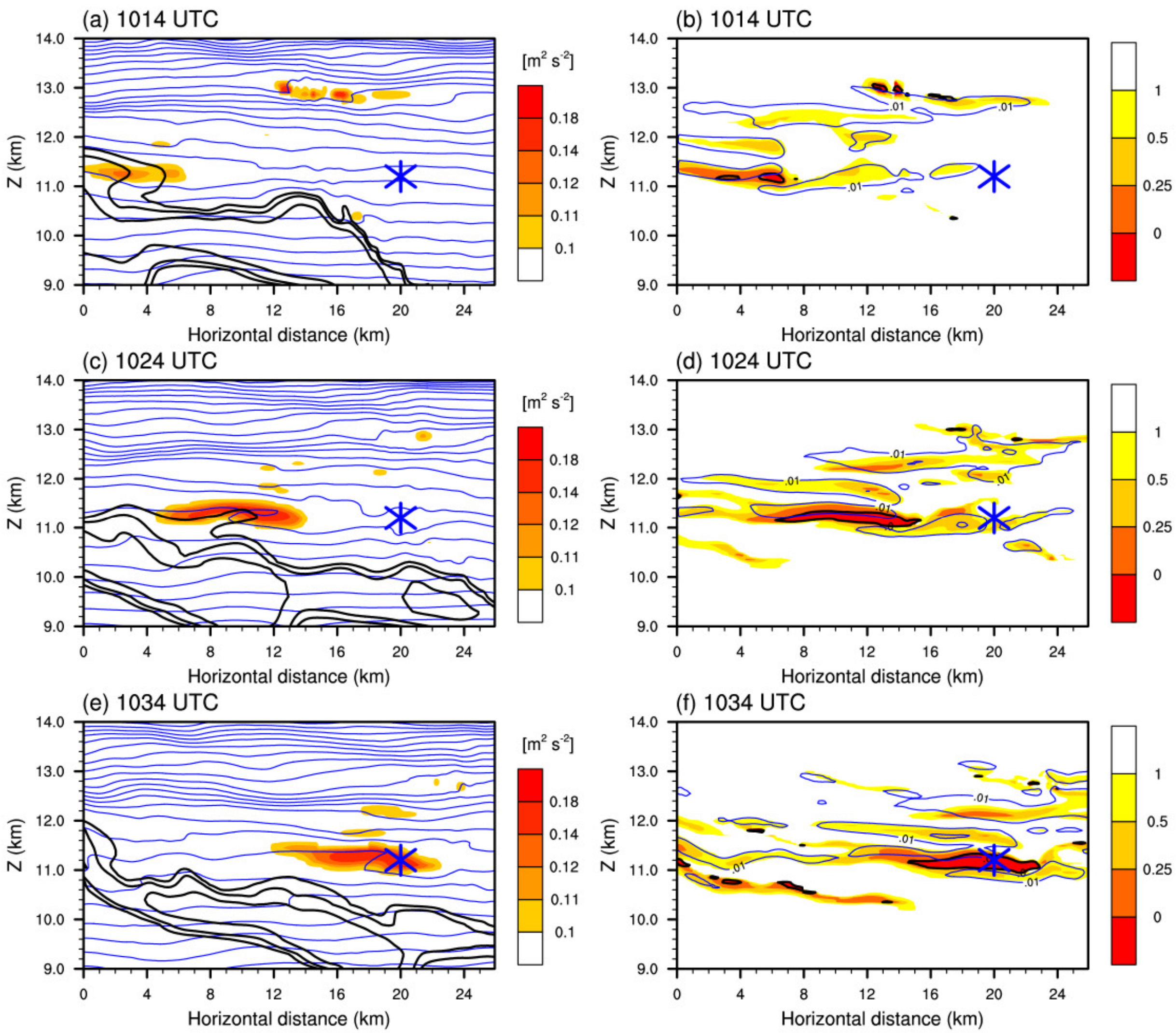


(b), (c): *y-vorticity* ($\partial u/\partial z - \partial w/\partial x$); **(b), (c)**: *total cloud mixing ratio.*

- ✓ **At 1014 UTC (a), southwesterly flow passing through the dissipating deep convection is perturbed on lee-side.**
- ✓ **Horizontal wind speed in a layer (z =10.2-11.2 km) is locally reduced, which enhances vertical wind shear on top of the dissipating convection.**
- ✓ **The enhanced shear, finally, causes positive *y*-vorticity that deforms leading edge of the cloud boundary.**
- ✓ **More intensified cloud deformation results in overturning of isentrope, activating turbulence at cloud edge.**

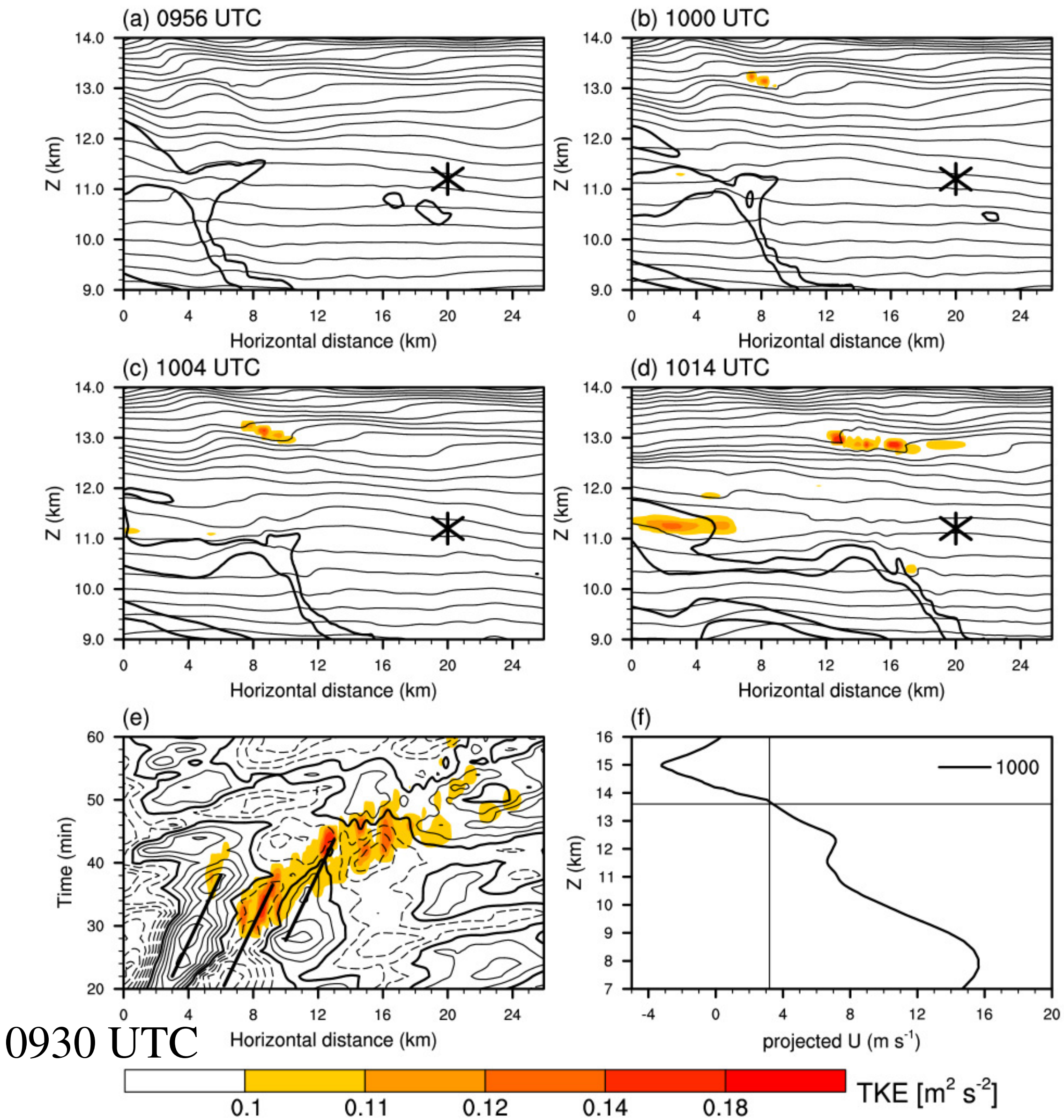
4.2. Generation mechanism of the out-of-cloud CIT

Model results in domain 6 (Δx = 0.12 km)



- ✓ **For 20 min, from 1014 to 1034 UTC, the turbulence generated at the cloud interface is advected by the dominant southwesterly flow, while the thickness of the dissipating convection shrinks continuously as the convection moves toward the observed turbulence encounter.**
- ✓ **The turbulence becomes wider and stronger at 1024 than 1014 UTC.**
- ✓ **Finally, it comes out of the highly deformed cloud boundary and locates about 1-2 km above the dissipating convection at 1034 UTC.**

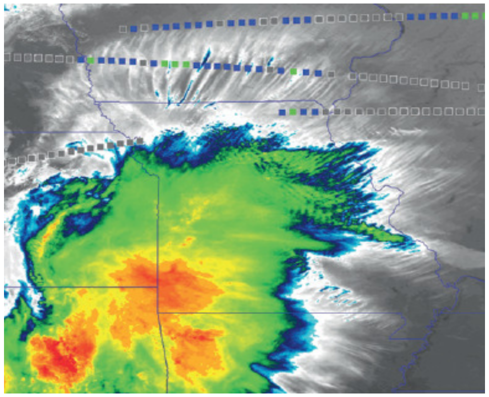
4.3. Subsequent breaking of convectively induced GW



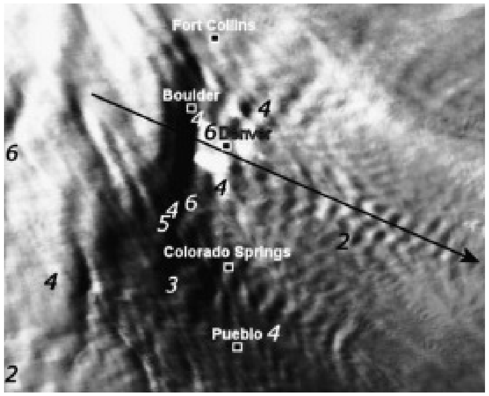
- At 0956 UTC, gravity waves initially generated by narrow tongue propagate vertically, and then they start to break down and extends further downstream.
- According to the *t*-*x* cross-section for TKE and *w* in (e), phase speeds of the gravity waves are about 3.2 m s^{-1}.
- Given the background wind condition at 1000 UTC in (f), these waves meet their critical level at about z = 13.6 km.
- In this situation, the out-of-cloud CIT locates further aloft at about 2 km above the dissipating convection.

5. Summary and conclusions

- According to the evolution of the deep convection from both the MTSAT data and WRF model, observed severe turbulence occurs in the dissipating stage of the deep convection.
- 20 minutes before the incident time, shear induced *y*-vorticity intensifies deformation of cloud edge, activating turbulence through convective instabilities at cloud boundary.
- While the dissipating convection shrinking its thickness continues to move toward the observed turbulence region, the turbulence at the cloud interface is advected by the dominant southwesterly flow, emerging about 1-2 km above the dissipating convection.
- Vertically propagating convective gravity waves with their phase speeds of 3.2 m s^{-1} subsequently break down as they approach toward their critical levels. In this situation, the out-of-cloud CIT locates further aloft at about 2 km above the dissipating convection.
- Even though one case study is conducted, the current thunderstorm avoidance (e.g., FAA 2008) should reconsider not only in the developing stage but also in the dissipating stage.

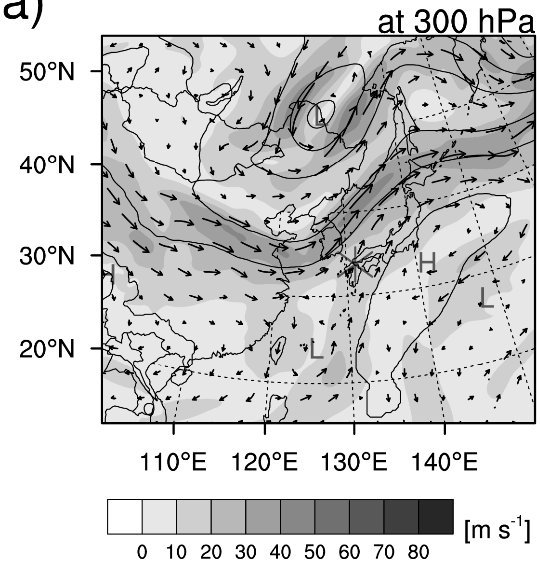



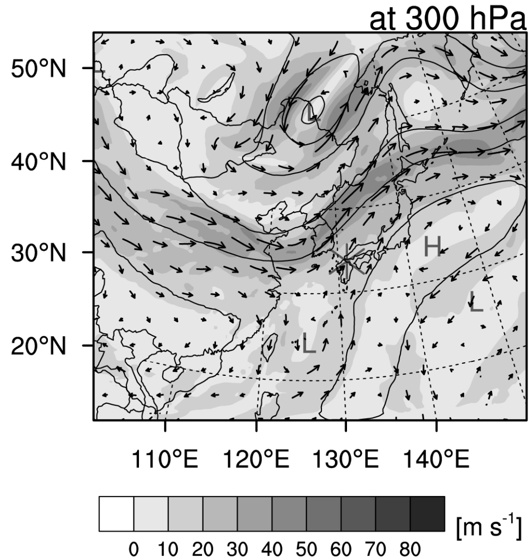

Thank you for your attentions.




Comparison between the obs. and model results

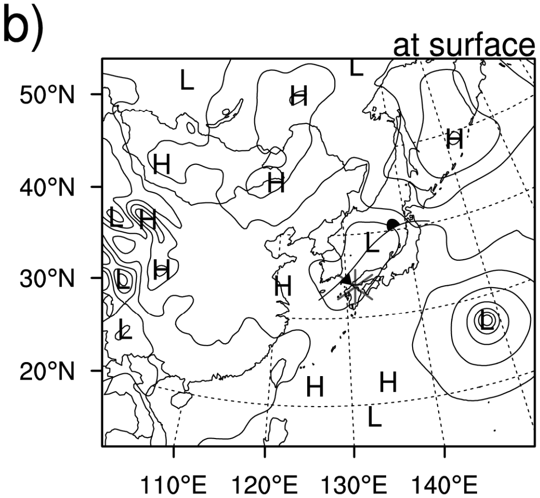
(a)

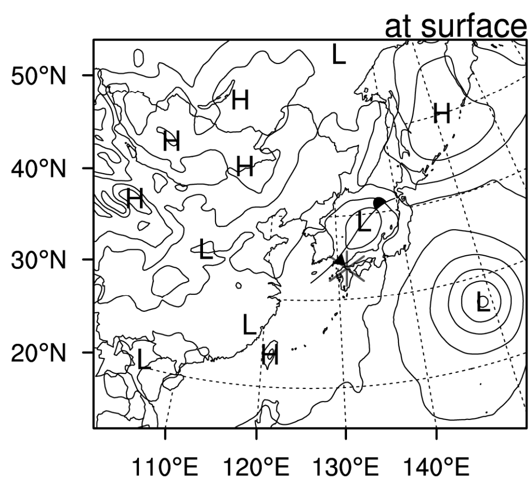


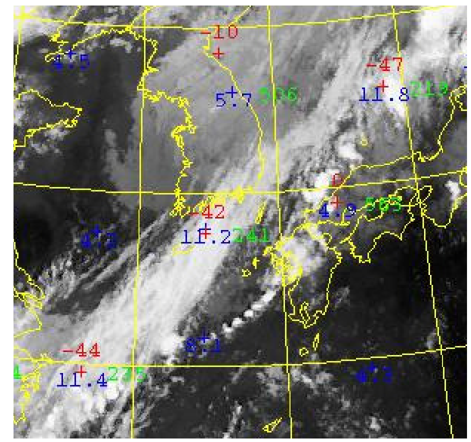


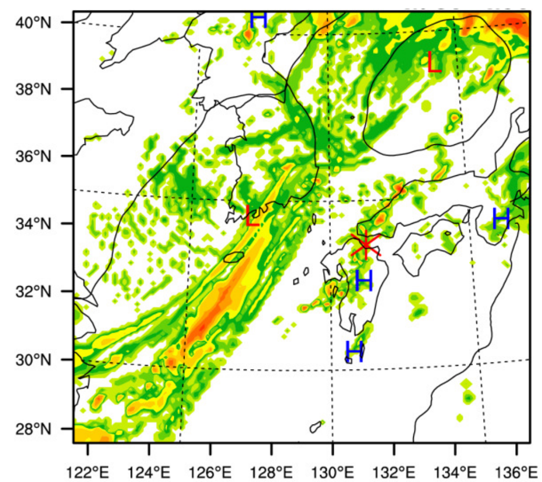
RDAPS 30 Reference Vector **WRF** 30 Reference Vector

(b)

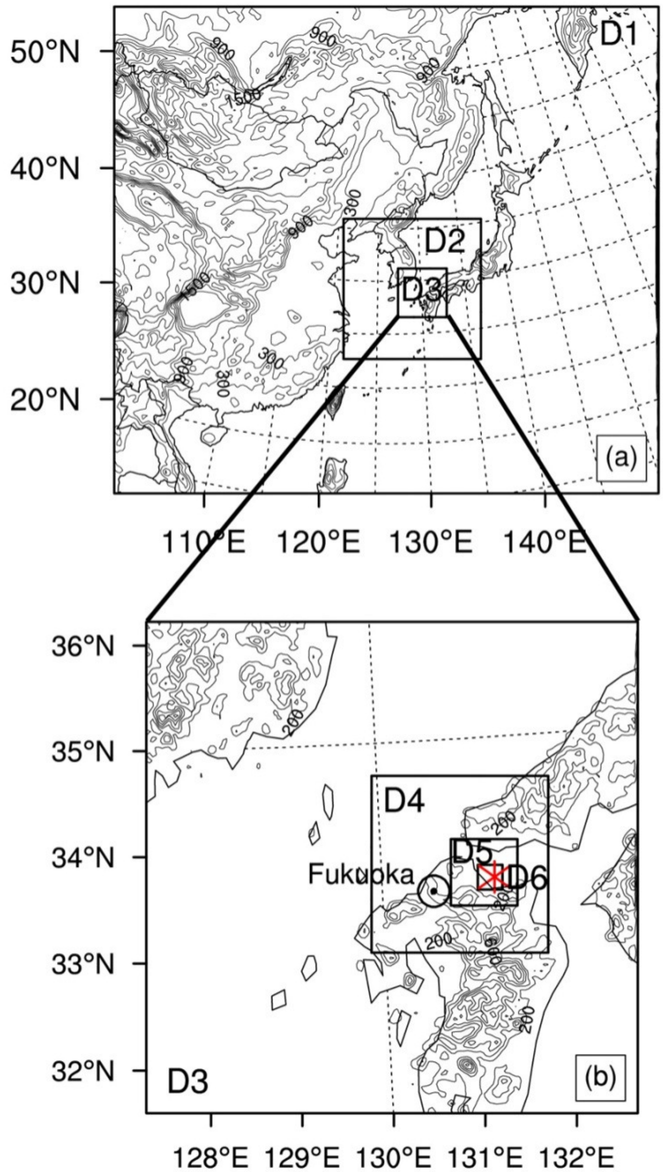




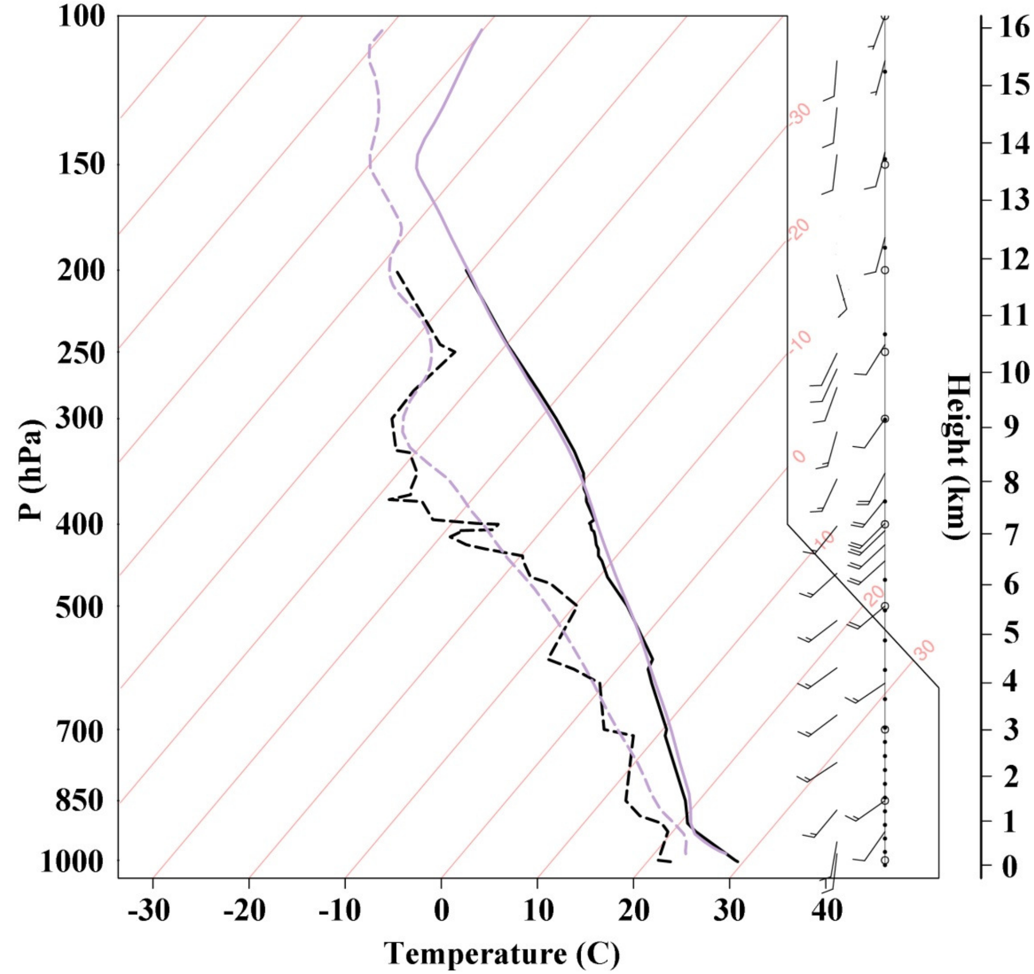




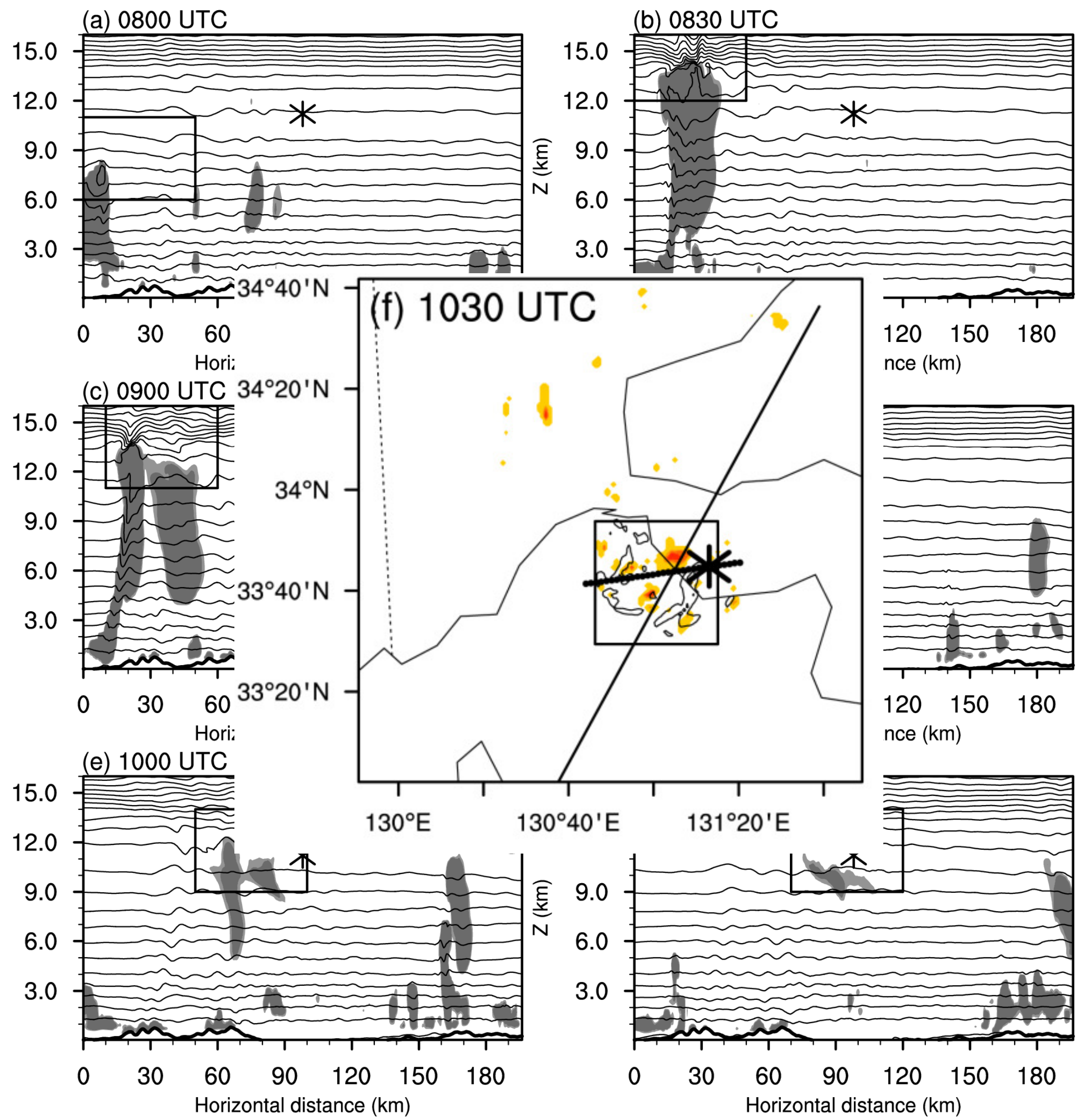
Comparison between the obs. and simulation

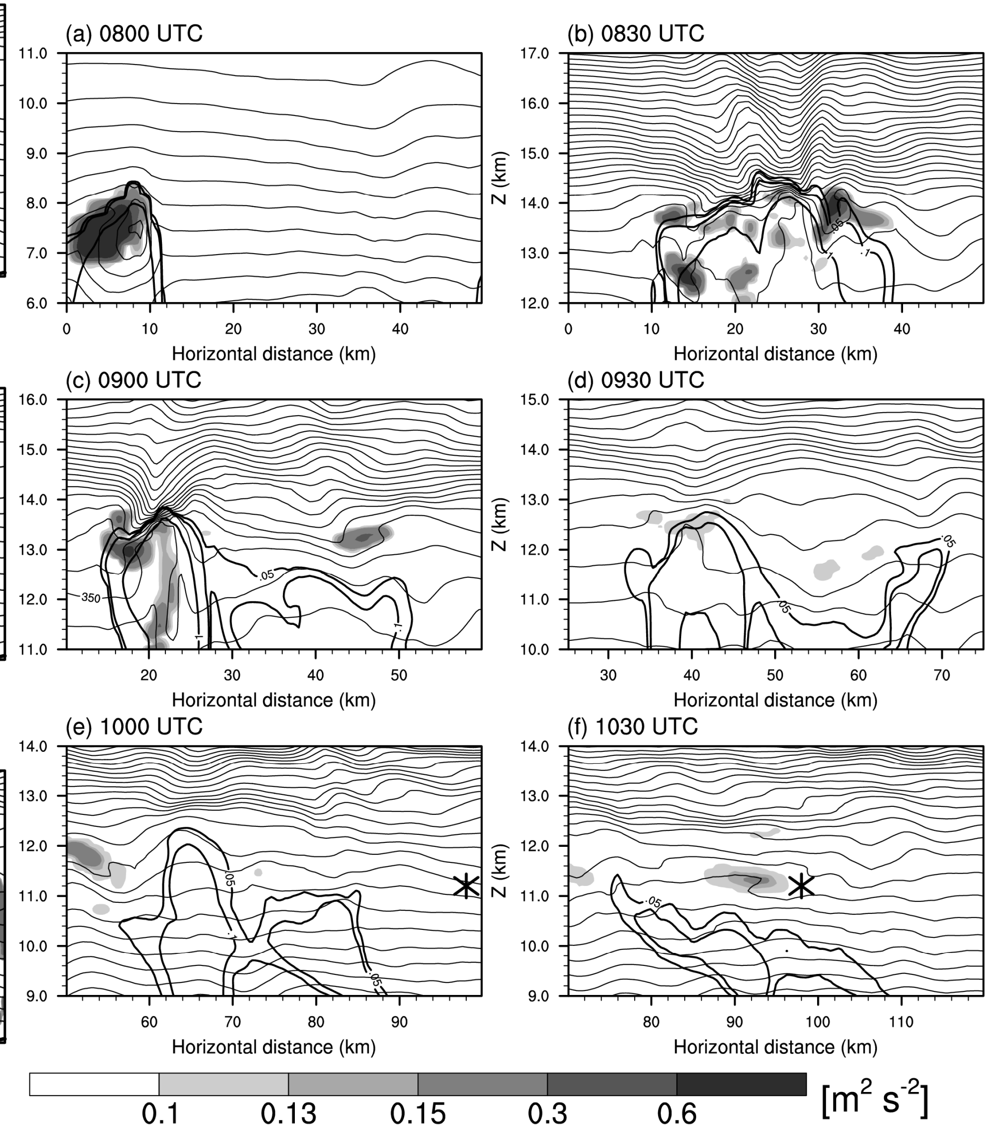


- Skew T-log p diagrams at Fukuoka at 0600 UTC 2 Sep 2007. Simulated (far right) and observed (right) wind.



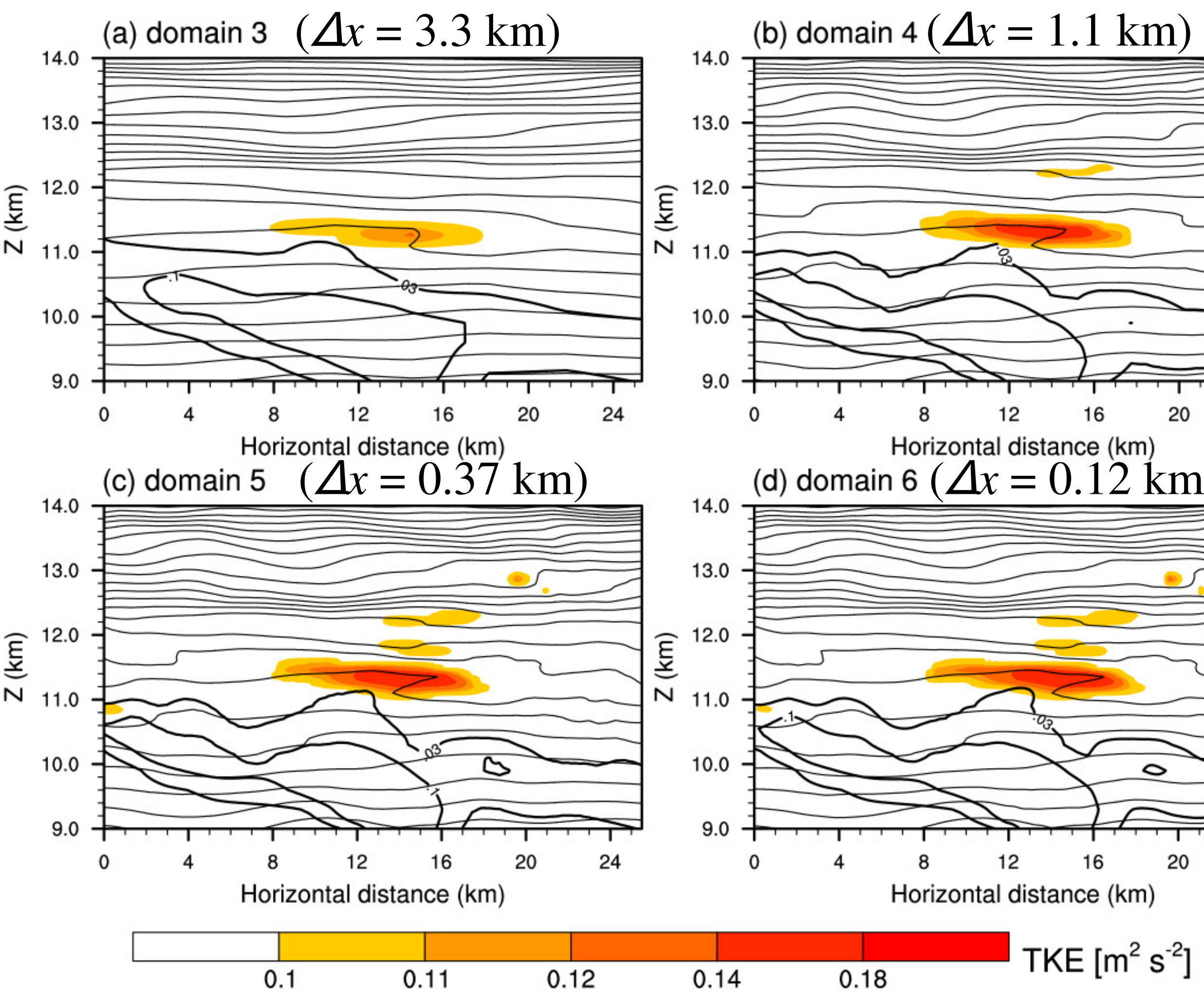
Vertical evolution of the targeted deep convection





4.4. Resolution dependency of simulated turbulence

< 1030 UTC >



- ✓ **Overall features of the non-zero TKE, potential temp., and cloud boundaries are similar to each domain. So, the out-of-cloud CIT at 1 km above the dissipating convection is not obviously different.**
- ✓ **However, detailed structures of clouds and small motions can be resolved in higher resolution domains.**
- ✓ **Wave breakings only appear in domains 5 and 6.**