A modeling study of the severe afternoon thunderstorm event at Taipei on 14 June 2015: The roles of sea breeze, microphysics, and terrain

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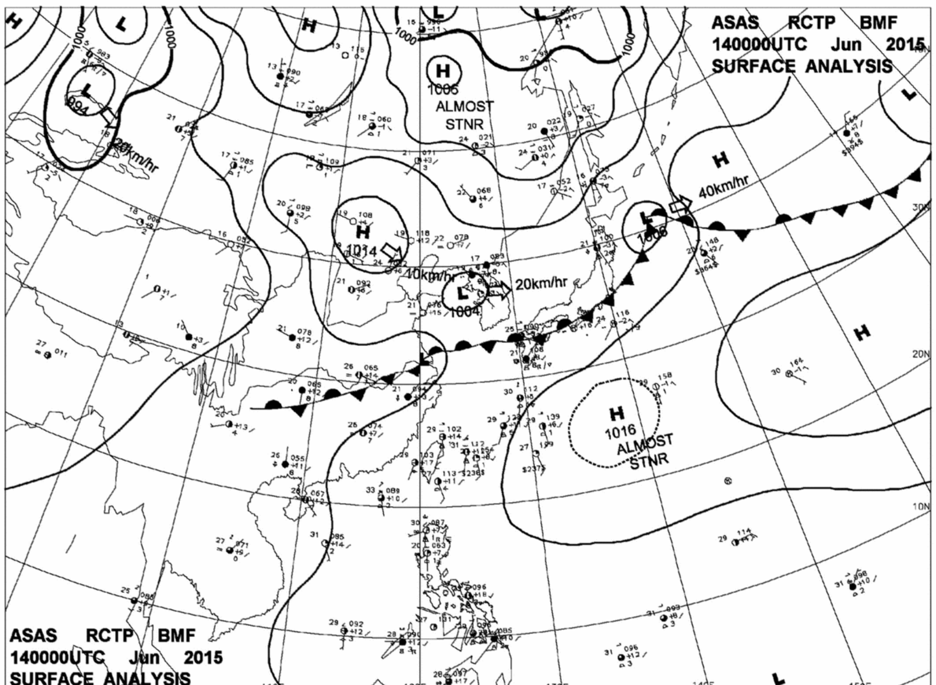
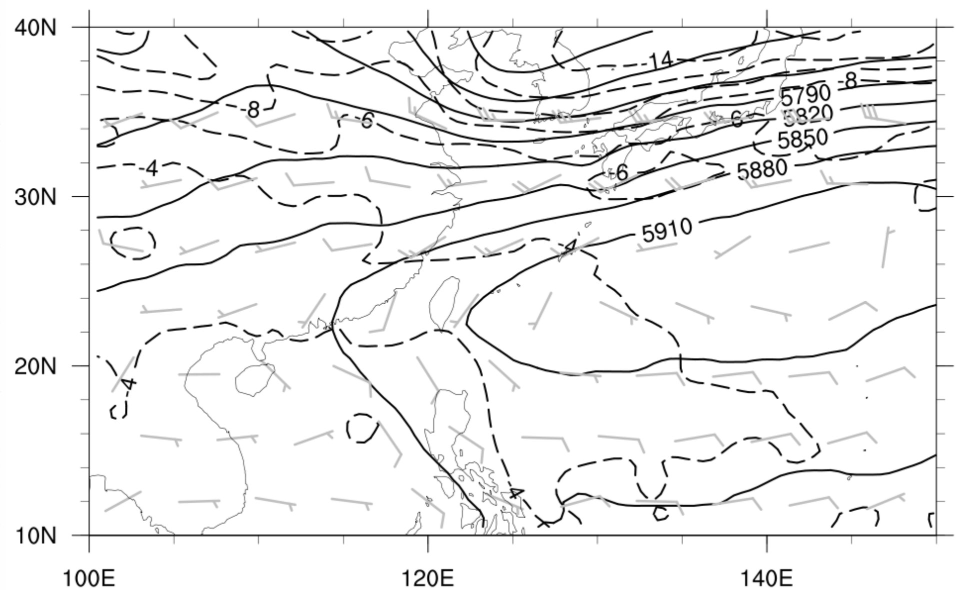
Weak Synoptic Forcing

Surface



CWB Synoptic Analysis

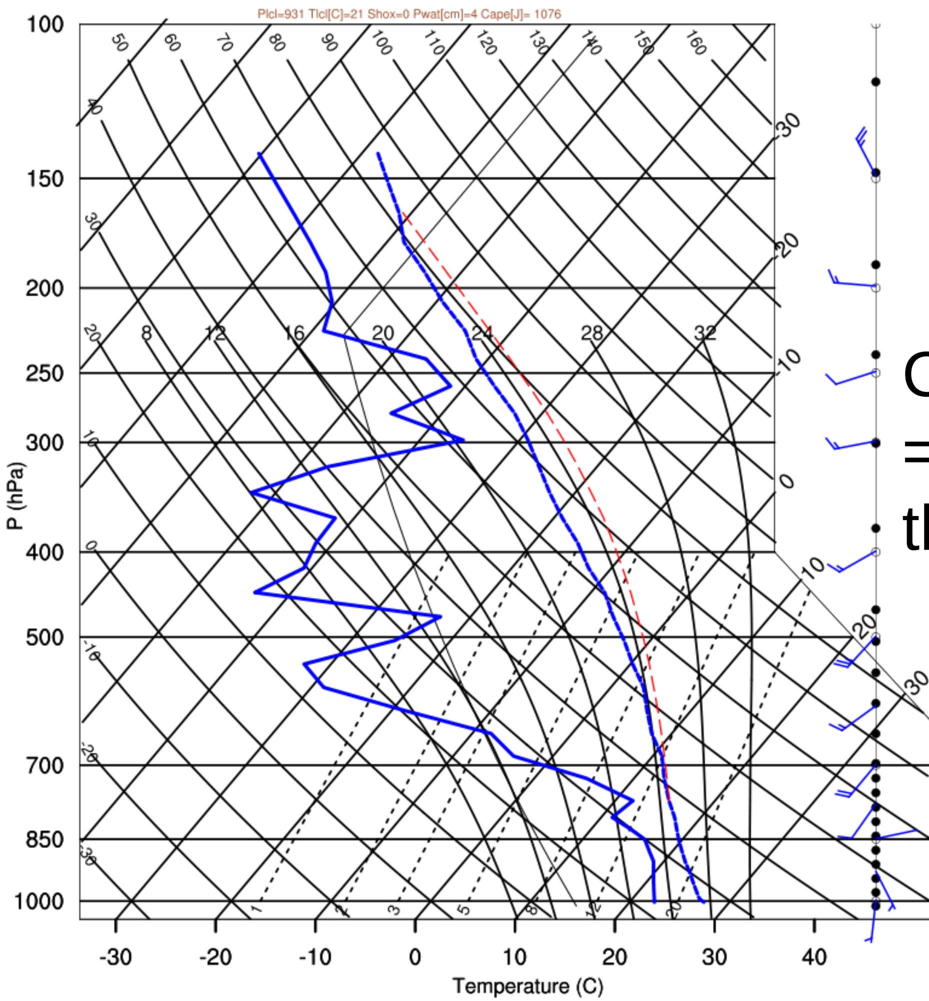
500 hPa



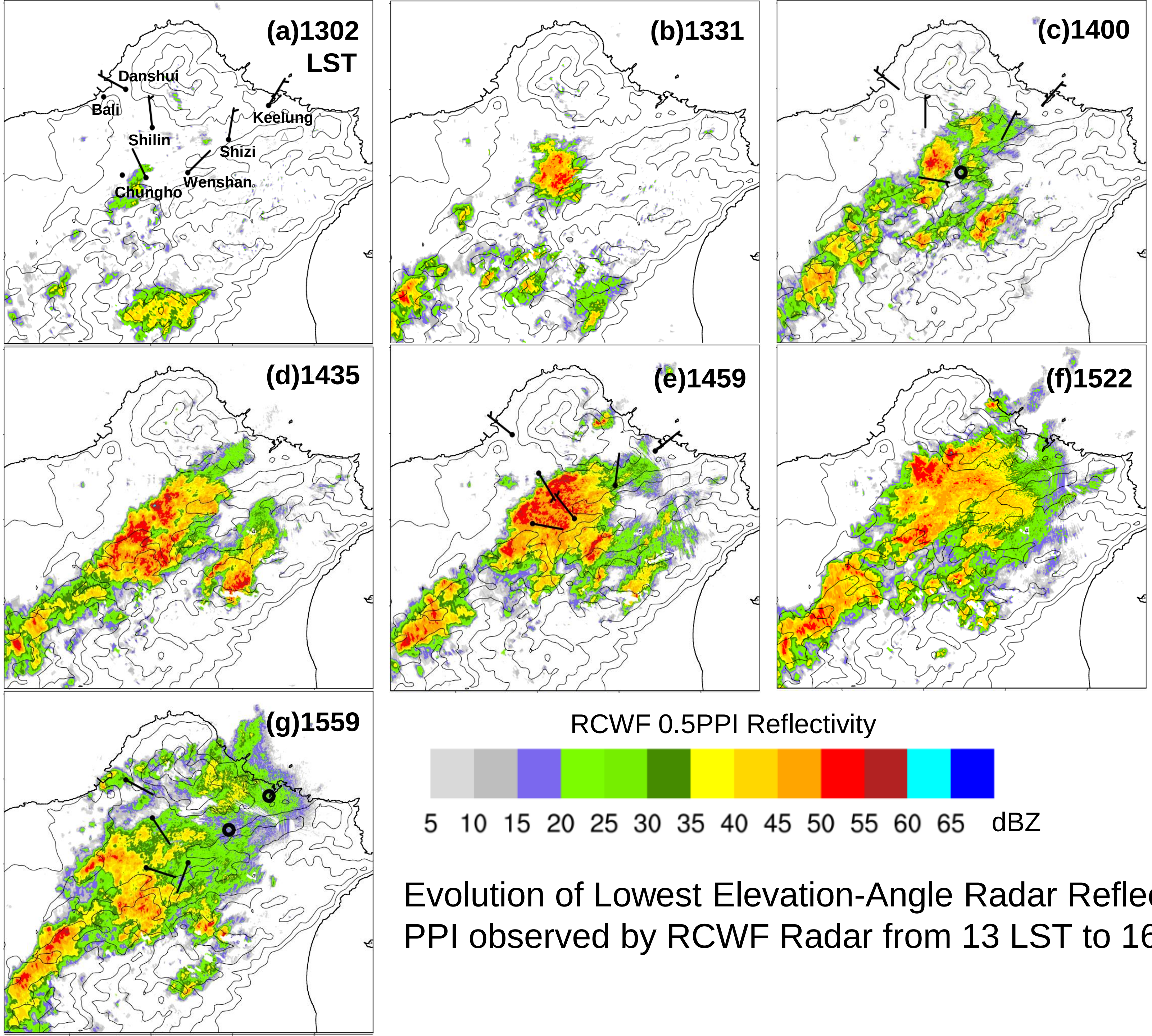
ERA-Interim reanalysis

Morning sounding

Banchiao sounding
08 LST 14 June 2015

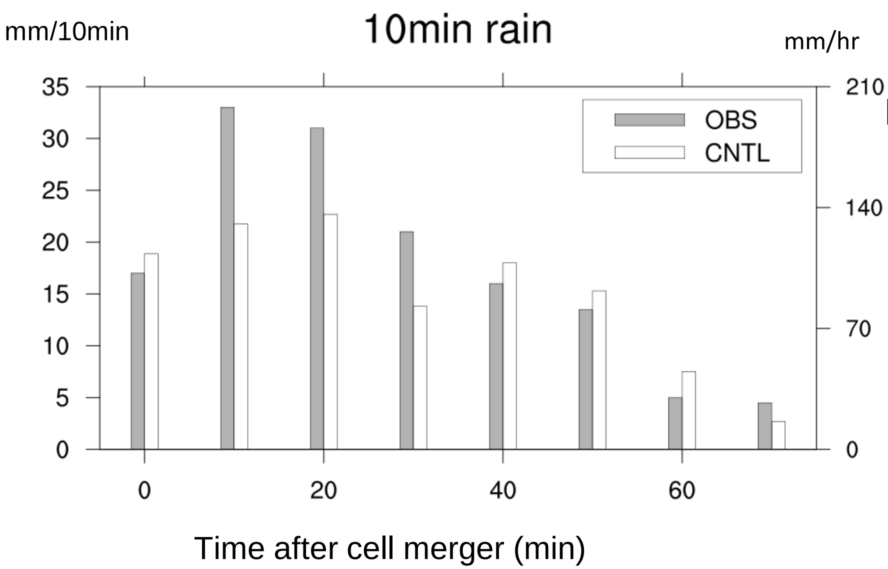


CAPE = 1076 J/kg at 08 LST
=> weak to moderate
thermodynamic instability

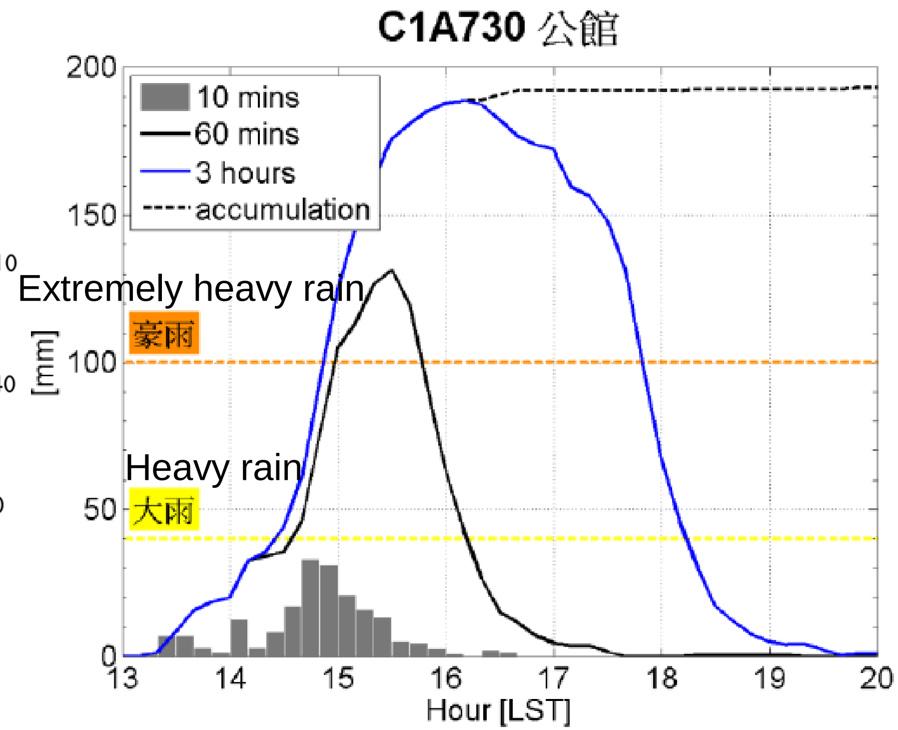


Evolution of Lowest Elevation-Angle Radar Reflectivity PPI observed by RCWF Radar from 13 LST to 16 LST

Time series of rainfall rate at NTU rain-gauge station



Miao and Yang
(2019; 大氣科學)

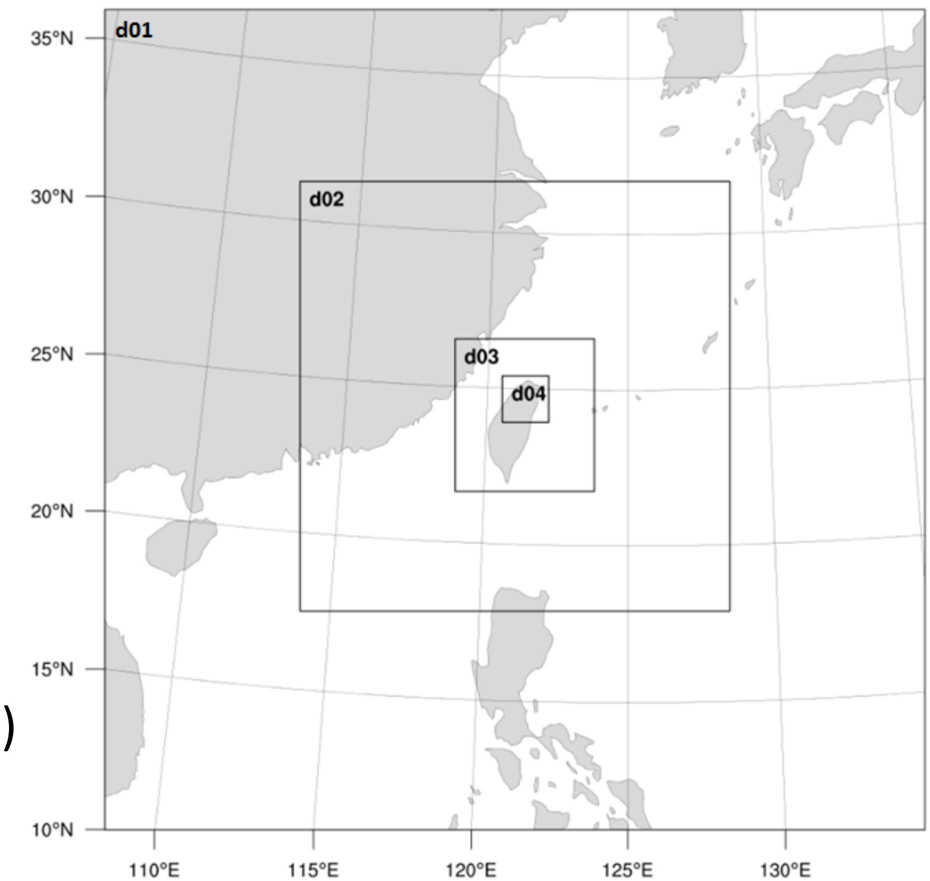


Jou at al.
(2016; 大氣科學)

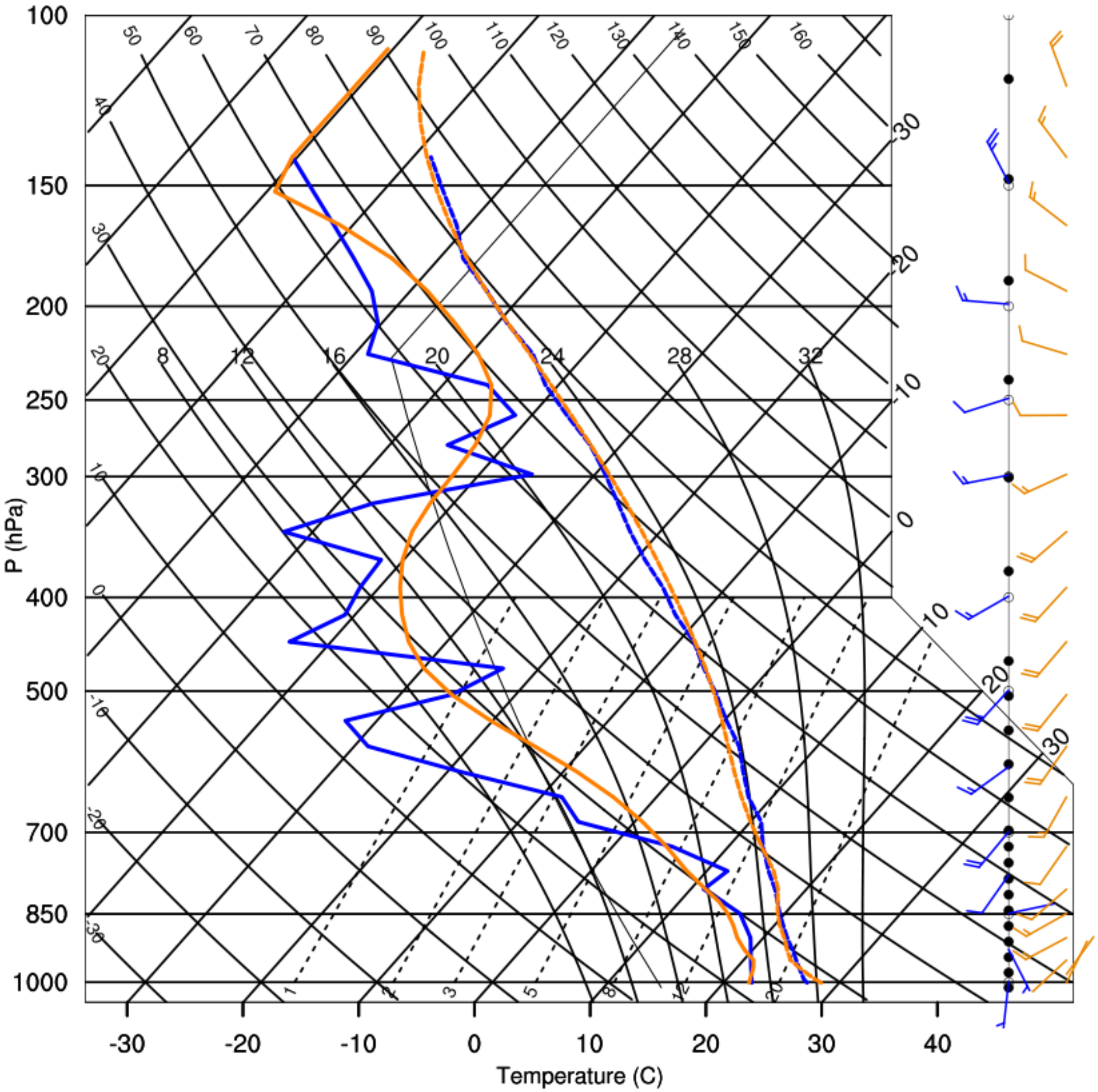
=> Both observation and model simulation show that rainfall rate increases significantly after cell merger!

Model Configuration

- Version 3.4 of WRF ARW
- two-way interactive 4 nested domains: 13.5, 4.5, 1.5 , **0.5 km**
- **55 vertical levels (8 layers within PBL)**
- microphysics scheme: WDM6
- Kain-Fritsch cumulus (only D1)
- Dudhia shortwave radiation
- RRTM longwave radiation
- Noah land surface model
- YSU PBL
- Landuse data: MODIS
- ECMWF ERA-Interim 0.75°x0.75°
- initial time: 6/13 12Z
- forecast hour: 24hr at t = 15hr)



Comparison between the simulated and observed soundings



Banchiao sounding at 0800 LST
OBS **WRF-CNTL**

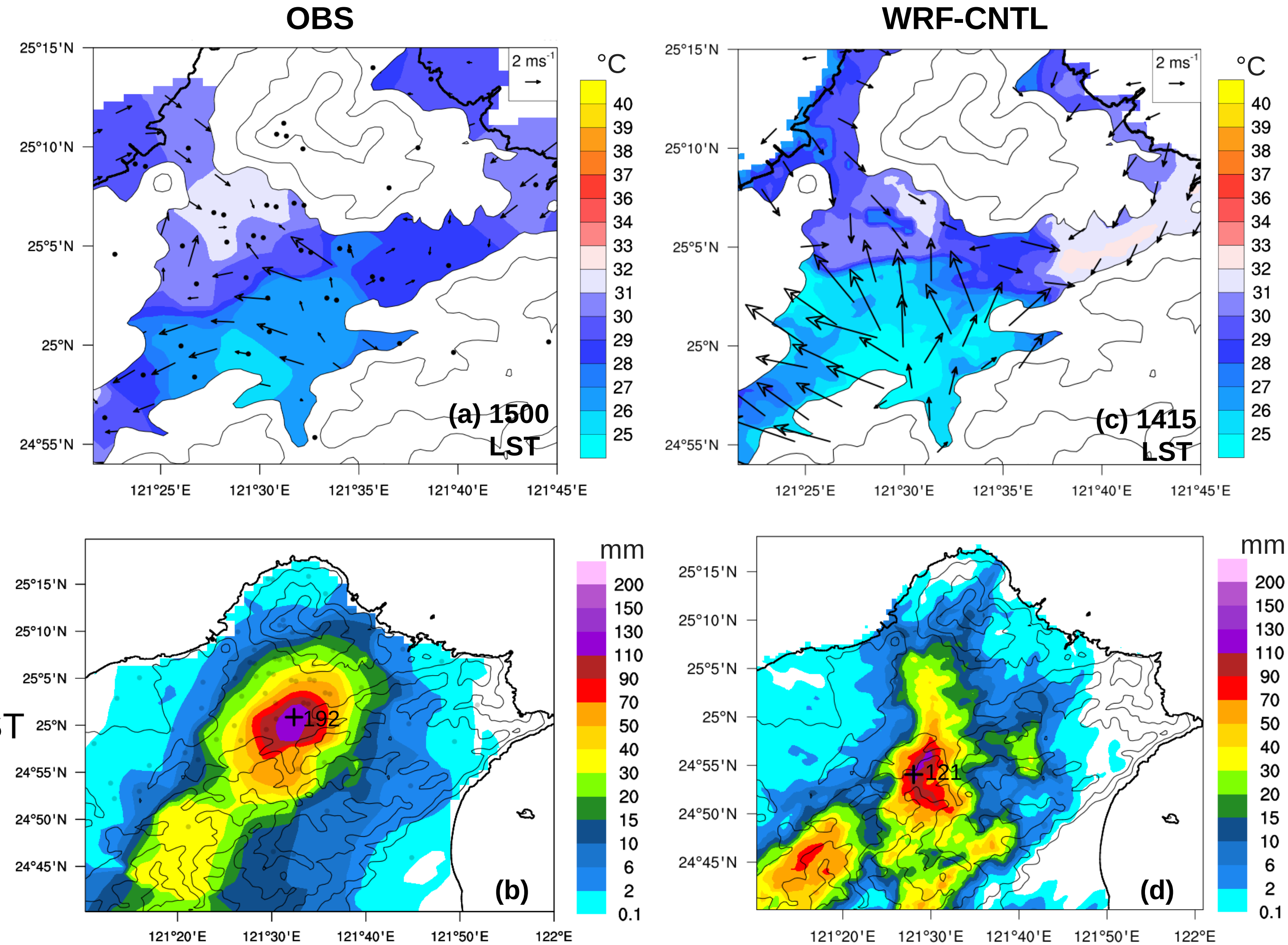
CAPE comparison:
=> OBS: 1076 J/kg
CNTL: 885 J/kg

Both show a mid-level dry layer.

Both show the southwesterly between 850 hPa and 400 hPa, and the westerly at upper level.

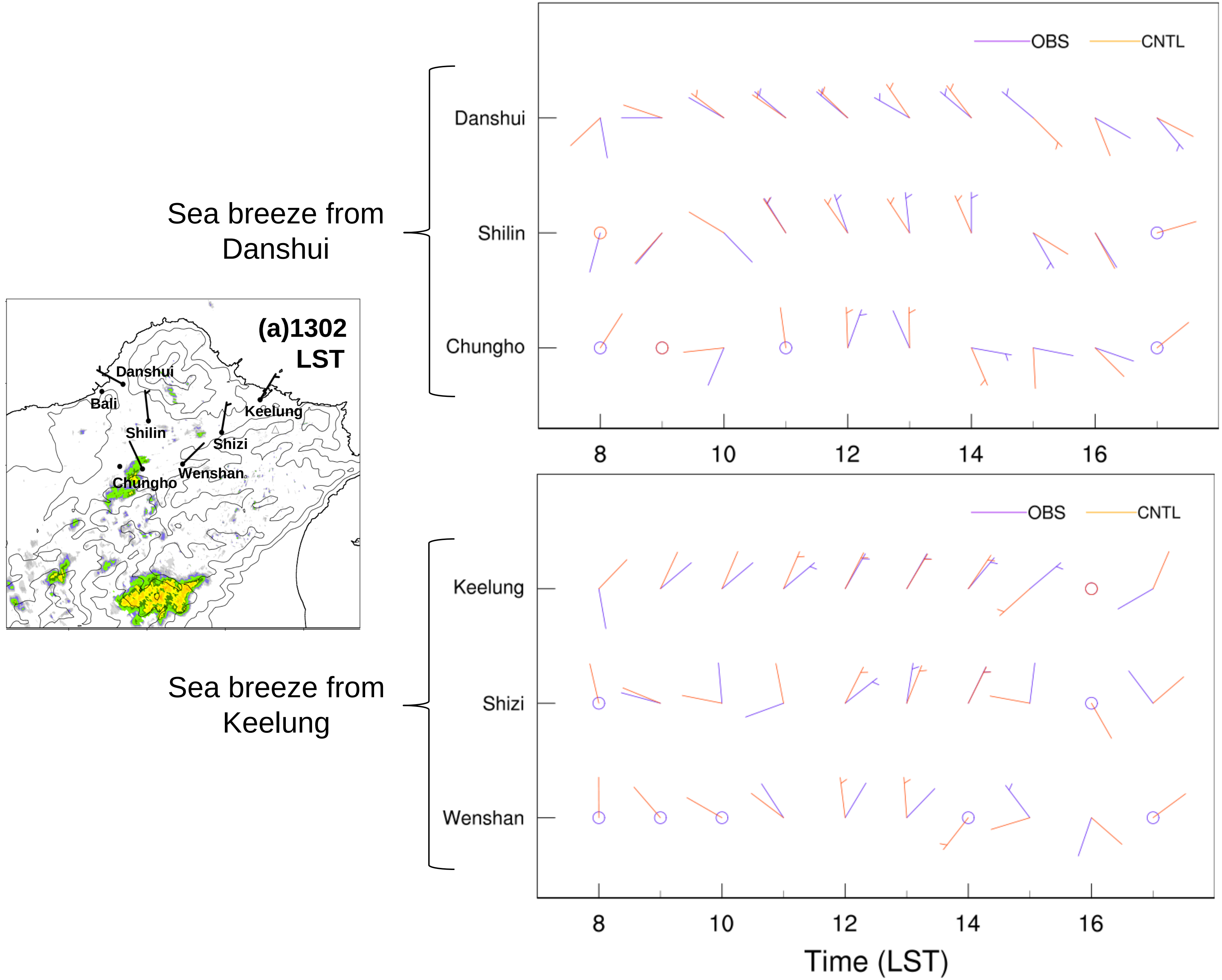
Temperature
Wind

1200-1800 LST
rainfall



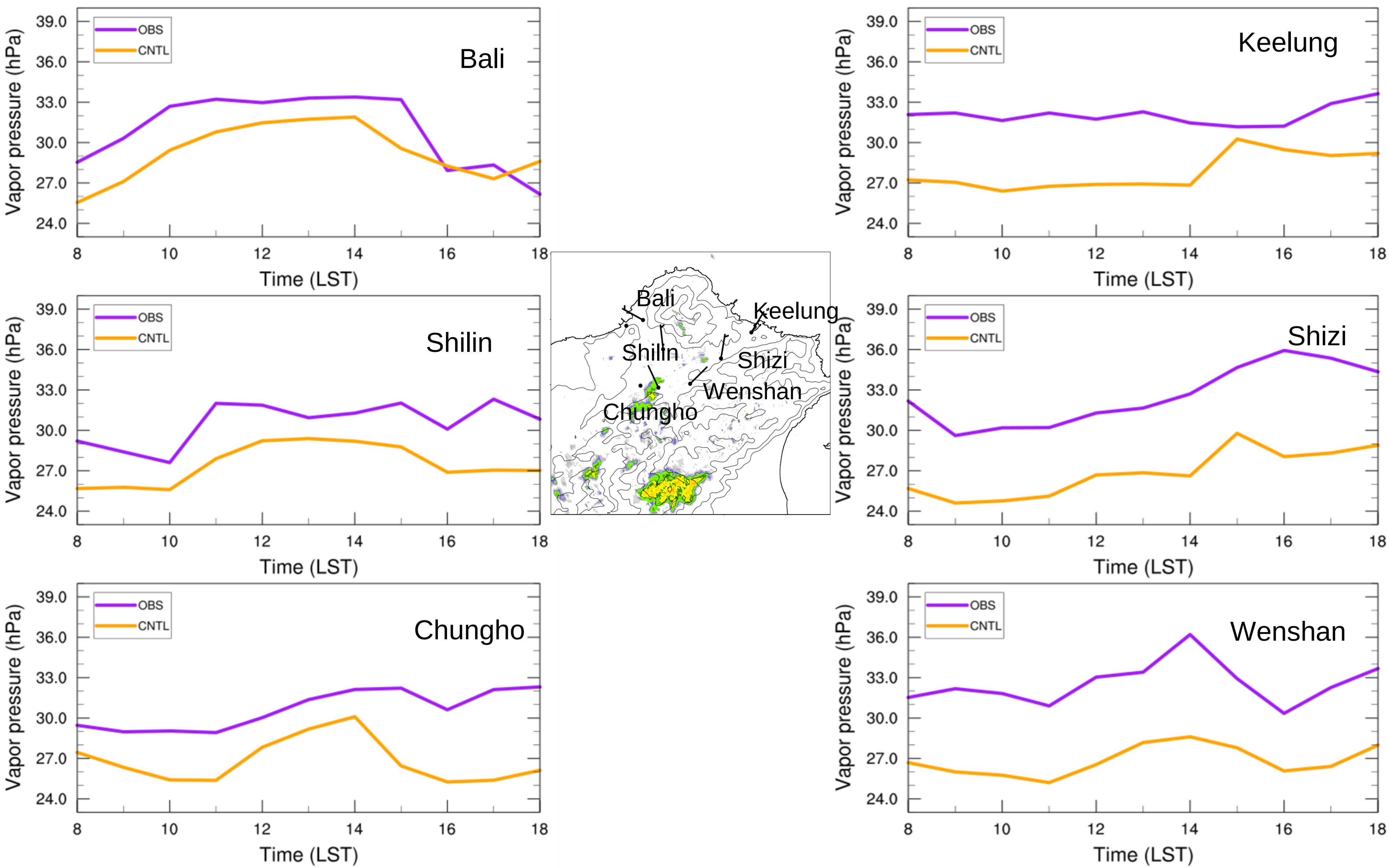
Miao and Yang
(2019; 大氣科學)

=> Low-level convergence produced by sea-breeze circulation and thunderstorm cold-air outflow at Taipei City



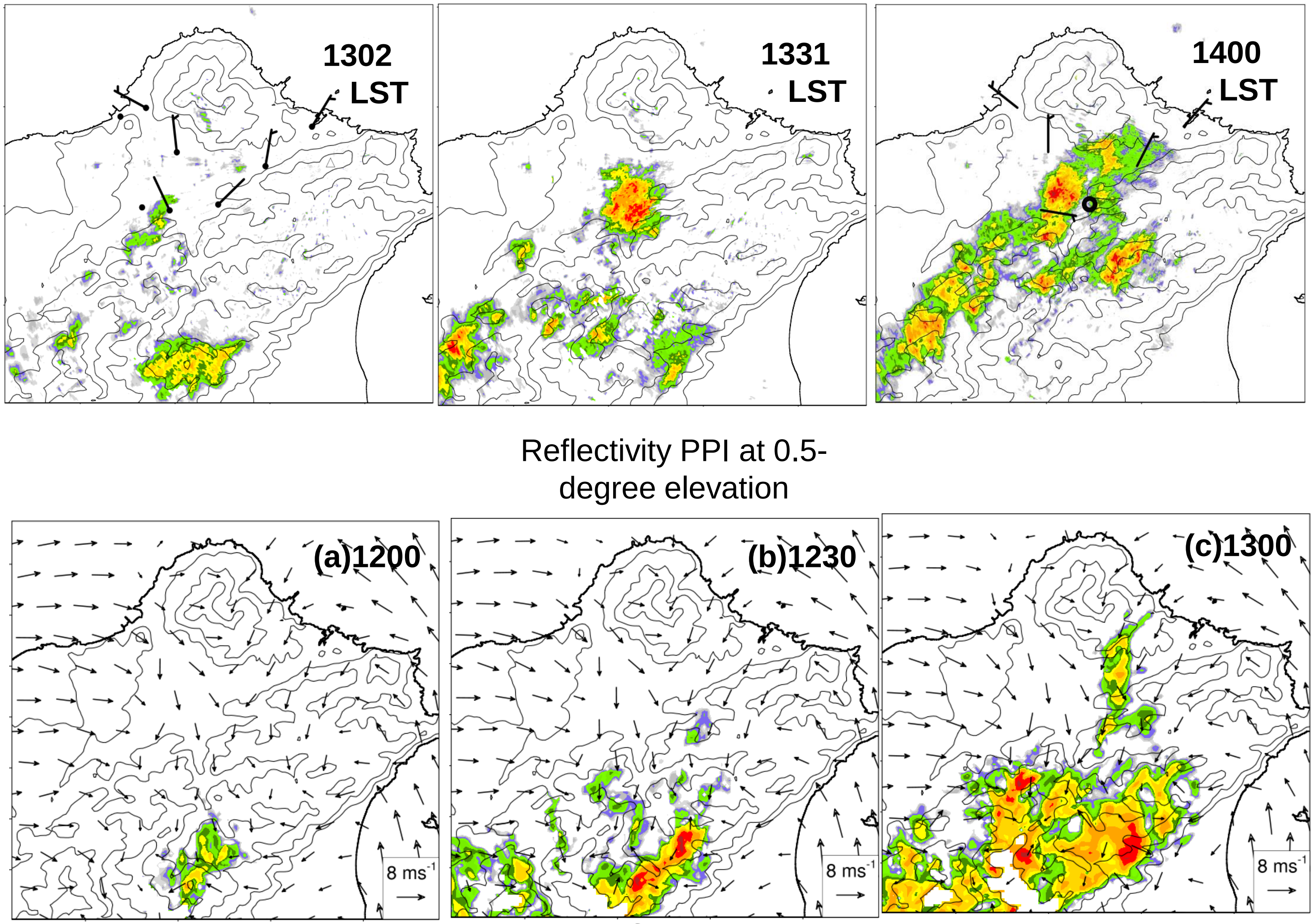
Sea breeze from Danshui
Sea breeze from Keelung
(a)1302 LST
Danshui
Bali
Keelung
Shilin
Shizi
Wenshan
Chungho
OBS
CNTL
Danshui
Shilin
Chungho
8
10
12
14
16
OBS
CNTL
Keelung
Shizi
Wenshan
8
10
12
14
16
Time (LST)

Water vapor comparison



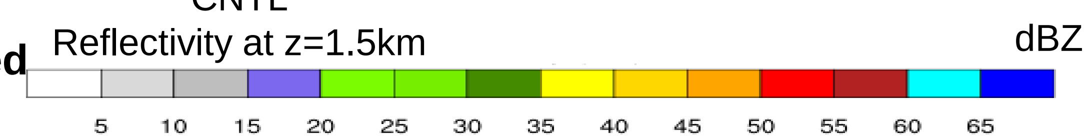
OBS

WRF



Reflectivity PPI at 0.5-degree elevation

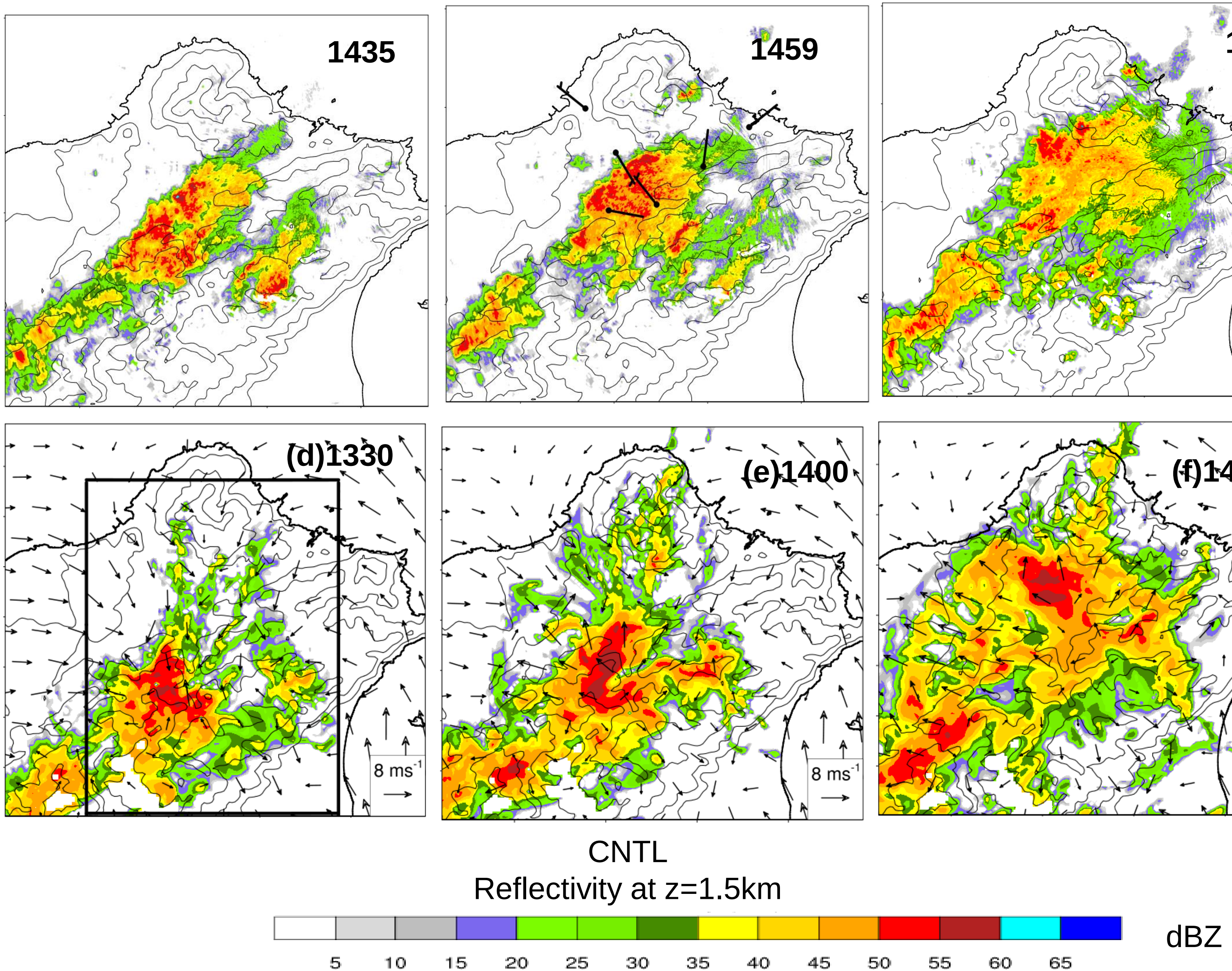
CNTL
Reflectivity at z=1.5km



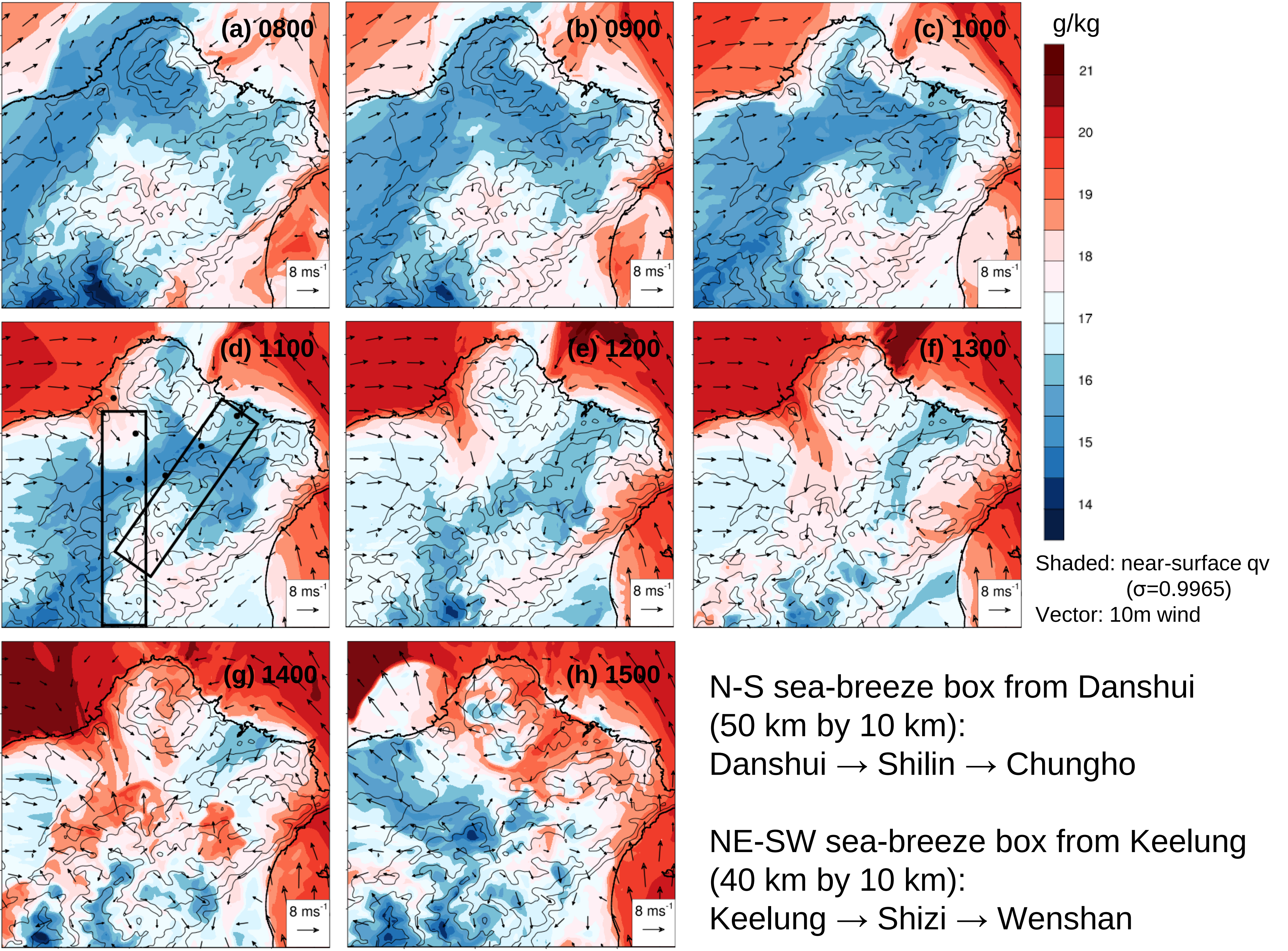
=> Simulated thunderstorms occurred one hour earlier than the observed.

OBS

WRF

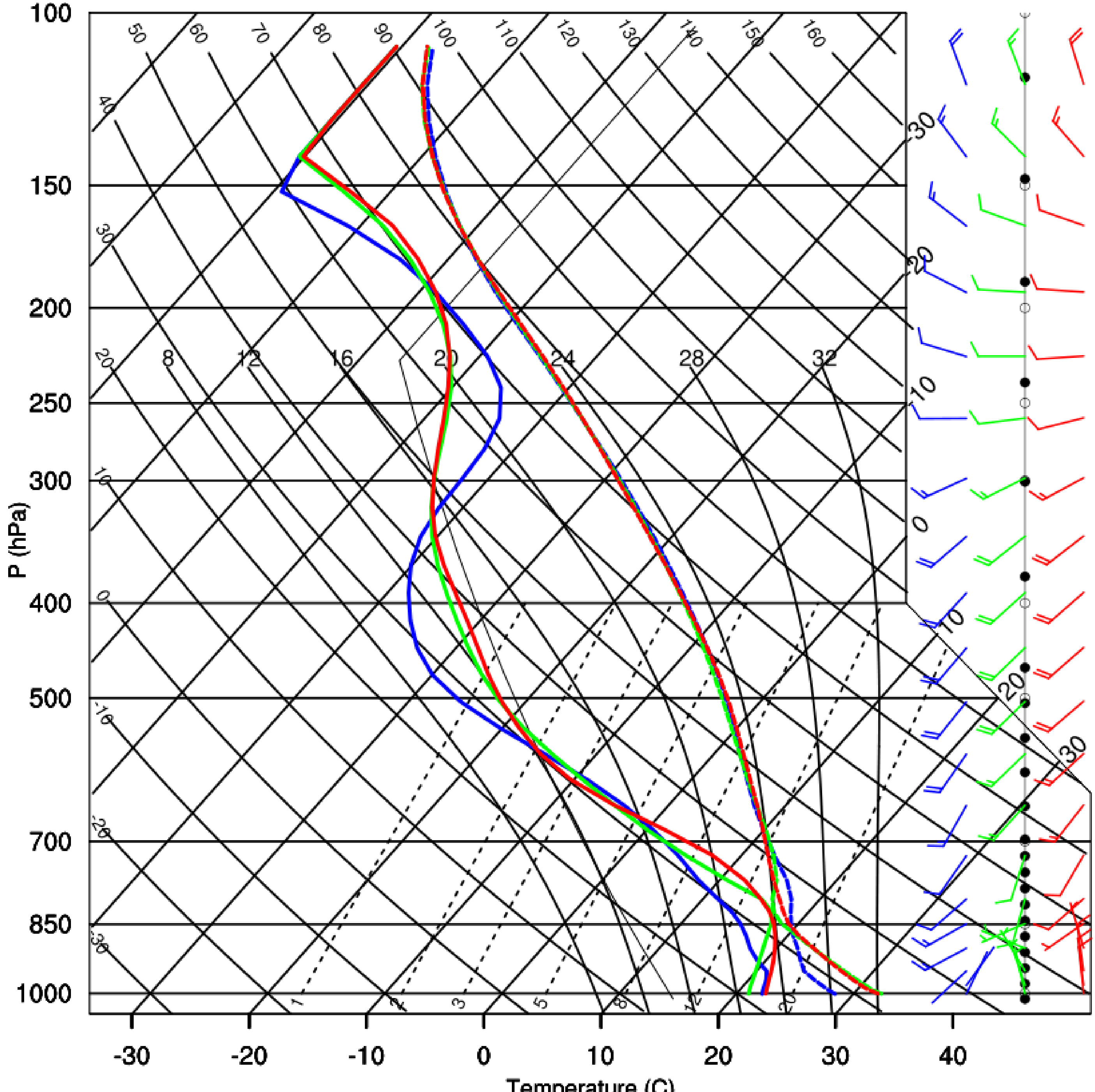


=> Simulated thunderstorms occurred one hour earlier than the observed.



N-S sea-breeze box from Danshui (50 km by 10 km):
Danshui → Shilin → Chungho

NE-SW sea-breeze box from Keelung (40 km by 10 km):
Keelung → Shizi → Wenshan



CAPE evolution

0800 LST

1100 LST

1200 LST

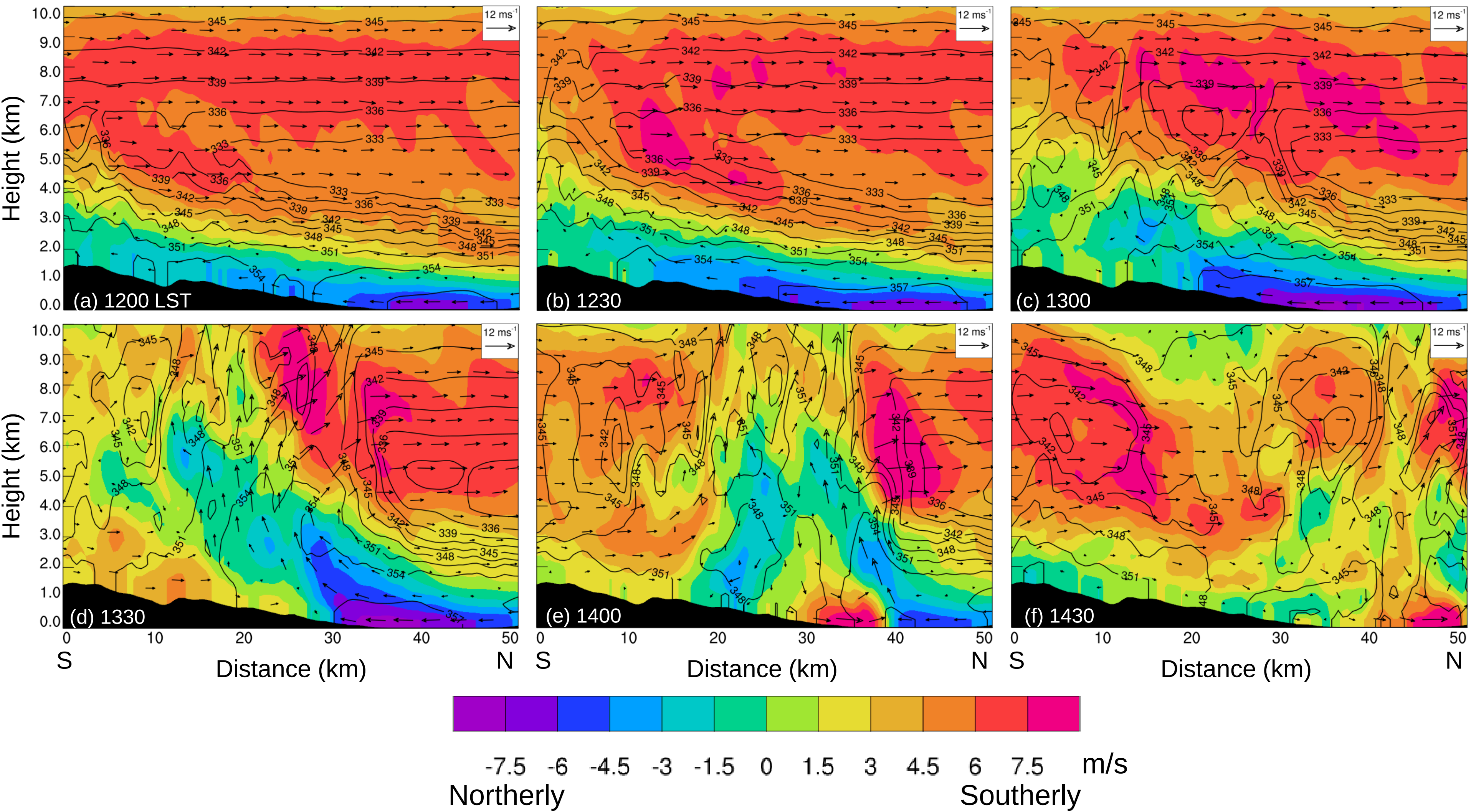
0800 LST:
CAPE = 885 J/kg

1100 LST:
CAPE = 1833 J/kg
Well-mixed PBL
Wind turns to northerly below 1km

1200 LST:
CAPE = 3268 J/kg
Dewpoint increases
Wind turns to northerly below 1.3 km.

Vertical Cross Section along the Sea Breeze from Danshui

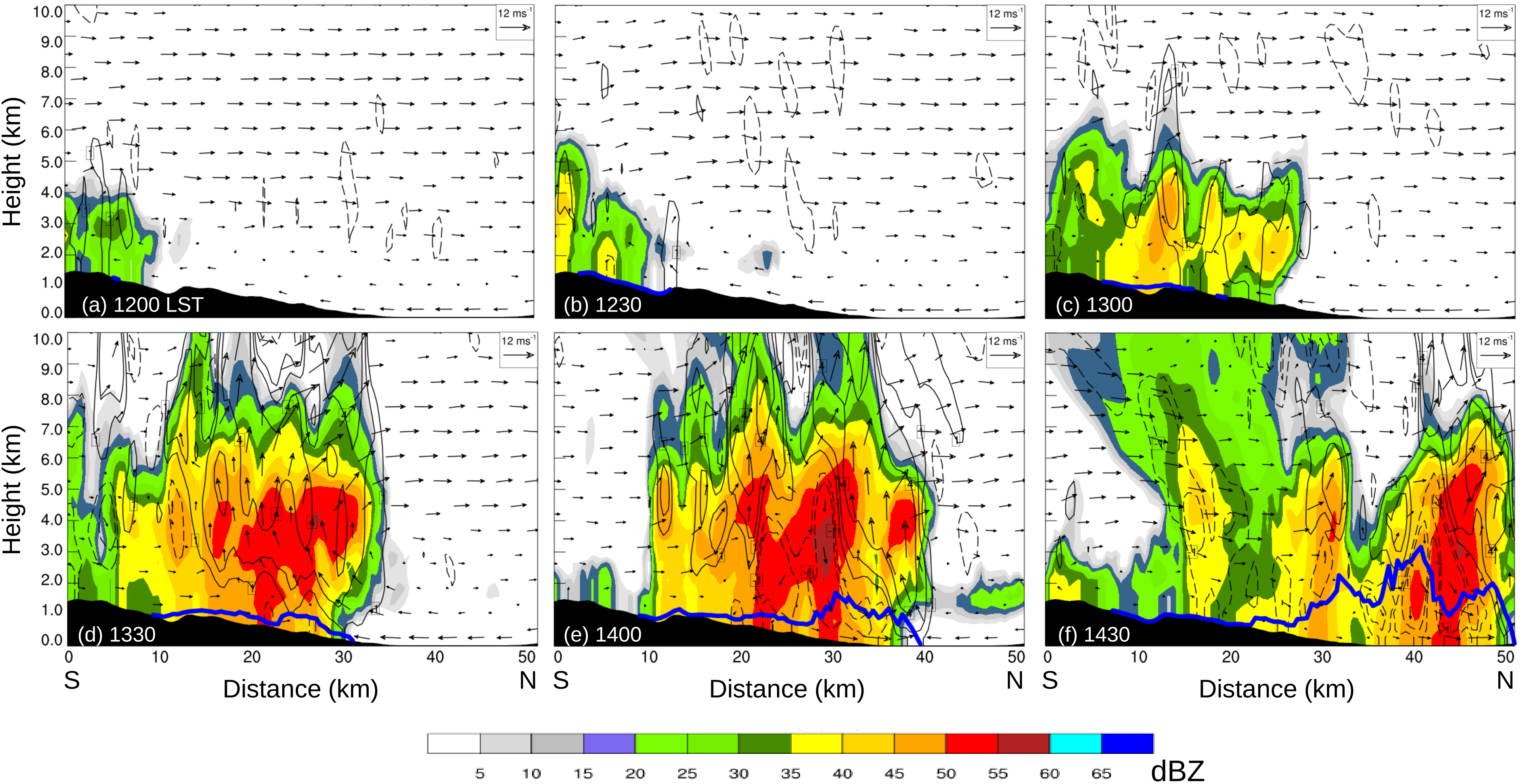
Shaded: meridional wind
Contour: equivalent potential temperature



Vertical Cross Section along the Sea Breeze from Danshui

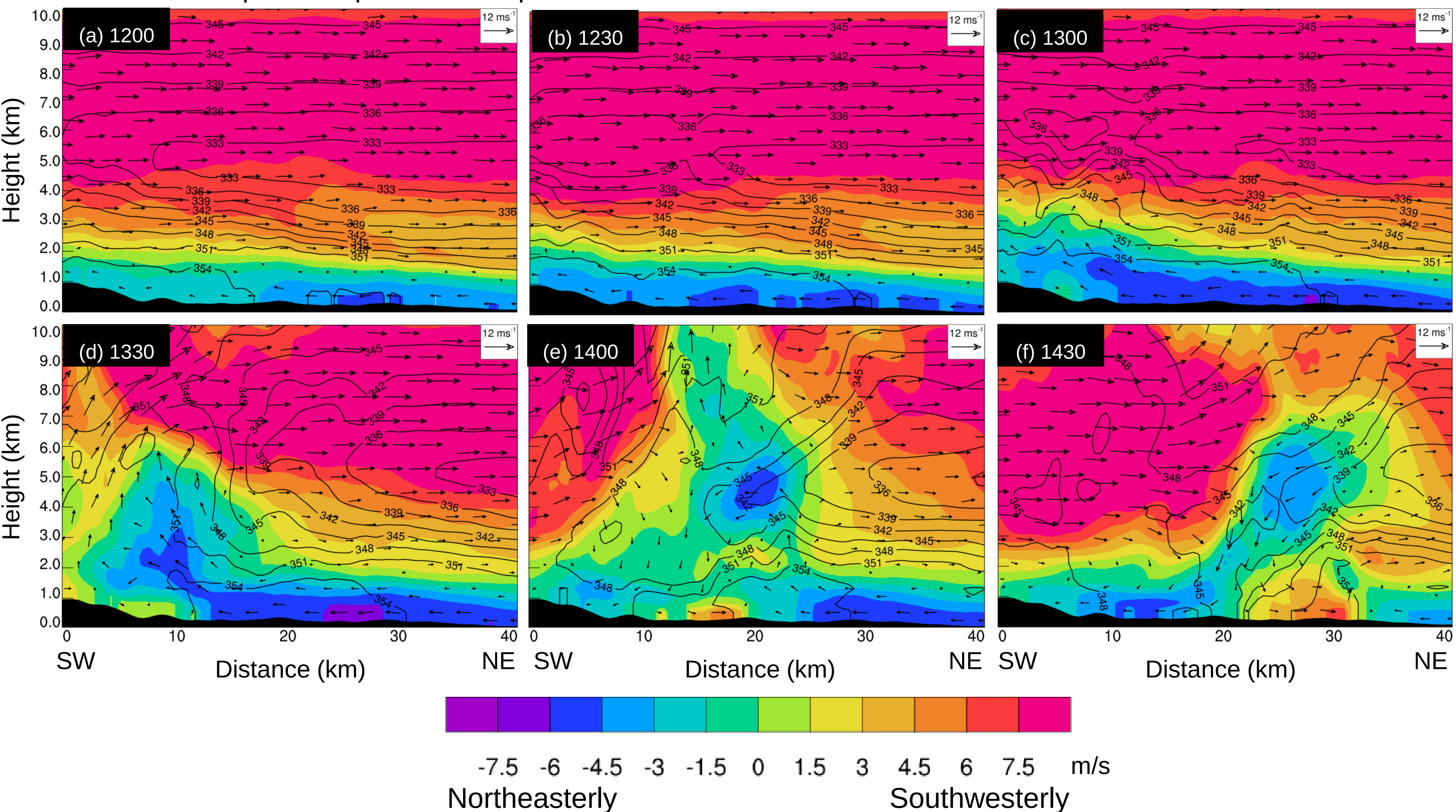
Shaded: radar reflectivity

Contour: vertical velocity = { -1, -0.5, 1, 2, 4, 8 } m/s



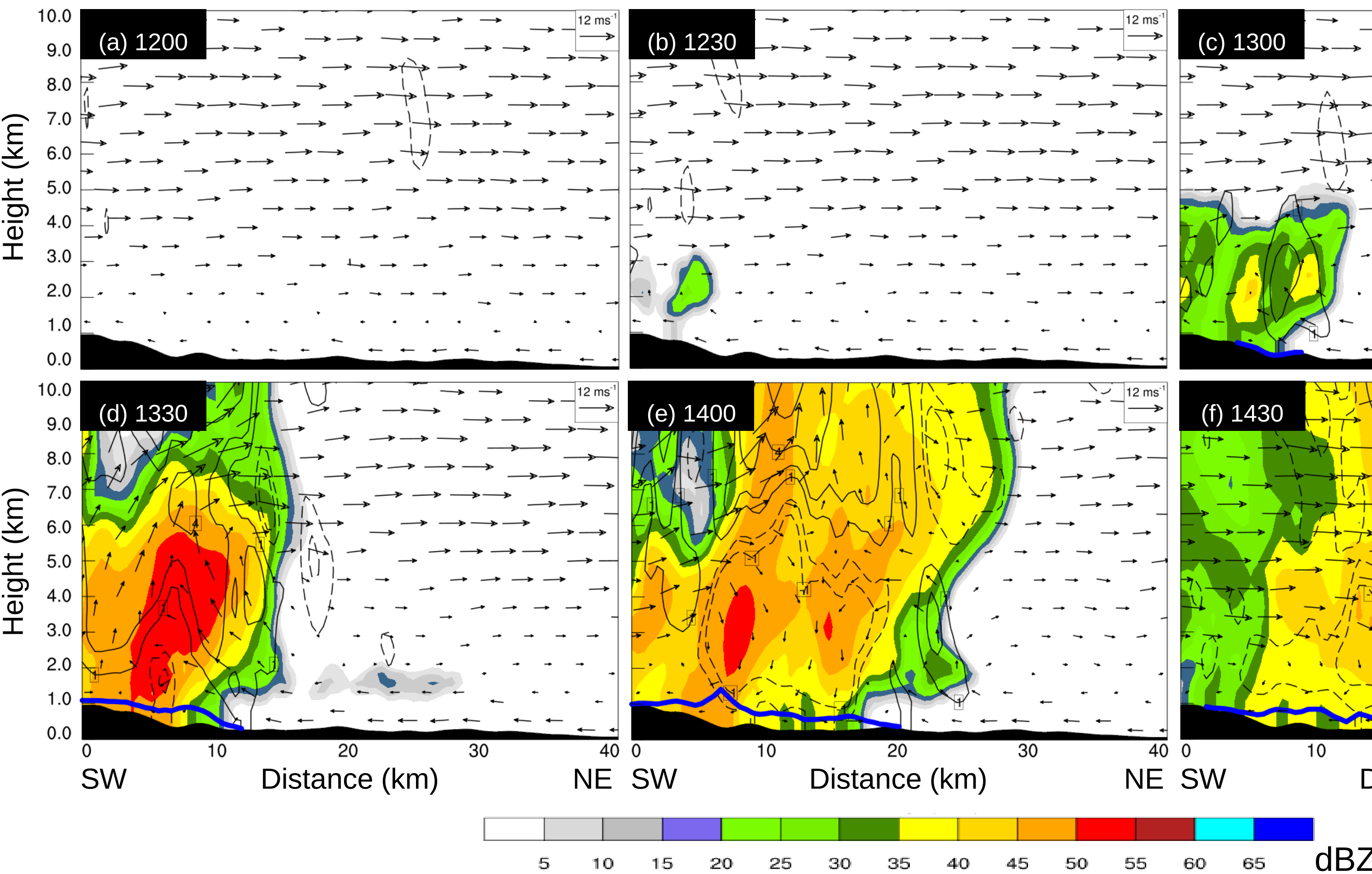
Vertical Cross Section along the Sea Breeze from Keelung

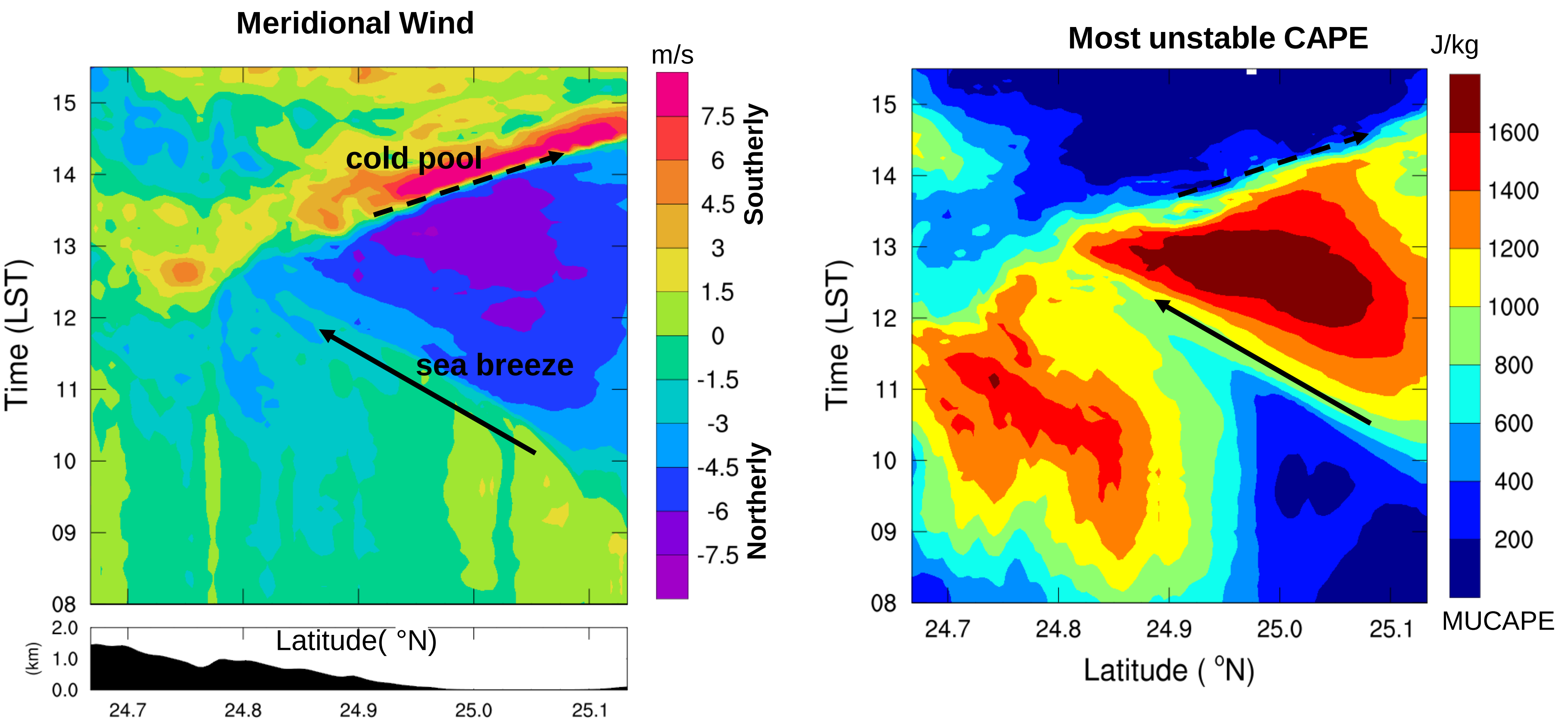
Shaded: plane-parallel wind
Contour: equivalent potential temperature



Vertical Cross Section along the Sea Breeze from Keelung

Shaded: radar reflectivity
Contour: vertical velocity = { -1, -0.5, 1, 2, 4, 8 } m/s



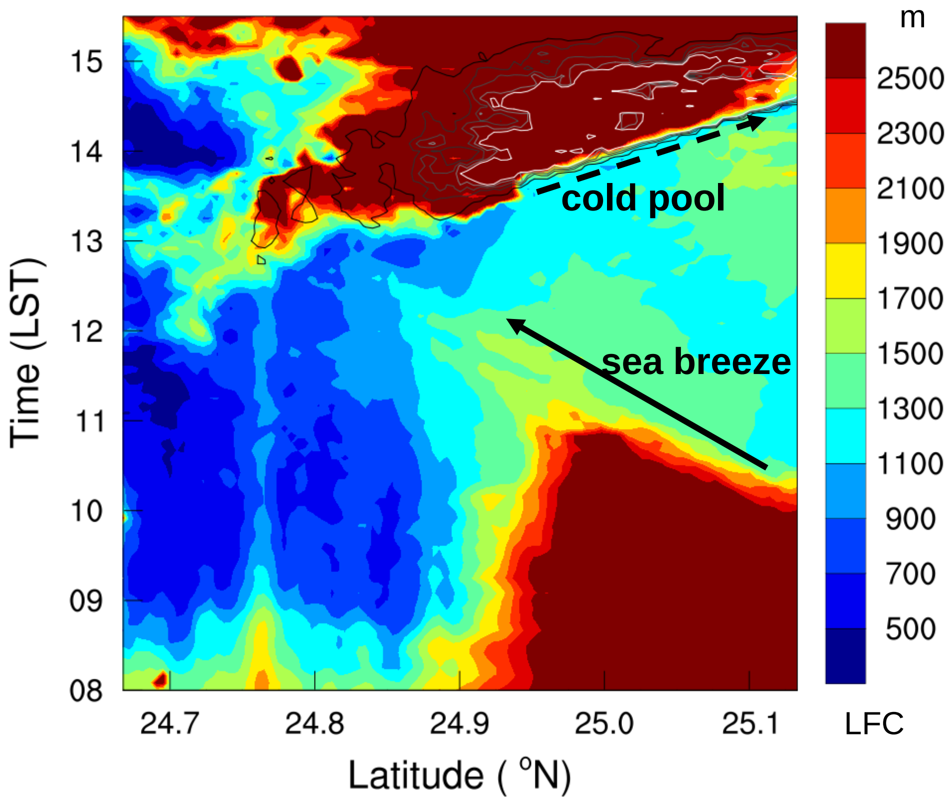


Hovmöller diagrams along the N-S sea breeze from Danshui

=> sea-breeze propagation speed ~4.6 m/s
cold pool propagation speed ~ 6.5 m/s

=> The MUCAPE is highly related to the meridional wind associated with sea-breeze circulation!

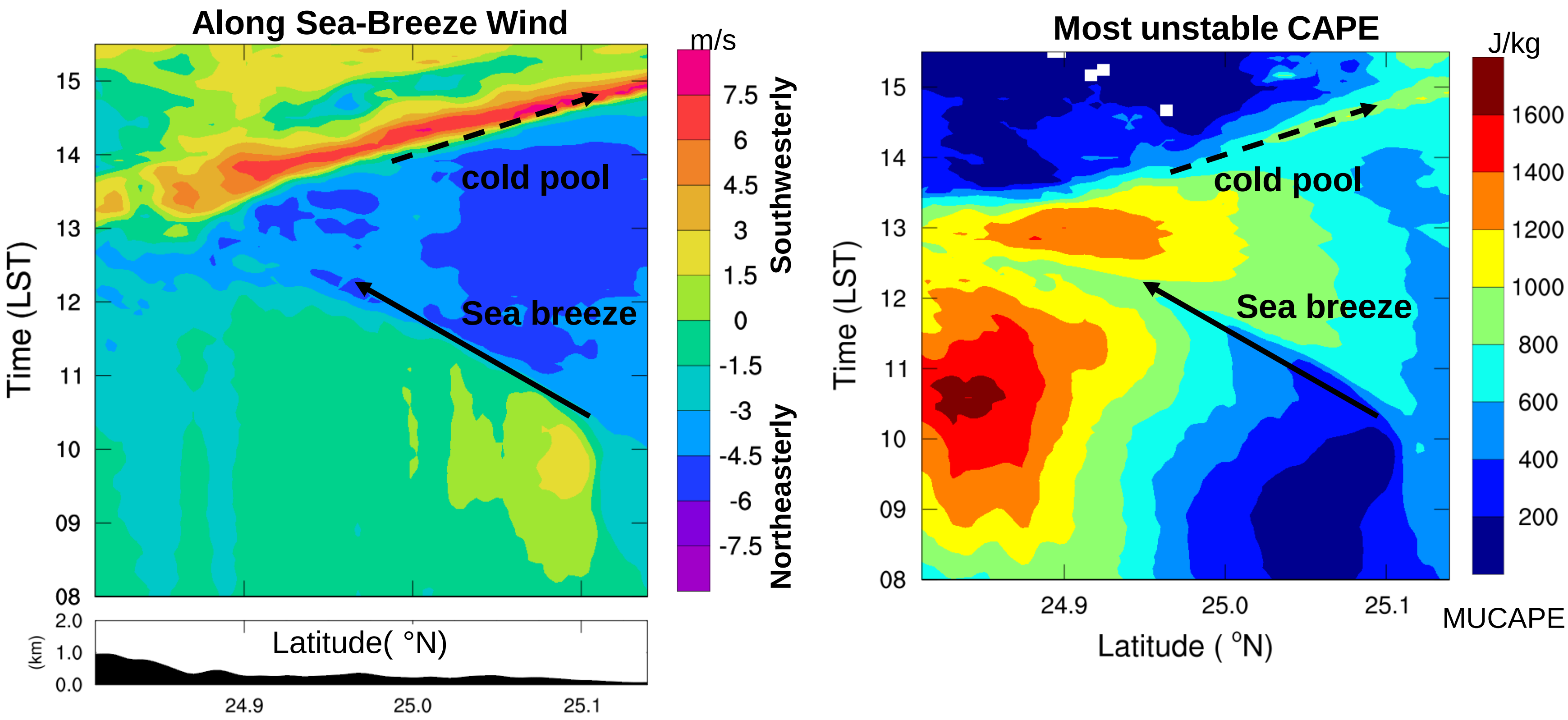
LFC Height



Hovmöller diagrams along the sea-breeze from Danshui: level of free convection & cold-pool height (contour)@ {200, 500, 700, 900,1100 m}

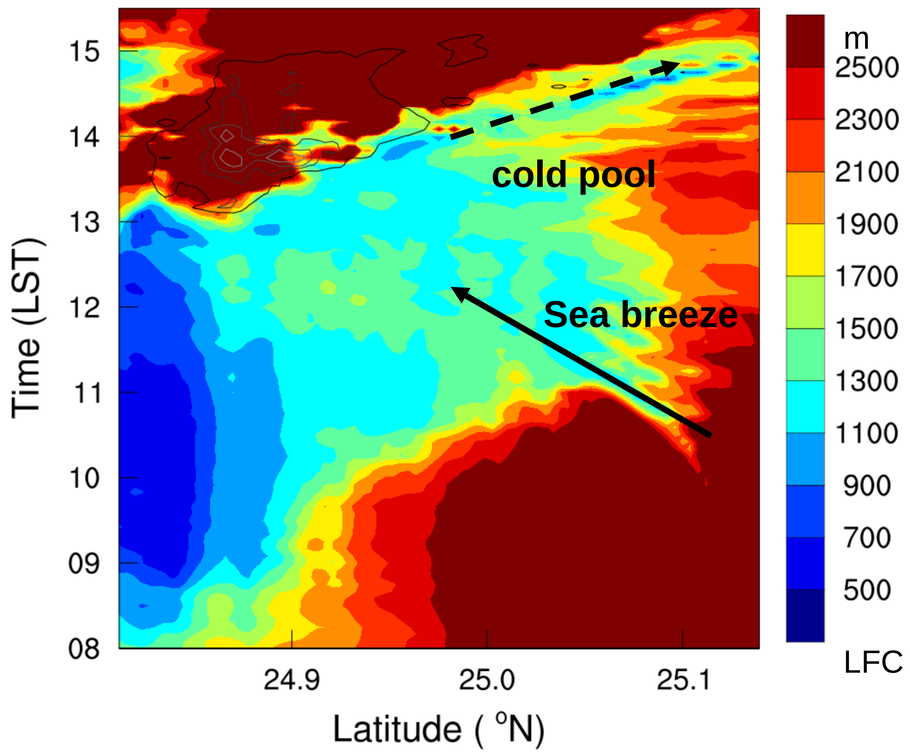
⇒ LFC is higher than cold-pool height

⇒ air parcels lifted above the cold pool can easily reach their LFCs and release their CAPEs



Hovmöller diagrams along the NE-SW sea-breeze from Keelung

=> The MUCAPE is also highly related to the sea-breeze speed, but the MUCAPE along Keelung sea breeze is weaker than that along the Danshui sea breeze by ~200 J/kg.

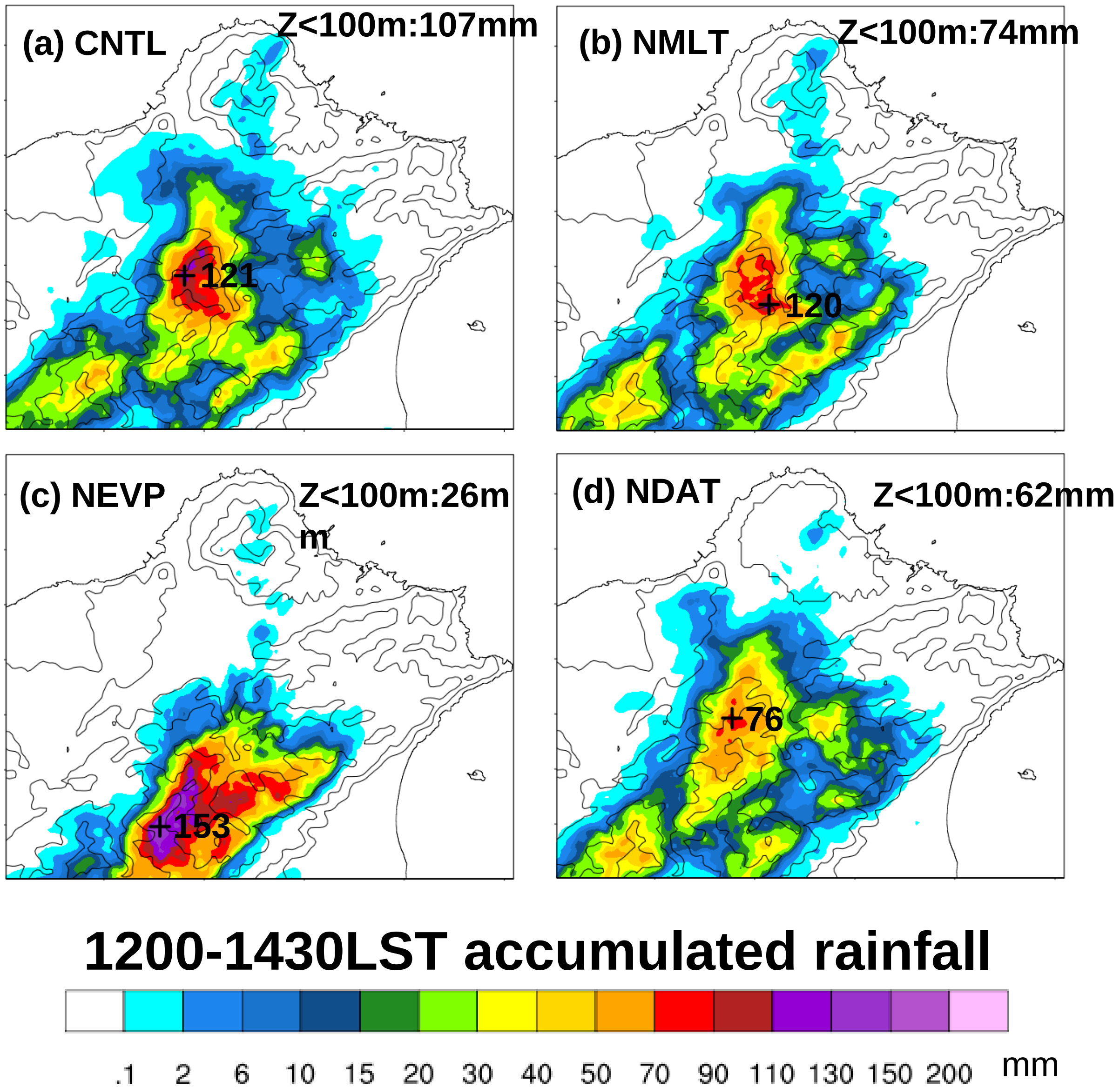


Hovmöller diagrams along the NE-SW sea-breeze from Keelung:
LFC height & cold-pool height (contour) @ {200, 500, 700, 900 m}

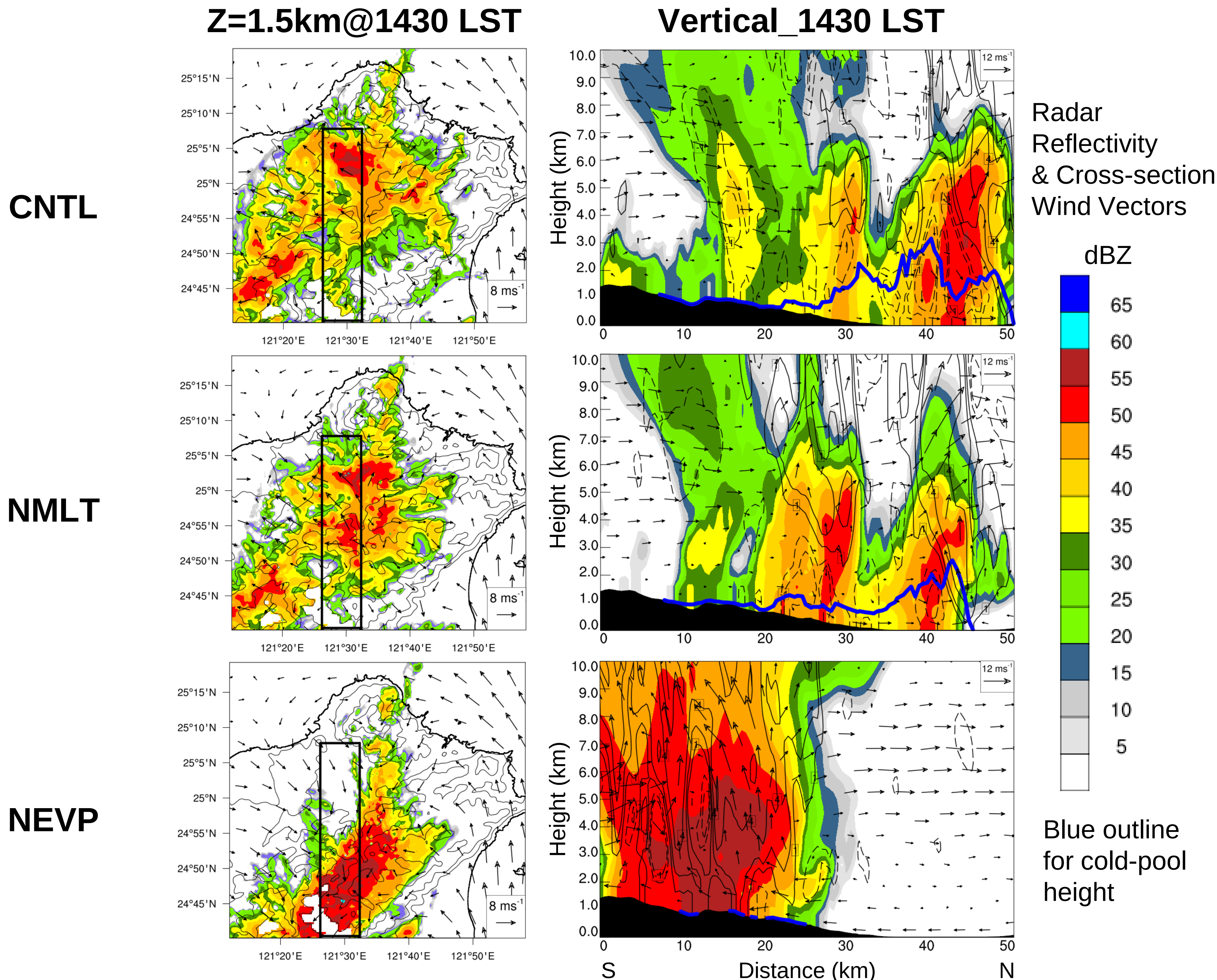
⇒ The relationship between LFC and cold-pool height is not so clear, particular for NE sea breeze from Keelung

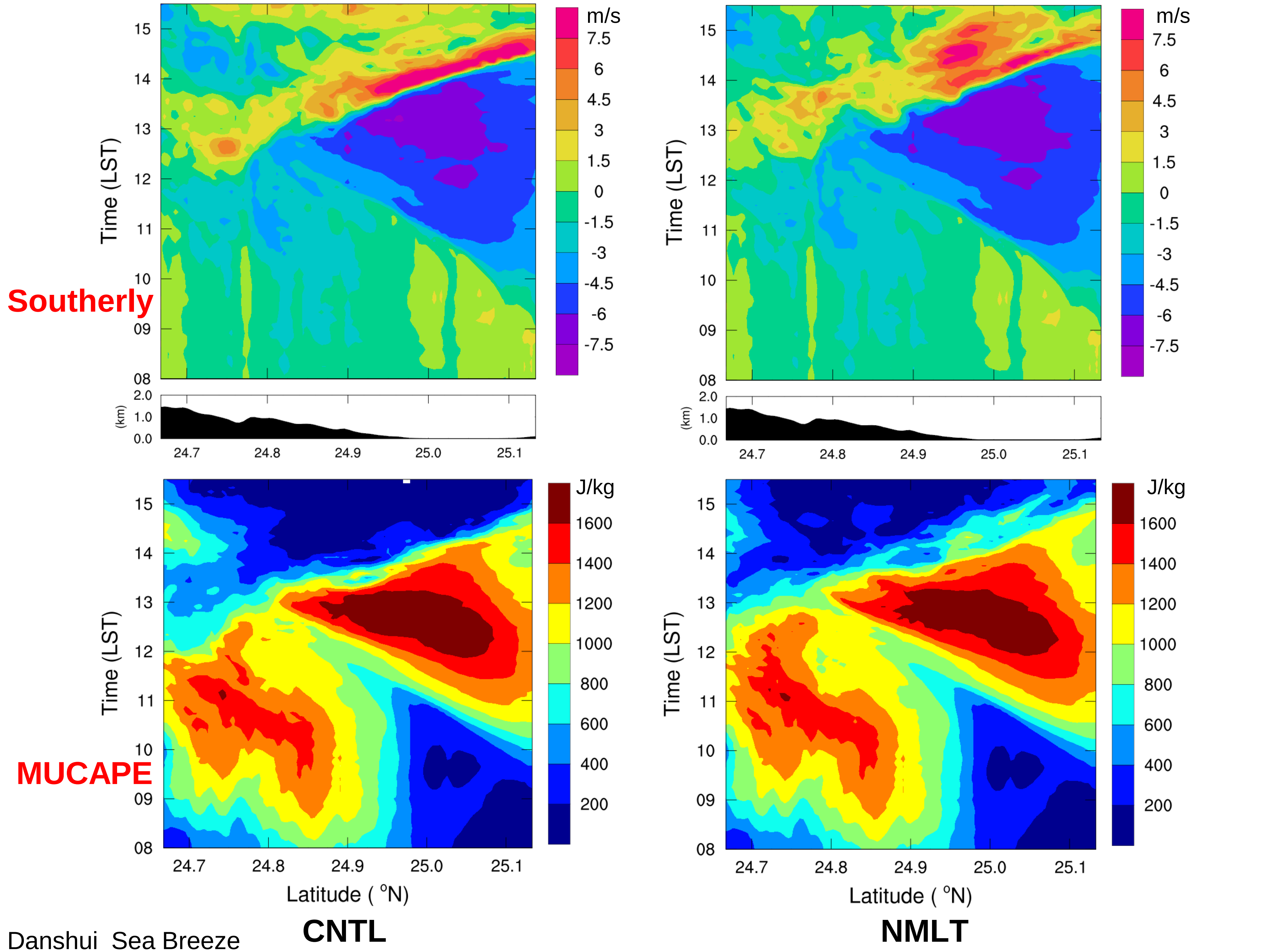
Sensitivity Experiments

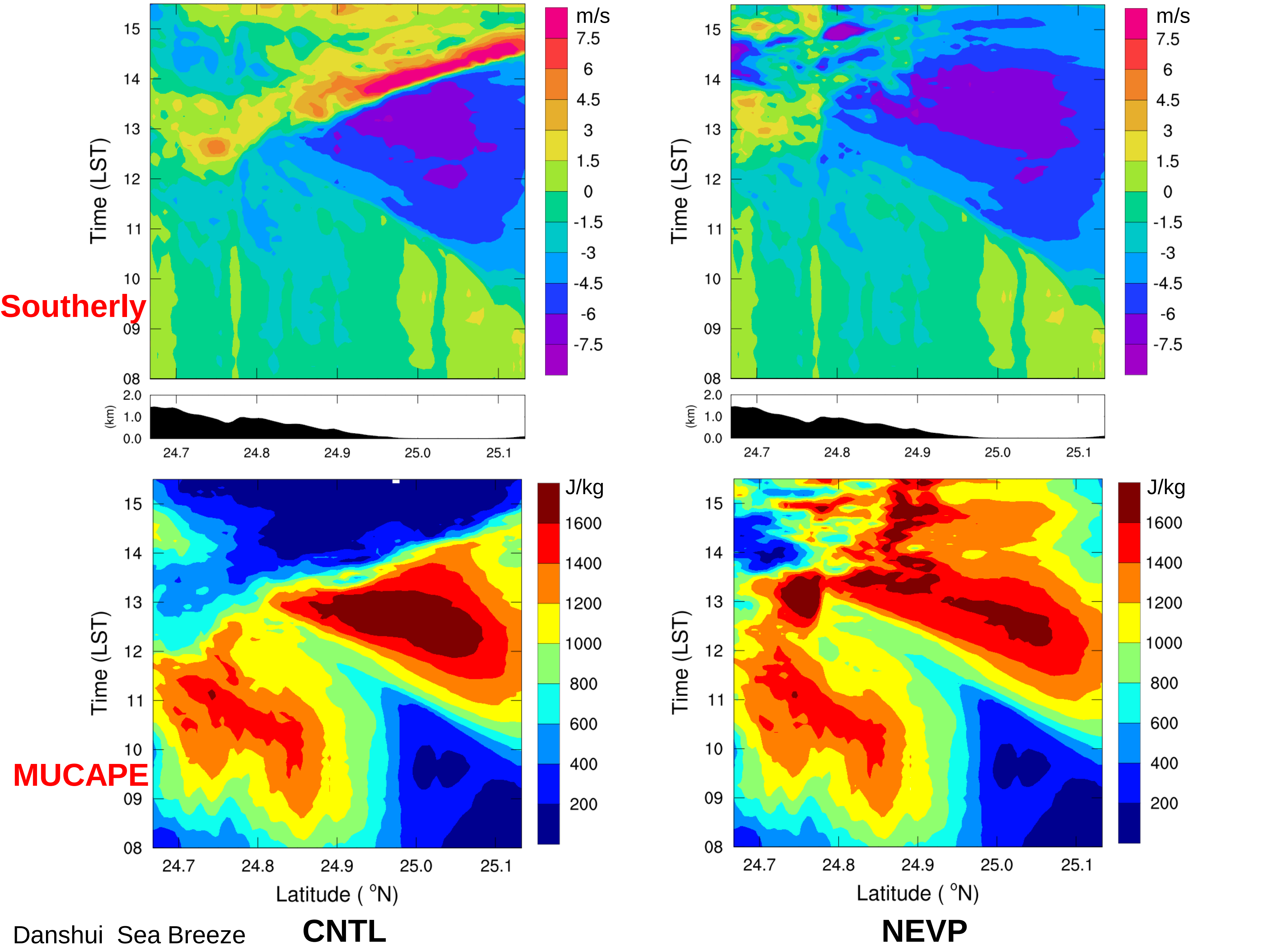
Run	Comments
CNTL	WRF run with full physics
NEVP	no evaporative cooling of rainwater after 08 LST 14 June
NMLT	no melting cooling of graupel after 08 LST 14 June
NDAT	Same as CNTL except for the removal of Mount Datun

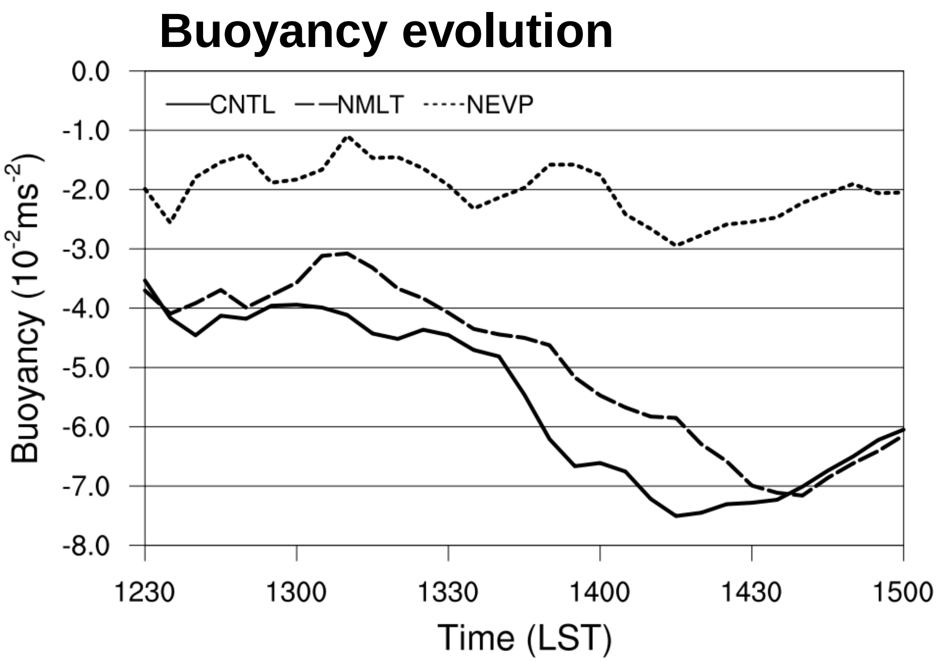


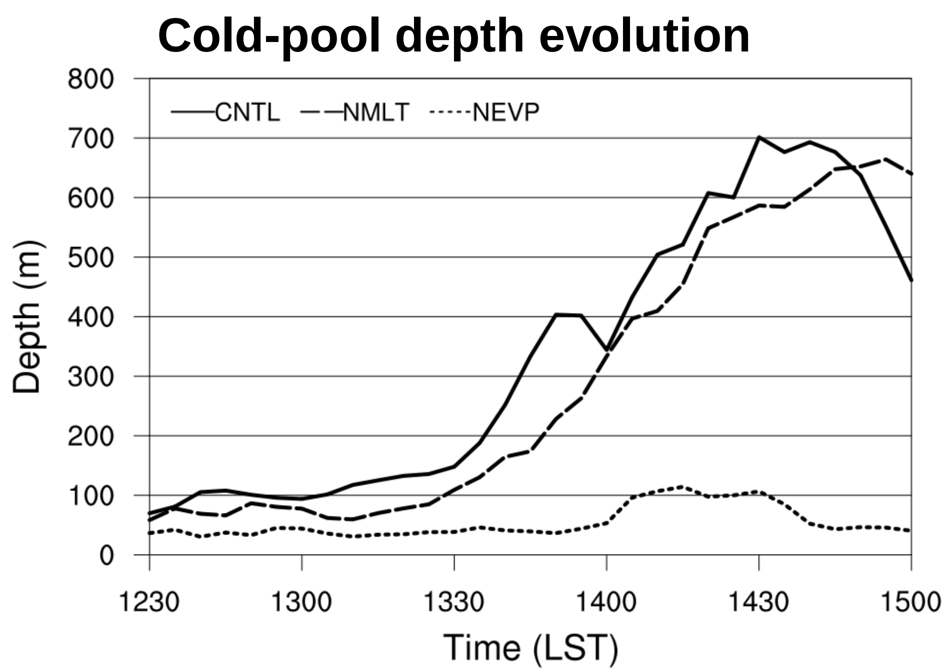
(a) CNTL
Z<100m:107mm
+121
(b) NMLT
Z<100m:74mm
+120
(c) NEVP
Z<100m:26m
m
+153
(d) NDAT
Z<100m:62mm
+76
1200-1430LST accumulated rainfall
.1 2 6 10 15 20 30 40 50 70 90 110 130 150 200
mm

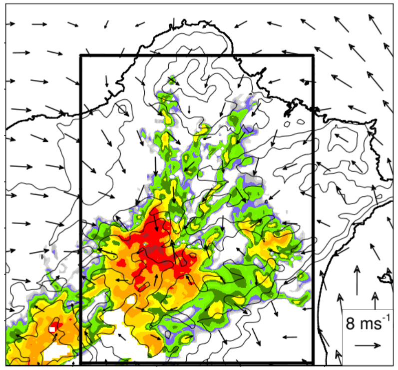

Z=1.5km@1430 LST
Vertical_1430 LST
CNTL
NMLT
NEVP
Radar Reflectivity & Cross-section Wind Vectors
dBZ
65
60
55
50
45
40
35
30
25
20
15
10
5
Blue outline for cold-pool height
Height (km)
Distance (km)
S
N
8 ms-1
12 ms-1
25°15'N
25°10'N
25°5'N
25°N
24°55'N
24°50'N
24°45'N
121°20'E
121°30'E
121°40'E
121°50'E


Southerly
MUCAPE
m/s
7.5
6
4.5
3
1.5
0
-1.5
-3
-4.5
-6
-7.5
J/kg
1600
1400
1200
1000
800
600
400
200
Time (LST)
(km)
Latitude (°N)
24.7
24.8
24.9
25.0
25.1
CNTL
NMLT
Danshui Sea Breeze


Southerly
MUCAPE
Time (LST)
m/s
7.5
6
4.5
3
1.5
0
-1.5
-3
-4.5
-6
-7.5
(km)
J/kg
1600
1400
1200
1000
800
600
400
200
Latitude (°N)
24.7
24.8
24.9
25.0
25.1
Danshui Sea Breeze
CNTL
NEVP

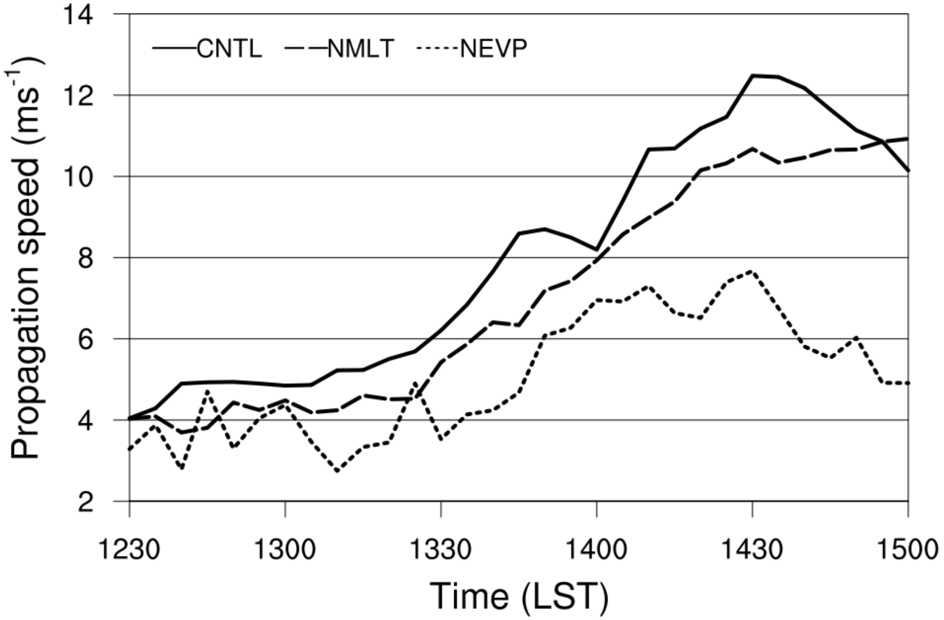


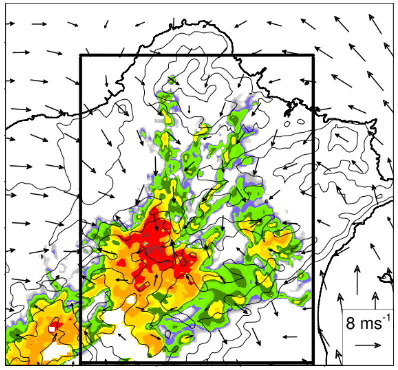




Taipei Basin Statistics

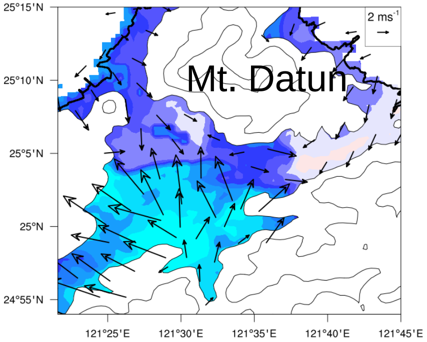
Cold-pool propagation speed



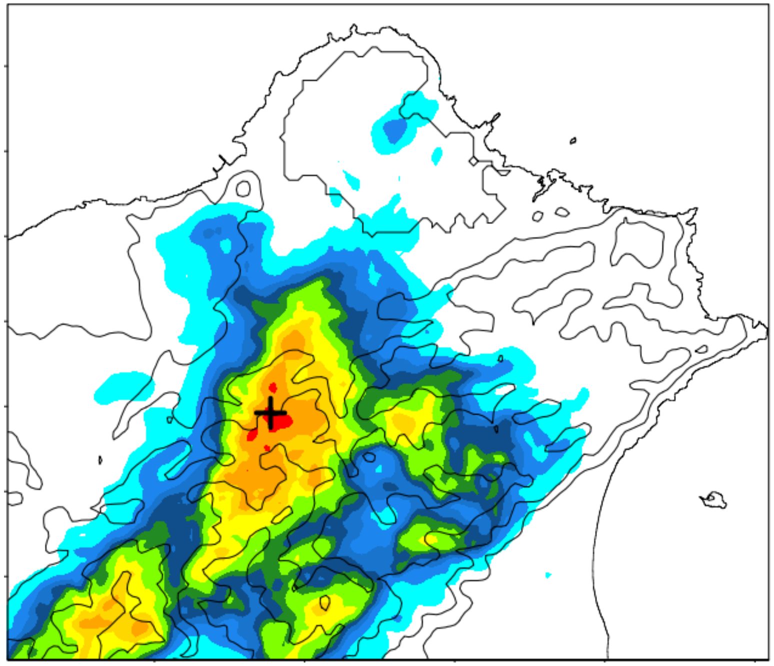


Taipei Basin Statistics

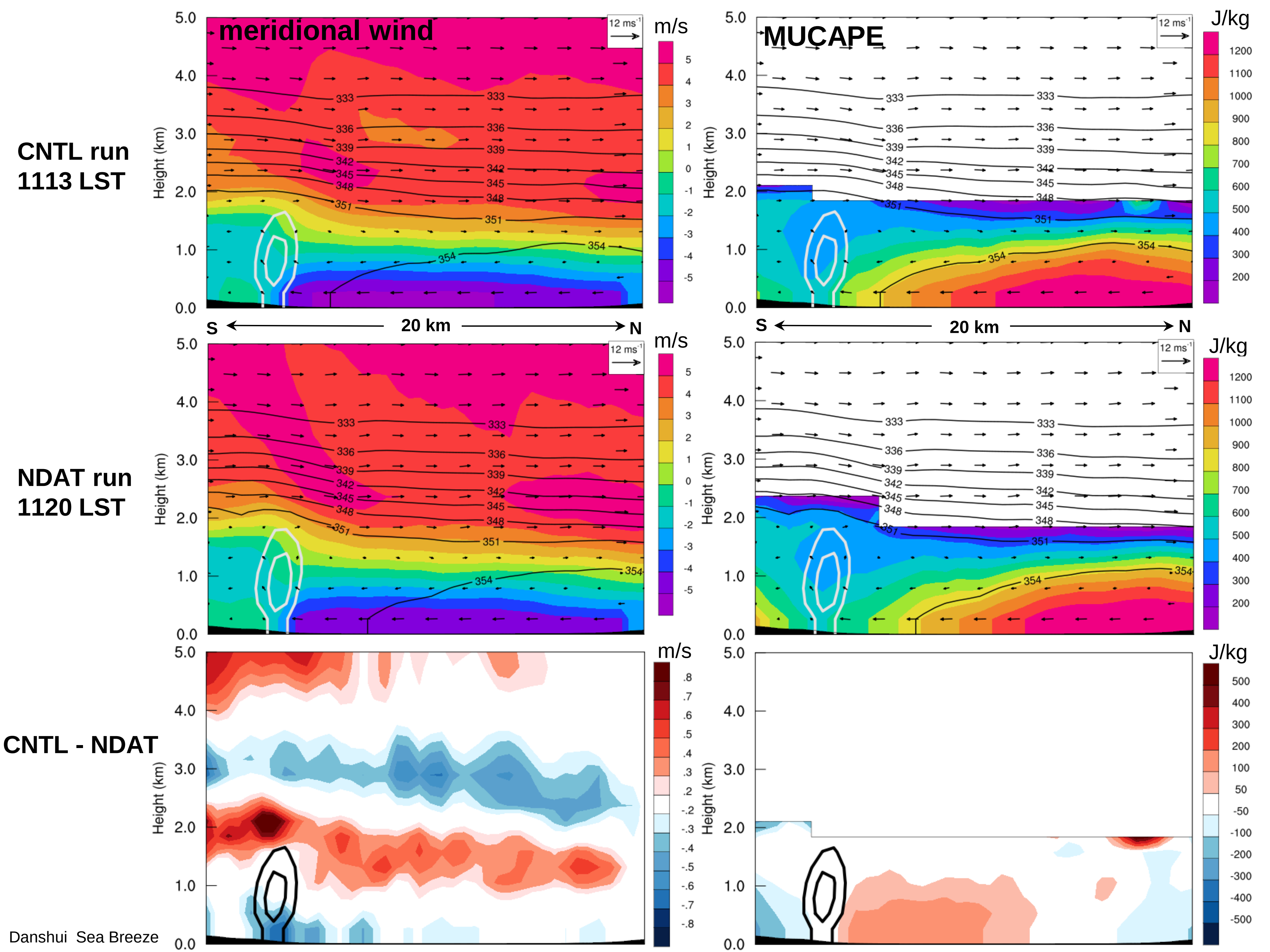
Q: What is the effect of Mount Datun on increasing local convergence and enhancing convection within Taipei Basin?



CNTL run



1200-1430LST accumulated rainfall
for NDAT experiment



meridional wind
MUCAPE
CNTL run
1113 LST
NDAT run
1120 LST
CNTL - NDAT
m/s
J/kg
12 ms-1
Height (km)
S
20 km
N
Danshui Sea Breeze

Conclusions I

- The **sea-breeze circulation** and afternoon thunderstorm system (with peak rainfall rate of 131 mm/h) were reproduced by the **0.5-km** WRF simulation reasonably well.
- **Sea-breeze circulation** was responsible for **convection initiation at foothill**, and **mountain-valley circulation** was for **convection initiated at mountain peak**, respectively.
- Convective available potential energy (**CAPE**) was increased by **800 to 3200 J/kg** with abundant **moisture transport by the sea breeze from 08 to 12 LST**, fueling large thermodynamic instability for the development of afternoon thunderstorm.

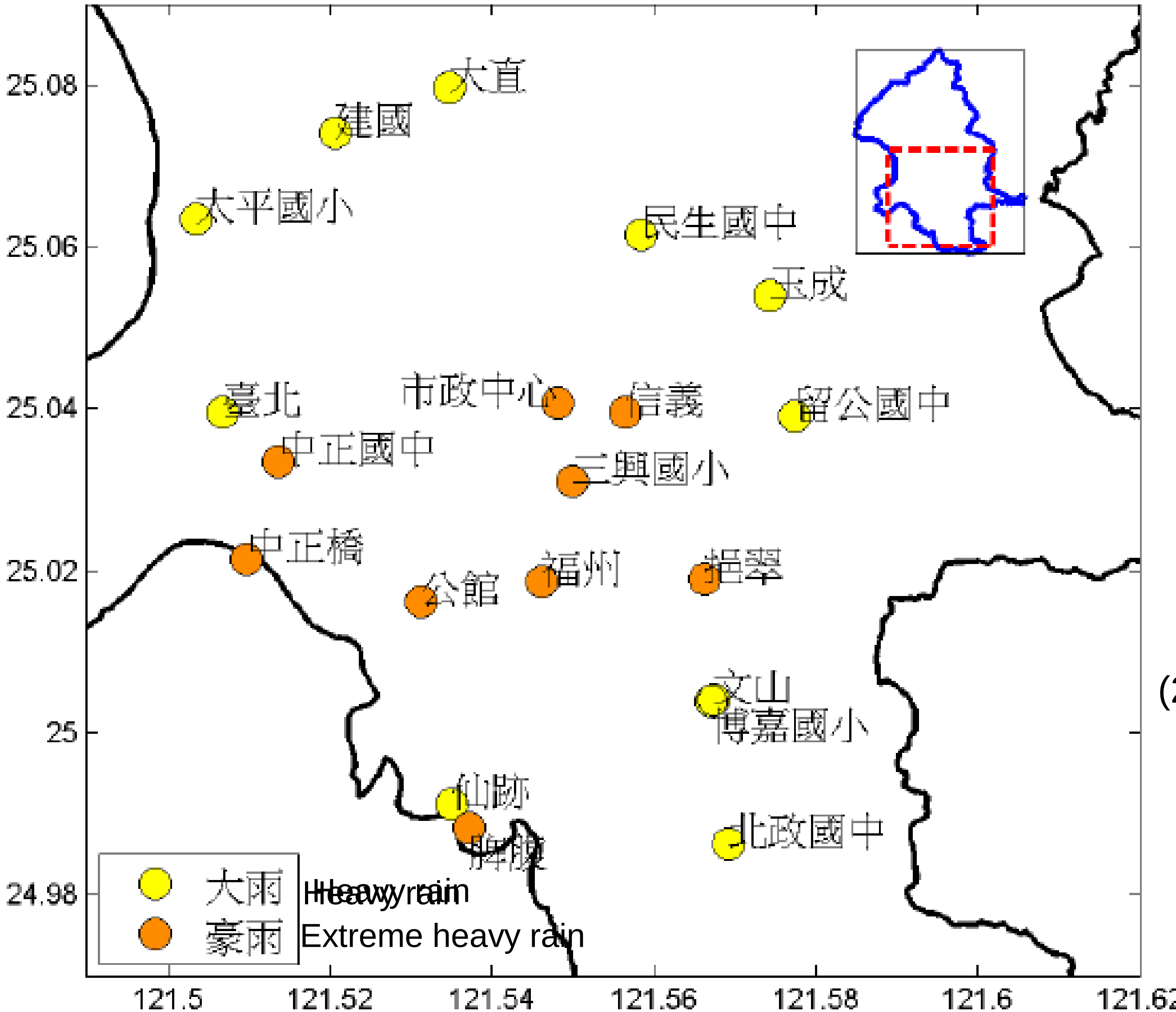
Conclusions II

- The **strong convergence** between **sea breeze** and **precipitation-induced cold-air outflow** trigger further development of intense convection, resulting in heavy rainfall and urban flooding inside Taipei City.

- **Evaporative cooling of raindrop** played an **major** role in the propagation and intensification of cold-air outflow, while **melting cooling of graupel** played a **minor** role.

- Local topography of **Mount Datun** produced the **channel effect** along **Danshui River Valley**, **intensified sea-breeze circulation** and transported more moisture, **increased CAPE** and resulted in **stronger thunderstorm** system with **heavier rainfall** inside Taipei City.

Thank you for listening



Jou at al.
(2016; 大氣科學)

圖 1　2015 年 6 月 14 日台北盆地發生豪雨型午後雷暴之雨量空間分布，橘色點代表 3 小時累積雨量超過 100 mm 測站，黃色點則代表 3 小時累積雨量未達到 100 mm 之測站。

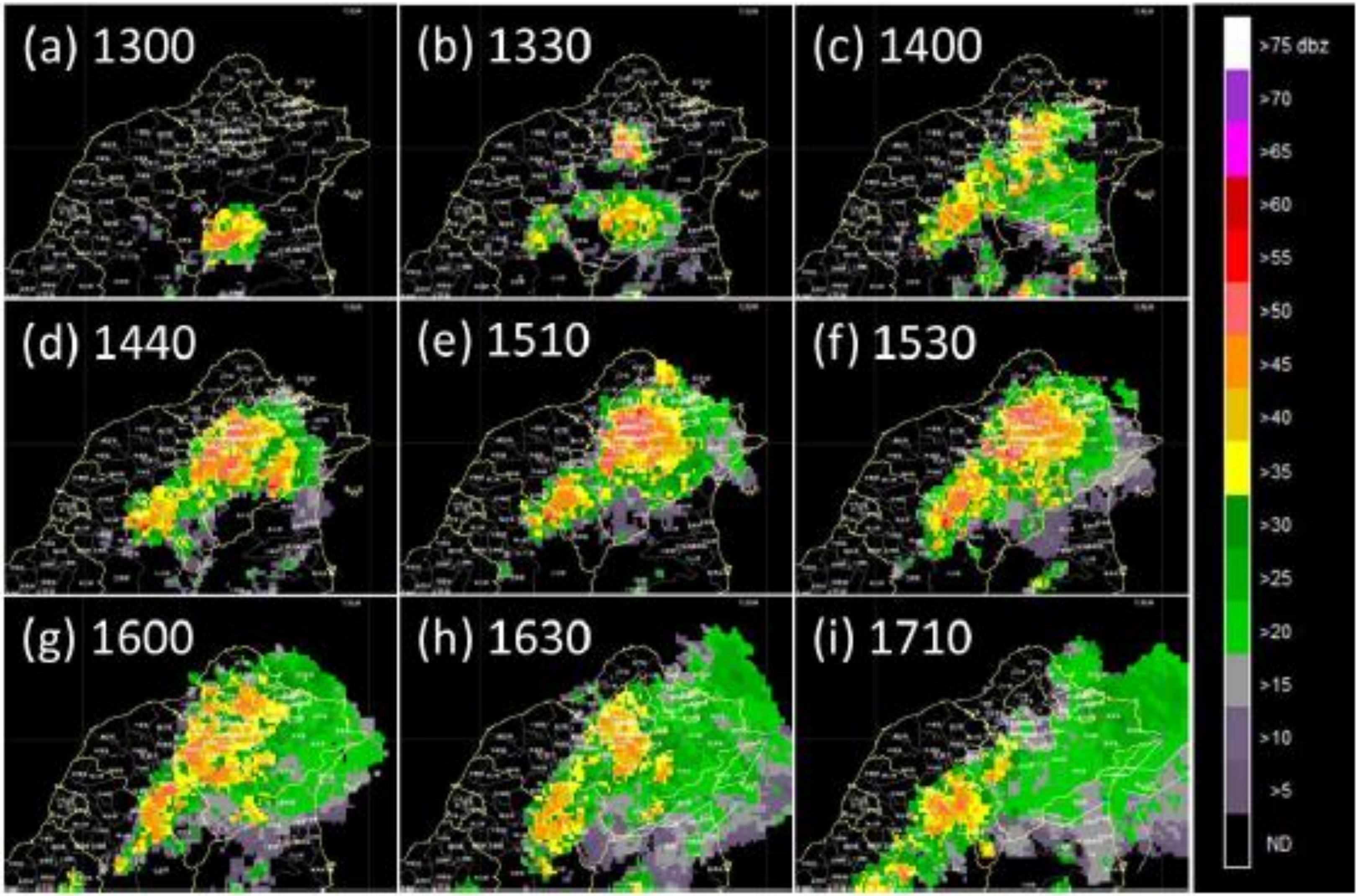
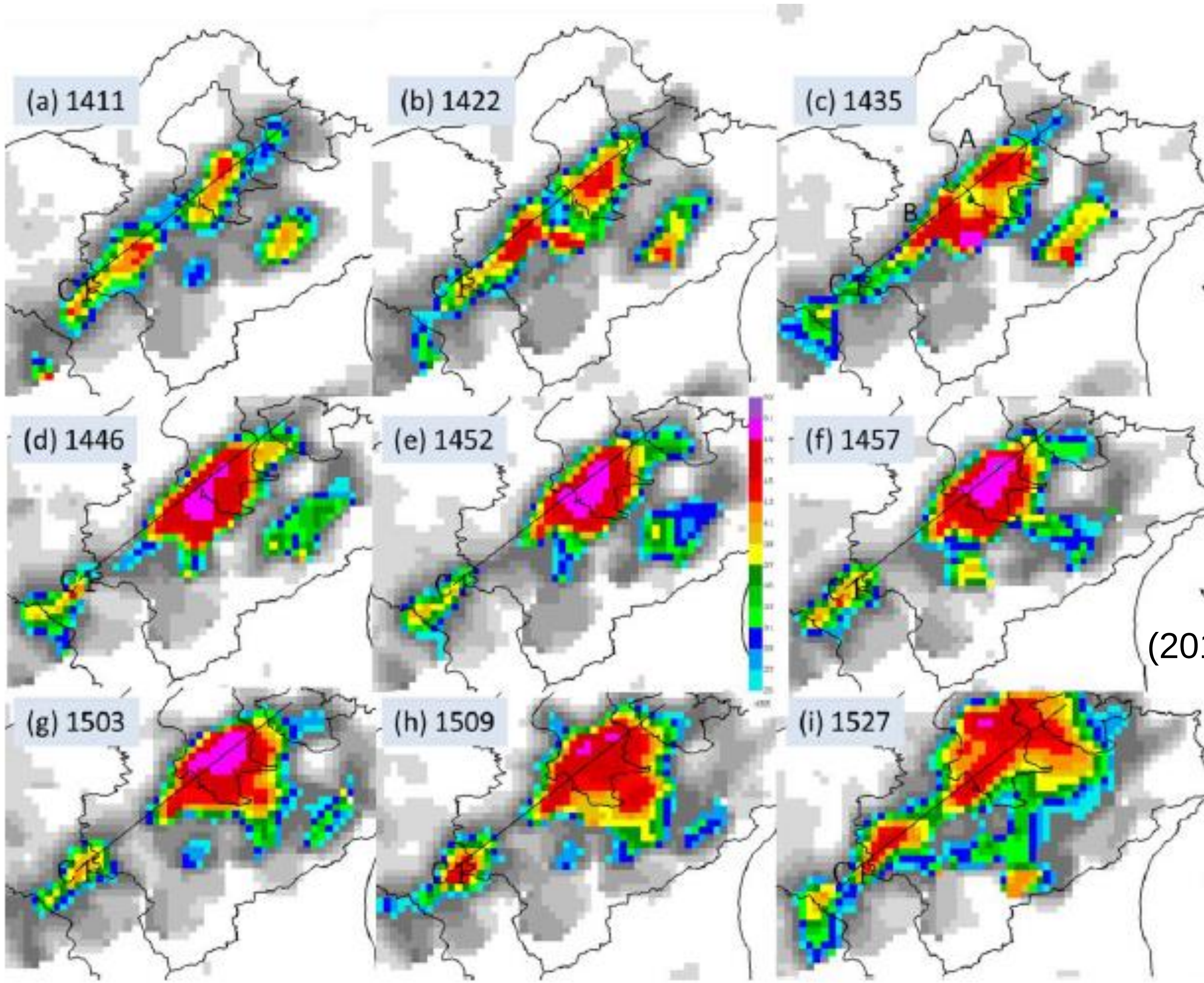


圖 4　2015 年 6 月 14 日北台灣區域 QPESUMS 合成雷達回波圖。

Jou at al.
(2016; 大氣科學)



Jou at al.
(2016; 大氣科學)

圖 5　2015 年 6 月 14 日五分山雷達觀測回波 0.5 PPI，時間分別為：(a) 1411 (b) 1422 (c) 1435 (d) 1446 (e)1452 (f) 1457 (g) 1503 (h) 1509 以及(i) 1527 LST。

Jou at al.
(2016; 大氣科學)

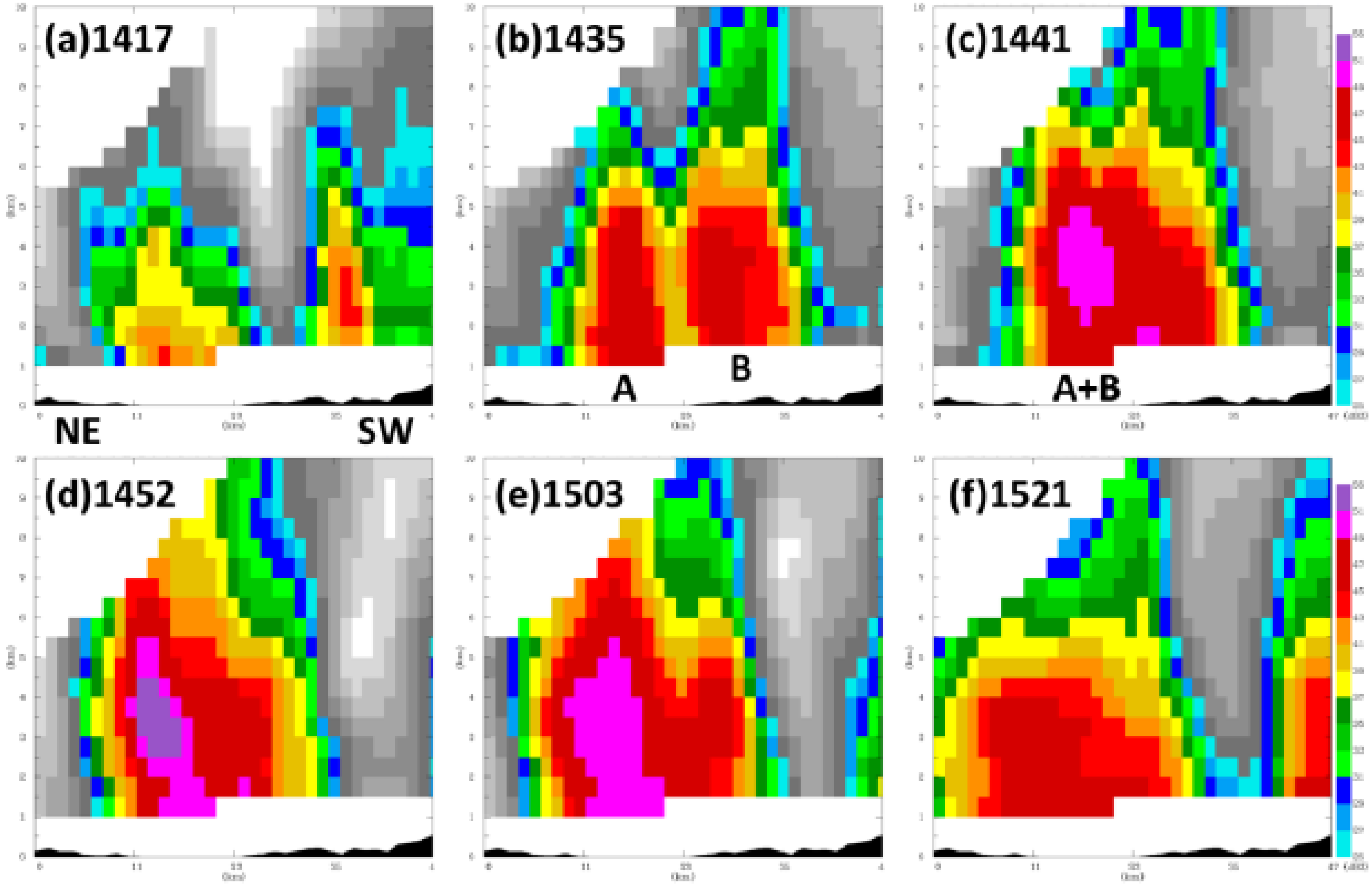


圖 6　沿圖 5 之 C1 五分山雷達回波垂直剖面：(a) 1417 (b) 1435 (c) 1441 (d) 1452 (e) 1503 以及 (f) 1521 LST。

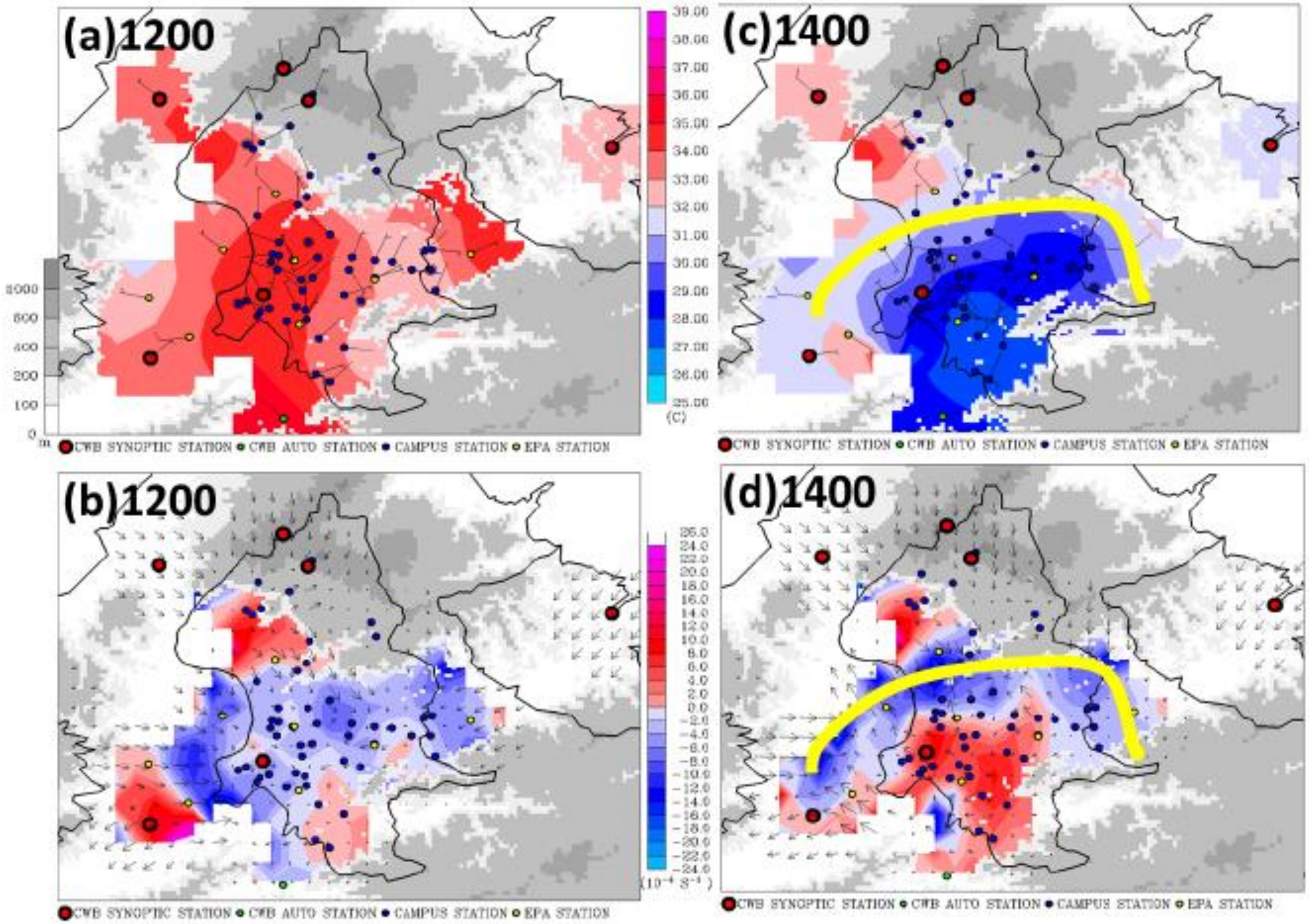


圖 7　2015 年 6 月 14 日台北市區地面測站 1200 LST 溫度場和風場(a)，以及水平輻散輻合場(b)；(c)和(d)與(a)和(b)同，但為 1400 LST。

Jou at al.
(2016; 大氣科學)

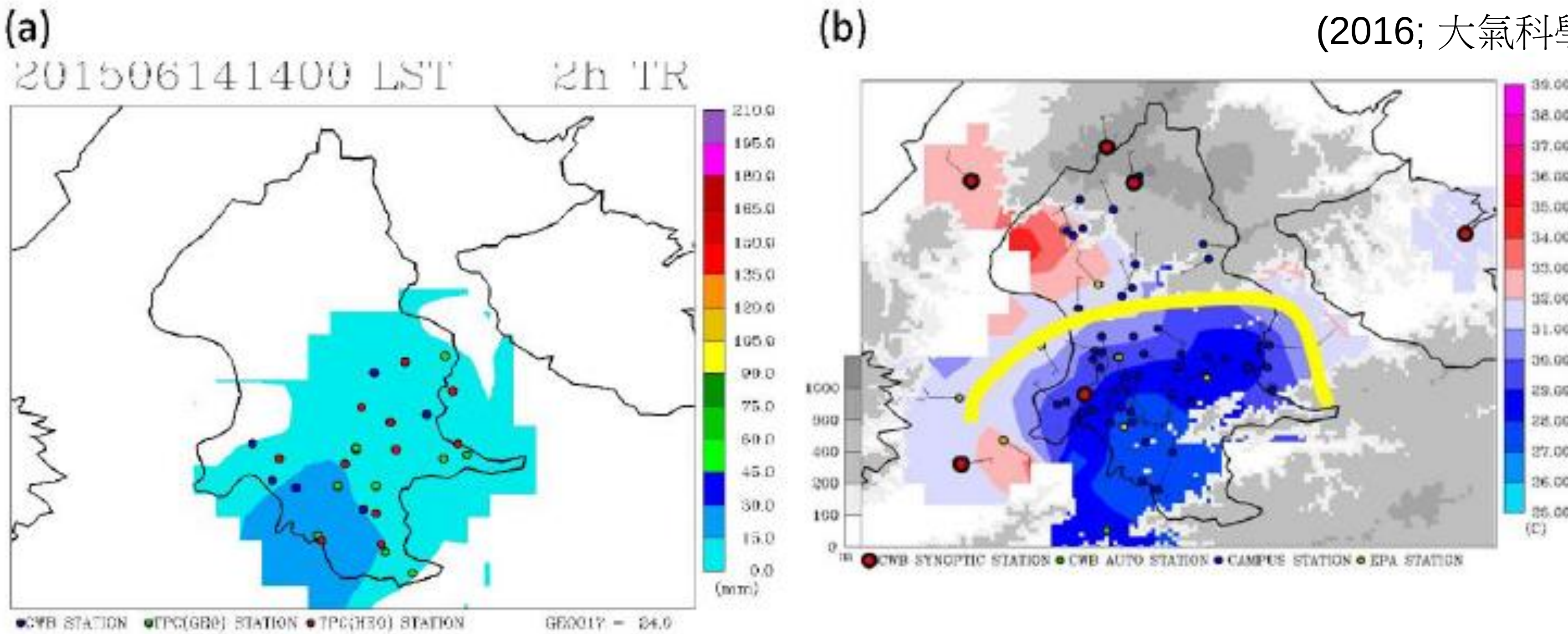


圖 12 2015 年 6 月 14 日台北市區(a) 1200-1400 LST 兩小時累積降雨，(b) 1400 LST 氣溫和風場分布，粗實線為主要輻合區。

Jou at al.
(2016; 大氣科學)

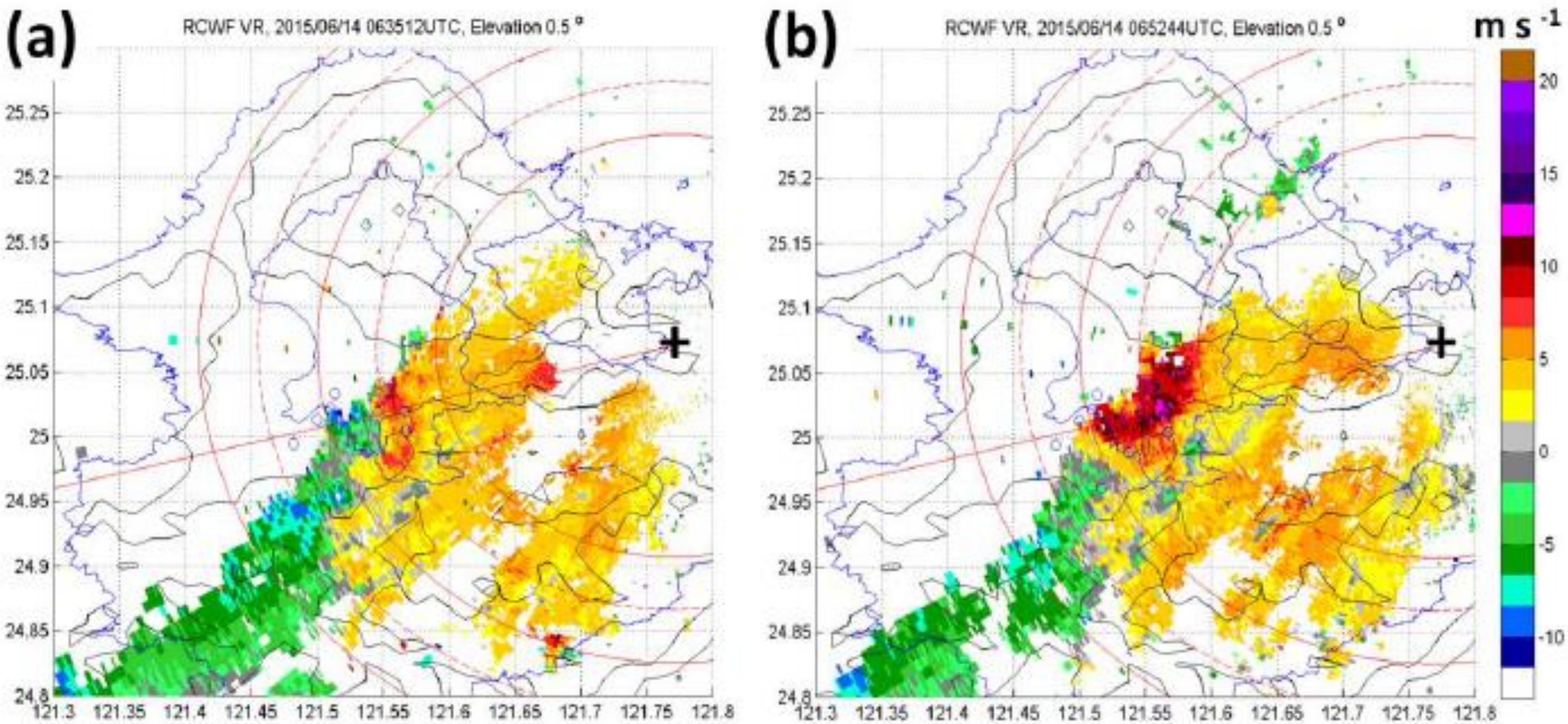


圖 8　2015 年 6 月 14 日五分山雷達（＋位置所在）0.5 度 PPI 都卜勒風場(a)1435LST 和(b)1452LST。紅實線分別代表離開雷達 20, 30, 40 公里距離，暖色系代表遠離雷達，冷色系代表接近雷達風場。

Jou at al.
(2016; 大氣科學)

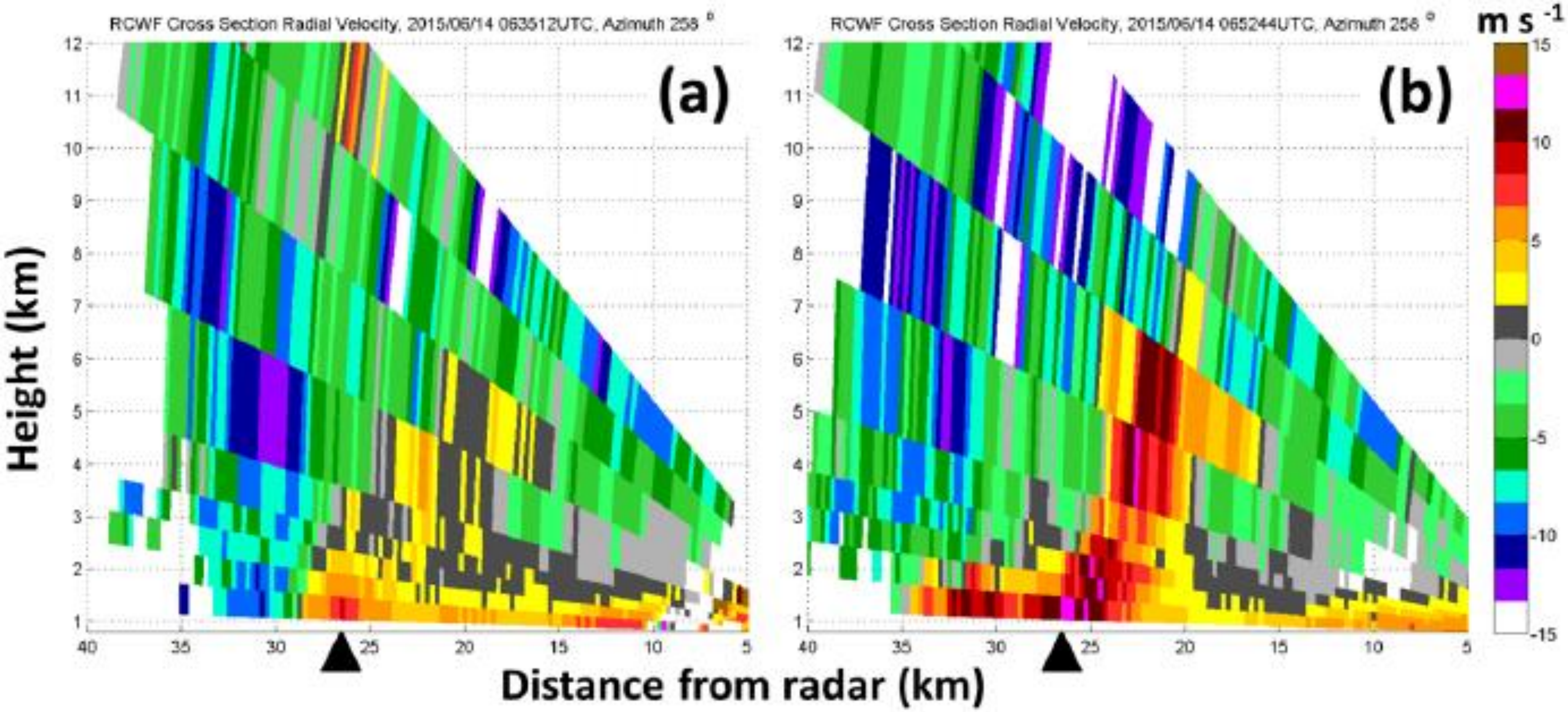


圖 9　2015 年 6 月 14 日五分山雷達觀測方位角 2580 都卜勒風場分布，(a) 1435LST 和(b)1452LST。雷大位置在右下角，三角點代表公館測站位置。

Jou at al.
(2016; 大氣科學)

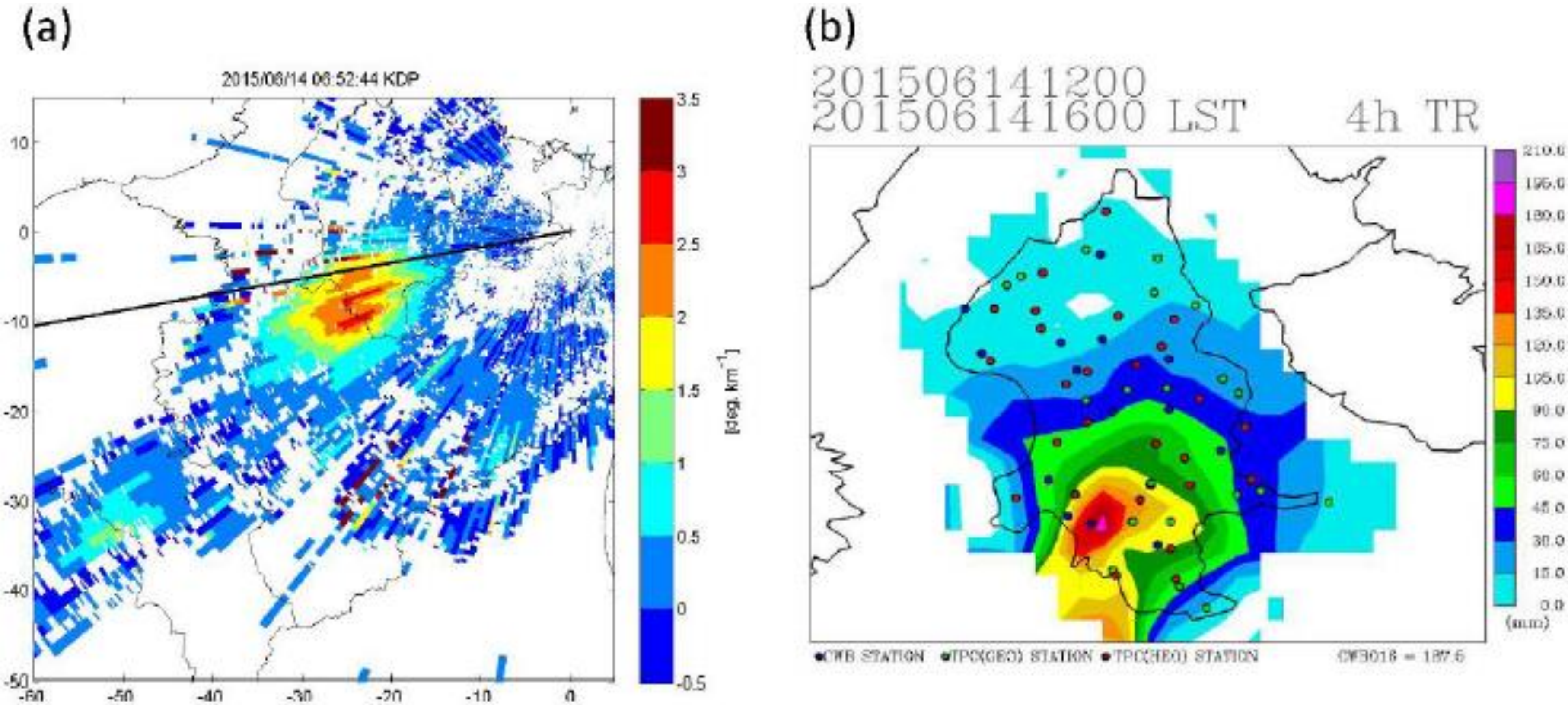
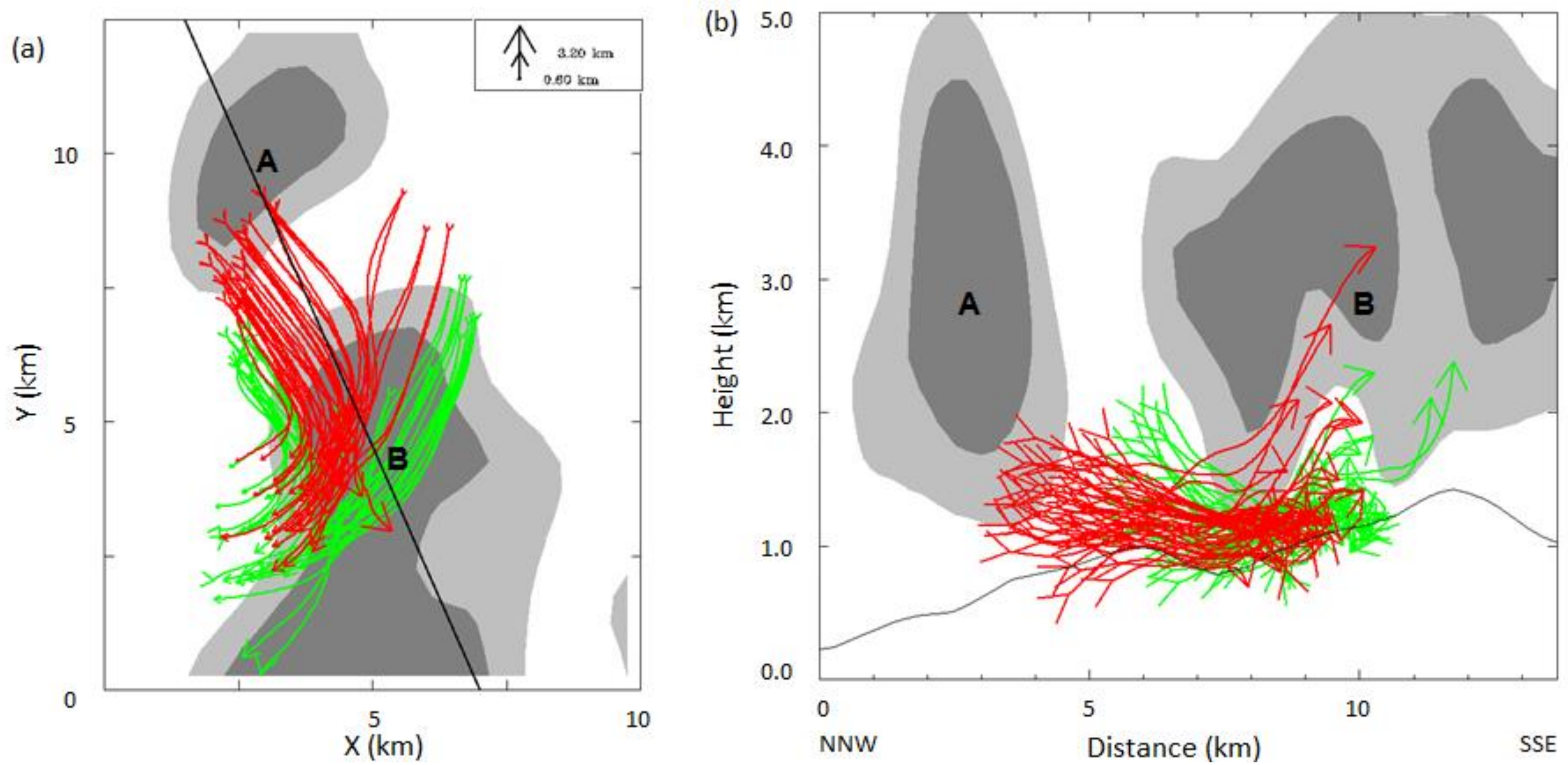


圖 13　2015 年 6 月 14 日(a) 1452 LST 五分山雷達 Kdp 分布；(b)台北市區 1200-1600 LST 降雨分布。

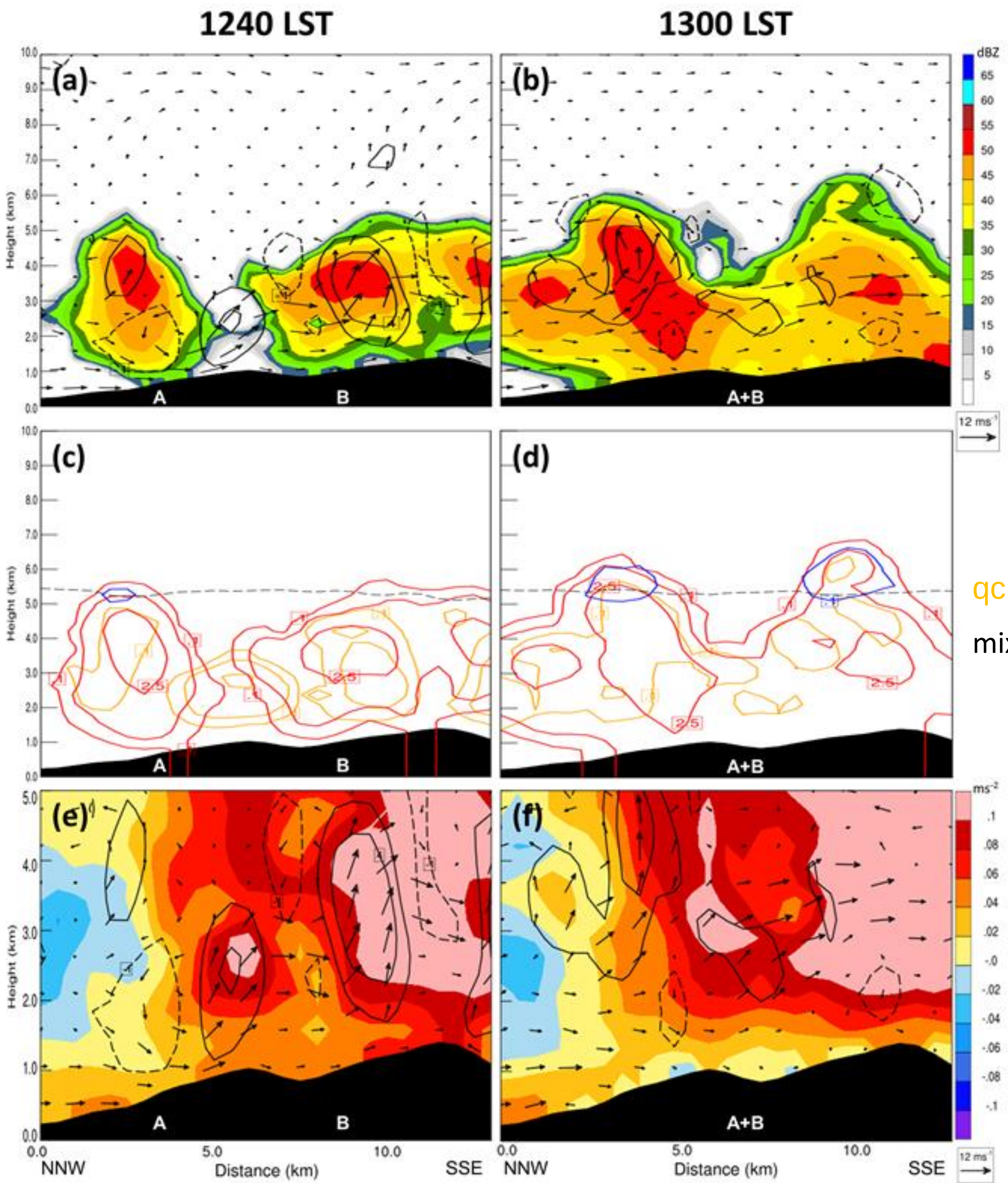
80 forward trajectories(1240 LST → 1305 LST) which passed through the region of flow convergence at the 1.2-km height

cell A: 44, cell B: 36

Miao and Yang (2019; 大氣科學)



The physical mechanism of single merger is the **"rear-end" collision** associated with the **difference of cell propagation speeds**.



shading: reflectivity

vertical velocity contours: {-1,2,4,8} m/s

qc, qr, qg

mixing ratio contours: {0.1, 0.5, 2.5, 10} g/kg

shading: buoyancy

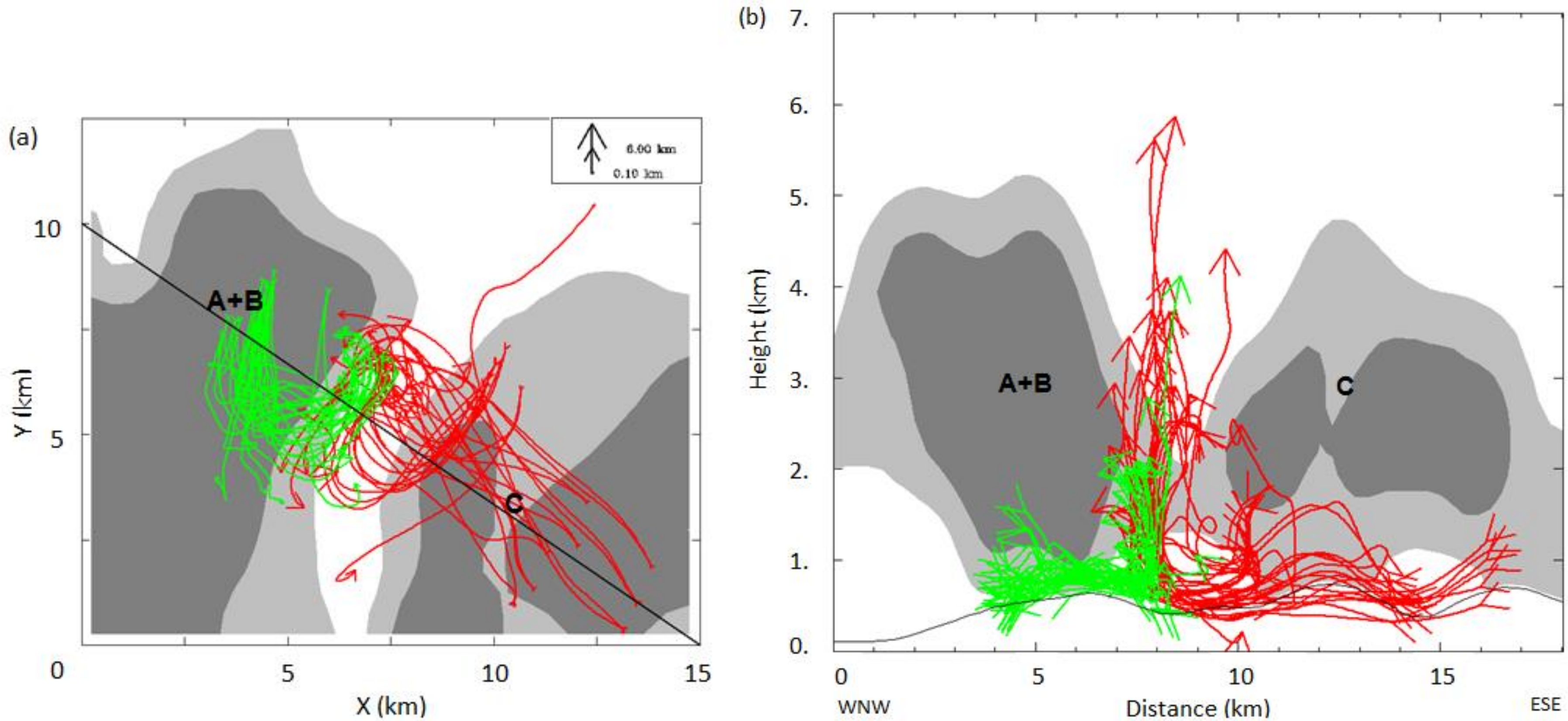
vertical velocity contours: {-1,2,4,8} m/s

Miao and Yang
(2019; 大氣科學)

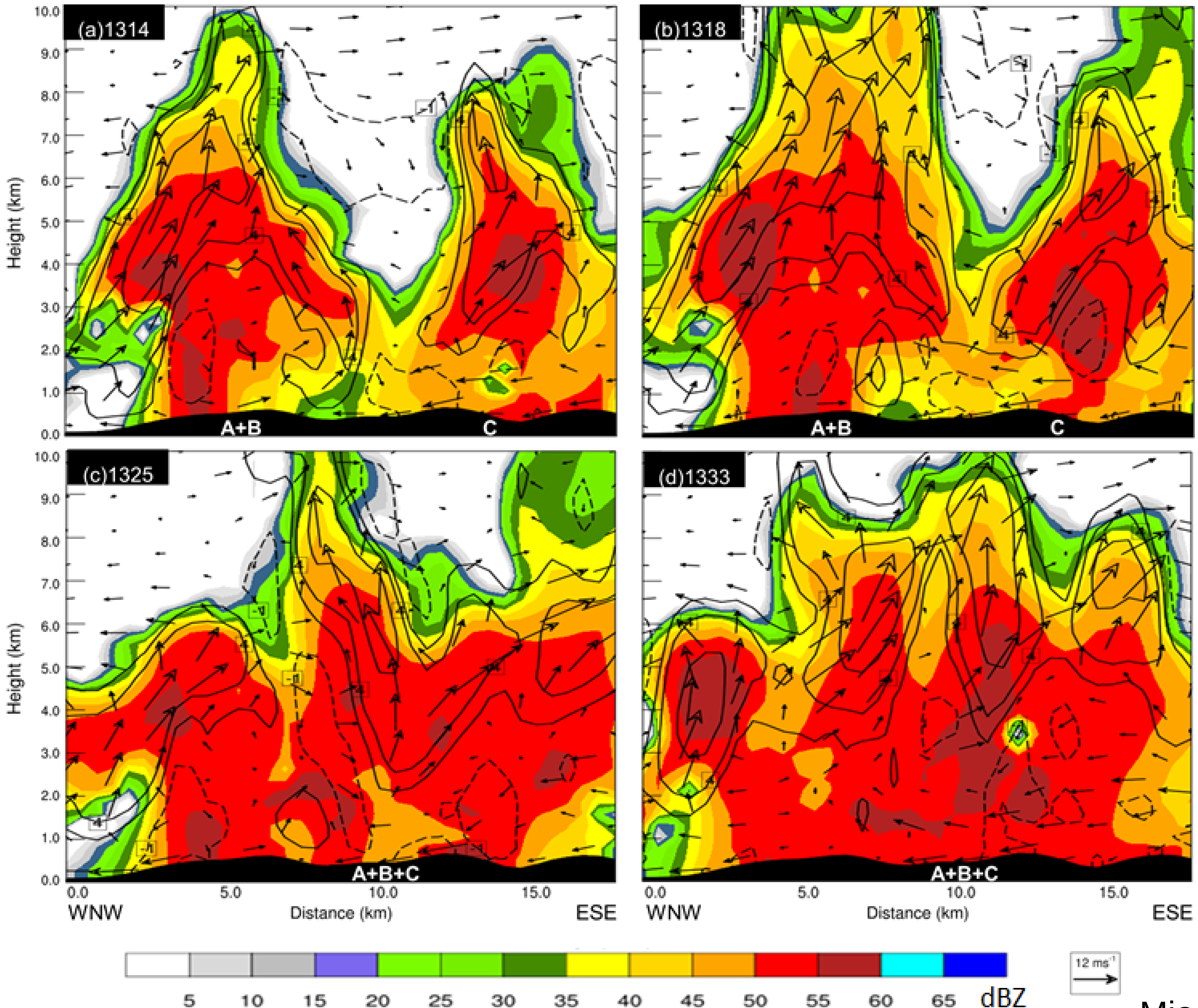
62 forward trajectories(1300 LST → 1336 LST) which passed through the region of flow convergence at the 0.75-km height

cell A+B: 32, cell C: 30

Miao and Yang (2019; 大氣科學)

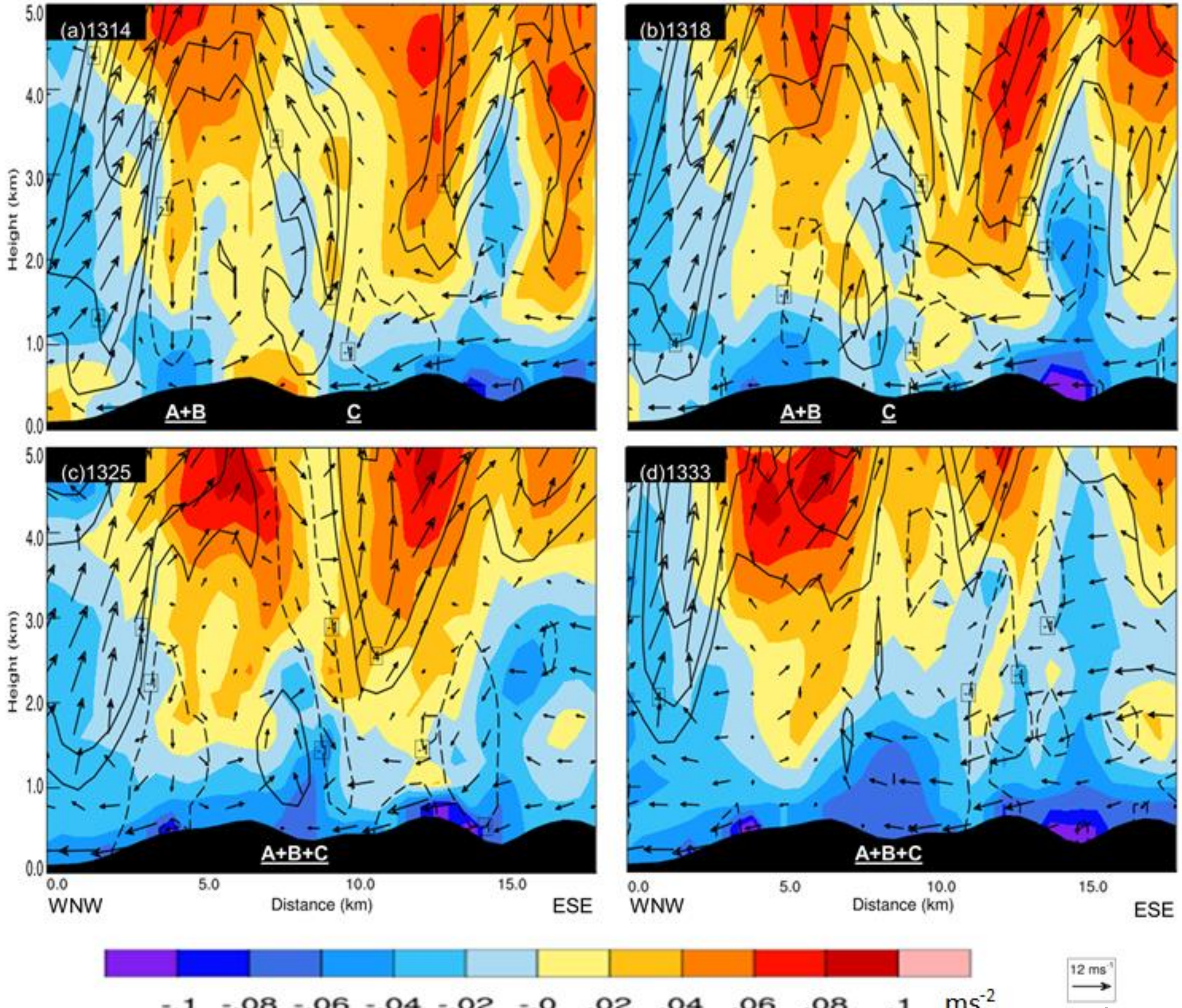


The physical mechanism of multiple merger is the **"head-on" collision** produced by the collision between **two cold-air outflows in opposite direction**.



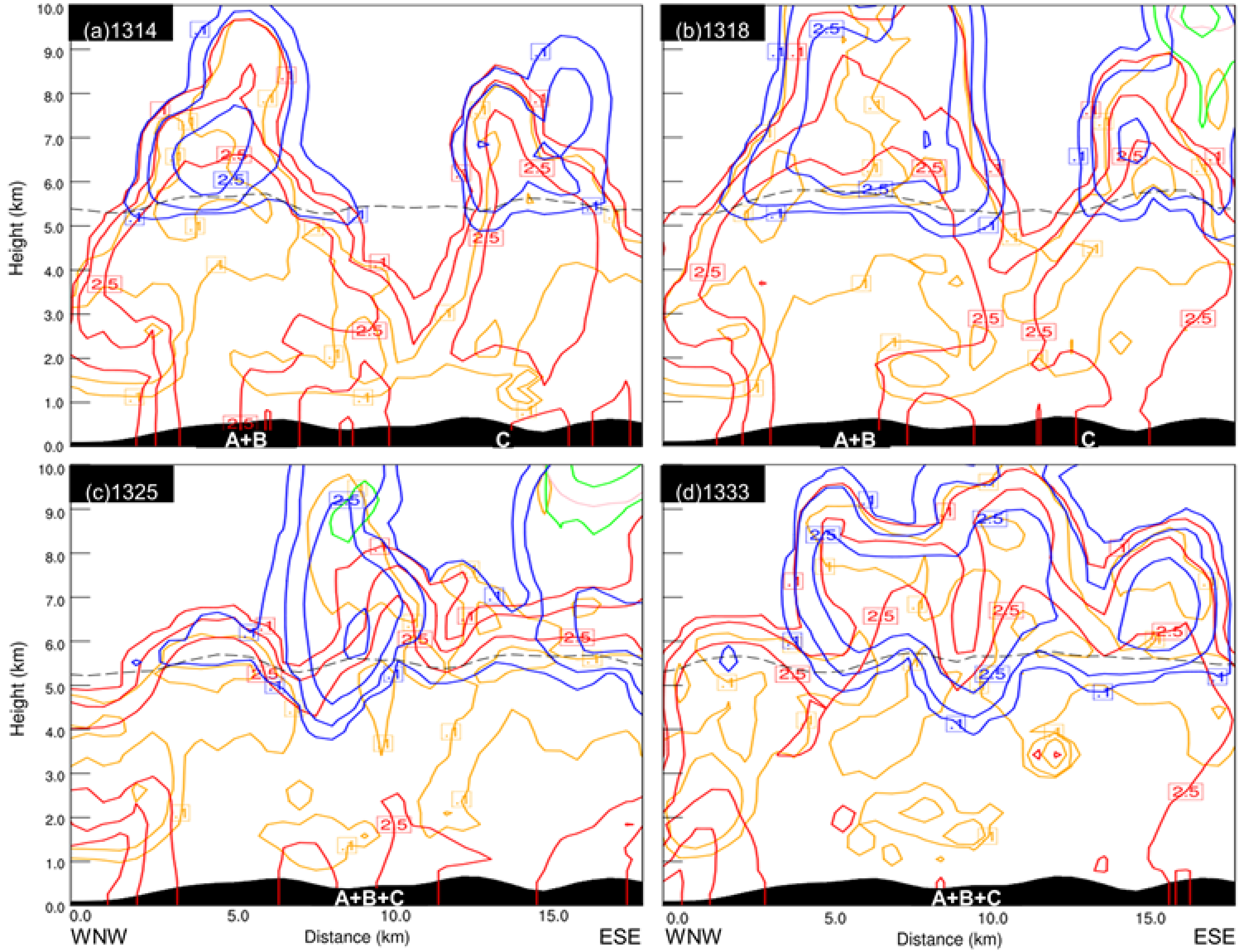
shading: reflectivity   vertical velocity contours: {-1,2,4,8} m/s

Miao and Yang (2019; 大氣科學)



shading: buoyancy vertical velocity contours: {-1,2,4,8} m/s

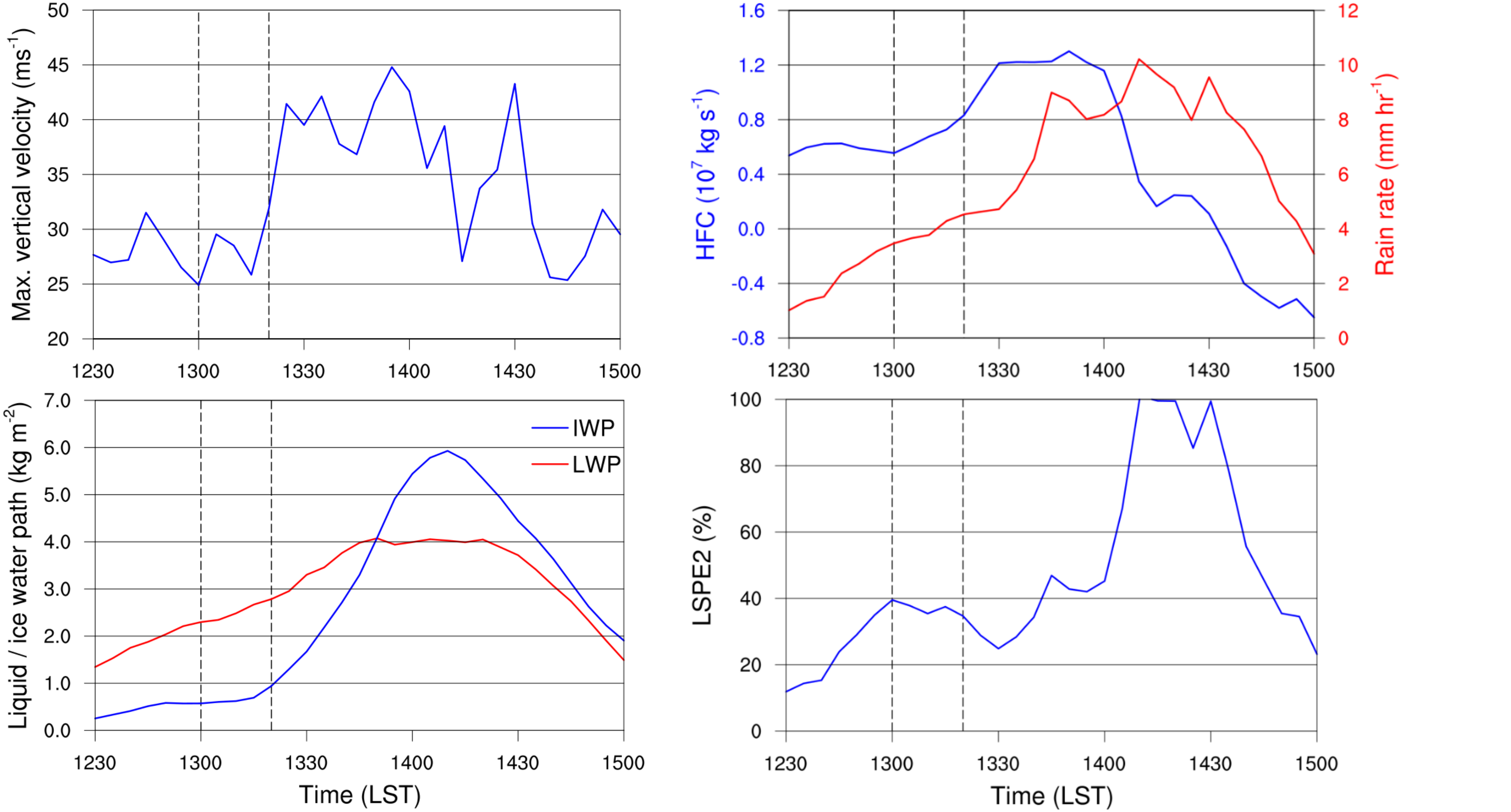
Miao and Yang (2019; 大氣科學)



qc, qr, qg, qs, qi mixing ratio contours: {0.1, 0.5, 2.5, 10} g/kg

Miao and Yang (2019; 大氣科學)

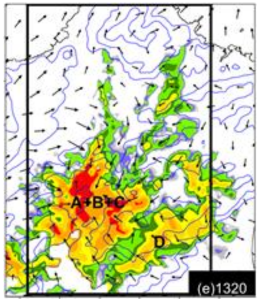
Area-mean Time Series after Cell Merger

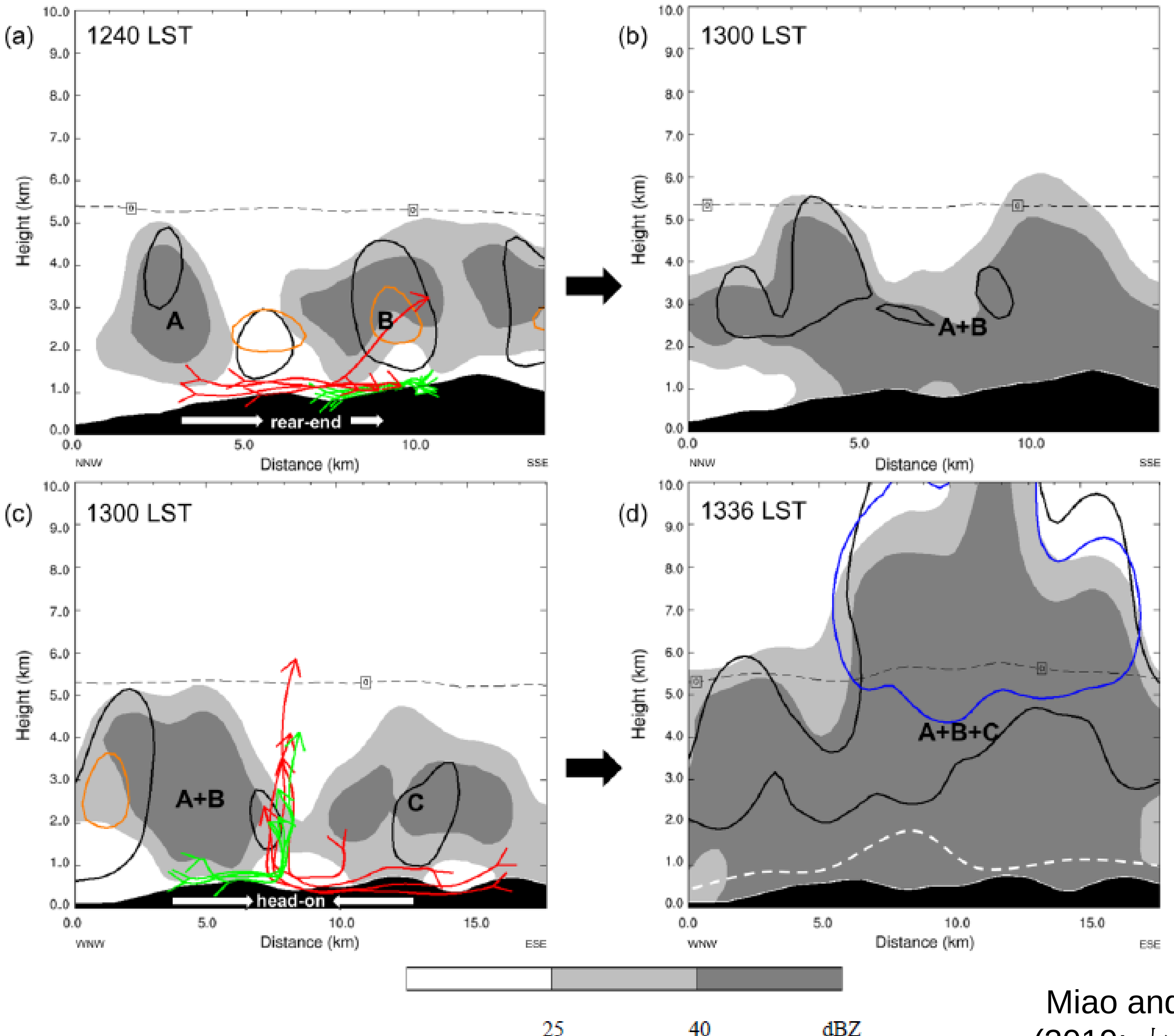


After the multiple merger to produce cell "A+B+C" (1320 LST):

1. The domain-maximum updraft increased and reached the peak intensity of 45 m/s.
2. HFC further increased and then reached its maximum around 1350 LST. The peak surface rainfall rate occurred about 1410 LST (20 minutes later).
3. Ice-water path was increased by 6 times.
4. The peak precipitation efficiency reached to 85–100 % during 1400–1430 LST.

Area:37.5km x 60km





Miao and Yang (2019; 大氣科學)