

Island Effects on Mei-Yu Jet/Front Systems and Rainfall Distribution during TIMREX IOP#3

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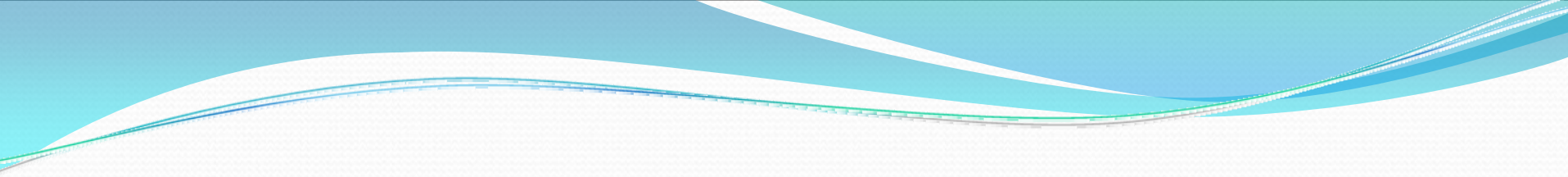
TiMREX Workshop 2010 Nov

Outline

- Introduction
- Data & Methods
WRF-ARW model setup
- Results
Case I- IOP#3 during 29-31 May 2008
Case II- 16 June 2008
- Comparison
- Conclusions

Introduction

- During the Mei-Yu season over Taiwan, the island-scale airflow and weather are not only controlled by the large-scale flow but also by orographic effects and the interactions between the large-scale flow and the island-induced circulations (Li et al. et al. 1997; Yeh and Chen 2002; Kerns et al., 2010).
- There are mesoscale convective systems (MCSs) embedded within the southwest monsoon flow (Wang et al. 1990; Tao et al. 1991; Lin et al. 1992; G. Chen and Chou 1993; Wang, 2004; Wang and Carey 2005). Some of these systems drift inland and interact with terrain and local winds (Bluestein and Hrebenach, 1994; Teng et al. 2000; C.-S. Chen et al. 2004; Wang et al. 2005).
- For a given synoptic setting, the rainfall and local weather can vary dramatically within a few kilometers (e.g., Li et al., 1997; Chen 2000; and others).
- For the development of heavy rainfall events, favorable synoptic conditions are required, whereas mesoscale variability, local-scale processes, and orographic effects are important in determining the timing and location of heavy rainfall.

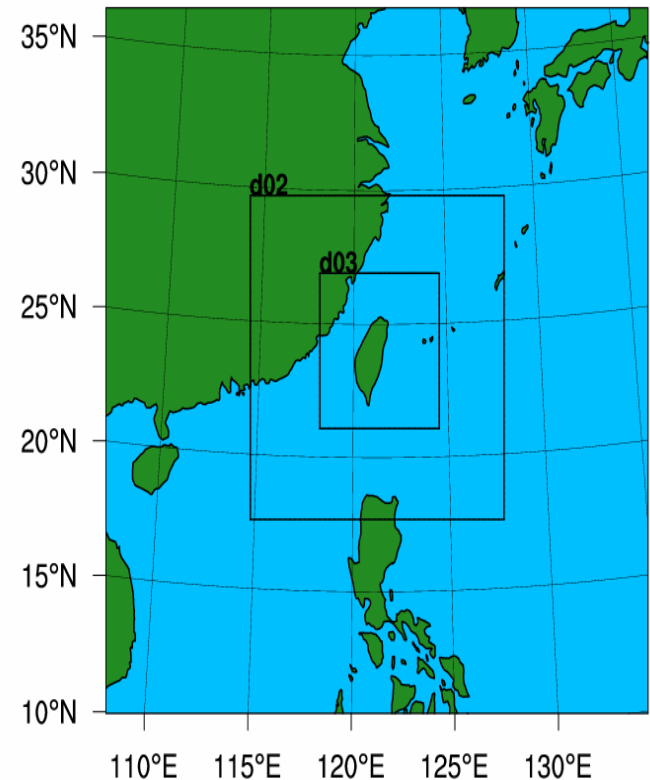
- 
- During SoWMEX/TiMREX, several Mei-Yu jet/front systems were well monitored during their passages over the Taiwan area. In this study our focus will be on the island effects on Mei-Yu Jet/Front Systems and rainfall distribution using the data collected during IOP #3.
 - The June 16 case during IOP #8 will also be studied and compared with the IOP #3 case.

Data & Method

- CWB: Rain gauge, Radar Reflectivities, IR satellite images
- YOTC reanalysis data: including observation took from field experiments (0.5deg horizontal resolution)
- High-resolution meso-scale modeling: WRF
Sensitivity test: Remove terrain to discuss the orographic effects on Mei-Yu jet/front systems and rainfall distribution during TiMREX #IOP₃ and the 6/16 case

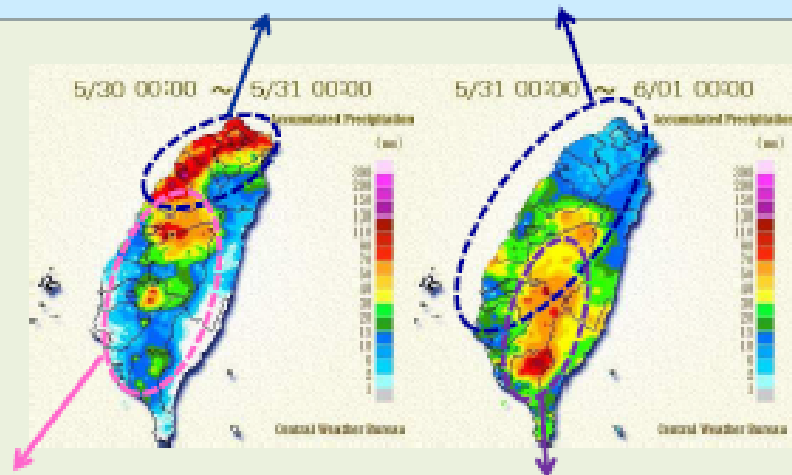
Weather Research and Forecasting (WRF-ARW) model setup

- The Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997), Dudhia (1989) radiation schemes
- Noah land-surface model (LSM) (Chen and Dudhia 2001)
- Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006)
- Betts-Miller-Janjic (BMJ) cumulus parameterization scheme (Janjic 1994, 2000)
- Ferrier microphysics scheme (Rogers et al. 2001; Ferrier et al. 2002). The Ferrier grid-scale cloud and precipitation scheme predicts variations of six species of water substances (cloud water, cloud ice/small ice crystals, rain, snow, graupel and sleet).
- 38 sigma levels from the surface to the 100-hPa level.
- The three domains with resolutions of 27, 9, and 3 km, respectively
- The cumulus parameterization is turned off in the 3-km-resolution domain (domain 3).
- The $1^\circ \times 1^\circ$ NCEP/FNL (Final Operational Global Analysis) data provide the initial and boundary conditions for the model simulation.



Case I: IOP#3 29-31 May

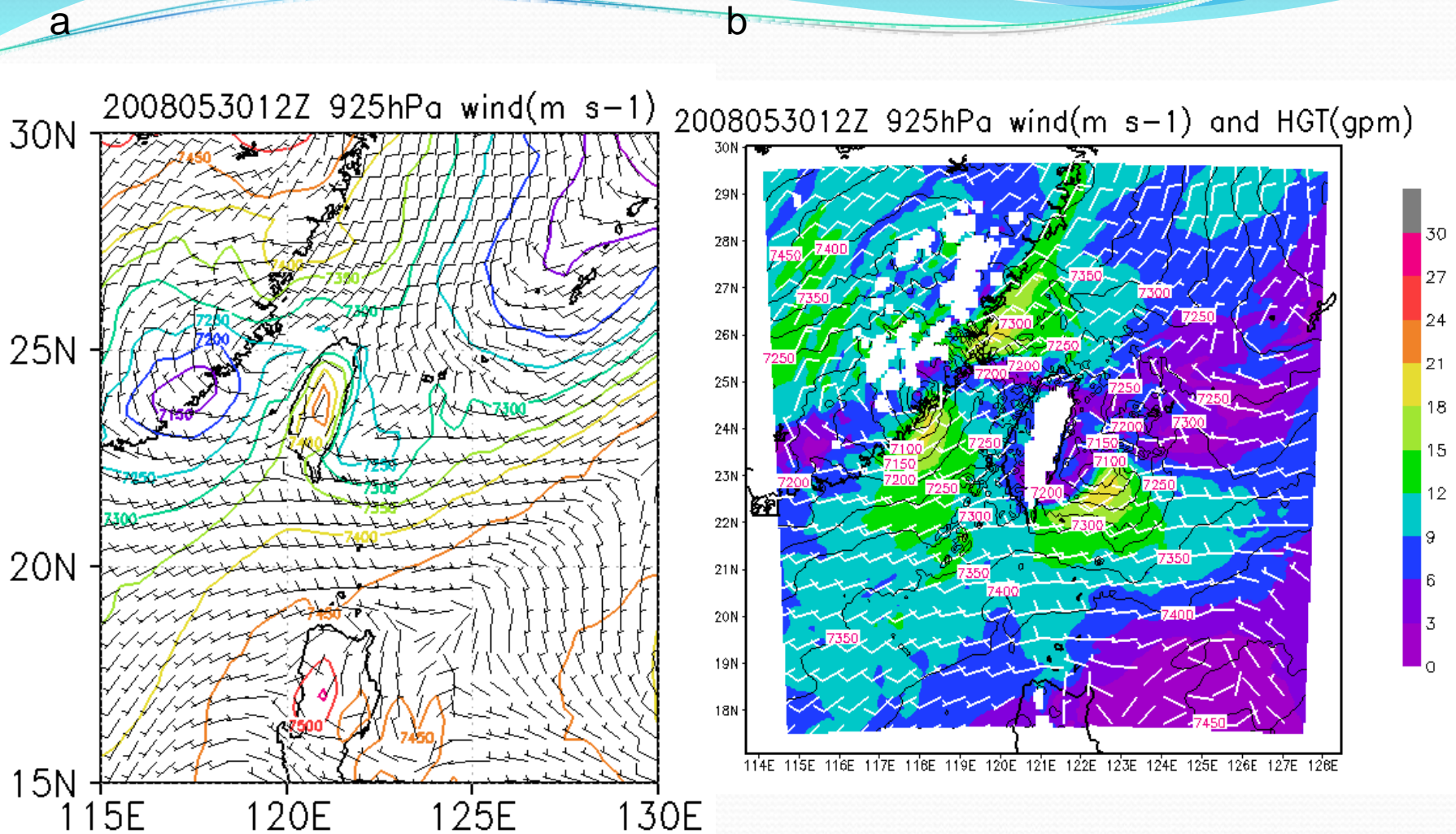
2) 5/30 1800-5/31 1400 (LST), an enhanced NE-SW orientated **Mei-Yu frontal convection line** northwest of Taiwan moved onshore over northwestern Taiwan and then propagated southward producing heavy rainfall over northwestern Taiwan



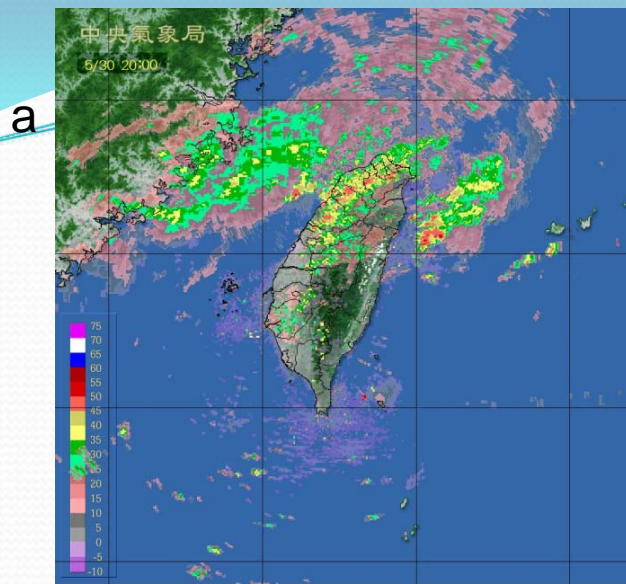
1) 5/30 0900-1800 (LST), in the **prefrontal SW flow regime**, the convection cells are enhanced by the terrain. Orographic lifting of the pre-frontal SW flow and a sea breeze contributed to heavy rainfall over the western Central Mountain Range.

3) 5/31 1400-2000, after the passage of the Mei-Yu front over the Taiwan Strait at the surface, the Mei-Yu frontal cyclone moved eastward across the Central Mountain Range. Orographic lifting of the convective cells by the SW flow ahead of the cyclone, combined with sea breezes, brought in heavy rainfall on the SW slopes of the mountains.

Figure 1. Daily rainfall accumulation (mm) over Taiwan on 30 and 31 May, 2008 (LST) (Courtesy of Central Weather Bureau).

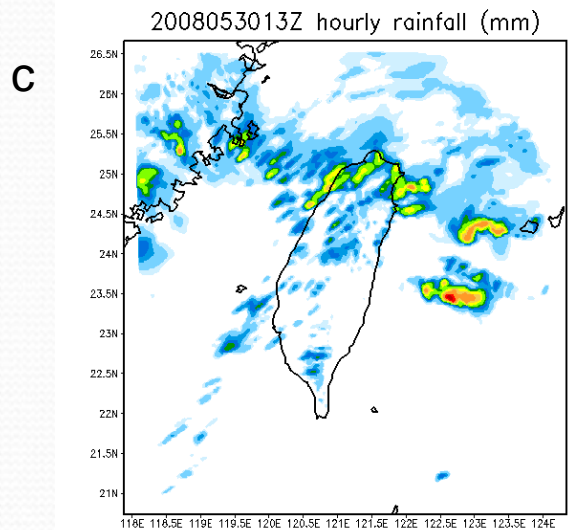
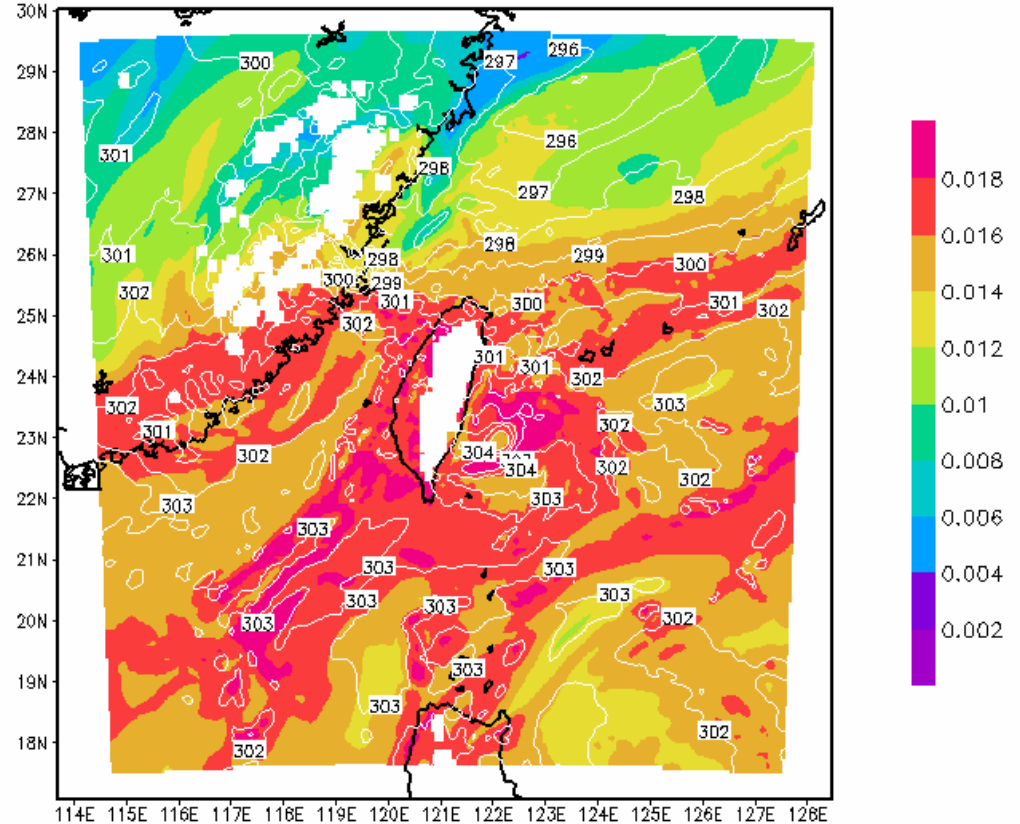


(a) YOTC 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹) and geopotential height (gpm, contoured) at 1200 UTC 30 May 2008 and (b) WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast with a 9-km horizontal resolution).

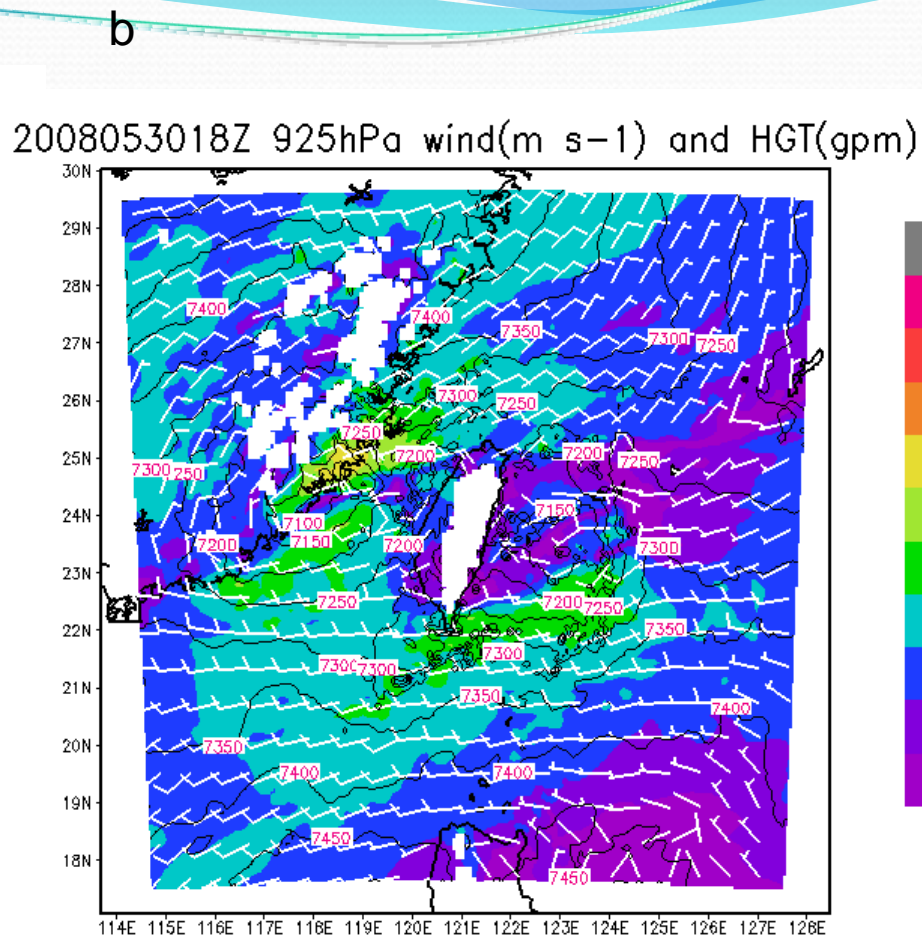
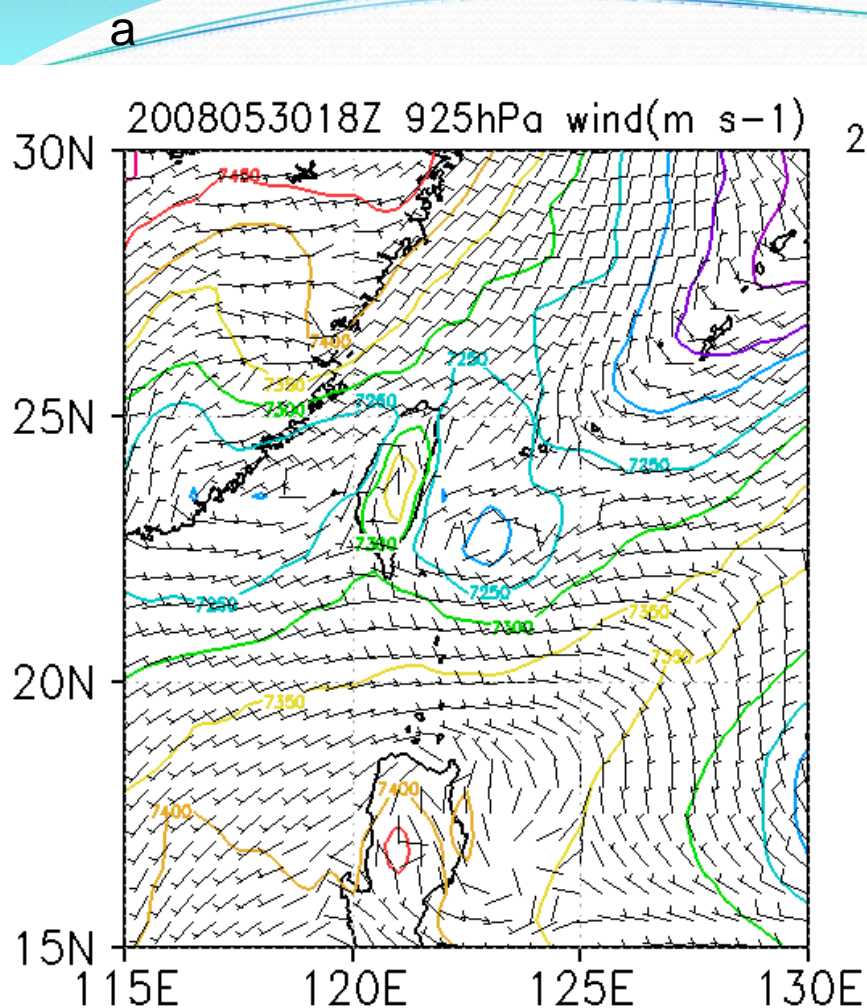


b

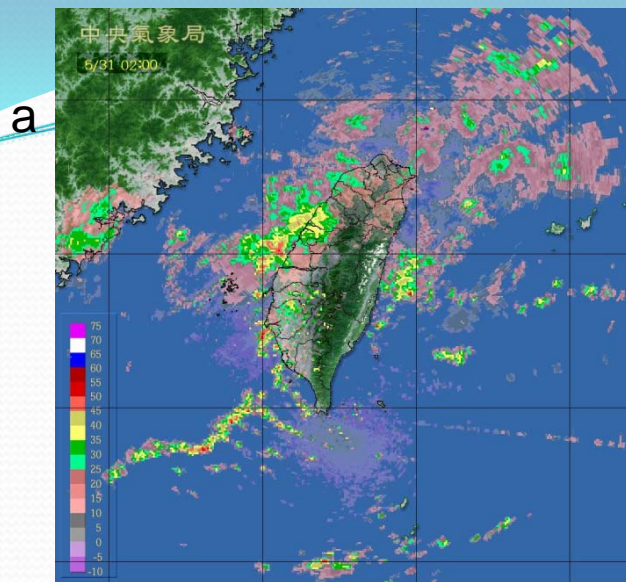
353012Z 925hPa vapor mixing ratio(kg kg^{-1})& theta(K)



(a) mosaic radar images at 1200 UTC 30 May 2008 (Courtesy of Central Weather Bureau), WRF model simulated (b) 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) with a 9-km horizontal resolution and (c) hourly rainfall accumulation (mm) from 1200-1300 UTC with a 3-km horizontal resolution using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast).

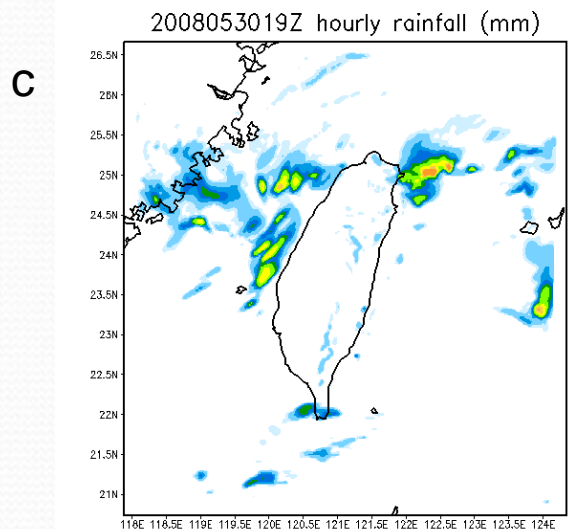
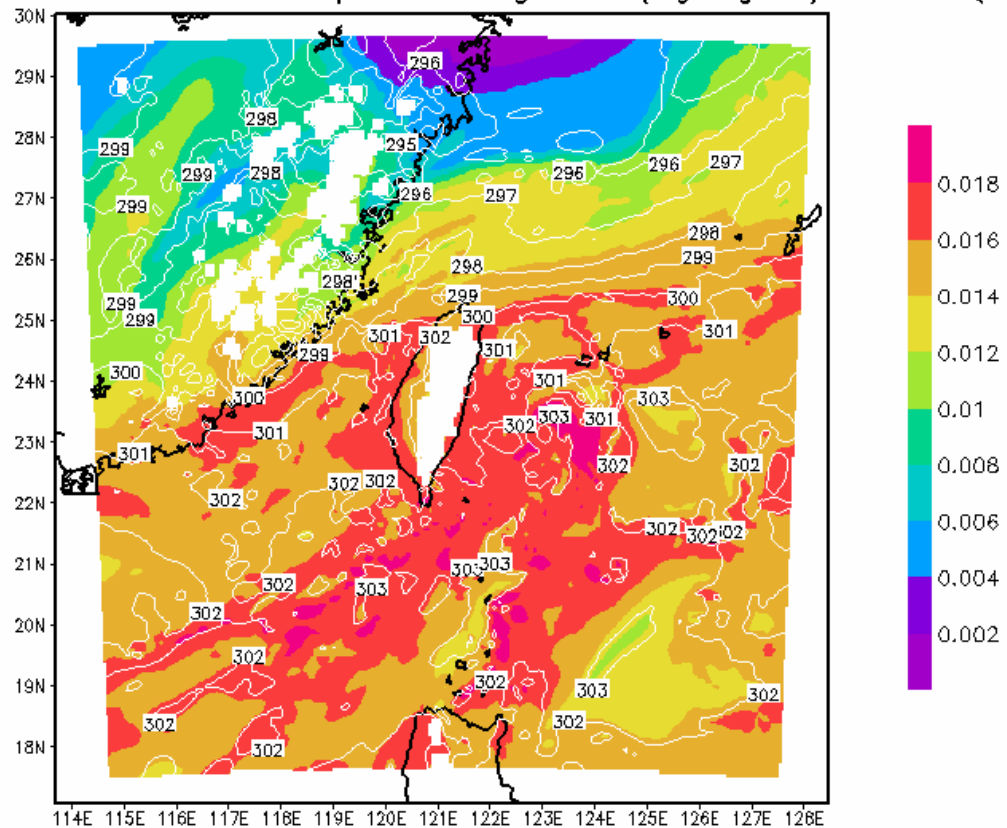


(a) YOTC 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹) and geopotential height (gpm, contoured) at 1800 UTC 30 May 2008 and (b) WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast with a 9-km horizontal resolution).

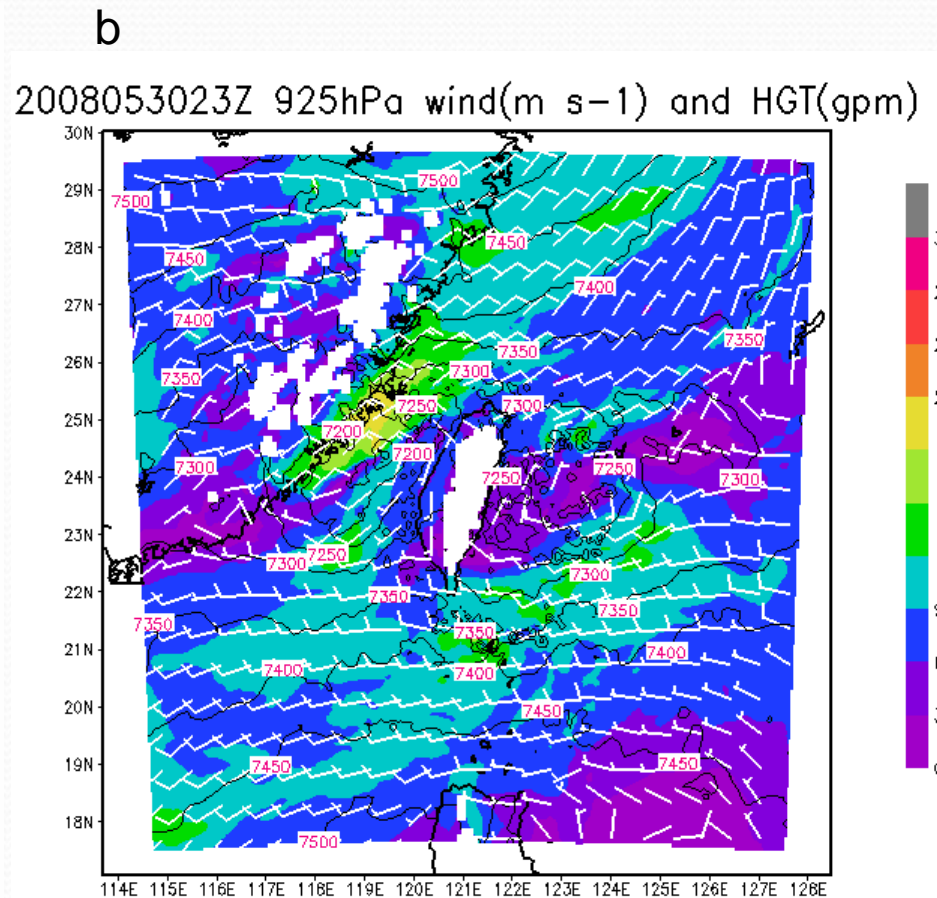
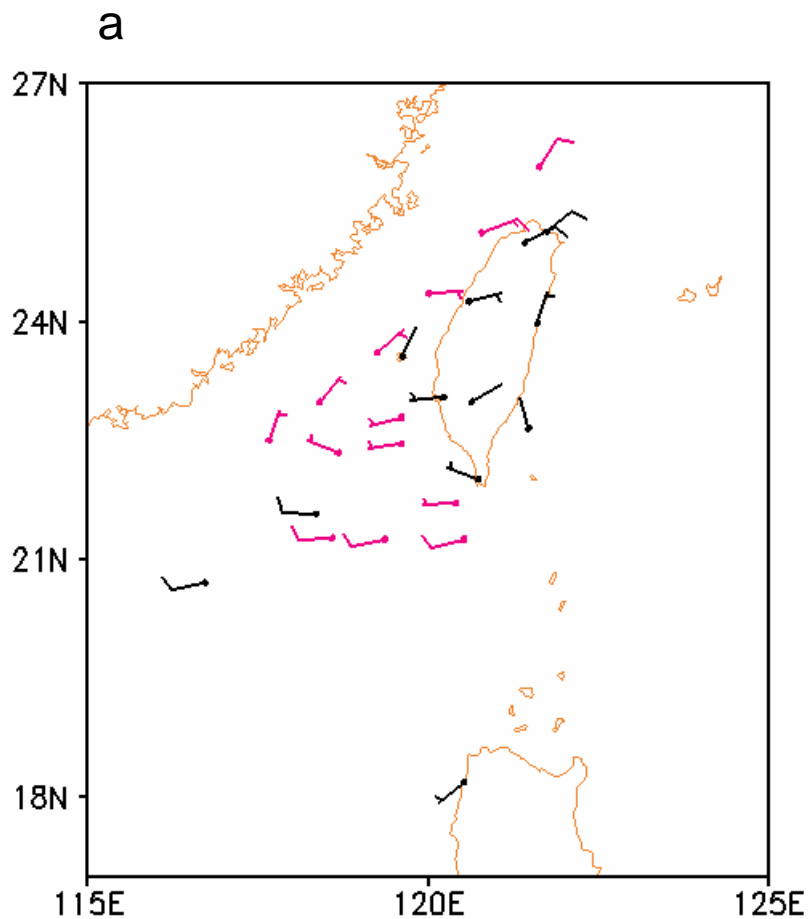


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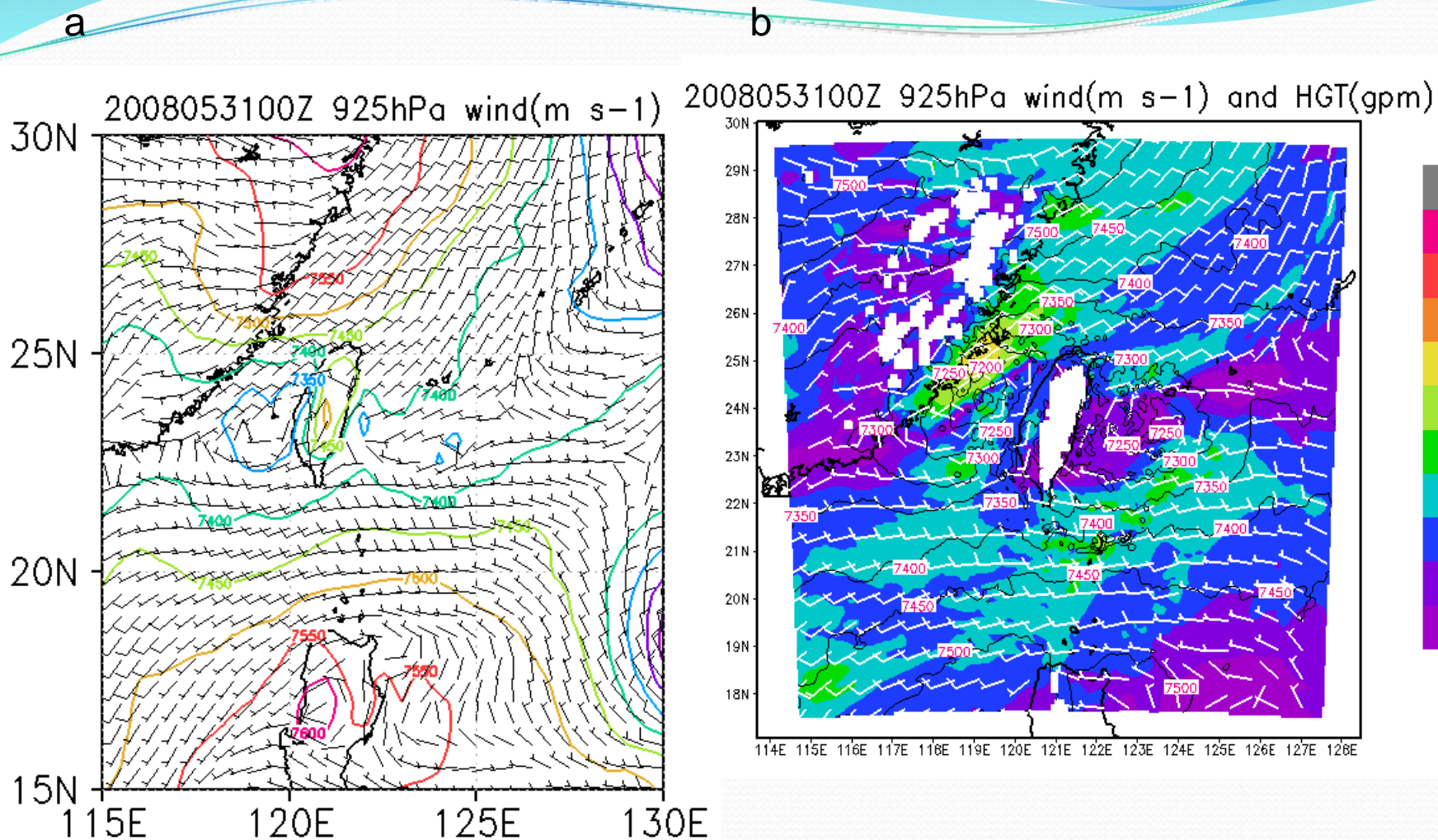
053018Z 925hPa vapor mixing ratio(kg kg⁻¹)& theta(K)



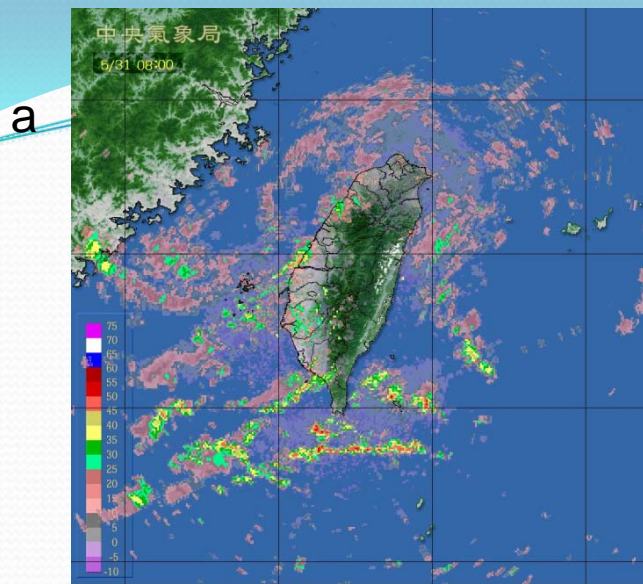
(a) mosaic radar images at 1800 UTC 30 May 2008 (Courtesy of Central Weather Bureau), WRF model simulated (b) 925-hPa water vapor mixing ratio (kg kg⁻¹, shaded) and theta (K, contoured) with a 9-km horizontal resolution and (c) hourly rainfall accumulation (mm) from 1800-1900 UTC with a 3-km horizontal resolution using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast).



(a) Dropsonde (red; during 2100-2300 UTC 30 May) and rawinsonde (black; at 0000 UTC 31 May) wind data at 925-hPa level (barbs, 1 full barb is 10 m s^{-1}) and (b) WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) using FNL 1 deg resolution data as initial and boundary conditions (23-h forecast with a 9-km horizontal resolution).

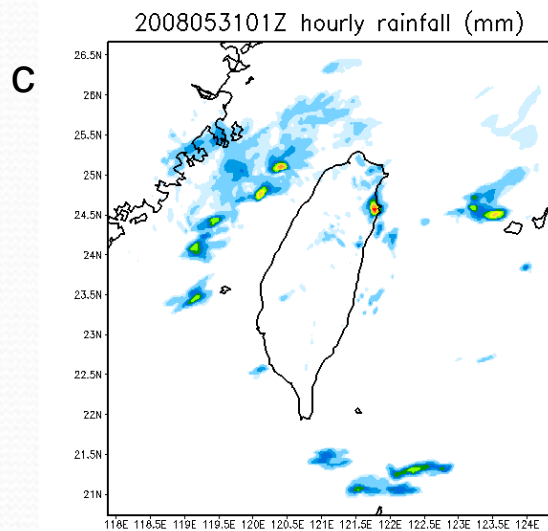
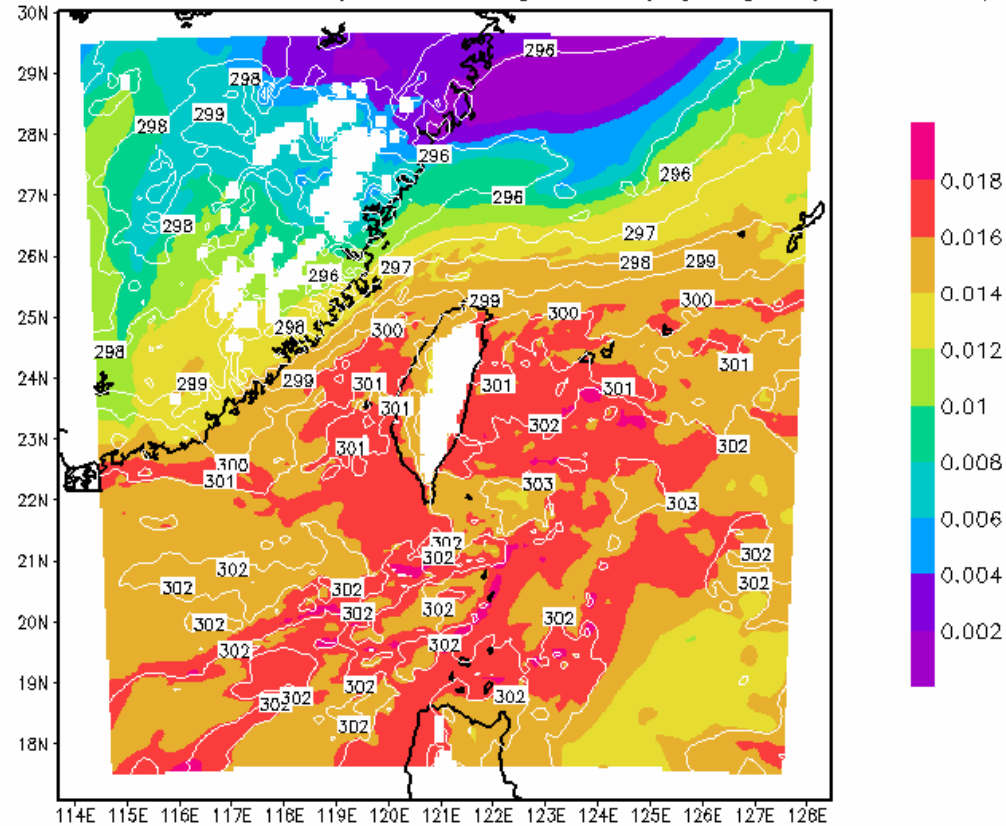


(a) YOTC 925-hPa winds (barbs, 1 full barb is 10 m s^{-1}) and geopotential height (gpm, contoured) at 0000 UTC 31 May 2008 and (b) WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) using FNL 1 deg resolution data as initial and boundary conditions (24-h forecast with a 9-km horizontal resolution).



b

353100Z 925hPa vapor mixing ratio(kg kg^{-1})& theta(K)

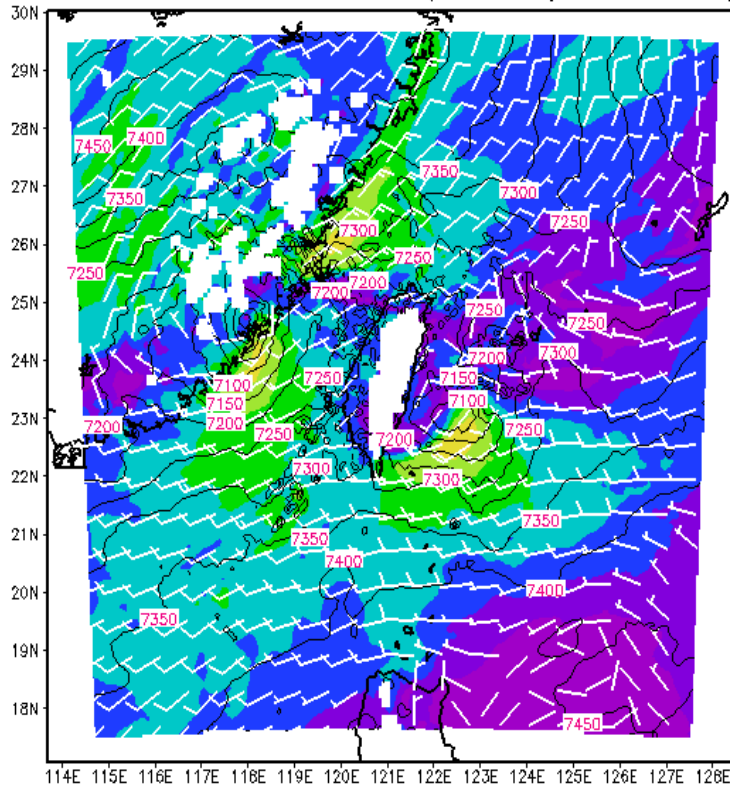


(a) mosaic radar images at 0000 UTC 31 May 2008 (Courtesy of Central Weather Bureau), WRF model simulated (b) 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) with a 9-km horizontal resolution and (c) hourly rainfall accumulation (mm) from 0000-0100 UTC with a 3-km horizontal resolution using FNL 1 deg resolution data as initial and boundary conditions (24-h forecast).

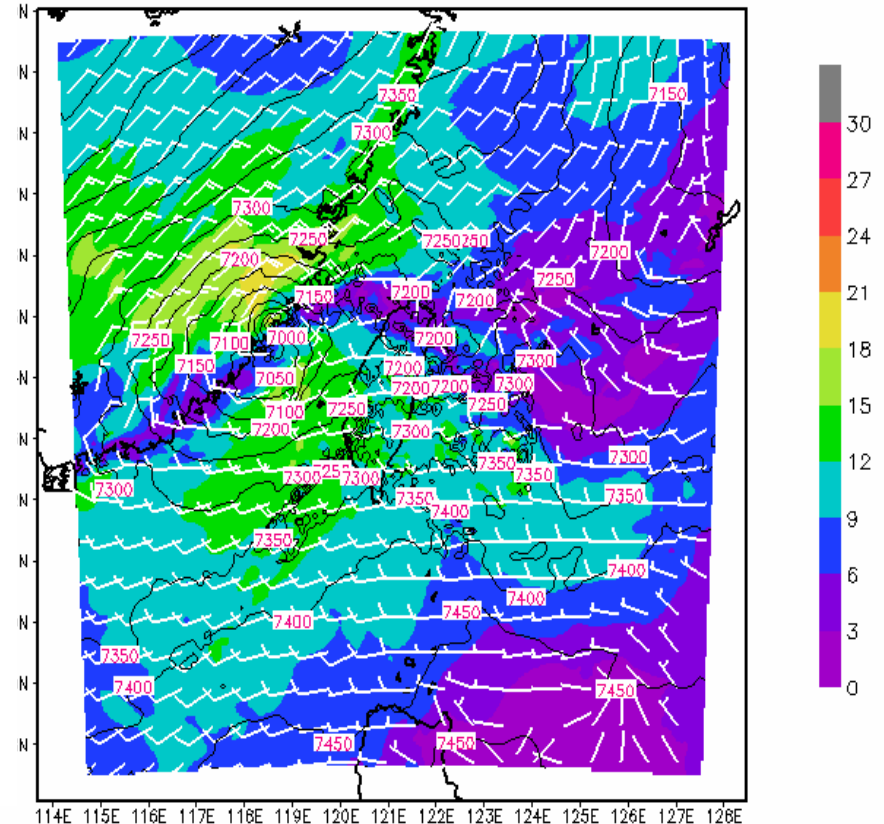
Effects of terrain

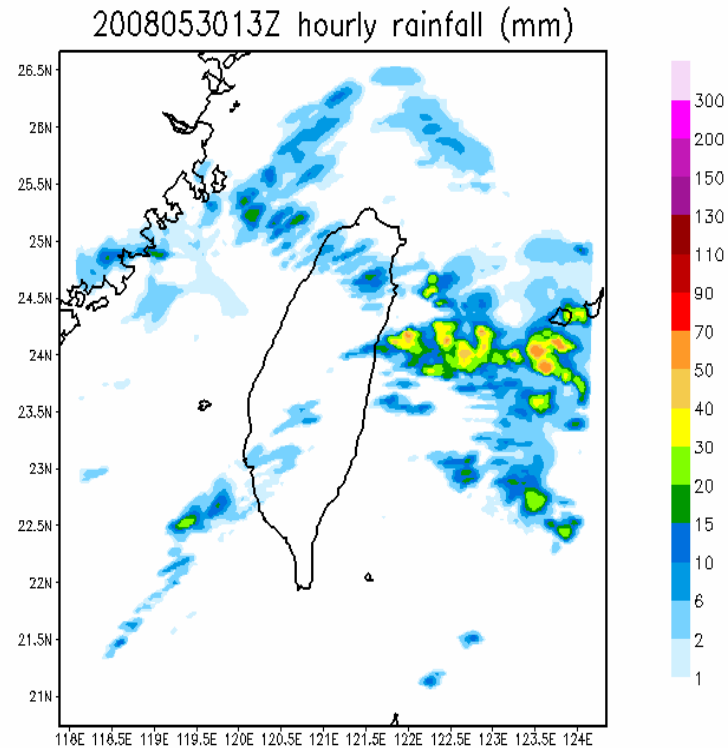
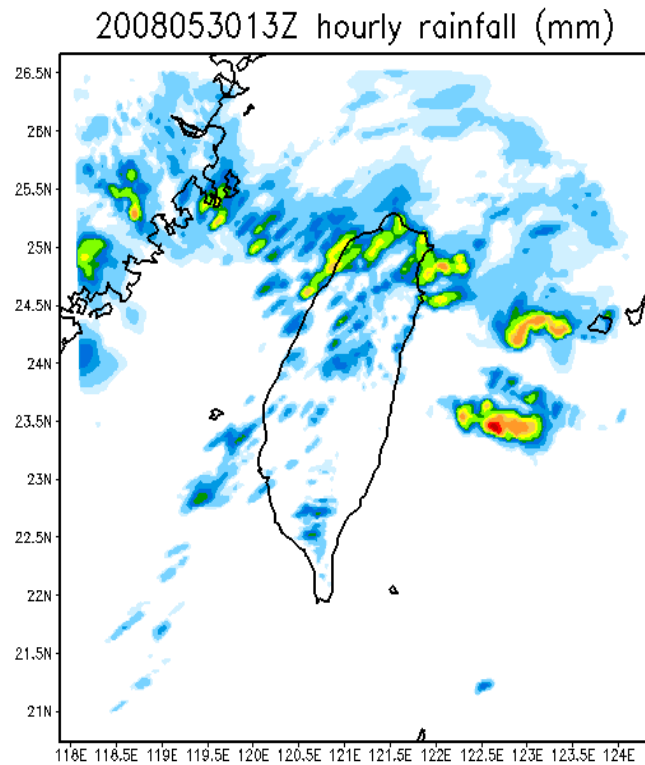
WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 1200 UTC 30 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 9-km horizontal resolution)
(a) with (left) and (b) without terrain (right) runs.

2008053012Z 925hPa wind(m s⁻¹) and HGT(gpm)



2008053012Z 925hPa wind(m s⁻¹)
and HGT(gpm)w/o terrain



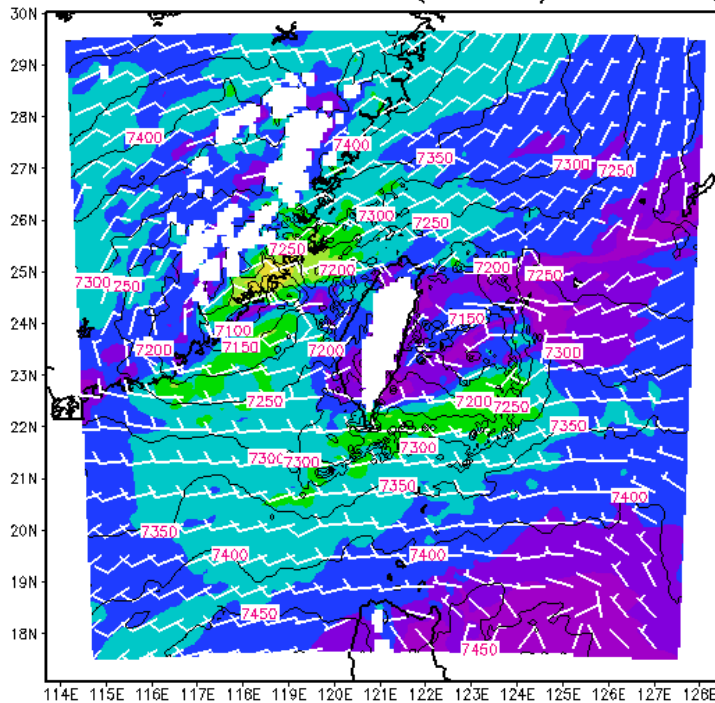


WRF model simulated hourly rainfall accumulation (mm) at 1300 UTC 30 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 3-km horizontal resolution) (a) with and (b) without terrain runs.

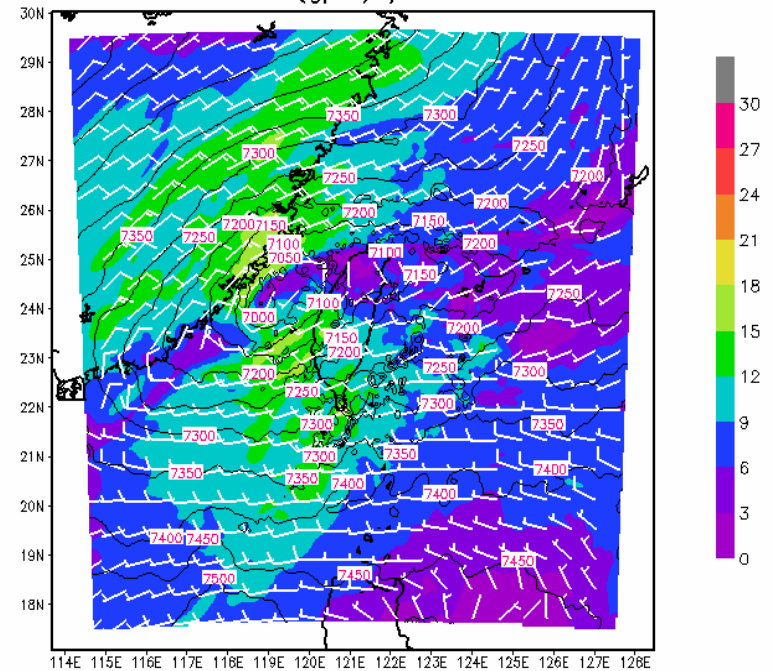
Effects of terrain

WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC 30 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 9-km horizontal resolution) (a) with (left) and (b) without terrain (right) runs. No blocking at SW coast of Taiwan. No lee vortex east of Taiwan

2008053018Z 925hPa wind(m s⁻¹) and HGT(gpm)

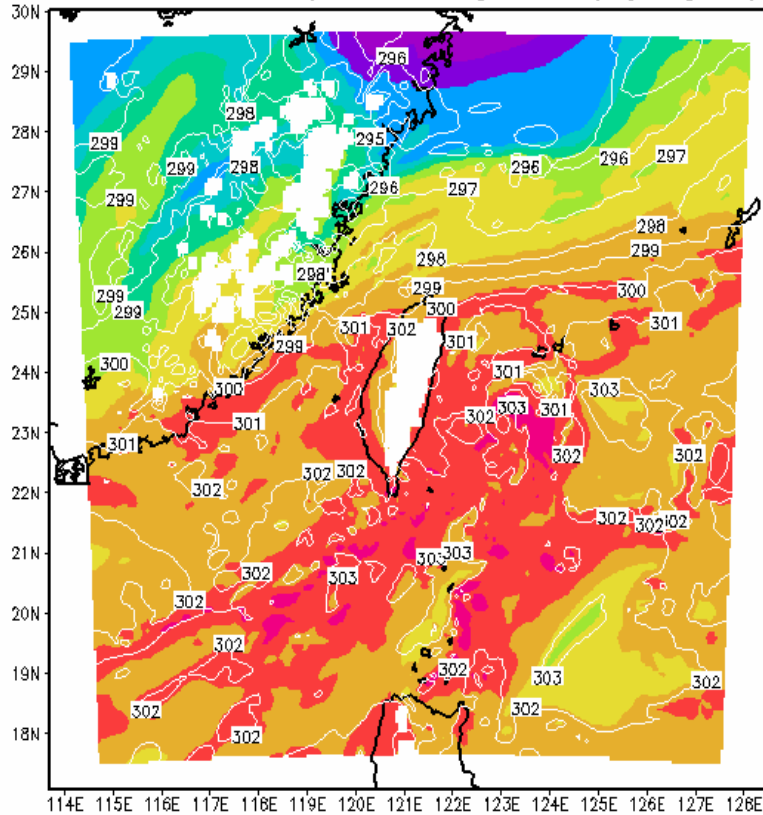


2008053018Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain

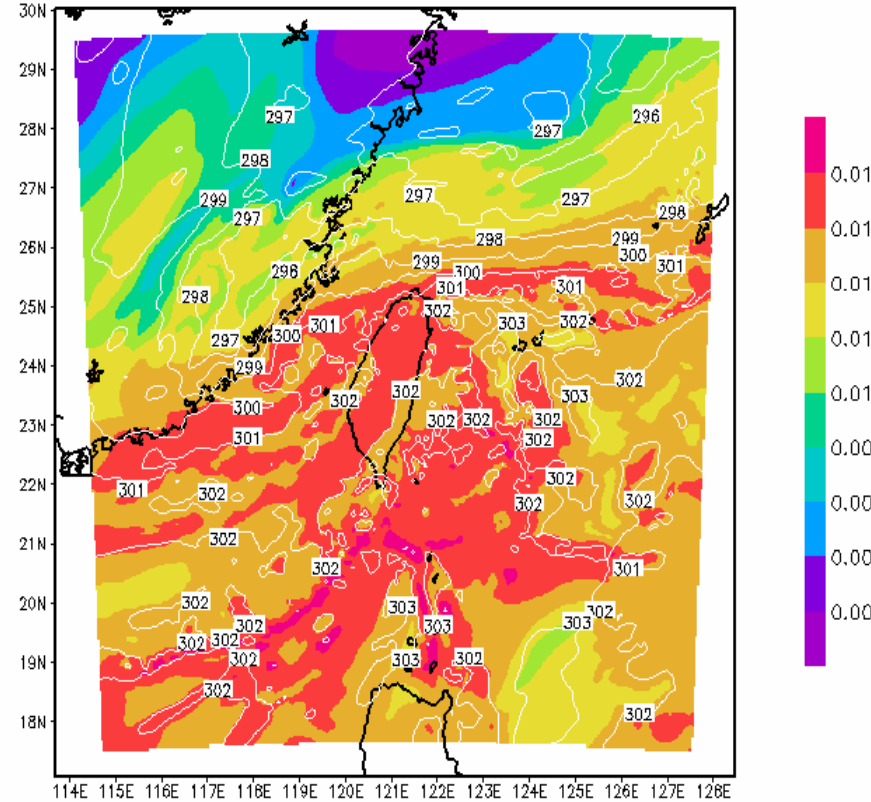


Water vapor mixing ratio (g/kg) and potential temperature (K) simulated at 1800 UTC May 30 with (left) and without terrain (right). Cold air penetrates farther south over SE China

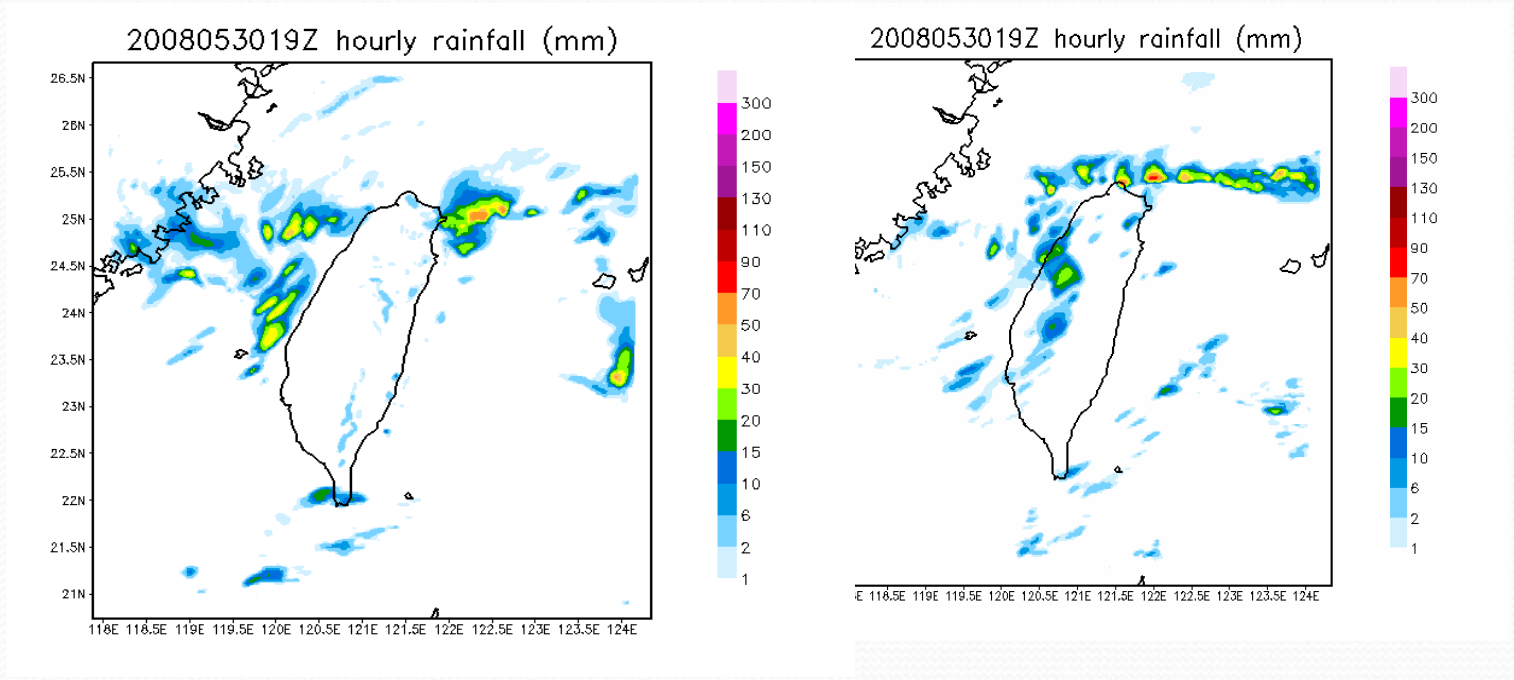
053018Z 925hPa vapor mixing ratio(kg kg⁻¹)&



2008053018Z 925hPa vapor mixing ratio(kg kg⁻¹)& theta(K) w/o terrain

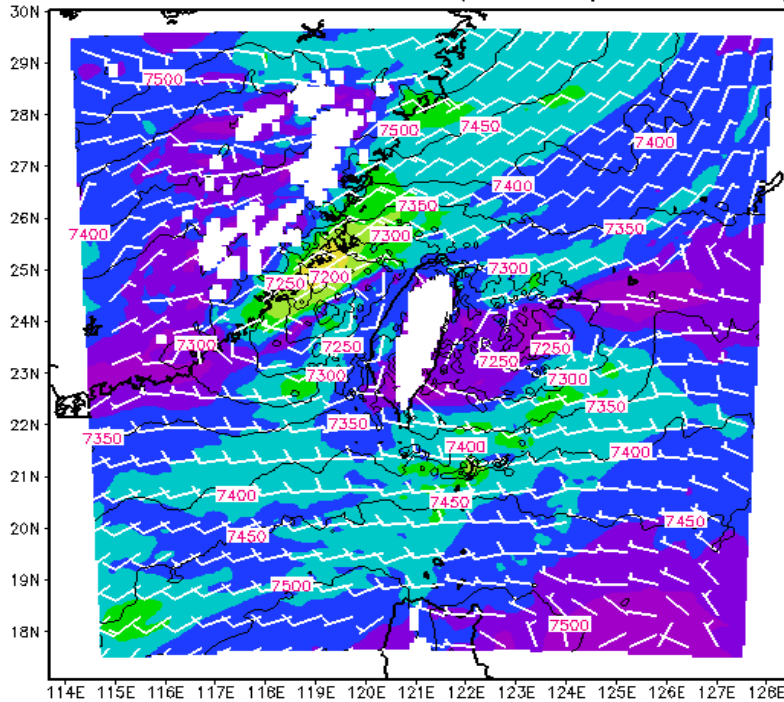


WRF model simulated hourly rainfall accumulation (mm) at 1900 UTC 30 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 3-km horizontal resolution) (a) with and (b) without terrain runs.

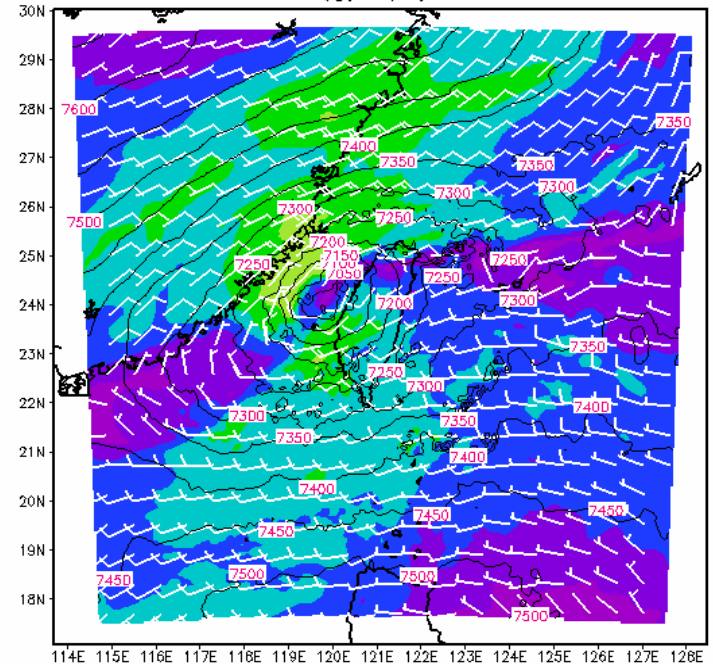


WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 18 0000 UTC 31 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 9-km horizontal resolution) (a) with (left) and (b) without terrain (right) runs. No blocking at SW coast of Taiwan. No lee vortex east of Taiwan

2008053100Z 925hPa wind(m s⁻¹) and HGT(gpm)

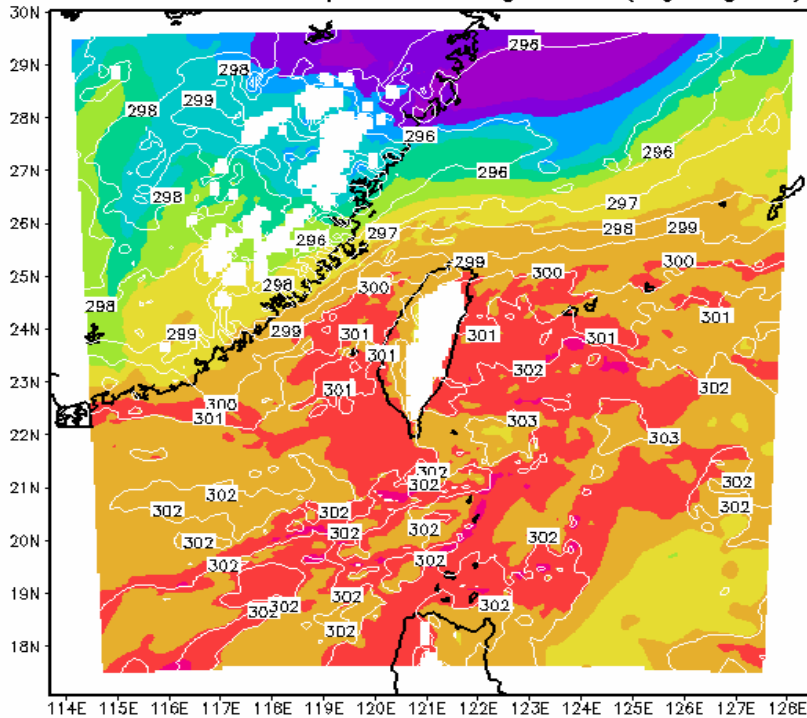


2008053100Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain

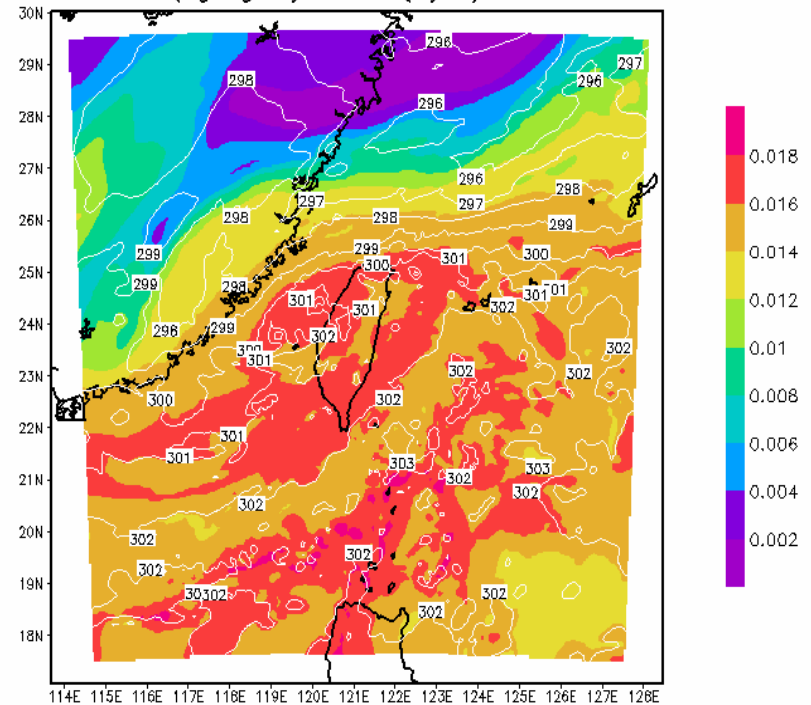


Water vapor mixing ratio (g/kg) and potential temperature (K) simulated at 0000 UTC May 31 with (left) and without terrain (right). Cold air penetrates farther south over SE China.

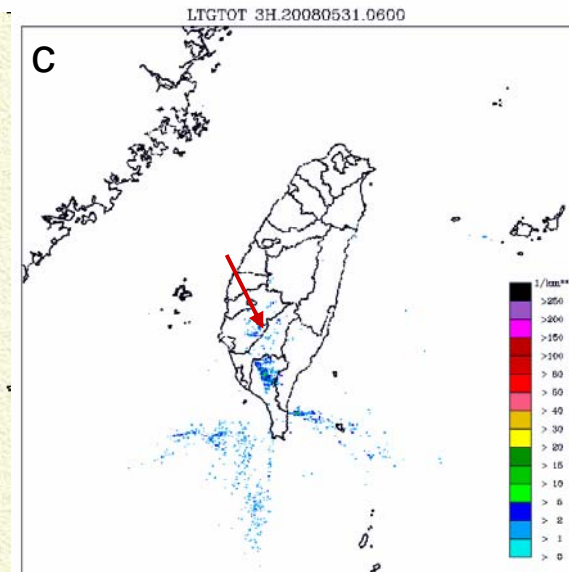
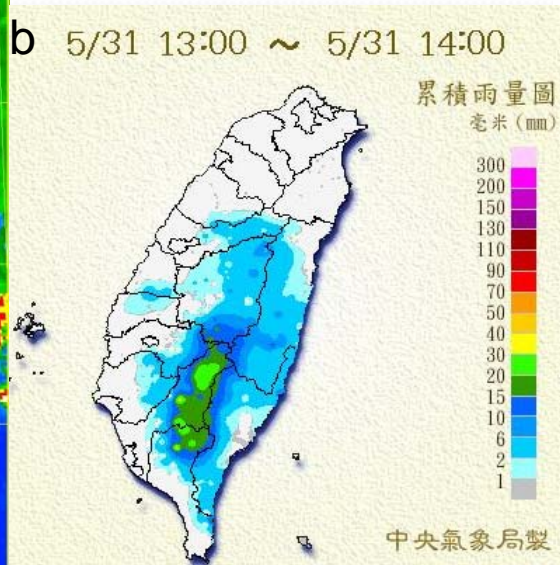
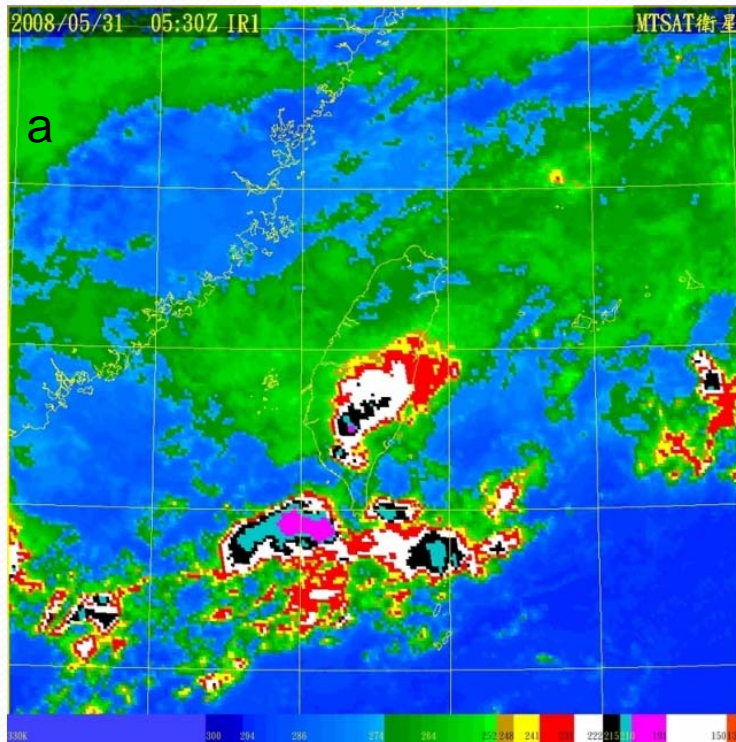
2008053100Z 925hPa vapor mixing ratio(kg kg⁻¹)&



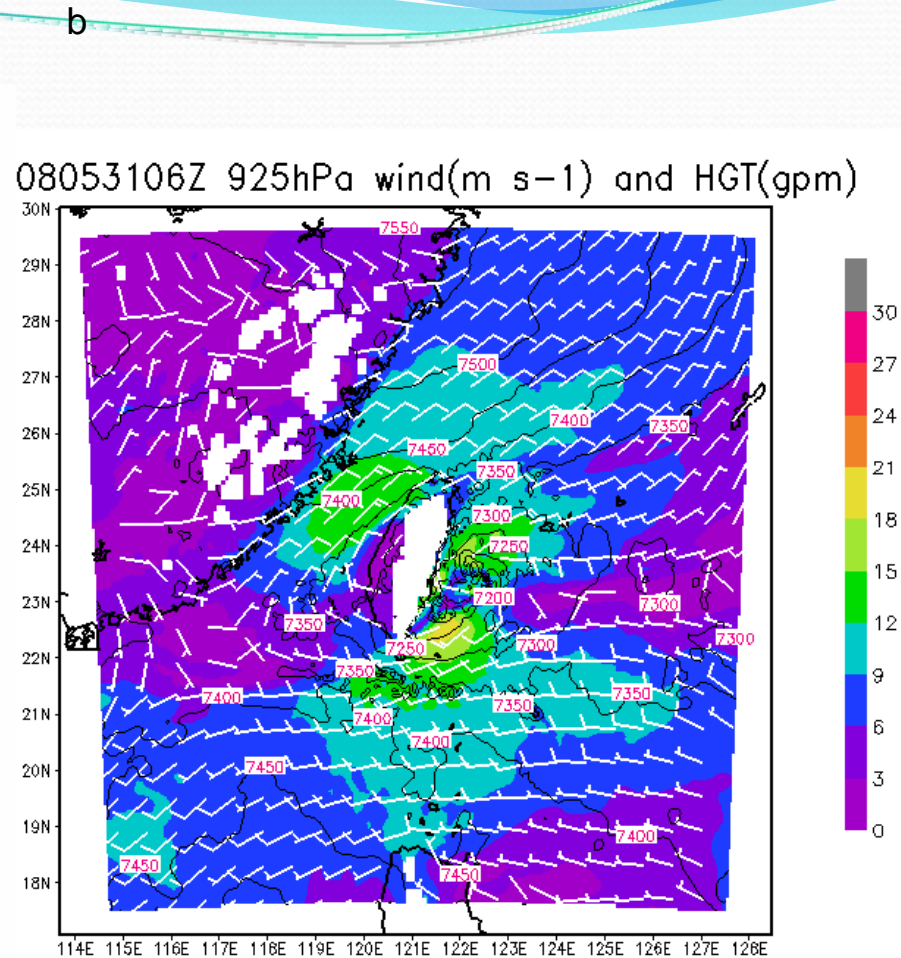
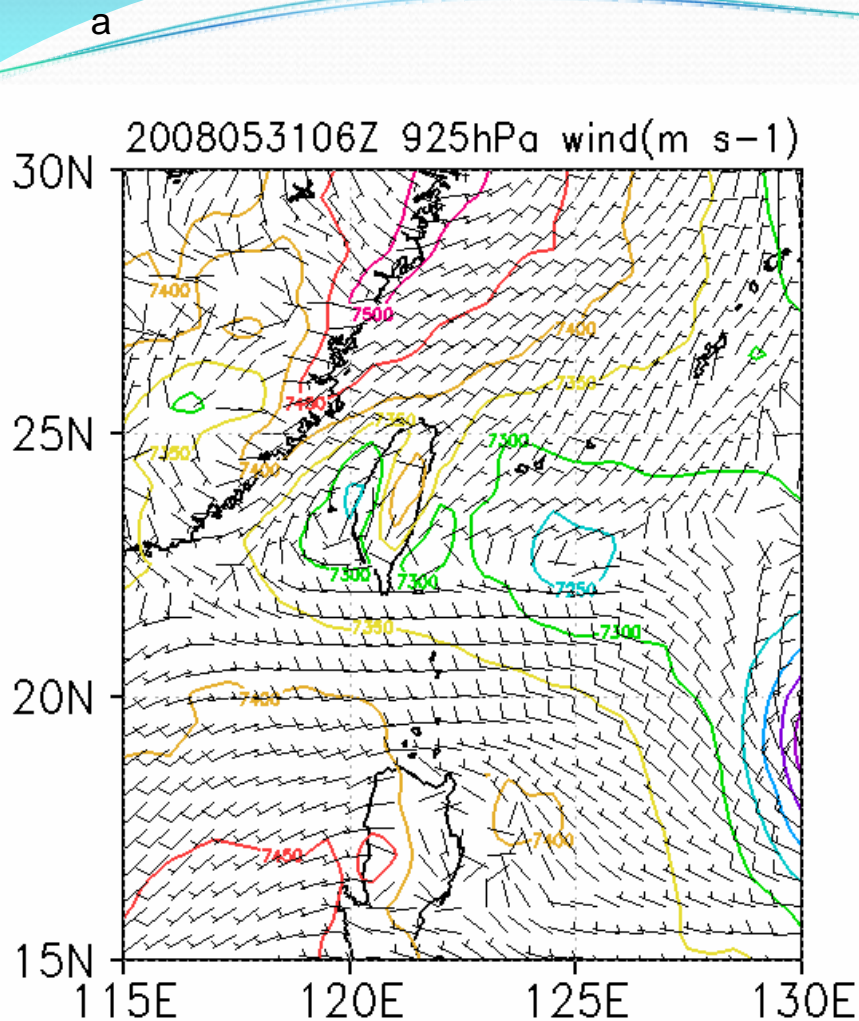
2008053100Z 925hPa vapor mixing ratio(kg kg⁻¹)& theta(K) w/o terrain



5/31 00Z-06Z as the frontal cyclone drifted inland, it interacted with CMR

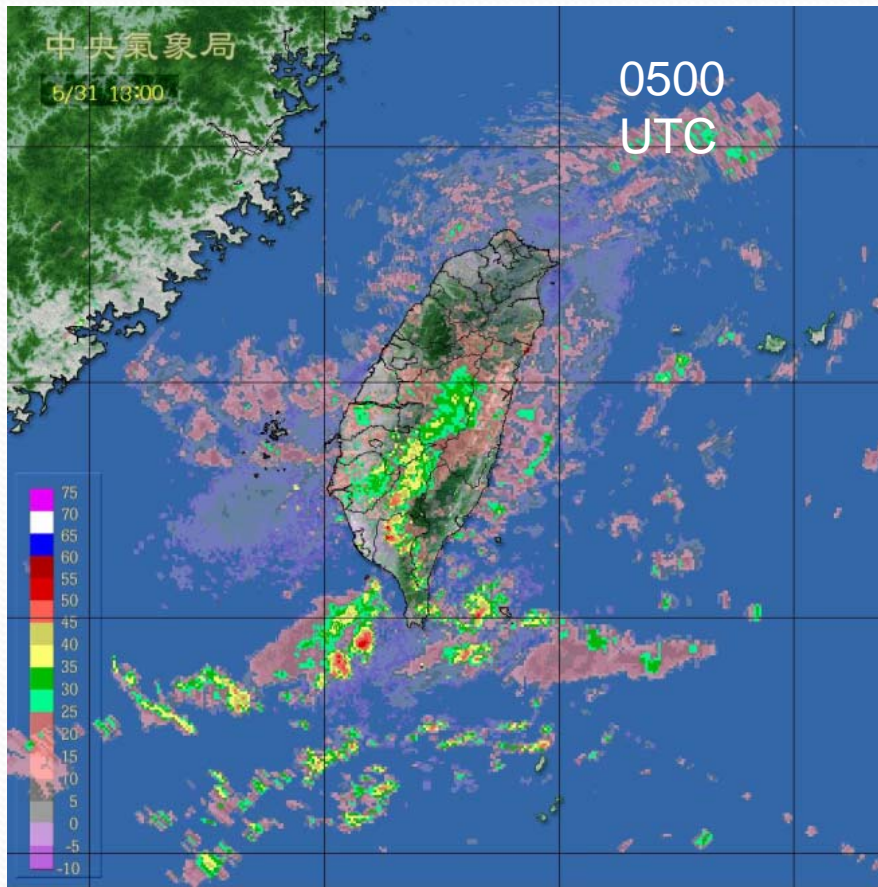


(a) IR image at 0530 UTC, (b) hourly rainfall accumulation during 0500-0600 UTC and (c) 3-h lightning data during 0300-0600 UTC 31 May 2008

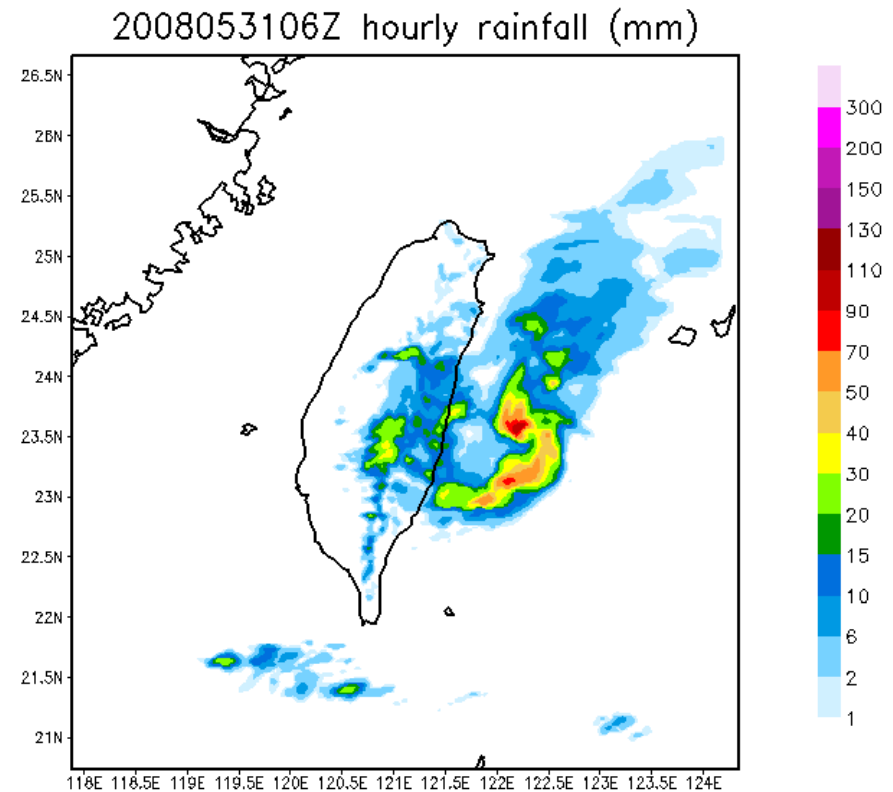


(a) YOTC 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹) and geopotential height (gpm, contoured) at 0600 UTC 31 May 2008 and (b) WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 9-km horizontal resolution).

a



b



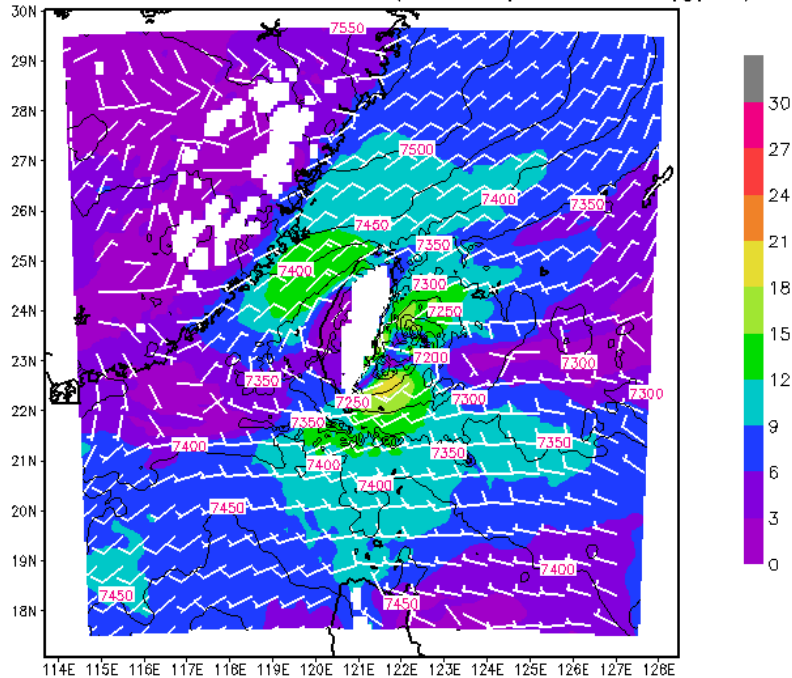
(a) mosaic radar images at 0500 UTC 31 May 2008 (Courtesy of Central Weather Bureau), (b) WRF model simulated hourly rainfall accumulation (mm) from 0500-0600 UTC using FNL 1 deg resolution data as initial and boundary conditions (5-h forecast with a 3-km horizontal resolution).

The convergence flow/cells ahead of the frontal cyclone might be a little bit north in the model simulation than the observation. However, we can still study the effects of CMR on the SE propagating Mei-Yu frontal cyclone.

Effects of the CMR on the propagating Mei-Yu frontal cyclone w/wo terrain

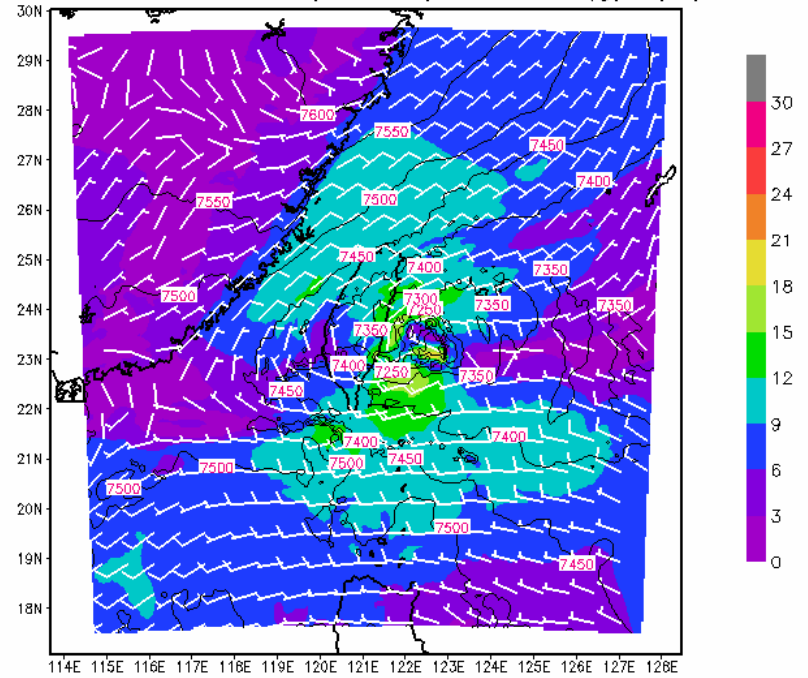
a

2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)



b

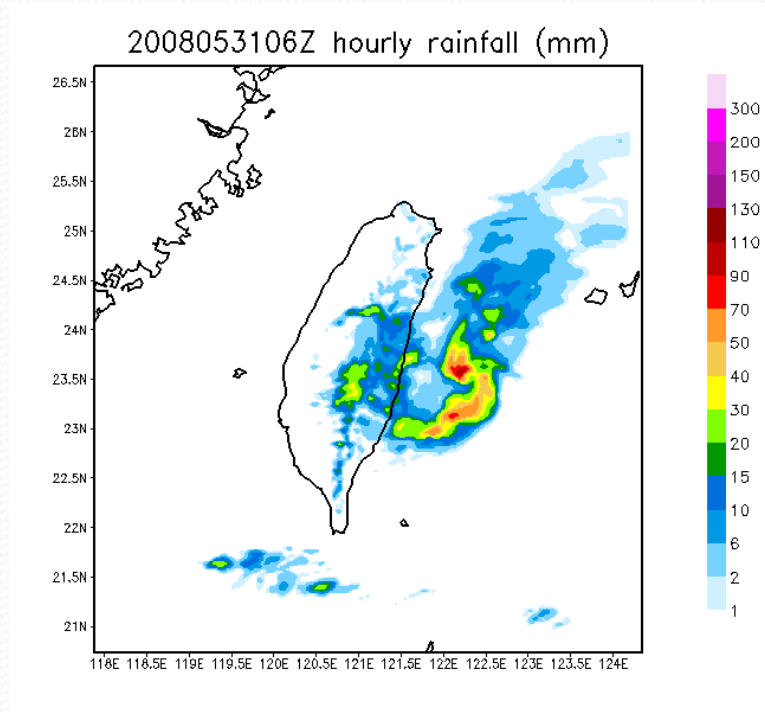
2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain



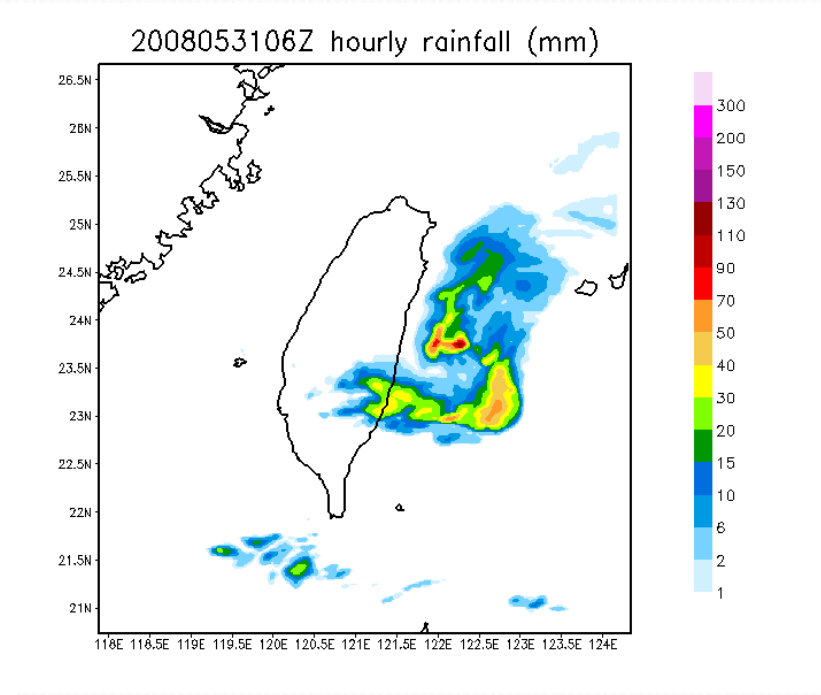
WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 0600 UTC 31 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 9-km horizontal resolution) (a) with and (b) without terrain runs.

Effects of the CMR on the propagating Mei-Yu frontal cyclone w/wo terrain

a



b

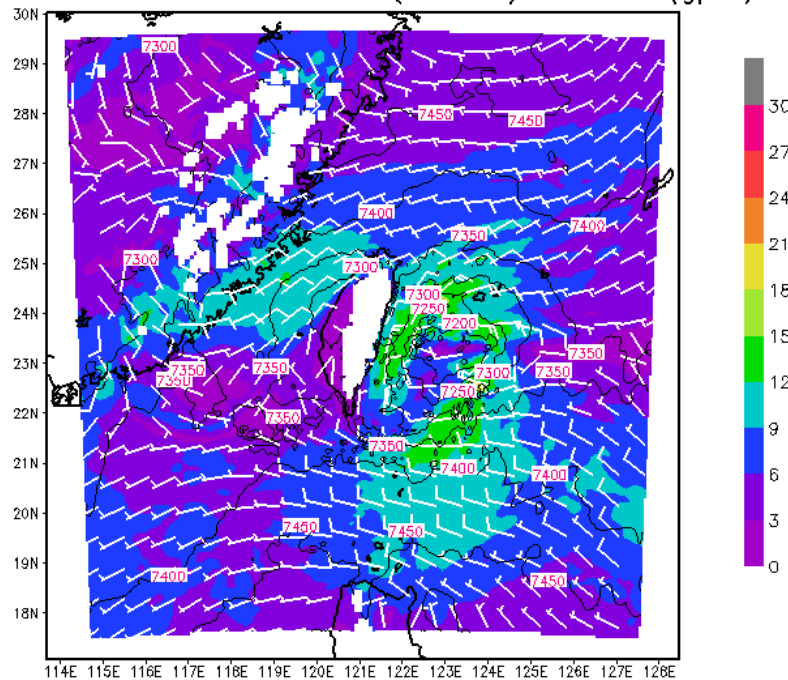


WRF model simulated hourly rainfall accumulation (mm) at 0600 UTC 31 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (6-h forecast with a 3-km horizontal resolution) (a) with and (b) without terrain runs.

Effects of the CMR on the propagating Mei-Yu frontal cyclone w/wo terrain

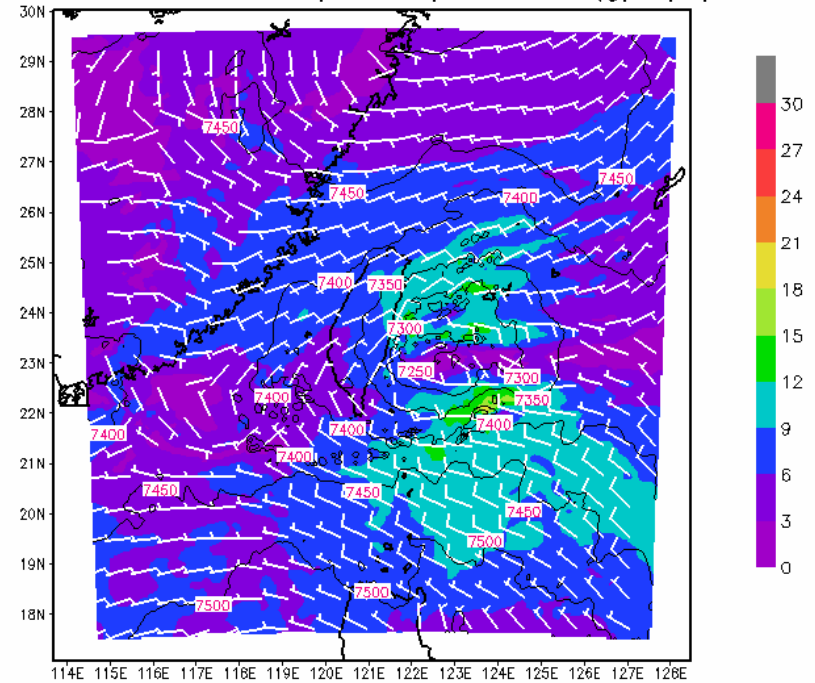
a

2008053112Z 925hPa wind(m s⁻¹) and HGT(gpm)



b

2008053112Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain

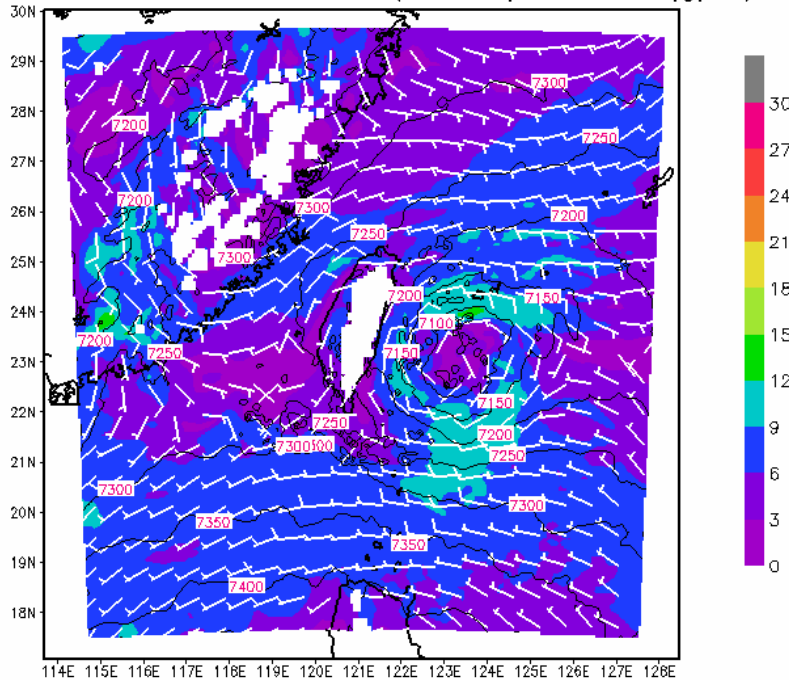


WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 1200 UTC 31 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast with a 9-km horizontal resolution) (a) with and (b) without terrain runs.

Effects of the CMR on the propagating Mei-Yu frontal cyclone w/wo terrain

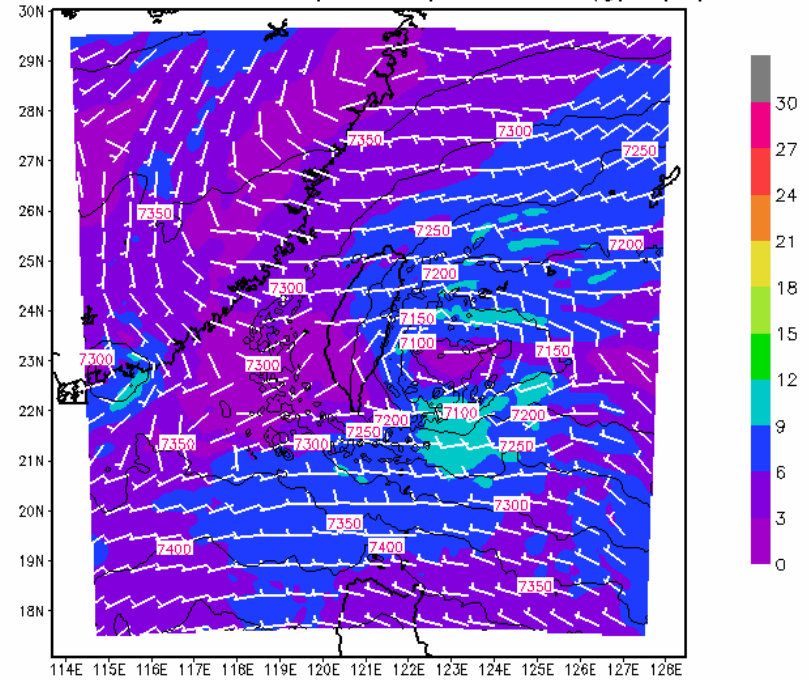
a

2008053118Z 925hPa wind(m s⁻¹) and HGT(gpm)



b

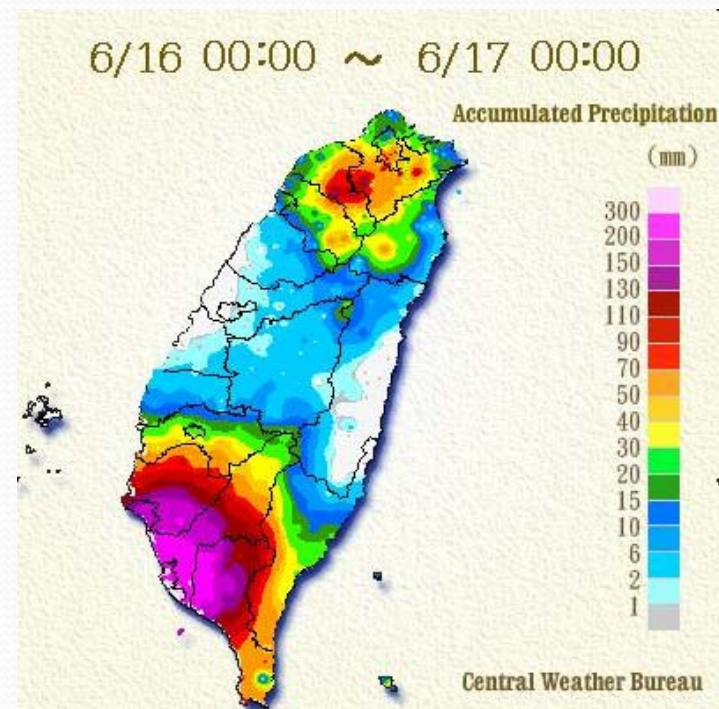
2008053118Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain



WRF model simulated 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹ with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC 31 May 2008 using FNL 1 deg resolution data as initial and boundary conditions (18-h forecast with a 9-km horizontal resolution) (a) with and (b) without terrain runs.

Case II:

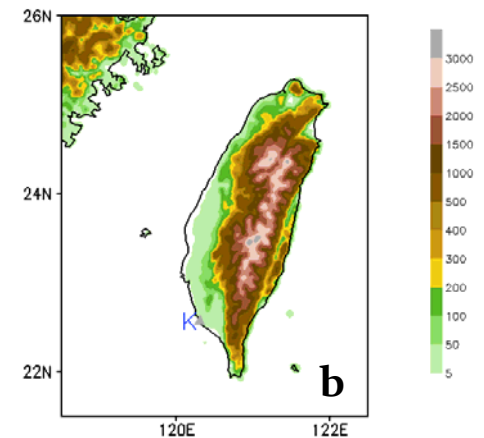
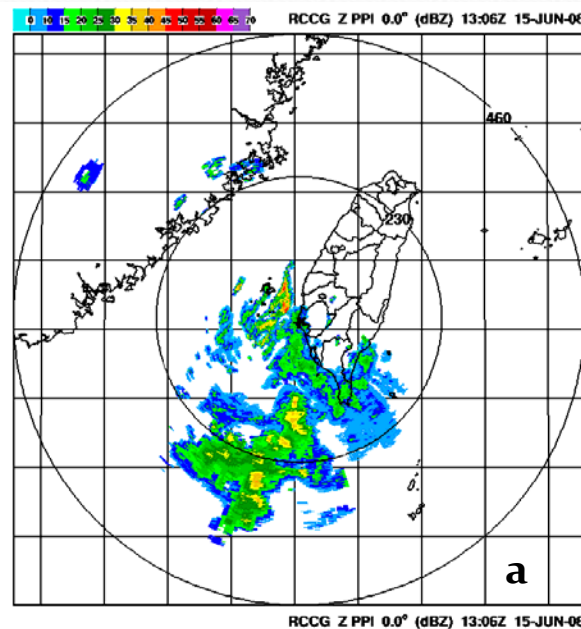
- 6/16 afternoon heavy rainfall at the coast regions without afternoon showers over southwestern mountain range
- Thunderstorm activity in Taipei



Daily (0000-2400 Local Time)
rainfall accumulation (mm) on 16
June.

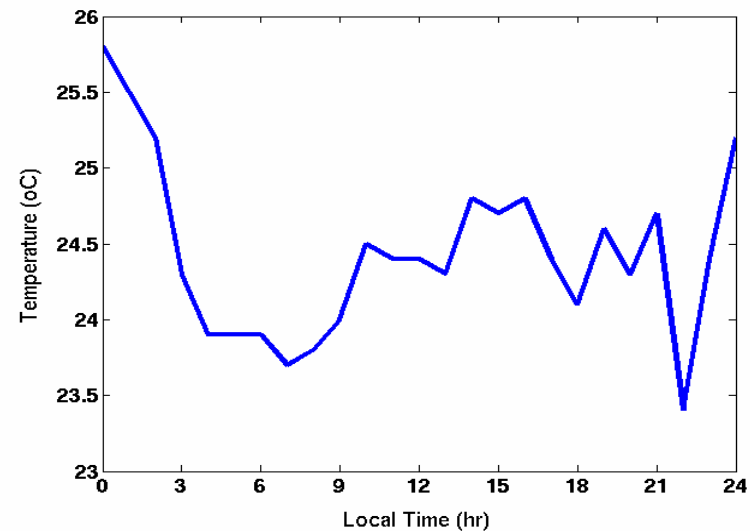
6/15 1306 UTC (2106LT)

- Previous day, night time significant blocking, land breeze and the SW monsoon flow converge along the coast.



(a) Composite radar reflectivities (dBZ) at 1306 UTC (2106 Local Time) 15 June 2008. (b) Terrain heights for Taiwan (m). K denotes the location of Kaohisung station.

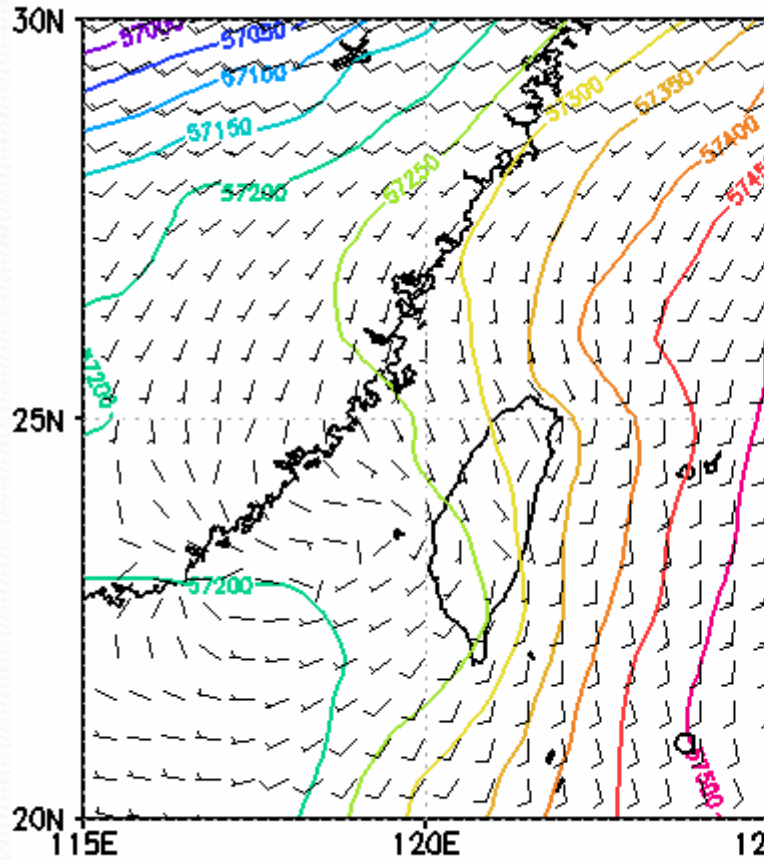
- Continuous rainfall along the coast results in cold air temperature at SW coast region in Taiwan.
- This might block the prevailing warm, moist westerly monsoon flow extend to SW Taiwan.
- This also limited the daytime sea breeze and upslope flow to develop.



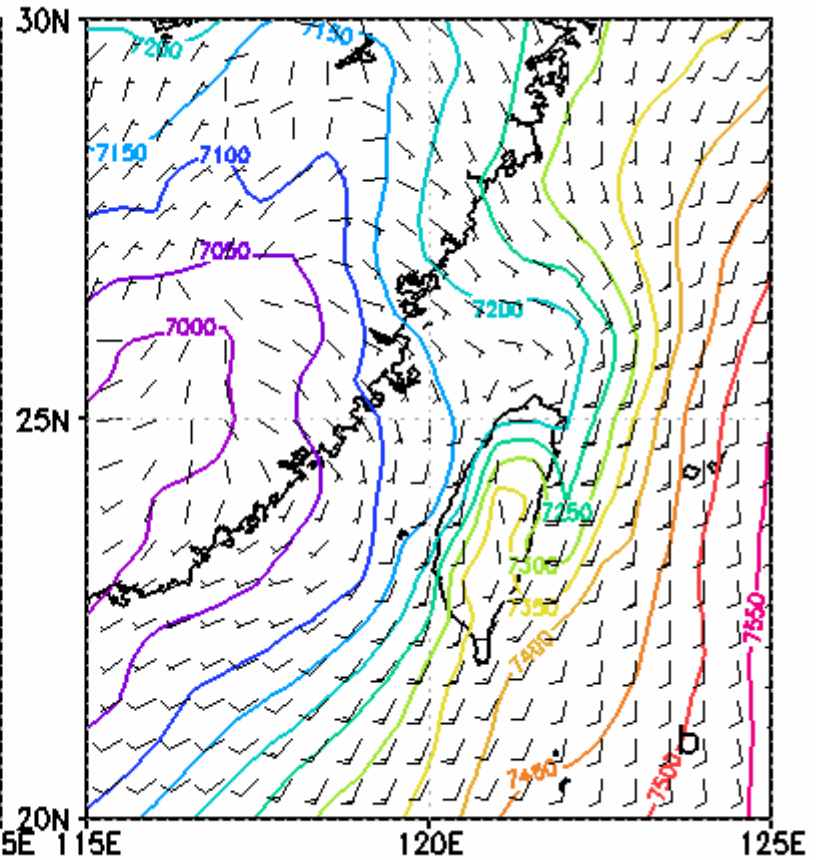
Time series of surface air temperature ($^{\circ}\text{C}$) during 0000-2400 Local Time June 16 at Kaohsiung (123.3°E , 22.57°N ; Symbol K in Fig. 2b)

6/16 0600 UTC (1400 LT)

a

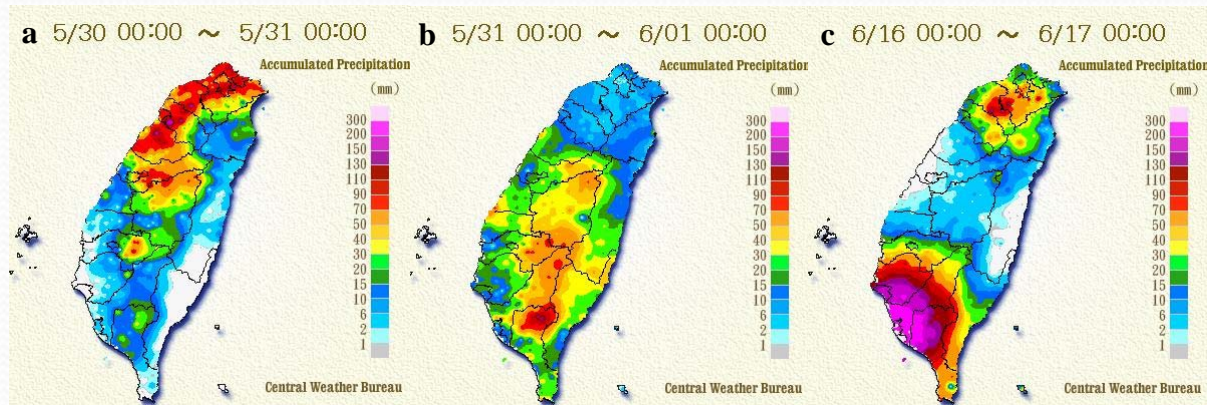


b

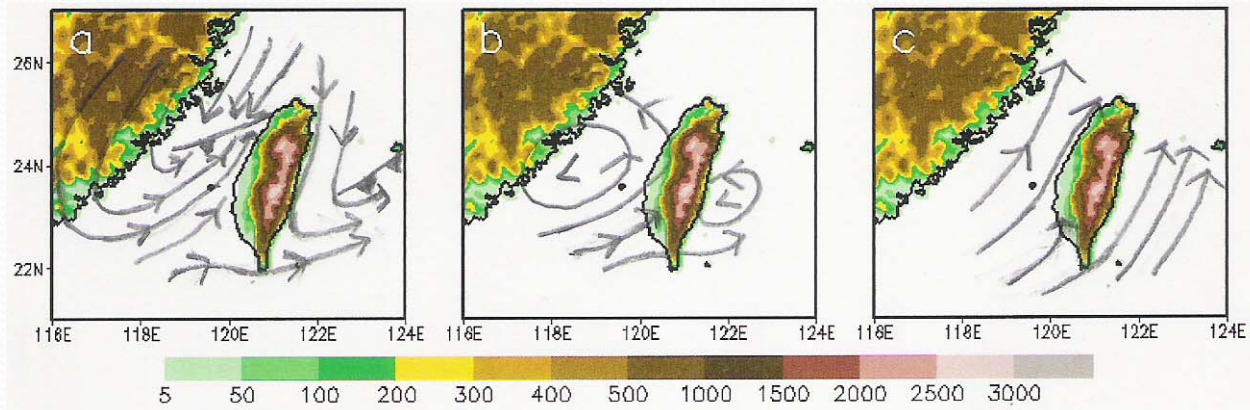


YOTC (a) 500-hPa and (b) 925-hPa winds (barbs, 1 full barb is 10 m s⁻¹) and geopotential height (gpm, contoured) at 0600 UTC (1400 LT) 16 June 2008.

Comparison



Daily (0000-2400 Local Time) rainfall accumulation (mm). (a) 30 May, (b) 31 May, (c) 16 June.



A schematic diagram showing: (a) 925-hPa-level flow pattern in the evening of May 30; (b) 850-hPa-level flow pattern in the early afternoon of May 31; (c) same as (b) but in the early morning of June 16.

Conclusions

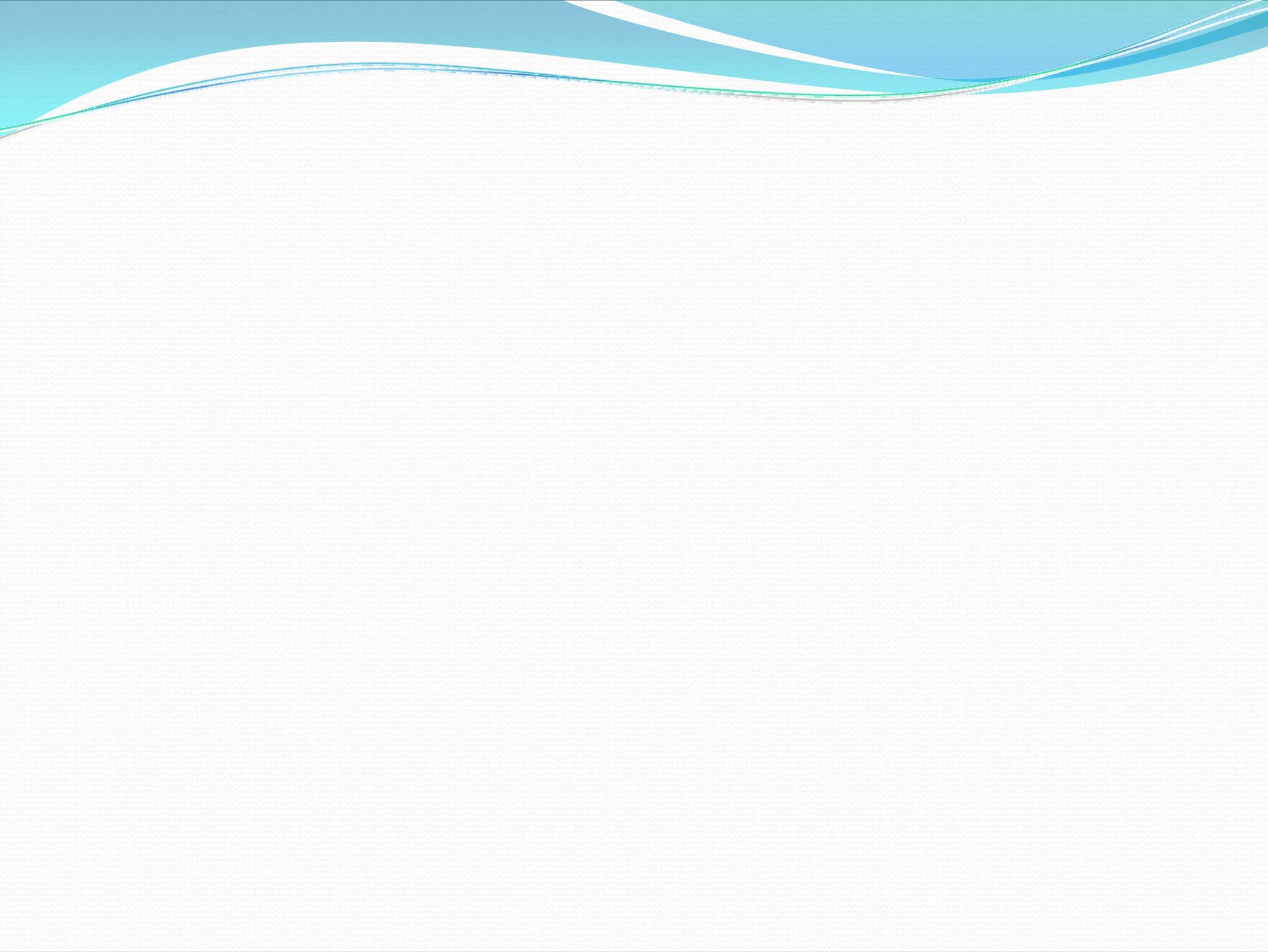
- The rainfall distributions for May 30, May 31 and June 16 are affected by terrain effects on the Mei-Yu jet/front system, orographic blocking of the prevailing winds and the diurnal heating cycle under synoptically disturbed conditions, and interactions between the pre-existing rain showers drifting inland and their interactions with the island-induced flow.
- During IOP #3, as the Mei-Yu jet/front system approaches Taiwan, a well-defined NE-SW orientated rainband over the northern Taiwan Strait in the early evening of May 30, 2008. The rainband over the northern Taiwan Strait is likely a result of the orographically enhanced convergence along the Mei-Yu front ahead of the mesoscale frontal cyclone . The rainband results in heavy rainfall over northwestern Taiwan in the evening as it moves inland.
- The rain showers embedded within the monsoon flow will be enhanced by the combined upslope/southwest monsoon flow in the afternoon hours as they drift inland. An example of this situation occurred on May 31 during TiMREX IOP #3 during the Mei-Yu frontal passage.
- For the southwest flow with a small westerly wind component (e.g., 16 June of TiMREX IOP #8), and under disturbed conditions, coastal rainfall at night and in the early morning over the south/southwestern coastal region is favored as the incoming south/southwest flow encounters the southern/southwestern end of the CMR. The cold pool produced by rain evaporative cooling of pre-existing convection may also enhance the convergence along the coast.

Future research

- The above results are only preliminary. Additional careful analyses using all the available TiMREX data together with modeling studies with sensitivity tests will be performed in the future.



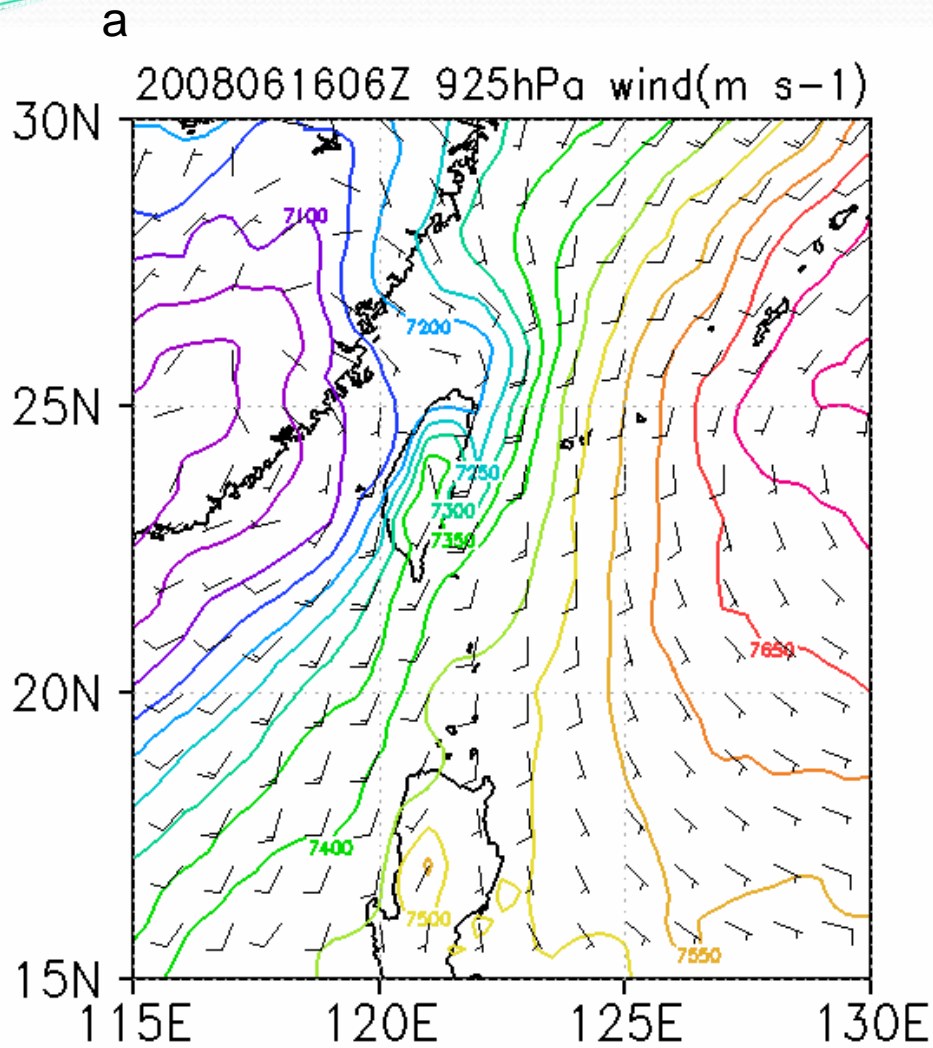
Thank you!



5/30 2300-5/31 0000UTC

- As the blocking of westerly flow enhanced trough night, the (barrier jet, split flow?) is paralleled to the western mountain slope so not much orographic lifting of moist air flow component.
- However, the SW prefrontal flow west of Taiwan in the Taiwan Strait and the Southerly flow along the western slope of CMR converges west of central Taiwan. A meso-scale convection cell develops just off shore of central Taiwan.
- Then, the convection cell moved southeastward inland and advanced CMR as the frontal cyclone move southeastward.
- The convection cell produced afternoon thunderstorm shower over the windward/western slope of CMR, where the environment remained moist and conditionally unstable.

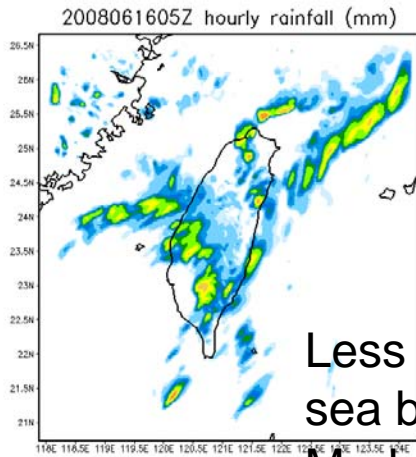
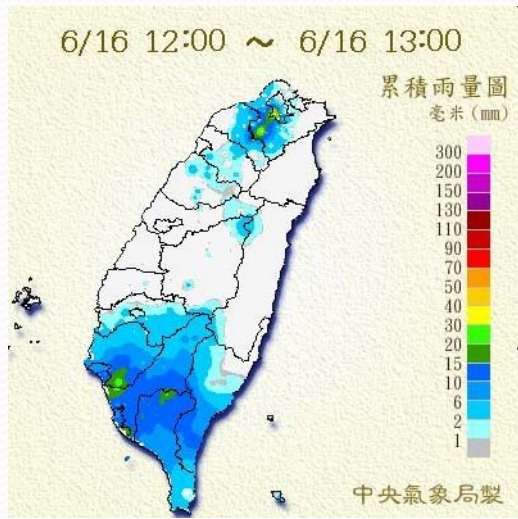
6/16 0600 UTC (1400 LT)



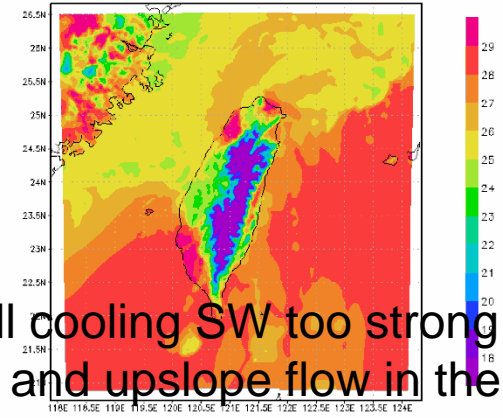
b

YOTC (a) 925-hPa and (b) 300-hPa winds (barbs, 1 full barb is 10 m s⁻¹) and geopotential height (gpm, contoured) at 0600 UTC (1400 LT) 16 June 2008.

Thunderstorm in the wake



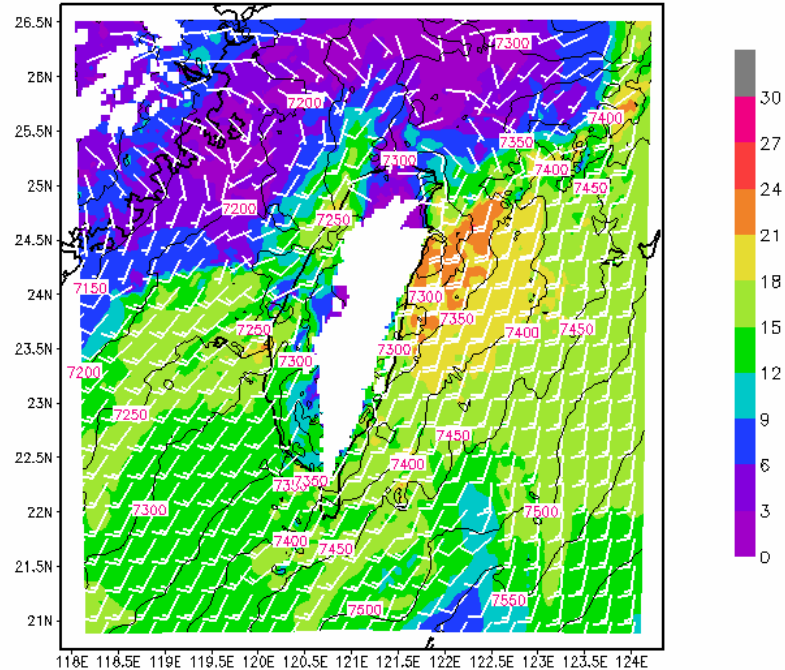
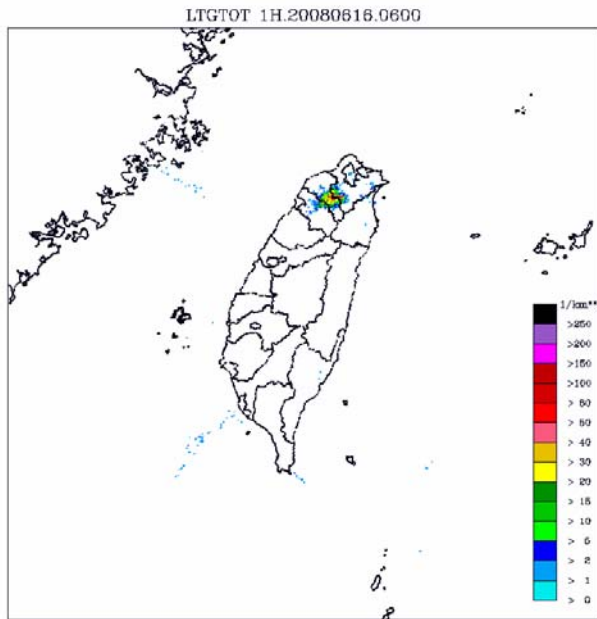
Temp at 2m



Less rainfall cooling SW too strong sea breeze and upslope flow in the

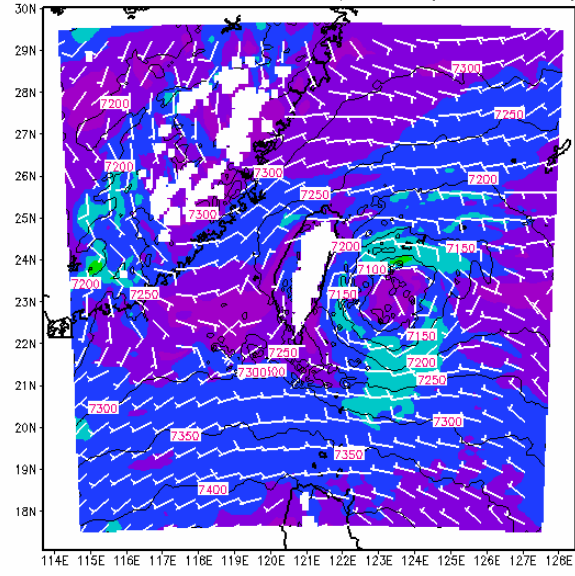
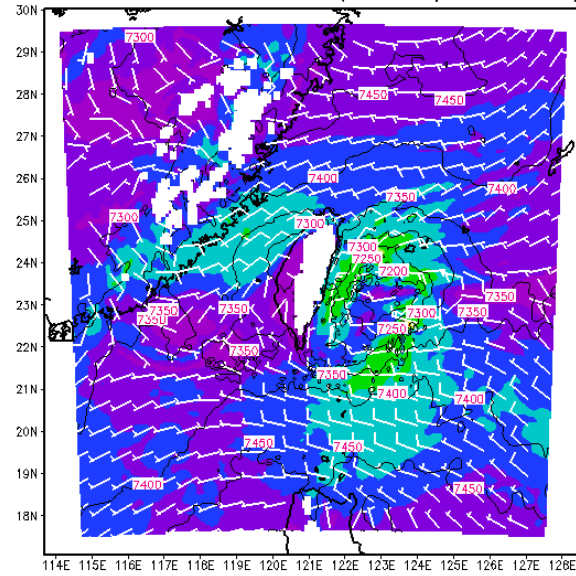
Model

2008061605Z 925hPa wind(m s⁻¹) and HGT(gpm)

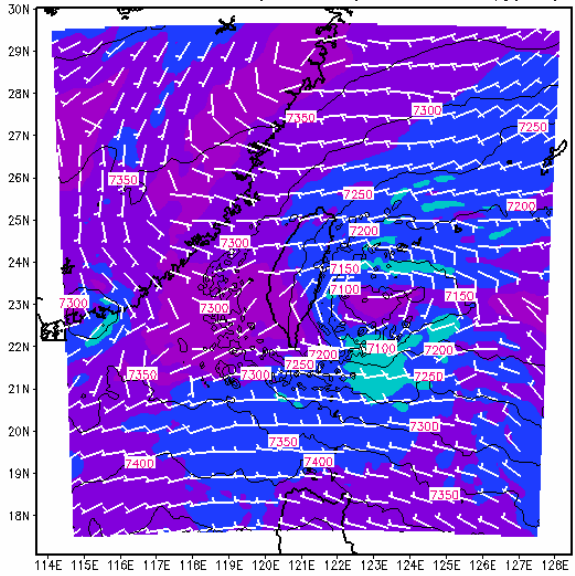
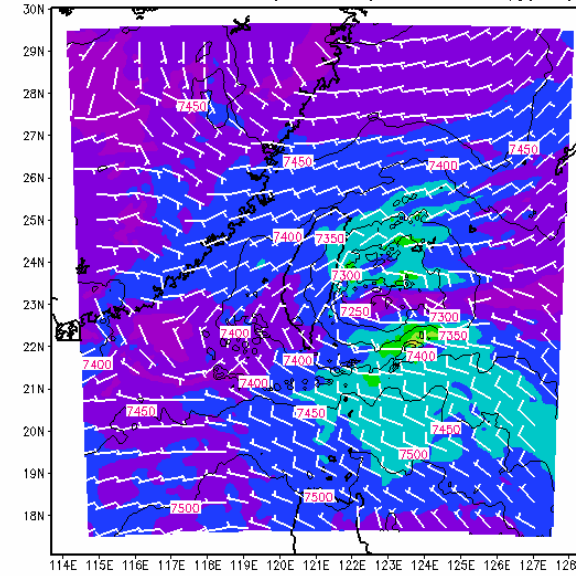


Effects of the CMR on the propagating Mei-Yu frontal cyclone w/wo terrain

2008053112Z 925hPa wind(m s⁻¹) and HGT(gf) 2008053118Z 925hPa wind(m s⁻¹) and HGT(gpm)

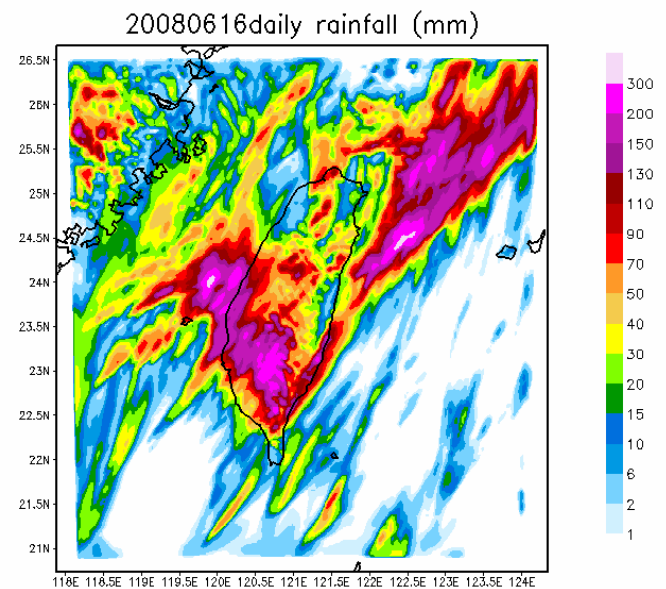
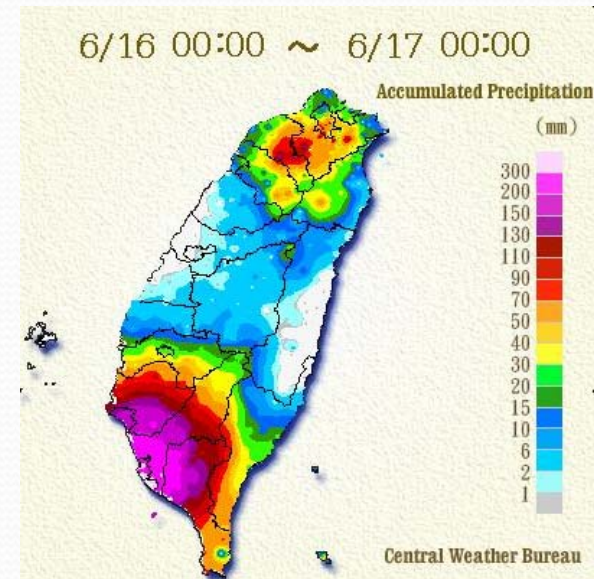


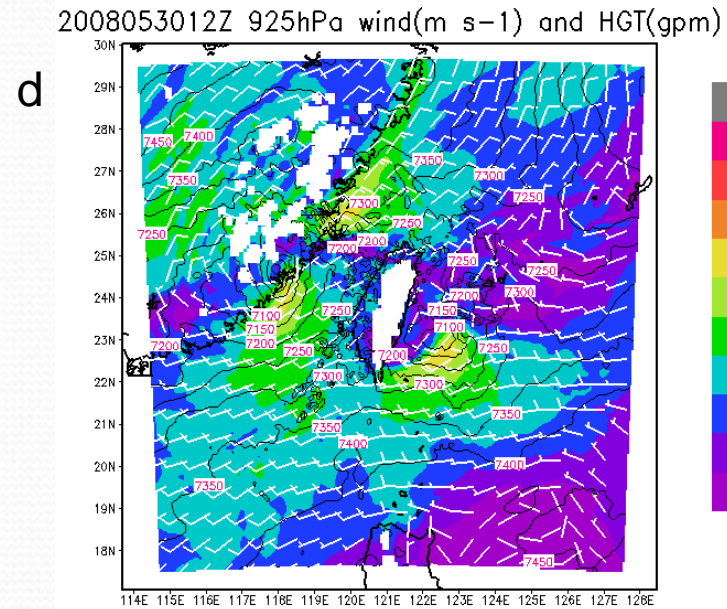
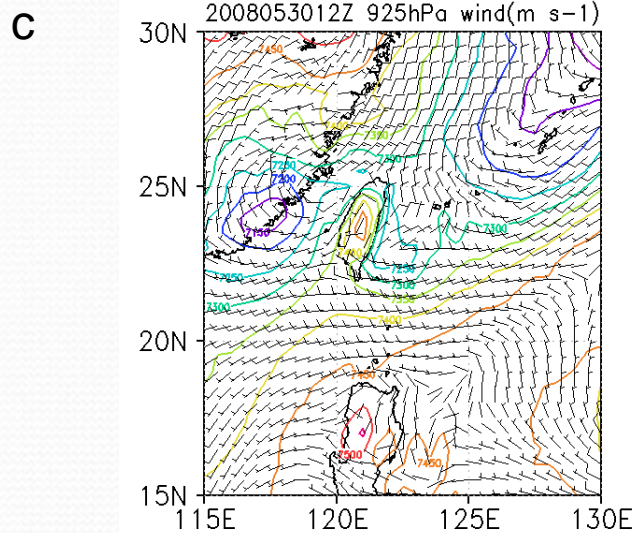
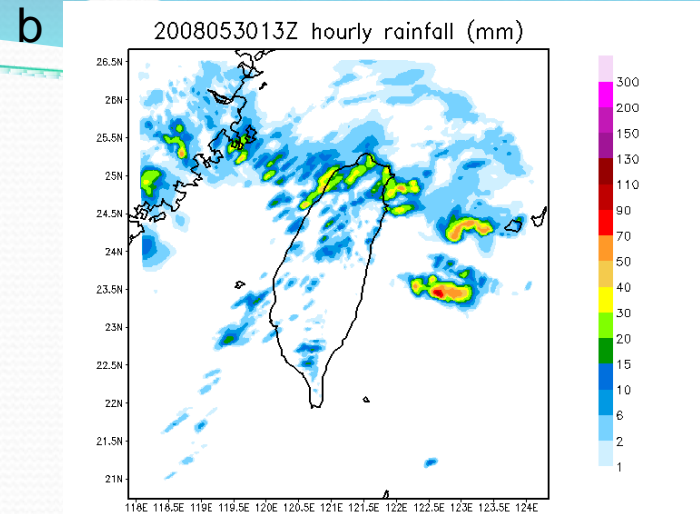
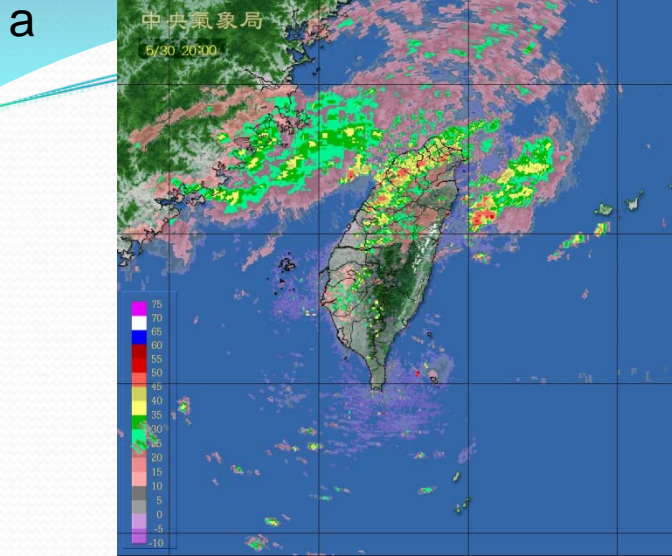
053112Z 925hPa wind(m s⁻¹) and HGT(gpm) 053118Z 925hPa wind(m s⁻¹) and HGT(gpm) w/o terrain



Part II:

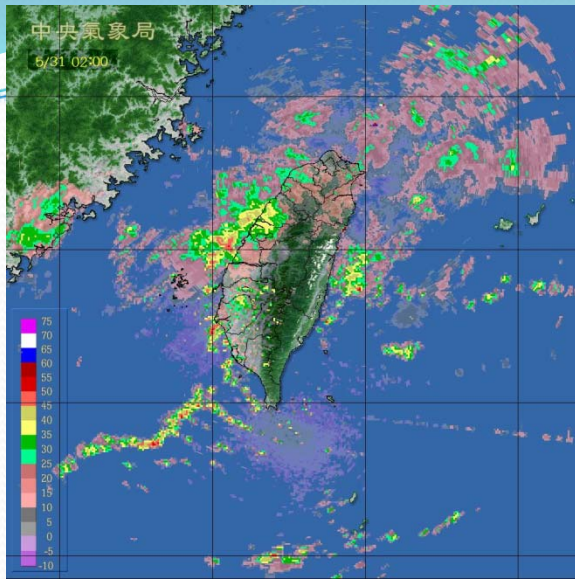
- 6/16 afternoon heavy rainfall at the coast regions without afternoon showers over southwestern mountain range
- Thunderstorm activity in Taipei



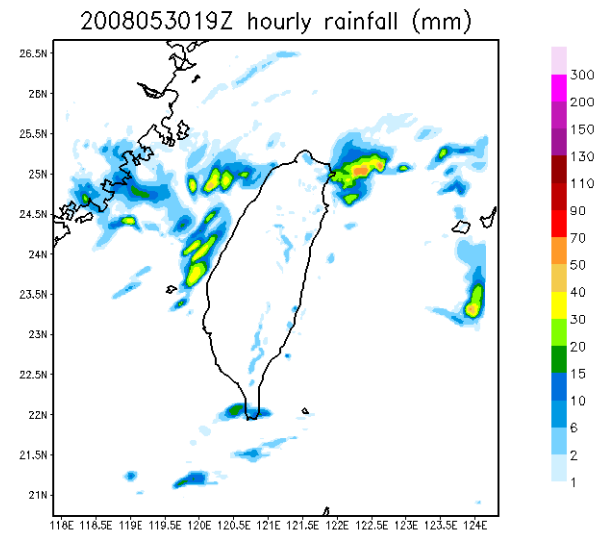


(a) 1200-1300 UTC lightning, (b) mosaic radar images at 1200 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio ($kg kg^{-1}$, shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is $10 m s^{-1}$ with wind speed shaded) and geopotential height (gpm, contoured) at 1200 UTC using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast with a 9-km horizontal resolution).

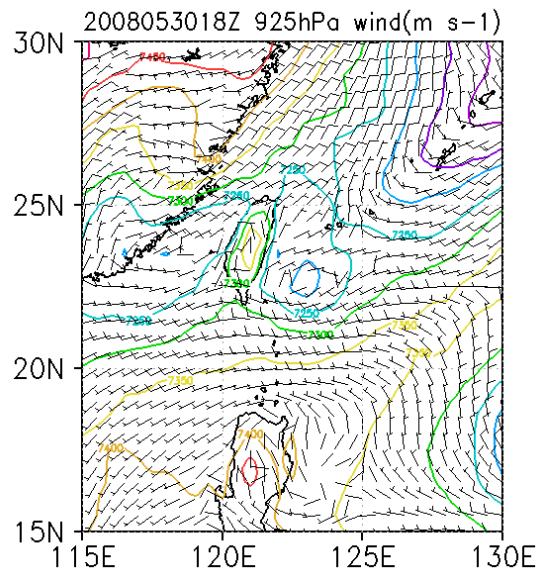
a



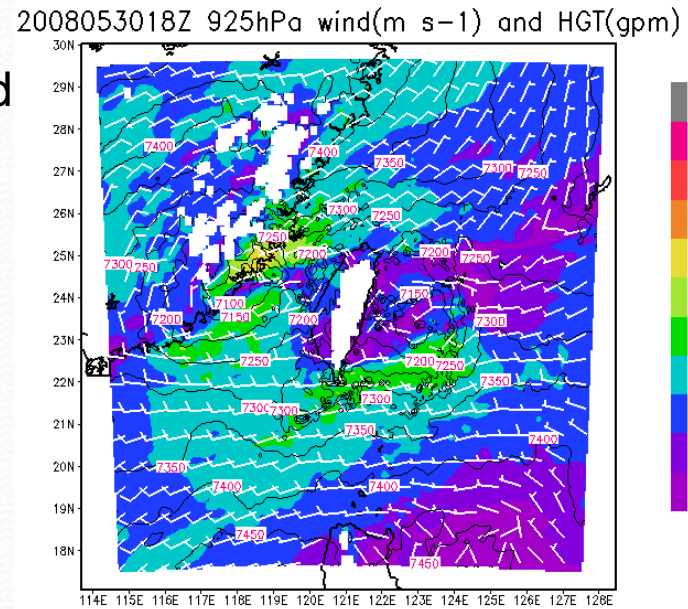
b



c

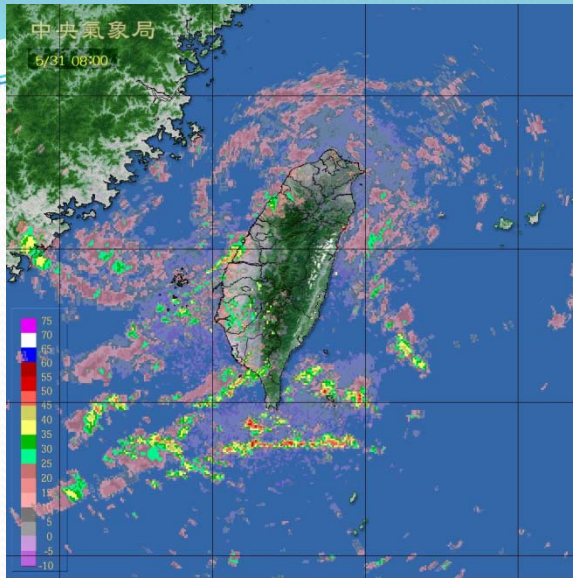


d

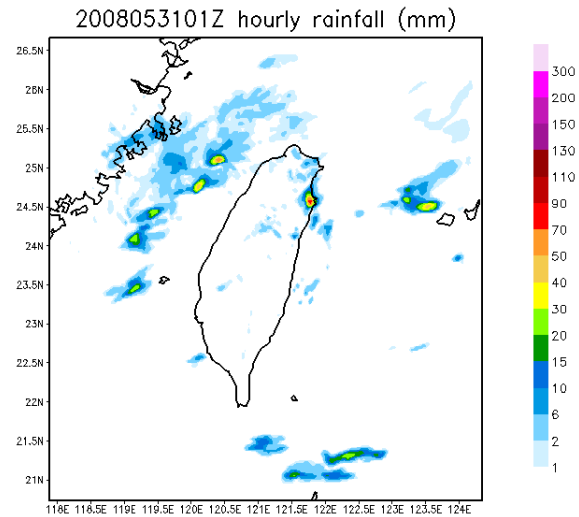


(a) 1800-1900 UTC lightning, (b) mosaic radar images at 1800 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC using FNL 1 deg resolution data as initial and boundary conditions (18-h forecast with a 9-km horizontal resolution).

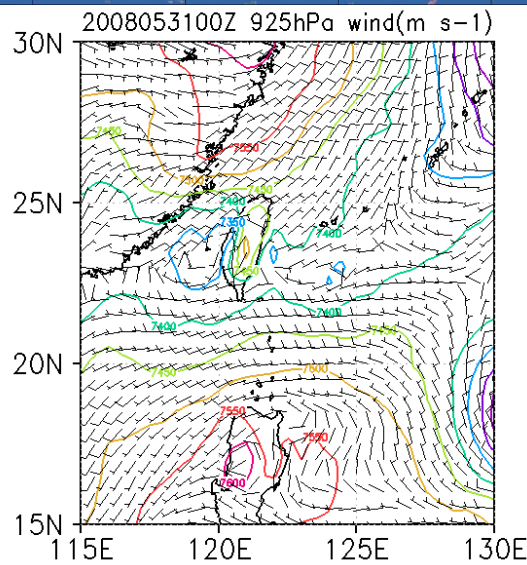
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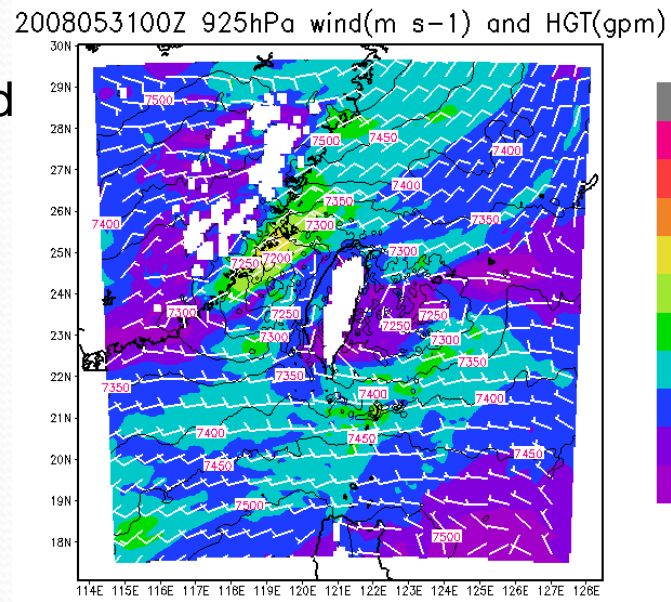
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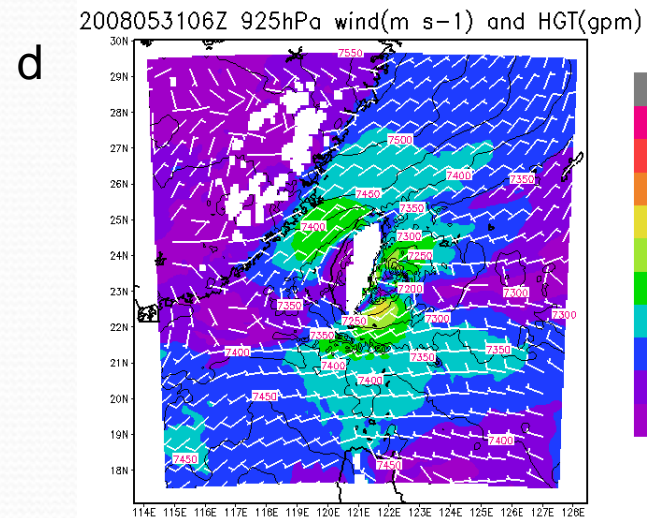
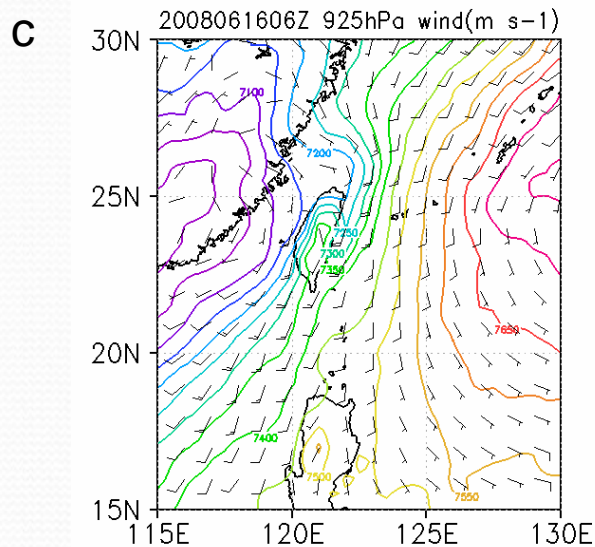
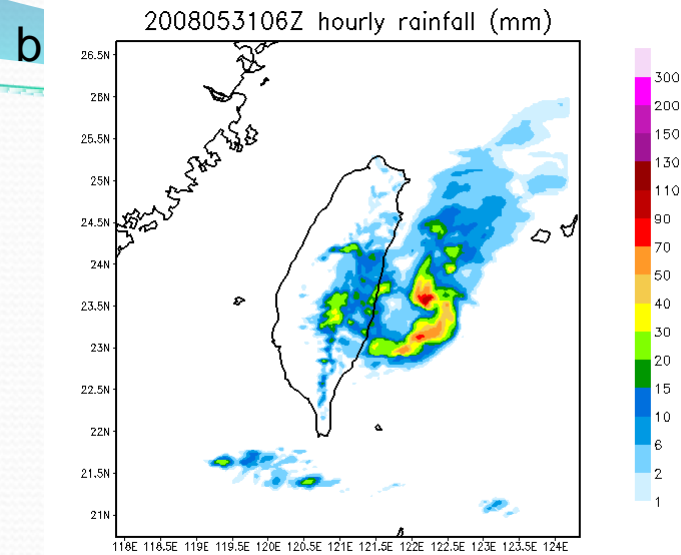
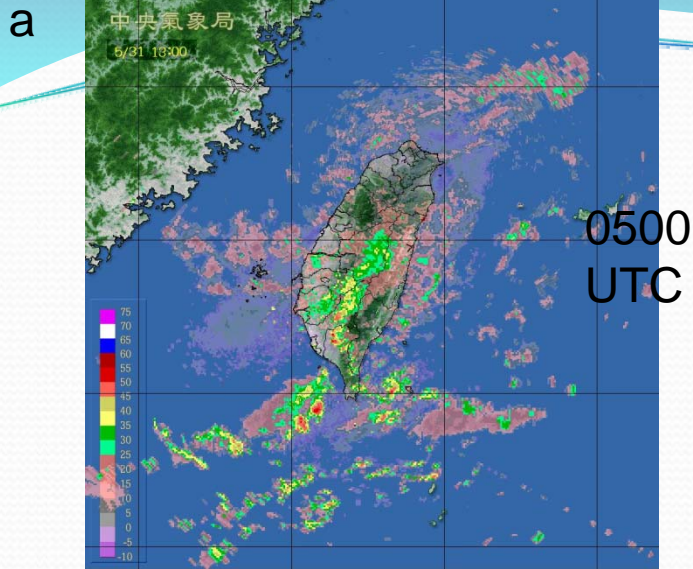
c



d



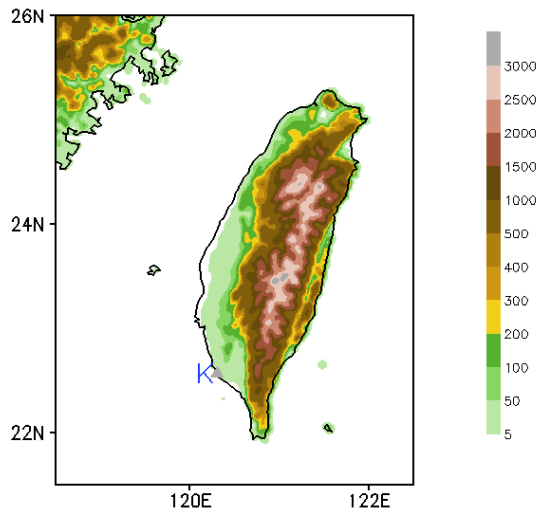
(a) 1800-1900 UTC lightning, (b) mosaic radar images at 1800 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC using FNL 1 deg resolution data as initial and boundary conditions (18-h forecast with a 9-km horizontal resolution).



(a) 1800-1900 UTC lightning, (b) mosaic radar images at 1800 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC using FNL 1 deg resolution data as initial and boundary conditions (18-h forecast with a 9-km horizontal resolution).

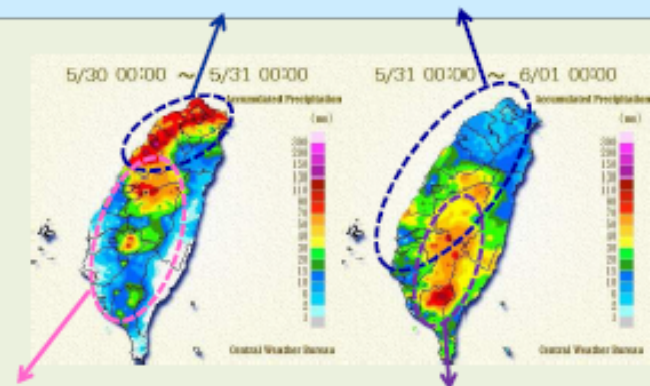
Part I

- A Mei-Yu front & frontal cyclone pass through Taiwan



I. The island/orographic effects on the complex Mei-Yu jet/front system and rainfall distribution during the South-West Monsoon Experiment (SoWMEX)/Terrain-induced Rainfall Experiment (TIMREX) Intensive Observing Period (IOP) #3 in 2008.

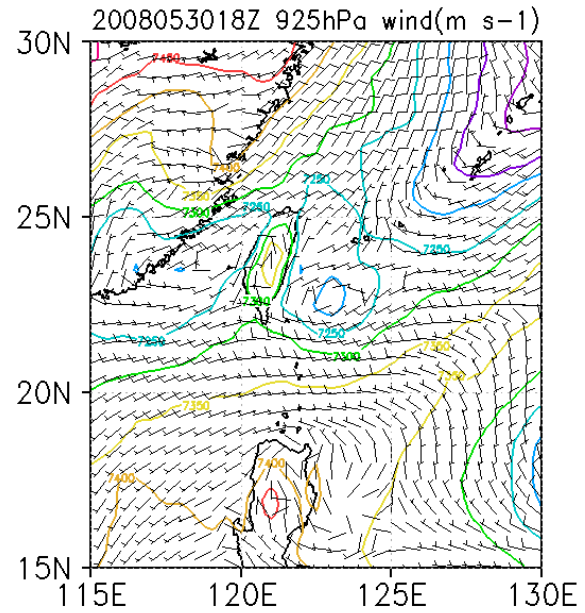
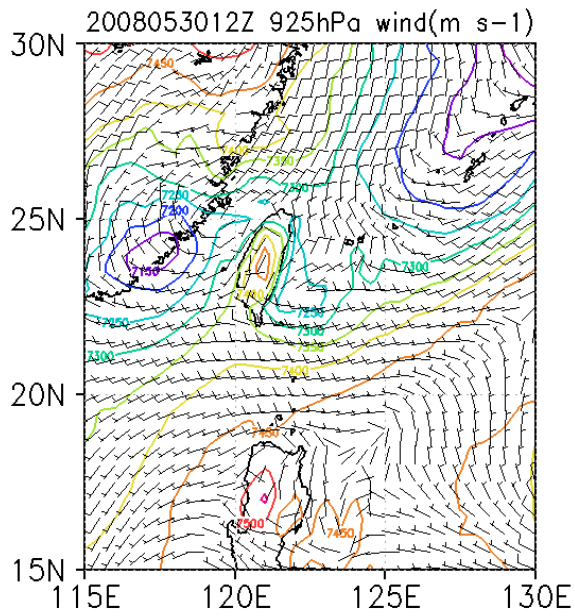
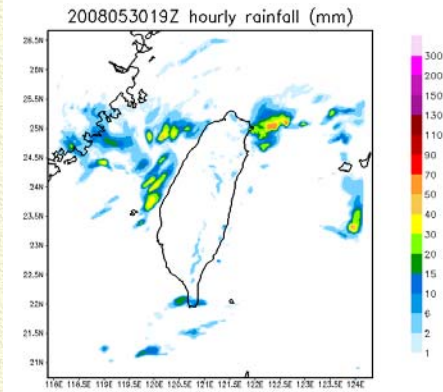
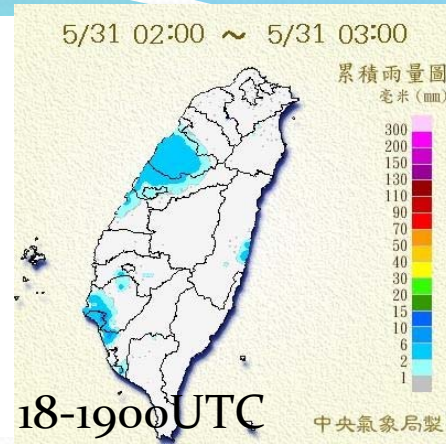
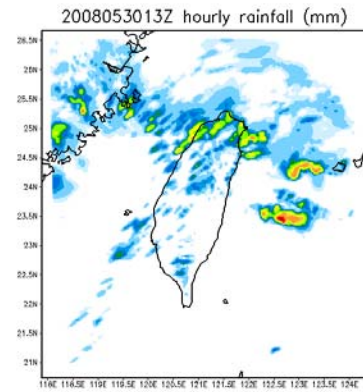
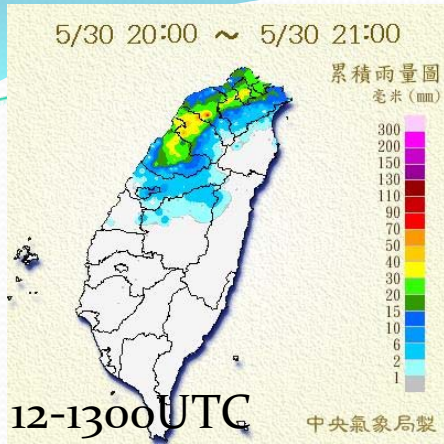
2) 5/30 1800-5/31 1400 (LST), an enhanced NE-SW orientated Mei-Yu frontal convection line northwest of Taiwan moved onshore over northwestern Taiwan and then propagated southward producing heavy rainfall over northwestern Taiwan



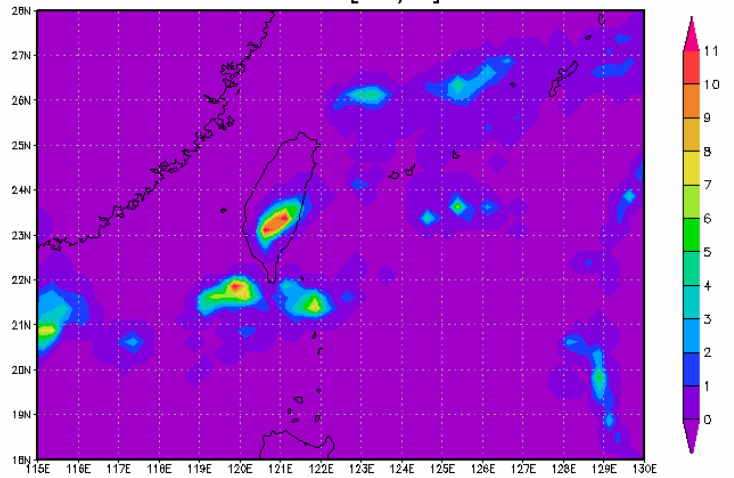
1) 5/30 0900-1800 (LST), in the prefrontal SW flow regime, the convection cells are enhanced by the terrain. Orographic lifting of the prefrontal SW flow and a sea breeze contributed to heavy rainfall over the western Central Mountain Range.

3) 5/31 1400-2000, after the passage of the Mei-Yu front over the Taiwan Strait at the surface, the Mei-Yu frontal cyclone moved eastward across the Central Mountain Range. Orographic lifting of the convective cells by the SW flow ahead of the cyclone, combined with sea breezes, brought in heavy rainfall on the SW slopes of the mountains.

Figure 1. Daily rainfall accumulation (mm) over Taiwan on 30 and 31 May, 2008 (LST) (Courtesy of Central Weather Bureau).



3-hourly TRMM 3B42(v6) 06Z31May2008
Rain Rate [mm/hr]

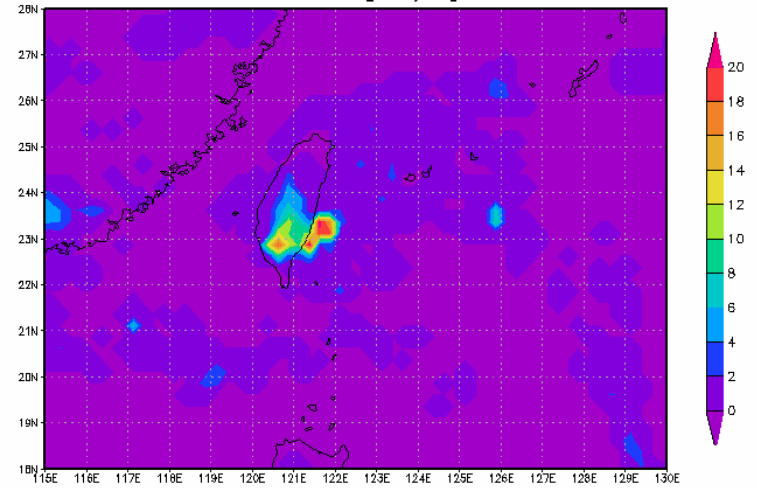


GRADS: ODLA/10ES

2010-10-28-09:13

Generated by NASA's Giovanni (giovanni.gsfc.nasa.gov)

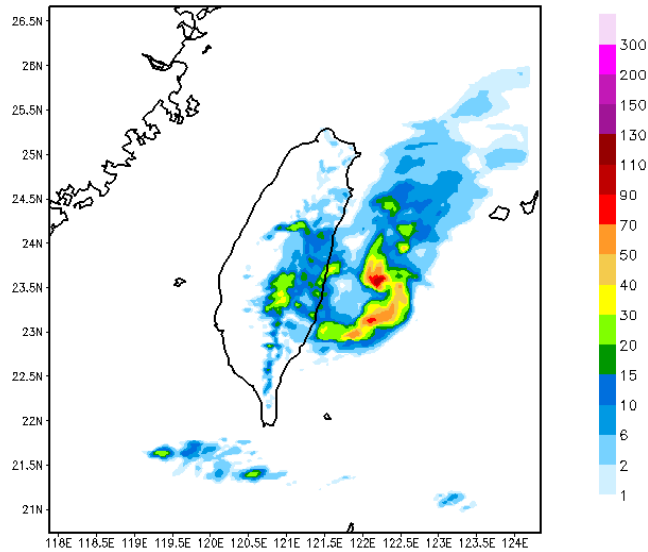
3-hourly TRMM 3B42(v6) 09Z31May2008
Rain Rate [mm/hr]



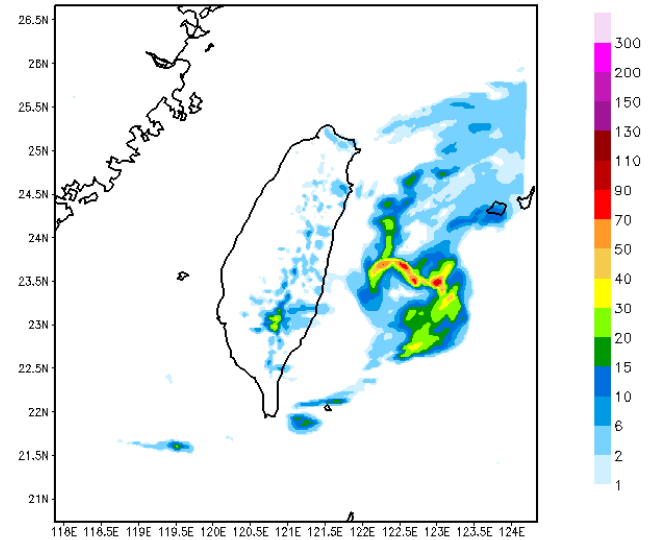
GRADS: ODLA/10ES

2010-10-28-09:13

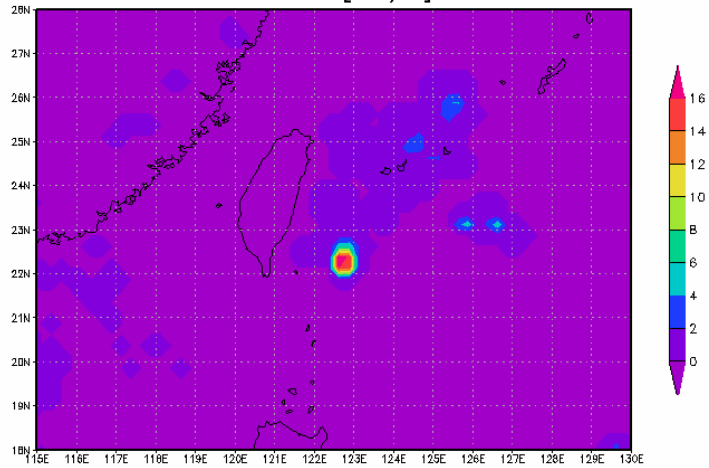
2008053106Z hourly rainfall (mm)



2008053109Z hourly rainfall (mm)



3-hourly TRMM 3B42(V6) 12Z31May2008
Rain Rate [mm/hr]

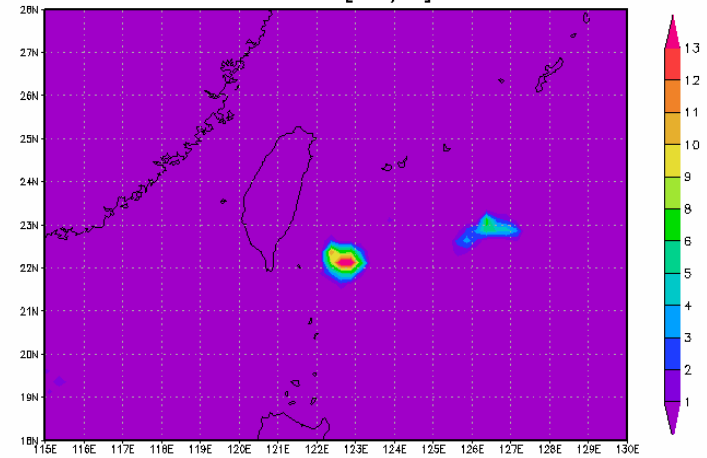


GRADS: ODLA/IGES

Generated by NASA's Giovanni (giovanni.gsfc.nasa.gov)

2010-10-28-09:14

3-hourly TRMM 3B42(V6) 15Z31May2008
Rain Rate [mm/hr]

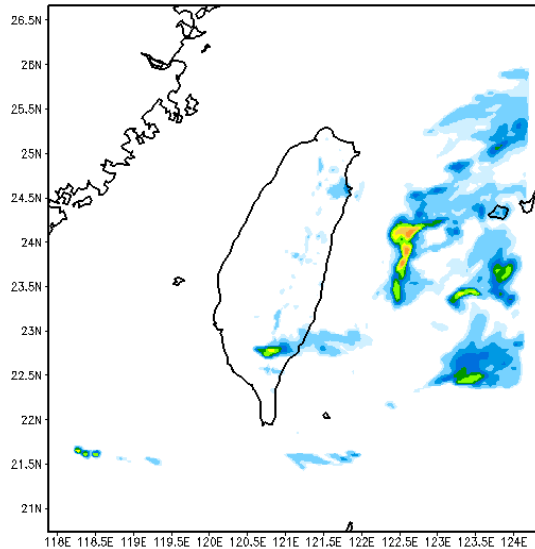


GRADS: ODLA/IGES

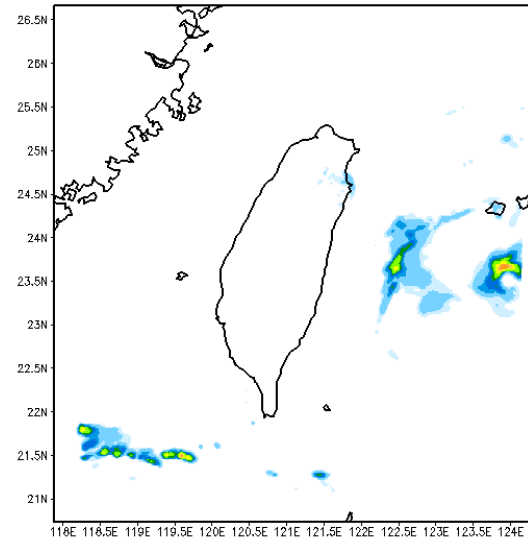
Generated by NASA's Giovanni (giovanni.gsfc.nasa.gov)

2010-10-28-09:15

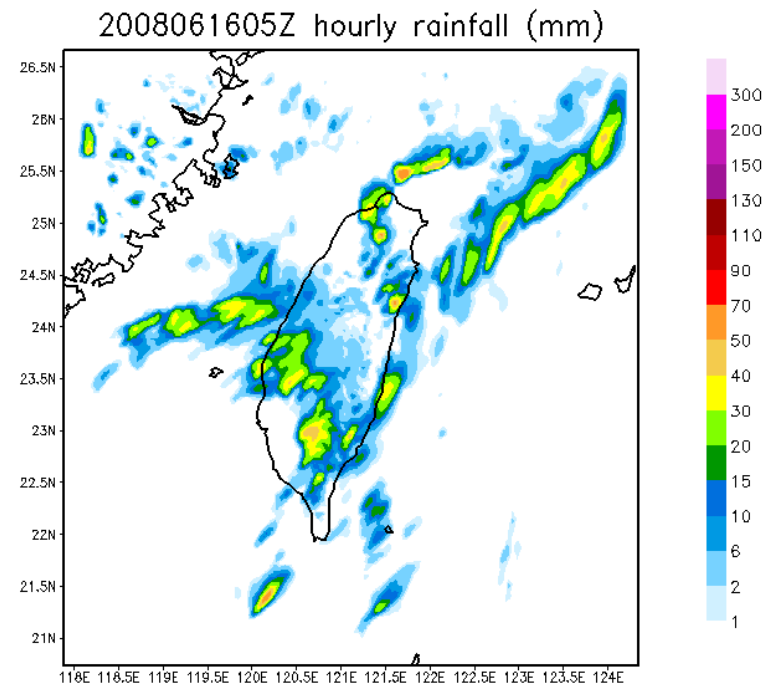
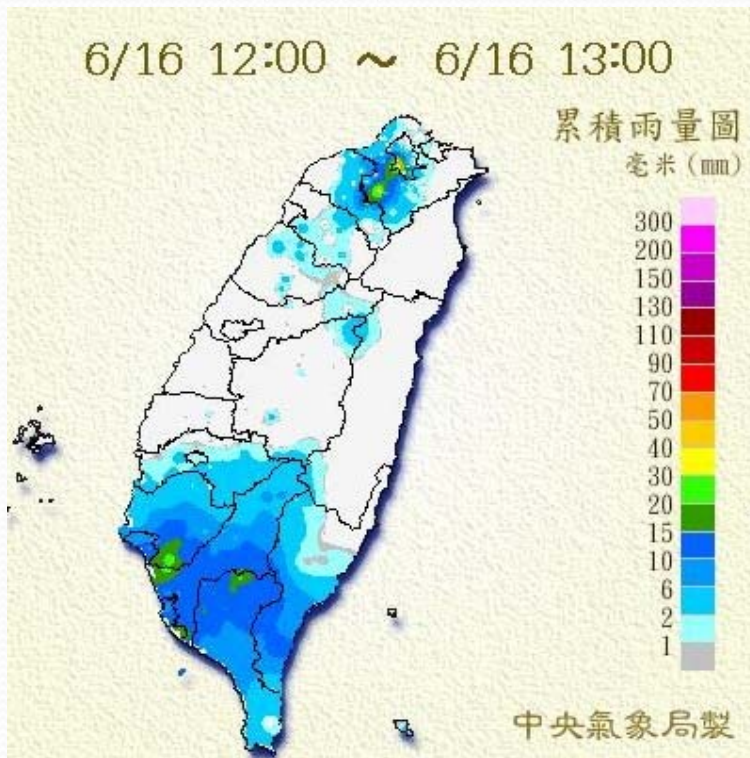
2008053112Z hourly rainfall (mm)



2008053115Z hourly rainfall (mm)

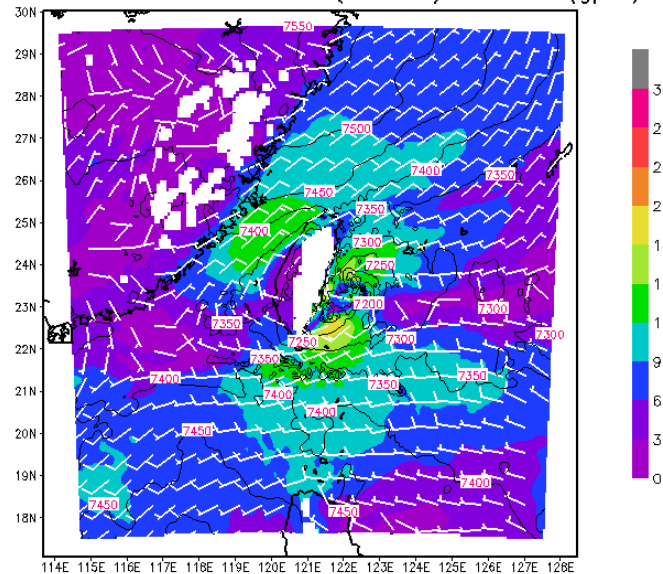


Thunderstorm in the wake

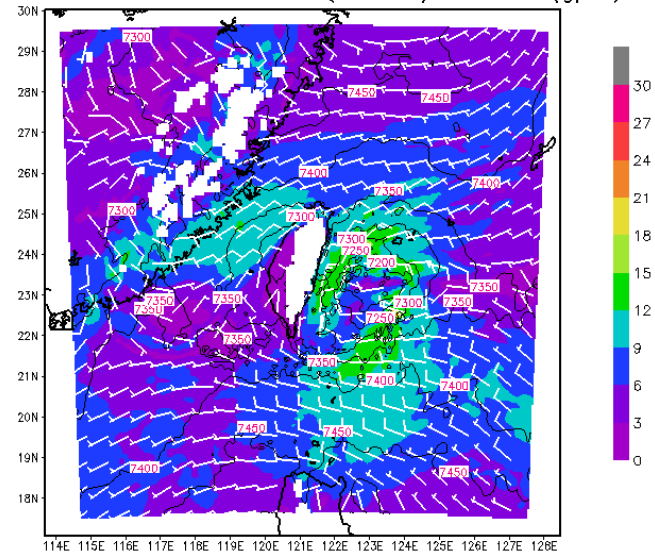


Effects of the CMR on the propagating Mei-Yu frontal cyclone

2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)



2008053112Z 925hPa wind(m s⁻¹) and HGT(gpm)

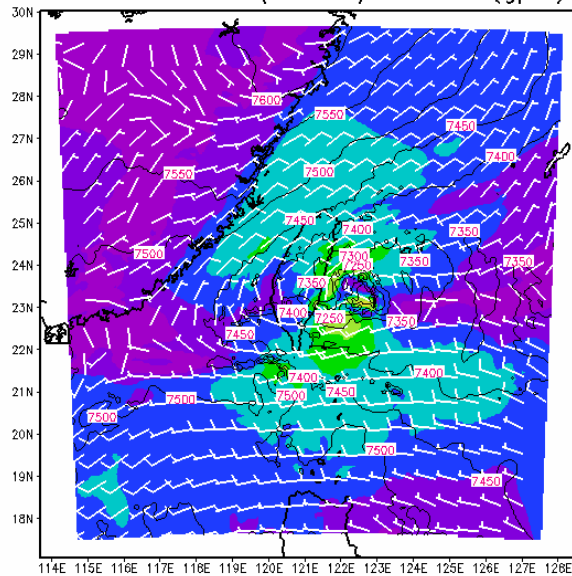


At 0600 UTC (1400LT), the frontal cyclone advanced CMR

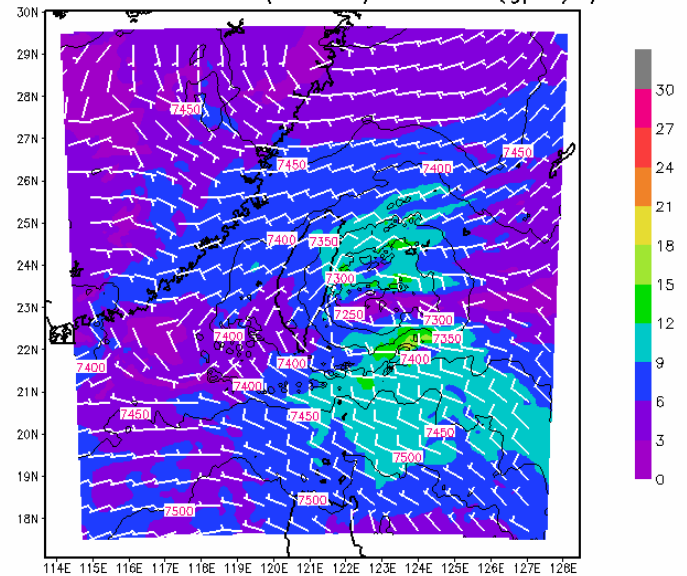
The MCS, along with the frontal cyclone, moved SE advanced CMR causing afternoon thunderstorm activity over the southern portion of the CMR.

Effects of the CMR on the propagating Mei-Yu frontal cyclone

2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain

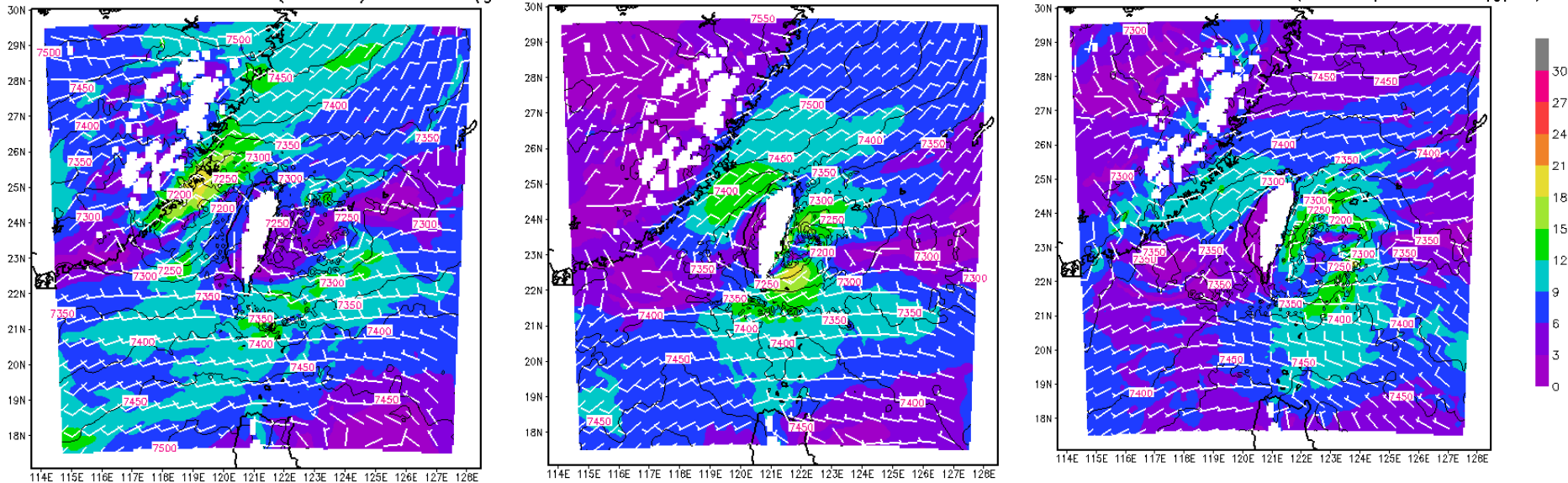


2008053112Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain



Effects of the CMR on the propagating Mei-Yu frontal cyclone

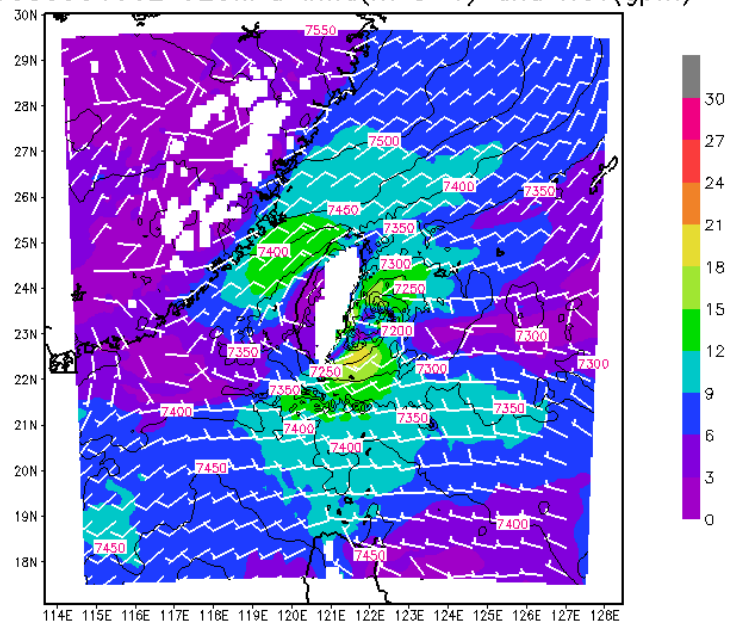
2008053023Z 925hPa wind(m s⁻¹) and HGT(g) 2008053106Z 925hPa wind(m s⁻¹) and HGT(g) 2008053112Z 925hPa wind(m s⁻¹) and HGT(gpm)



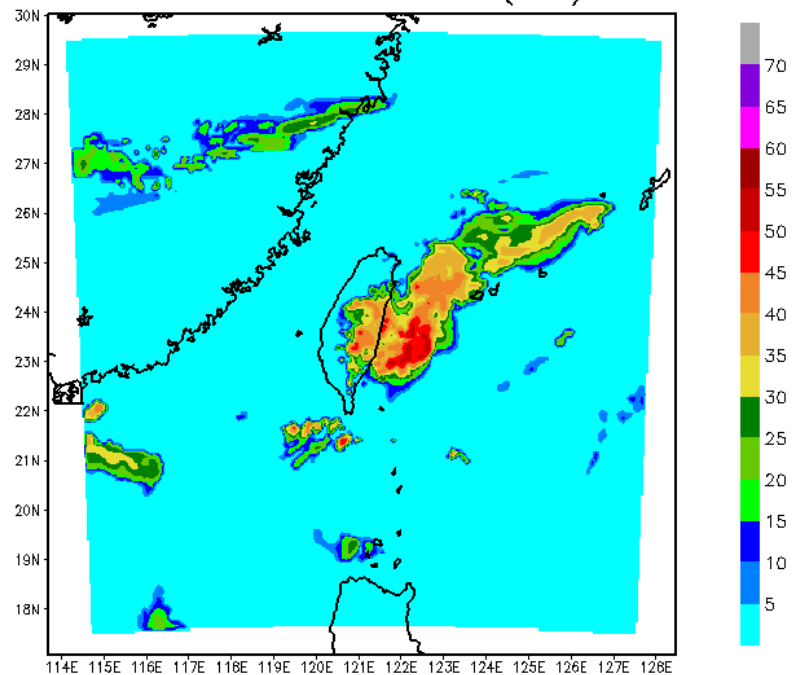
At 0600 UTC (1400LT), the frontal cyclone advanced CMR

The MCS, along with the frontal cyclone, moved SE advanced CMR causing afternoon thunderstorm activity over the southern portion of the CMR.

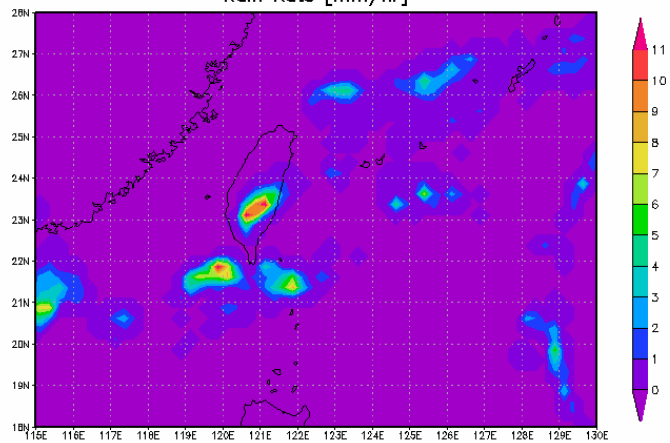
2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)



2008053106Z max ref (dBZ)

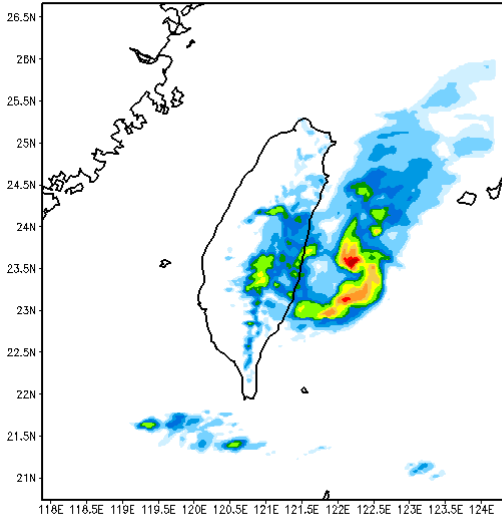


3-hourly TRMM 3B42(v6) 06Z31May2008
Rain Rate [mm/hr]

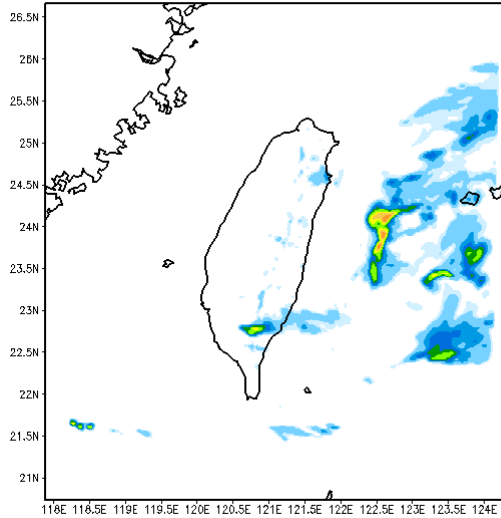


Rainfall ? Ref?

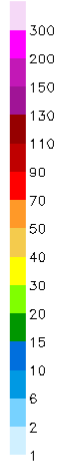
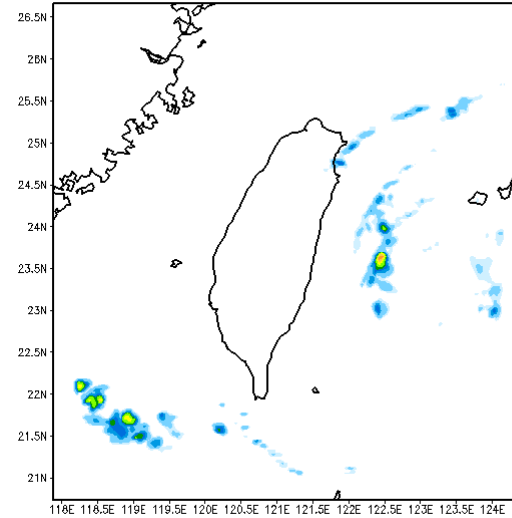
2008053106Z hourly rainfall (mm)



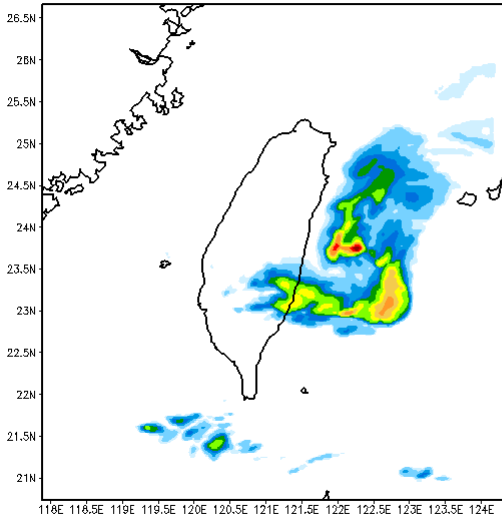
2008053112Z hourly rainfall (mm)



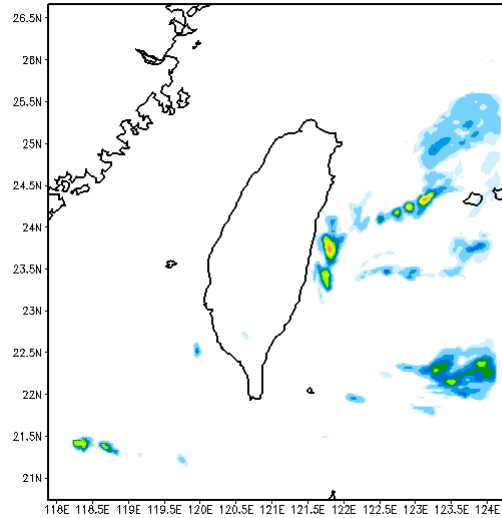
2008053118Z hourly rainfall (mm)



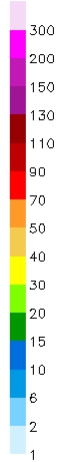
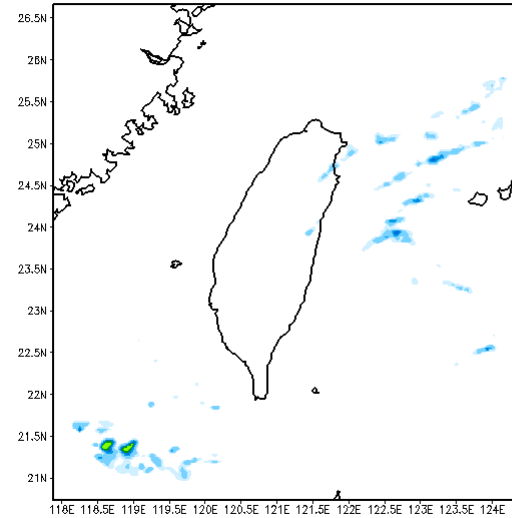
2008053106Z hourly rainfall (mm)



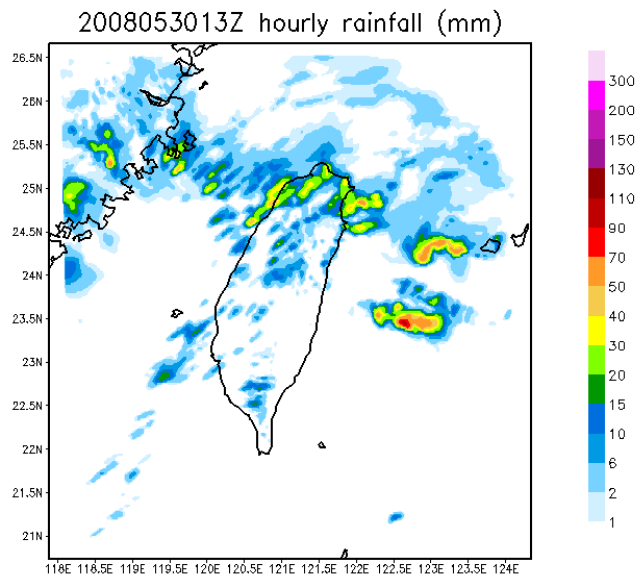
2008053112Z hourly rainfall (mm)



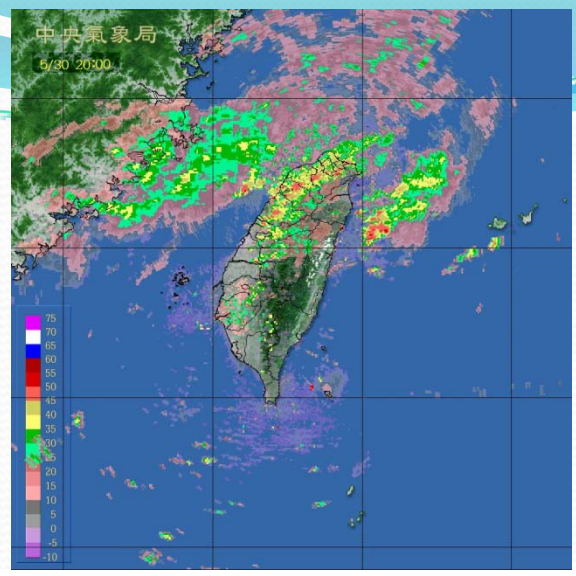
2008053118Z hourly rainfall (mm)



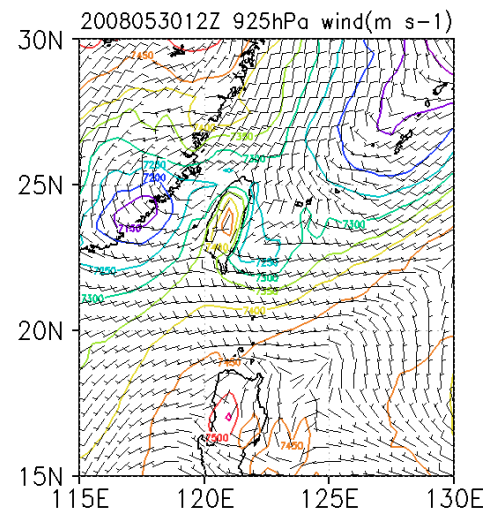
a



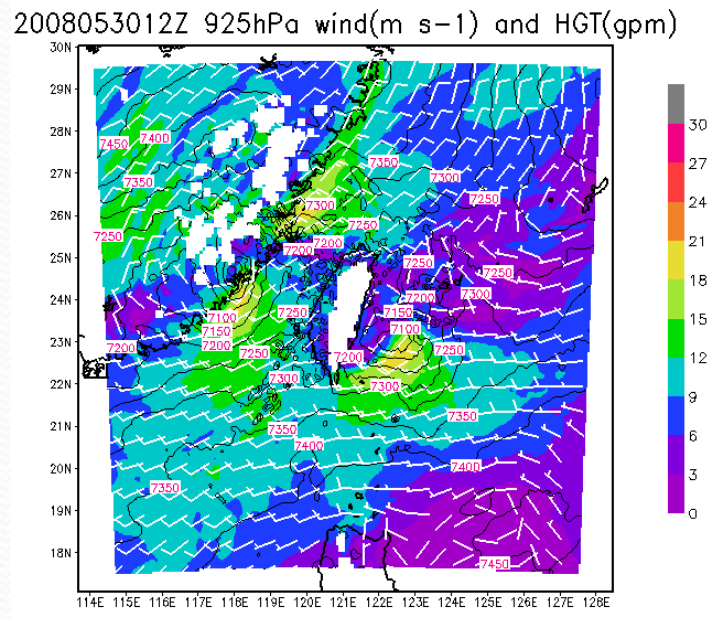
b



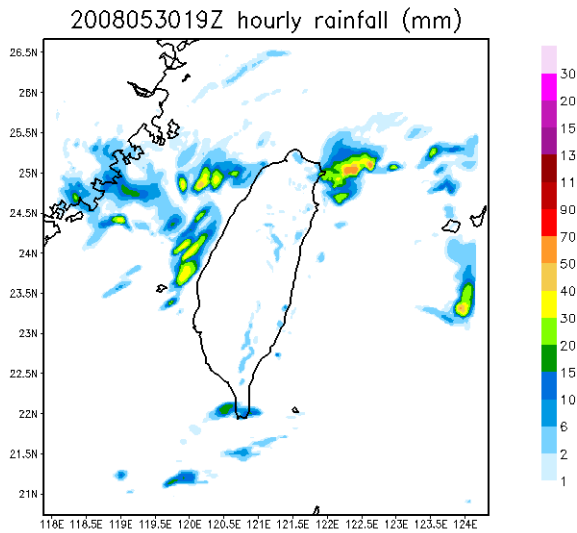
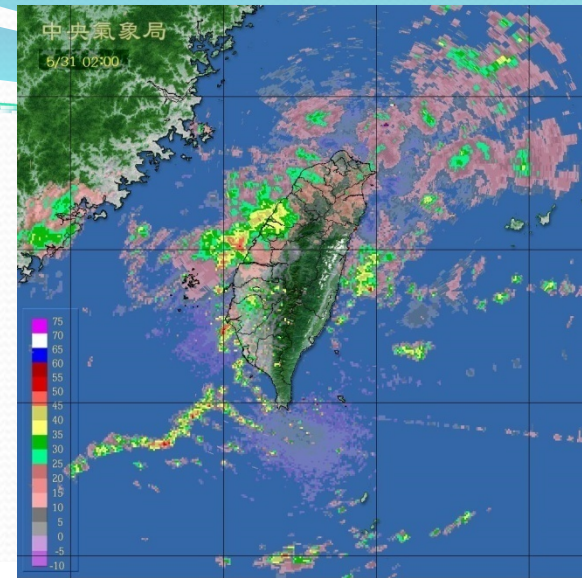
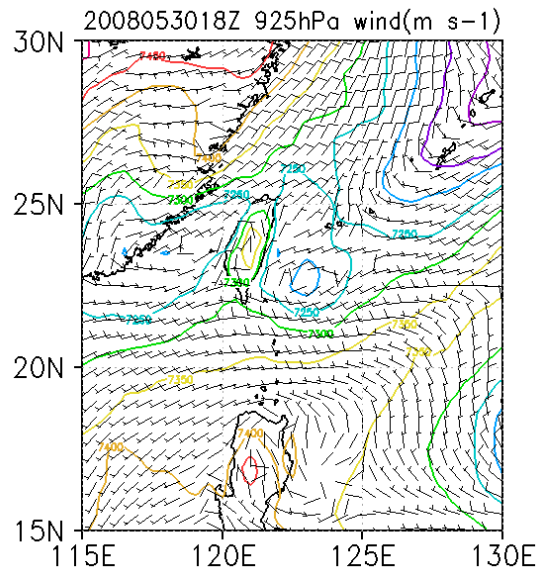
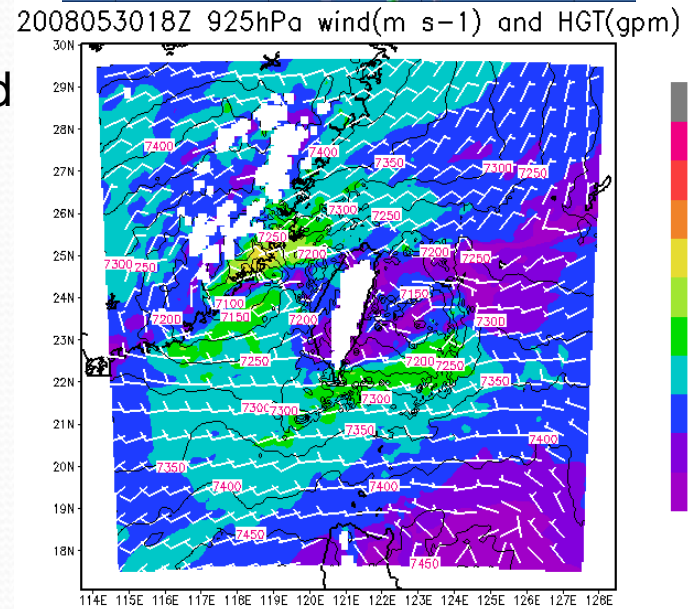
c



d

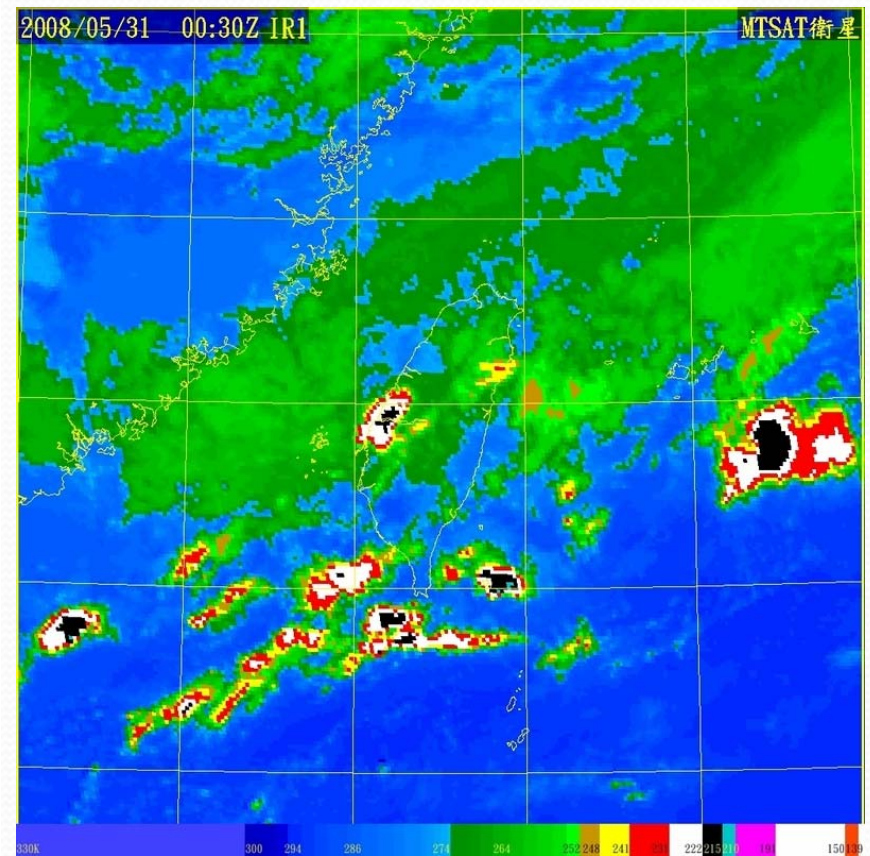
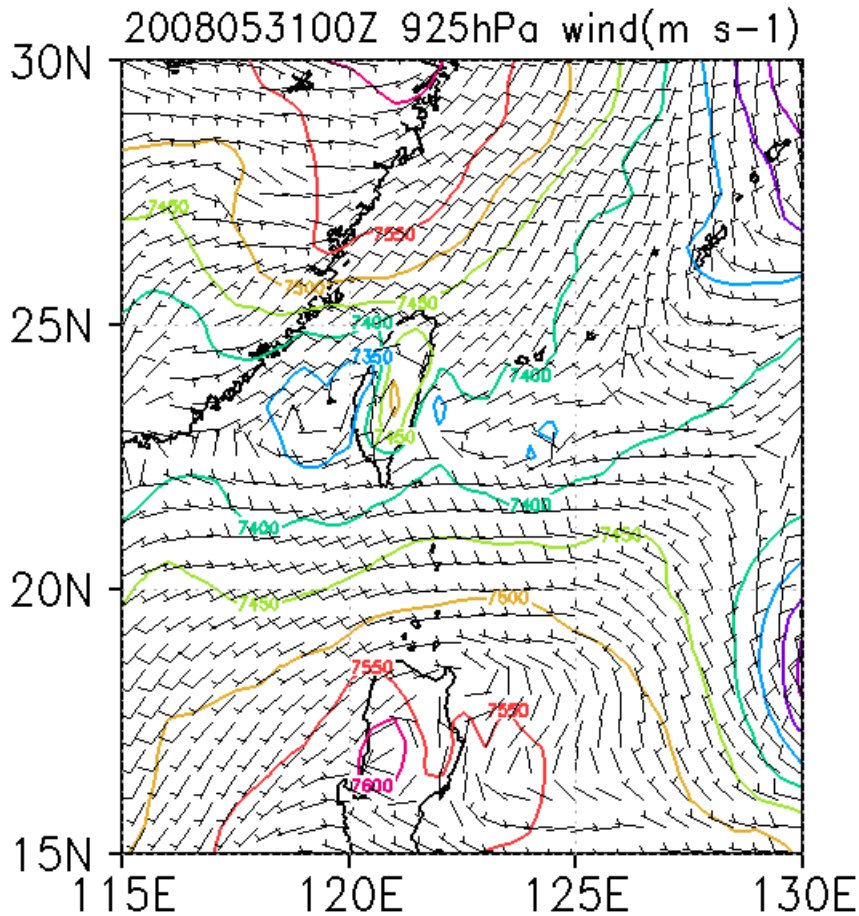


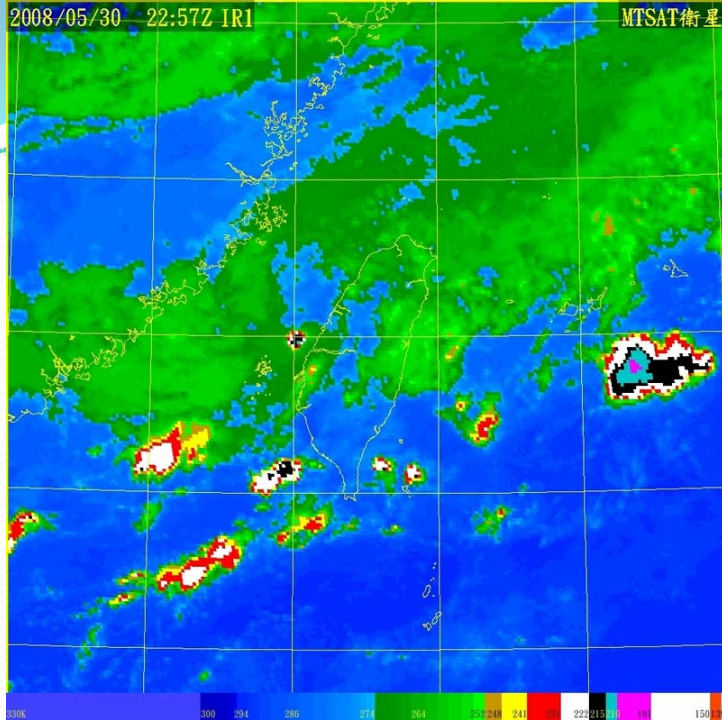
(a) 1200-1300 UTC lightning, (b) mosaic radar images at 1200 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) at 1200 UTC using FNL 1 deg resolution data as initial and boundary conditions (12-h forecast with a 9-km horizontal resolution).

a**b****c****d**

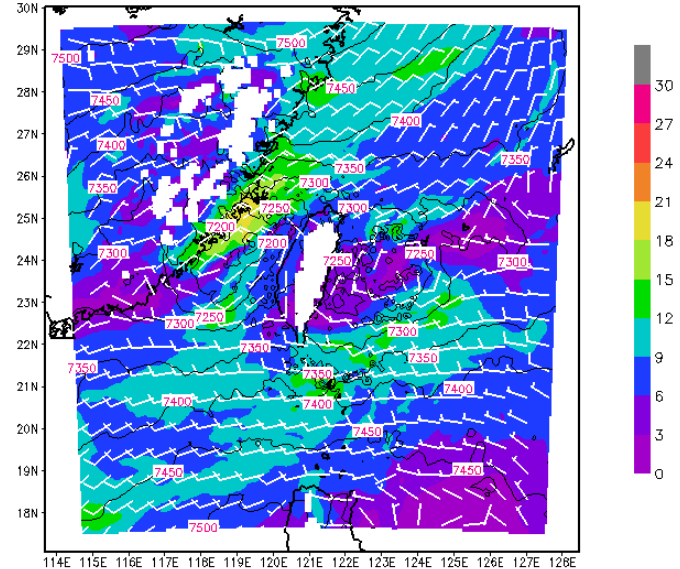
(a) 1800-1900 UTC lightning, (b) mosaic radar images at 1800 UTC (Courtesy of Central Weather Bureau), (c) WRF model simulated 925-hPa water vapor mixing ratio (kg kg^{-1} , shaded) and theta (K, contoured) and (d) 925-hPa winds (barbs, 1 full barb is 10 m s^{-1} with wind speed shaded) and geopotential height (gpm, contoured) at 1800 UTC using FNL 1 deg resolution data as initial and boundary conditions (18-h forecast with a 9-km horizontal resolution).

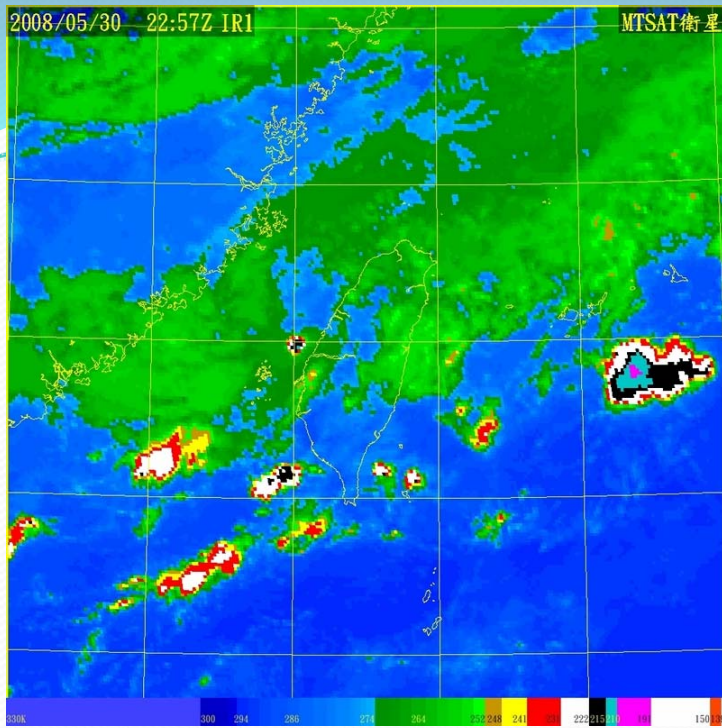
YOTC winds (m s^{-1}) and Geopotential ($\text{m}^2 \text{s}^{-2}$). (a) 925 hPa (b) 850hPa at 0000 UTC (0800 Local Time) 31 May. (Winds: Full barb, half barb represent 10 and 5 m s^{-1} , respectively).



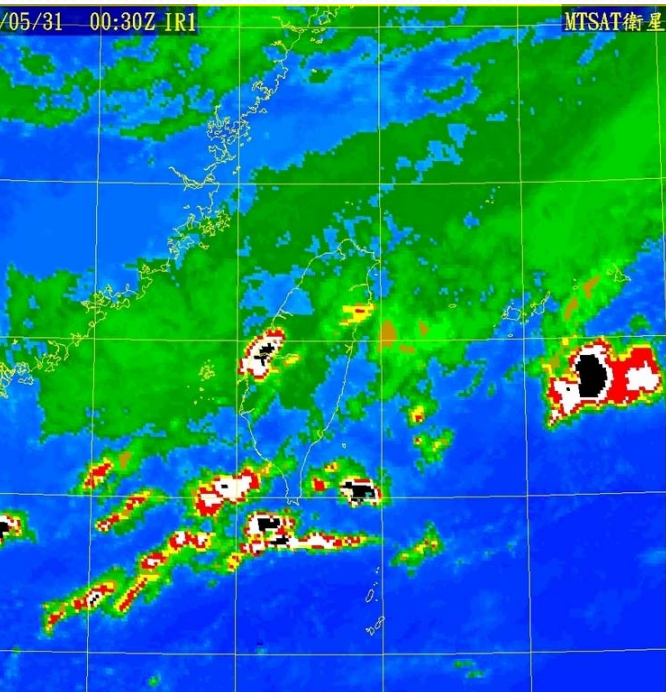
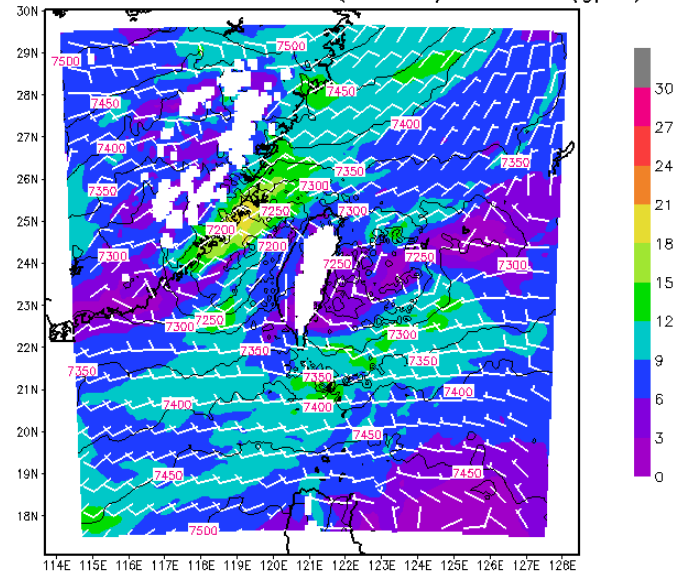


2008053023Z 925hPa wind(m s⁻¹) and HGT(gpm)

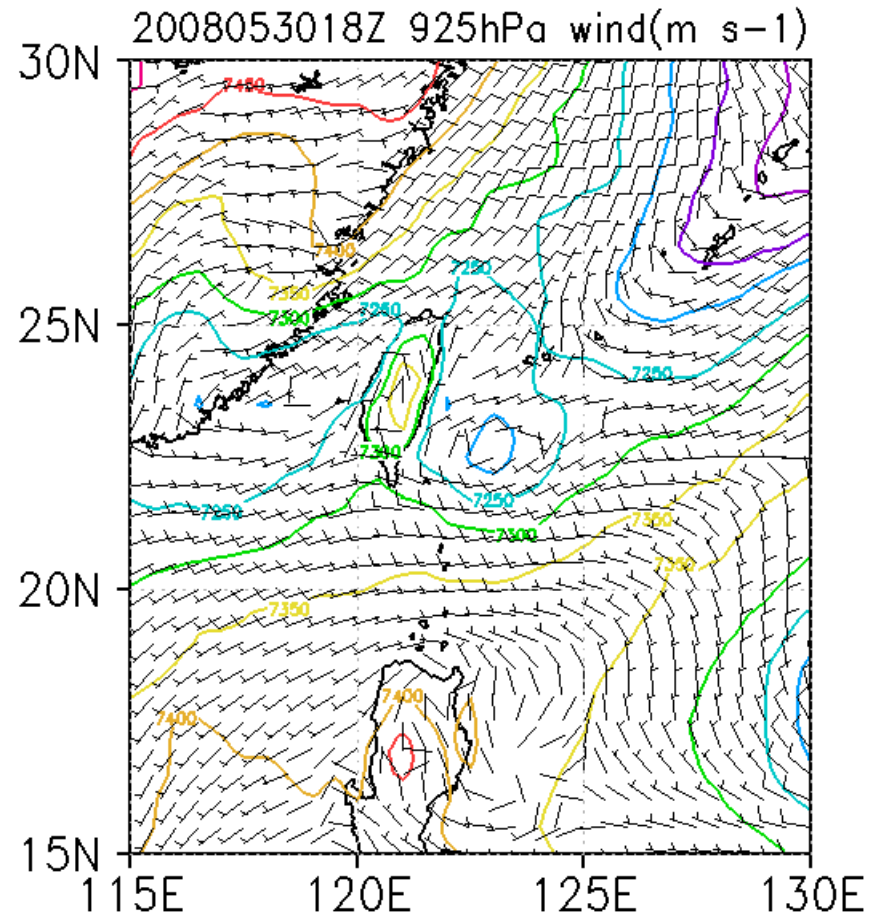
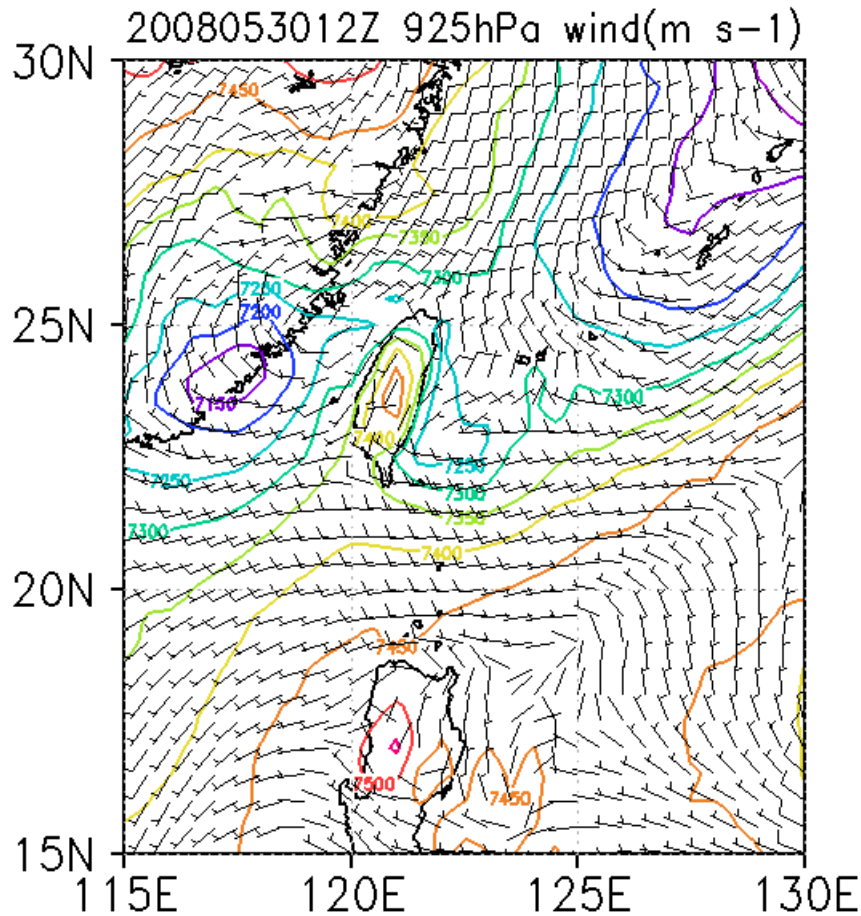




2008053023Z 925hPa wind(m s⁻¹) and HGT(gpm)



YOTC winds (m s^{-1}) and Geopotential ($\text{m}^2 \text{s}^{-2}$). 925 hPa at (a) 1200 UTC (2000 Local Time) 30 May, (b) 1800 UTC 30 May (0200 LT 31 May). (Winds: Full barb, half barb represent 10 and 5 m s^{-1} , respectively).

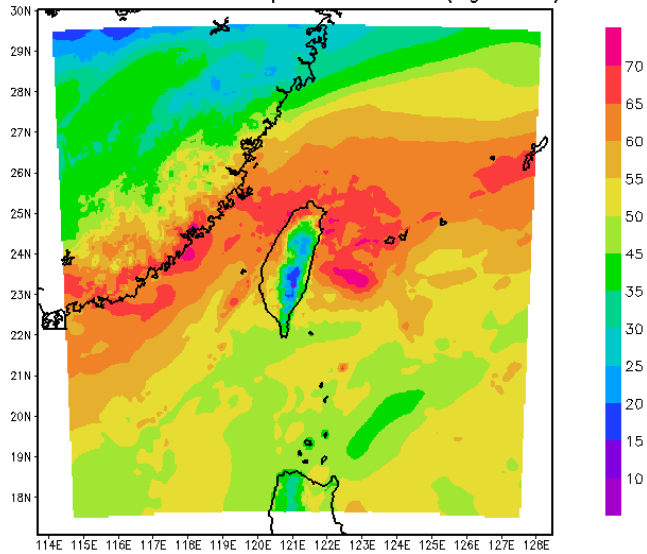


- A Mei-Yu frontal mesocyclone was over southeastern China. The NE-SW orientated Mei-Yu front associated with the frontal cyclone was off the northwestern Taiwan coast (Fig. 2d). The cold air behind the front over southeastern China was retarded by the hilly terrain along the coast but was advected southward along the coast by the strengthened northerly winds, similar to the cases presented by Chen and Hui (1990; 1992) (Figs. 2c-d).

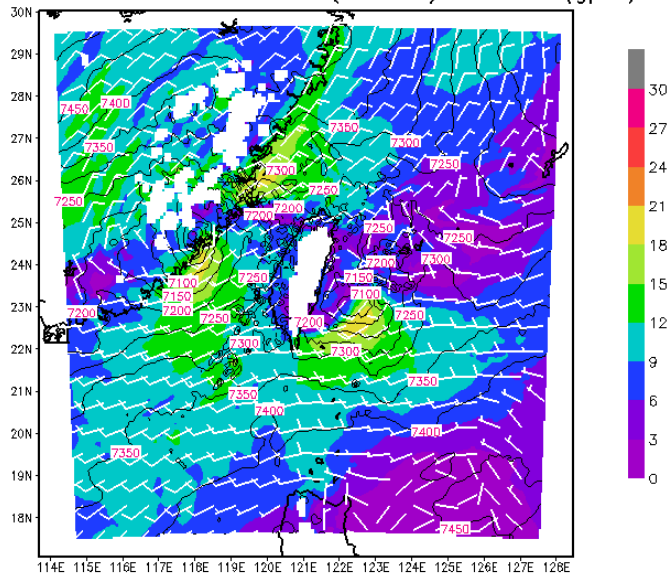
- Ahead of the Mei-Yu front, the prefrontal southwesterly (SW) flow over the Taiwan Strait was strengthened due to the presence of the frontal cyclone to the west and an orographically induced high to the east over southwestern Taiwan (Fig. 2d). The strengthened SW flow upstream of Taiwan was blocked and deflected by the orographically induced high with upstream flow splitting over southwestern Taiwan and relatively strong winds off the western coast (Li and Chen, 1998).

- The convergence along the Mei-Yu front was orographically enhanced by the strengthened SW flow ahead and NE flow behind the front with a well defined convective line (Fig. 2b). The convection line brought in heavy rainfall and lightning activity (Fig. 2a) to northwestern Taiwan as it advanced southward and moved inland.

2008053012Z Precipitable water (kg m⁻²)

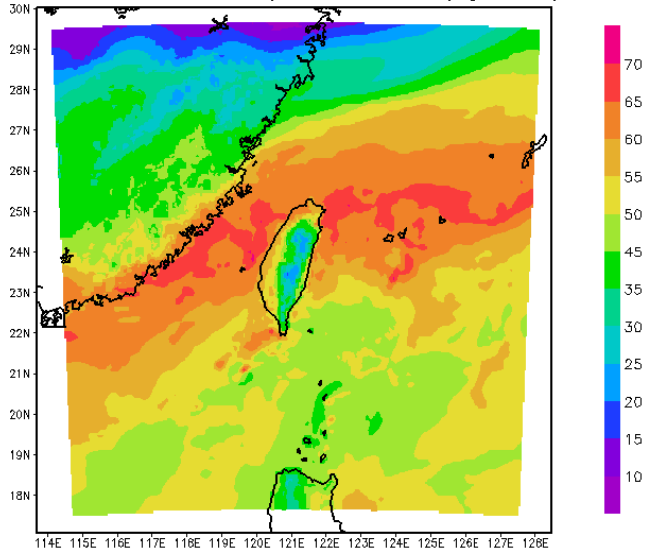


2008053012Z 925hPa wind(m s⁻¹) and HGT(gpm)

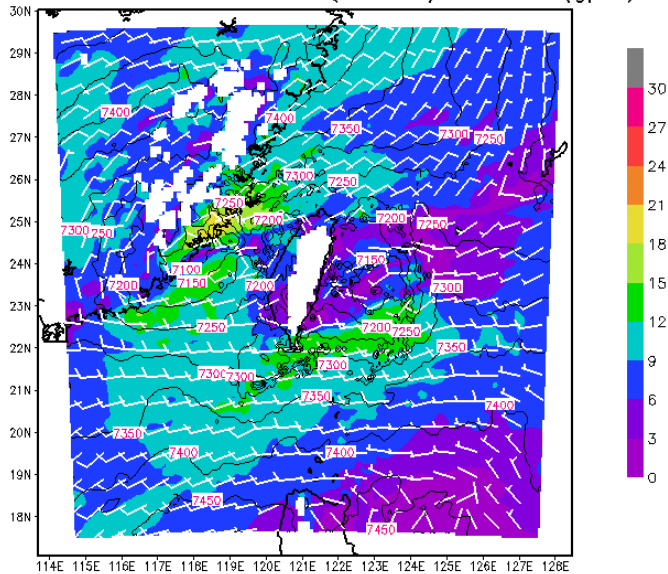


5/30 1800UTC

2008053018Z Precipitable water (kg m^{-2})



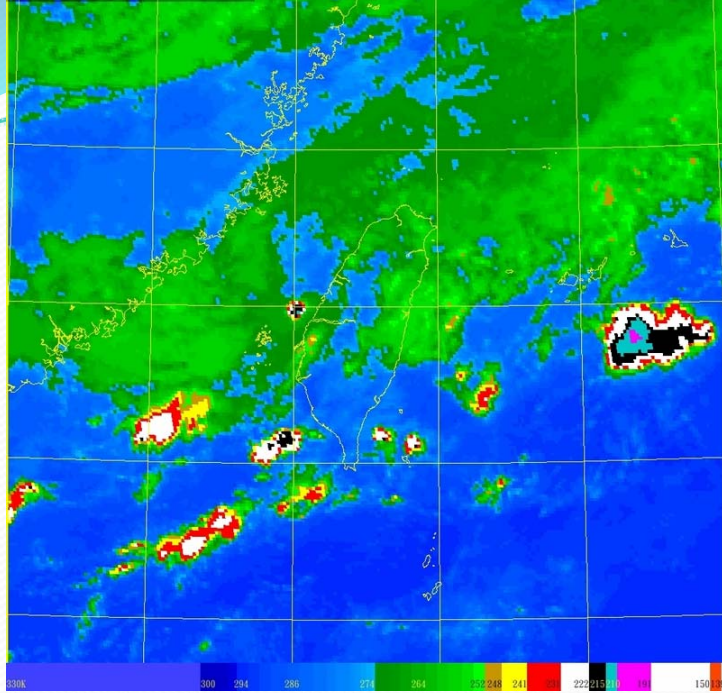
2008053018Z 925hPa wind (m s^{-1}) and HGT (gpm)



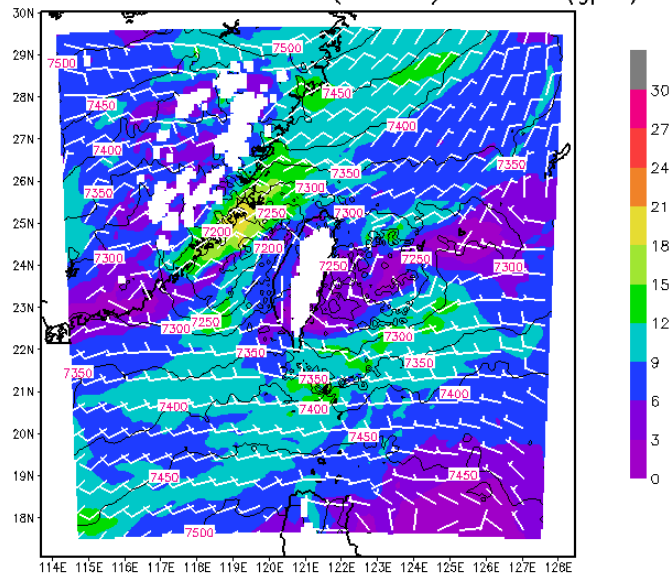
- Mei-Yu front west of Taiwan already moved southward and pass through the NW Taiwan NE-SW mountain range. (No frontal lifting combined with orographic lifting over NW mountainous regions in Taiwan)
- As the SW flow become more westerly component with **weaker amplitude**, the western branch of the split flow is along the coast line. Also, blocking is evident. Moisture brought by the SW flow is prevented by the blocking.

2008/05/30 22:57Z IR1

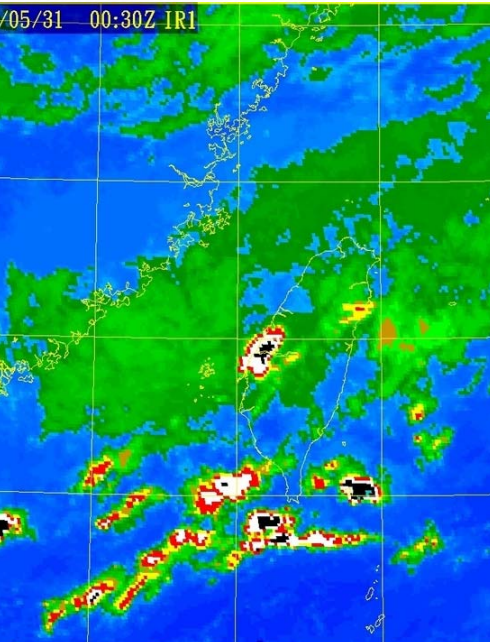
MTSAT衛星



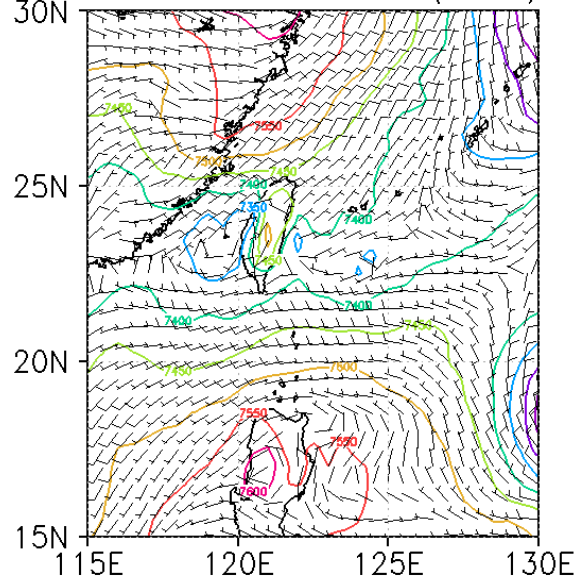
2008053023Z 925hPa wind(m s⁻¹) and HGT(gpm)



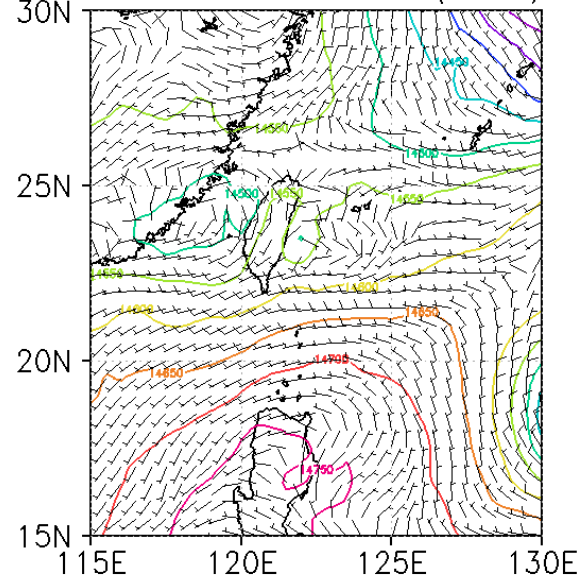
2008/05/31 00:30Z IR1



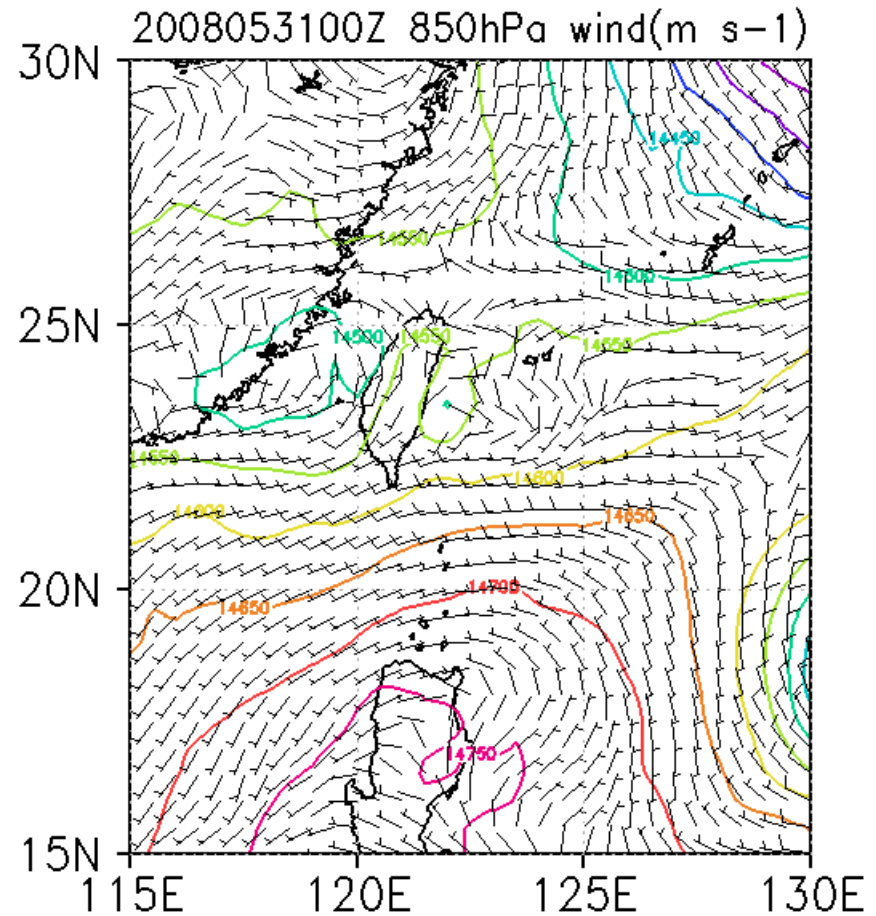
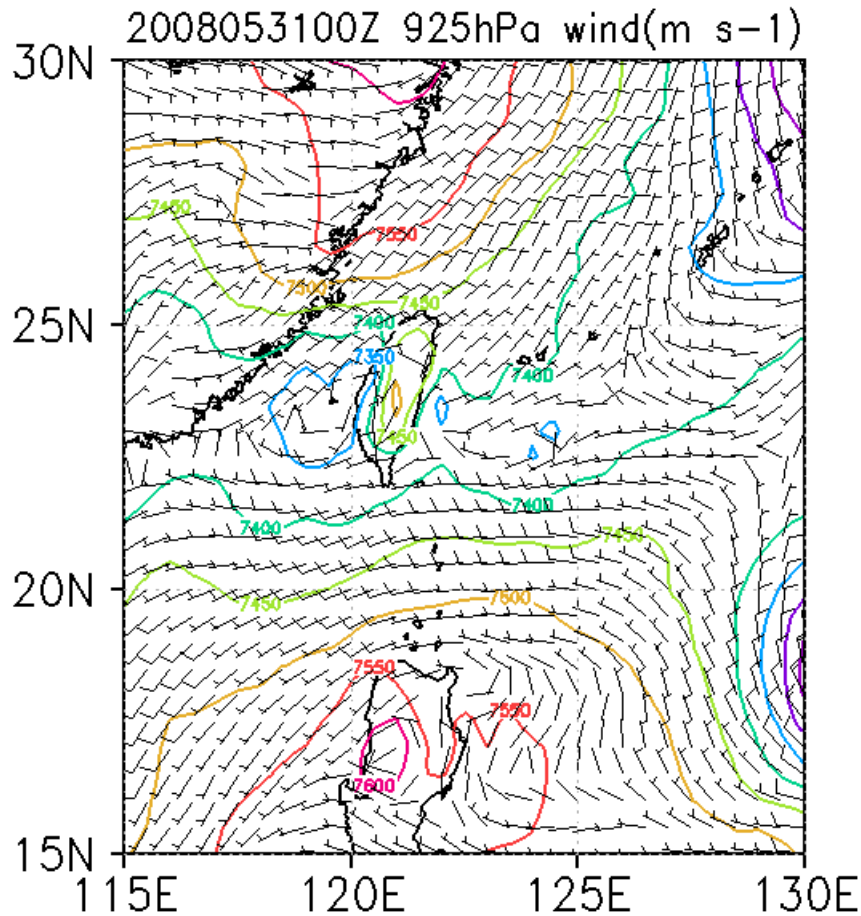
2008053100Z 925hPa wind(m s⁻¹)

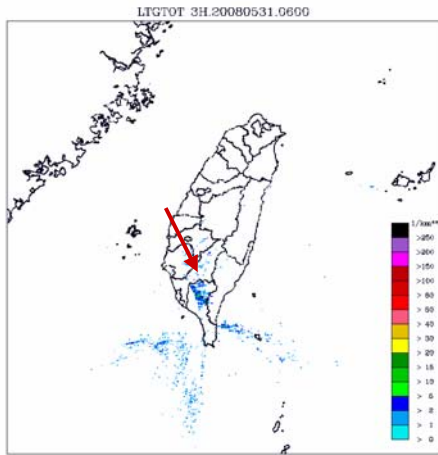


2008053100Z 850hPa wind(m s⁻¹)



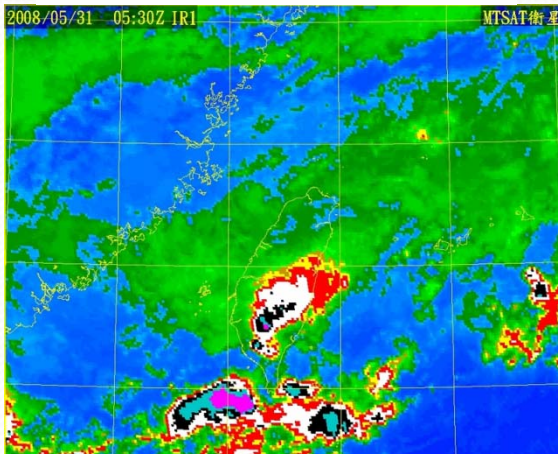
YOTC winds (m s^{-1}) and Geopotential ($\text{m}^2 \text{s}^{-2}$). (a) 925 hPa (b) 850hPa at 0000 UTC (0800 Local Time) 31 May. (Winds: Full barb, half barb represent 10 and 5 m s^{-1} , respectively).



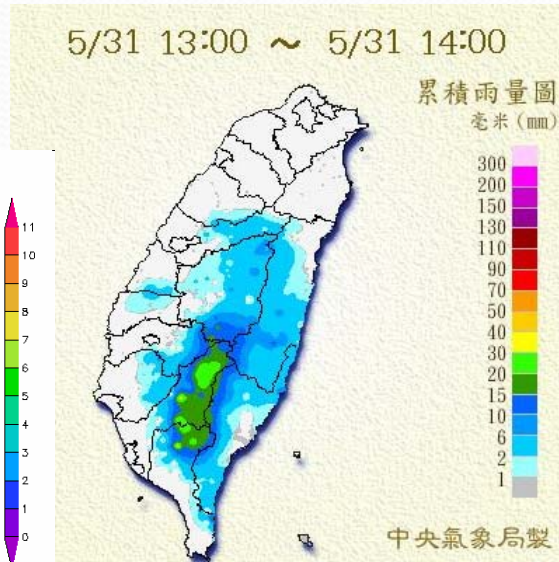
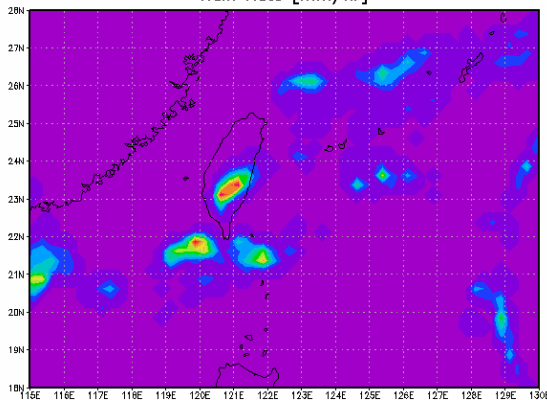


5/31 00Z-06Z as the frontal cyclone drifted inland, it interacted with CMR

- The convergence flow/cells ahead of the frontal cyclone might be a little bit north than the observation. However, we can still study the effects of CMR on the SE propagating Mei-Yu frontal cyclone.



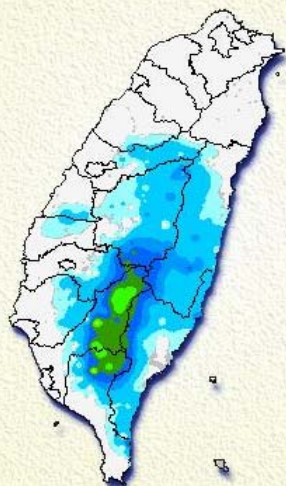
3-hourly TRMM 3B42(V6) 06Z31May2008
Rain Rate [mm/hr]



Rainfall

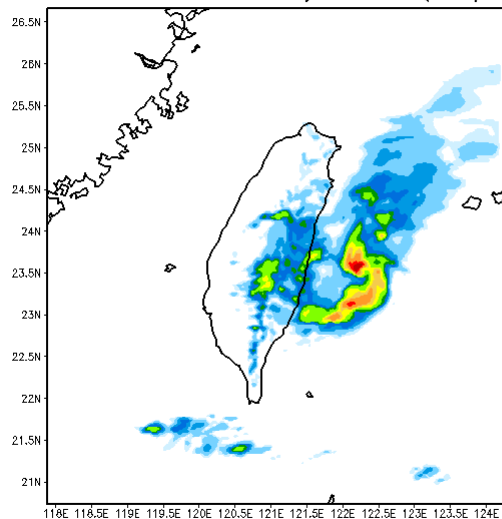
5/31 13:00 ~ 5/31 14:00

累積雨量圖
毫米 (mm)

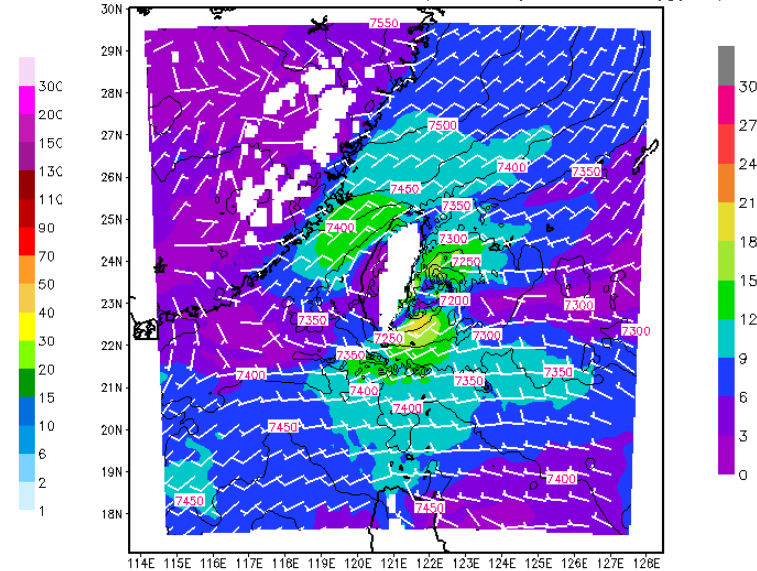


中央氣象局製

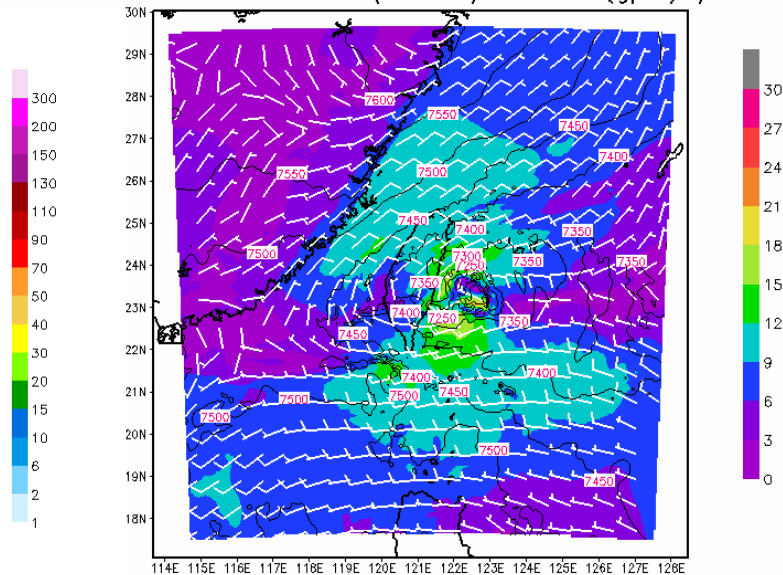
2008053106Z hourly rainfall (mm)



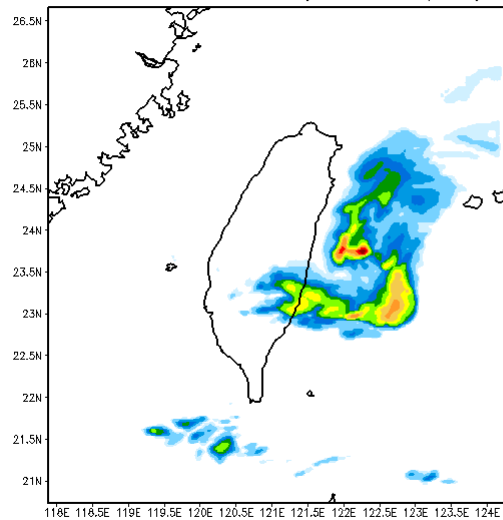
2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)



2008053106Z 925hPa wind(m s⁻¹) and HGT(gpm)w/o terrain



2008053106Z hourly rainfall (mm)



Data & Method

- CWB: Rain gauge, Radar Reflectivities, IR satellite images
- YOTC reanalysis data: including observation took from field experiments
- High-resolution meso-scale modeling: WRF
Sensitivity test: Remove terrain to discuss the orographic effects on Mei-Yu jet/front systems and rainfall distribution during TiMREX #IOP₃ and the 6/16 case
- (Tunnel effects and blocking effects (e.g. flow splitting) as a Mei-Yu front past through Taiwan and a frontal cyclone advanced CMR of Taiwan)