Environmental Modeling System

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Outline:

- **Part 1: Introduction on WRF-CMAQ model**
  - Meteorology model: WRF
  - Chemical transport model: CMAQ
- **Part 2: Simulation of Biomass Burning Plumes and its transport**
  - Introduction
  - Modeling configuration
- **Part 3: Simulation of Asian Dust Storm and its transport**
  - Introduction
  - Modeling configuration
- **Part 4: Real-time weather forecast system**
  - Introduction
  - Modeling configuration

Part 1:
Introduction to Chemical Weather Prediction (CWP) system

Introduction: Chemical Weather Prediction (CWP) model

- CWP is a set of complex physics and math equation to solve weather factors & air pollutants amount
- CWP solves these ordinary (time dependent) and partial (time and space dependent) differential equations with finite-difference or other methods such as parameterized or empirical equation.
- This equations are designed to simulate the real-life phenomenon

CWP =

Numerical Weather Prediction (NWP)

- Forecast (future) and hindcast (historical) of meteorological condition

WRF

Moisture

Temp

Pres

Wind

+

Chemical Transport Model (CTM)

- Predict distribution of pollutants
- Reference for regulatory policies

CMAQ

O_3

NO_2

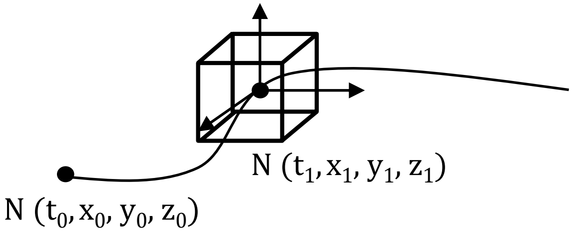
$PM_{2.5}$

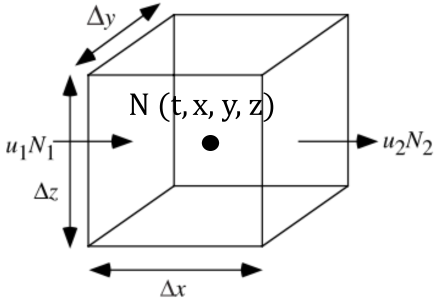
PM_{10}

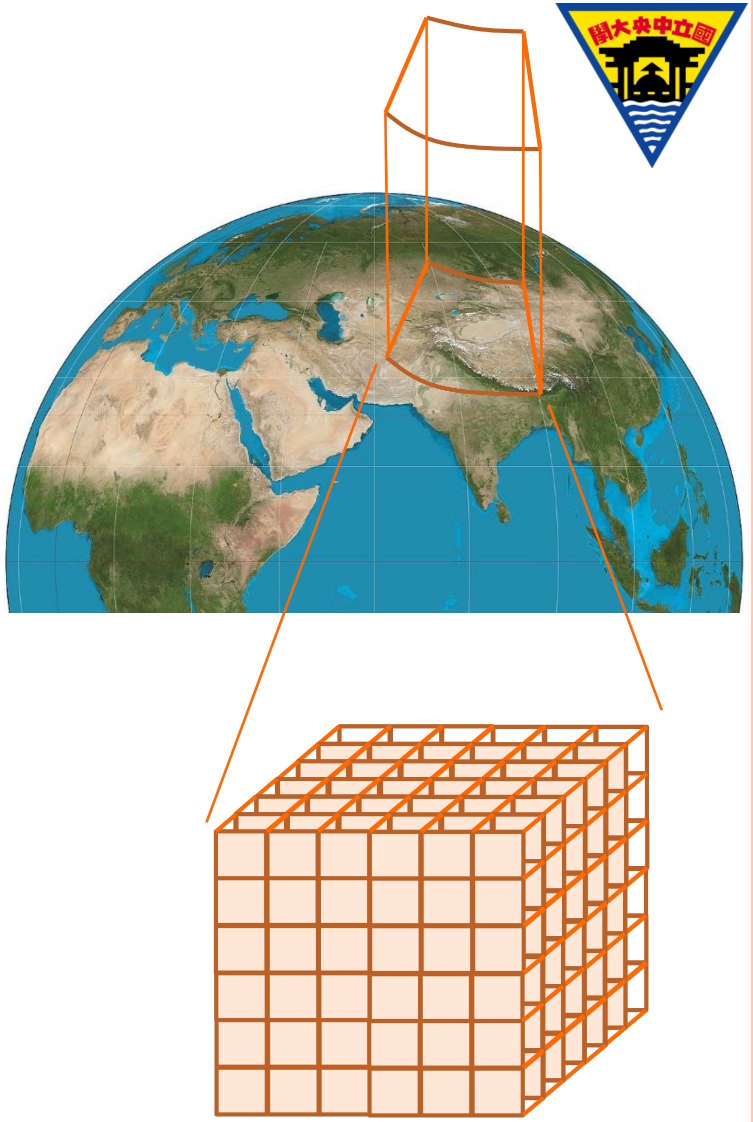
SO_2

Eulerian model – Gridded model

	Lagrange / Lagrangian	Euler / Eulerian
Frame of reference	Moves relative to a fixed coordinate system	Fixed coordinate system
Example	HYSPLIT, NAME	WRF, CMAQ, GEOS



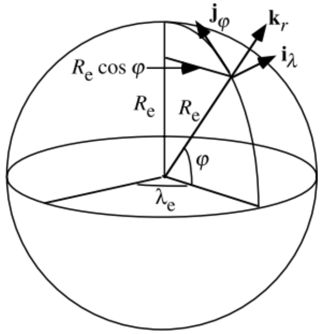




<u>Coordinate system</u>

- Horizontal:

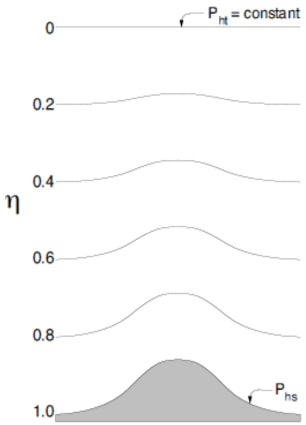
Cartesian → Spherical



Extracted from Jacobson (2005)

- Vertical:

Pressure, Terrain, Hybrid

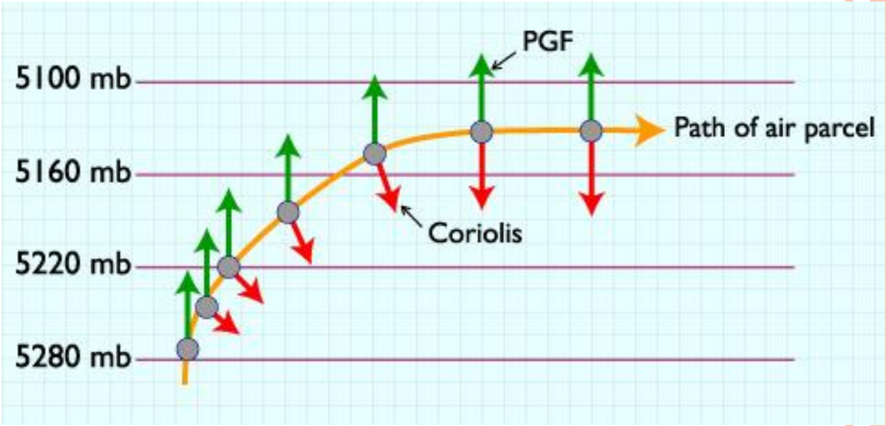


Extracted from WRF User guide

NWP: Weather Research and Forecast (WRF) *Wolf → "Worf"*

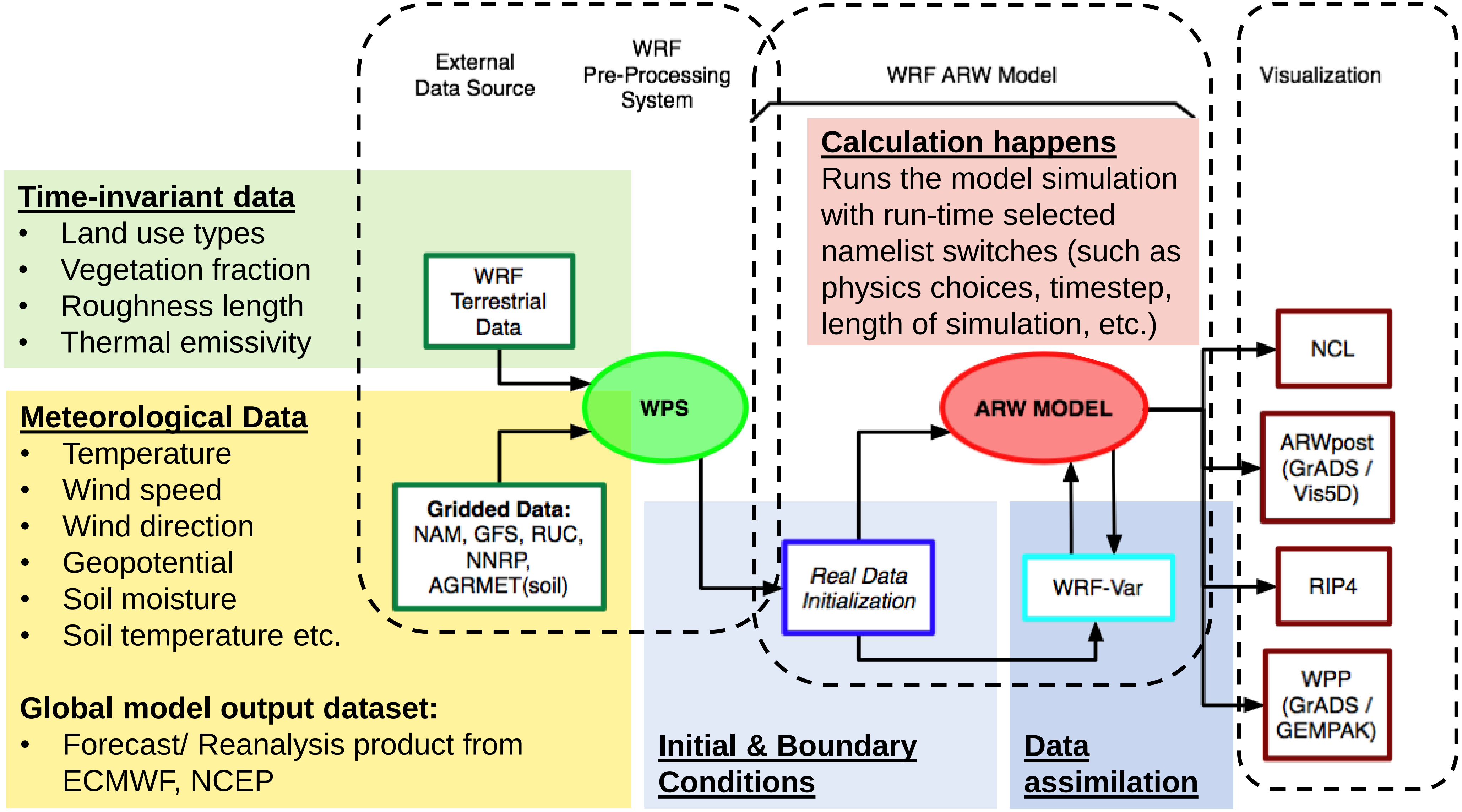
- WRF is a NWP software for atmospheric research and forecasting weather
- Scale: mesoscale to synoptic scale (1 – 20km)
- It is a supported "community model", i.e. a free and shared resource with distributed development and centralized support

Dynamical cores	Advanced Research WRF (ARW)	Nonhydrostatic Mesoscale Model (NMM)
Support	NCAR/MMM	NCEP/EMC
Development		NCAR/DTC
Main purpose	Research	Operation/ Forecast
Physics, framework, dataset process	Same	



- Collaborative development of
  - National Center for Atmospheric Research (NCAR)
  - National Oceanic and Atmospheric Administration (NOAA) - National Centers for Environmental Protection (NCEP) Forecast Systems Laboratory (FSL))
  - Air Force Weather Agency (AFWA)
  - Naval Research Laboratory
  - University of Oklahoma
  - Federal Aviation Administration (FAA)

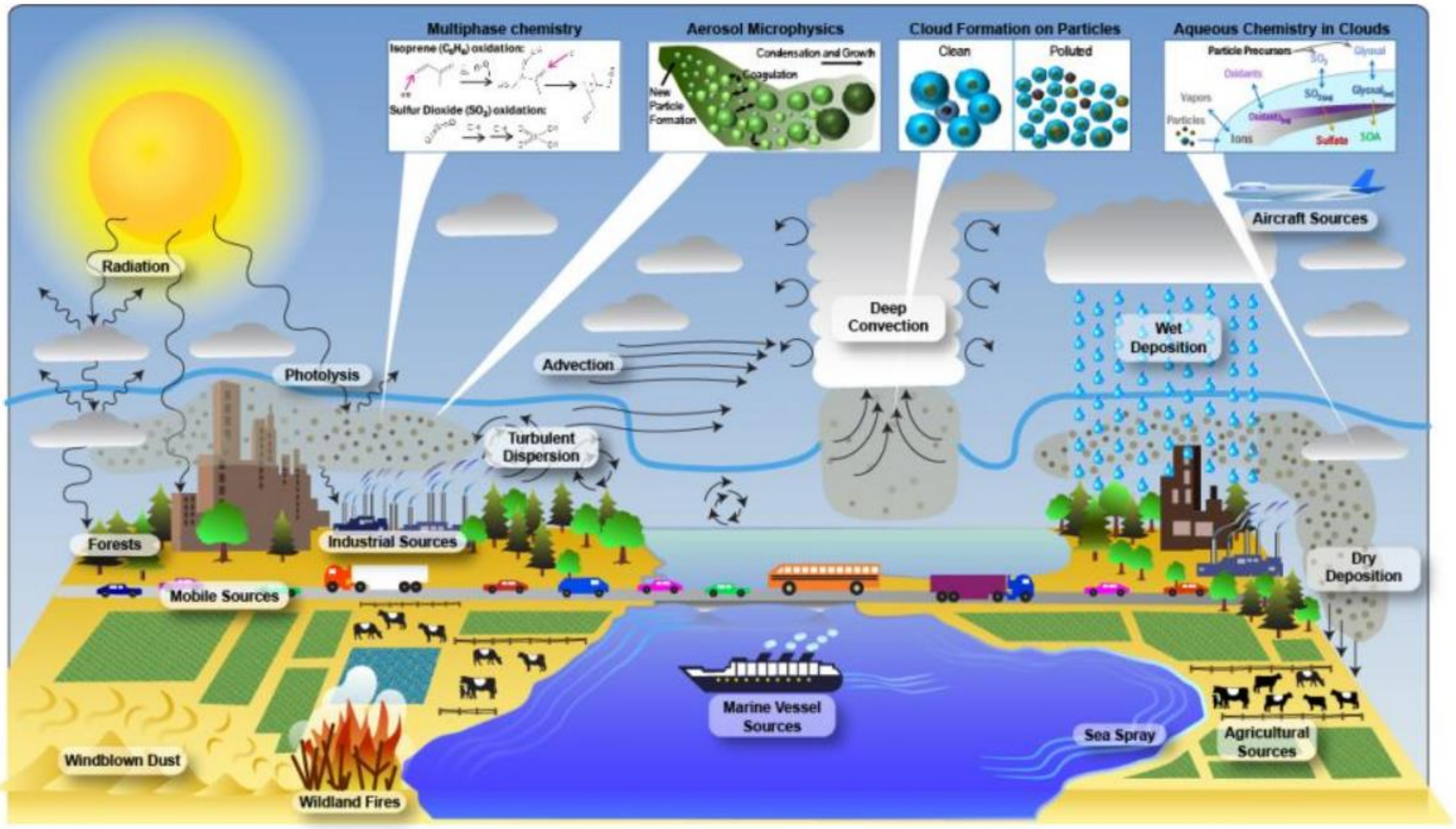
WRF System Flowchart (Detailed)



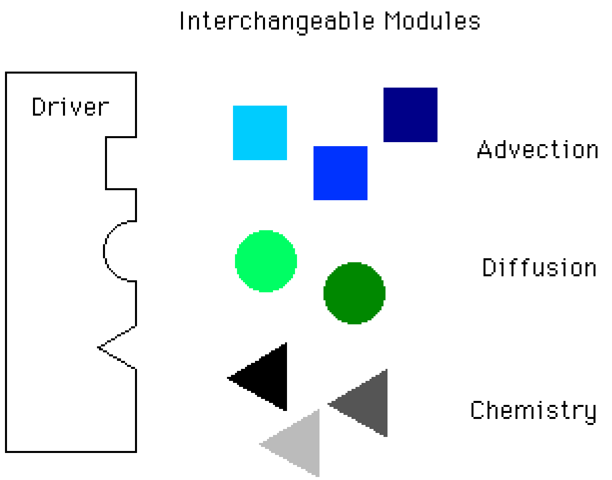
Extracted from WRF user document

CTM: Community Multiscale Air Quality Modeling System (CMAQ) *“see-mak”*

- CMAQ is a regulatory model for air quality model simulations used by U.S. EPA
- The “one-atmosphere” design is embodied is able to solve the complex interactions of multiple atmospheric pollutants simultaneously



Extracted from CMAQ official webpage



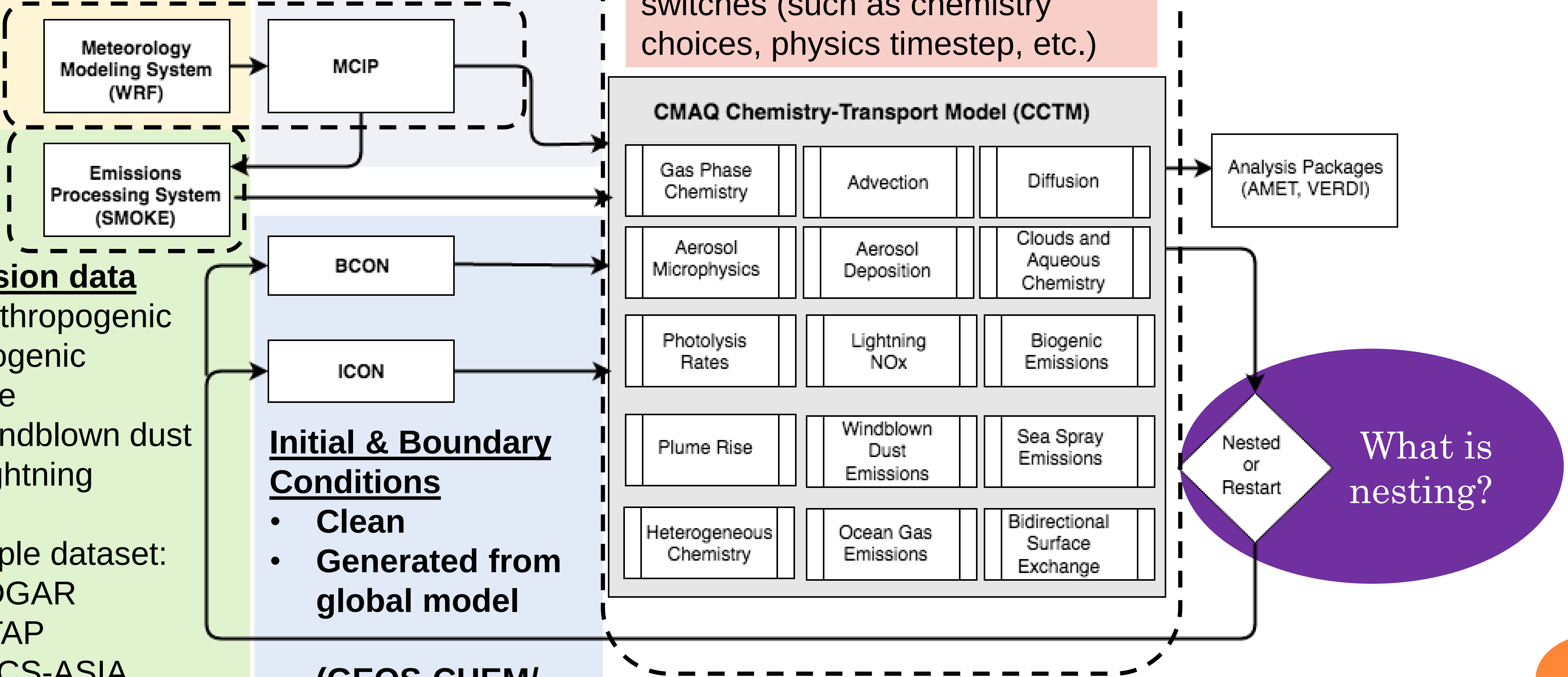
Extracted from CMAQ user document

Community Multi-scale Air Quality modelling system (CMAQ)

WRF output
- Weather field

Conversion tool
WRF (netCDF) ➔ CMAQ (I/O API) format

Calculation happens
Runs the model simulation with run-time selected namelist switches (such as chemistry choices, physics timestep, etc.)



Emission data
- Anthropogenic
- Biogenic
- Fire
- Windblown dust
- Lightning

Example dataset:
- EDGAR
- HTAP
- MICS-ASIA
- TEDS

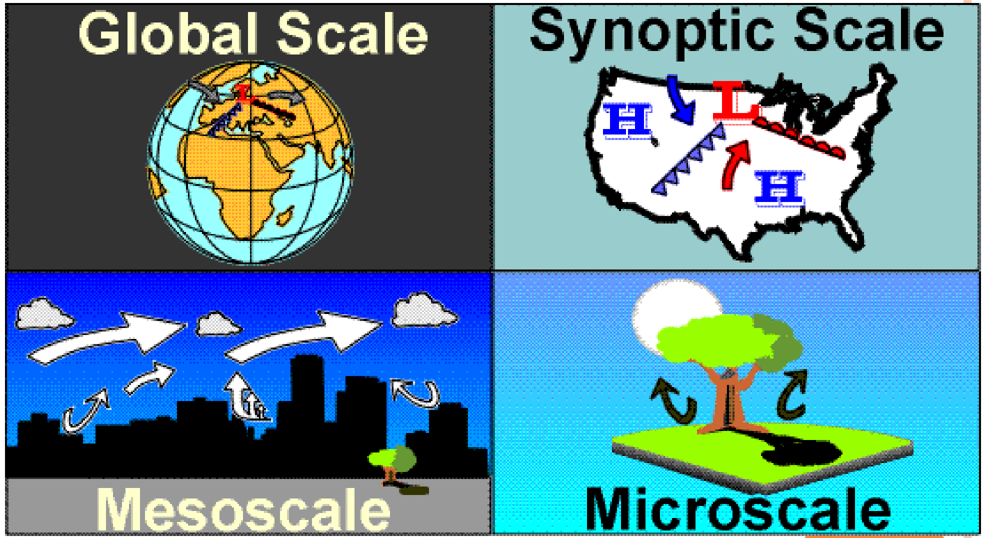
Initial & Boundary Conditions
- **Clean**
- **Generated from global model**

(GEOS-CHEM/ MOZART)

Nesting (Multi-scale modelling)

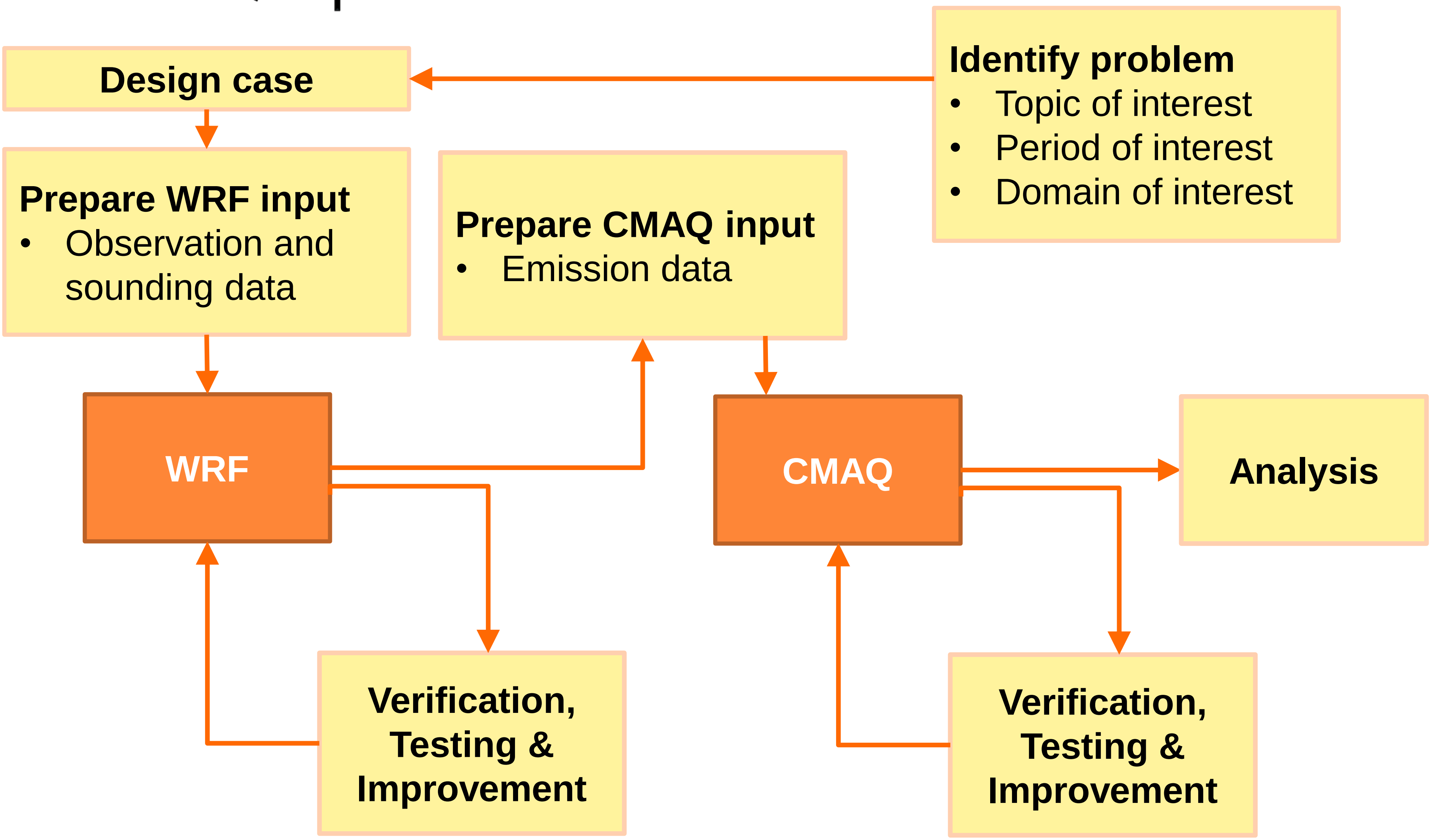
- Nesting allows us to study and capture atmospheric/chemistry dynamics on different scale
  - Boundary condition data is produced from global model and usually available in coarse time and spatial resolution
  - Take influence of large-scale system into small-scale local phenomenon.
  - Nesting is required for higher resolution studies, example:
    - ozone photochemistry (short chemistry reaction), convective precipitations (short weather phenomenon)

Popular Data	Resolution
NCEP GFS forecast	1° x 1°
NCEP FNL reanalysis	0.25° x 0.25° (2015 onwards)
ECMWF forecast	0.2° x 0.2°
ERA5 reanalysis	0.281° x 0.281°



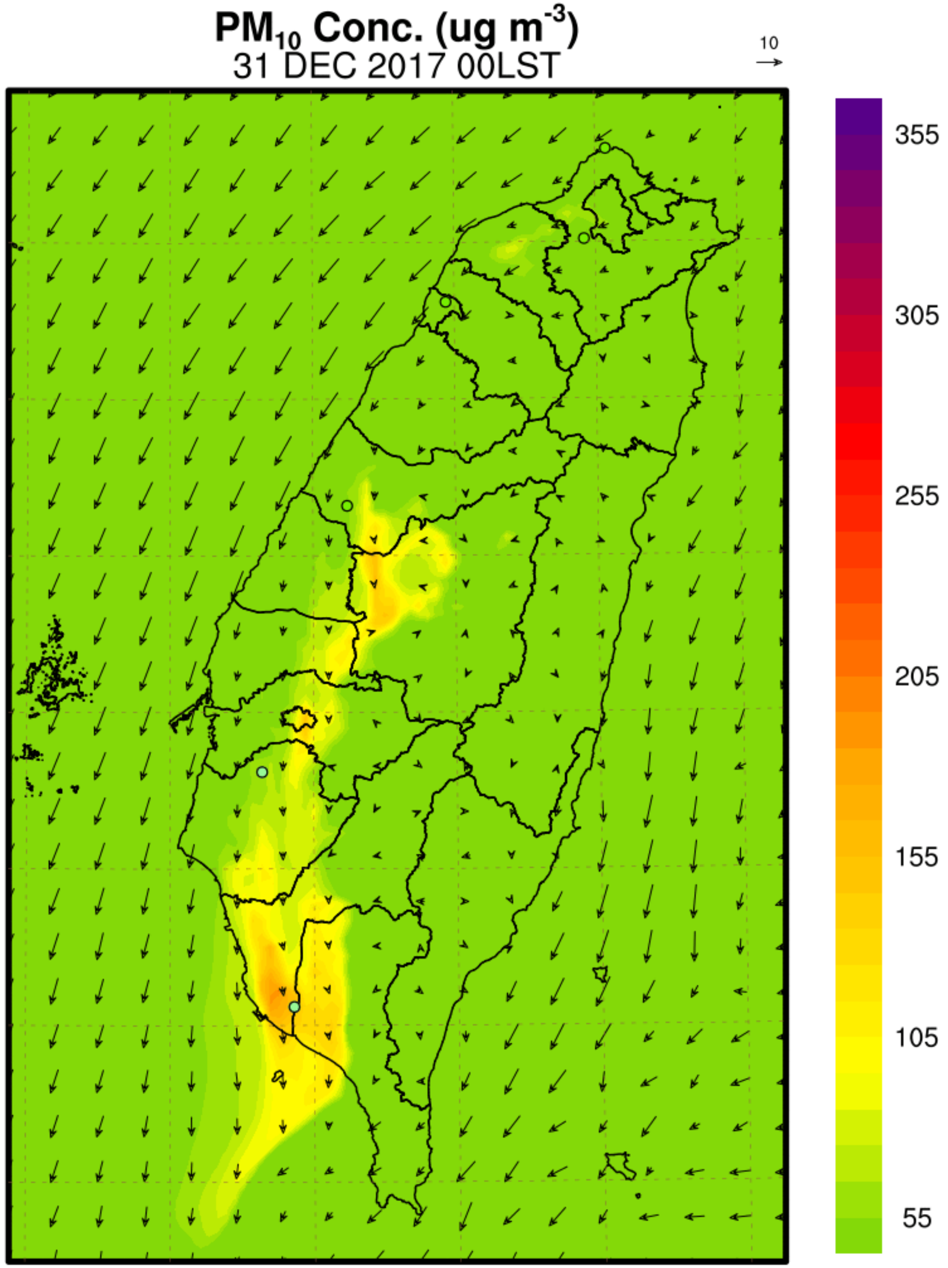
- Different scale of atmospheric motions

WRF-CMAQ Operation



What a model CANNOT do

- Produce 100% correct output
  - Limited density coverage of observation data
  - Uncertainties in weather field
  - Uncertainties in emission field
  - Uncertainties in chemistry field
- **Garbage In Garbage Out!!**



What a model CAN do

- Overcome limitation of observation data
- Predict possible trend if the model can reproduce values at available observation stations
- Coupled with observation data to predict better model result (data assimilation)

Useful WRF materials

WRF Users Home Page: http://www2.mmm.ucar.edu/wrf/users/

- Users' page. All the documents stated below can be obtained through hyperlinks in this home page
- Latest update for the modeling system

WRF ARW User's Guide: http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/contents.html

- Must have document for operation of WRF
- Always use the latest version, i.e. v4.1.1 (debugged version of v4.1)

WRF ARW Technical note: http://www2.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf

- Technical architecture and physics of the model

WRF model download: http://www2.mmm.ucar.edu/wrf/users/downloads.html

- Requires to create account yourself because you can choose to subscribe to updates and news related to the software.

WRF compilation guide:

- Offical presentation: http://www2.mmm.ucar.edu/wrf/users/tutorial/201607/compiling.pdf
- Online tutorial: http://www2.mmm.ucar.edu/wrf/OnLineTutorial/compilation_tutorial.php

User Support Email: wrfhelp@ucar.edu

Useful CMAQ materials

CMAQ Users Home Page:https://www.epa.gov/cmaq

- Users' page. All the documents stated below can be obtained through hyperlinks in this home page
- Latest update for the modelling system

CMAQ ARW User's Guide & Compilation Guide:

https://github.com/USEPA/CMAQ/blob/5.2.1/DOCS/User_Manual/README.md

- Must-have document for operation of CMAQ
- Always use the latest version, i.e. v5.2.1 (debugged version of v5.2). Avoid Beta!

CMAQ Science note: https://www.cmascenter.org/cmaq/science_documentation/

- Technical architecture and physics of the model

CMAQ model download: https://www.epa.gov/cmaq/access-cmaq-source-code

- Requires to create account yourself because you can choose to subscribe to updates and news related to the software.

Online tutorial: https://github.com/USEPA/CMAQ/blob/5.2.1/DOCS/Tutorials/README.md

- Data download: https://www.epa.gov/cmaq/cmaq-inputs-and-test-case-data

User Support Forum:https://www.epa.gov/cmaq/forms/contact-us-about-community-multiscale-air-quality-modeling-system

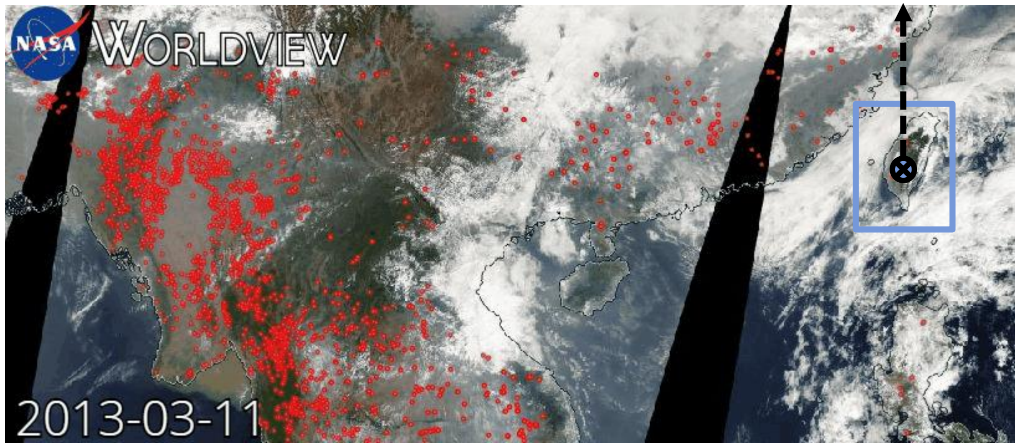
Part 2:

Modelling of biomass burning (BB) plumes transport

Introduction

Mountain Lulin, Taiwan
(receptor)

25°N

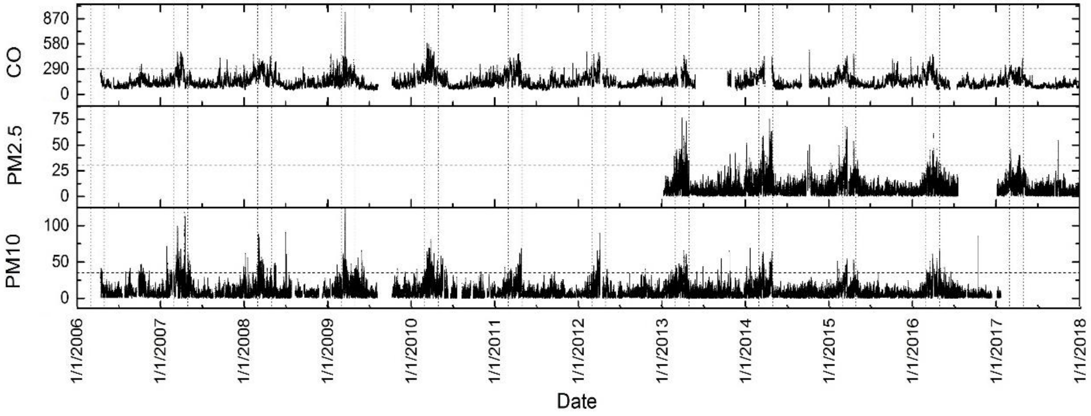


10°N

95°E 125°E

Red -burning hotspots;
Grey shades - potential aerosols from burning

Measurement result on Mountain Lulin (2006 – 2017)



Pollutant threshold value:

CO:
300 ppb

PM2.5:
30 ugm^{-3}

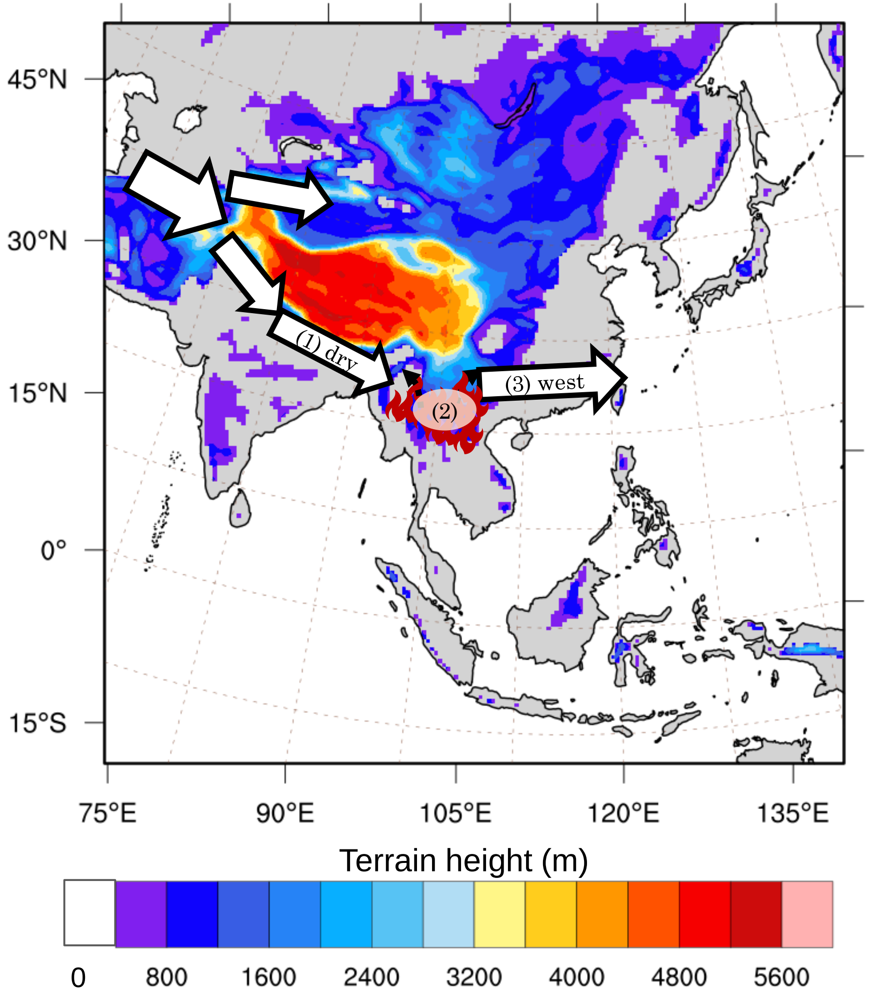
PM10:
35 ugm^{-3}

- Biomass burning in northern Indochina occurs during the dry season from December to April every year (Lin et al., 2013).
- Focus of study
  - Source: Burning in northern Indochina
  - Receptor: Lulin Atmospheric Background Station (LABS) [2862 m]
- Transboundary haze is more commonly apparent at Mt. Lulin in March and April (vertical dashed lines).

Introduction of biomass burning transport

Mechanism of plume transport to Mt. Lulin

1. **India-Burma trough (IBT)** subsides dry air mass from the Tibetan plateau to support the burnings (Huang et al., 2016)
2. **Topography lifting** of airmass passing through Yunguei mountains in IndoChina to height of 700 hPa (~3-5km) (Lin et al., 2009; Yen et al, 2013)
   - Front side elevation
   - Leeside trough
3. **Subtropical westerlies jet** carries lifted plumes eastwards towards Taiwan



ENSO (El-Niño Southern Oscillation)

- The anomaly of hotter sea surface over tropical eastern/central Pacific Ocean, might affect weather over tropical Pacific Ocean and their adjacent areas.
- Weather condition in Southeast Asia is hot and dry

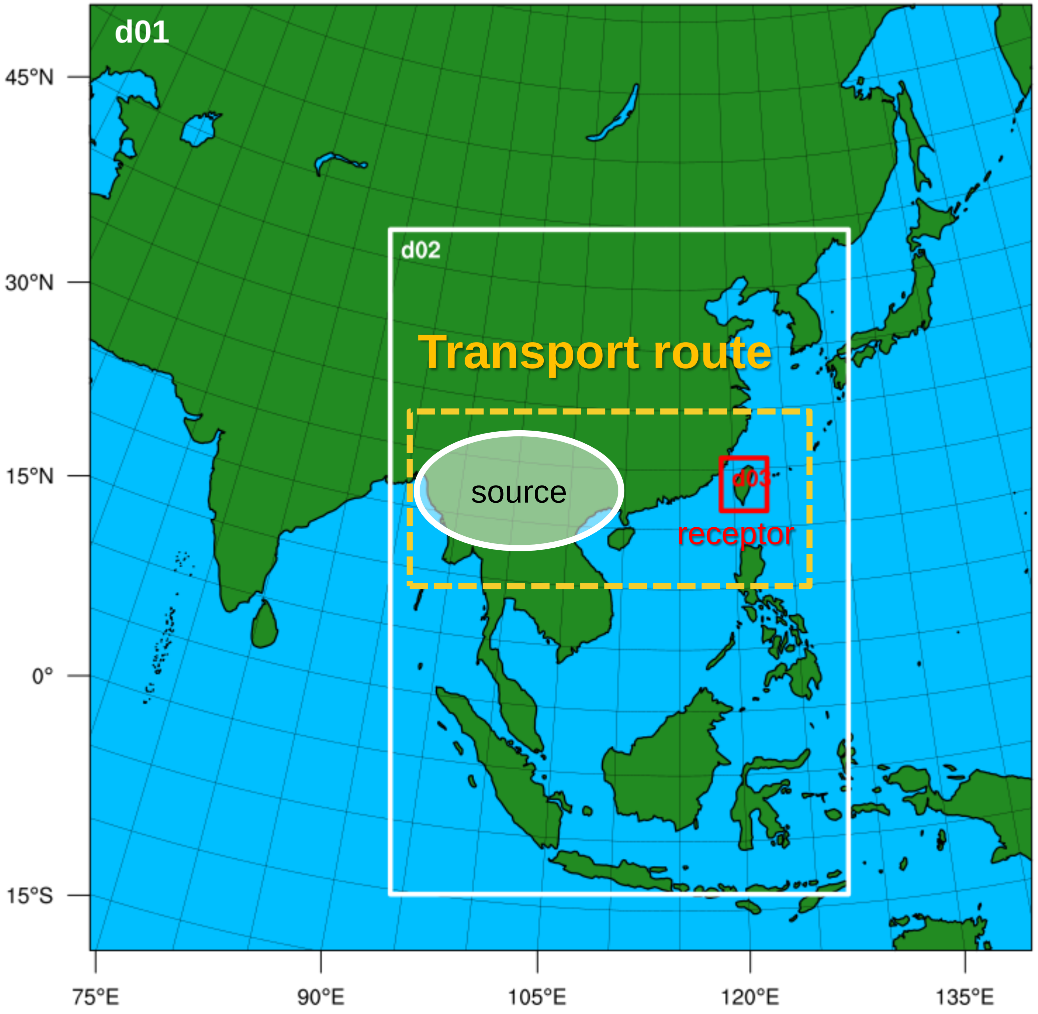
Improvement of plume rise

Aim:

- To improve the prediction of fire emission for north Indochina and its downwind area (Taiwan)

Model settings:

	Settings
Weather model	WRF version 3.9.1
Boundary condition and	NCEP FNL lateral boundary condition
Weather nudging	Grid and observation nudging
Planetary boundary	ACM2
Surface layer (land surface)	Pleim-Xiu (Pleim-Xiu)
Longwave (shortwave) radiation	RRTM (Goddard)
Microphysics (cumulus) scheme	Goddard (Kain-Fritsch for d01, d02 only)
Chemistry transport model	CMAQ version 5.2.1
1st domain (45km)	Include LRT of Taiwan emission to entire SEA
2nd domain (15km)	Cover transport route
3rd domain (5km)	Taiwan (Receptor)
Period	1st– 31th Mar 2013 (after spin up)
Emission inventory (Anthropogenic + biogenic)	d01, d02, d04: MICS-ASIA 2010 include biogenic emission produced from MEGAN v2.10 d03: Taiwan local emission inventory (TEDS v8.1)
Emission inventory (Fire)	FINN
Vertical	41 layers up to 50 hPa with 10 layers in the bottom 2km

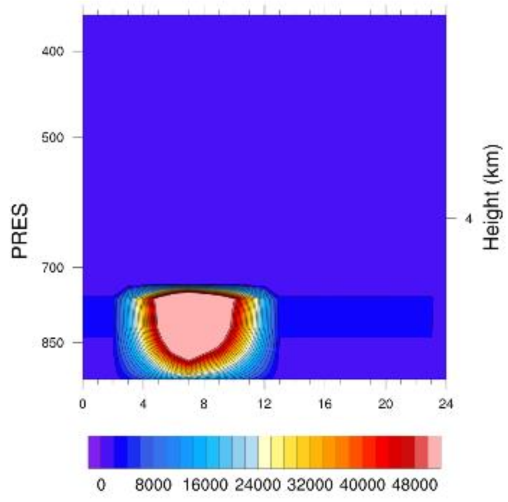


Plume rise types

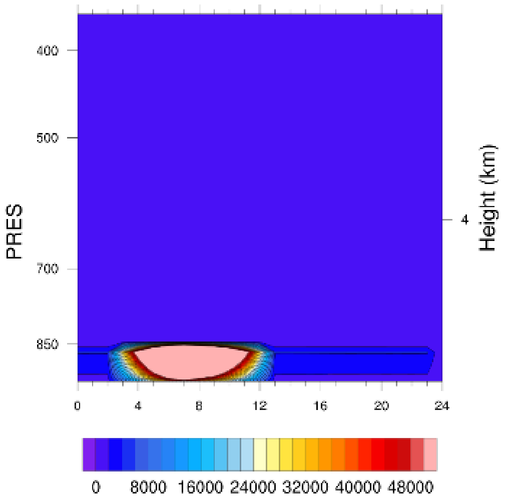
Fire emission	Plume rise model	Plume rise height	Plume top and bottom	Smoldering fraction (1 – BE)
No	-	-	-	-
Off9_800	Offline	Plume top: 800 m, Plume bottom = 0		-
Off9_2000	Offline	Plume top: 2000 m, Plume bottom = 0		-
In9_cctm	Inline	Fire heat flux and atmospheric stability	1.5 x effective plume rise height	BE depends on empirical equation of acres burnt
Off9_wrap	Offline	Fire heat flux and prescribed bins of acres burnt		BE depends give as function of hour and emissions

Initial plume rise allocation

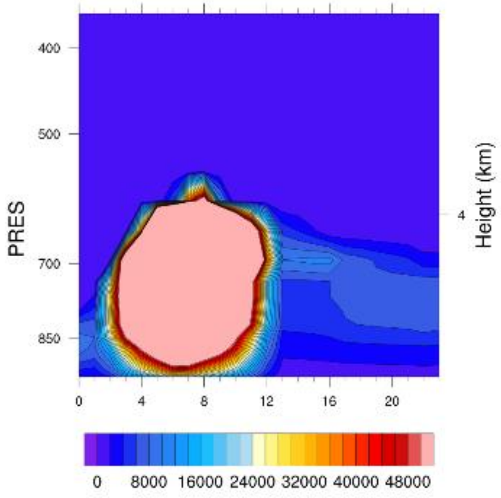
(a) Off9_2000



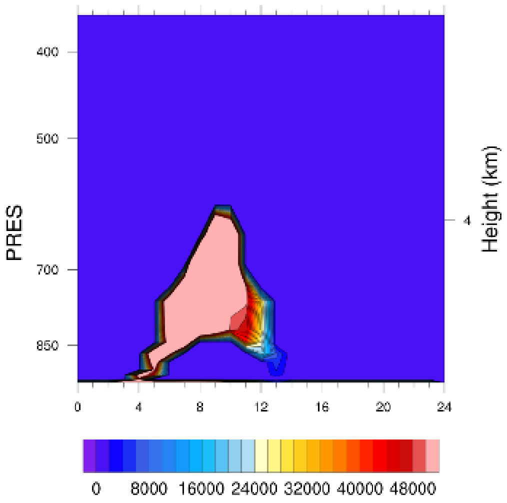
(a) Off9_800



(a) In9_cctm



(a) Off9_wrap



Verification Result – Mt. Lulin

Weather parameters

Parameters	Index	Standard	no fdda	fdda	fdda	fdda
			-	RIN = 240 km	RIN = 100 km	Model lay = 4
T2	MB	-1.5< x< 1.5	1.62	2.29	2.33	**0.17**
	MAE	x< 3	2.6	2.89	2.89	**1.52**
WS	MB	-1.5< x< 1.5	-2.61	-1.93	-1.92	**0.92**
	RMSE	x< 3	3.52	3	3	**2.28**
WD	WNMB	-10< x < 10	0.3	-3.96	-2.81	3.38
	WNME	x< 30	12.61	12.7	12.21	**8.88**

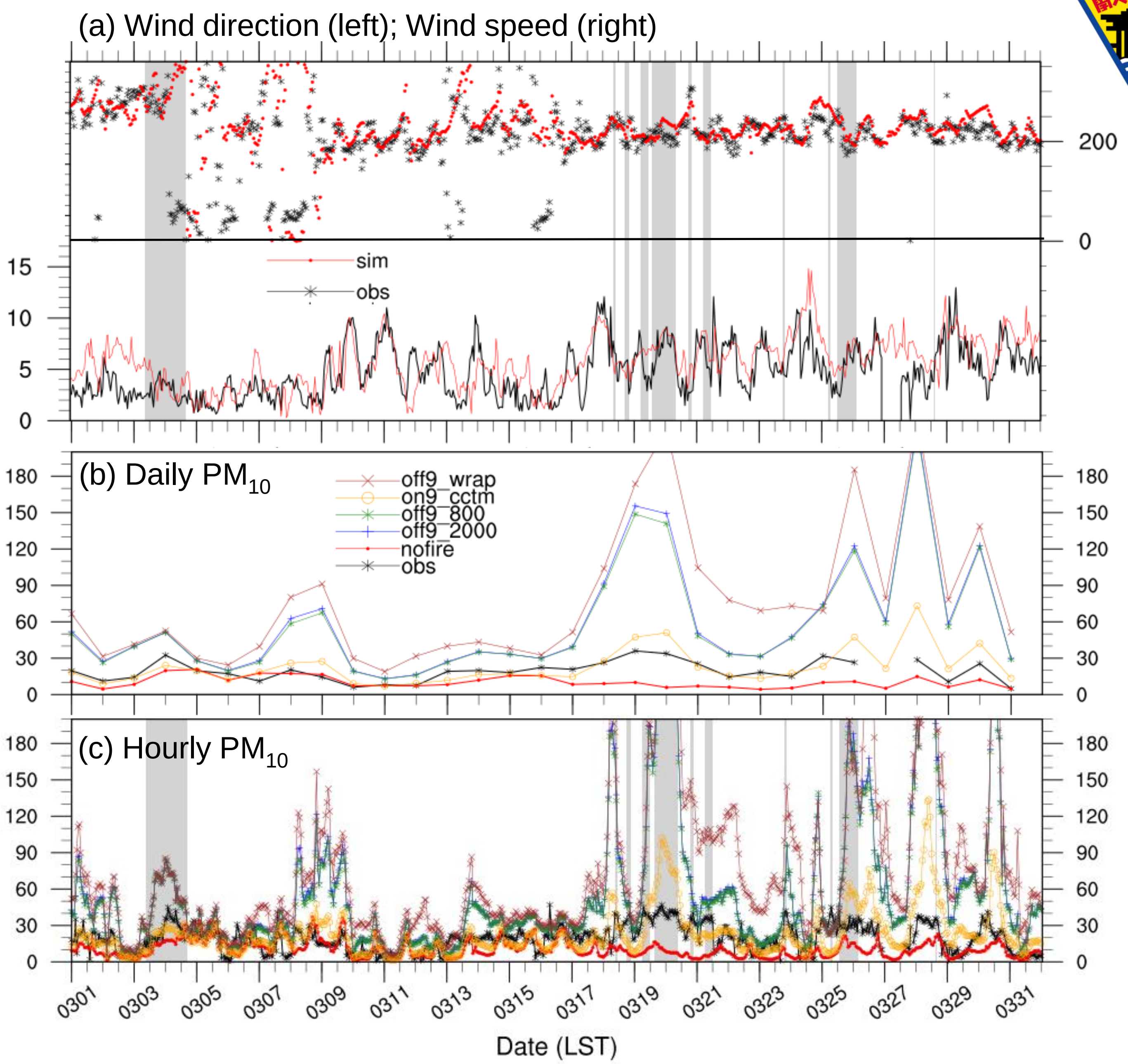
Air quality parameters

Parameters	Index	Standard	Off9_2000	Off9_800	In9_cctm	Off9_wrap
Daily PM_{10}	R	x > 0.5	**0.69**	**0.69**	**0.69**	0.65
	MFB	-0.35< x< 0.35	0.82	0.80	**0.11**	1.07
	MFE	x< 0.55	0.82	0.80	**0.33**	1.07
Hourly O_3 (>40 ppb)	R	x > 0.45	0.46	0.46	**0.49**	**0.52**
	MNB	-0.15< x< 0.15	0.11	0.10	**0.18**	**0.22**
	MNE	x< 0.35	0.20	0.20	**0.24**	**0.26**
Hourly CO	R	x > 0.35	0.60	0.59	**0.62**	0.61
	MNB	-0.5< x< 0.5	0.51	0.50	**0.45**	0.63
	MNE	x< 0.5	0.55	0.55	**0.50**	0.66

Plume rise model

Result – Mount Lulin (TW)

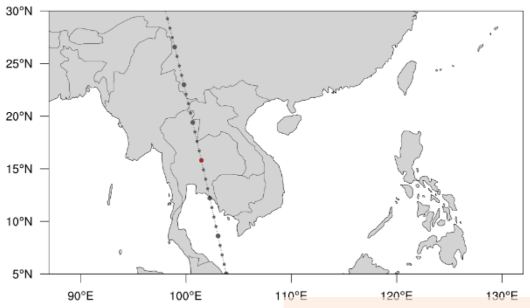
- Inline system (In9_cctm) gives closest correlation with the measured ground station.
- The importance of atmospheric stability-based plume rise model to capture the plume rise variation at the source site with complex terrain like the northern Thailand



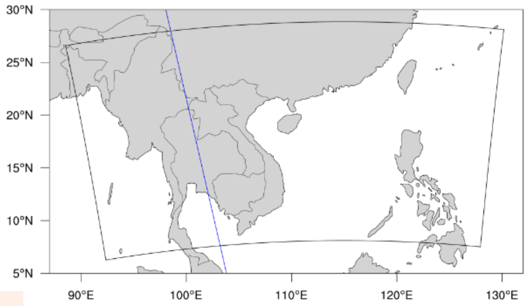
Plume rise model

Comparison with CALIPSO aerosol product - 13th March 2013 (14:00 LST)

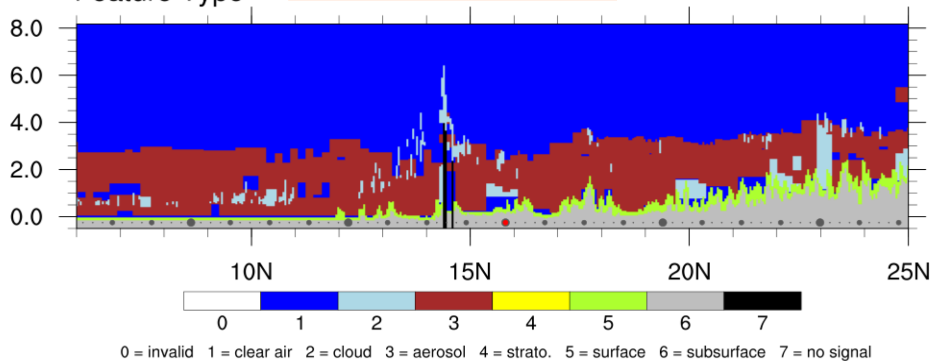
Satellite swath

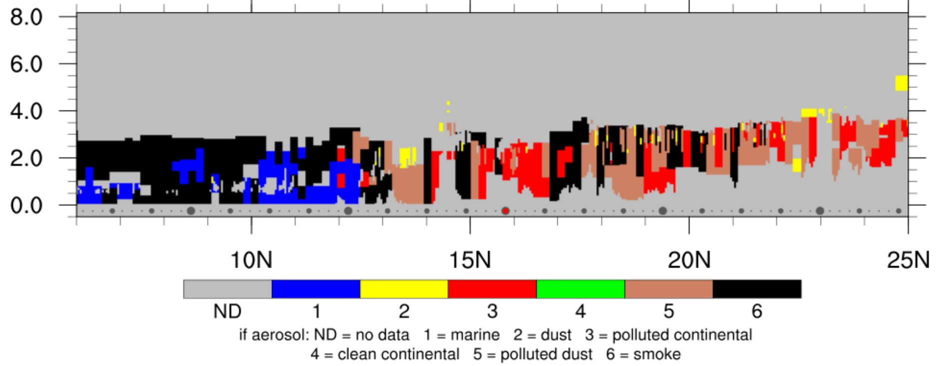


CMAQ cross-section



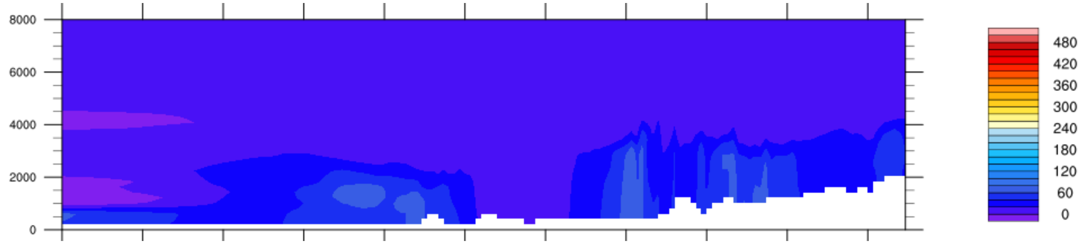
Satellite data



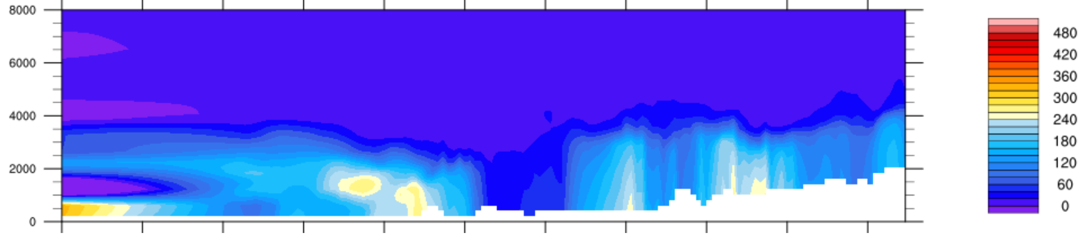


CMAQ model output

In9_cctm



Off9_wrap (All off9 result is similar)



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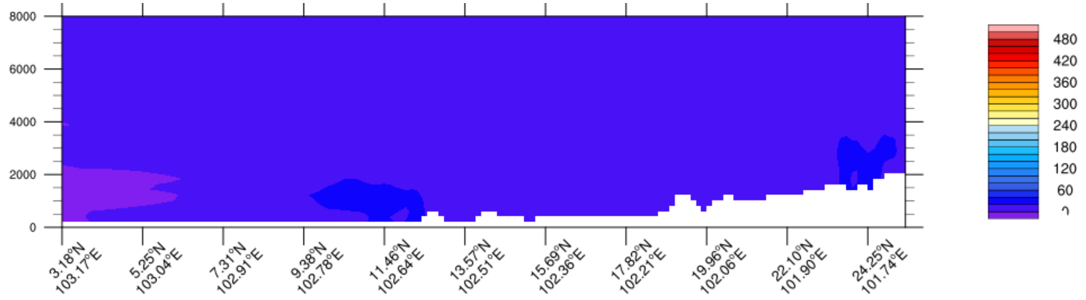
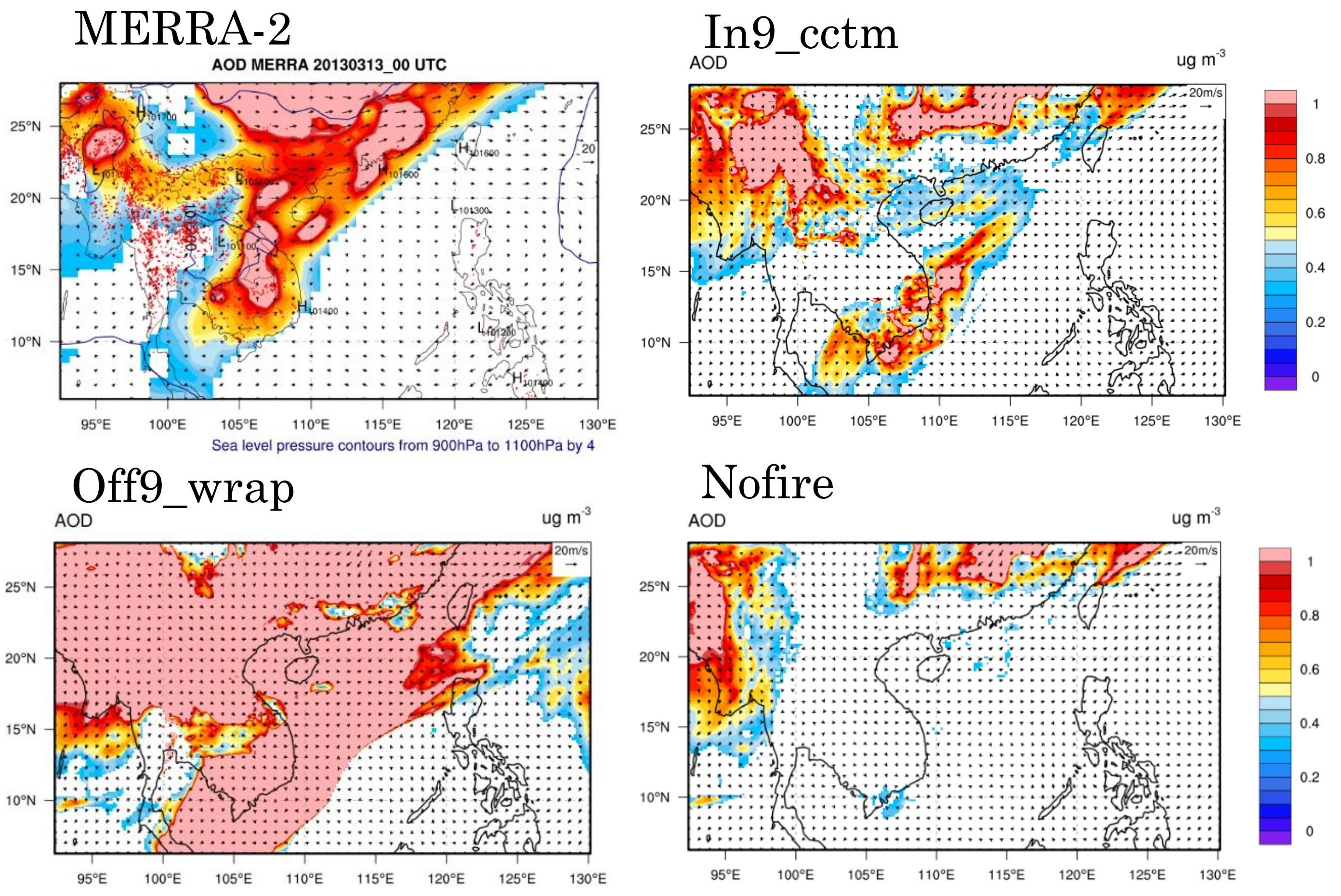


Plume rise model

Comparison with MERRA-2 AOD product



- The AOD captured for In9_cctm is similar to MERRA-2 while the Off9_wrap overpredicts the amount of AOD.
- The bad dispersion of the emission, i.e. lower injection height, has caused the widespread of the AOD value for Off9 models

Influence of ENSO on transport of emission to Taiwan

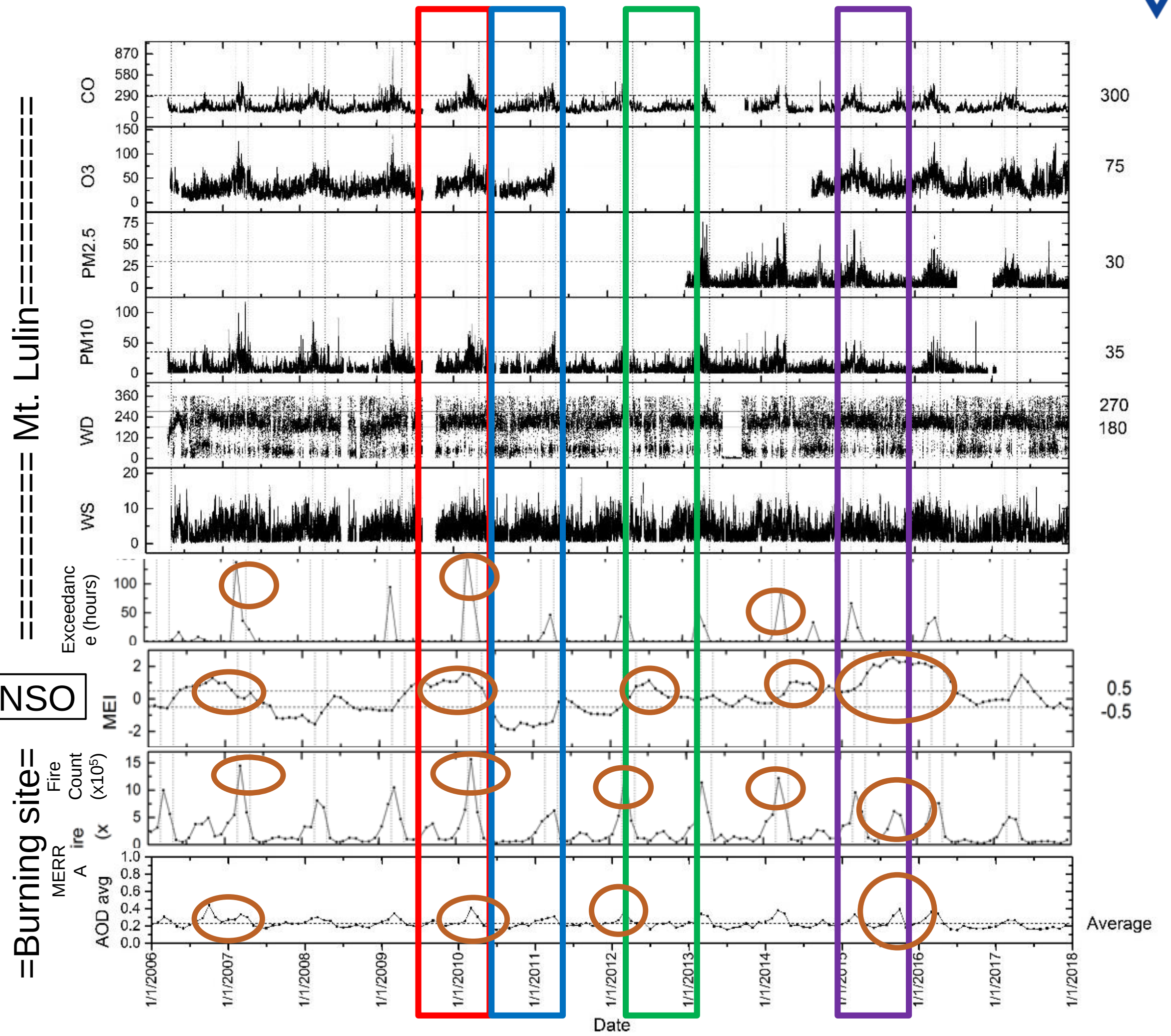
- Indicator: Multivariate ENSO Index (MEI)
- When MEI is high (> 0.5), strong ENSO

  Mt Lulin higher pollution (Transport)

  Hotspot count (Burning)

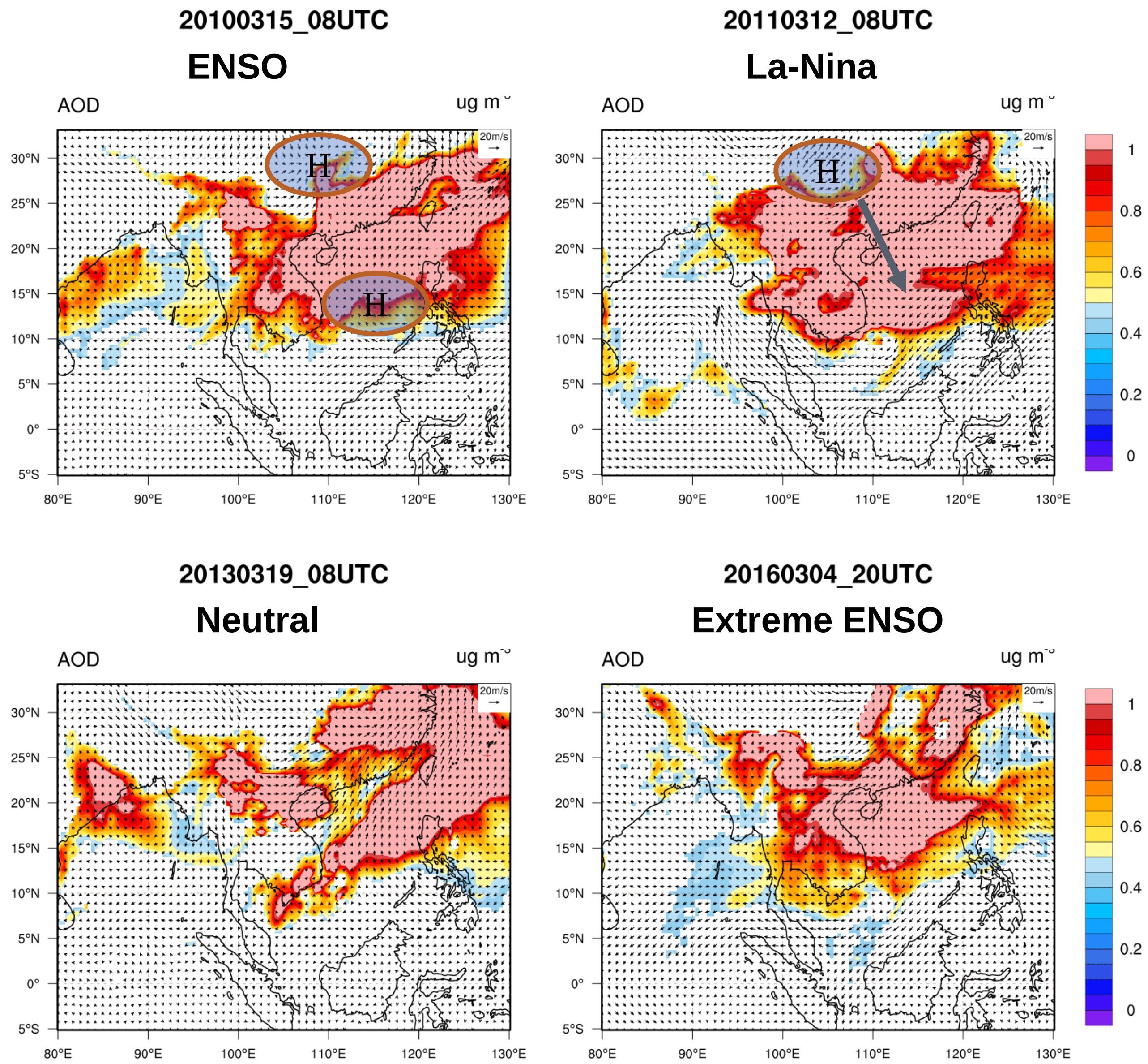
  AOD (Emission)

Mar	ENSO levels	Fire Hotspot ($x10^5$)	Avg AOD	Lulin polluted hours
2010	Strong ENSO	**15.6**	**0.41**	**94**
2011	Strong La-Niña	5.2	0.30	15
2013	Neutral	11.3	0.34	55
2016	Extreme ENSO	7.8	0.36	31



Influence of ENSO on transport of emission to Taiwan

High pollution period in Lulin for each year



- **Model setup:**
  - **Same amount of fire emission**
  - **Different year of meteorology**

SCS : south china sea

- ENSO:
  - Strong cold surge + SCS anticyclone that induced an push-and-pull effect when either one is prevailed.
  - SCS anticyclone inhibits plume to carry southwards
- La-Nina:
  - Less cold surge and/or SCS cyclone but stronger intrusion of cold surge to the north SCS region
  - It is able to carry the plume southwards, but pollutants are dispersed over large area and becomes lower in concentration
- Extreme ENSO:
  - Very frequent cold surge
  - Similar to ENSO but higher occurrence

Conclusion

CMAQ model performance

- In-line plume rise model is applied in CMAQ model
- The model showed fairly well performing AOD and pollutant result during biomass burning period, however, the further effort will need to look into the distribution of species of PM and vertical lifting and distribution of the plumes.

Role of ENSO

- Burning (hotspot counts and burning area AOD) in northern Indochina is greatly influenced by ENSO condition, but not for the extreme ENSO episode.
- Transportation of biomass burning plume is governed by the interaction of cold surge from East Asian monsoon and SCS anticyclone – ENSO might not be as conducive as other condition, but most conducive during the extreme ENSO period.
- Burning and emission control are important during both ENSO and extreme ENSO years; ENSO is prone to create dry environment for burning to sustain, extreme ENSO years is able to transport more emission to Mt Lulin.

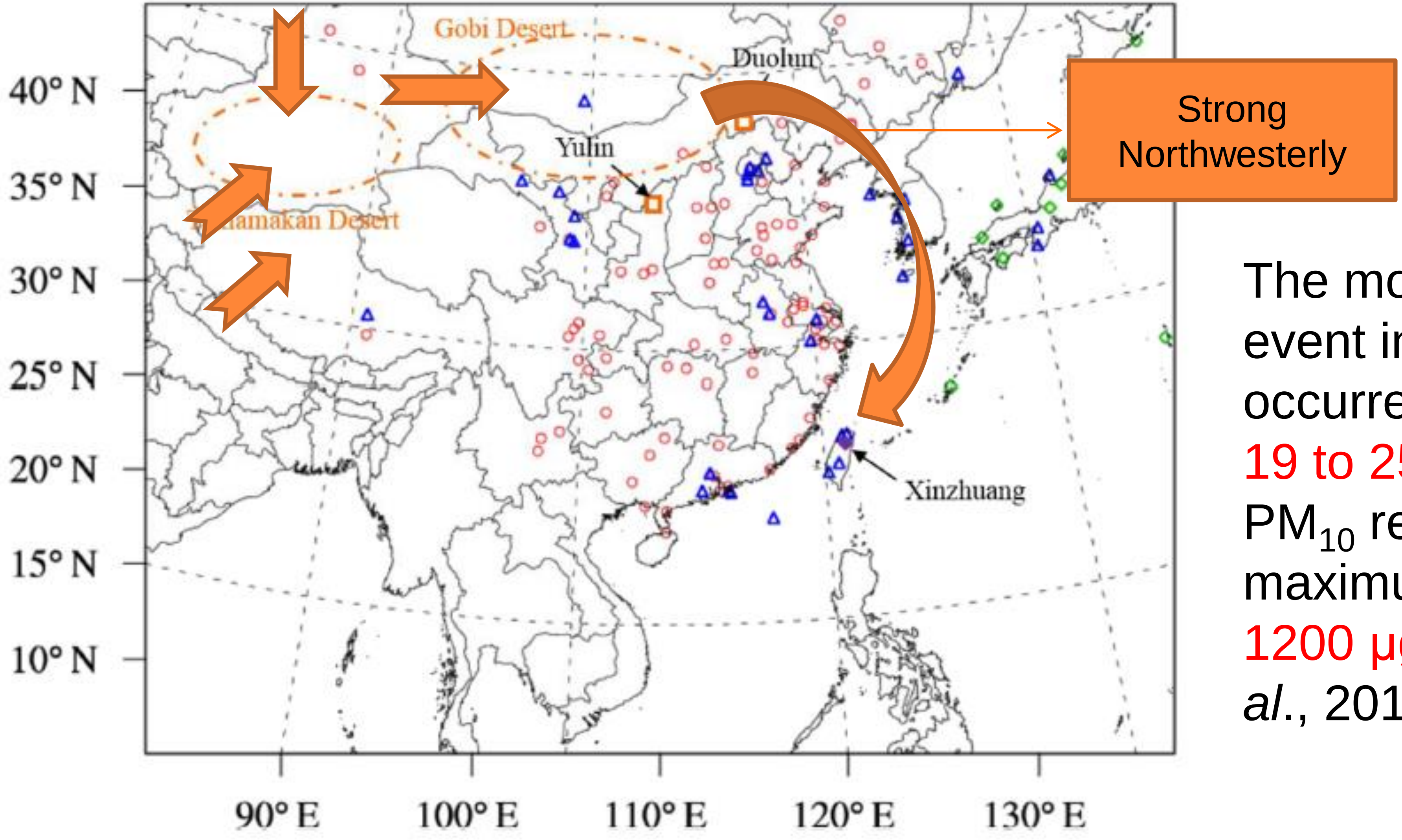
Part 3:
Simulating the impact of East Asian Dust Event during the Spring Season in Taiwan

Introduction

- Global source of mineral dust with diameters below 10um is between 1000 and 4000 Tg year^{-1} (IPCC, 2003).

- Mineral dust has been a great concern towards human beings as it carried huge impact on the earth's system. It brings important implication for air quality, reduced the visibility (Seinfeld *et al*., 2004) , change the earth's radiation budget (Miller *et al*., 2006), hydrological process (Zhao *et al*, 2011) and atmospheric chemistry (Dong *et al*., 2016 and Wang *et al*., 2012).

Dust transport route



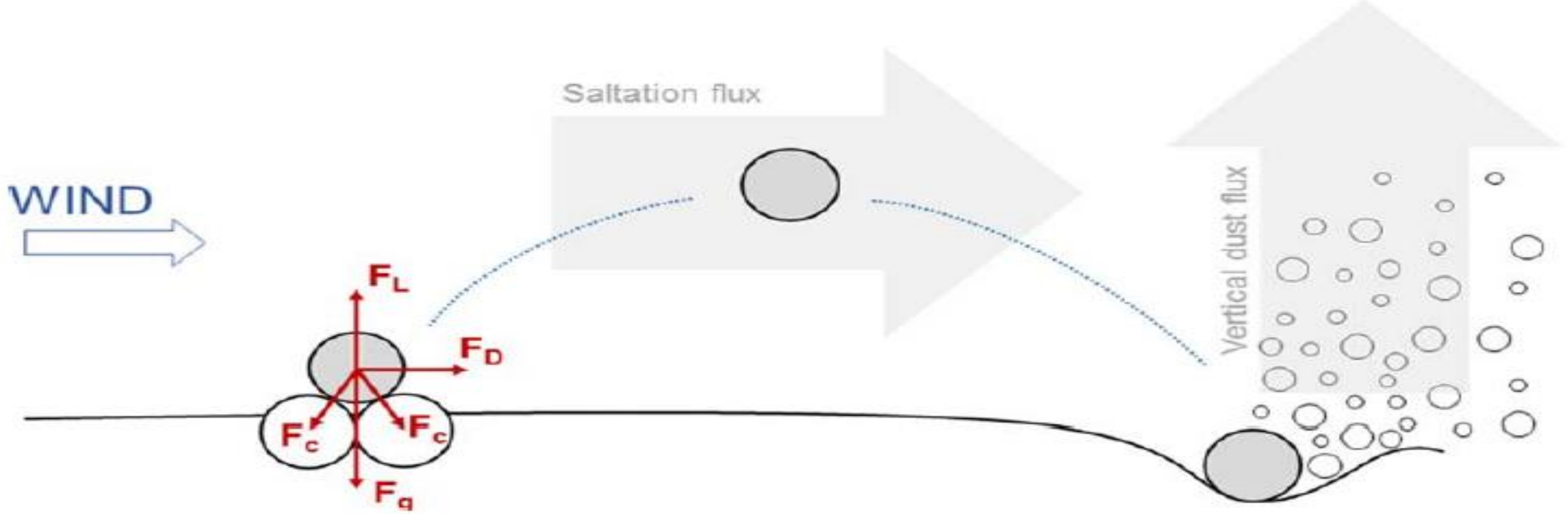
Shao & Dong (2006) and Dong et al. (2016)

The most severe dust event in Taiwan occurred from March 19 to 25, 2010 with PM_{10} reaching a maximum beyond 1200 μg m^{-3} (Tsai *et al.*, 2013).

Heavy dust event day

Dusty sky is seen amid a floating dust weather in downtown Taipei, southeast China's Taiwan, March 21, 2010. A sandstorm hit the island on Sunday. (Xinhua/Wu Ching-teng)

Physics-based windblown dust model



Update	Implication
Threshold Friction Velocity	More realistic values of the threshold velocity smoothly distributed
Roughness Factor	Include the effect of roughness elements (both solid and vegetation)
Surface Roughness Length	Develop a new relation for surface roughness from several different studies
Vegetation Cover	Spatially and temporally variable vegetation fraction based on satellite observation

(Foroutan *et al*., 2017)

FENGSHA dust emission scheme

Dust Emission Algorithm

The FENGSHA dust emission scheme is based on a modified Owen's equation:

Land use type Soil type Air density Soil erodible potential

Vertical flux

$$F = \sum_{i=1}^{M}\sum_{j=1}^{N} K \times A \times \frac{\rho}{g} \times S_i \times SEP \times u_* \times (u_*^2 - u_{*ti,j}^2)$$

Constants Land use type Friction velocity Threshold friction velocity

(Tong *et al.*, 2011)

Threshold Friction Velocity (1)

$$u_{*,t} = u_{*,t0} \; f_m \; f_r \qquad (1)$$

Where $u_{*,t}$ is the threshold friction velocity, $u_{*,t0}$ is the ideal threshold friction velocity, f_m and f_r are the correction factor of the soil moisture and surface roughness.

$$u_{*,t0}(D) = \sqrt{A_N \left(\frac{\rho_p g D}{\rho_a} + \frac{\Gamma}{\rho_a D} \right)} \qquad (2)$$

Where D is the sand particle diameter, p_p and p_a are the particles and air densities, A_N and ɼ are being set as 0.0123 and 1.65×10^{-4} kg/s^2 respectively.

Friction Velocity (1)

$$u_* = \frac{\kappa u_z}{\ln\left(\frac{z}{z_0}\right)} \tag{7}$$

Where u_z is the wind speed at the reference height, K is the von Karman constant, z_0 is the surface roughness length.

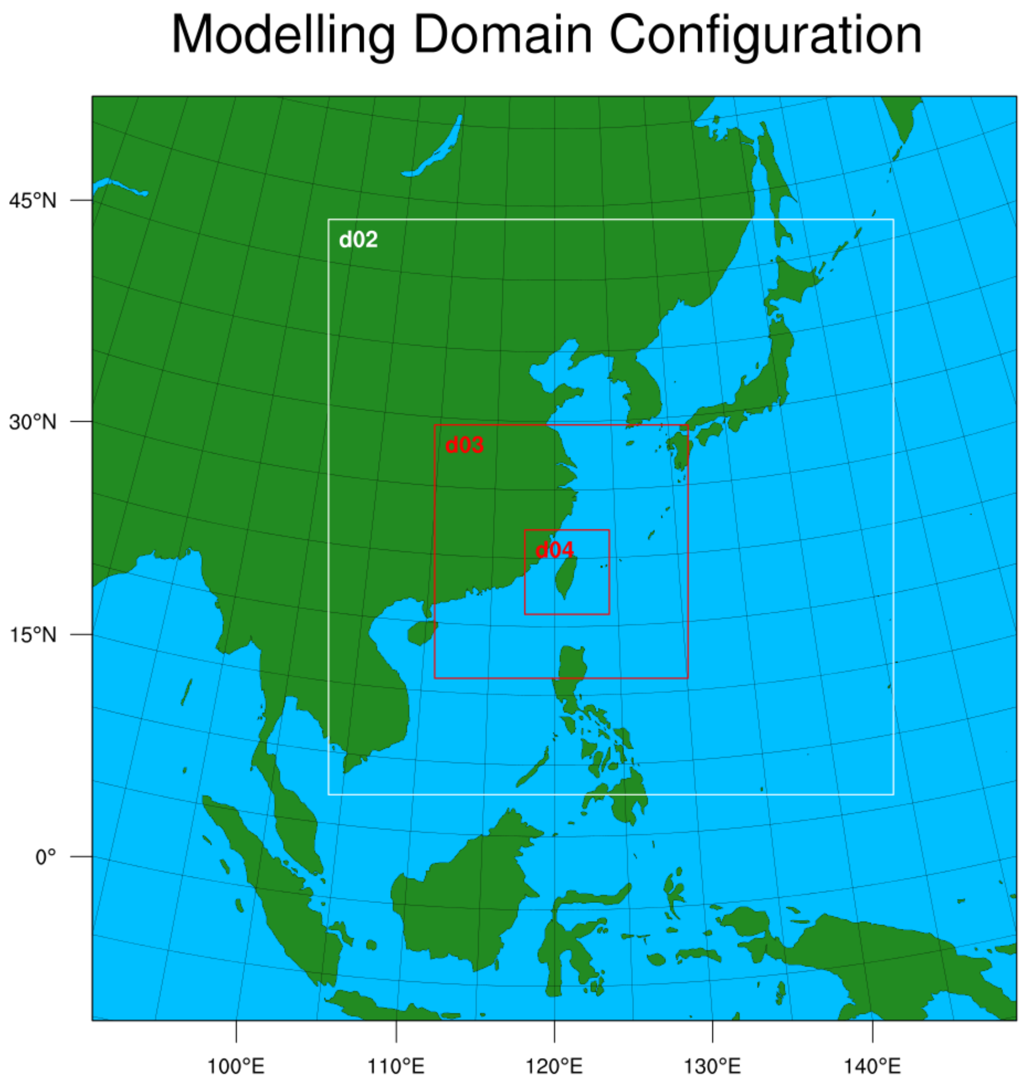
z can be obtained from mesoscale atmospheric model (WRF), with modeled wind speed at 10 m (z=10m).

The friction velocity from WRF using a predefined aerodynamic roughness length z_0 , which is significantly higher than the 'microscopic length' relevant to dust generation.

Objectives

- To examine the performance of the new physic based dust model in projecting the dust event, by comparing with the ground measurement.
- To optimize the performance of the dust model.
- To propose an effective method in projecting the dust event in East Asia region.

Model settings:



- Horizontal Resolution:
  81km,27km,9km,3km
- NCEP GFS Global Forecast System
- Taiwan Emission Database (TEDS9.0)

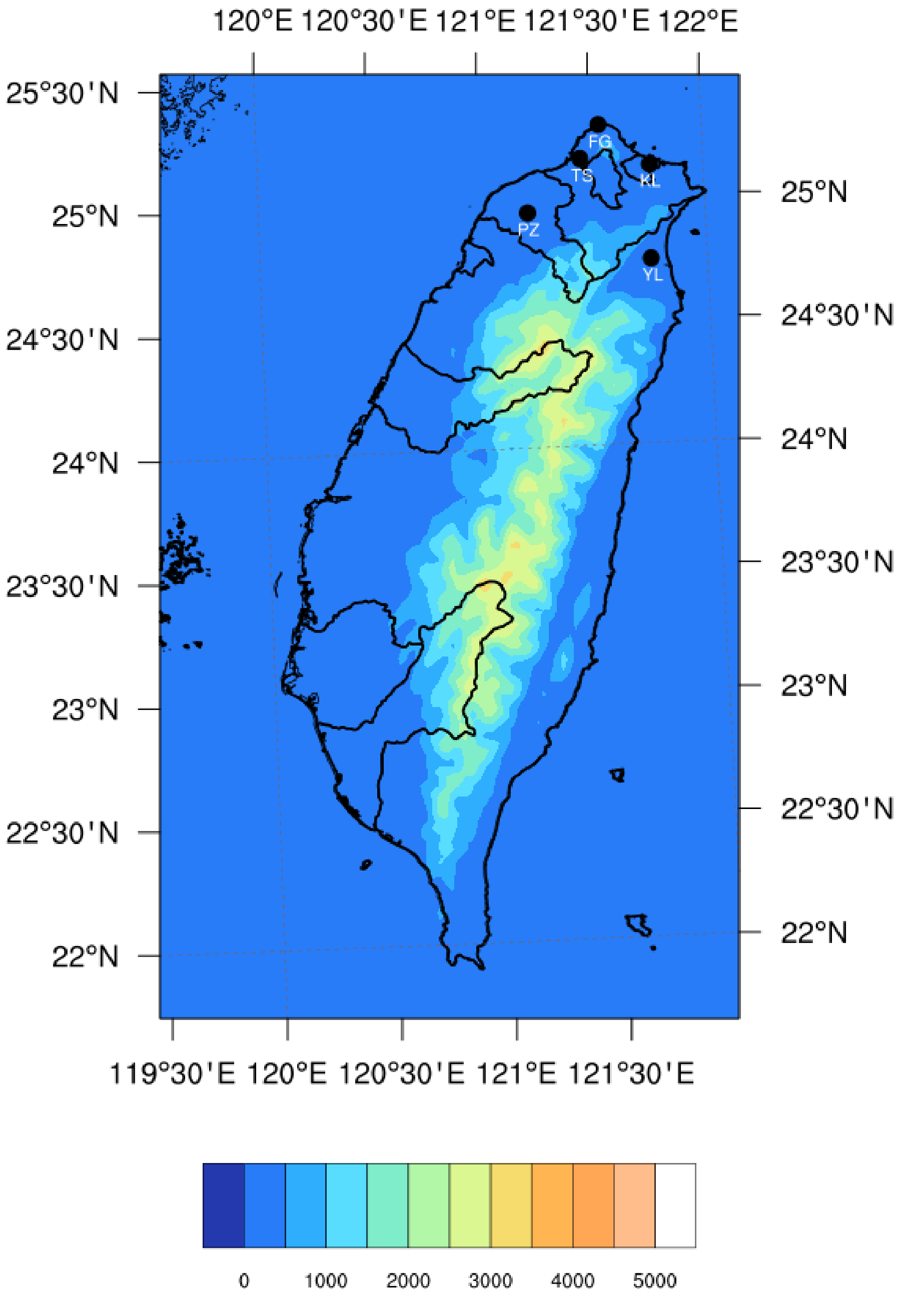
- Carbon Bond mechanism (CB05e51) for gas-phase chemistry
- AERO6 aerosol module
- In-line photolysis calculation
- In-line windblown dust scheme

Simulation scenarios

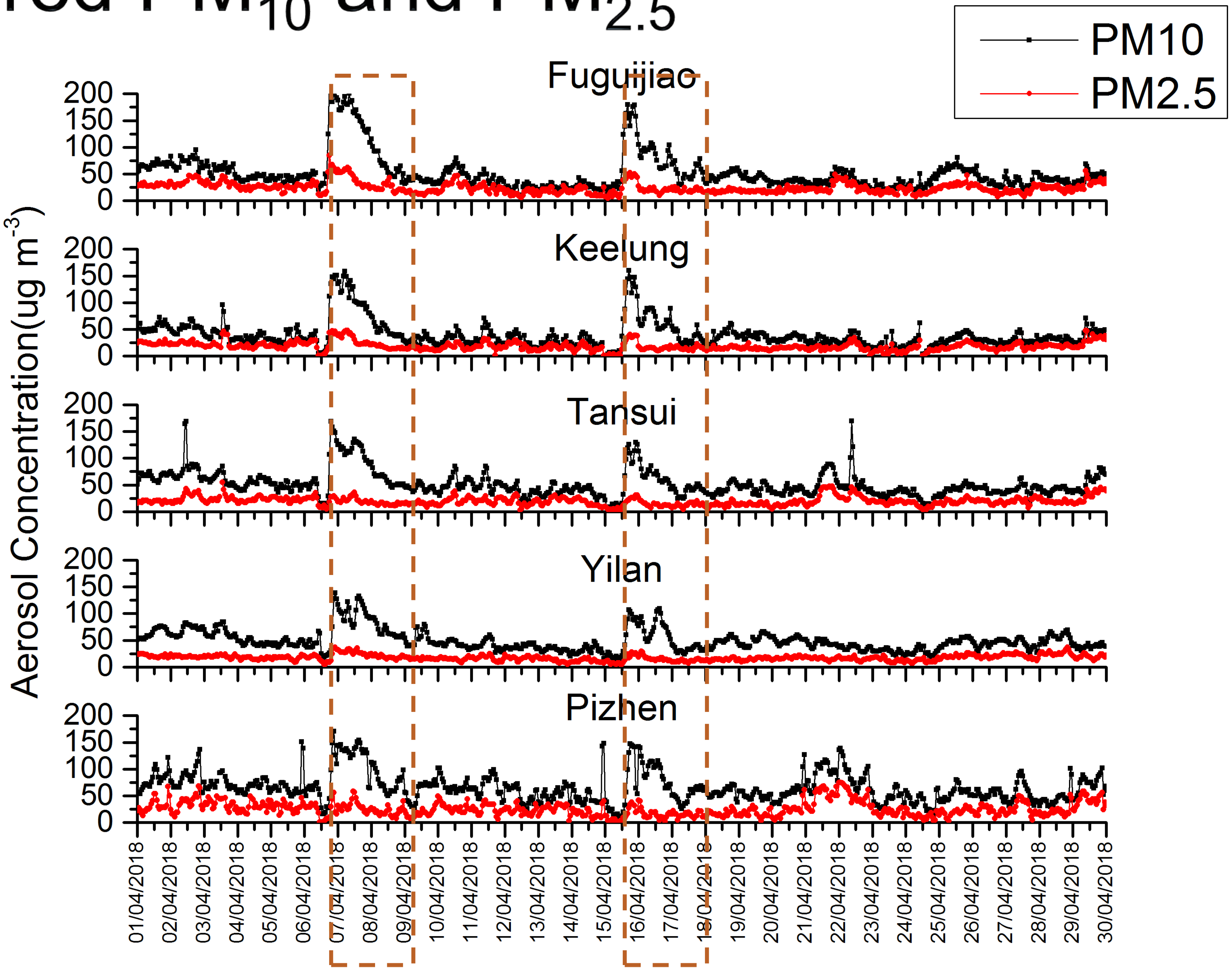
Scenarios	Descriptions
DUST_Off	Without in-line calculation of dust
DUST_Default	With default wind-blown dust emission scheme (Foroutan et al., 2017)
DUST_Revised_1	Revised the threshold friction velocity through removing the double counting of soil moisture. (Dong et al., 2016)
DUST_Revised_2	Revised the ideal threshold friction velocity based on Chinese data ($u'_{*,ti,j}$ ≈ 0.3 and PM2.5/PM10 = 0.1) (Fu et al., 2014)
DUST_Revised_3	Combining both CMAQ_Revised_1 and CMAQ_Revised_2

Observation sites

- Chosen to be in the northern Taiwan
- The first points that captured the entrance of dust to Taiwan
- Marked in dots on map

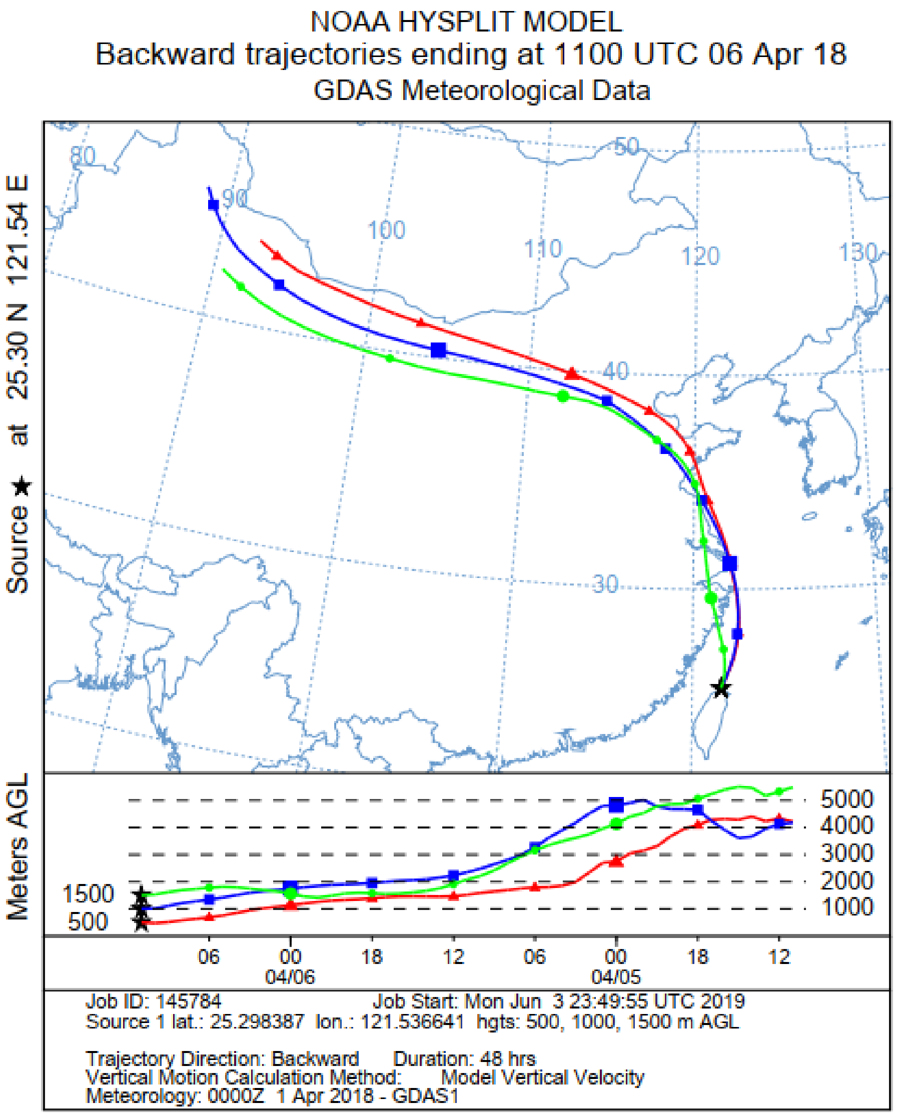


Measured PM_{10} and $PM_{2.5}$

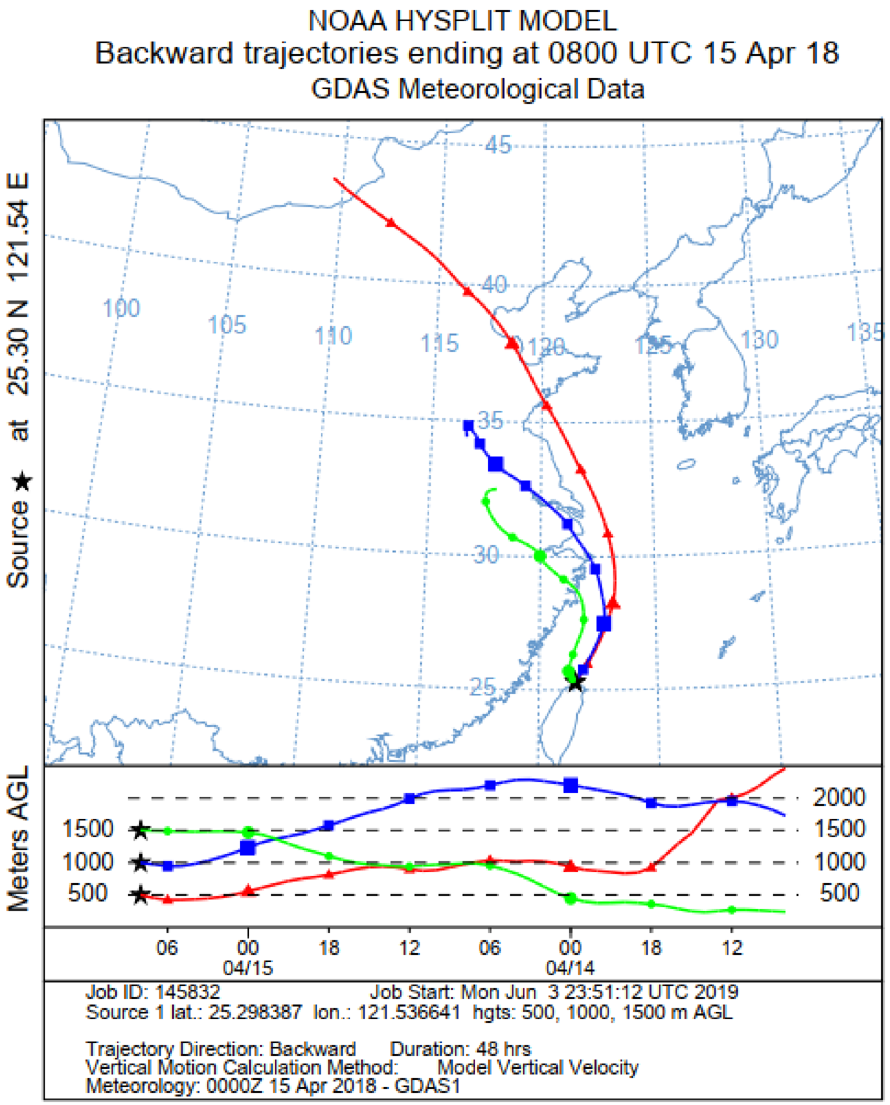


Backward Trajectories

Station 1

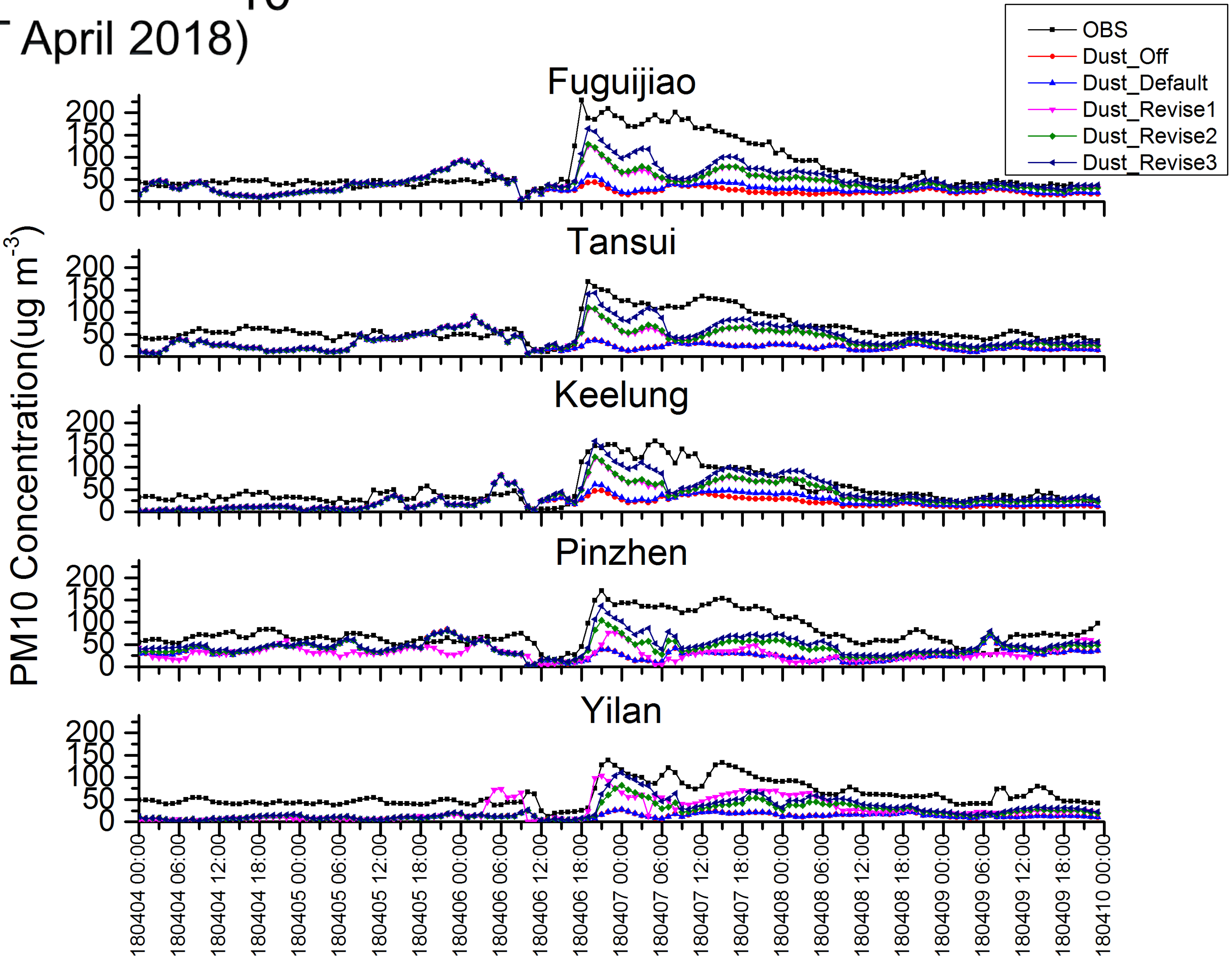


Station 2



Modelled PM_{10}

(04-09 LST April 2018)



CMAQ Model Evaluation for PM_{10}

(6 days simulation ~ 04-09 April 2018)

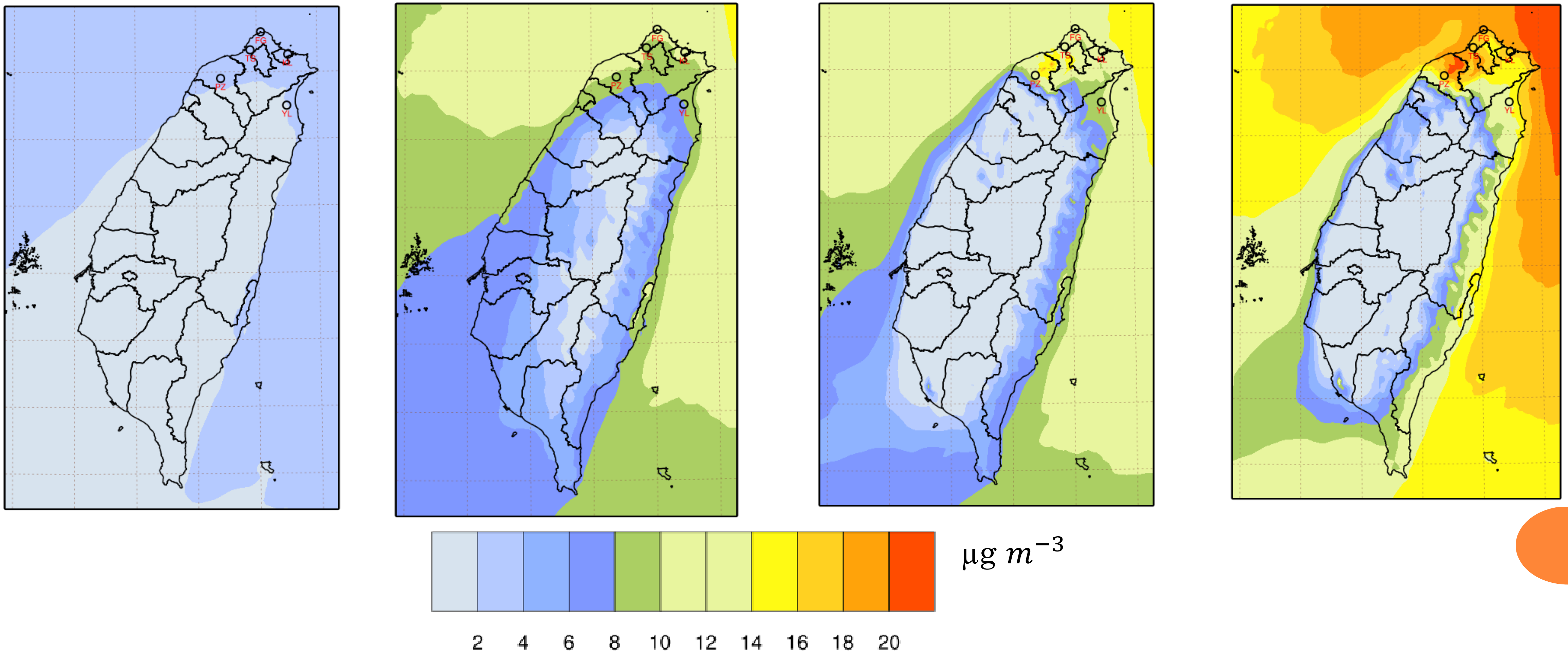
Index	Benchmark	Simulation Scenarios				
		OFF	*Default*	*Revised_1*	*Revised_2*	*Revised_3*
MeanObs		72.92	72.92	72.92	72.92	72.92
MeanMod		29.79	32.93	43.69	44.18	51.42
MNB	*Range: -50% +80%*	-41.30	-37.59	-25.87	-25.49	-17.50
MNE	*1.50*	0.55	0.52	0.41	0.41	0.35
NMB	± *85%*	-59.15	-54.84	-40.09	-39.41	-29.48
NME	< *85%*	59.15	54.84	40.09	39.41	29.48
IOA	> *0.6*	0.82	0.85	0.94	0.94	0.97
R	> *0.35*	-0.05	0.11	0.63	0.65	0.76
FAC2		0.59	0.62	0.74	0.75	0.83

Difference of Model output with Dust Off

Taiwan domain (d04)

DUST_Default **DUST_Revised_1** **DUST_Revised_2** **DUST_Revised_3**

Minus DUST_off

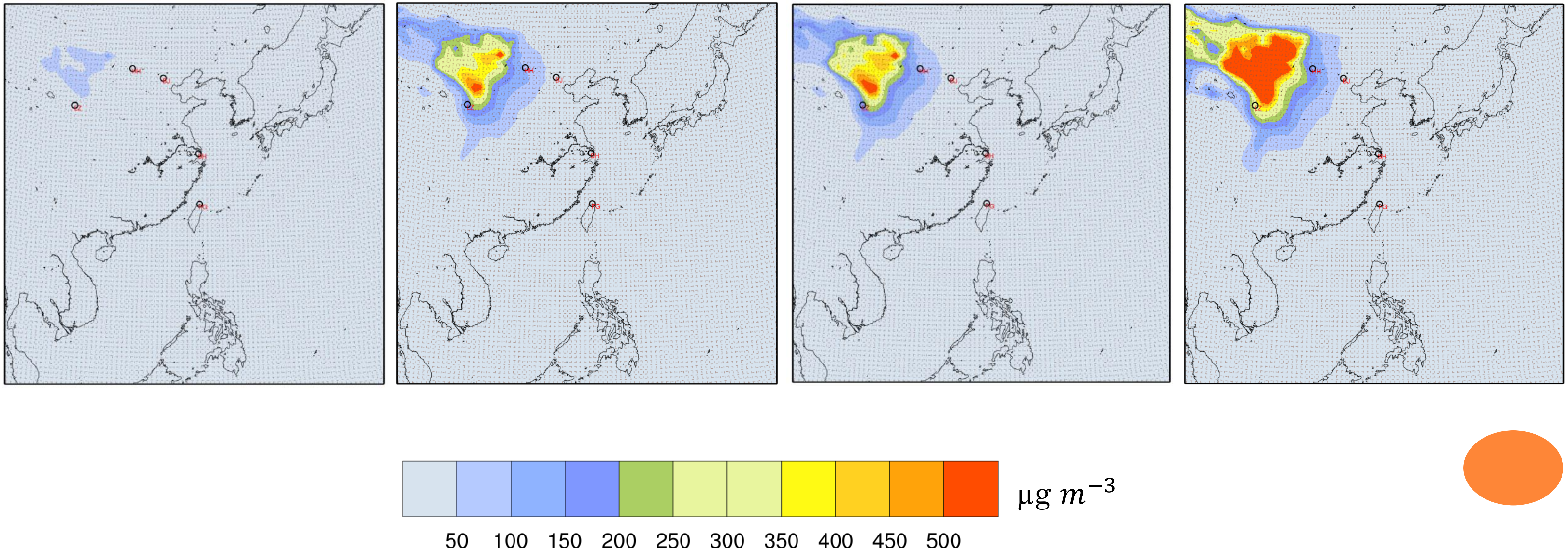


Difference of Model output with Dust Off

East Asia *domain (d02)*

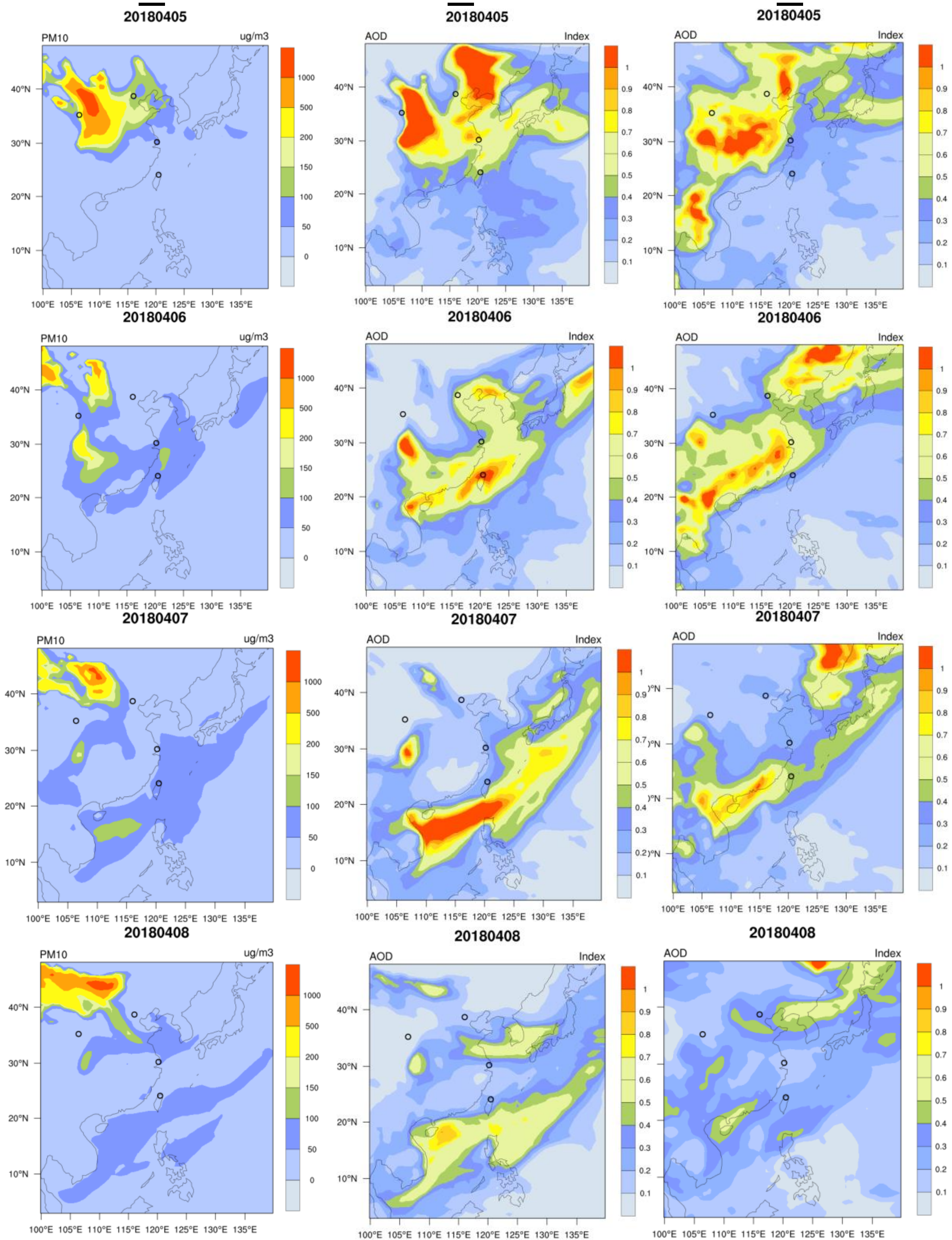
DUST_Default **DUST_Revised_1** **DUST_Revised_2** **DUST_Revised_3**

Minus DUST_off

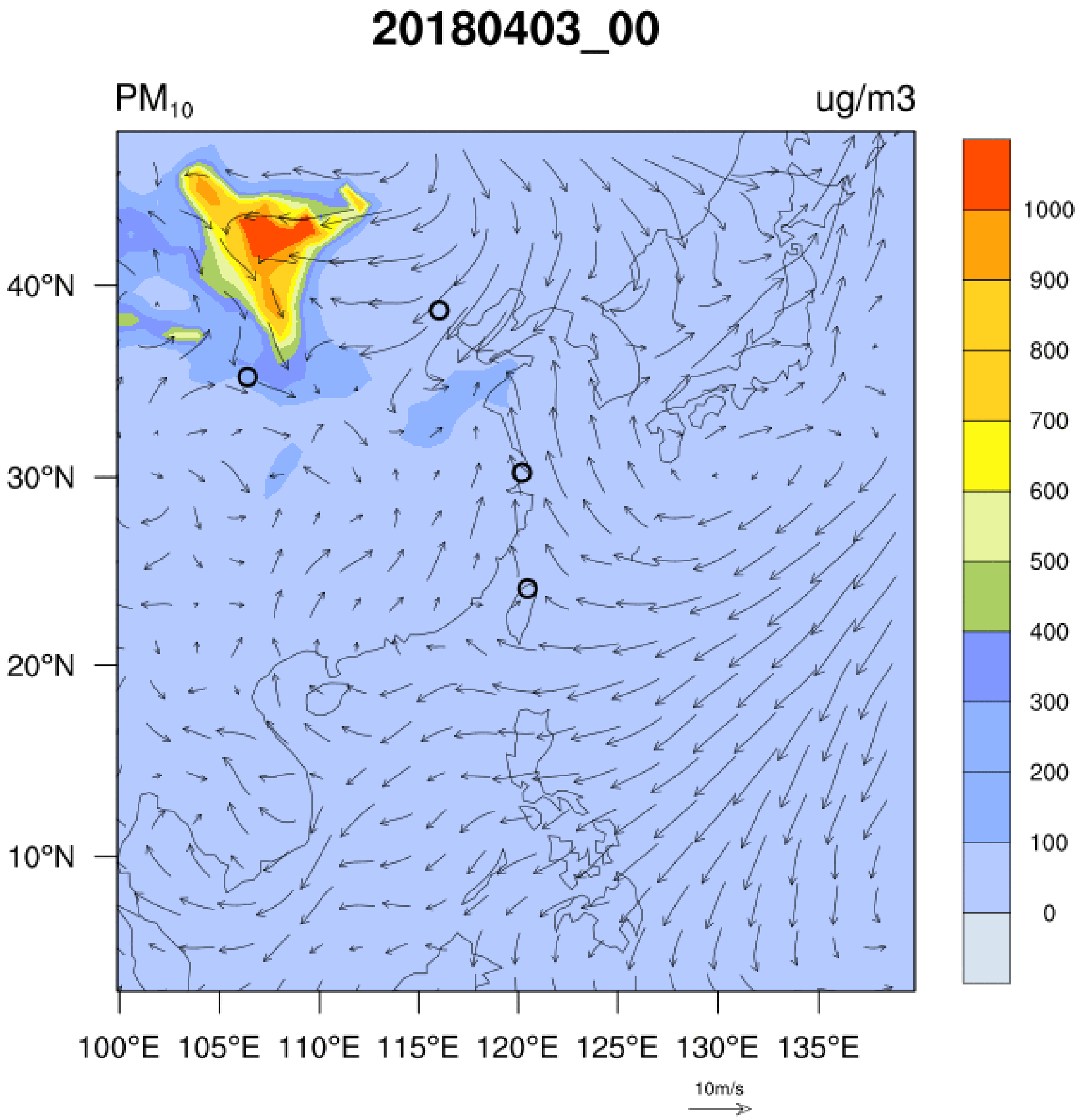


Comparing between CCTM and MERRA

PM10_CCTM AOD_CCTM AOD_Merra



Source and Transport of Dust Event



Conclusion

- As summary, the present work indicates a general good performance between the newly developed wind-blown dust treatment in CMAQ and observations.
- A significant improvement was found with the revised dust scheme as compared to the CMAQ_Nodust and CMAQ_Defaultdust.
- This result suggested that the CMAQ_REVISED_3 is a useful tool to analysis the dust events in Taiwan.

Part 4:
NCU Air Quality Modelling Forecast System

Introduction

- The Real-Time Air Quality Forecast (RT-AQF) system that is based on a three-dimensional air quality model provides a powerful tool to forecast air quality and advise the public with proper preventive actions (Chuang et al., 2011).
- Similar domain is adopted as shown in the DUST transport model setup

How to run a forecast?

- The National Center for Environmental Prediction's (NCEP) meteorological forecast is downloaded at 7 PM (Local Standard Time) to initialize a 120-h forecasting cycle.
- The forecasts during the first 24-h of each 120-h cycle are for spin-up and not used for real-time forecasts. The forecasts during the remaining 96-h are used to provide a four-day forecast.
- This process of data-downloading and 96-h forecasting is repeated every day.
- Website (Click here.)

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THANK YOU !