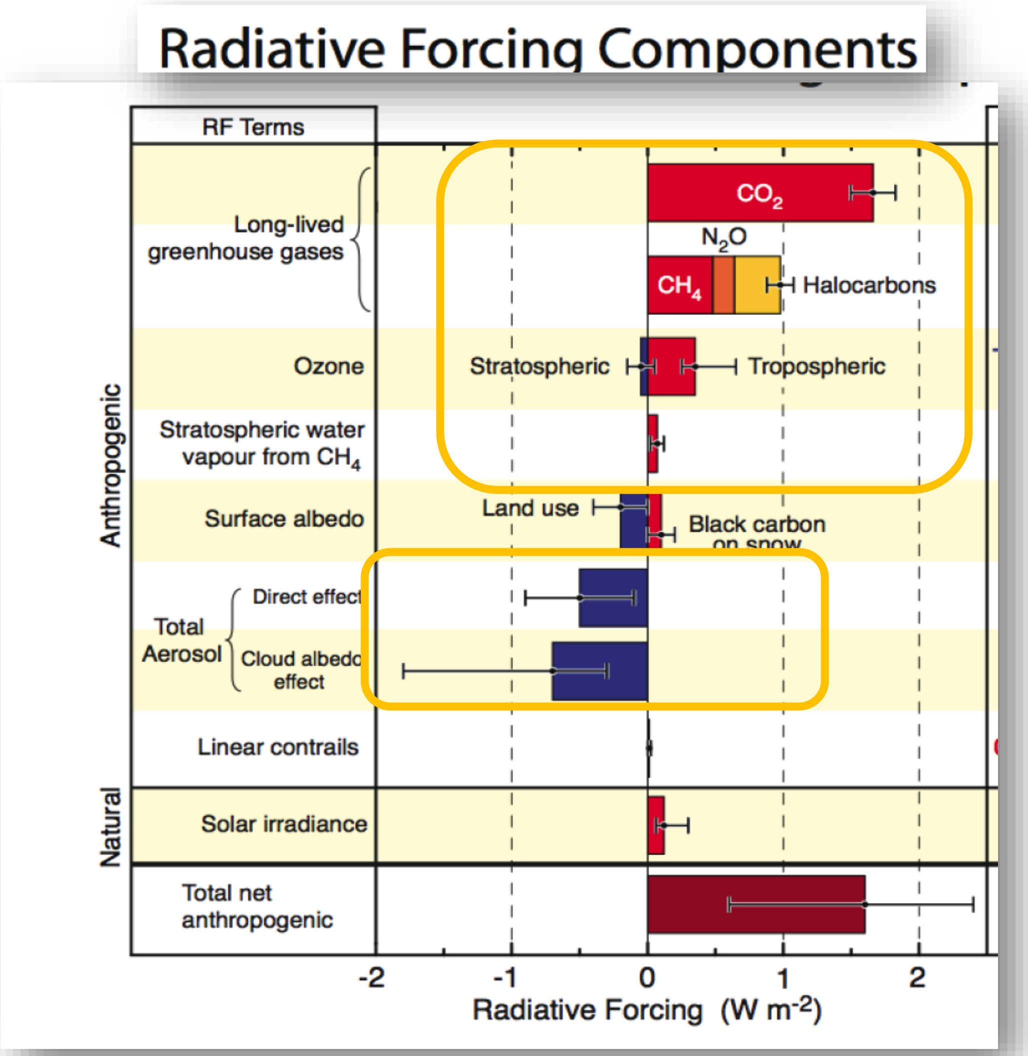
Numerical simulation on extreme weather, air pollution and environmental changes

Chuan-Yao Lin

Research Center for Environmental Changes, Academia Sinica, Taiwan

Deeper Understanding of Natural Disasters: Joint DMCC, UMD & Environmental Computing Workshop
March, 24, 2021

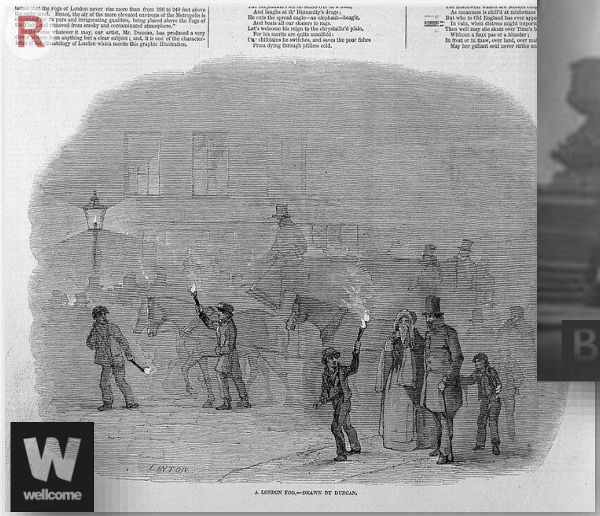
Air pollution and climate



- Significant climate forcing by “chemically active” species
- They are most amenable to short-term relief
- Climate Change Impact felt through Chemistry! (e.g., change in air pollution).

IPCC AR-4 Exec. Summary

Historical events…….



London, 1847

London, 1952

Los Angeles, 1964

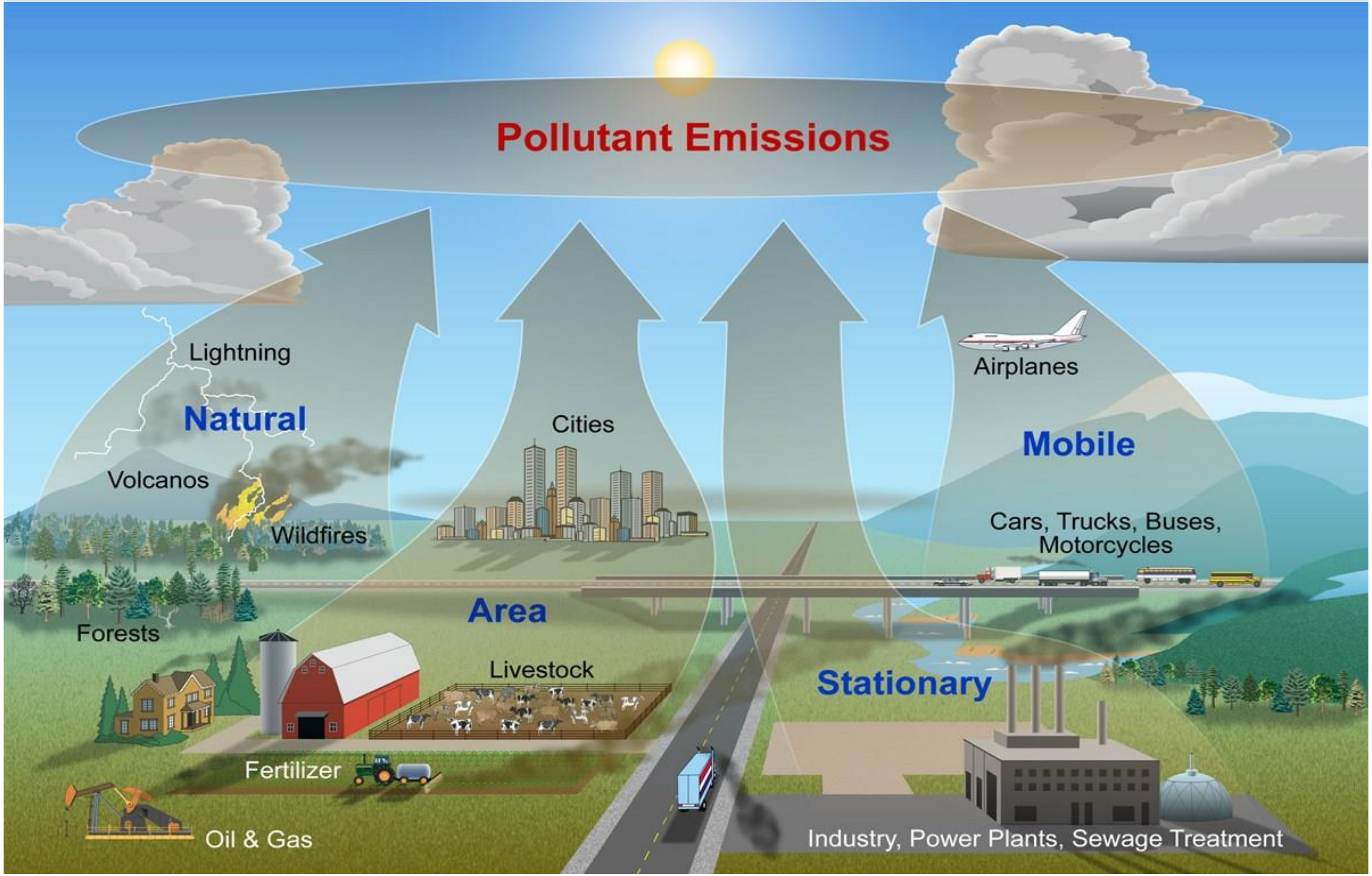
Paris, 2015

Beijing, 2015

New Delhi, 2019

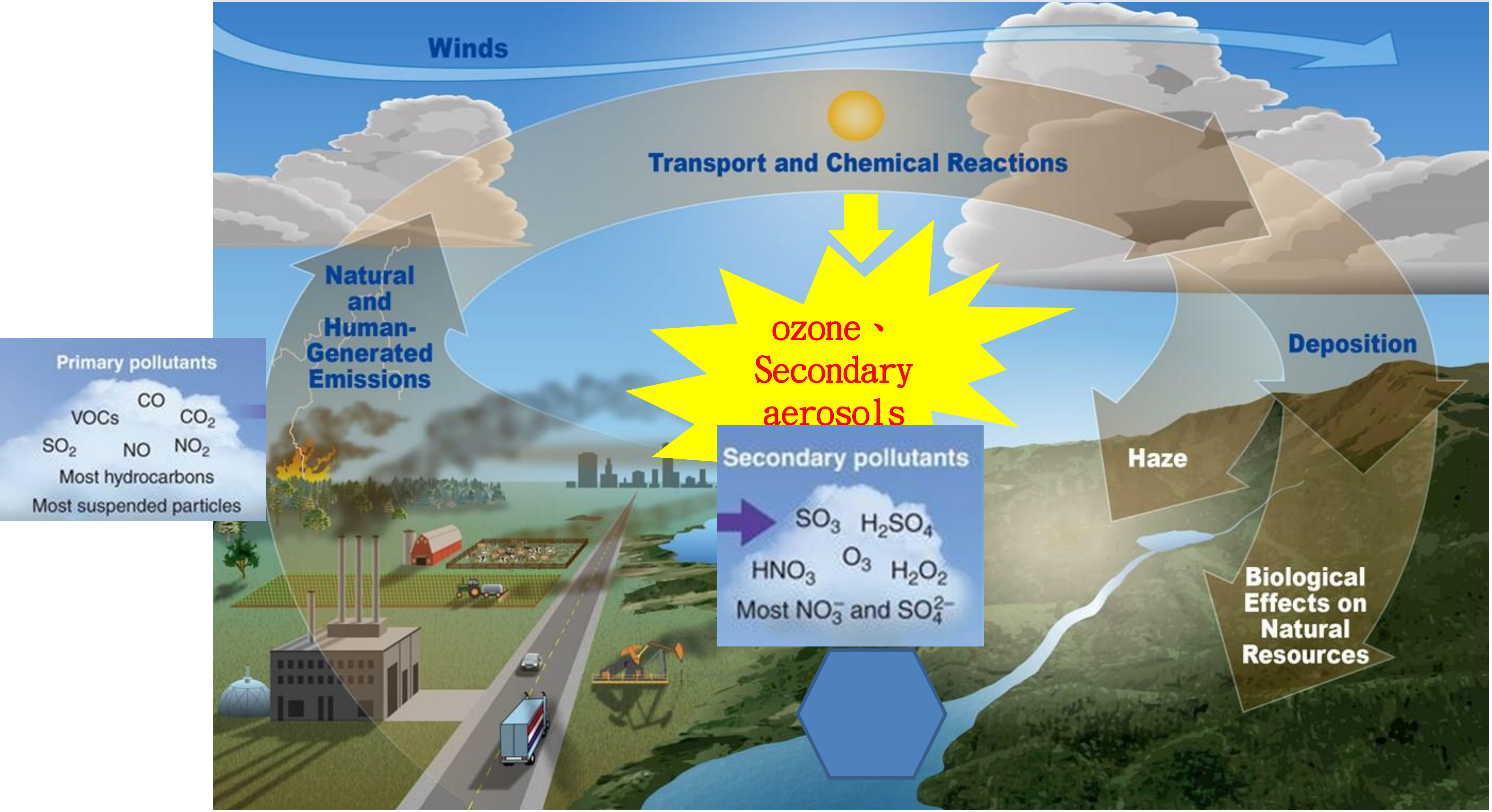
Kaohsiung, 2019

Sources of air pollutants



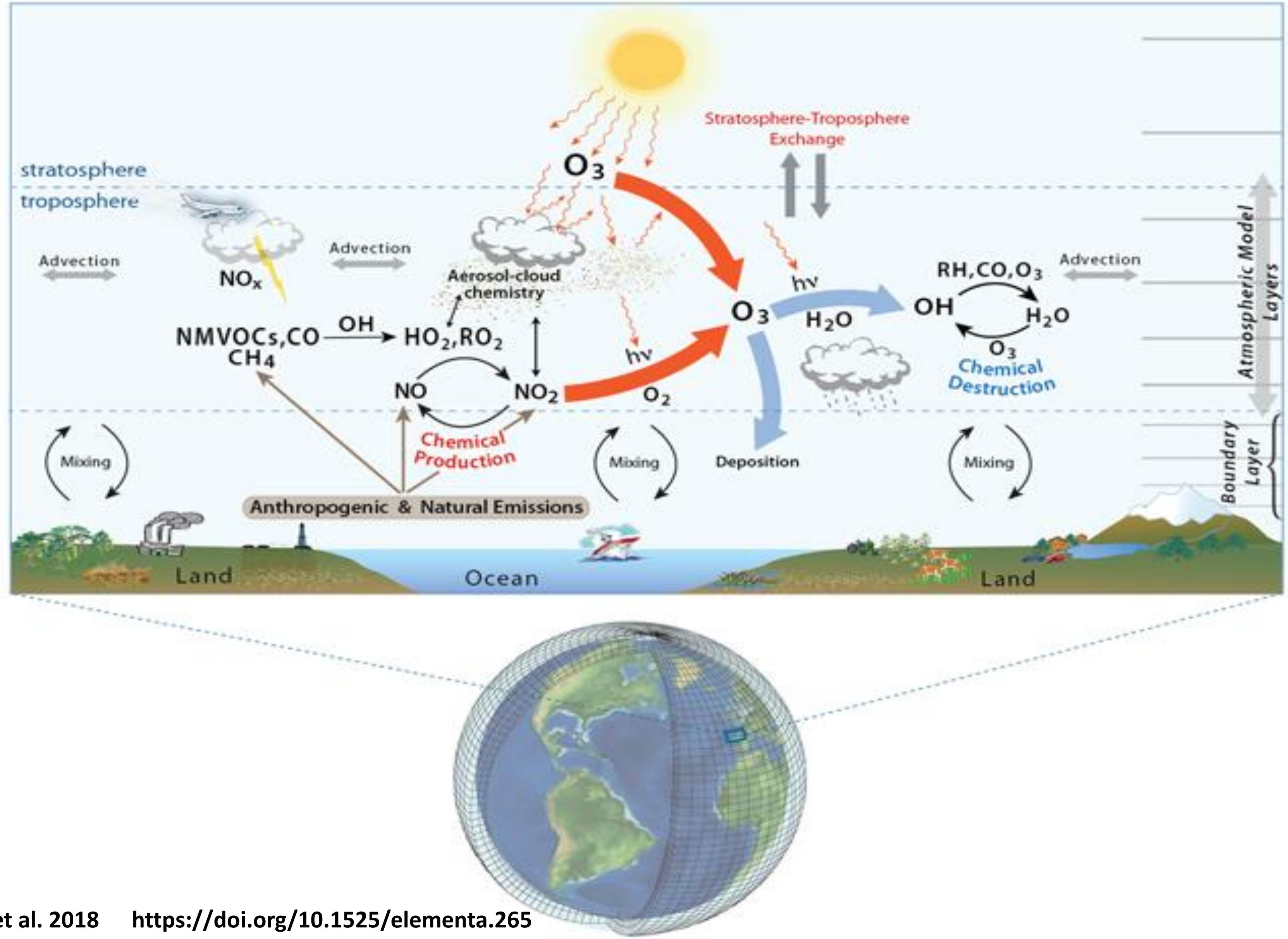
https://www.nps.gov/subjects/air/sources.htm

Sources of air pollutants



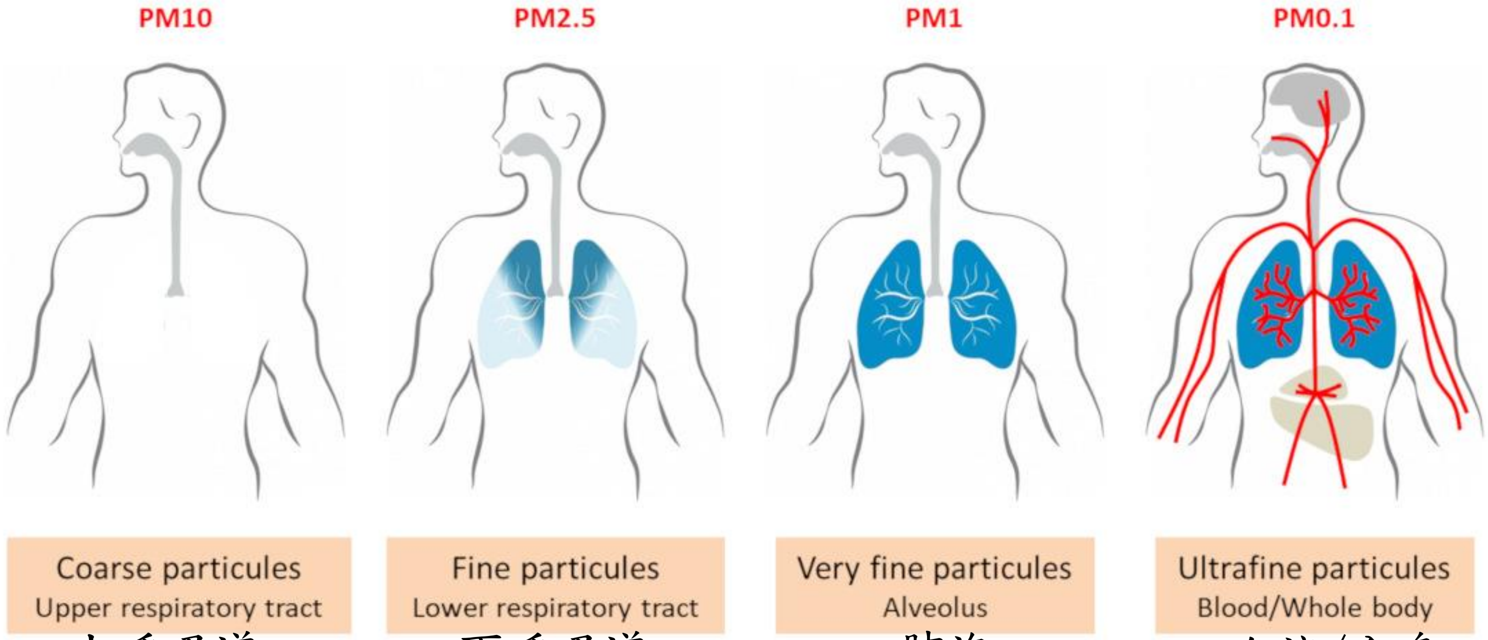
https://www.nps.gov/subjects/air/sources.htm

Sources of air pollutants

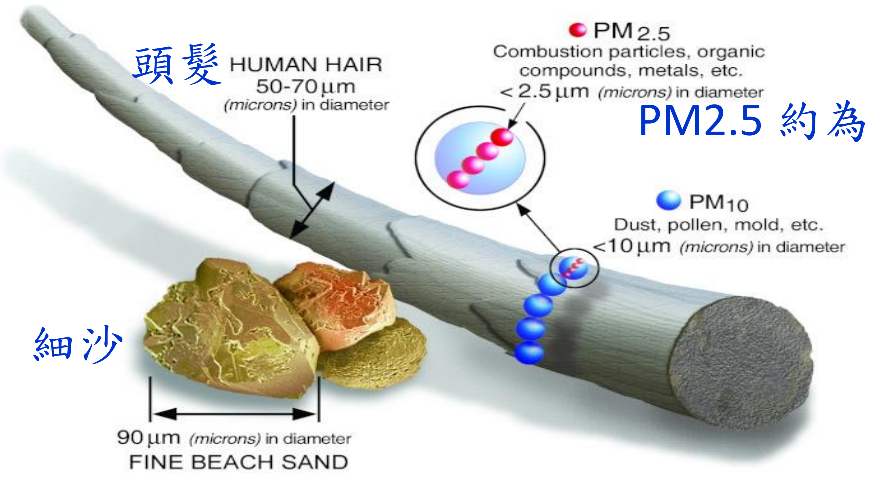


Young, PJ, et al. 2018 https://doi.org/10.1525/elementa.265

Health effects

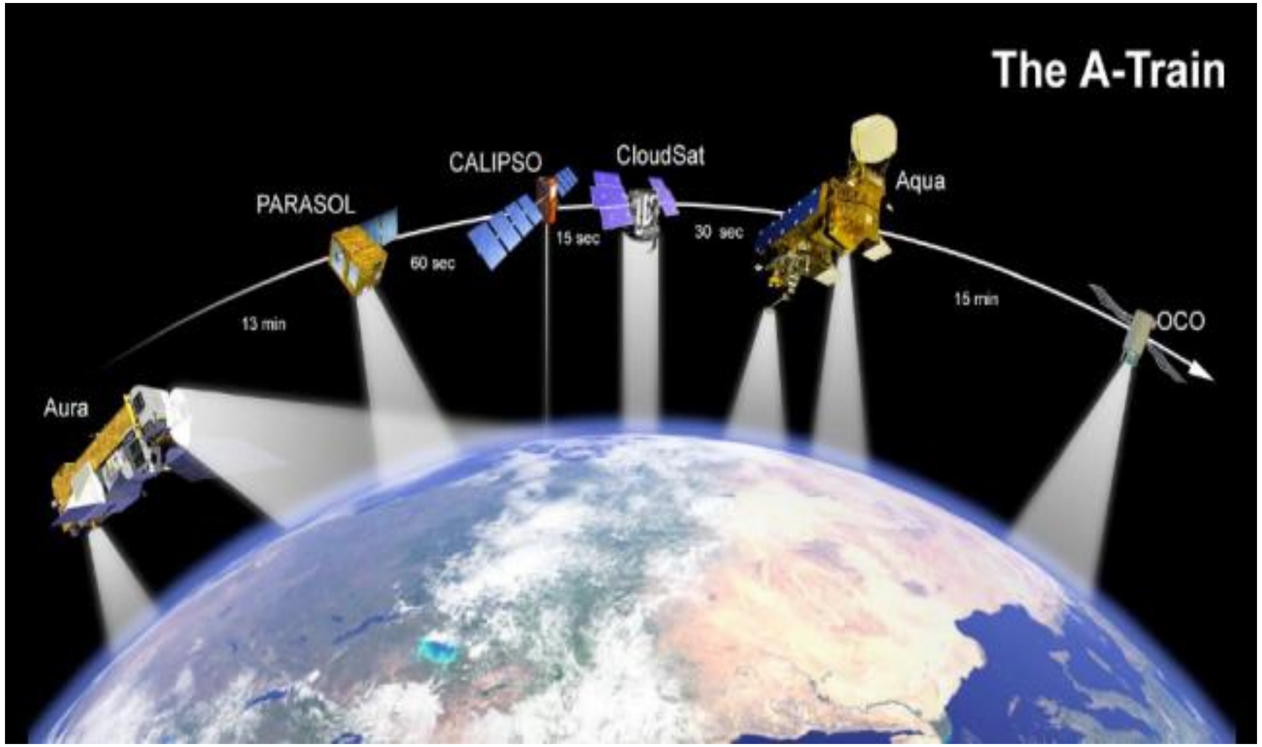


上呼吸道　下呼吸道　肺泡　血液/全身

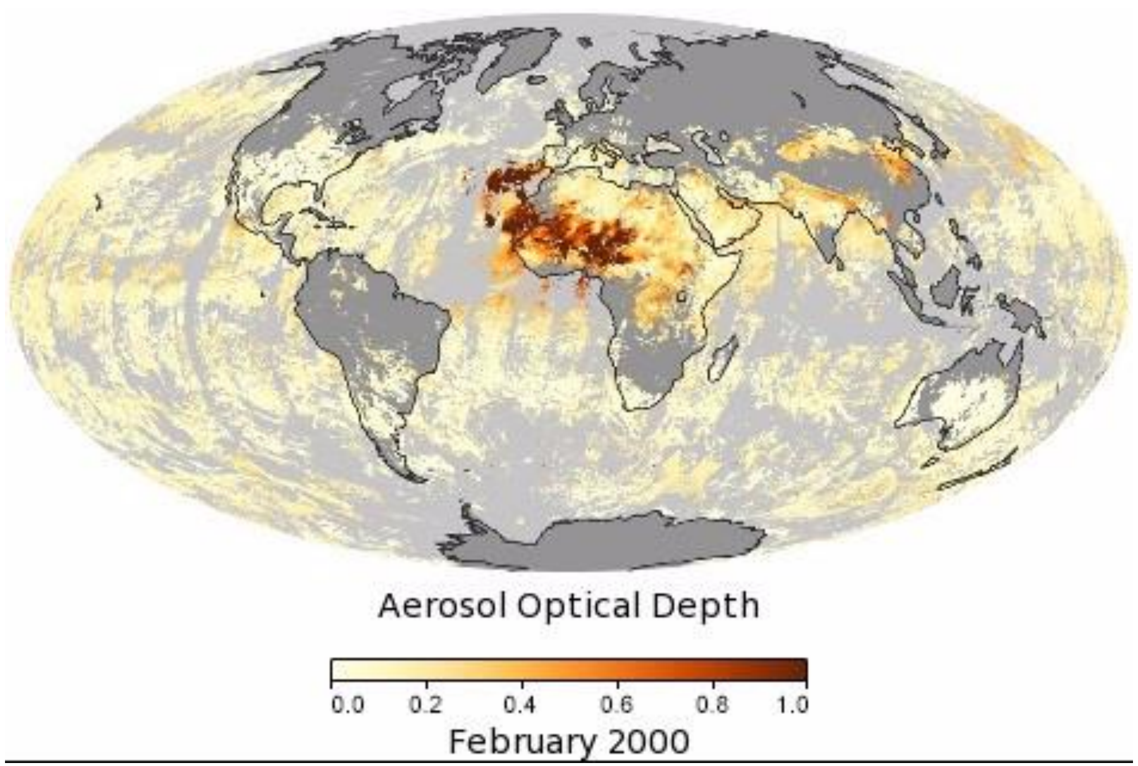


https://www.encyclopedie-environnement.org/en/health/airborne-particulate-health-effects/

Measurement from Satellite



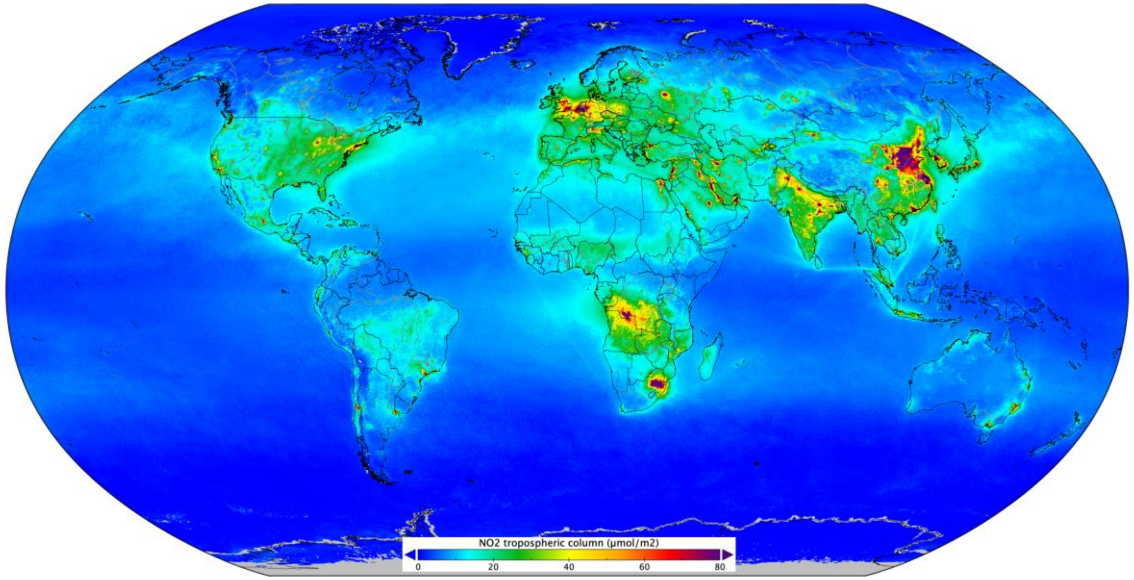
氣膠光學厚度
from MODIS satellite



These maps show average monthly aerosol amounts around the world based on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite.

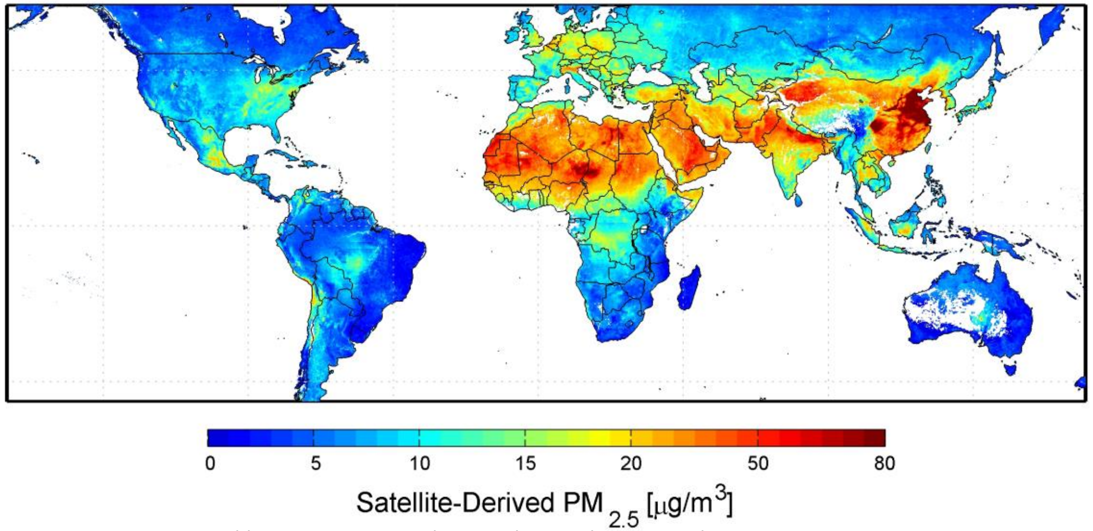
Worldwide air pollution

NO2



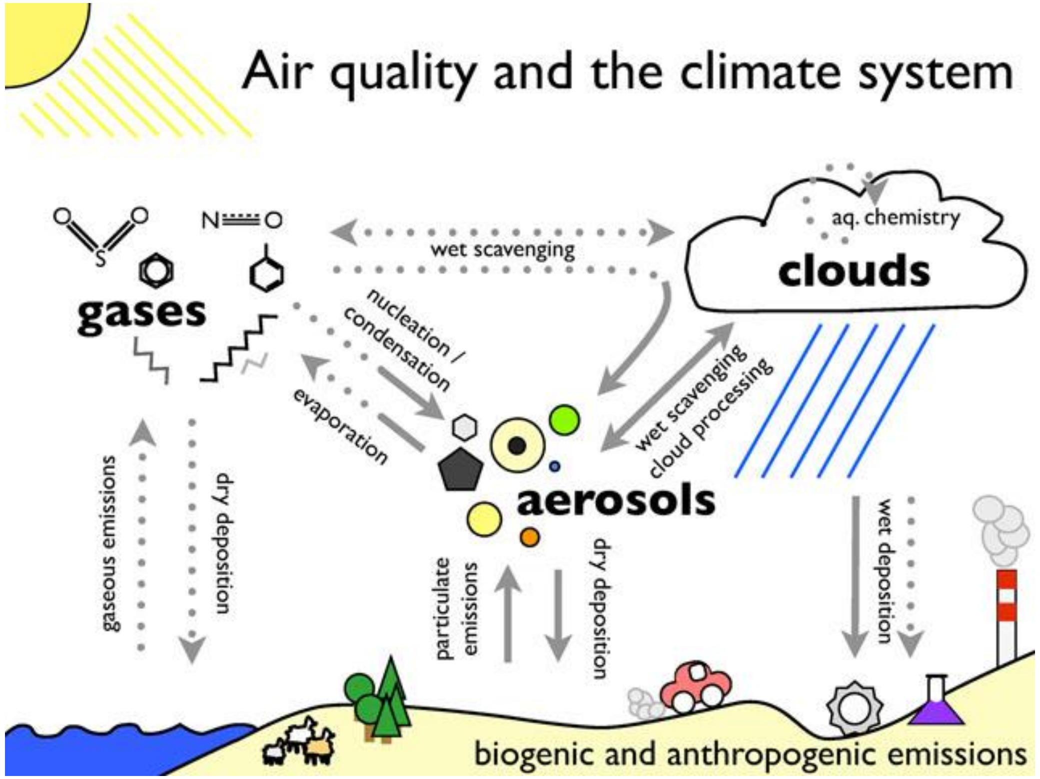
(https://www.esa.int/ESA_Multimedia/Images/2019/03/Nitrogen_dioxide_worldwide)

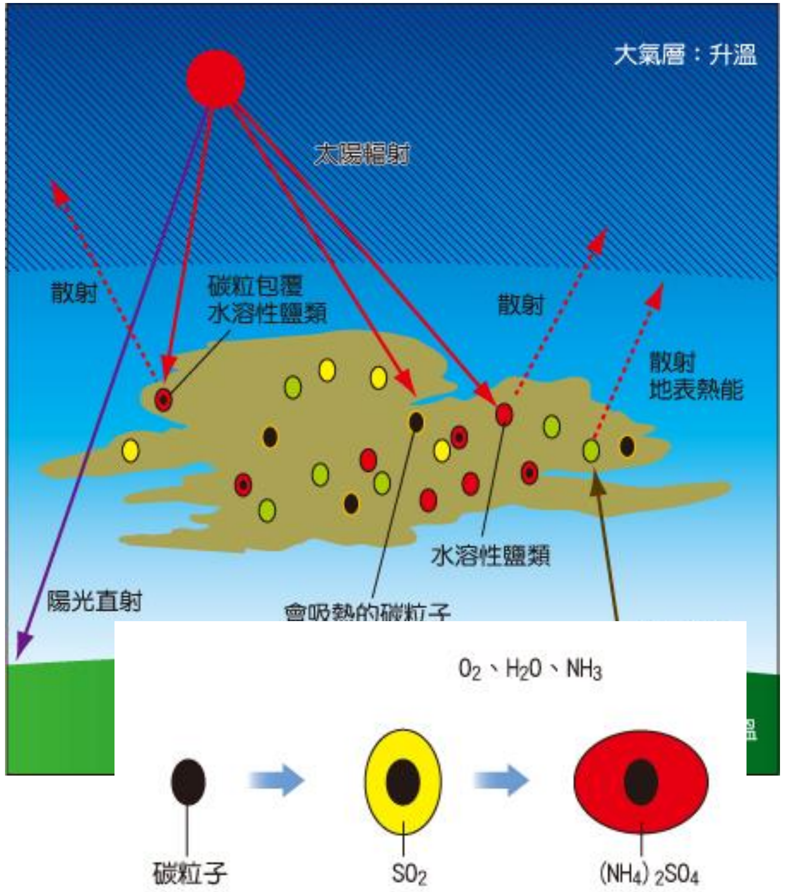
PM2.5



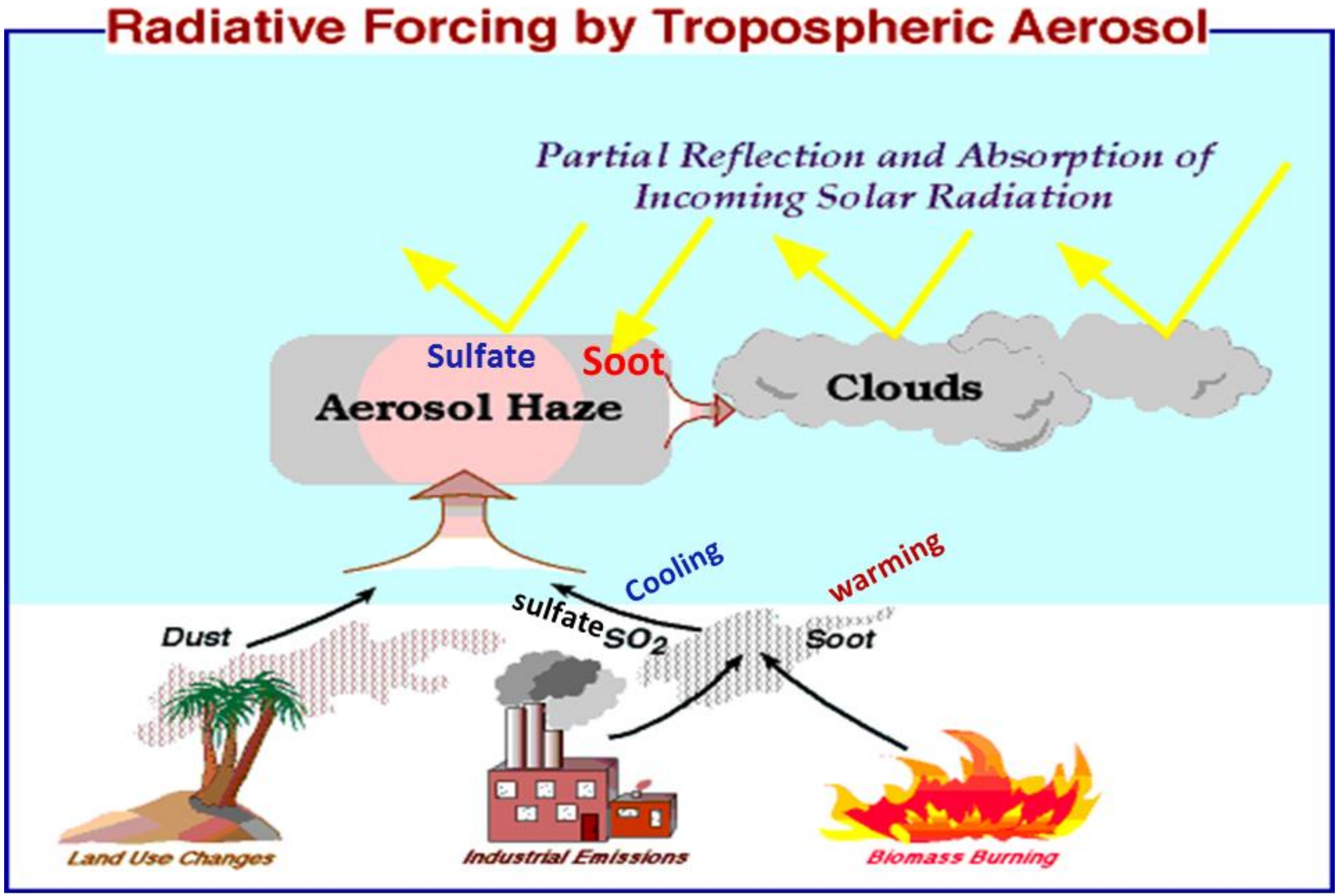
(https://www.nasa.gov/topics/earth/features/health-sapping.html)

Aerosol、cloud and climate change



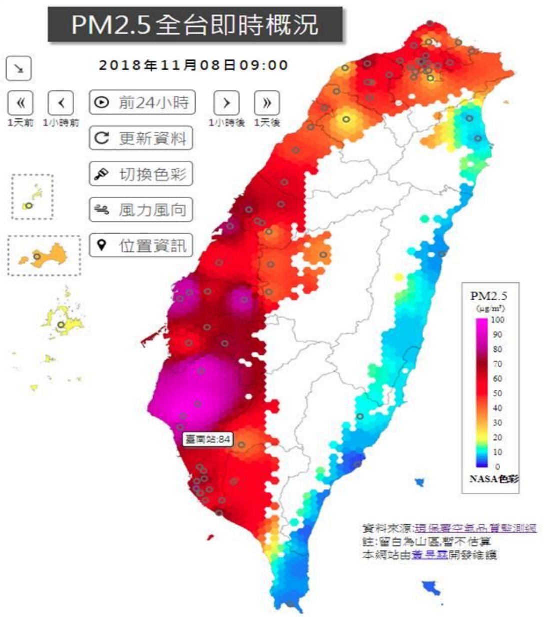


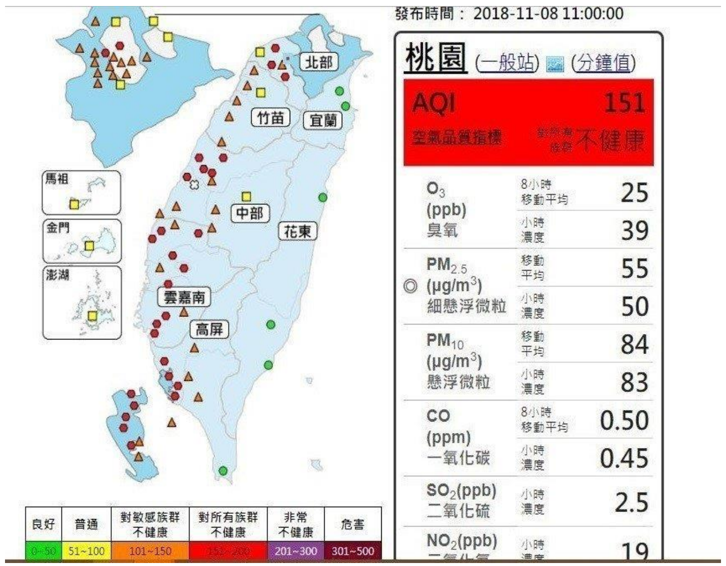
http://sa.ylib.com/MagArticle.aspx?Unit=easylearn&id=1489



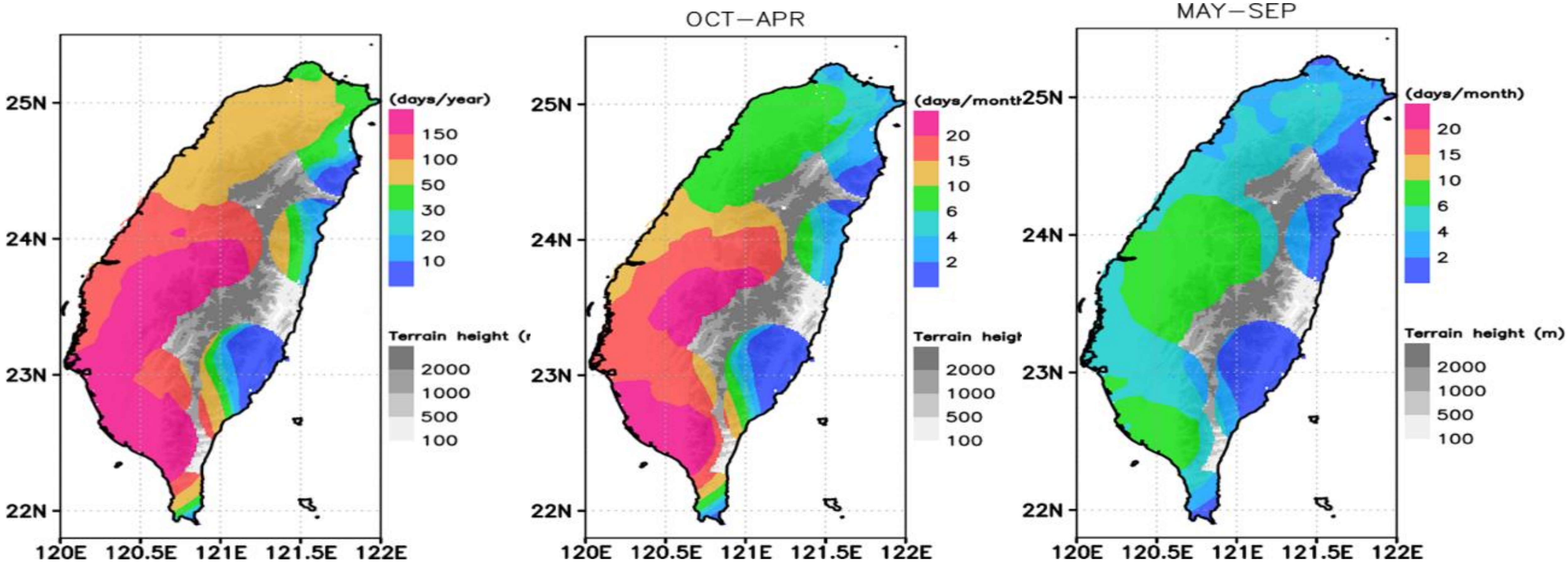
https://static.secure.website/wscfus/8025341/uploads/Aerosols_NOAA_plus.png

Air pollution in Taiwan

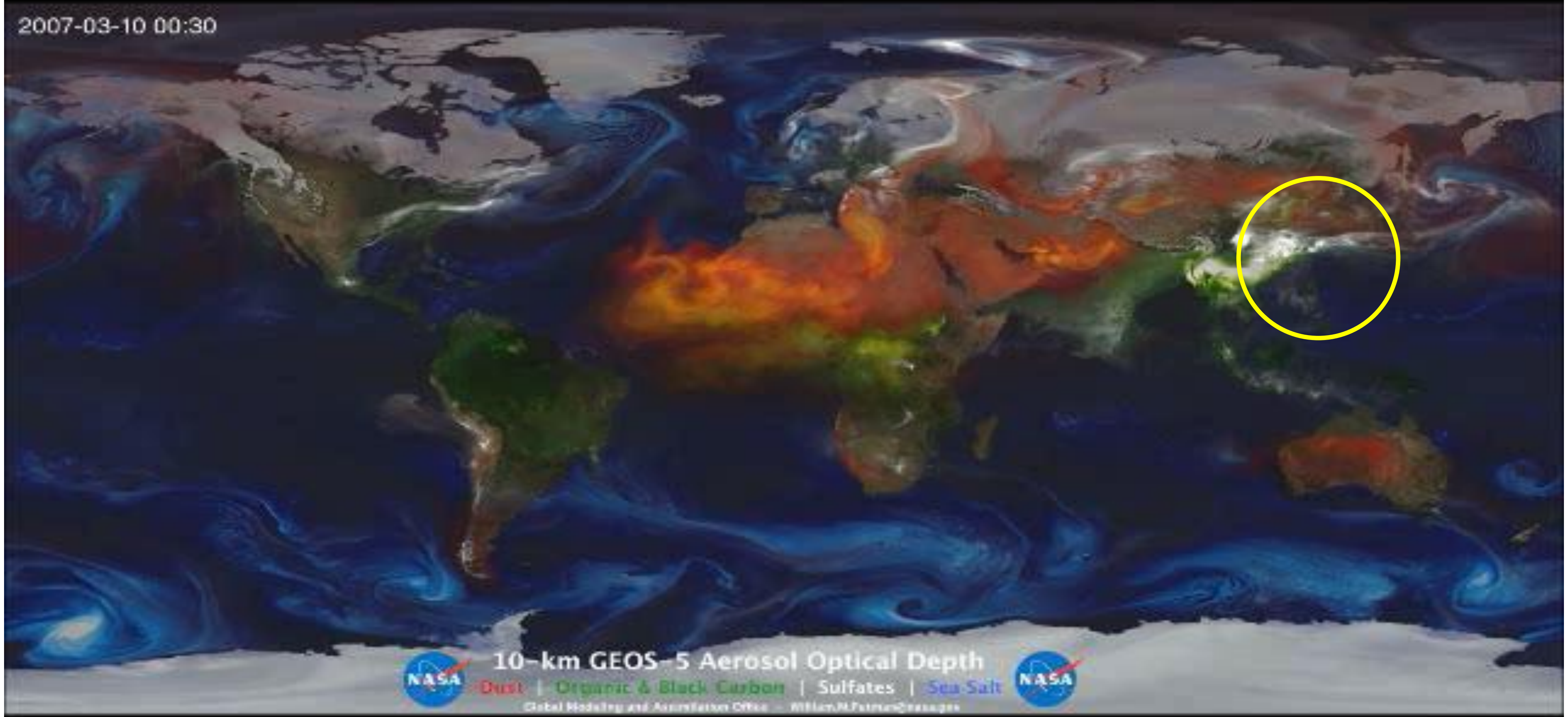




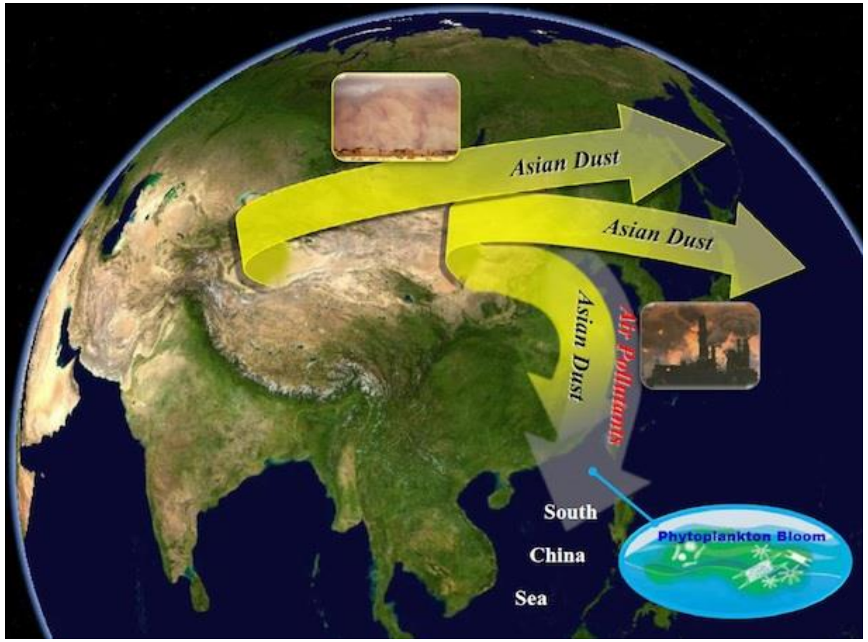
Spatial distribution of air quality event days (AQI >100) in 2005-2019

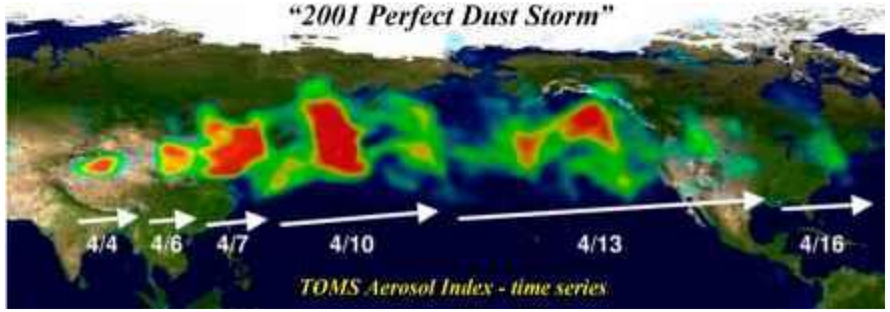


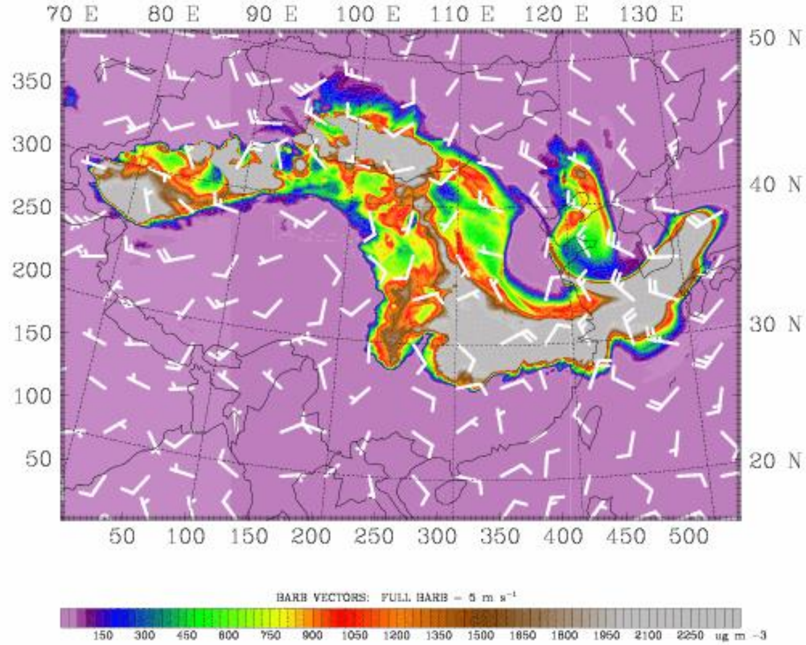
(a) number of annual mean days (b) number of monthly mean days during winter monsoon (Oct.-Apr.) and, (c) number of monthly mean days during summer monsoon (May-Sep.)


2007-03-10 00:30
10-km GEOS-5 Aerosol Optical Depth
Dust | Organic & Black Carbon | Sulfates | Sea Salt

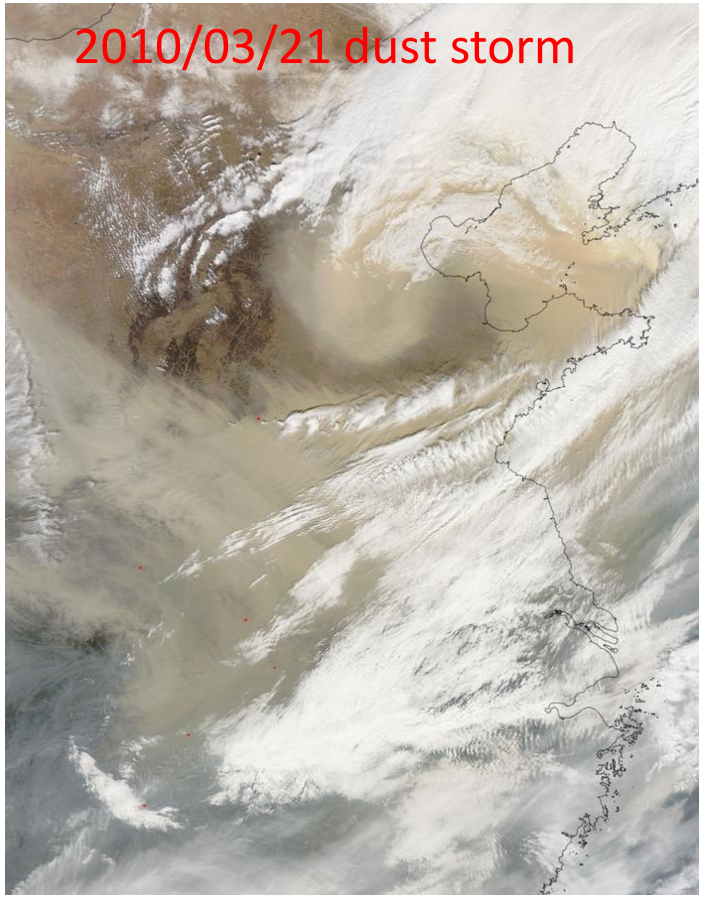
Long-range transport: Asian Dust





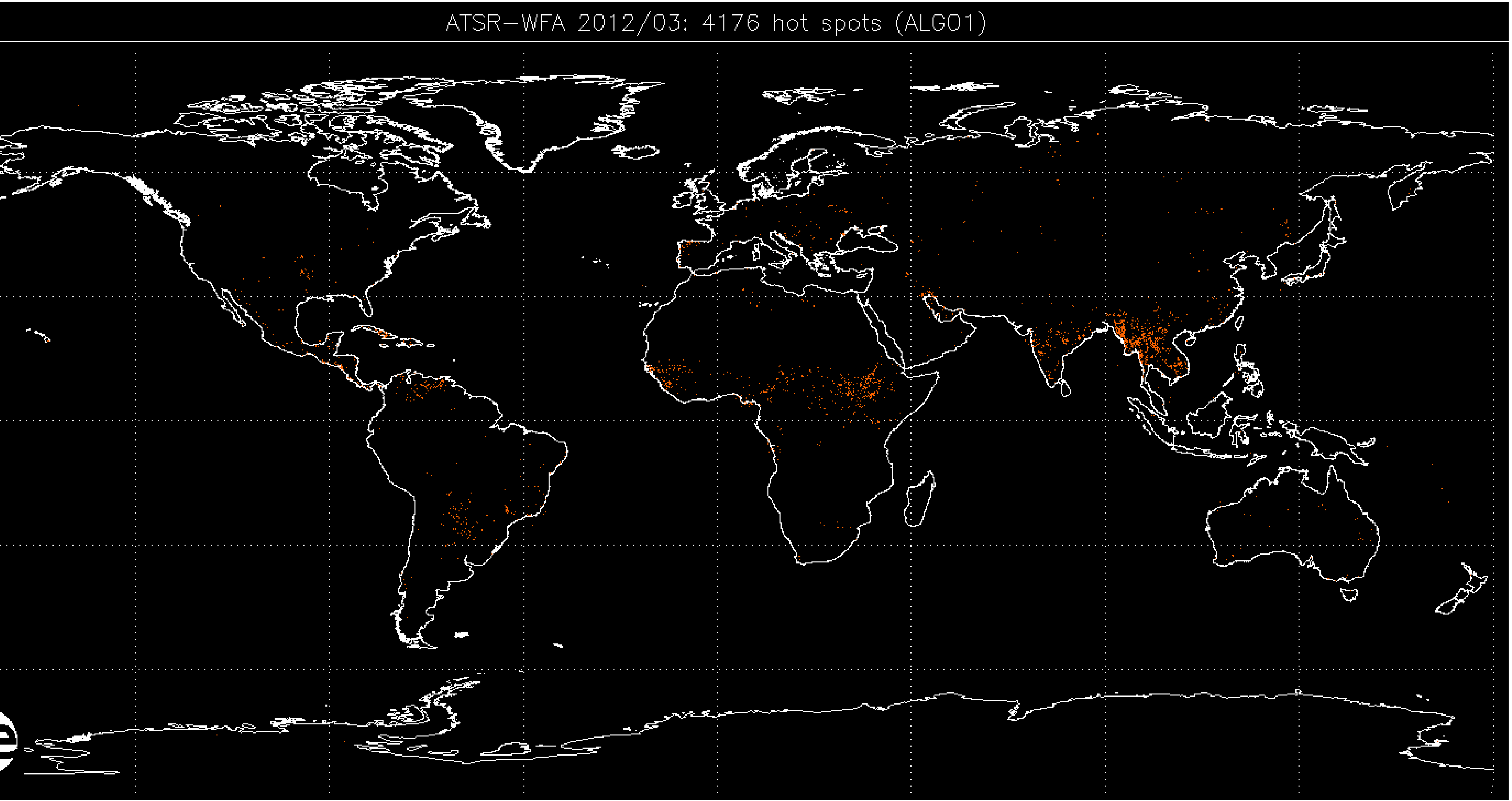


(Lin et al. 2012 ACP)



ATSR-WFA Hot Spots

(2012 01-03)



Mean annual fire carbon emissions during 1997-2009

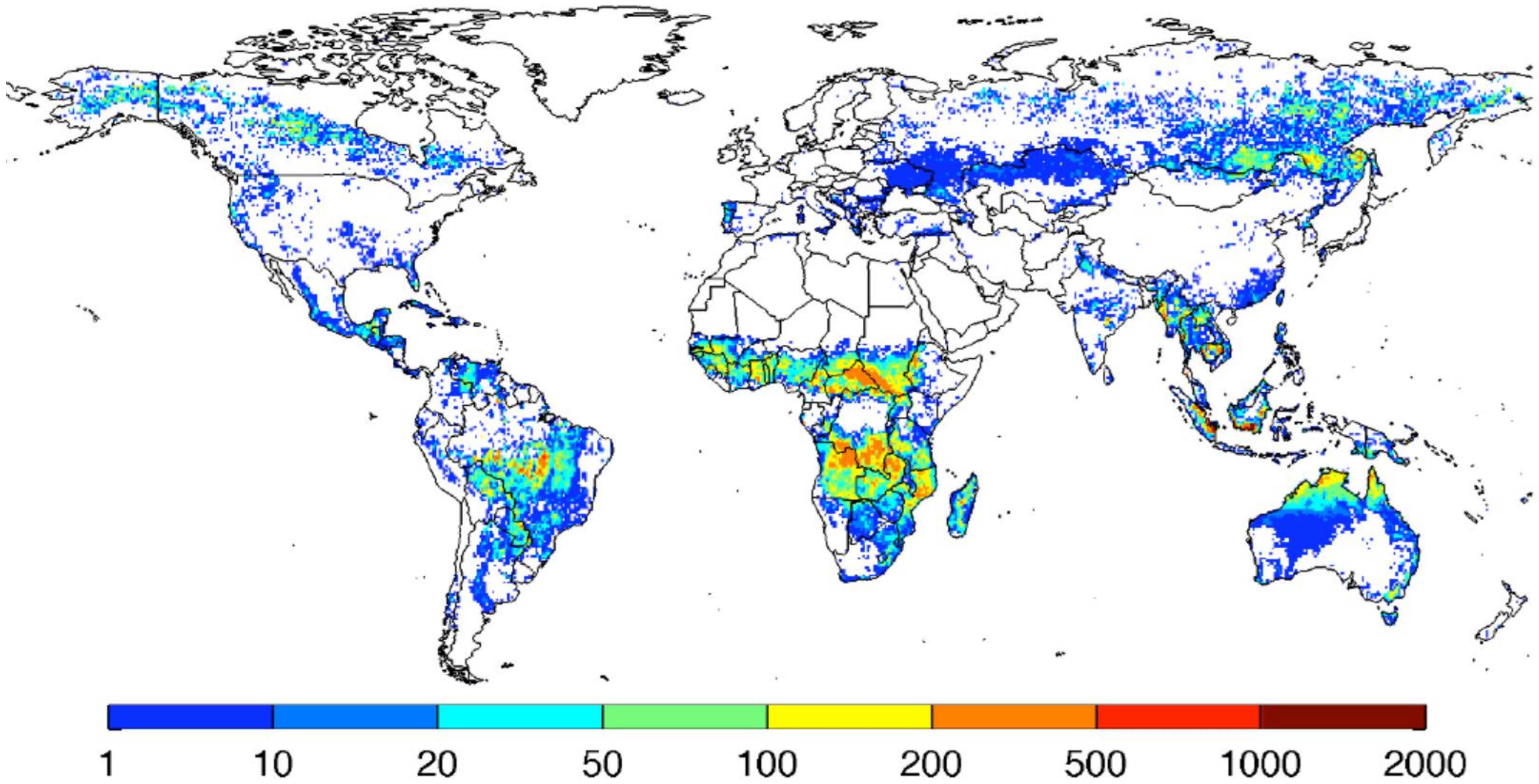


Fig. 11. Mean annual fire carbon emissions ($g\,C\,m^{-2}\,year^{-1}$), averaged over 1997–2009. This quantity is the product of the fuel consumption (e.g., Fig. 6) and the burned area within the grid cell, divided by the total area of the grid cell.

(van der Werf et al. 2010)

Seasonal Optical Depths

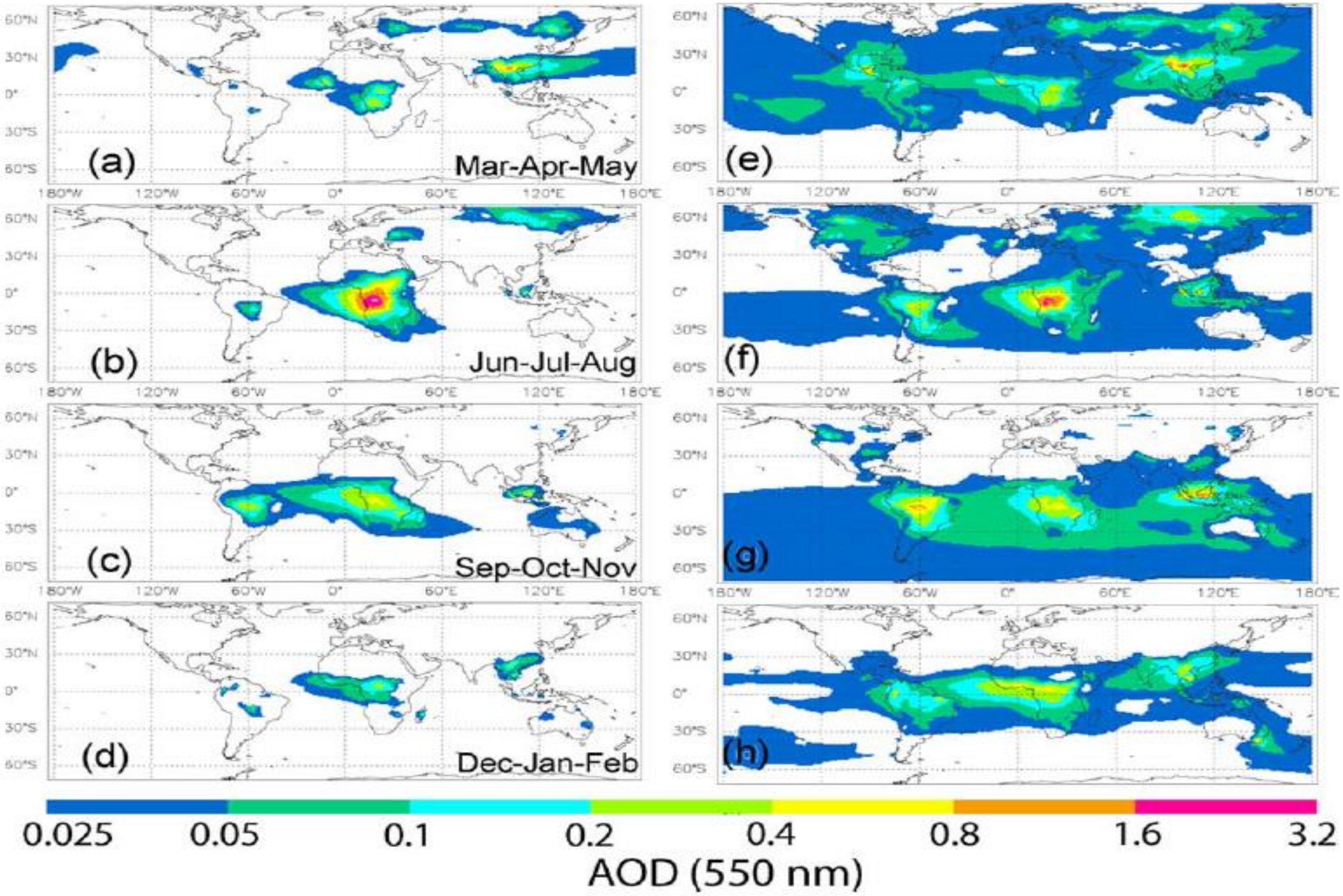


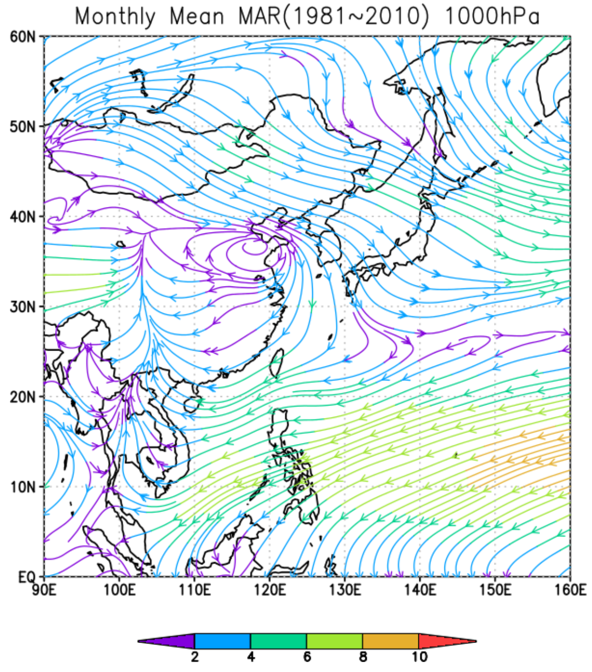
Fig. 3. FLAMBE/NAAPS seasonal optical depths (550 nm) from the natural run using the baseline FLAMBE emissions product (a)–(d) and MODIS AOT data assimilation (e)–(h).

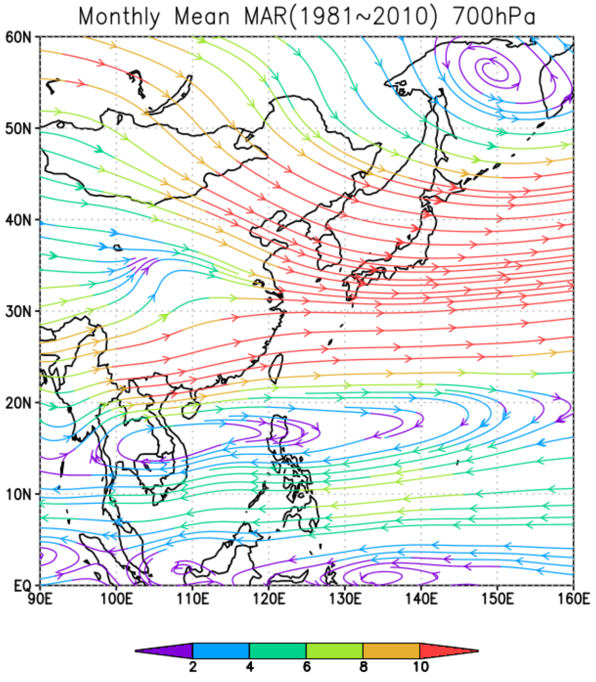
(Reid et al. 2009)

Fire Locating and Modeling of Burning Emission (FLAMBE)

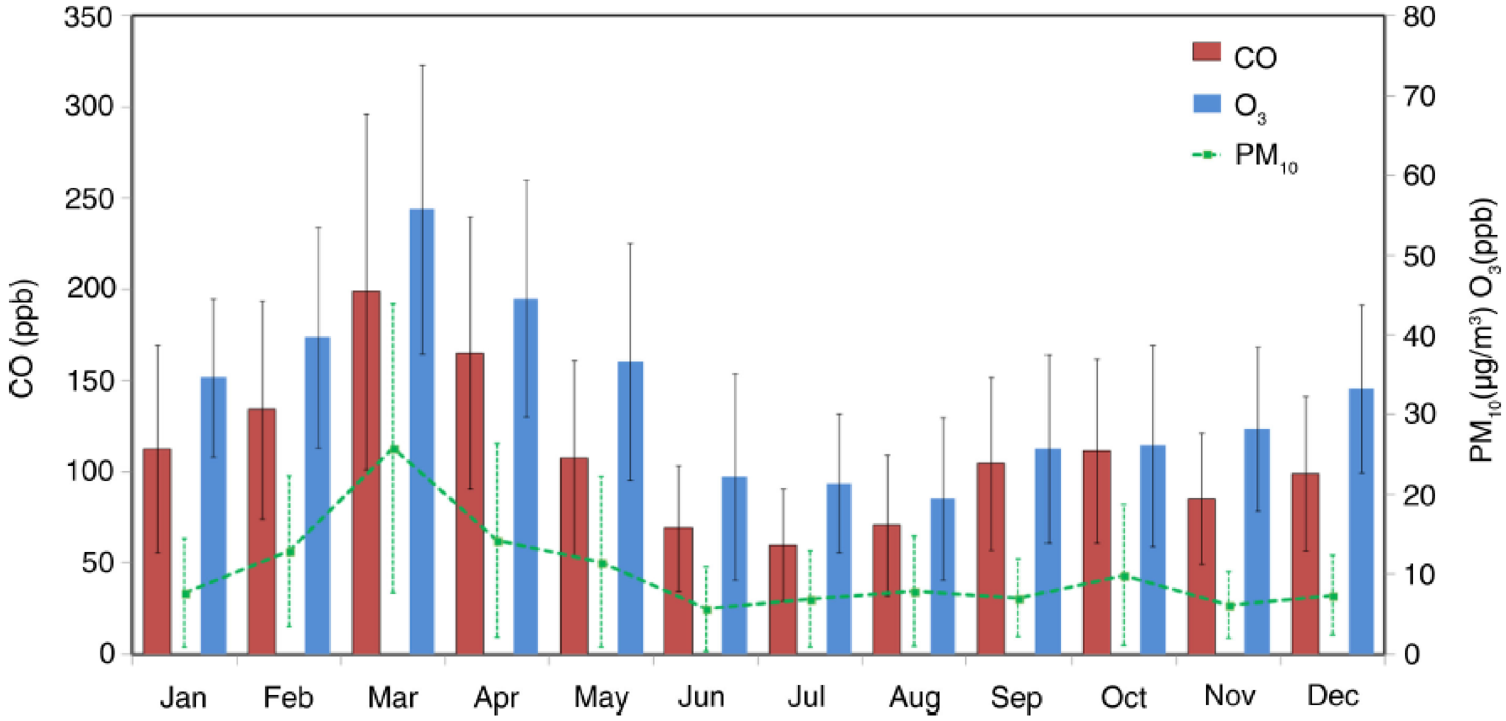
Long-range transport events

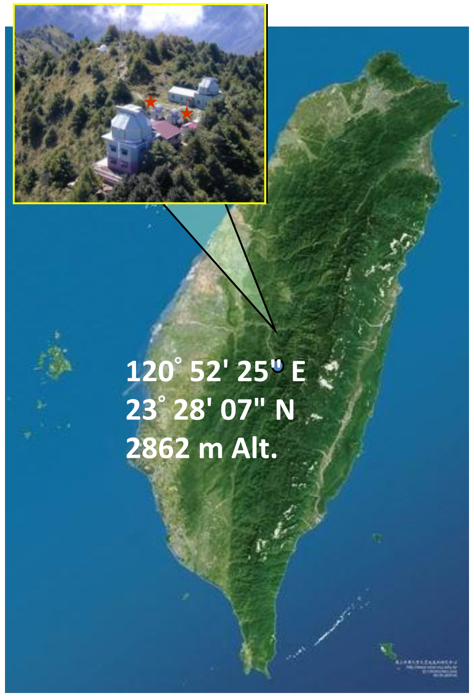
- **Asian dust and air pollutants from China**
- **Impact of Biomass burning pollutants from Indochina**





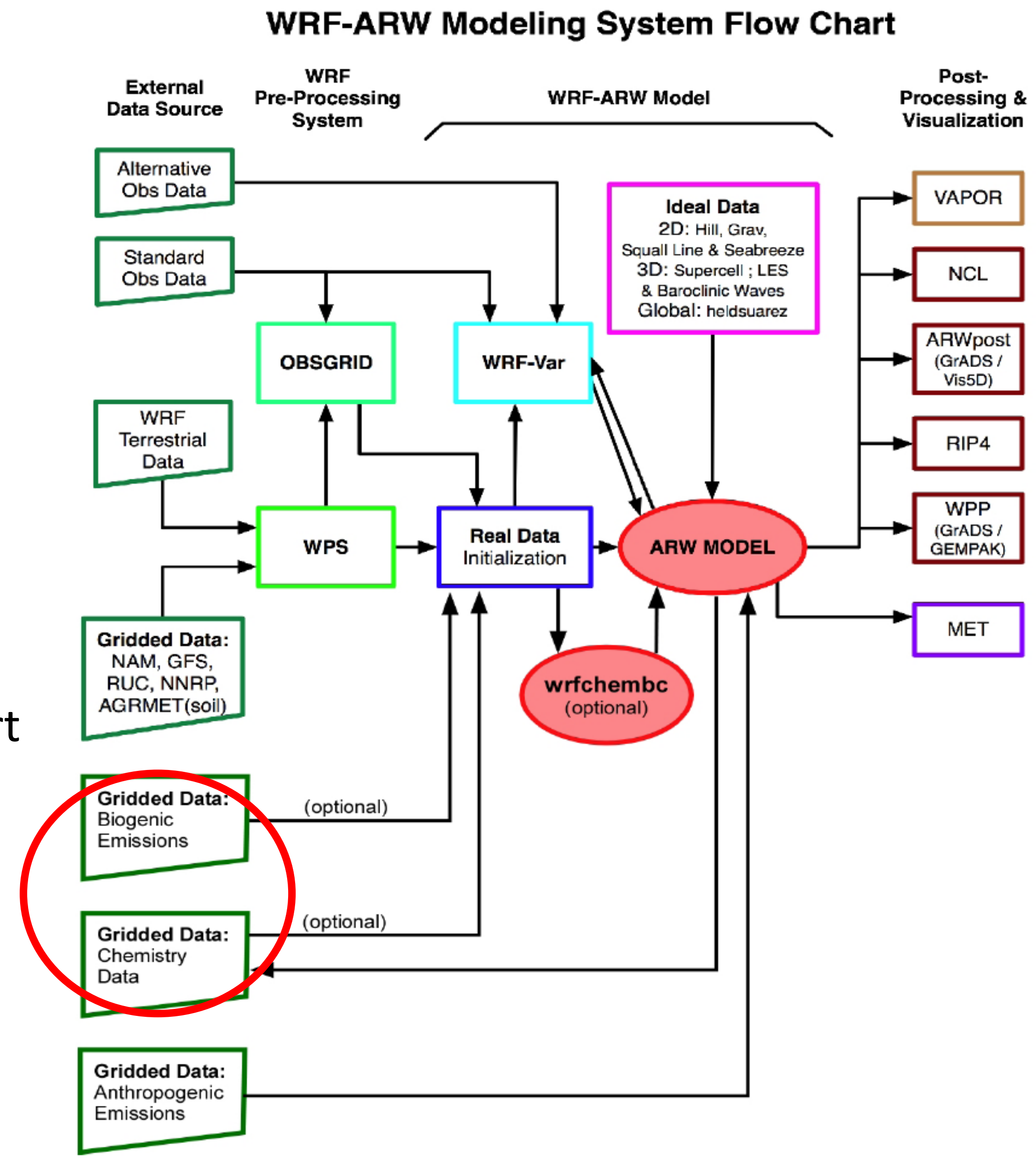
Seasonal variation of CO, O3 and PM10 at LuLin Mountain station (2006-2009)



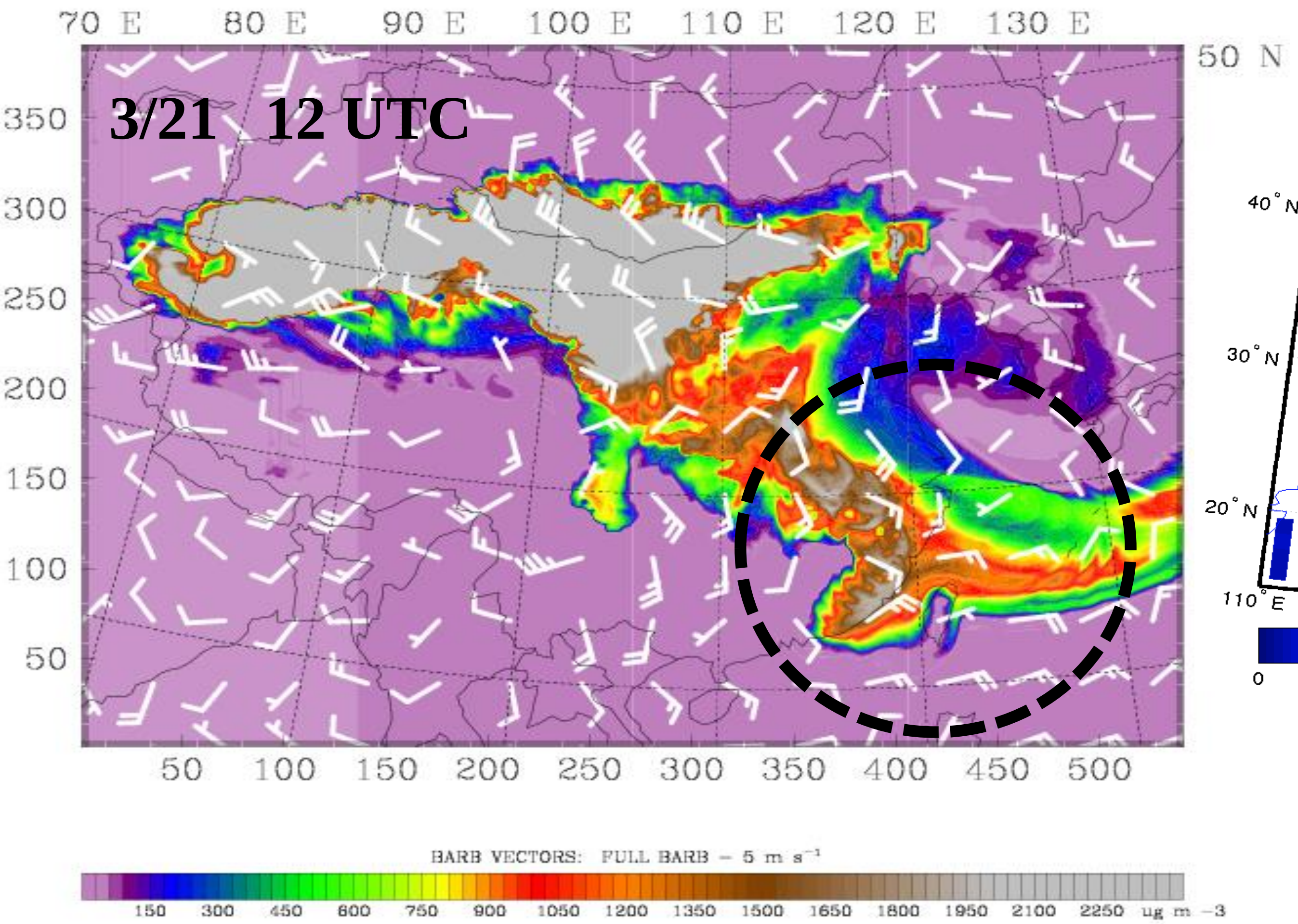


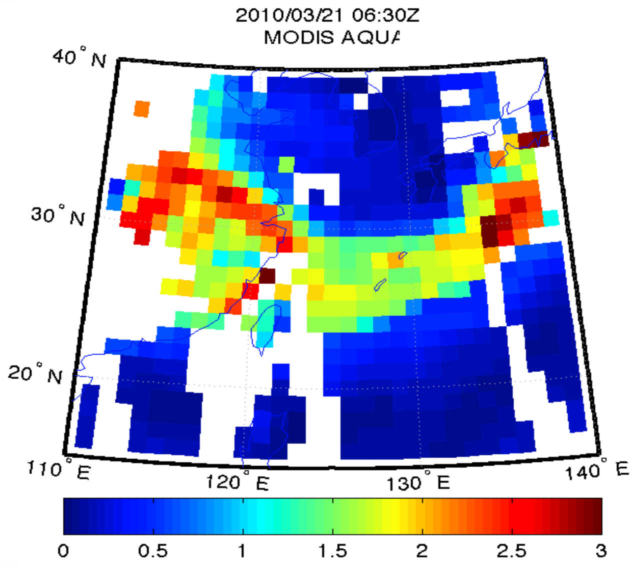
WRF-Chem

- Chemistry is online, completely embedded within WRF model
- Consistent: all transport done by meteorological model
  - Same vertical and horizontal coordinates
  - Same physical parameterization for subgrid scale transport
  - No interpolation in time



Simulation spatial distribution of Dust transport





(Lin et al. 2011 ACP)

Tellus SERIES B CHEMICAL AND PHYSICAL METEOROLOGY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Modelling of long-range transport of Southeast Asia biomass-burning aerosols to Taiwan and their radiative forcings over East Asia

By CHUAN-YAO LIN[1]*, CHUN ZHAO[2], XIAOHONG LIU[2,3], NENG-HUEI LIN[4] and WEI-NEI CHEN[1], [1]*Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan;*

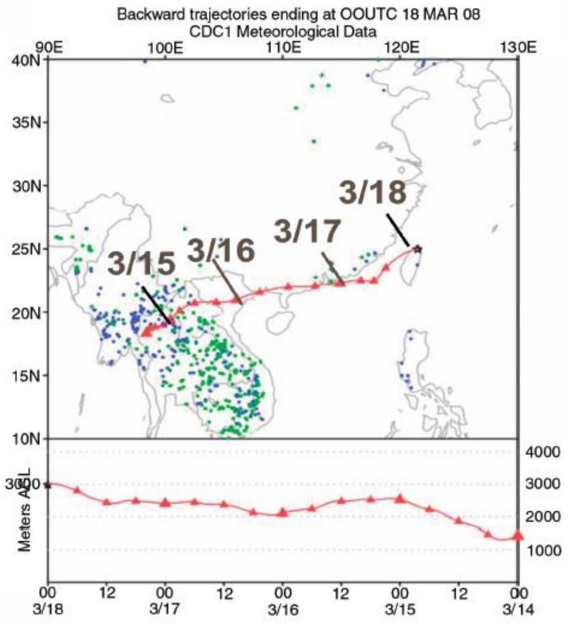
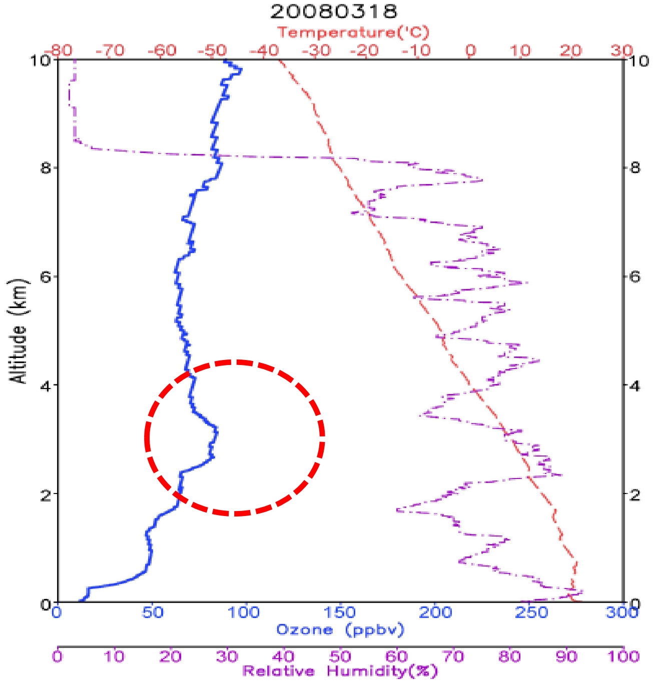


Fig. 6. Backward trajectory analysis results obtained using HYSPLIT model starting at 00:00 UTC (08:00LST) on 18 March 2008 at altitude 3000 m at Banchiao station in northern Taiwan. Distribution of active fires detected by MODIS from 15 (green dots) to 16 (blue dots) March 2008.

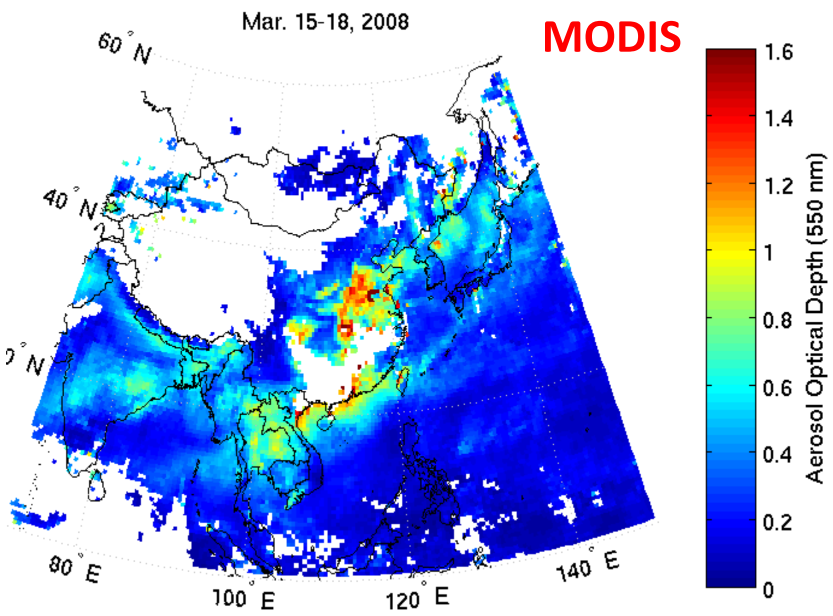


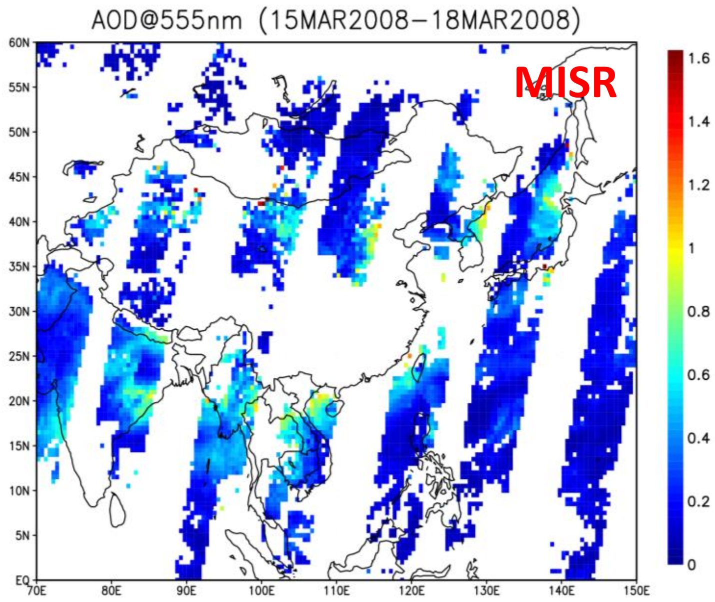
WRF/chem configures

- Radiaton: RRTMG
- PBL: Mellor Yamada Janjic (MYJ)
- Chemistry driver: RADM2
- **Aerosol driver**: MADE/SORGAM
- **Anthropogenic emission**: Street D.(2006)
- **Biomass mass burning emission**: FINN1
- Domain: resolution 15 km,
  vertical 35 levels.
- Case : 3/15-3/19, 2008
- spin up time: 5 days (3/10~3/14).

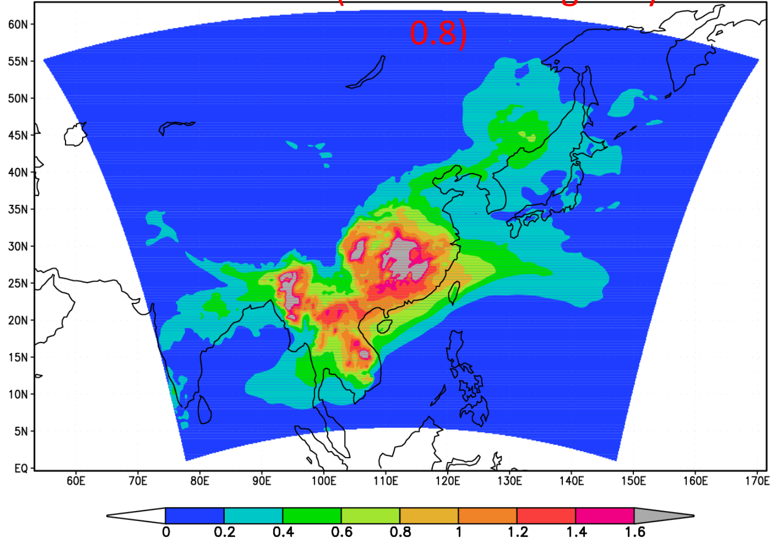
(Lin et al. 2014)

Model evaluation

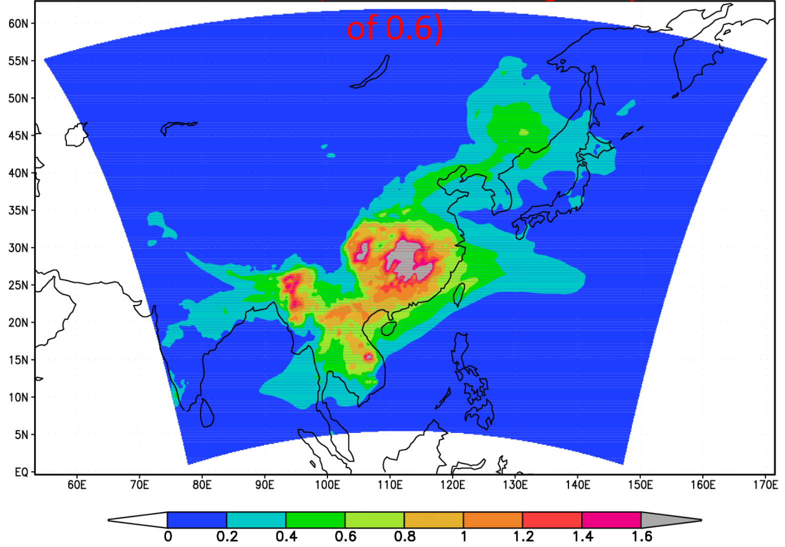


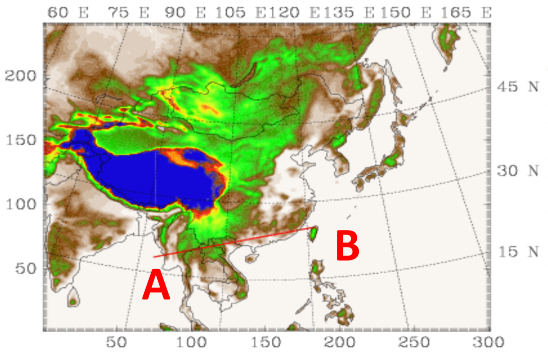


Simulation AOD (emission changed by factor of 0.8)

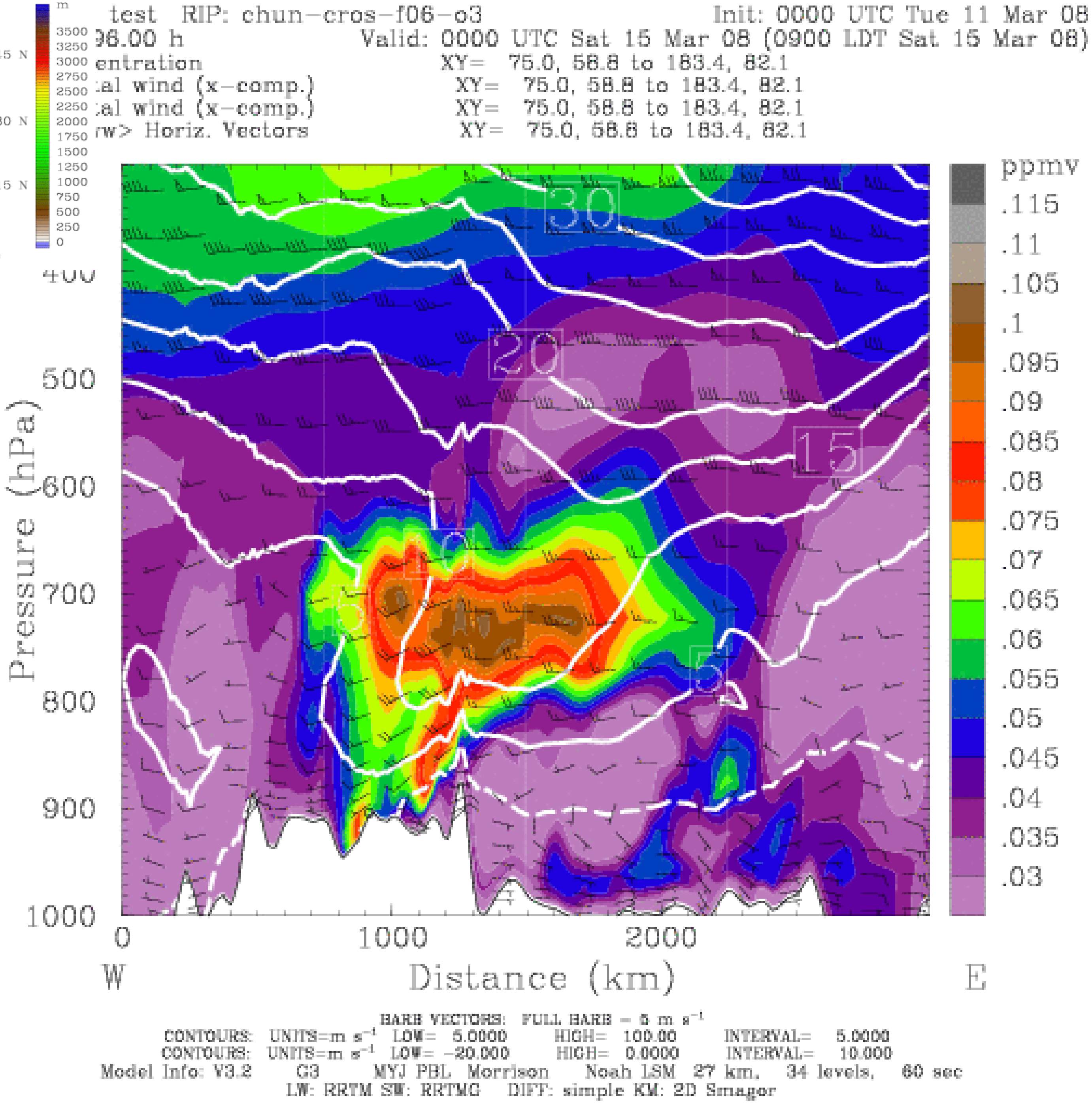


Simulation AOD (emission changed by factor of 0.6)

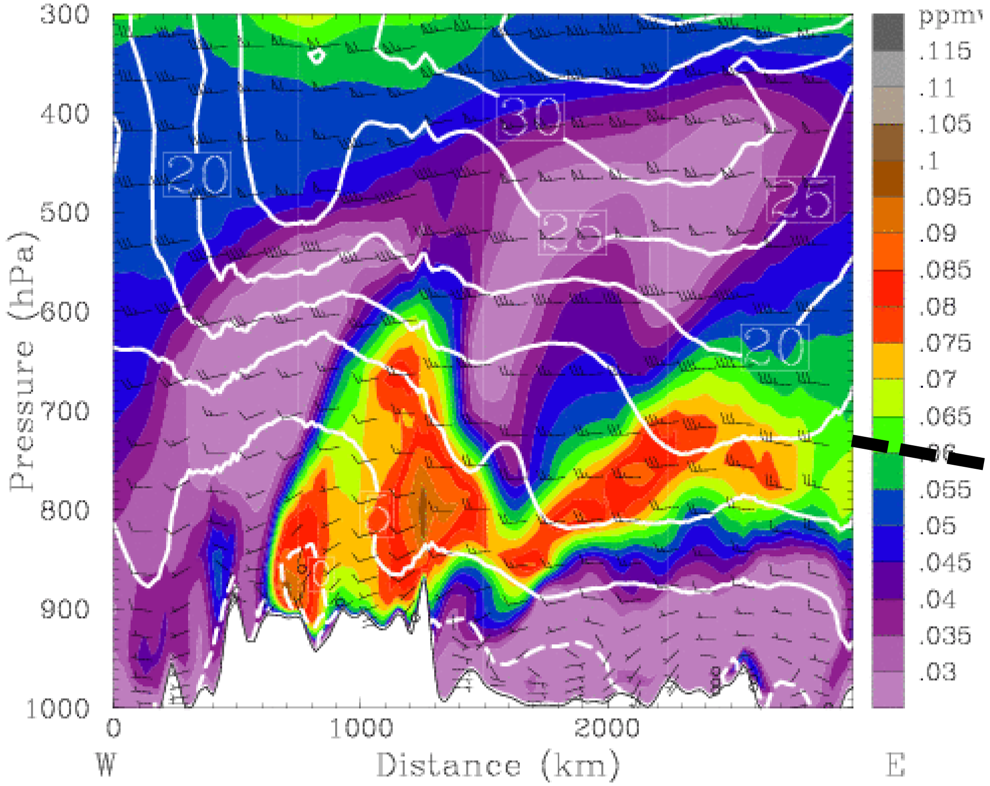


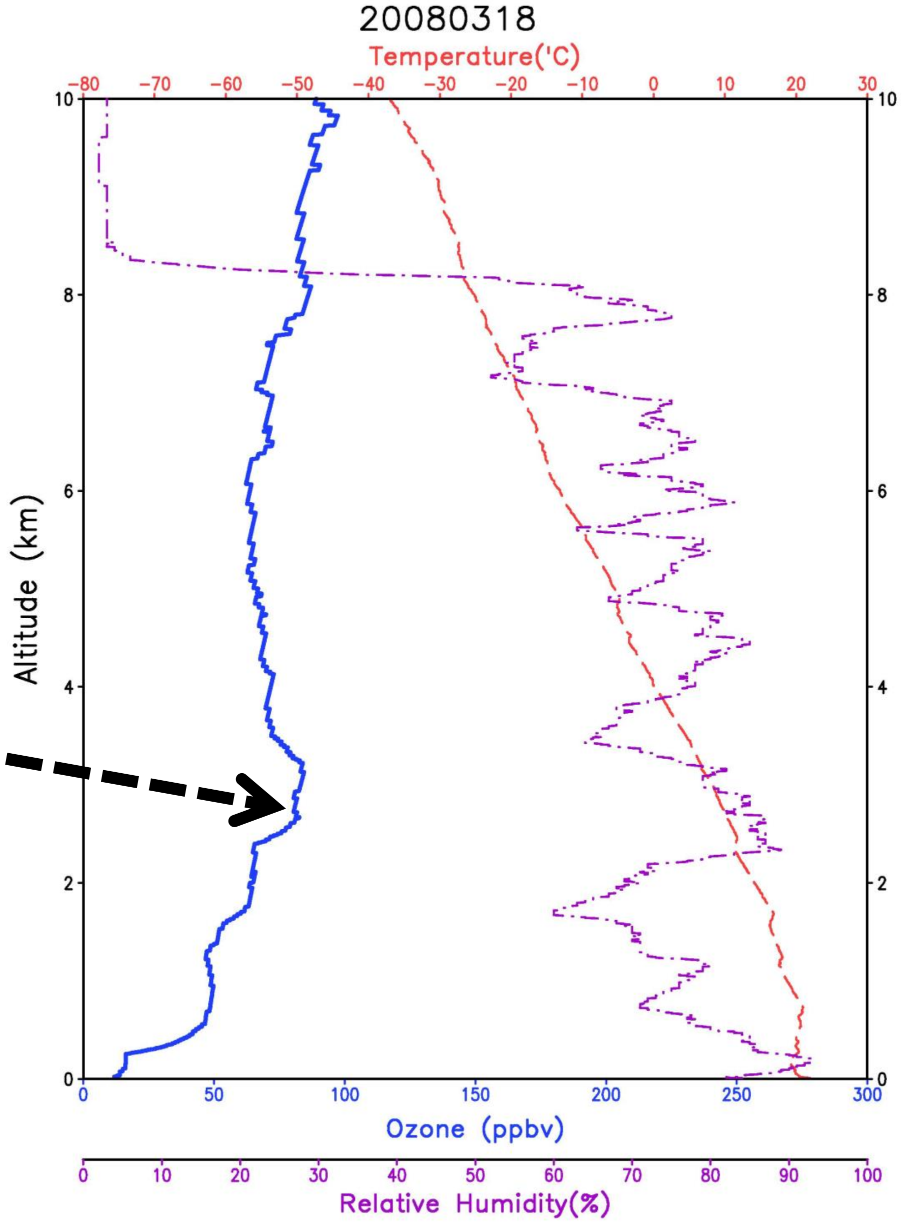


Ozone simulation

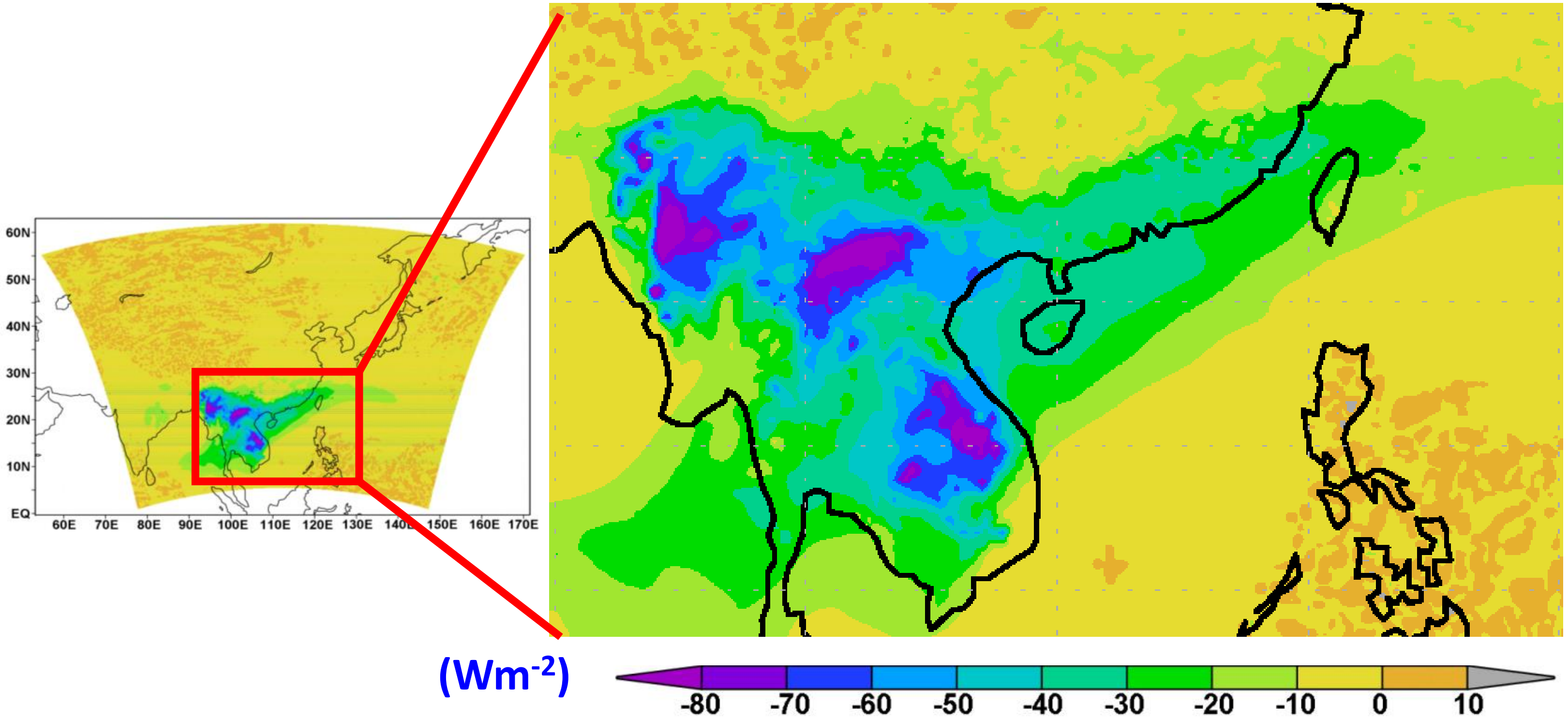


03/18 00Z (0800LST) O3





Difference of downward shortwave flux at surface (biomass burning emission turn on and off)



Average reduction in shortwave radiation fluxes at ground surface simulated with and without biomass-burning emission during 15-18 March, 2008 (unit W m^{-2}).

(Lin et al. 2014)

Impact of the COVID-19 Pandemic on Regional Air Quality

Chuan-Yao Lin, Charles C.-K. Chou
Yi-Chun Chen, Chian-Yi Liu,

Changes in the Atmospheric Column Density of Air Pollutants over the East and North China

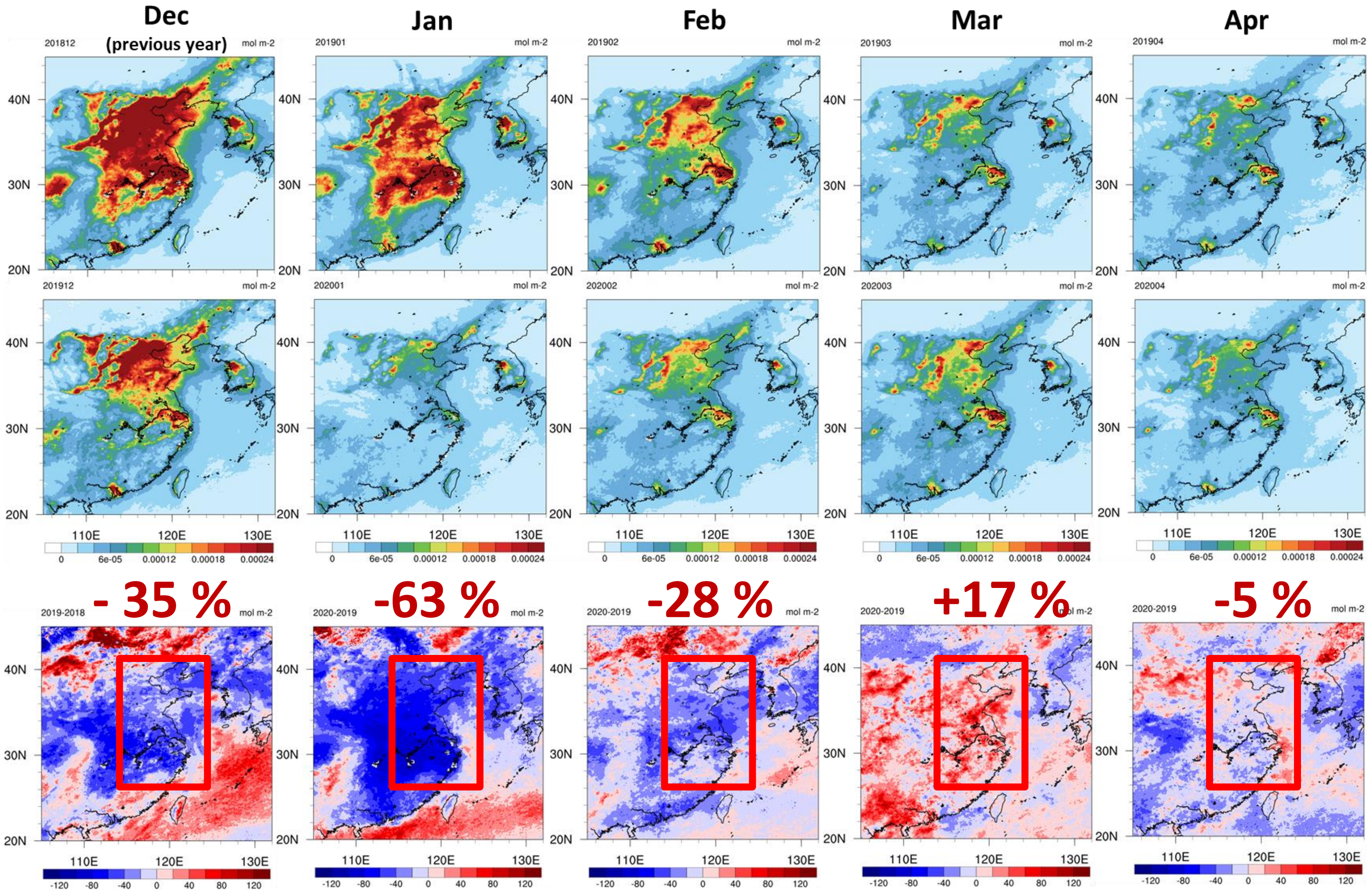
Tropomi/S5P

NO_2 column density reduced significantly over the East and North China during the period of National Lockdown (Lunar Jan 2020), and has bounced back since Lunar Feb 2020.

2019 (Lunar)

2020 (Lunar)

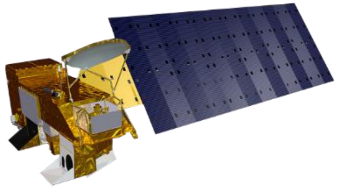
Fractional Changes



Changes in the Atmospheric Column Density of Air Pollutants over the East and North China

Tropomi/S5P

- Significant reduction in NO_2 and aerosols
- Nearly "No Change" in SO_2 and CO
- The discrepancies were likely due to the atmospheric lifetime and regional background of each species

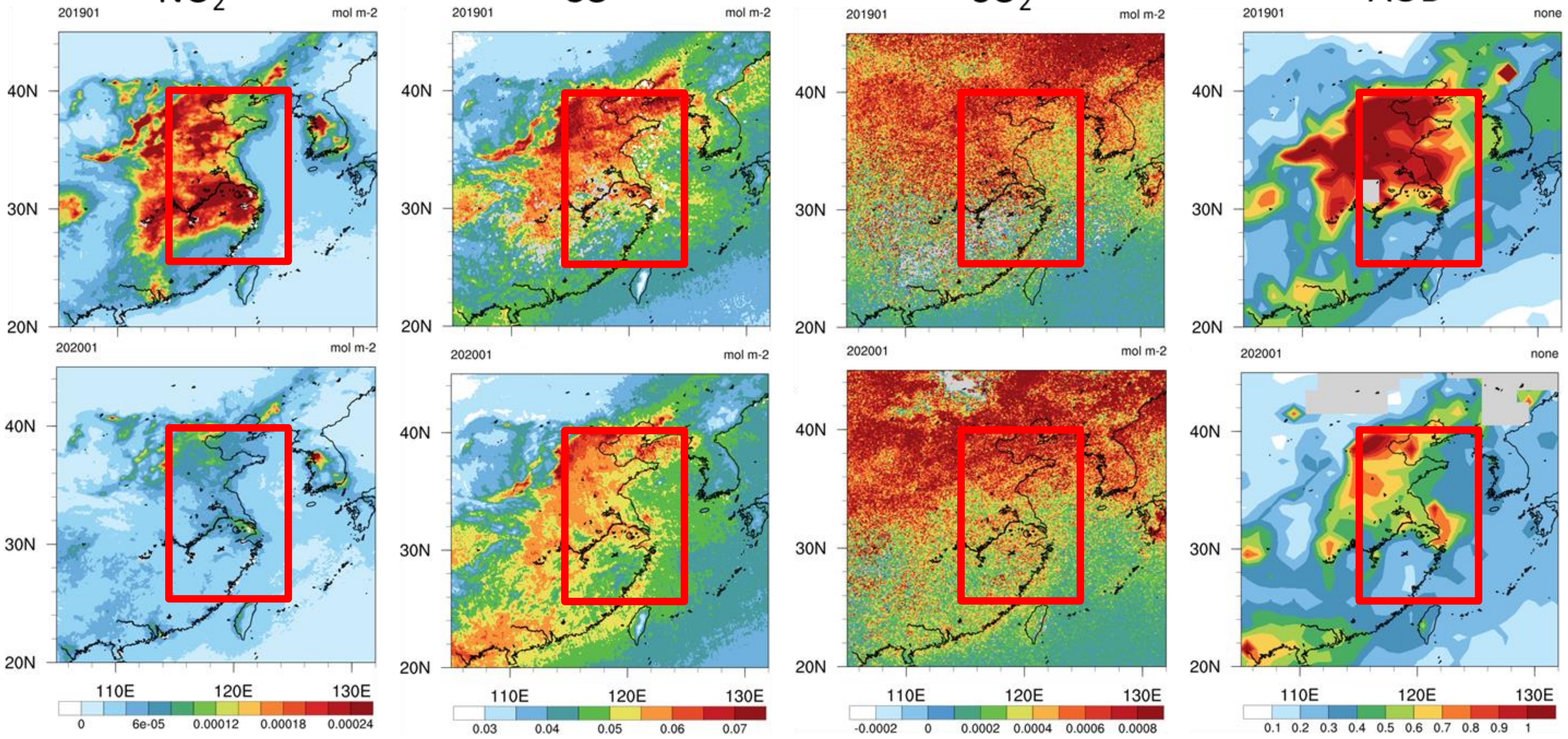


MODIS/Aqua

NO_2 CO SO_2 AOD

Jan 2019 (Lunar)

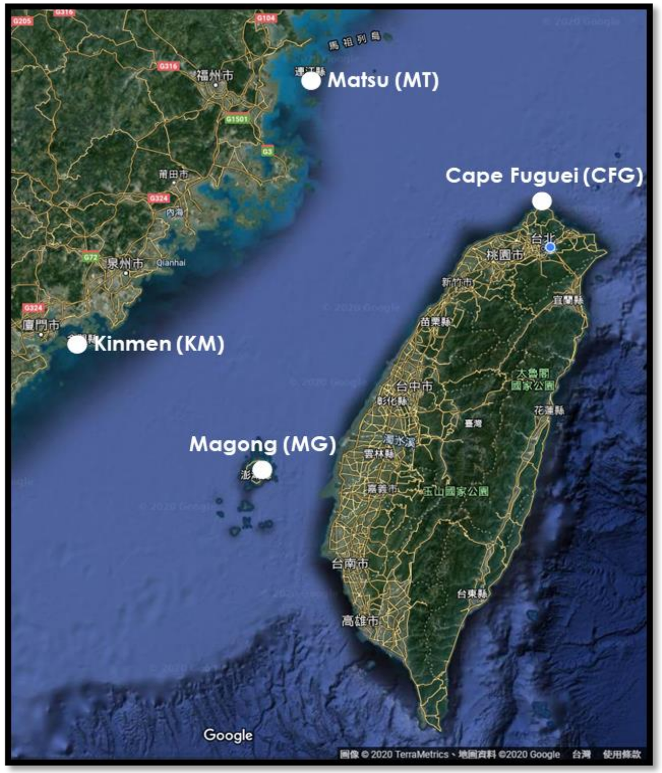
Jan 2020 (Lunar)



-63 % -3 % +2 % -32 %

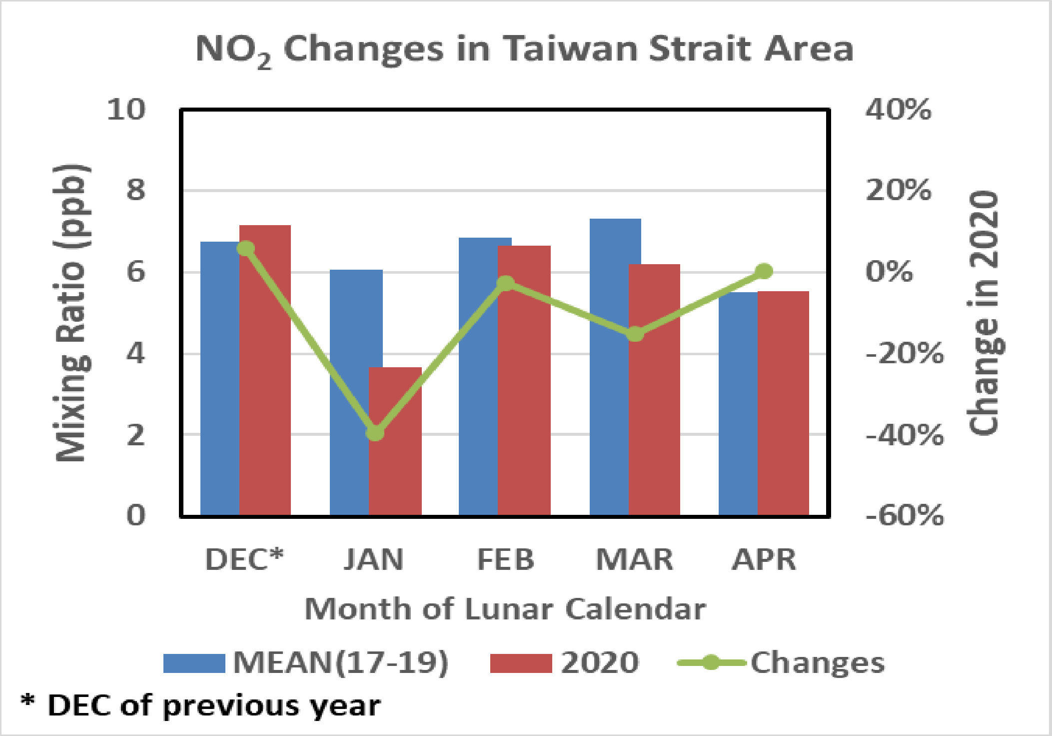
Changes in the Ambient levels of Air Pollutants over the Taiwan Strait Area

- Ambient NO_2 level reduced by 40 % in the Lunar January of 2020, likely due to the emission reduction in upwind sources.
- The NOx level bounced back in the Lunar February of 2020.



Taking average of measurements of air pollutants from the four AQ stations (MT, CFG, KM, MG) of Taiwan EPA to represent the ambient AQ level over Taiwan Strait Area.

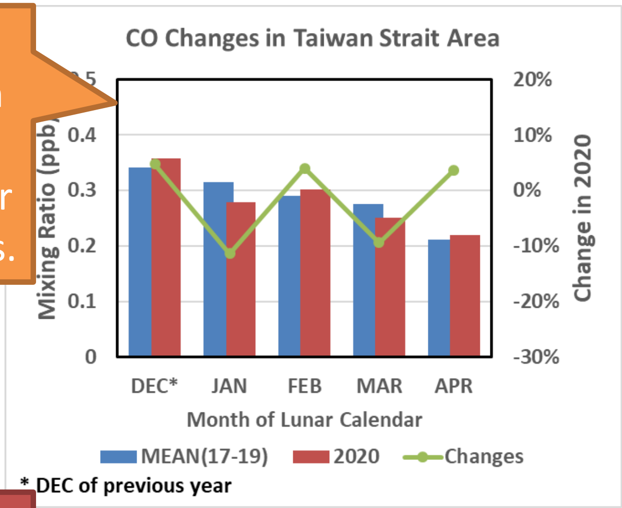
- A regular "Chinese New Year" effect accounted for ~10 % reduction in Lunar Jan, comparing to the Dec of previous year (based on measurements of 2017 – 2019).
- An UNUSUAL low [NO_2] observed in the Lunar Jan 2020, which decreased by 49 % from previous month, and 40 % from the mean of Jan 2017-2019.

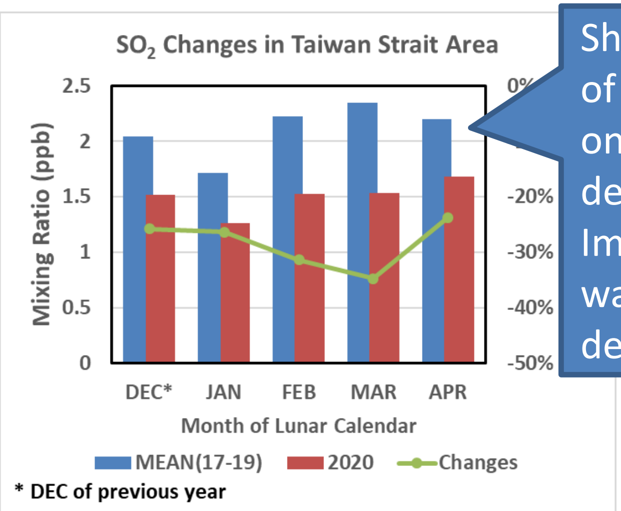


Changes in the Ambient levels of Air Pollutants over the Taiwan Strait Area

- Ambient [CO], [SO_2], [PM2.5] reduced respectively by 11 %, 26 %, and 29% in the Lunar January of 2020, comparing to the monthly mean of 2017 – 2019, whereas [O_3] increased by 9%.
- The pollution level "returned to normal" in the Lunar February of 2020.

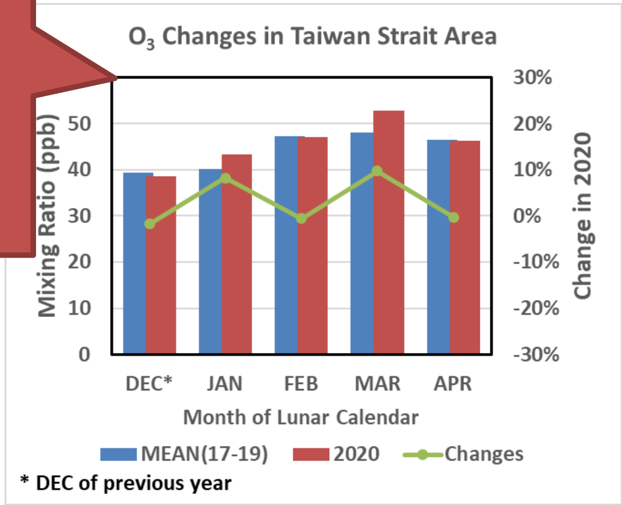
CO exhibited consistently with NOx, suggesting reduction in their common sources.

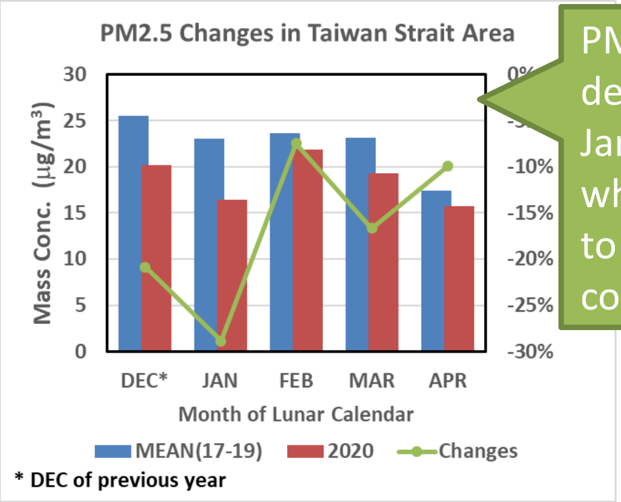




Short-term change of SO_2 superposed on its long-term decreasing trend. Impact of lockdown was not well defined.

Ozone exhibited reversely because of the decline in chemical sink.

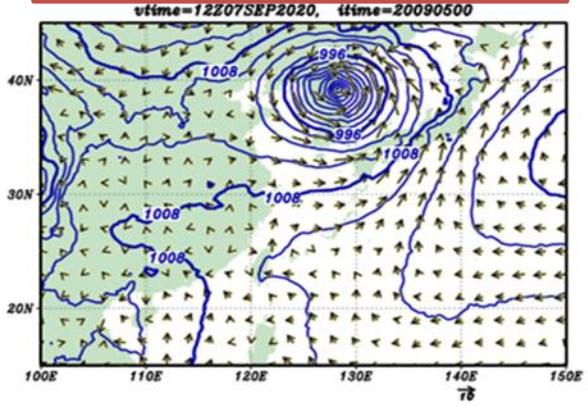




PM2.5 exhibited a decline in not only Jan but also Dec, which was subject to meteorological conditions.

Simulation on the Changes in Air Pollution

NECP Meteo-Data

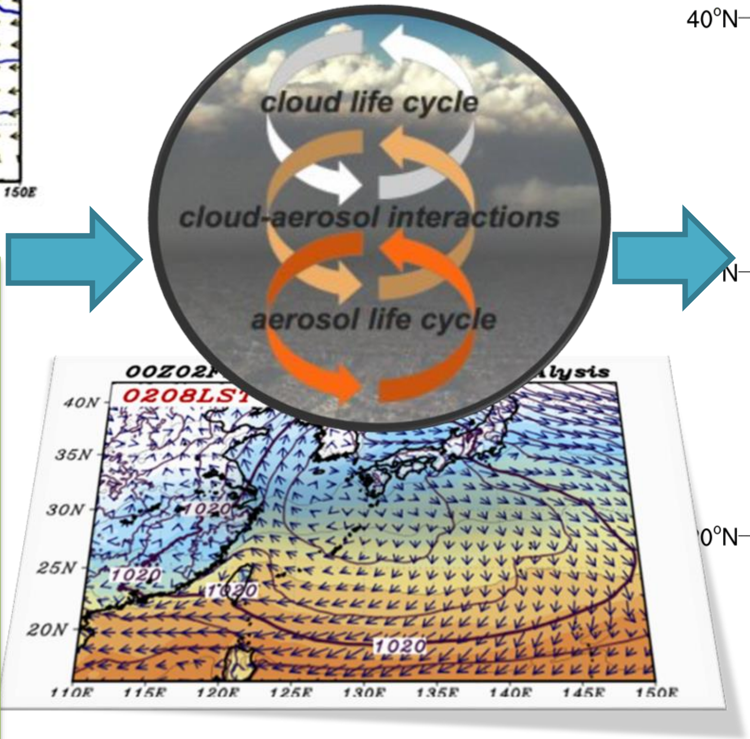


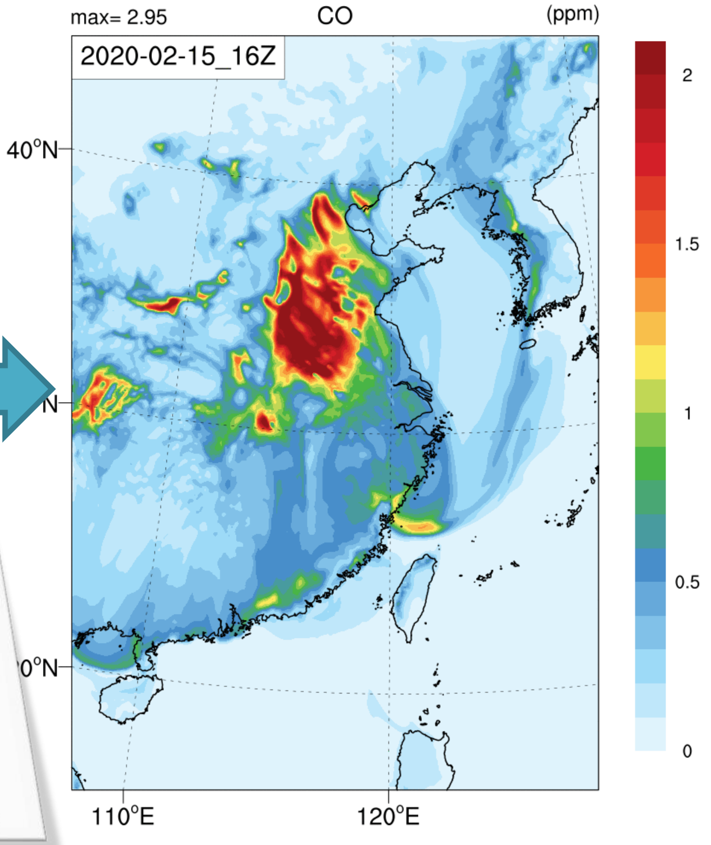
Emission Scenarios

1. Control Run with emissions in business as usual
2. Reduction case as suggested by Huang et al. (2020)
3. All emissions in China reduced by 80%

Emission Inventories

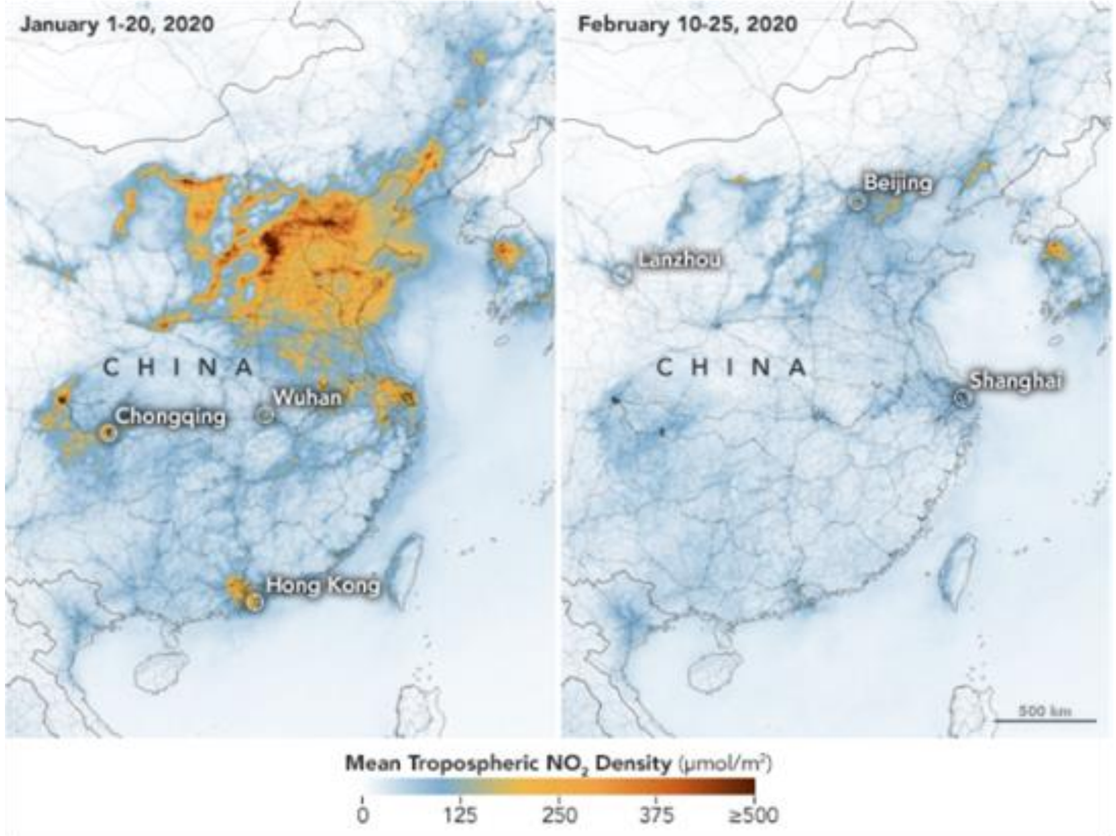
Weather Research and Forecasting–Chemistry Model (WRF-Chem)

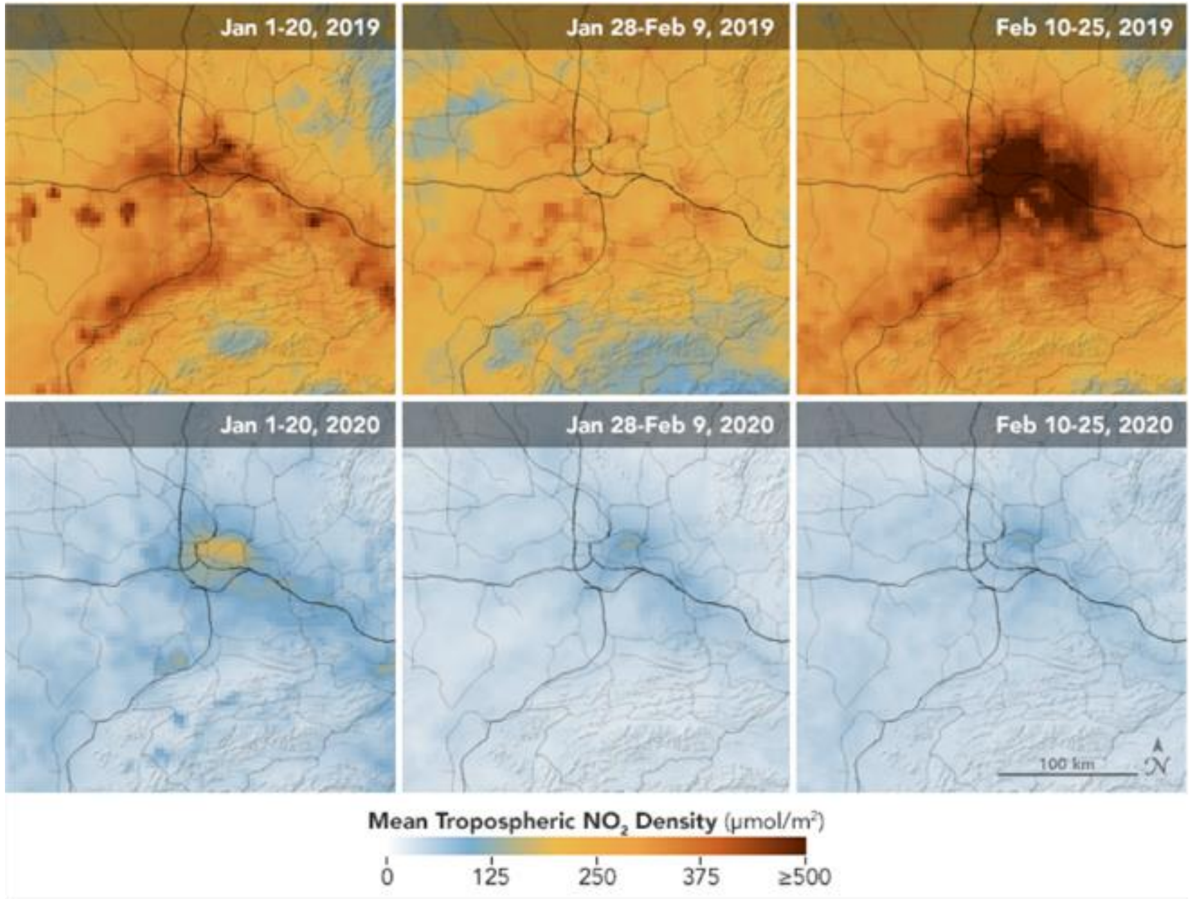




Satellite Results

❑NASA 衛星資料推估





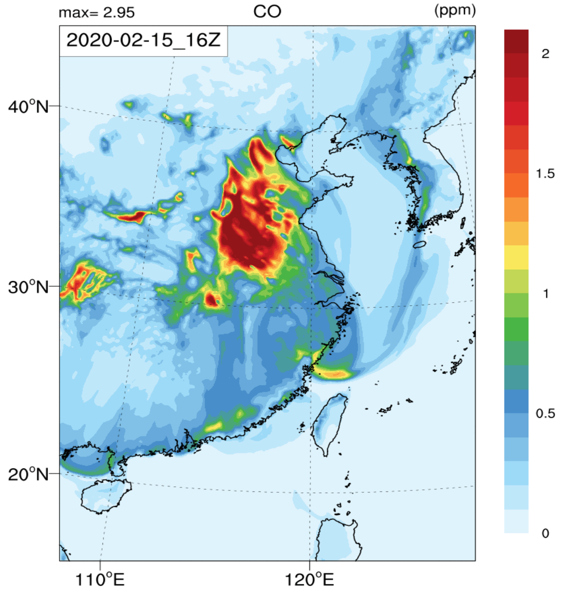
https://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china

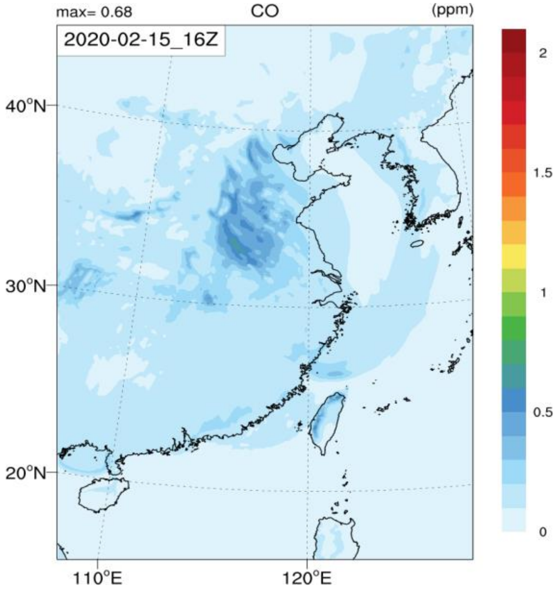
Simulation on the Changes in Air Pollution

❑以2020年2月16-17 日

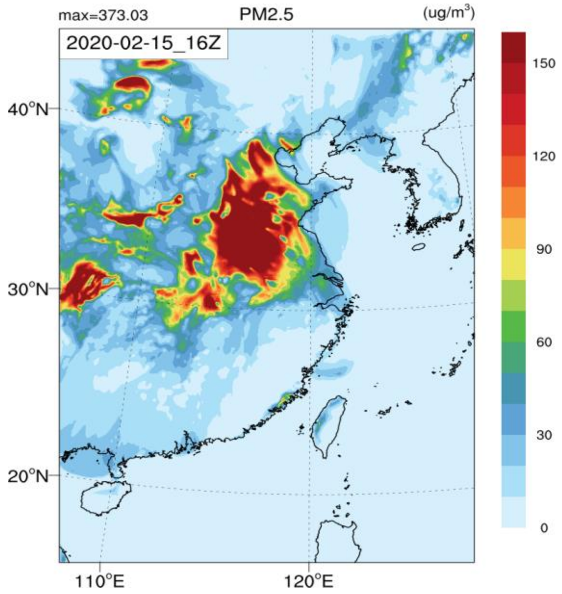
Emission reduction scenario

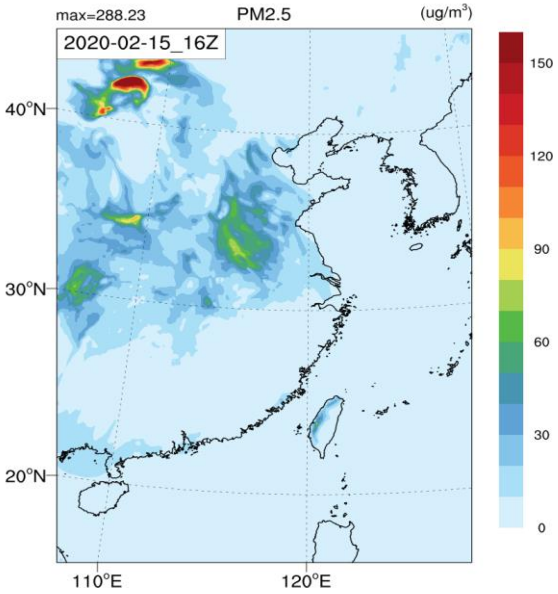
CO





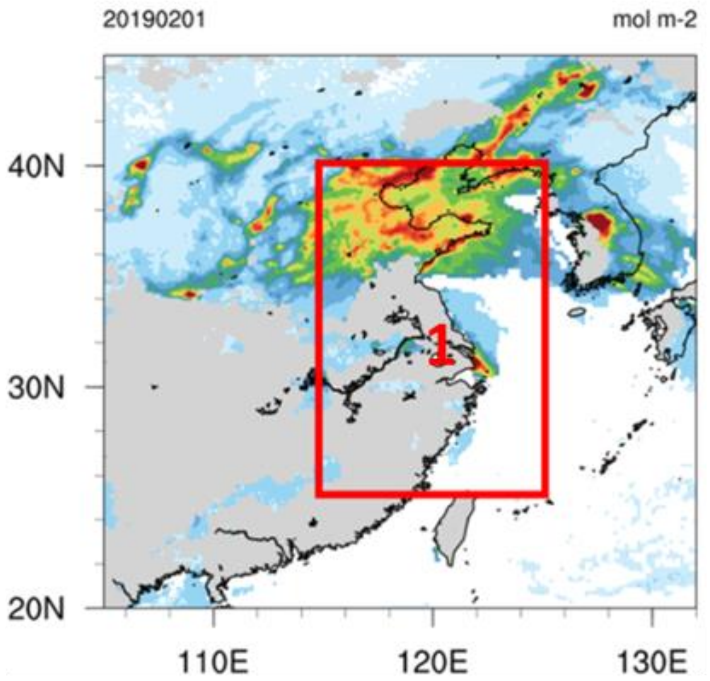
$PM_{2.5}$





Simulation on the Changes in Air Pollution

differece in Feb. between 2020 and 2019

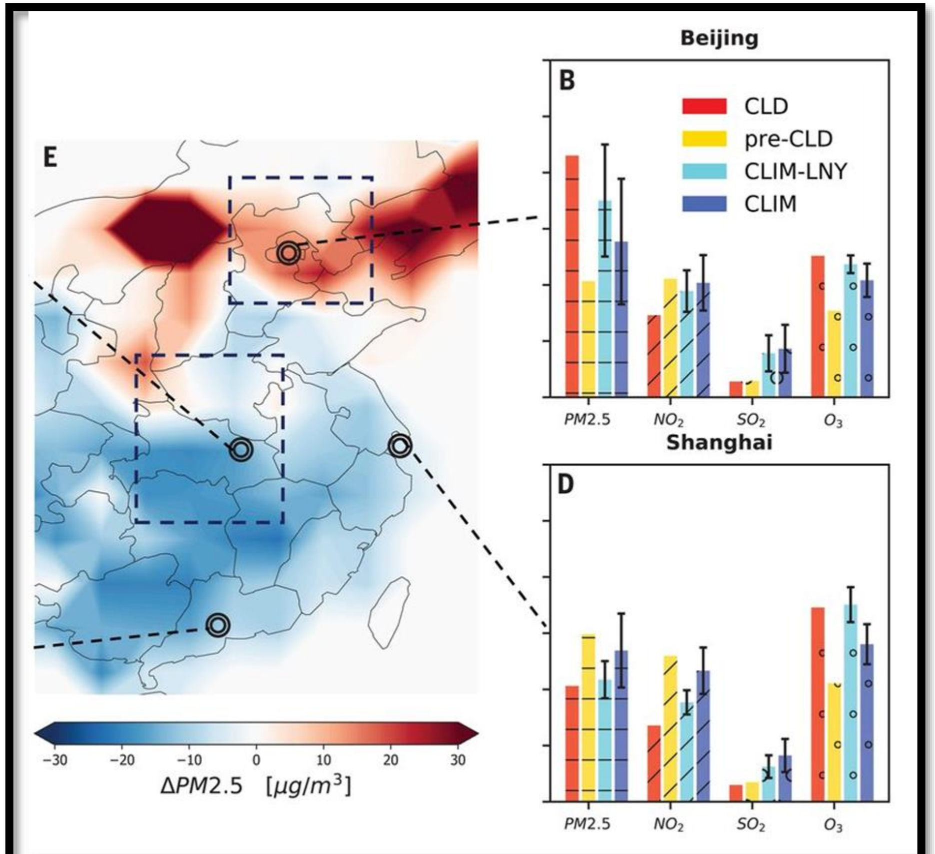


- The effects of NO2 emission reduction 80% are diminished in the downwind areas.

AREA 1	NO2	CO	SO2	PM10	PM2.5	O3
Cut80%	-83%	-63%	-80%	-55%	-67%	+11%

Changes in the Ambient levels of Air Pollutants over the Taiwan Strait Area

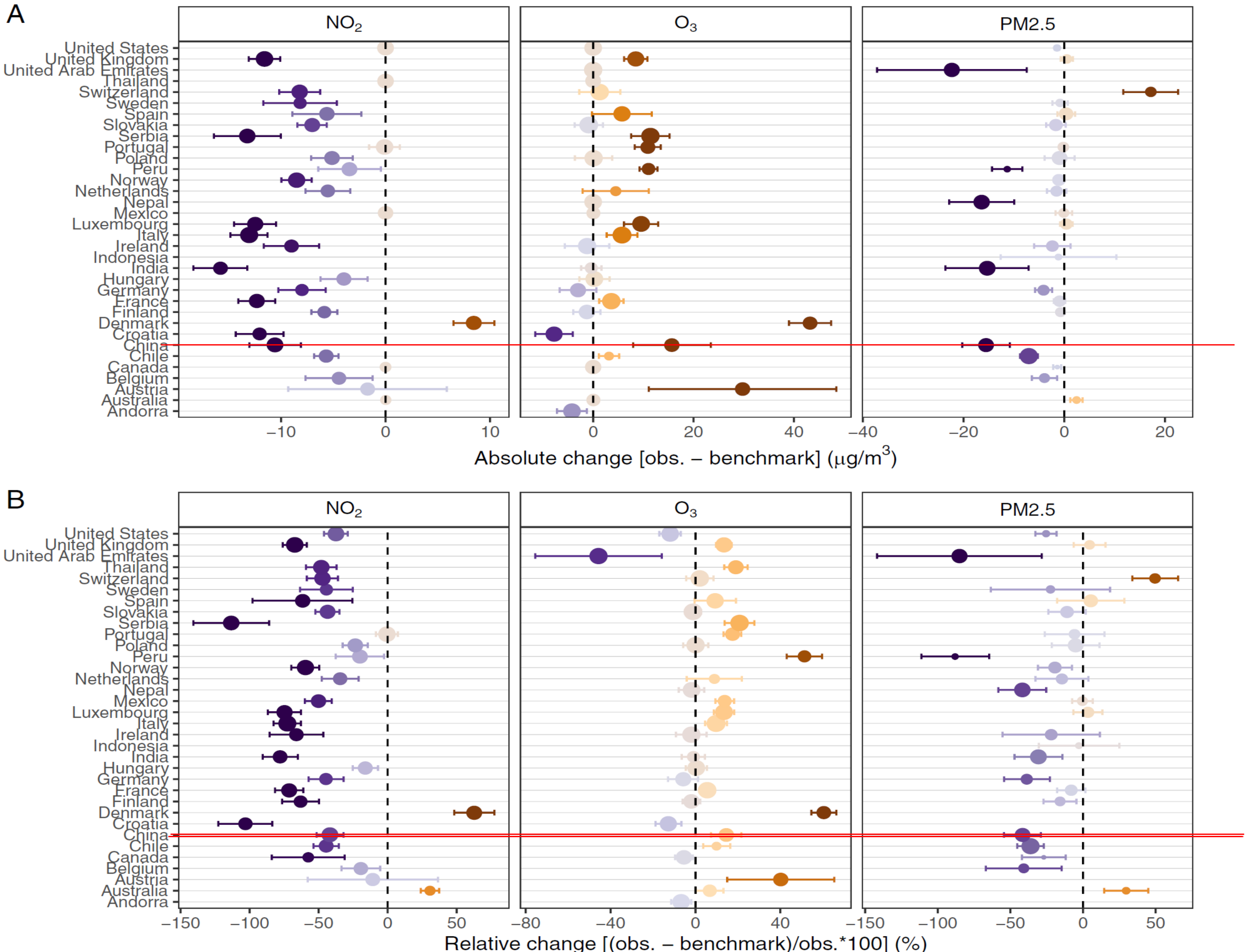
- Le et al. (2020) reported O3 increases observed at Beijing and Shanghi, and PM2.5 increase at Beijing during the Chinese Lockdown.
- Huang et al. (2020) reported estimates of emission reduction over China, which were comparable with the observation in Taiwan Strait.



Tianhao Le et al. Science 2020;369:702-706

	CO	NO_x	SO_2	VOC	$PM_{2.5}$	BC	OC
Beijing	**22%**	**45%**	**26%**	**45%**	**18%**	**46%**	**8%**
Tianjin	21%	38%	20%	41%	14%	22%	6%
Hebei	15%	45%	16%	36%	12%	17%	5%
Shanxi	18%	40%	20%	33%	16%	19%	10%
Inner Mongolia	14%	29%	15%	34%	13%	16%	6%
Liaoning	21%	40%	28%	36%	16%	28%	8%
Jilin	16%	39%	23%	34%	13%	18%	5%
Heilongjiang	17%	37%	27%	28%	13%	15%	7%
Shanghai	**35%**	**48%**	**42%**	**45%**	**34%**	**54%**	**42%**
Jiangsu	23%	50%	26%	41%	16%	35%	7%
Zhejiang	41%	50%	29%	45%	30%	49%	20%
Anhui	14%	56%	22%	31%	11%	22%	4%
Fujian	29%	51%	30%	42%	19%	31%	7%
Jiangxi	24%	53%	21%	43%	19%	30%	9%
Shandong	23%	50%	25%	39%	19%	35%	9%
Henan	23%	57%	22%	41%	18%	35%	8%
Hubei	19%	55%	23%	35%	16%	23%	10%
Hunan	22%	51%	25%	36%	20%	24%	15%
Guangdong	38%	50%	33%	46%	27%	42%	13%
Guangxi	24%	50%	28%	39%	17%	27%	5%
Hainan	24%	44%	25%	36%	14%	25%	4%
Chongqing	18%	53%	32%	37%	14%	20%	4%
Sichuan	16%	50%	27%	33%	9%	15%	3%
Guizhou	24%	39%	25%	30%	22%	25%	20%
Yunnan	24%	51%	25%	41%	18%	21%	8%
Tibet	16%	35%	15%	35%	14%	14%	5%
Shaanxi	19%	45%	18%	34%	13%	22%	5%
Gansu	13%	47%	16%	29%	9%	13%	3%
Qinghai	23%	46%	22%	39%	20%	20%	7%
Ningxia	24%	36%	24%	39%	20%	23%	8%
Xinjiang	16%	35%	15%	35%	14%	14%	5%
CHINA	22%	46%	24%	37%	17%	26%	9%
Taiwan Strait	**11%**	**40%**	**26%**		**29%**		

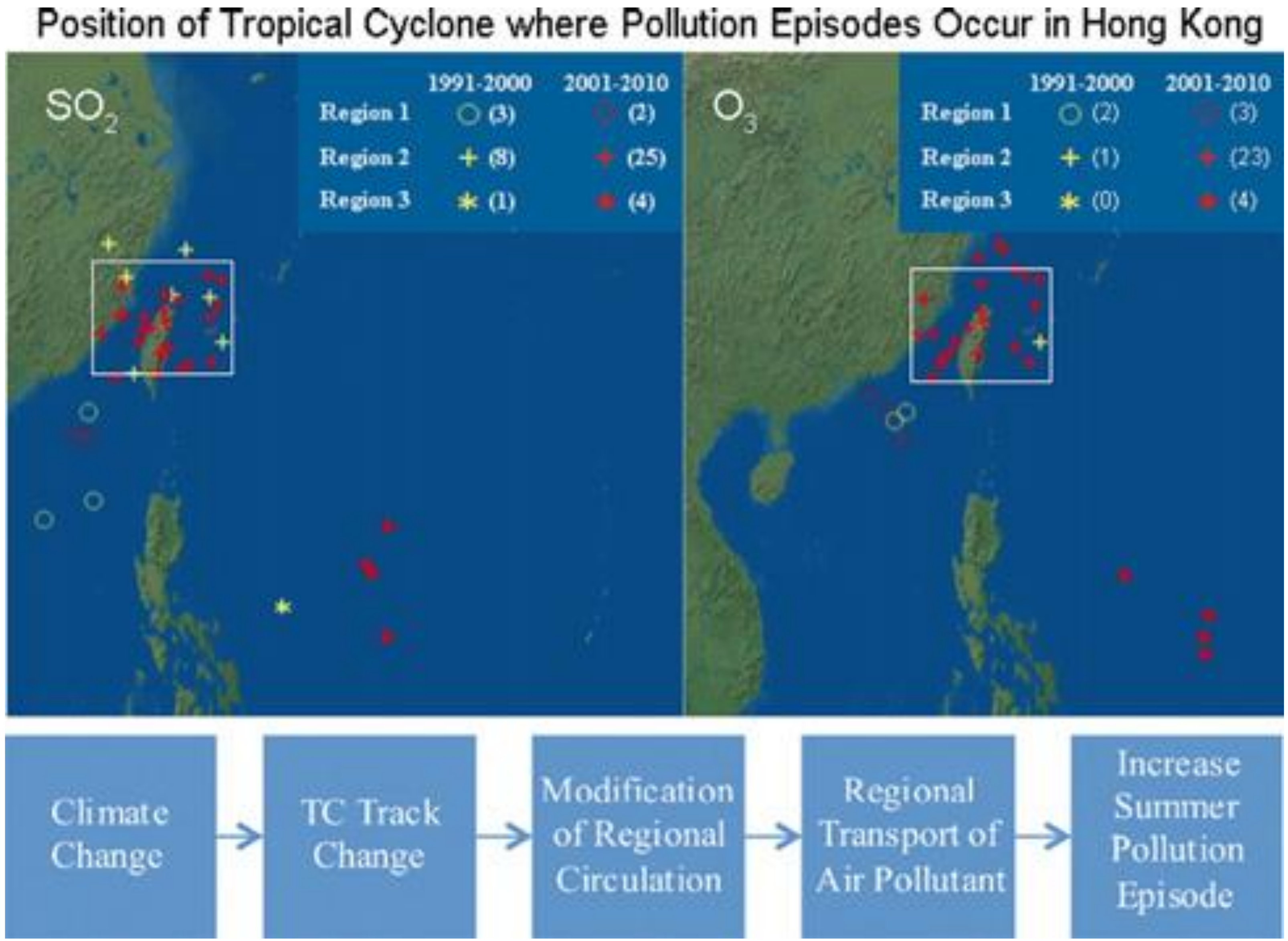
Xin Huang et al. National Science Review 2020.



(Venter et al., 2020; PNAS)

Air quality deterioration episode associated with typhoon over the complex topographic environment in central Taiwan

(Lin et al. 2021 submitted)



Lam et al. (2018)

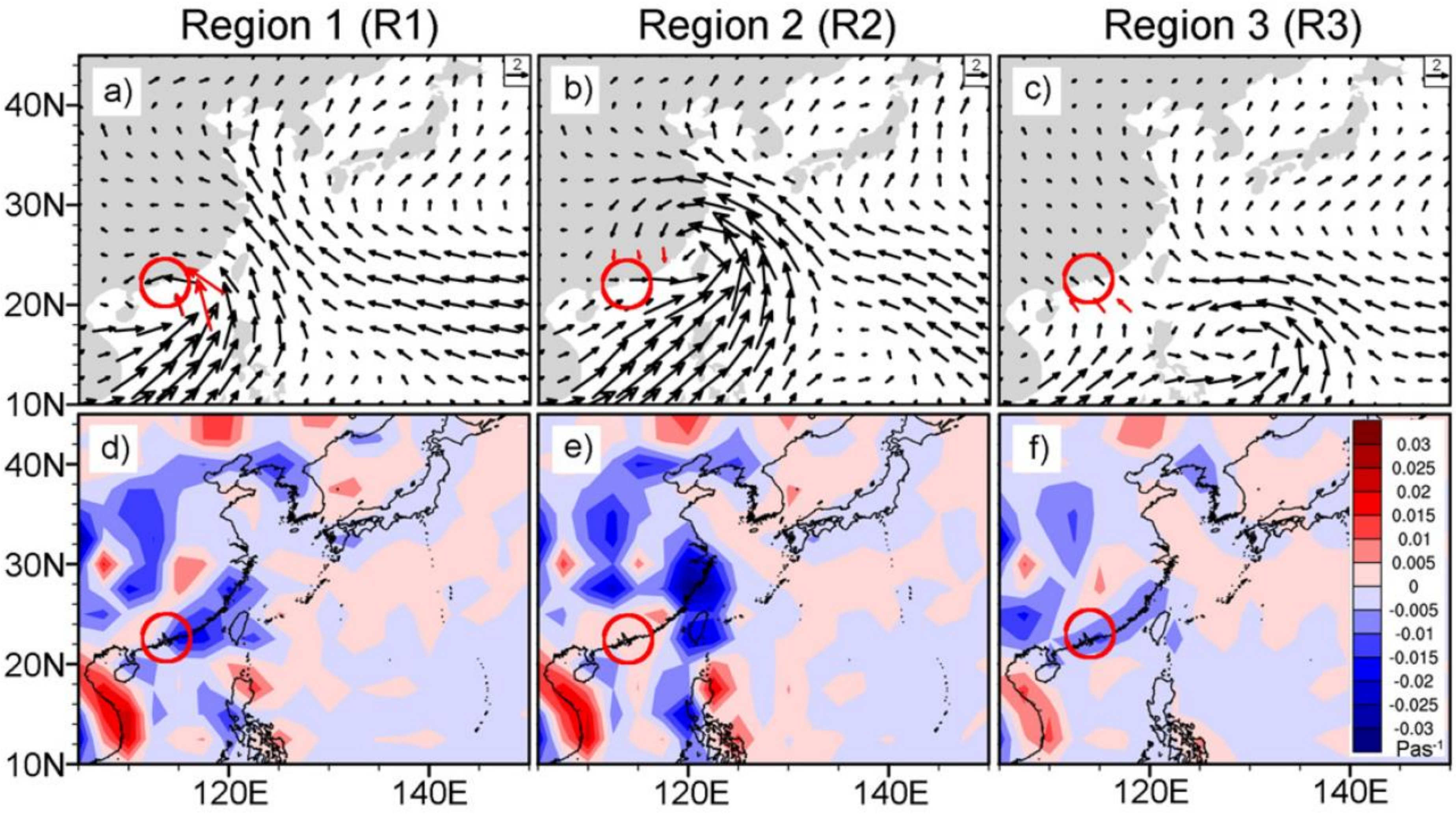


Fig. 3. Composite of horizontal wind at 1000 hPa when TCs are in (a) R1, (b) R2, and (c) R3, and vertical velocity (omega) in Pa s^{-1} at 1000 hPa when TCs are in (d) R1, (e) R2, and (f) R3. Positive values (red) indicate downdrafts motion. Red circles indicate the position of HK, and red arrows signify the prevailing wind direction over HK under the influence of TCs in different regions.

Lam et al. (2018)

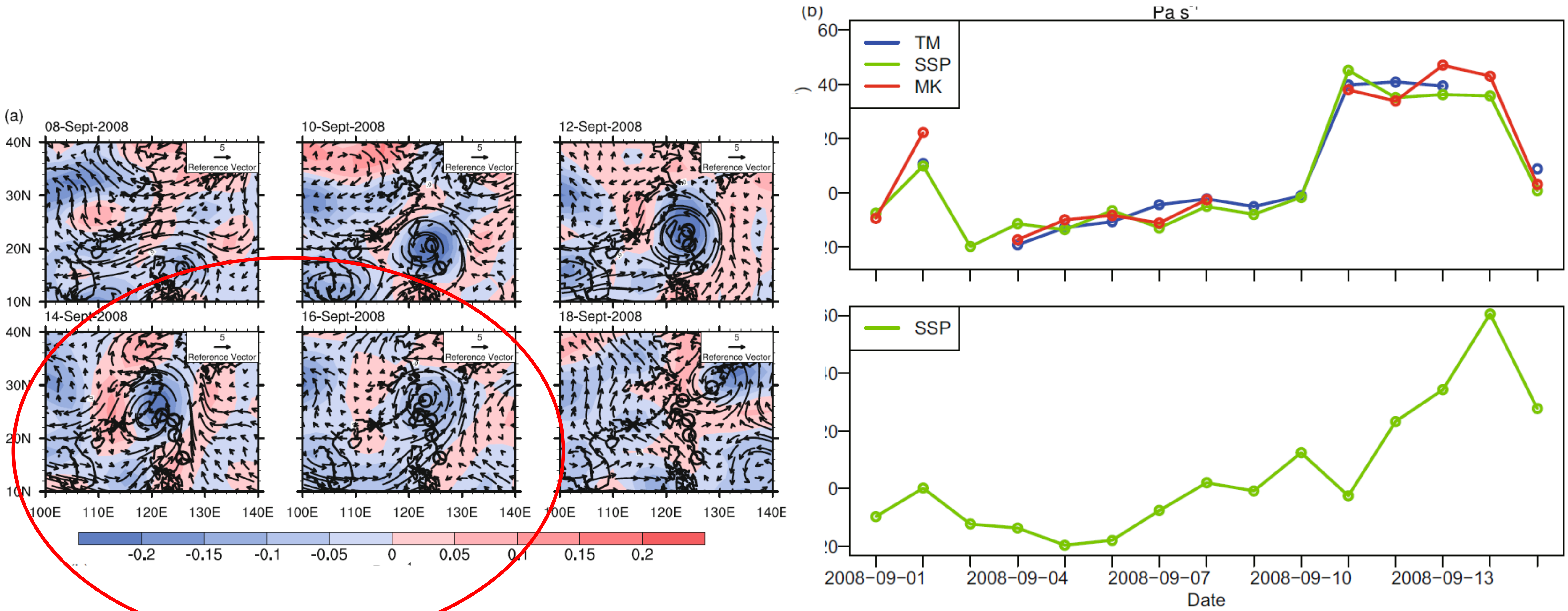
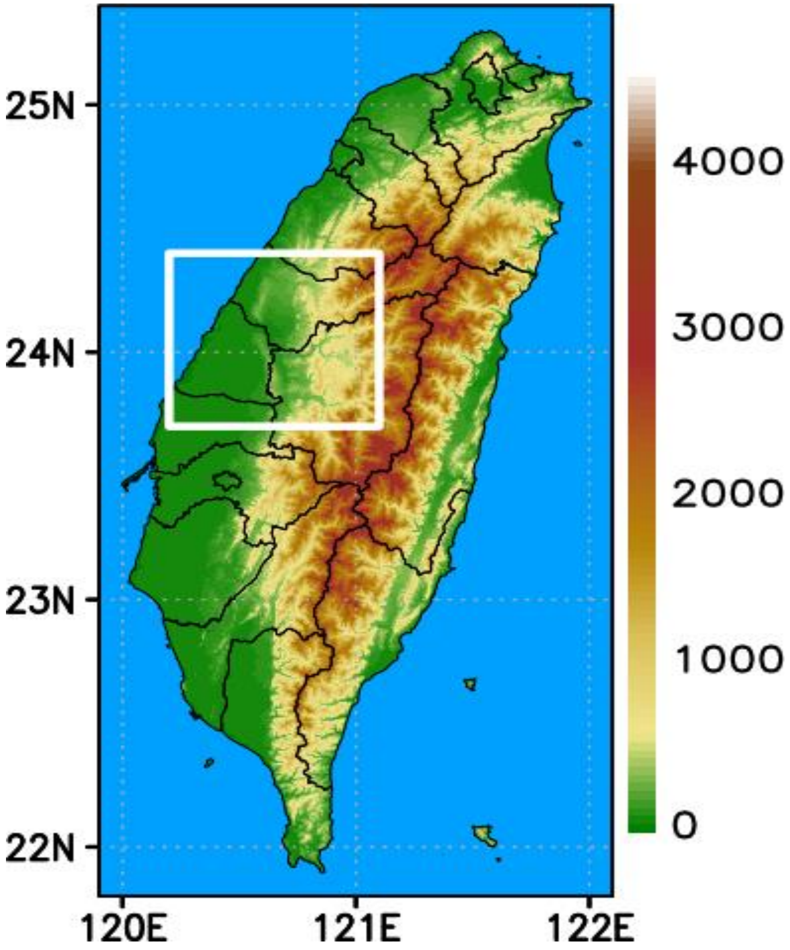


Fig. 2. The (a) atmospheric conditions during Typhoon Sinlaku during 8–18 September 2008, and the (b, c) time series of the (b) anomalous PM_{10} concentration (units: µg m^{-3}) and (c) anomalous O_3 concentration (units: µg m^{-3}) during 1–15 September 2008. The shading and vectors in (a) denote vertical velocity (units: Pa s^{-1}) and horizontal wind velocity (m s^{-1}), respectively. TM, SSP, and MK in (b, c) represent observations from Tap Mun, Sham Shui Po, and Mong Kok stations, respectively.

Chow (et al. 2018)

Typhoon Tracks over Taiwan during 1911-2019



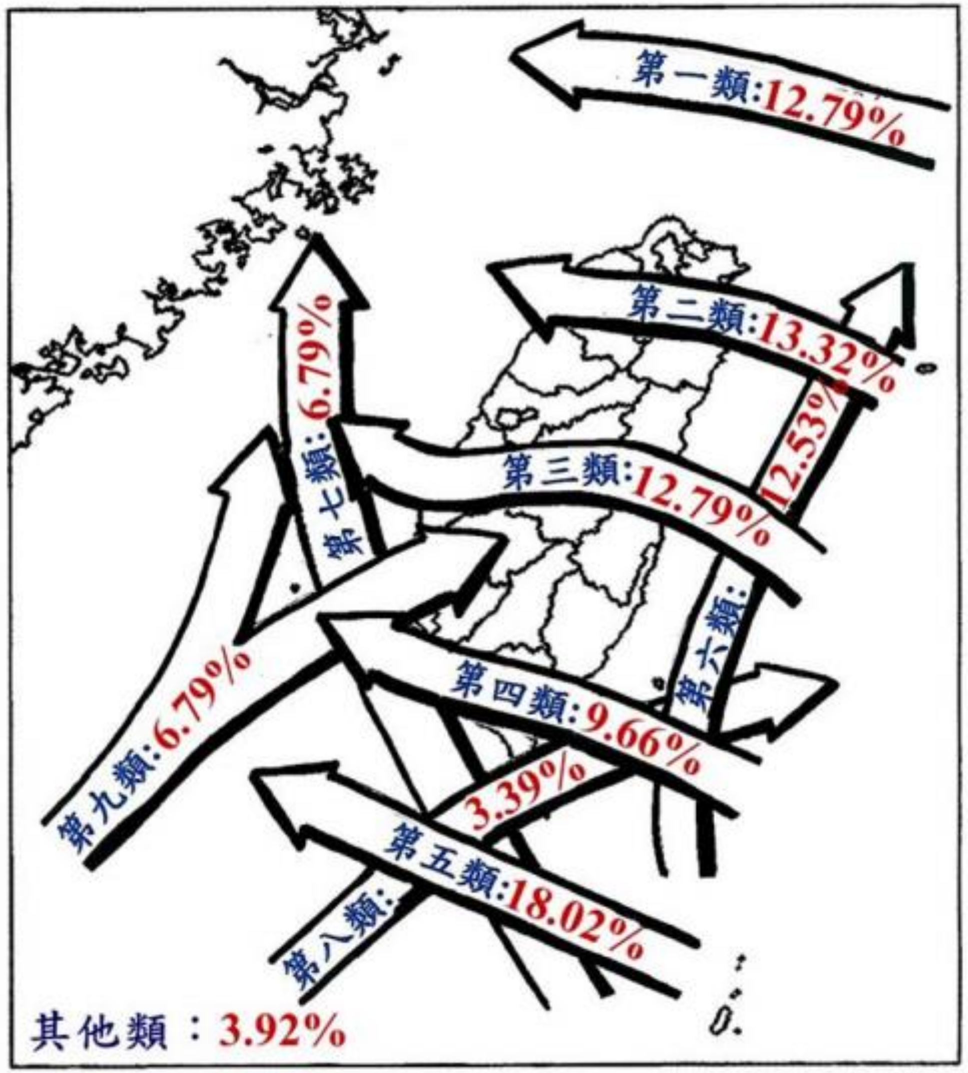
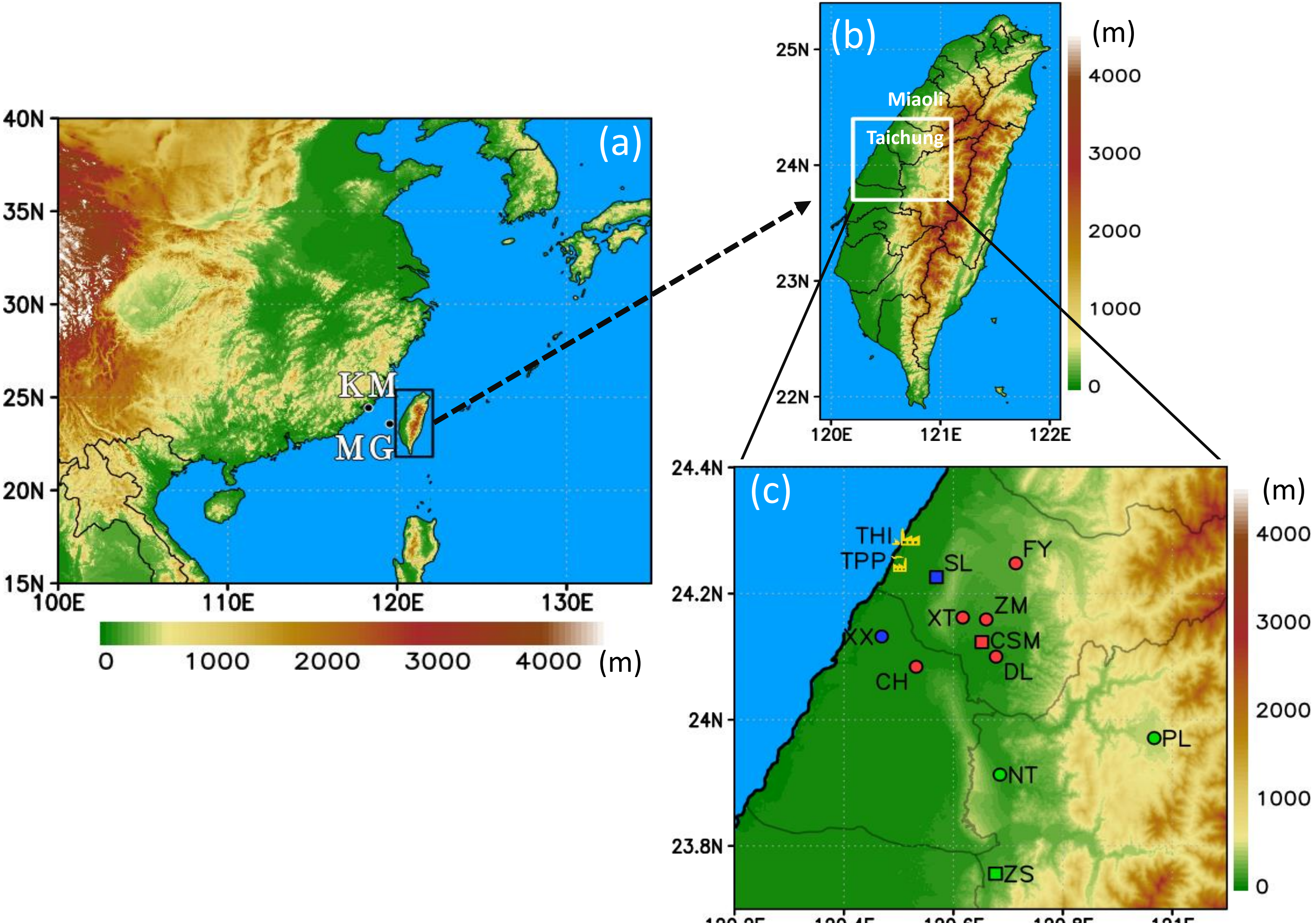


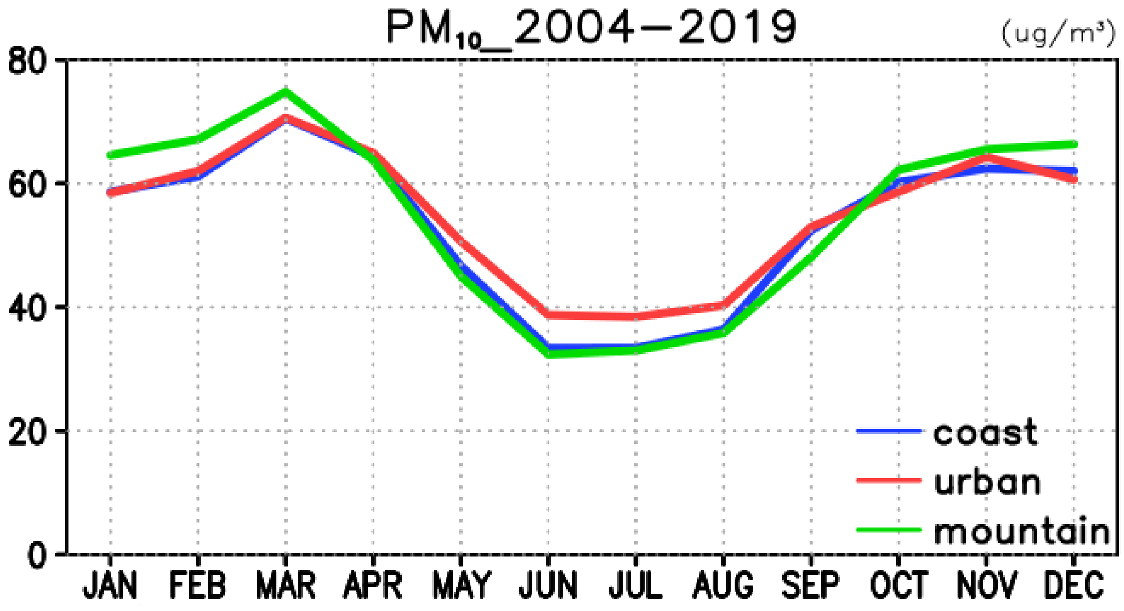
圖 12　影響臺灣地區颱風路徑分類圖(1911－2019 年)。

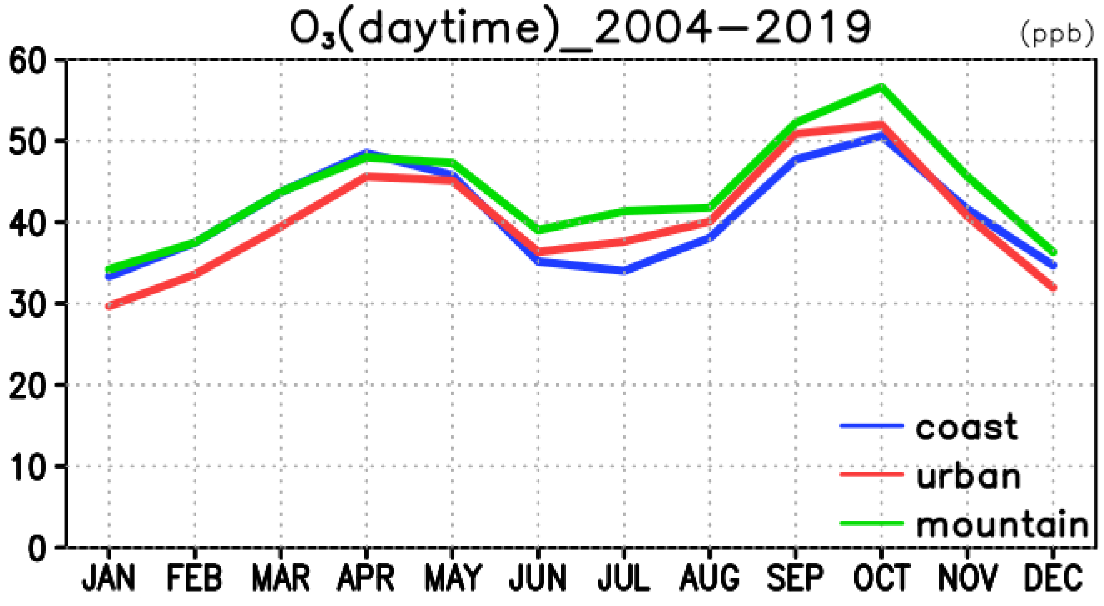
[Reference] https://www.cwb.gov.tw/V8/C/K/Encyclopedia/typhoon/typhoon.pdf

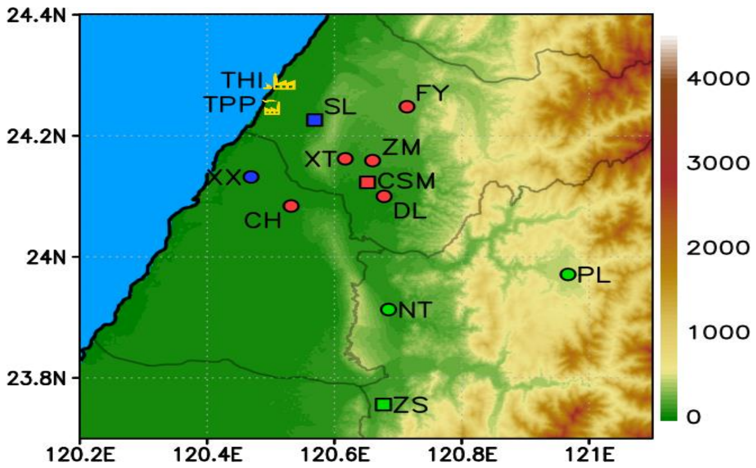


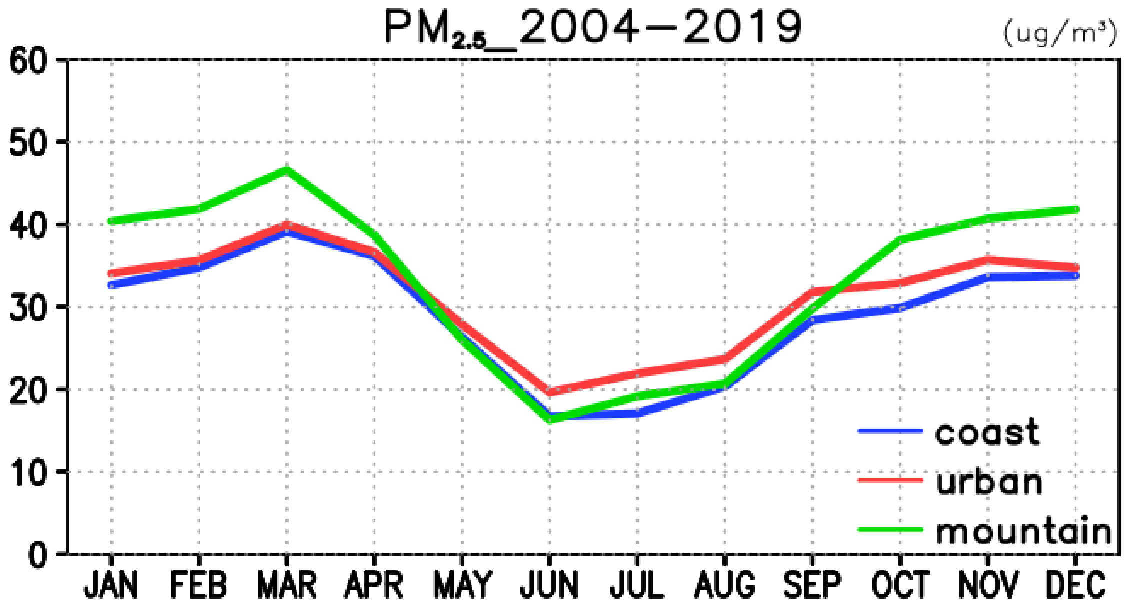
(a)
40N
35N
30N
25N
20N
15N
100E
110E
120E
130E
KM
MG
0
1000
2000
3000
4000
(m)
(b)
Miaoli
Taichung
25N
24N
23N
22N
120E
121E
122E
(m)
4000
3000
2000
1000
0
(c)
24.4N
24.2N
24N
23.8N
THI
TPP
SL
FY
XT
ZM
XX
CSM
DL
CH
PL
NT
ZS
(m)
4000
3000
2000
1000
0

Characteristics of air quality over central Taiwan

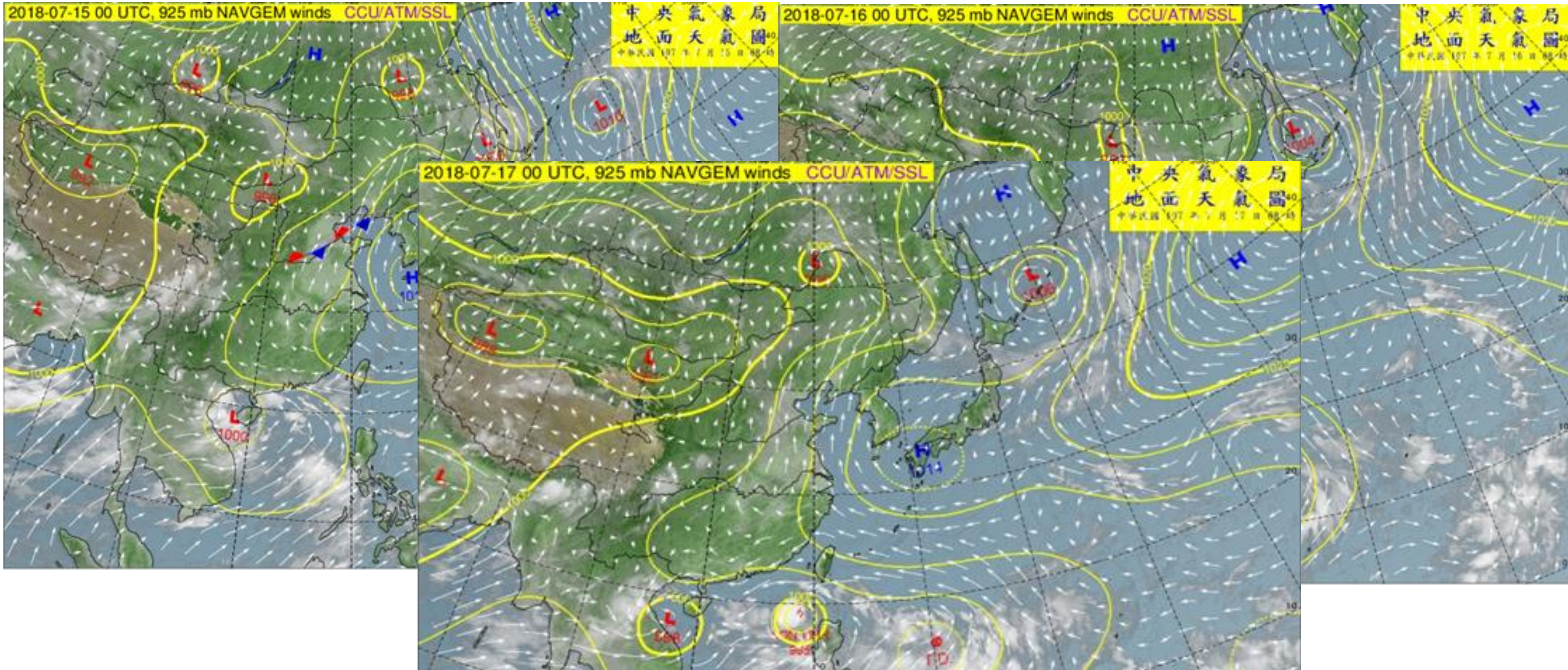




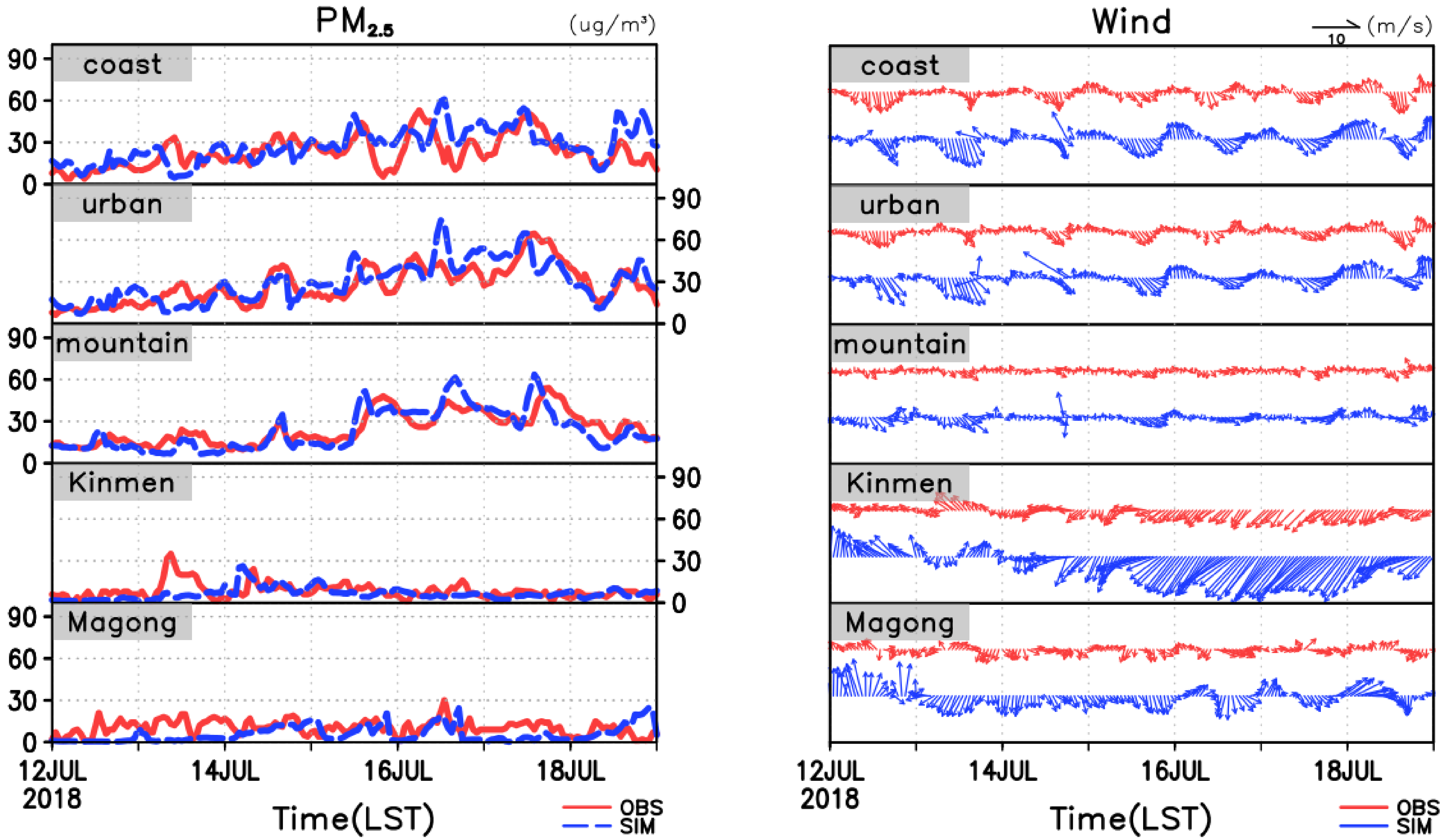


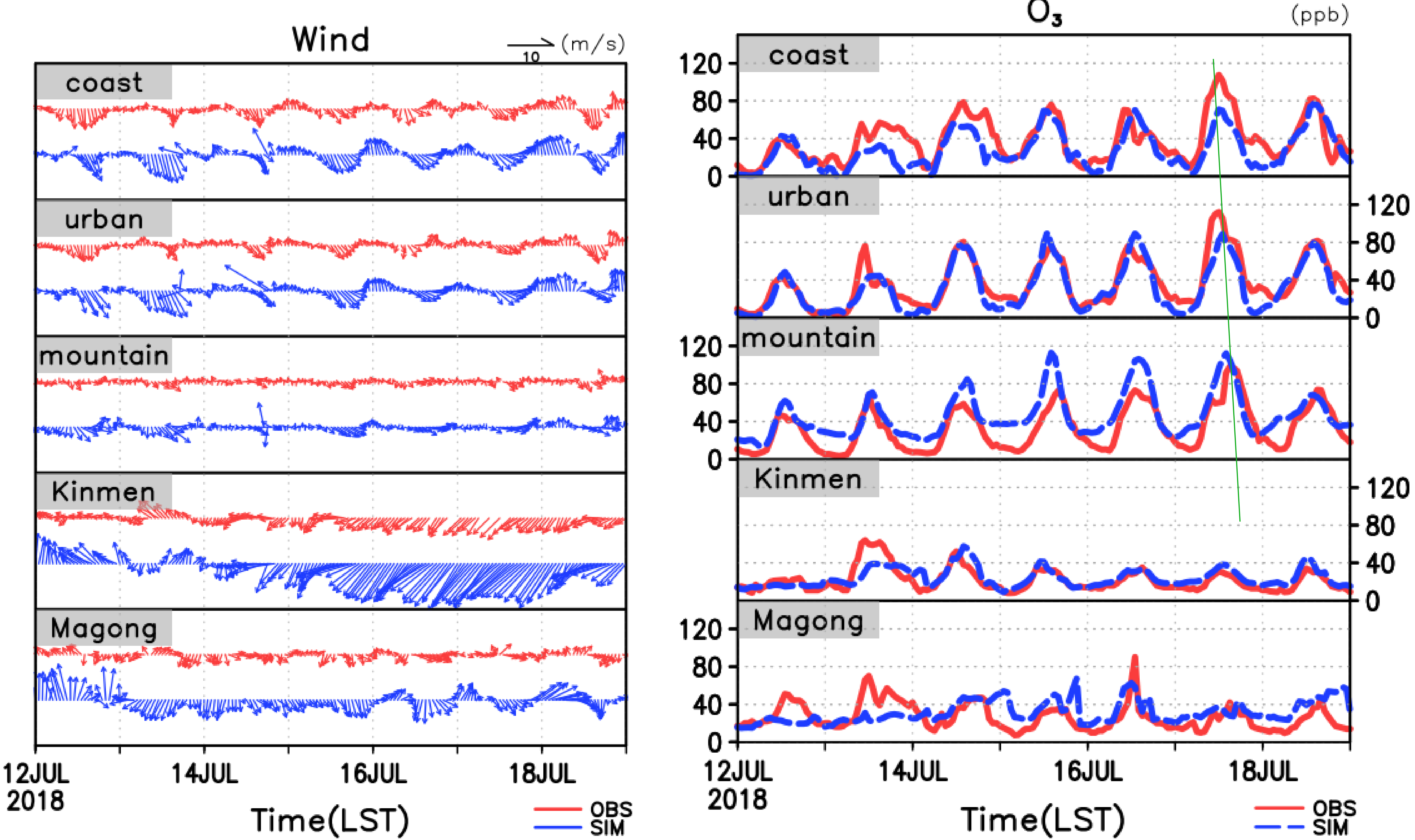


Air quality deterioration case during 15–17 July 2018

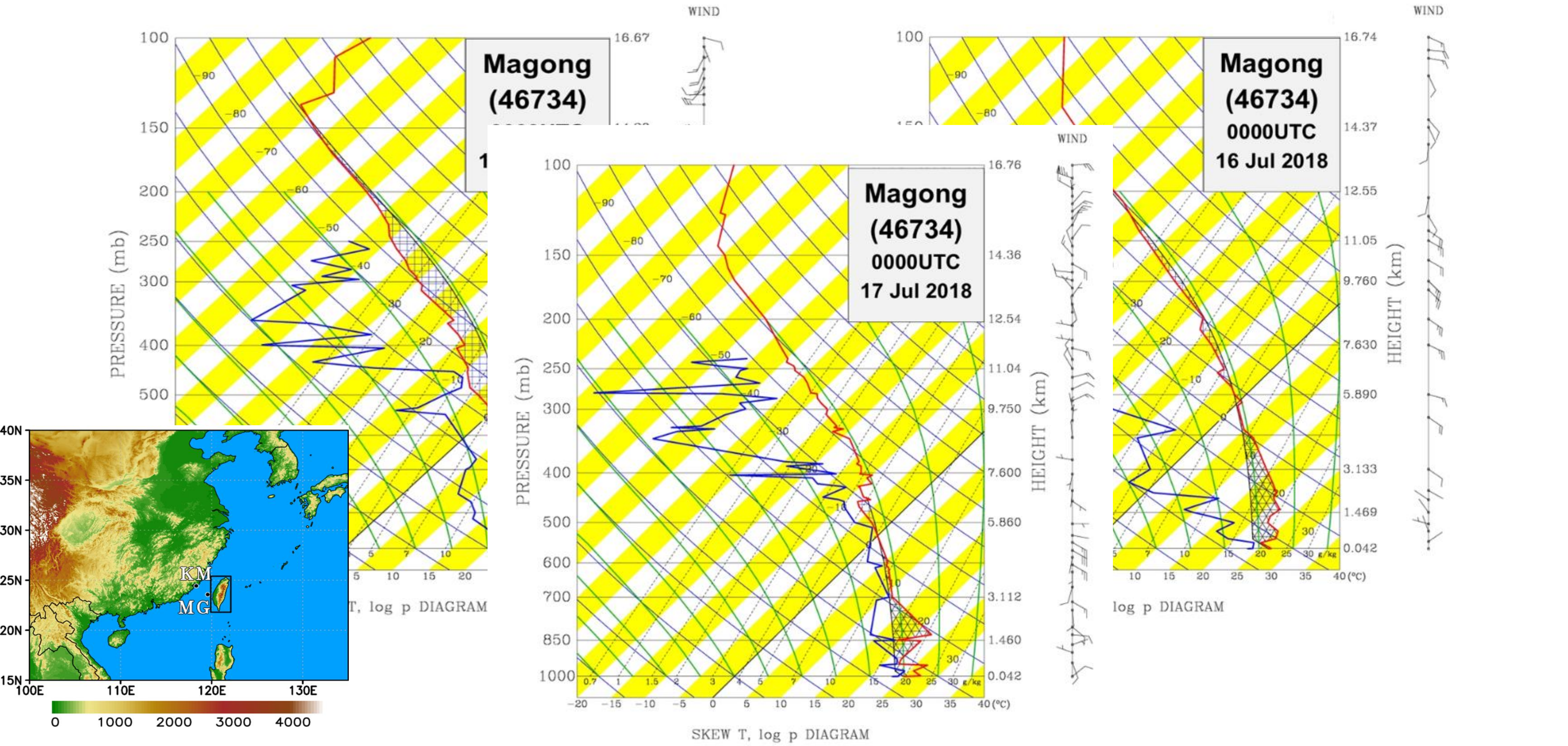


Air quality deterioration case during 15-17 July 2018

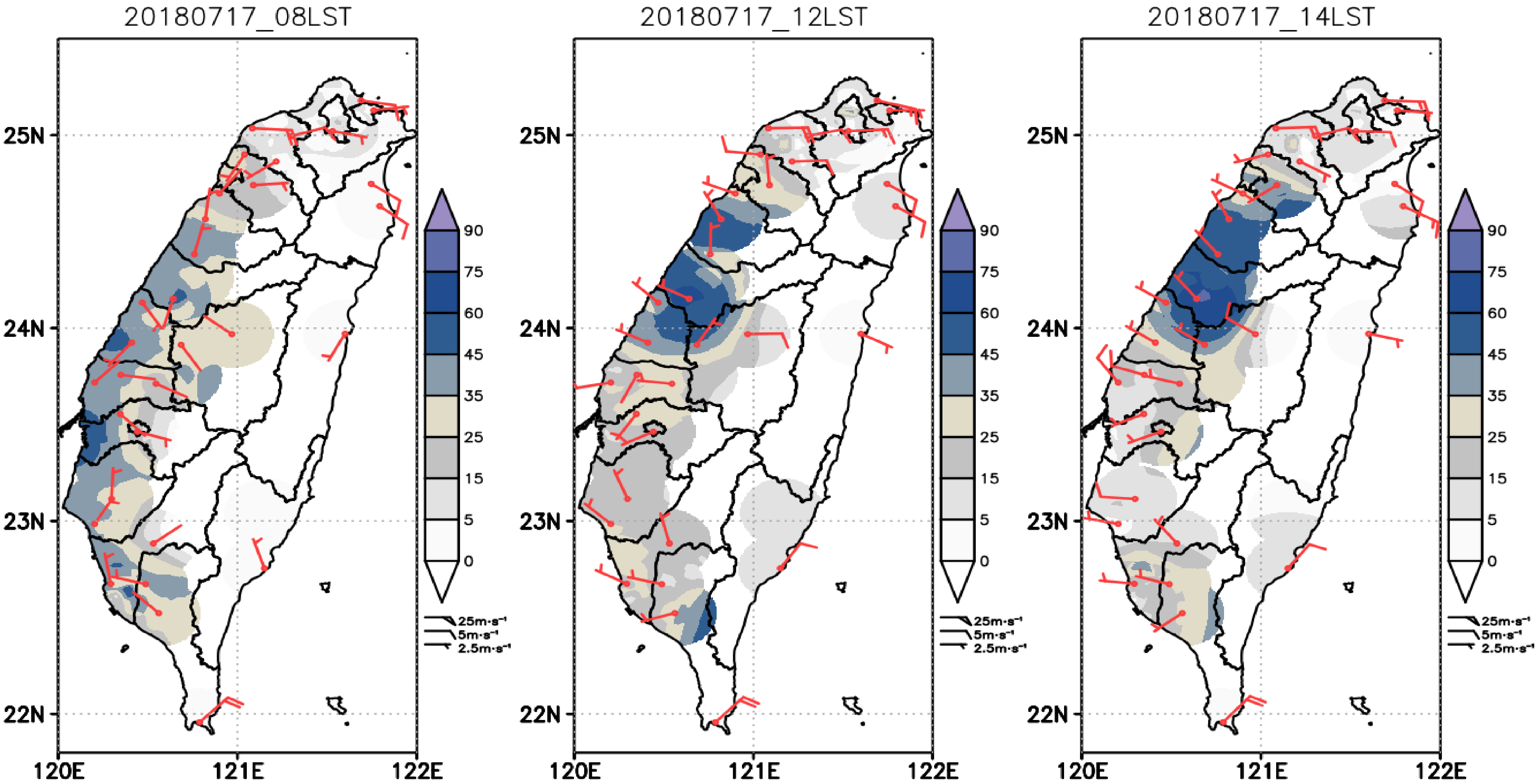



Wind
10 (m/s)
coast
urban
mountain
Kinmen
Magong
12JUL 2018
14JUL
16JUL
18JUL
Time(LST)
OBS
SIM
O3
(ppb)
coast
urban
mountain
Kinmen
Magong
0
40
80
120
12JUL 2018
14JUL
16JUL
18JUL
Time(LST)
OBS
SIM

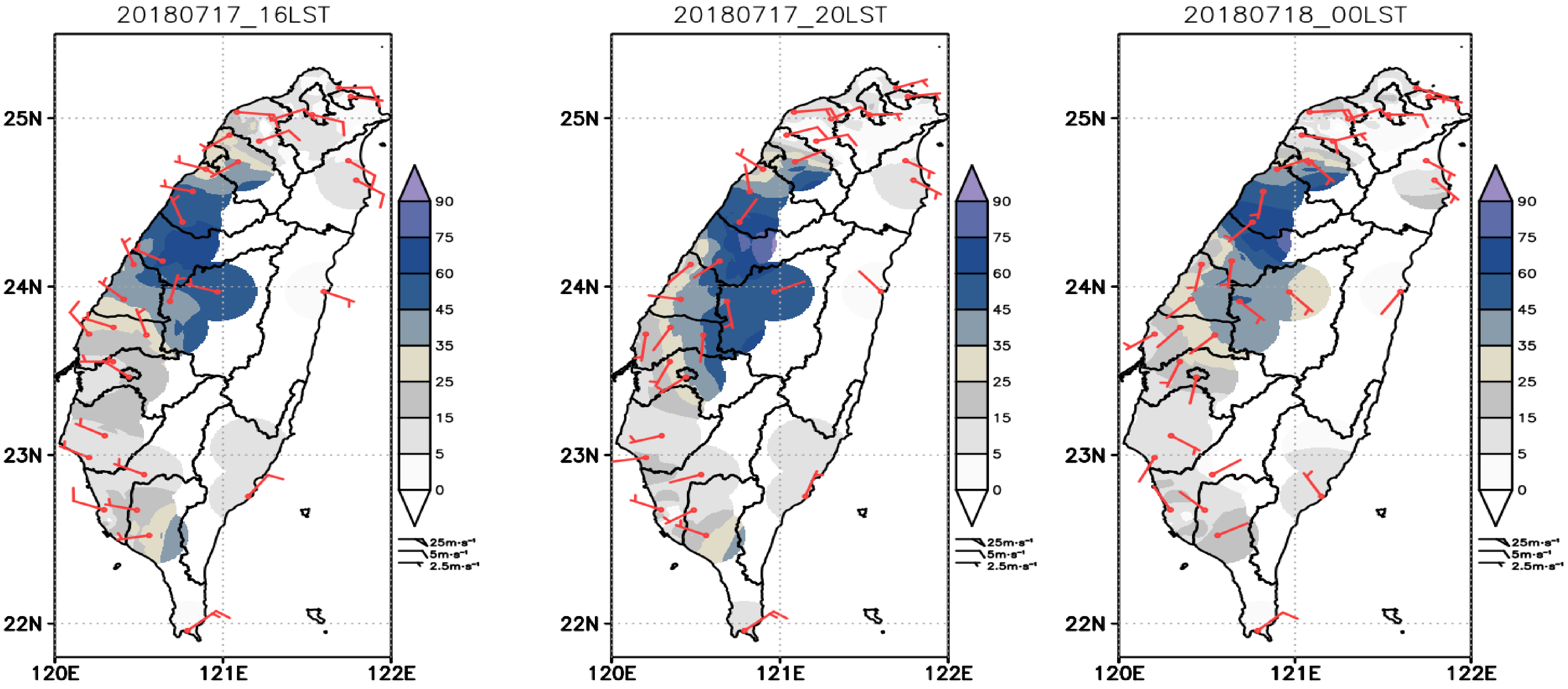
Magong sounding during 15–17 July 2018

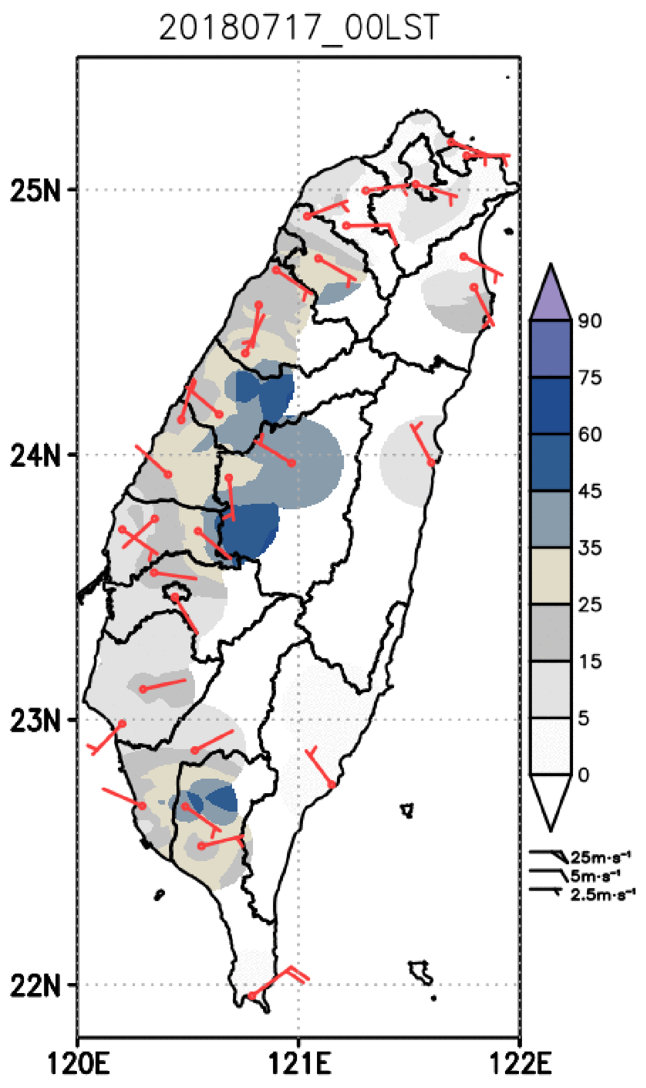


Measurement PM2.5 concentration and wind field

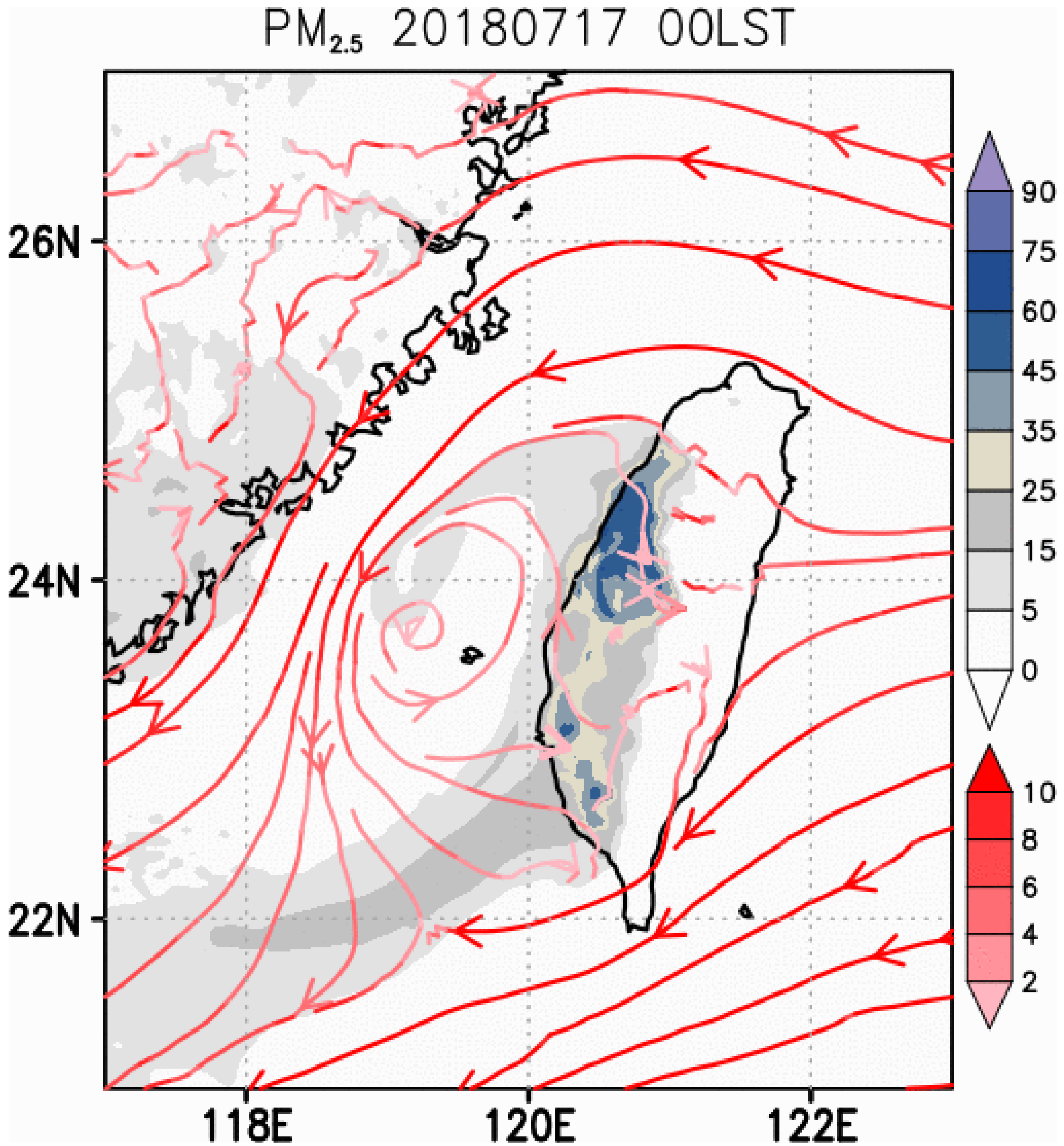


Measurement PM2.5 concentration and wind field



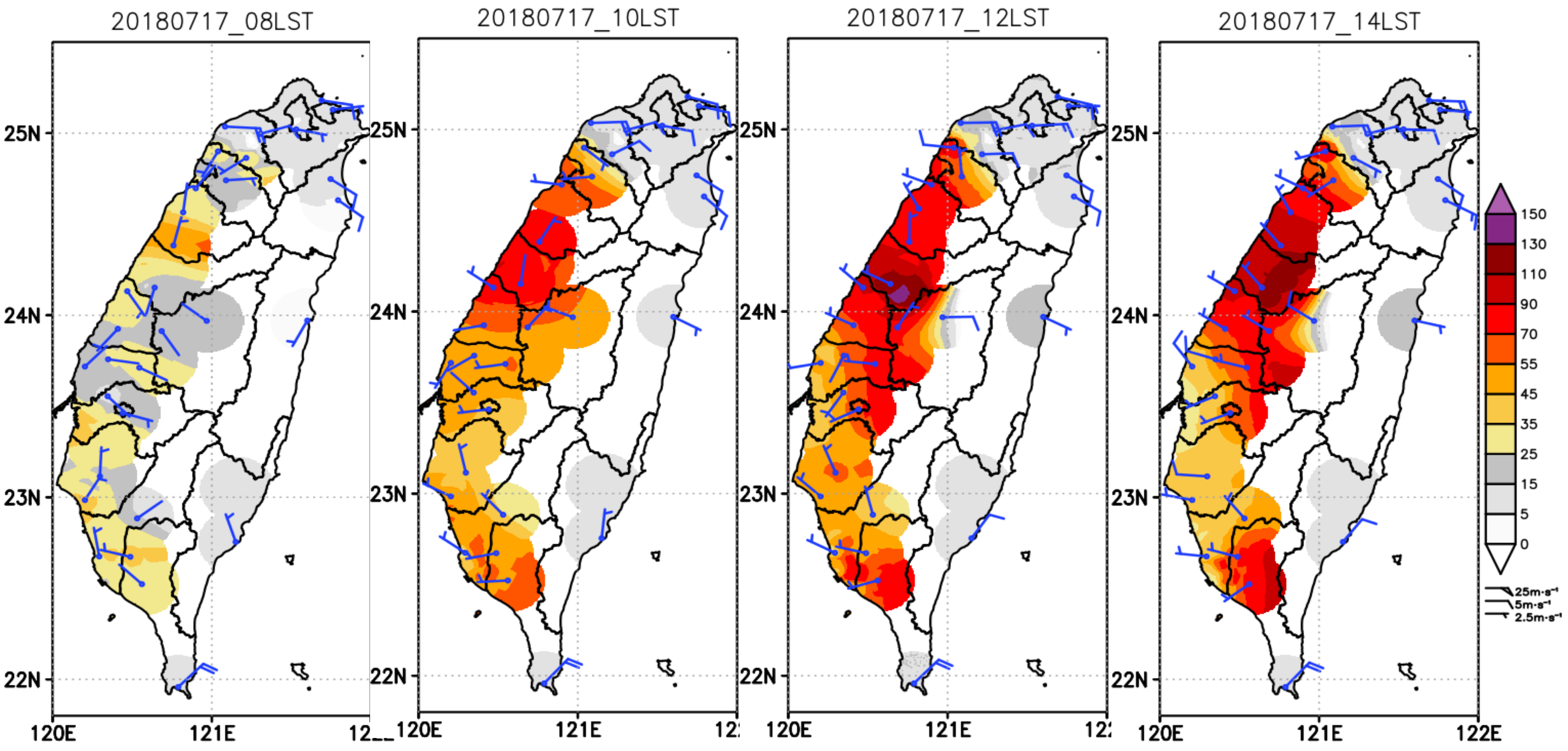


20180717_00LST
25N
24N
23N
22N
120E
121E
122E
90
75
60
45
35
25
15
5
0
25m·s⁻¹
5m·s⁻¹
2.5m·s⁻¹

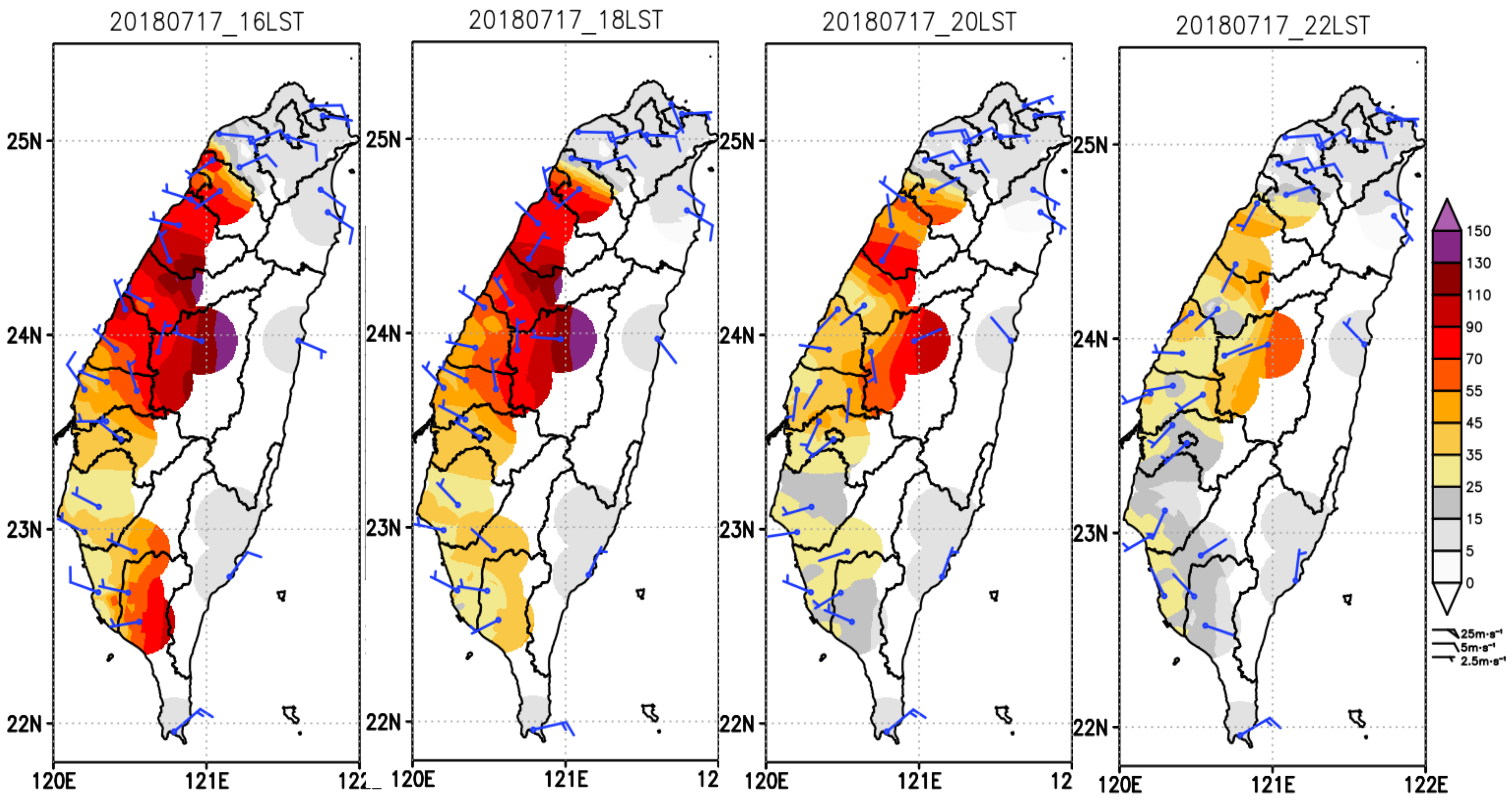


PM2.5 20180717 00LST
26N
24N
22N
118E
120E
122E
90
75
60
45
35
25
15
5
0
10
8
6
4
2

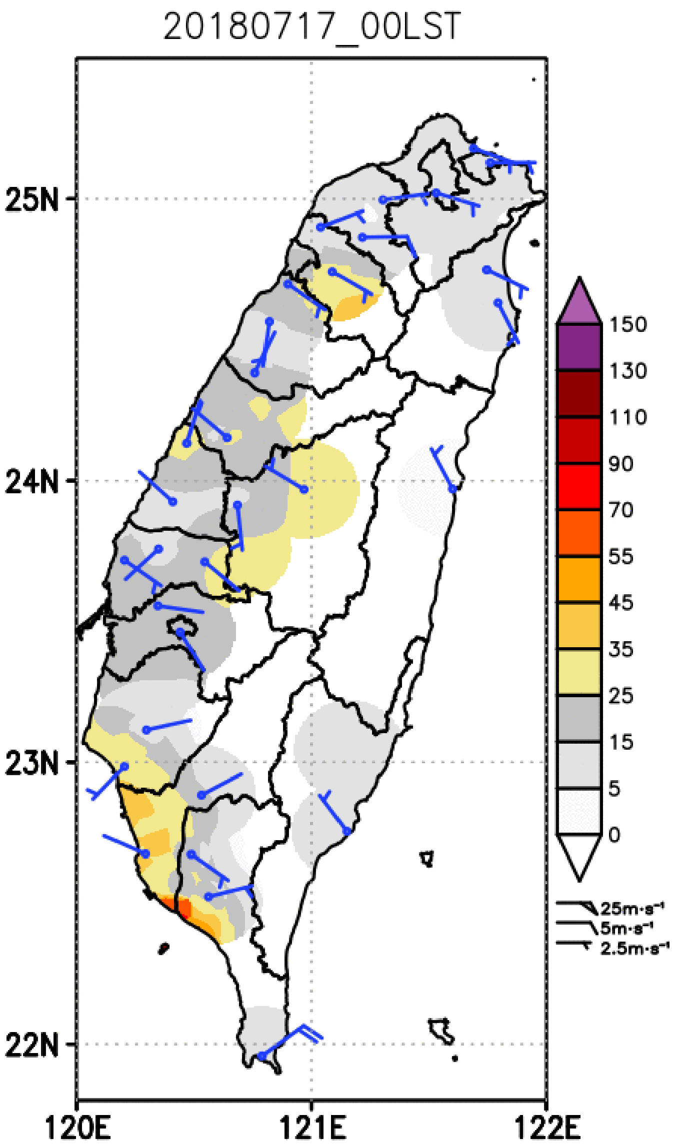
Measurement ozone concentration and wind field



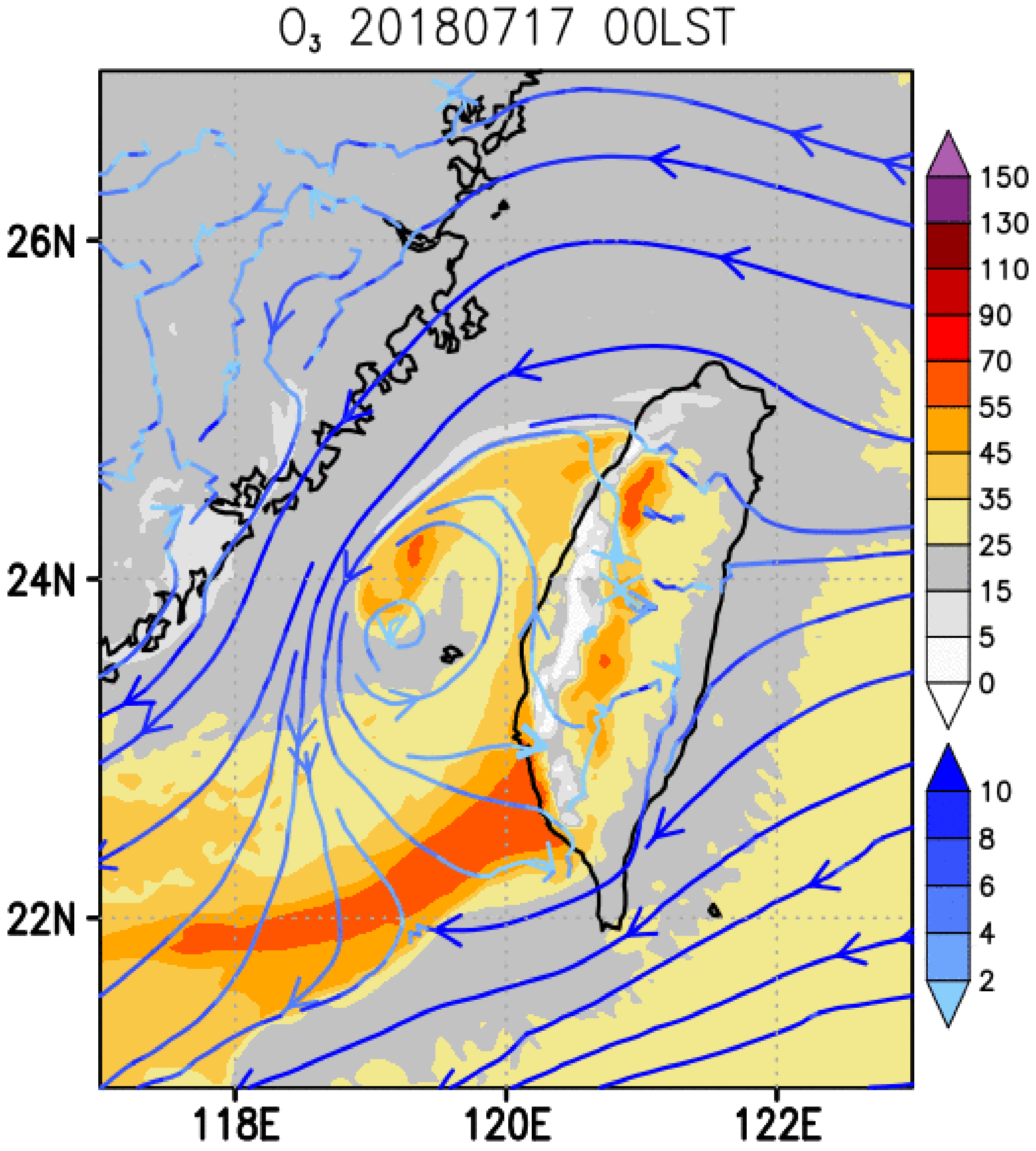
Ozone concentration and wind field

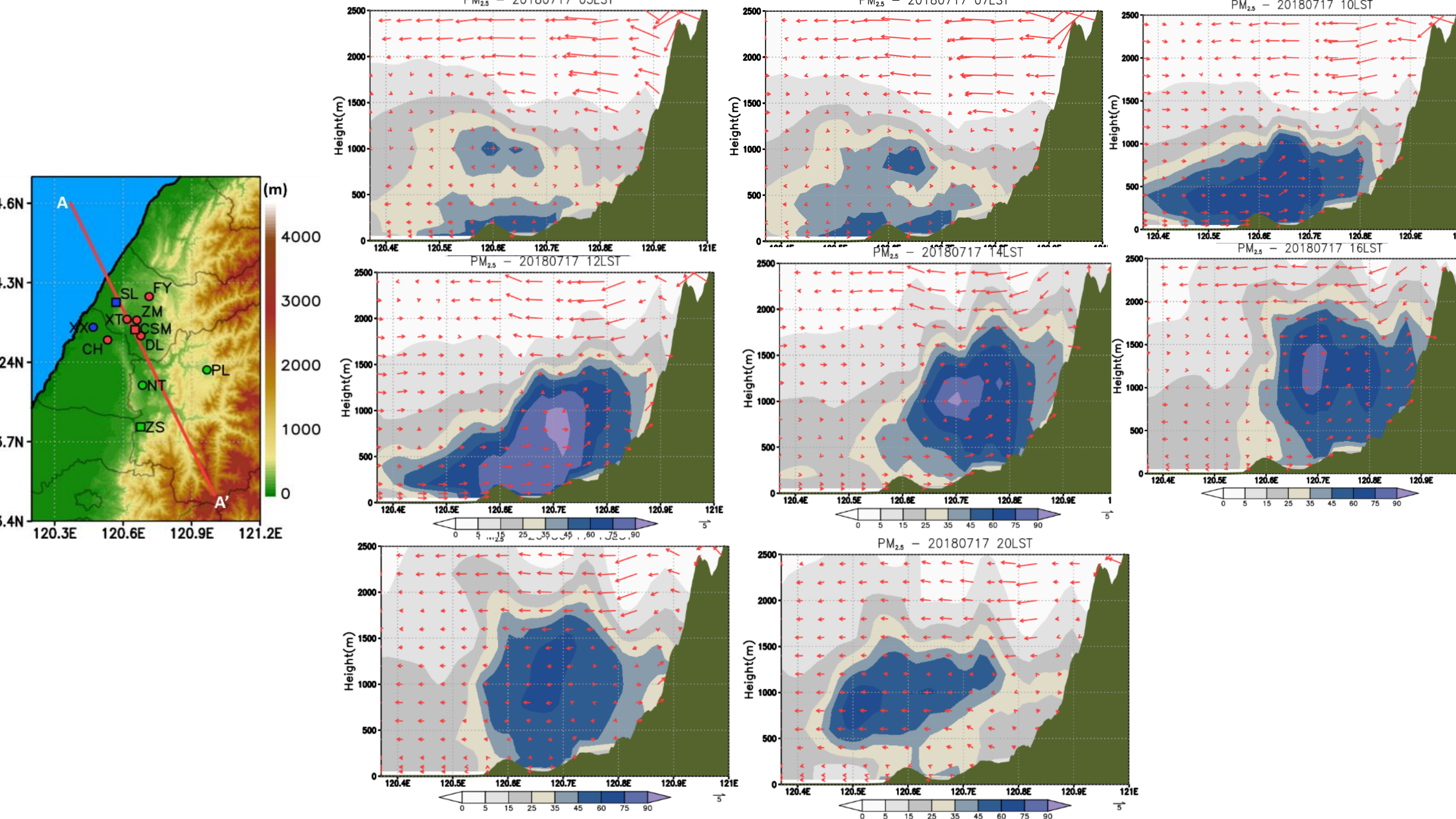


Observation

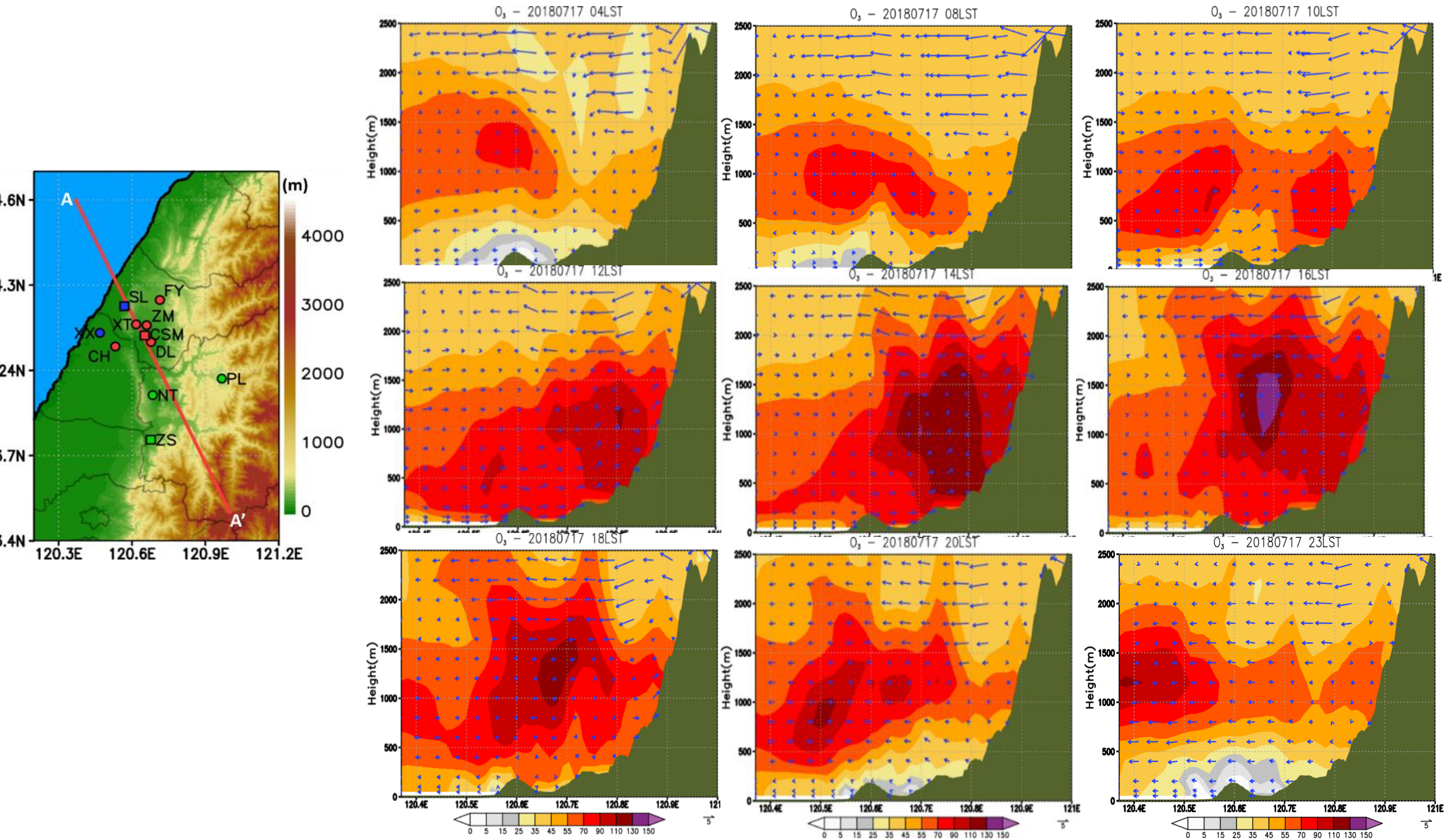


Simulation





A
A'
SL
FY
ZM
XT
CSM
XX
CH
DL
PL
NT
ZS
(m)
4000
3000
2000
1000
0
120.3E
120.6E
120.9E
121.2E
PM2.5 – 20180717 10LST
PM2.5 – 20180717 12LST
PM2.5 – 20180717 14LST
PM2.5 – 20180717 16LST
PM2.5 – 20180717 20LST
Height(m)
120.4E
120.5E
120.6E
120.7E
120.8E
120.9E
121E
0
5
15
25
35
45
60
75
90



A
A'
SL
FY
ZM
XX
XT
CSM
DL
CH
PL
NT
ZS
(m)
4000
3000
2000
1000
0
120.3E
120.6E
120.9E
121.2E
O3 - 20180717 04LST
O3 - 20180717 08LST
O3 - 20180717 10LST
O3 - 20180717 12LST
O3 - 20180717 14LST
O3 - 20180717 16LST
O3 - 20180717 18LST
O3 - 20180717 20LST
O3 - 20180717 23LST
Height(m)
120.4E
120.5E
120.6E
120.7E
120.8E
120.9E
121E
0 5 15 25 35 45 55 70 90 110 130 150

Figures

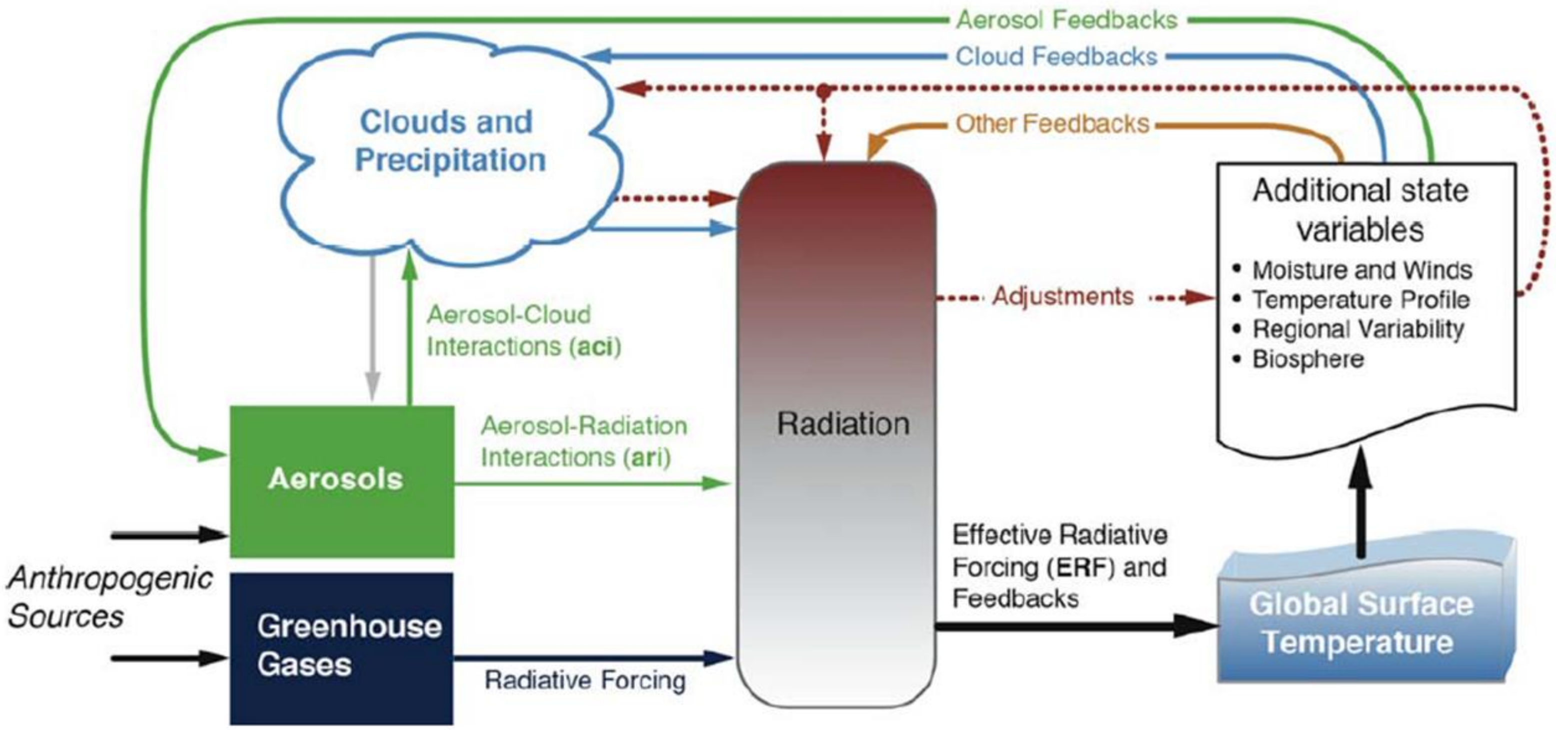
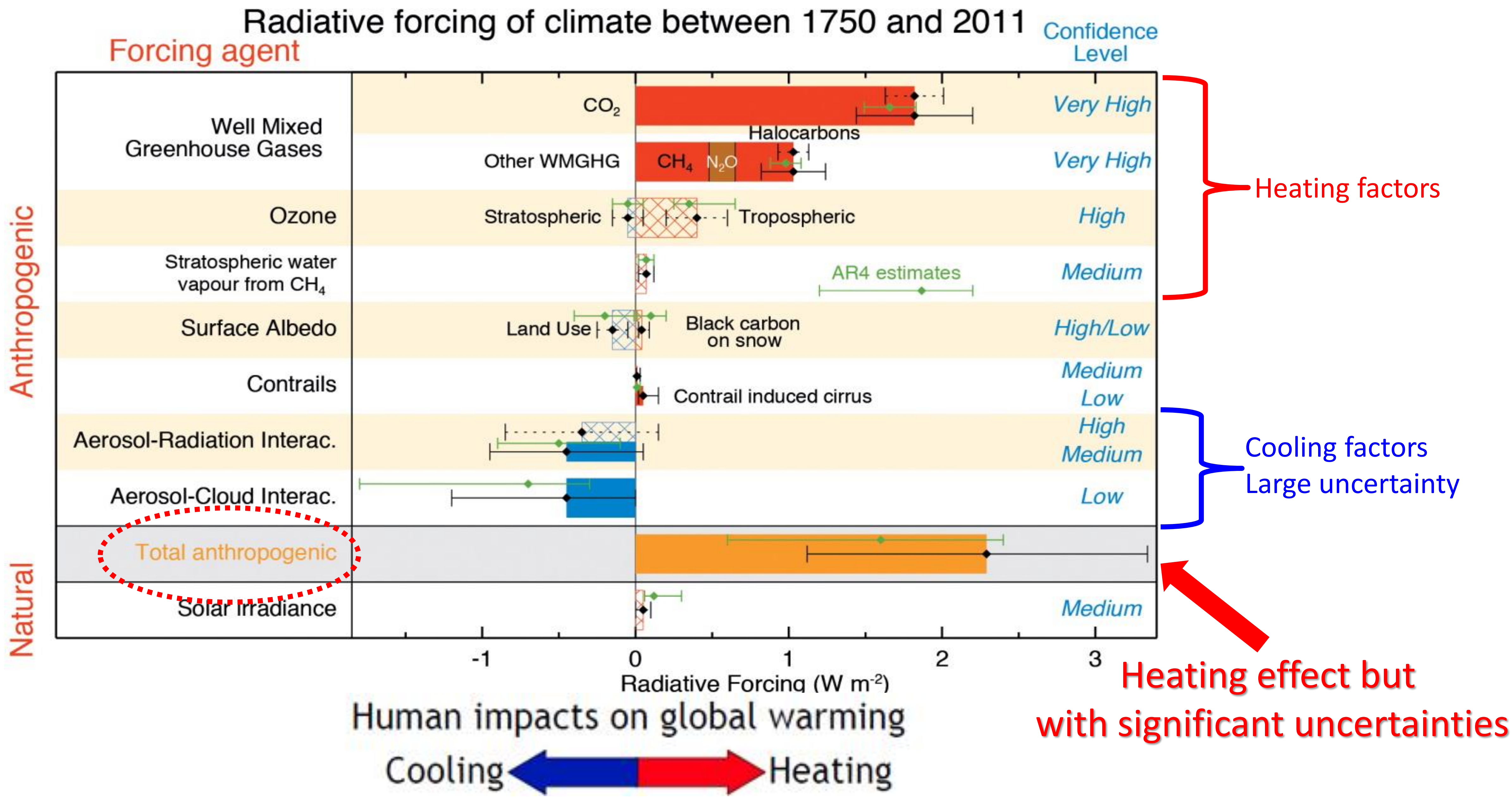


Figure 7.1: Overview of forcing and feedback pathways involving greenhouse gases, aerosols and clouds. Forcing agents are in the green and dark blue boxes, with forcing mechanisms indicated by the straight green and dark blue arrows. The forcing is modified by rapid adjustments whose pathways are independent of changes in the globally averaged surface temperature and are denoted by brown dashed arrows. Feedback loops, which are ultimately rooted in changes ensuing from changes in the surface temperature, are represented by curving arrows (blue denotes cloud feedbacks; green denotes aerosol feedbacks; and orange denotes other feedback loops such as those involving the lapse rate, water vapour and surface albedo). The final temperature response depends on the effective radiative forcing (ERF) that is felt by the system, i.e., after accounting for rapid adjustments, and the feedbacks.

(IPCC report)

Challenges


Radiative forcing of climate between 1750 and 2011
Forcing agent
Confidence Level
Anthropogenic
Natural
Well Mixed Greenhouse Gases
CO2
Very High
Halocarbons
Other WMGHG
CH4
N2O
Very High
Ozone
Stratospheric
Tropospheric
High
Stratospheric water vapour from CH4
AR4 estimates
Medium
Surface Albedo
Land Use
Black carbon on snow
High/Low
Contrails
Contrail induced cirrus
Medium
Low
Aerosol-Radiation Interac.
High
Medium
Aerosol-Cloud Interac.
Low
Total anthropogenic
Solar irradiance
Medium
-1
0
1
2
3
Radiative Forcing (W m-2)
Human impacts on global warming
Cooling
Heating
Heating factors
Cooling factors
Large uncertainty
Heating effect but
with significant uncertainties