Numerical simulation on extreme weather, air pollution and environmental changes

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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.)
Historical events.......
Sources of air pollutants

- Ozone
- Secondary aerosols

Primary pollutants:
- VOCs
- CO
- CO₂
- SO₂
- NO
- NO₂
- Most hydrocarbons
- Most suspended particles

Secondary pollutants:
- SO₃
- H₂SO₄
- HNO₃
- O₃
- H₂O₂
- Most NO₃⁻ and SO₄²⁻

Natural and Human-Generated Emissions

Transport and Chemical Reactions

Winds

Deposition

Haze

Biological Effects on Natural Resources

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

Coarse particulates
Upper respiratory tract

Fine particulates
Lower respiratory tract

Very fine particulates
Alveolus

Ultrafine particulates
Blood/Whole body

PM10

PM2.5

PM0.1

Head:
HUMAN HAIR
50-70 μm (microns) in diameter

PM2.5:
Combustion particles, organic compounds, metals, etc.
< 2.5 μm (microns) in diameter

PM10:
Dust, pollen, mold, etc.
< 10 μm (microns) in diameter

Fine sand:
FINE BEACH SAND
90 μm (microns) in diameter

PM2.5 約為頭髮1/28
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

PM2.5
Aerosol, cloud and climate change
Air pollution in Taiwan

PM2.5 pollution map for Taiwan, showing high levels on 07 Nov. 2018 and 08 Nov. 2018.

AQI details for桃園 (Taoyuan), showing AQI of 151 on 08 Nov. 2018.
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.)
Long-range transport: Asian Dust

(Lin et al. 2012 ACP)
ATSR-WFA Hot Spots
(2012 01-03)
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)
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)
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)

![Map of LuLin Mountain station with coordinates: 120° 52' 25" E, 23° 28' 07" N, 2862 m Alt.]

![Bar chart showing CO, O3, and PM_{10} concentrations over months]

- CO
- O3
- PM_{10}
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

MODIS Aerosol Optical Depth

(Lin et al. 2011 ACP)
Modelling of long-range transport of Southeast Asia biomass-burning aerosols to Taiwan and their radiative forcings over East Asia

By CHUAN-YAO LIN1,*, CHUN ZHAO2, XIAOHONG LIU2,3, NENG-HUEI LIN4 and WEI-NIEI CHEN1, *Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan.

WRF/chem configures

- Radiaton: RRTMG
- PBL: Mellor Yamada Janjic (MYJ)
- Chemistry driver: RADM2
- Aerosol driver: MADE/SORGAM
- Biomass mass burning emission: FINN1
- Domain: resolution 15 km, vertical 35 levels.
- 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
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

NO₂ 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.
Changes in the Atmospheric Column Density of Air Pollutants over the East and North China

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

- Ambient NO\textsubscript{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.

- 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\textsubscript{2}] observed in the Lunar Jan 2020, which decreased by 49 % from previous month, and 40 % from the mean of Jan 2017-2019.

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

- Ambient [CO], [SO₂], [PM2.5] reduced respectively by 11 %, 26 %, and 29% in the Lunar January of 2020, comparing to the monthly mean of 2017 – 2019, whereas [O₃] 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.

Ozone exhibited reversely because of the decline in chemical sink.

Short-term change of SO₂ superposed on its long-term decreasing trend. Impact of lockdown was not well defined.

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

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 Scenarios

Emission Inventories
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

Emission reduction scenario

以2020年2月16-17日

CO

PM$_{2.5}$
The effects of NO2 emission reduction 80% are diminished in the downwind areas.

<table>
<thead>
<tr>
<th>AREA 1</th>
<th>NO2</th>
<th>CO</th>
<th>SO2</th>
<th>PM10</th>
<th>PM2.5</th>
<th>O3</th>
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<td>Cut80%</td>
<td>-83%</td>
<td>-63%</td>
<td>-80%</td>
<td>-55%</td>
<td>-67%</td>
<td>+11%</td>
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difference in Feb. between 2020 and 2019
Changes in the Ambient levels of Air Pollutants over the Taiwan Strait Area

- Le et al. (2020) reported O3 increases observed at Beijing and Shanghai, 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.

<table>
<thead>
<tr>
<th>Region</th>
<th>CO (%)</th>
<th>NOx (%)</th>
<th>SO2 (%)</th>
<th>VOC (%)</th>
<th>PM2.5 (%)</th>
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Air quality deterioration episode associated with typhoon over the complex topographic environment in central Taiwan

(Lin et al. 2021 submitted)
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.
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.
Typhoon Tracks over Taiwan during 1911-2019

Characteristics of air quality over central Taiwan

\textbf{PM\textsubscript{10} 2004–2019} (\text{ug/m\textsuperscript{3}})

\textbf{O\textsubscript{3}(daytime) 2004–2019} (\text{ppb})

\textbf{PM\textsubscript{2.5} 2004–2019} (\text{ug/m\textsuperscript{3}})
Air quality deterioration case during 15-17 July 2018
Air quality deterioration case during 15-17 July 2018

PM$_{2.5}$ (µg/m$^3$)

- Coast
- Urban
- Mountain
- Kinmen
- Magong

Wind (m/s)

- Coast
- Urban
- Mountain
- Kinmen
- Magong

Time (LST) 12 JUL 2018 14 JUL 16 JUL 18 JUL
Magong sounding during 15–17 July 2018
Measurement PM2.5 concentration and wind field
Measurement PM2.5 concentration and wind field
Measurement ozone concentration and wind field

20180717_08LST

20180717_10LST

20180717_12LST

20180717_14LST

25N

24N

23N

22N

120E

121E

122E

Wind direction arrows indicate the predominant direction of the wind.
Ozone concentration and wind field
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.
Challenges

Radiative forcing of climate between 1750 and 2011

Heating factors:
- Well Mixed Greenhouse Gases
- Ozone
- Stratospheric water vapour from CH₄
- Surface Albedo
- Contrails
- Aerosol-Radiation Interac.
- Aerosol-Cloud Interac.
- Total anthropogenic

Cooling factors:
- Solar Irradiance
- Human impacts on global warming

Heating effect but with significant uncertainties