The US's new $PM_{2.5}$ standard, carbon neutrality co-benefit, and AI-driven AQ applications

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Ministry of Environment Taiwan
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Outlines

- The US's new $PM_{2.5}$ standard
- Net-zero carbon co-benefit
- AI-driven AQ applications

Outlines

- **The US's new $PM_{2.5}$ standard**
- **Net-zero carbon co-benefit**
- **AI-driven AQ applications**

U.S. EPA National Ambient Air Quality Standards (NAAQS)

- The Clean Air Act (CAA) gives the U.S. EPA the authority to establish NAAQS to protect public health and the environment
- NAAQS have been established for six pollutants:
  - Ozone(O_3), particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), sulfur dioxide (SO_2)
- EPA reviews the standards every five years
- Independent Clean Air Scientific Advisory Committee (CASAC) advises EPA in the standard development process

U.S. EPA NAAQS Review Process

Planning

- Begins with a **science policy workshop** to gather input from **scientific community and public**

Integrated Science Assessment (ISA)

- Comprehensive review, synthesis, and evaluation of the most policy-relevant **science**

Risk/Exposure Assessment (REA)

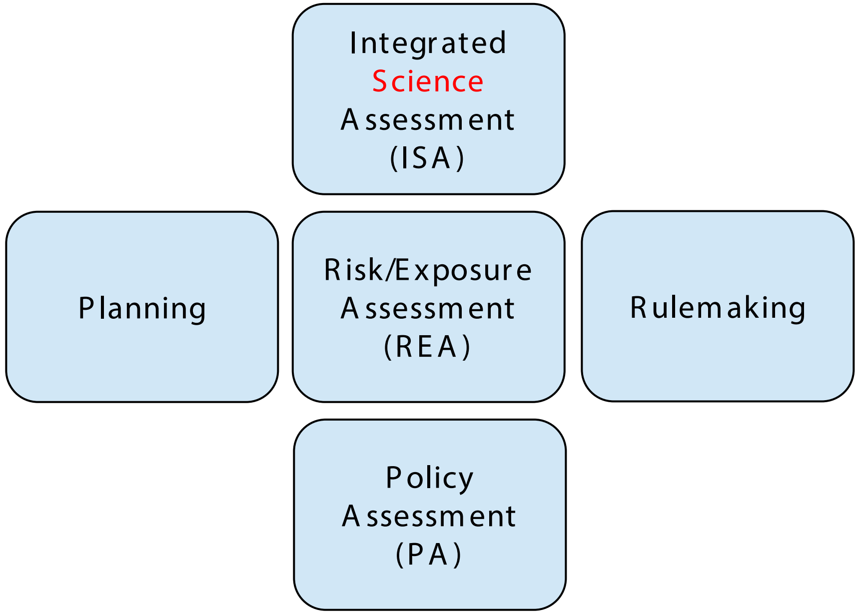
- Assessment draws on previous information to characterize exposures and associated risks to health and the environment

Policy Assessment (PA)

- Staff analysis of **scientific bases** for alternative policy options for consideration

Rulemaking

- EPA develops and publishes a notice of proposed rulemaking for updating NAAQS based on information from prior steps



https://www.epa.gov/criteria-air-pollutants/process-reviewing-national-ambient-air-quality-standards

U.S. EPA NAAQS Compliance Assessment

- The U.S. EPA uses "design values" to describe a given location's air quality levels relative to the NAAQS
  - Designates 'nonattainment' areas
  - Assesses progress towards meeting the NAAQS, classified as 'Maintenance'
- Design values are calculated as 3-year averages of the pollutant's 'form' (see previous table)
  - Ex: The 24-hour design value site for a nonattainment area has the following 98th percentile readings for the most recent 3 years of data; Ozone design value is the annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years;
- Design values exclude erroneous measures, measures captured during 'exceptional events', and measures captured by monitors with network/site issues

EPA Map of Design Values:
https://epa.maps.arcgis.com/apps/MapSeries/index.html?appid=bc6f3a961ea14013afb2e0d0e450b0d1

EPA design values assessment tables:
https://www3.epa.gov/airquality/greenbook/kdtc.html

Main Elements of the PM NAAQS Final Decision

- On Feb. 7, 2024, EPA strengthened the National Ambient Air Quality Standards for Particulate Matter ("PM NAAQS") to protect millions of Americans from harmful and costly health impacts, such as heart attacks and premature death.
- EPA strengthened the level of the primary (health-based) annual standard for fine particles ($PM_{2.5}$) to 9.0 micrograms per cubic meter ($\mu g/m^3$) to reflect the latest available health science.
- EPA did not change all other PM standards:
  - The primary (health-based) and secondary (welfare-based) 24-hour $PM_{2.5}$ standards stay at the level of 35 $\mu g/m^3$
  - The primary and secondary 24-hour PM_{10} standards stay at level of 150 $\mu g/m^3$
  - The secondary annual $PM_{2.5}$ standard stays at the level of 15.0 $\mu g/m^3$
- EPA also:
  - Revised the Air Quality Index (AQI) to improve public communications about the risks from $PM_{2.5}$ exposures
  - Made changes to the monitoring network to enhance protection of air quality in communities overburdened by air pollution

Primary (Health-Based) $PM_{2.5}$ Standard

NAAQS Decision	Annual ($\mu g/m^3$)	24-hr ($\mu g/m^3$)
1997	15	65
2006	15*	35
2012	12	35*
2020	12*	35*
2024	**9**	**35***

*Retained, without revision

Air quality index (AQI)

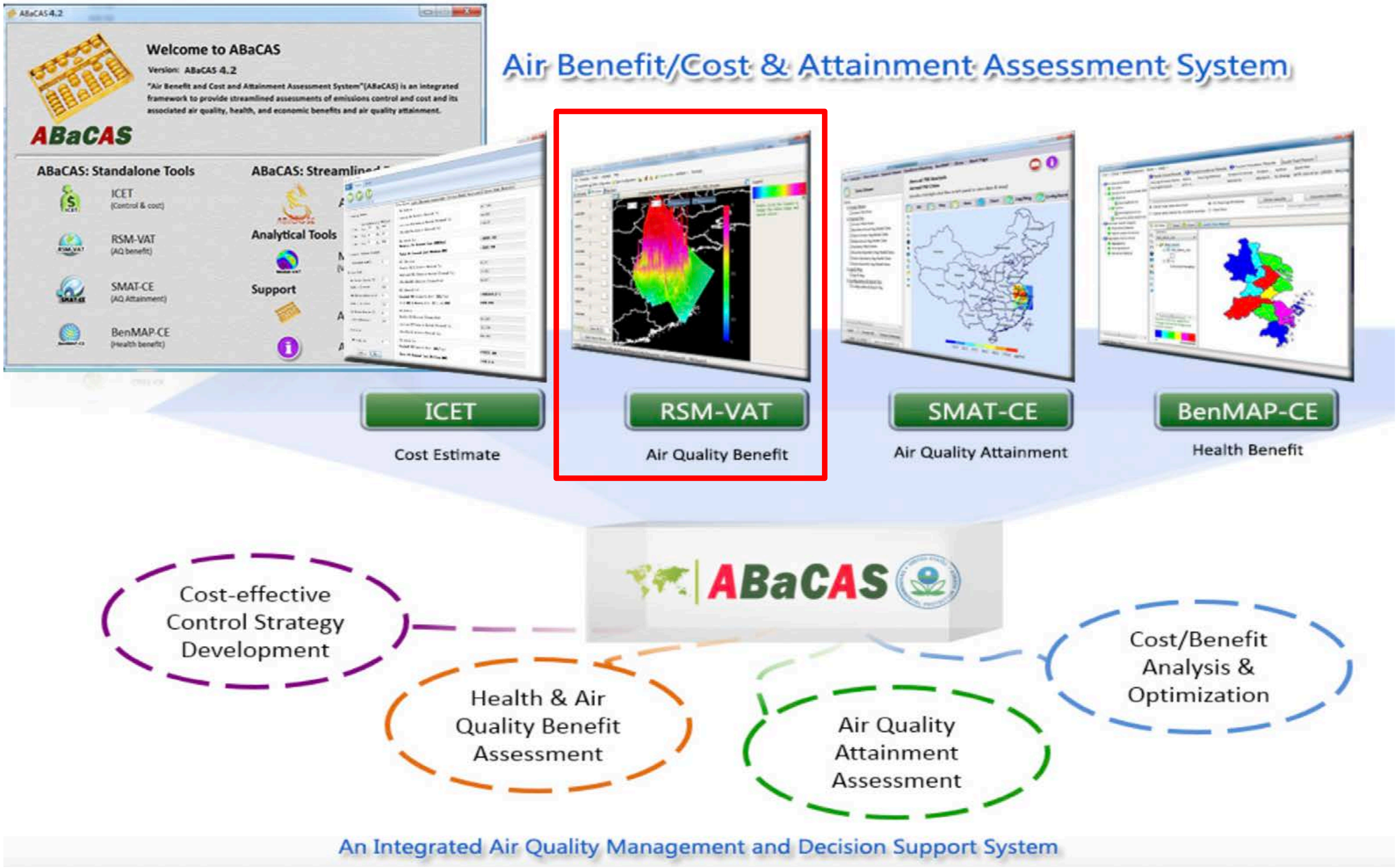
2024 AQI for Fine Particle Pollution
(Breakpoints are in micrograms per cubic meter)

AQI Category and Index Value	Previous AQI Category Breakpoints	Updated AQI Category Breakpoints	What changed?
Good (0 – 50)	0.0 to 12.0	0.0 to 9.0	EPA updated the breakpoint between Good and Moderate to reflect the updated annual standard of 9 micrograms per cubic meter
Moderate (51 – 100)	12.1 to 35.4	9.1 to 35.4	
Unhealthy for Sensitive Groups (101 – 150)	35.5 to 55.4	35.5 to 55.4	No change, because EPA retained the 24-hour fine PM standard of 35 micrograms per cubic meter.
Unhealthy (151 – 200)	55.5 to 150.4	55.5 to 125.4	EPA updated the breakpoints at the upper end of the unhealthy, very unhealthy, and hazardous categories based on scientific evidence about particle pollution and health. The Agency also combined two sets of breakpoints for the Hazardous category into one.
Very Unhealthy (201 – 300)	150.5 to 250.4	125.5 to 225.4	
Hazardous (301+)	250.5 to 350.4 and 350.5 to 500	225.5+	

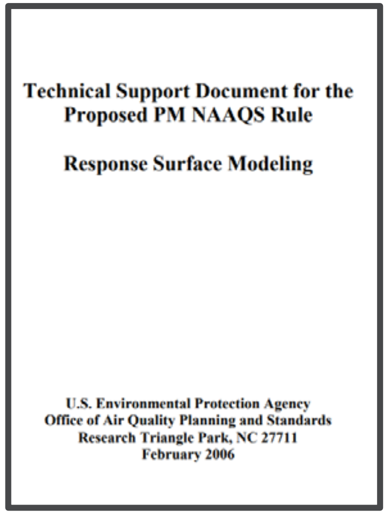
Implementation Timeline Annual $PM_{2.5}$ NAAQS

- Effective date of final revised NAAQS, May 6, 2024 – Revised standard applies with respect to pre-construction Prevention of Significant Deterioration permitting upon the effective date, May 6, 2024
- Within 2 years after the promulgation, by February 7, 2026, of a revised NAAQS – Based on available information, including most recent monitoring data, EPA must "designate" areas as meeting (attainment) or not meeting (nonattainment) the revised NAAQS considering input from states and tribes.
  - All $PM_{2.5}$ nonattainment areas are initially classified as "Moderate." (CAA §188)
- Within 3 years after the promulgation, by February 7, 2027, of a revised NAAQS – All states and territories are required to submit SIP revisions to show they have the basic air quality management program components in place to implement the final NAAQS and address interstate transport (commonly referred to as "infrastructure SIPs"). (CAA §110)
- Within 18 months after the effective date of nonattainment designation – SIPs for attaining the $PM_{2.5}$ NAAQS are due, likely in Fall 2027. (CAA §189)
- End of the 6th calendar year after the effective date of designations – "Moderate" area attainment date, likely in 2032. (CAA §188)

Air Benefit and Cost and Attainment Assessment System (ABaCAS)

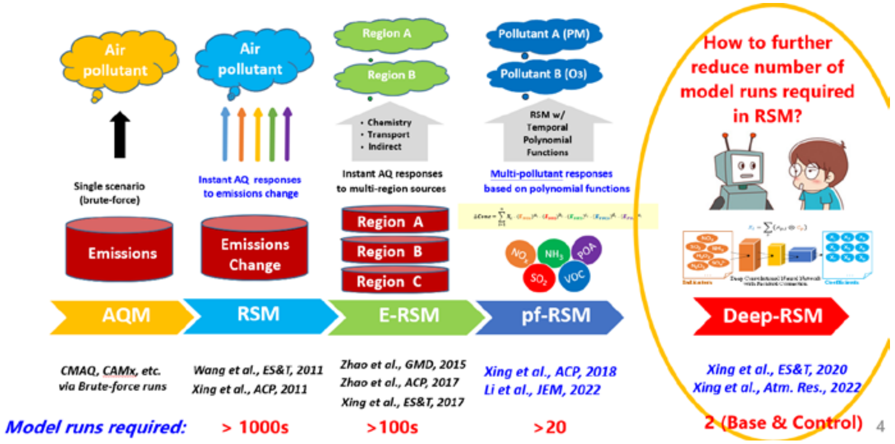


DeepRSM: Deep-learning air quality response surface model

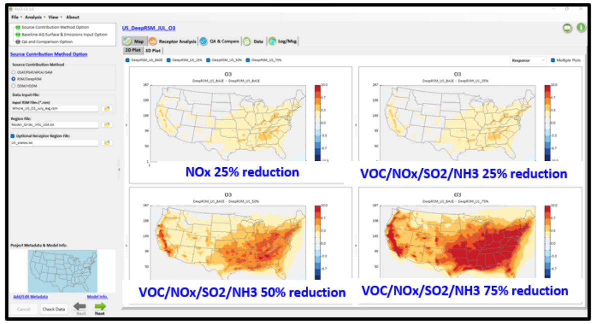

Technical Support Document for the Proposed PM NAAQS Rule

Response Surface Modeling

U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711
February 2006



Pilot Application of Deep Learning Response Surface Model (DeepRSM)



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CMAS at Chapel Hill, NC
Oct 2023

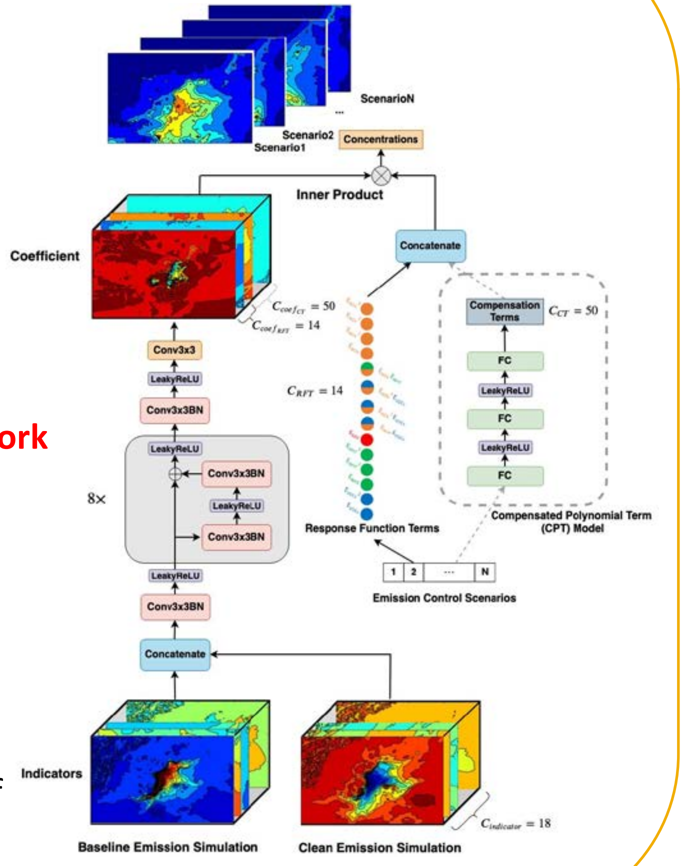
Disclaimer: The views expressed in this presentation are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

Huang et al., CMAS conference, 2023

Emission-concentration relationship characterized as **polynomial functions**

Deep neural network (ResNet)

chemical indicators imply the nonlinearity of response



New version: high efficiency and accuracy

Xing et al., ES&T, 2020

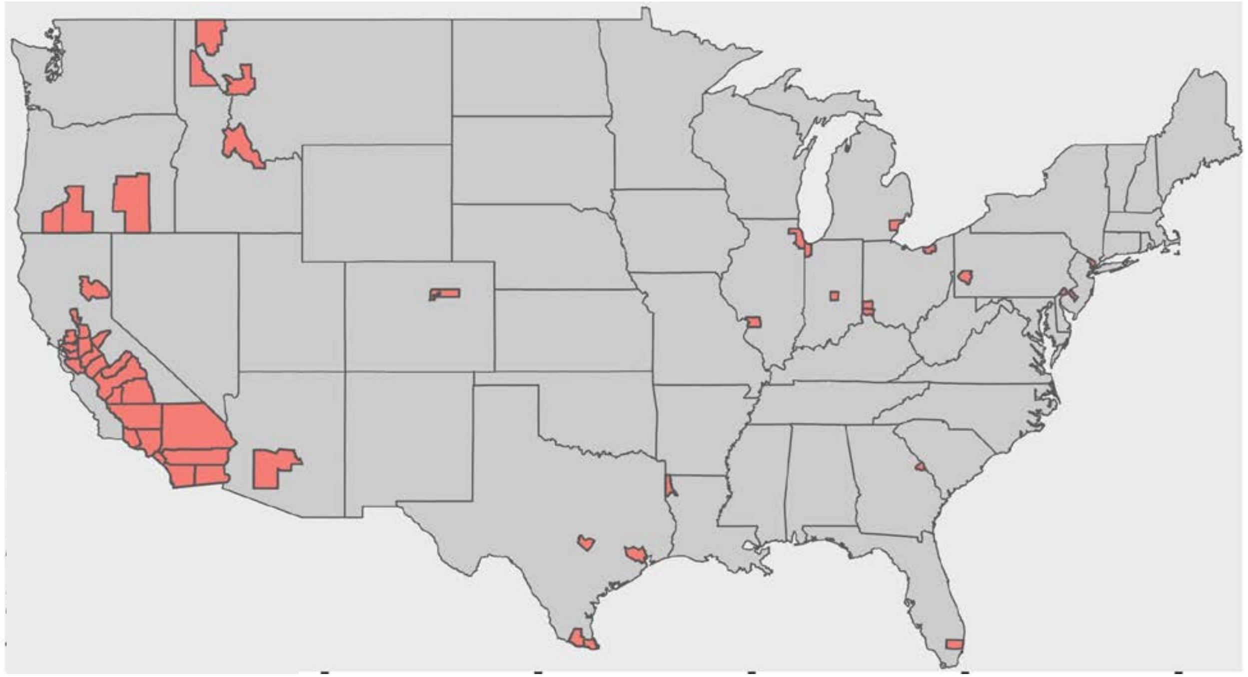
Modeling $PM_{2.5}$ for a Future Analytic Year

- Understanding of the scope of $PM_{2.5}$ attainment challenges under the 2024 NAAQS can be improved by examining the exceedances that remain after accounting for expected emission reductions from finalized rules
- In the PM NAAQS RIA, national 12-km photochemical air quality modeling was performed with CMAQ for 2018 and 2032 to project 2032 DVs using 2016-2020 $PM_{2.5}$ monitoring data
- Finalized rules* reflected in the 2032 emissions case include:
  - EGU: Inflation Reduction Act of 2022 (IRA) Tax Incentive Provisions; 2023 Final Good Neighbor Plan; 2021 Revised Cross-State Air Pollution Rule Update; 2016 Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources; 2011 Mercury and Air Toxics Rule (MATS)
  - Mobile: 2022 Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards; 2021 Final Rule to Revise Existing National GHG Emissions Standards for Passenger Cars and Light Trucks Through Model Year 2026; 2020 Heavy-Duty Engine and Vehicle Standards SAFE Vehicles Final Rule for Model Years 2021-2026; 2016 GHG Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, Phase 2; 2014 Tier 3 Motor Vehicle Emission and Fuel Standards

Change in U.S. Anthropogenic Emissions: 2018 to 2032

Pollutant	% Change	Absolute Change (million tons)
NOx	-41	-3.6
SO_2	-48	-1.1
$PM_{2.5}$	-4	-0.12
VOC	-7	-0.9
NH_3	+4	+0.2

Projected Nonattainment for 2032 Analytic Year



Counties with monitors projected to exceed the annual standard in 2032 can be classified as follows:

- Pacific NW and N. California: Exceedances are associated with woodsmoke emissions in small mountain valleys that experience wintertime temperature inversions as well as wildfire influence
- Major CA Air Basins: Exceedances due to complex/long-standing local challenges in meeting $PM_{2.5}$ NAAQS (e.g., SJV/SoCAB) as well as wildfires
- US-Mexico Border: Counties are influenced by cross-border transport, dust, and local emissions
- Eastern US: Exceedances are generally associated with the urban, near-road, and nearby source $PM_{2.5}$ increment

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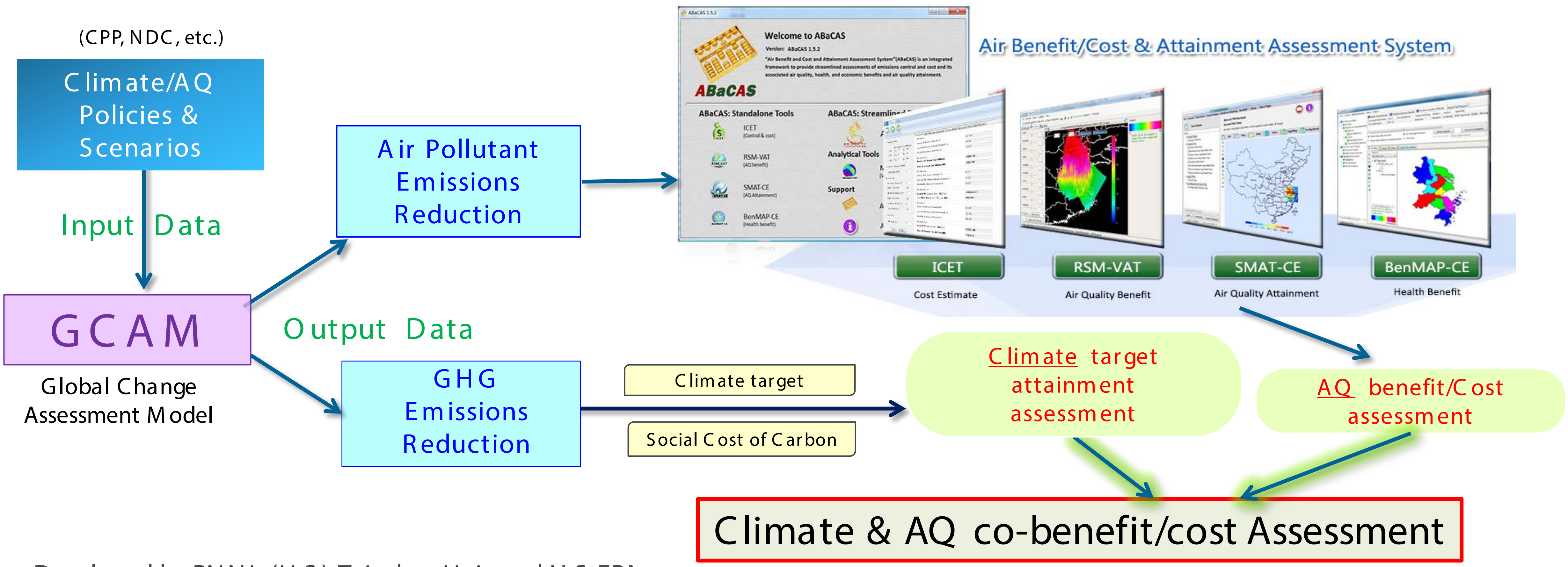
GCAM-ABaCAS integrate assessment system in the U.S.

- GCAM-ABaCAS system: climate and air quality (AQ) strategy, energy structure projection, non-energy activity rate, air quality and health assessment



Developed by PNNL (U.S.), Tsinghua Univ. and U.S. EPA

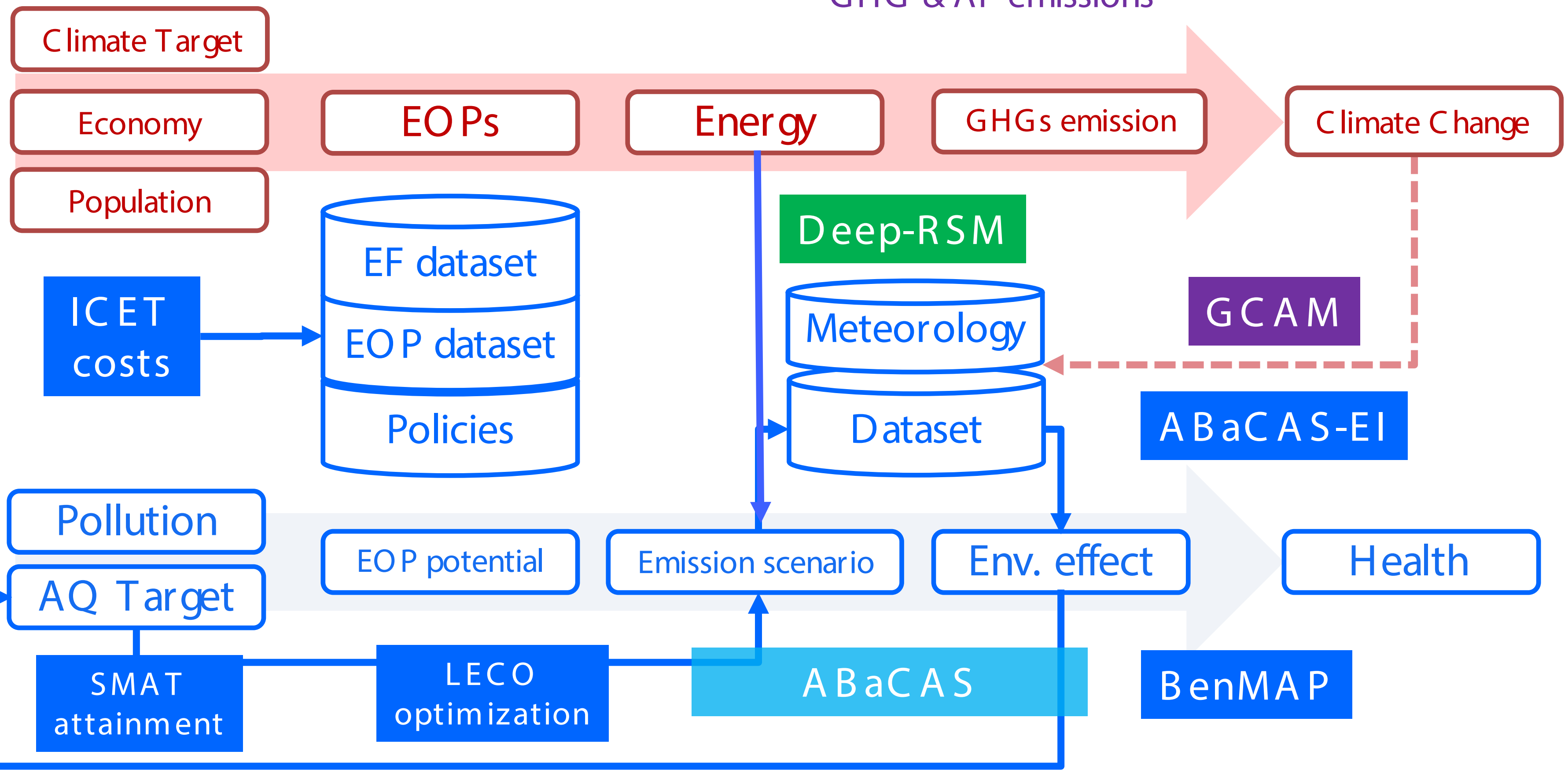
GCAM-ABaCAS integrate assessment system in the U.S.

➢ GCAM-ABaCAS system : GCAM + RSM + BenMAP

GCAM
- Economic concern
- Energy projection
- GHG & AP emissions

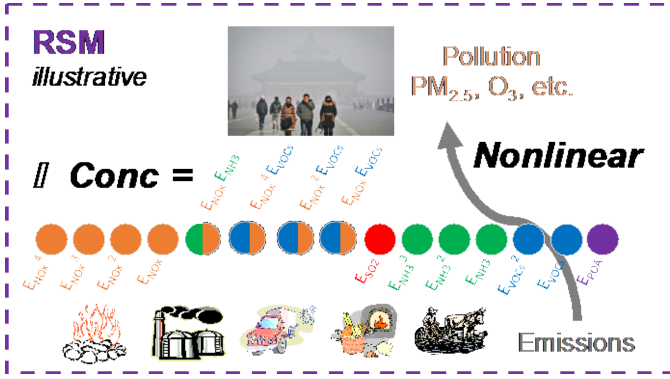
RSM
- Air quality under different scenarios

BenMAP
- Health impact under different air quality & population scenarios

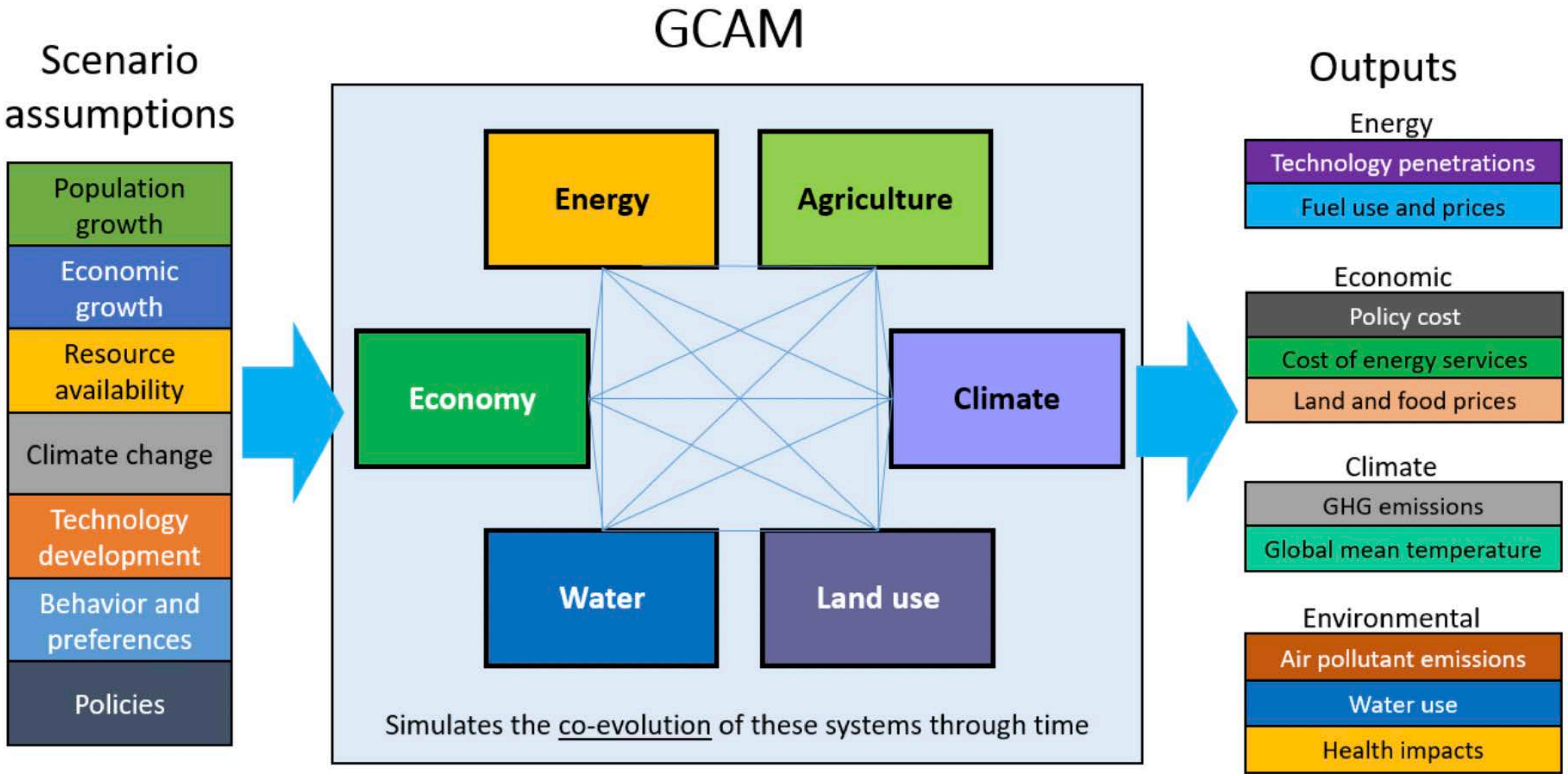


\+ others

Deep-RSM illustrative



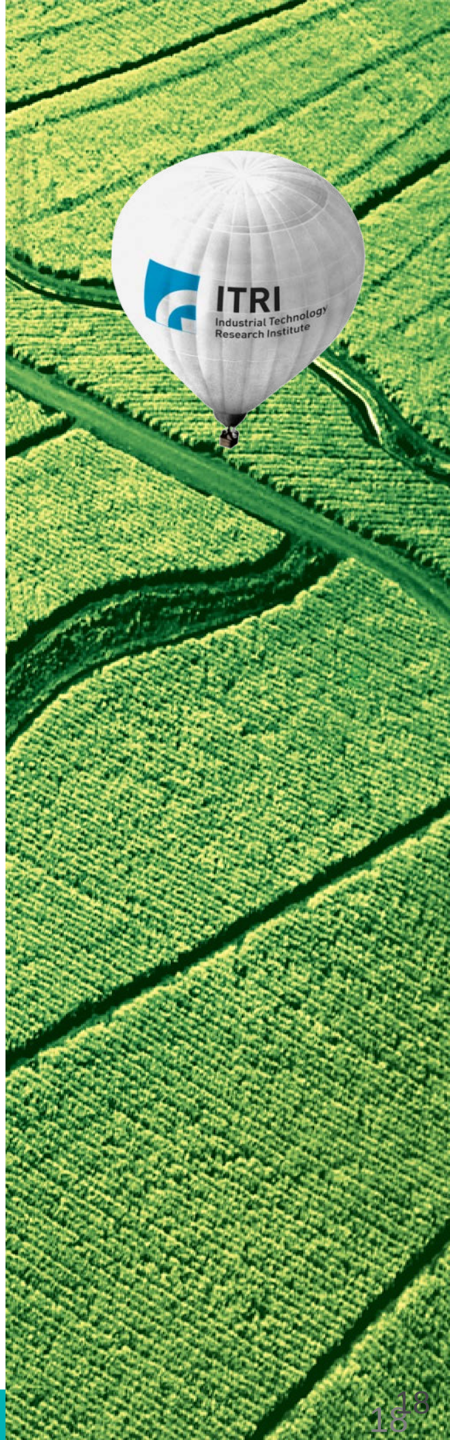
GCAM Long-term Interactive Multi-Pollutant Scenario Evaluator (GLIMPSE)



工業技術研究院
Industrial Technology
Research Institute

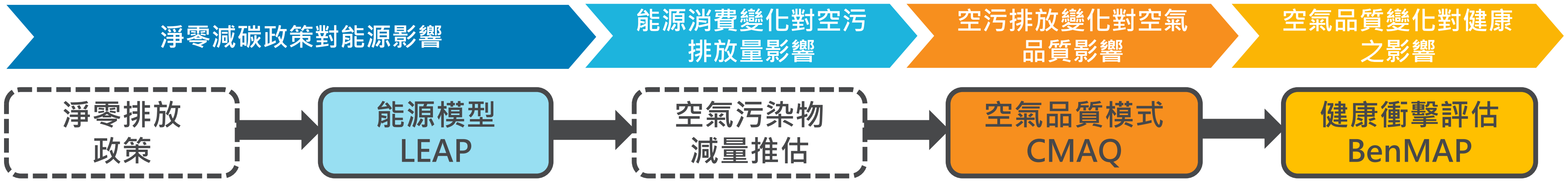
臺灣2050淨零路徑下空氣品質模式模擬與健康共伴效益評估

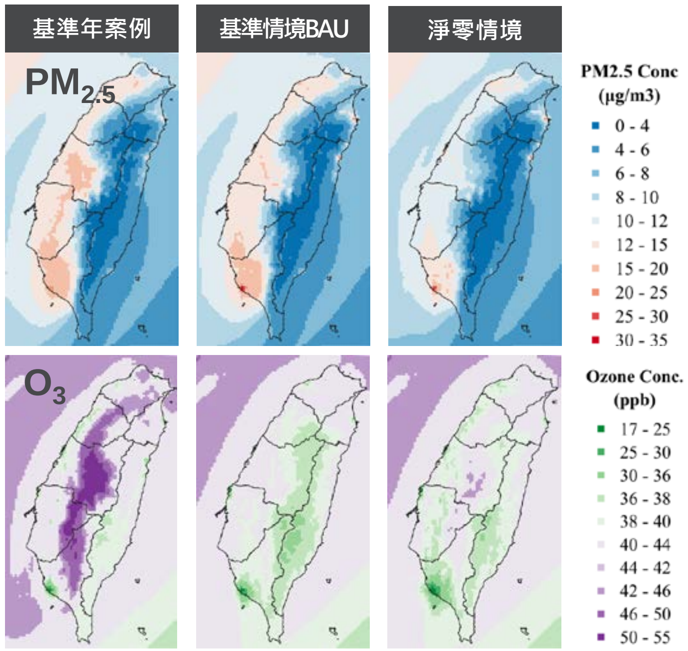
綠能所 郭承彬



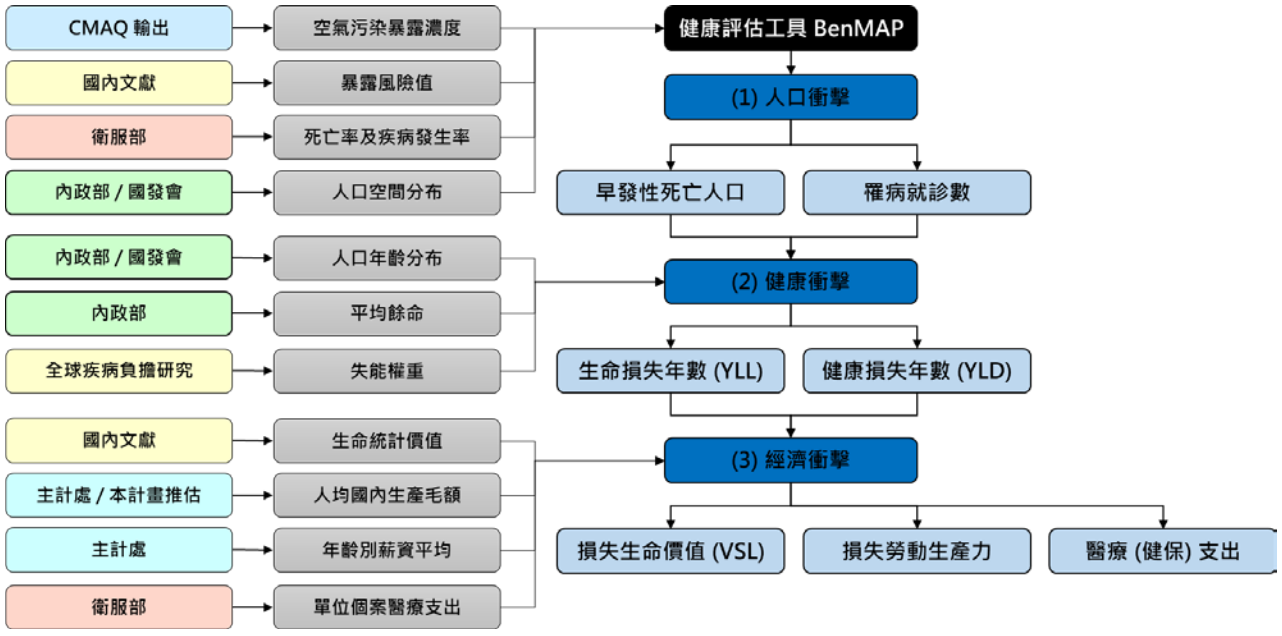
臺灣2050淨零路徑健康共伴效益評估成果

- 採用**LEAP-CMAQ-BenMAP架構**串接能源消費、空氣品質變化與健康衝擊
- **BenMAP**採用**本土參數**與**LEAP預估經濟參數**以反映對於台灣**健保醫療支出**與**國內經濟**之衝擊





- 淨零政策下，整體$PM_{2.5}$和**臭氧**濃度**顯著改善**
- **臭氧**在部分人口密集地區則有潛在**增加趨勢**



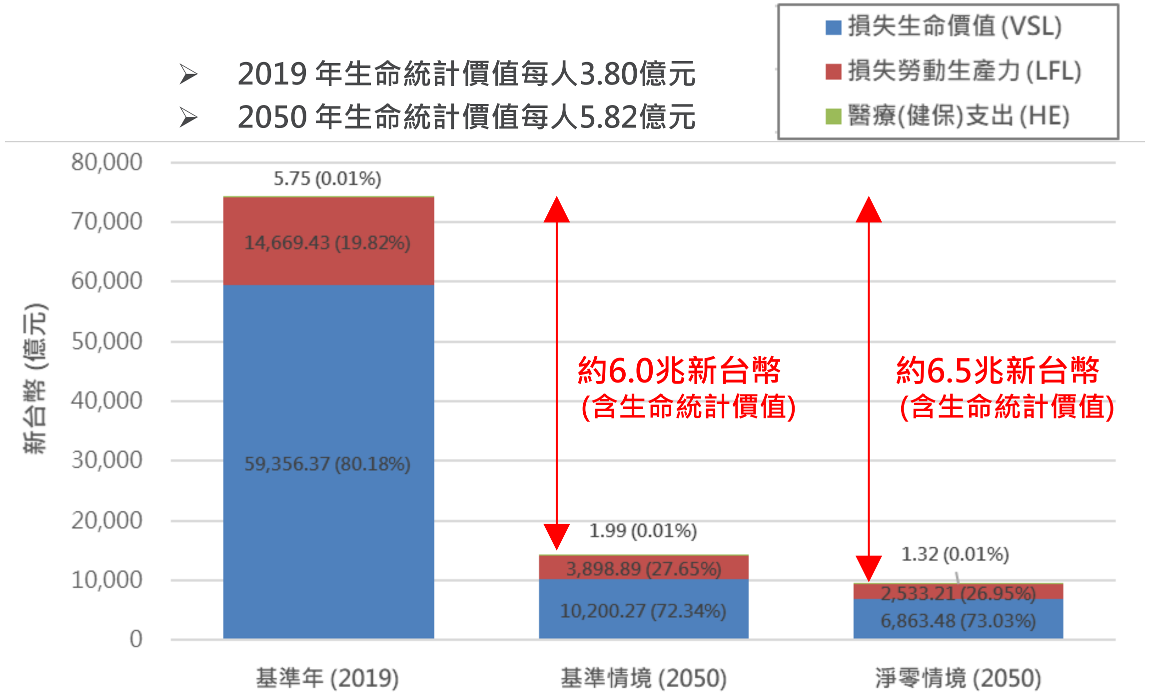
臺灣2050淨零路徑健康共伴效益評估成果

- 淨零政策下，空氣污染對於人口、健康與經濟的衝擊皆有顯著改善，主要來自於$PM_{2.5}$改善
- 受$PM_{2.5}$與臭氧暴露導致的早發性死亡人數與罹病就診人數顯著下降92%
- 生命價值 (VSL) 可減少新台幣5.25兆元損失；國內生產毛額 (GDP) 減少新台幣1.21兆元損失
- 醫療健保支出可節省新台幣4.43億元

指標	單位	情境			基準健康效益[1]	最大健康效益[2]
		基準年 (2019)	基準情境 (2050)	淨零情境 (2050)		
早發性死亡人口數	人	15,635	1,753	1,180	13,882	14,456
罹病就診人數	人次	1,607,074	197,105	129,419	1,409,969	1,477,655
潛在生命損失年數 (YLL)	人年	552,089	47,187	31,776	504,903	520,313
健康生命損失年數 (YLD)	人年	1,364,806	143,618	92,093	1,221,188	1,272,713
損失生命價值 (VSL)	億元 (新台幣)	59,356.37	10,200.27	6,863.48	49,156.10	52,492.90
損失勞動生產力 (LFL)	億元 (新台幣)	14,669.43	3,898.89	2,533.21	10,770.54	12,136.23
醫療(健保)支出 (HE)	億元 (新台幣)	5.75	1.99	1.32	3.75	4.43
佔全國生產毛額比例[3]	%	7.86	0.89	0.58	-	

[1] 基準健康效益為基準情境個案數扣除基準年個案數之差距。
[2] 最大健康效益為淨零情境個案數扣除基準年個案數之差距。
[3] 為損失生命價值 (VSL) 與醫療支出 (HE) 加總占當年國內生產毛額 (GDP) 之比例，2019年國內生產毛額為186,692億元，2050年本計畫推估國內生產毛額為438,582億元。

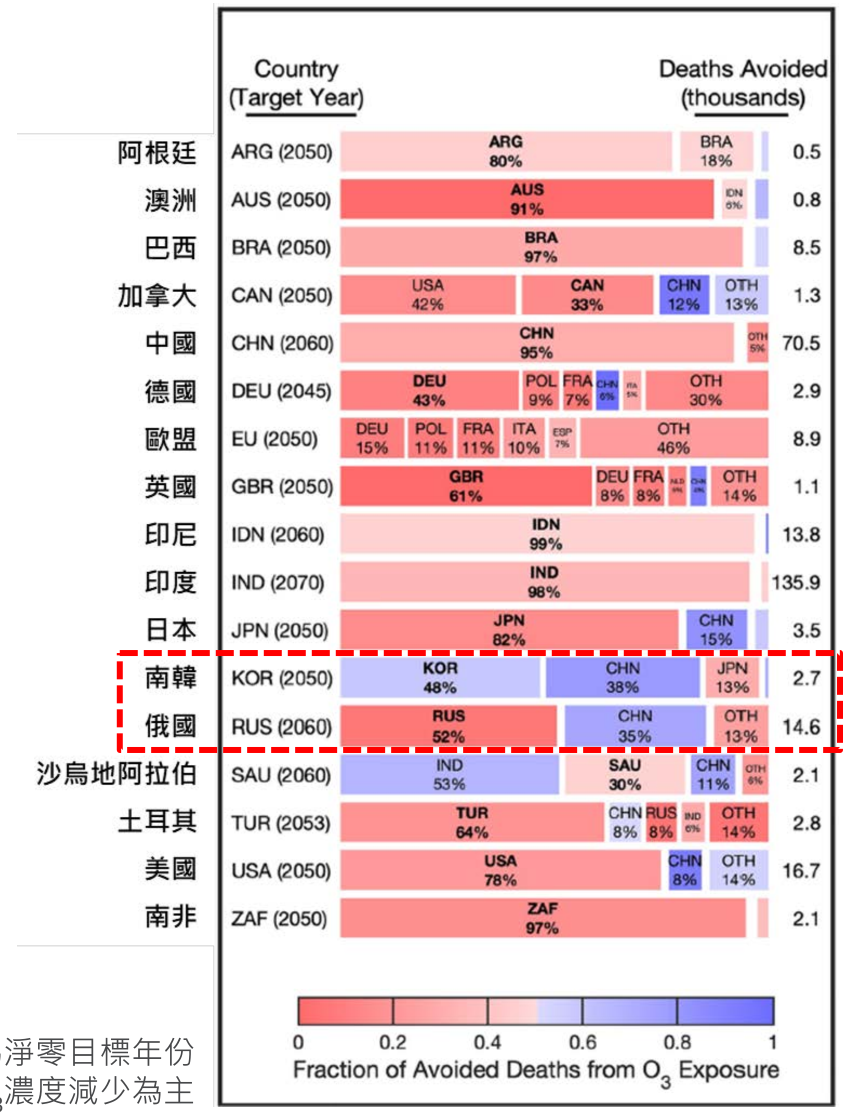
- 2019 年生命統計價值每人3.80億元
- 2050 年生命統計價值每人5.82億元



全球氣候變遷下
區域空污研究趨勢

鄰國減量與臭氧減量的重要性 (全球)

- 大部分共伴效益評估研究僅評估**$PM_{2.5}$減量效益**
- 評估**G20**成員國在淨零路徑下，各國2040年因為**$PM_{2.5}$**與**臭氧**暴露減少所可避免的**死亡人口**
- 在氣候變遷條件件**溫度逐漸升高**與**生物性VOC排放增加**下，**臭氧濃度**可能惡化
- 大部分成員國的共伴效益來自於**本土排放量減少**
  - **加拿大**之外，約有42%來自於**美國**
  - **日本**與**南韓**減量有部分來自於**中國**減量
- 大部分共伴效益主要來自於**$PM_{2.5}$濃度減少**；**沙烏地阿拉伯**與**南韓**的共伴效益主要來自於**臭氧濃度減少**

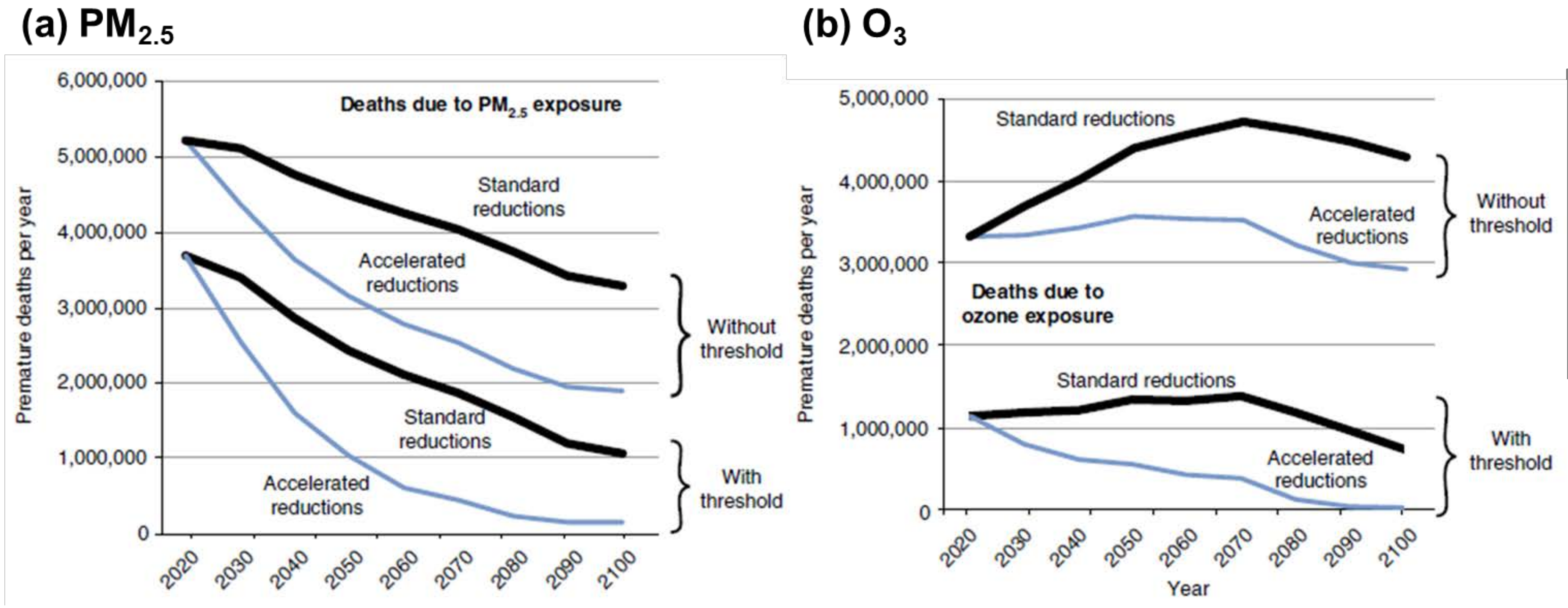


括弧年份為淨零目標年份
紅色為以$PM_{2.5}$濃度減少為主；藍色為以O_3濃度減少為主

Nawaz et al. (2023)

對於負碳技術商業化過於樂觀 (全球)

- 目前全球淨零進程**過於緩慢**，導致無法實現全球碳排目標；**負碳技術 (negative carbon emission)** 仍未達**商業化規模**，且**不夠具體**，大部分國家都以**再生能源**作為替代方案
- 在**RCP2.6情境 (氣候暖化減緩)** 下，**負碳技術情境**及**再生能源使用情境**皆能減少全球**空氣污染**和**死亡人數**，但**負碳技術情境**效益更高



standard reduction
有使用負碳排技術

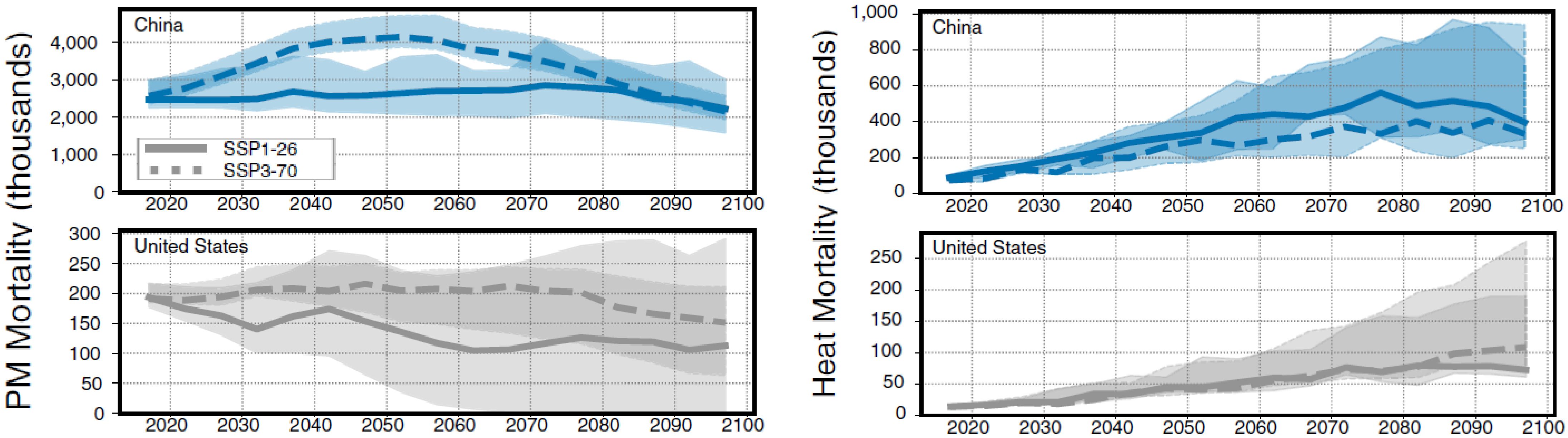
accelerated reduction
無使用負碳排技術
使用再生能源替代

Shindell et al. (2018)

氣候變遷下空污與熱危害的加乘效應 (全球)

- **空污暴露**與**熱危害**的評估將是城市**氣候調適 (climate adaption)** 重要的一環
- **氣候變遷條件**下，**空污暴露**與**熱危害**導致的死亡人口會持續增長
  - 美國：**熱危害減少**的共伴效益大於**PM$_{2.5}$暴露減少**的共伴效益
  - 中國：**PM$_{2.5}$暴露減少**的共伴效益則大於因**熱危害減少**的共伴效益。

21世紀高排放情境 (SSP3-7.0) 下，PM$_{2.5}$暴露與高溫熱危害導致的死亡人口持續增長



Shindell et al. (2024)

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DeepCTM: Mimic the CTM modeling

Input1: Emissions

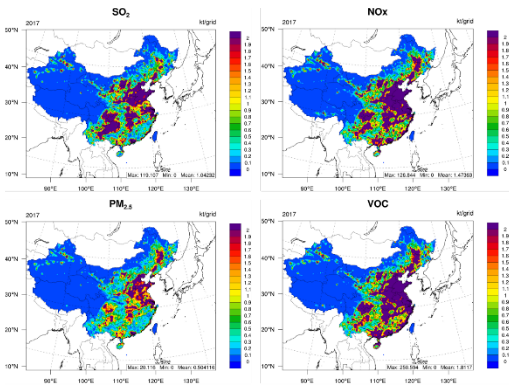
(Row, Col, Ht, Time)

5 key pollutants:

- SO_2, NOx, NH_3, VOC, PM

6 key sectors:

- Power
- Industry
- Domestic
- Transport
- Agriculture

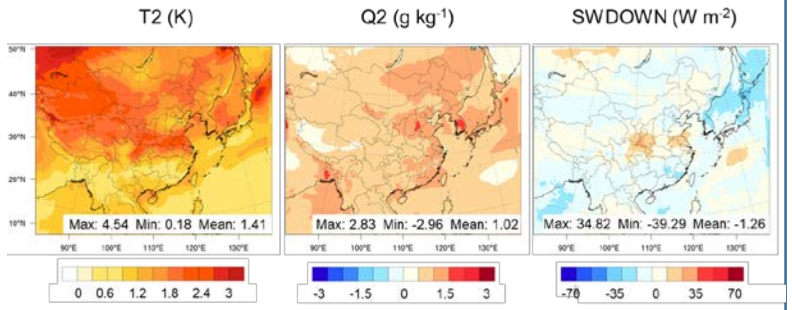


Input2: Meteorology

(Row, Col, Ht, Time)

selected key variables:

- T2, Q2, WS, WD, PBL
- Radiation, Precipitation, etc

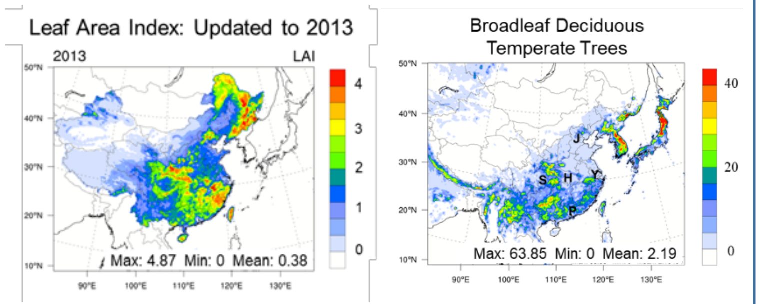


Input3: Geography

(Row, Col)

selected key variables:

- LAI, land cover, elevation, etc



ML-CTM

Output: Concentrations

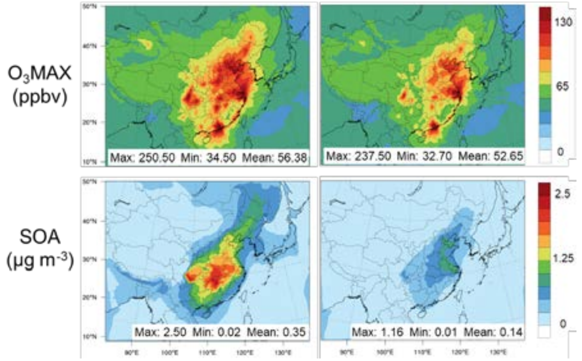
(Row, Col, Ht, Time)

4 key pollutants:

- SO_2, NO_2, O_3, $PM_{2.5}$

Selected other species:

- NH_3, VOC, PM species (sulfate, nitrate, SOA)



Atmospheric system

- Deterministic system
- Mathematical equations based on physical laws
- Influenced by neighbor grids and previous days

Single-step model

feature selection

Emission:

- ✓ NOx-surface/near-surface/upper layer
- ✓ Total VOC

Meteorology (surface):

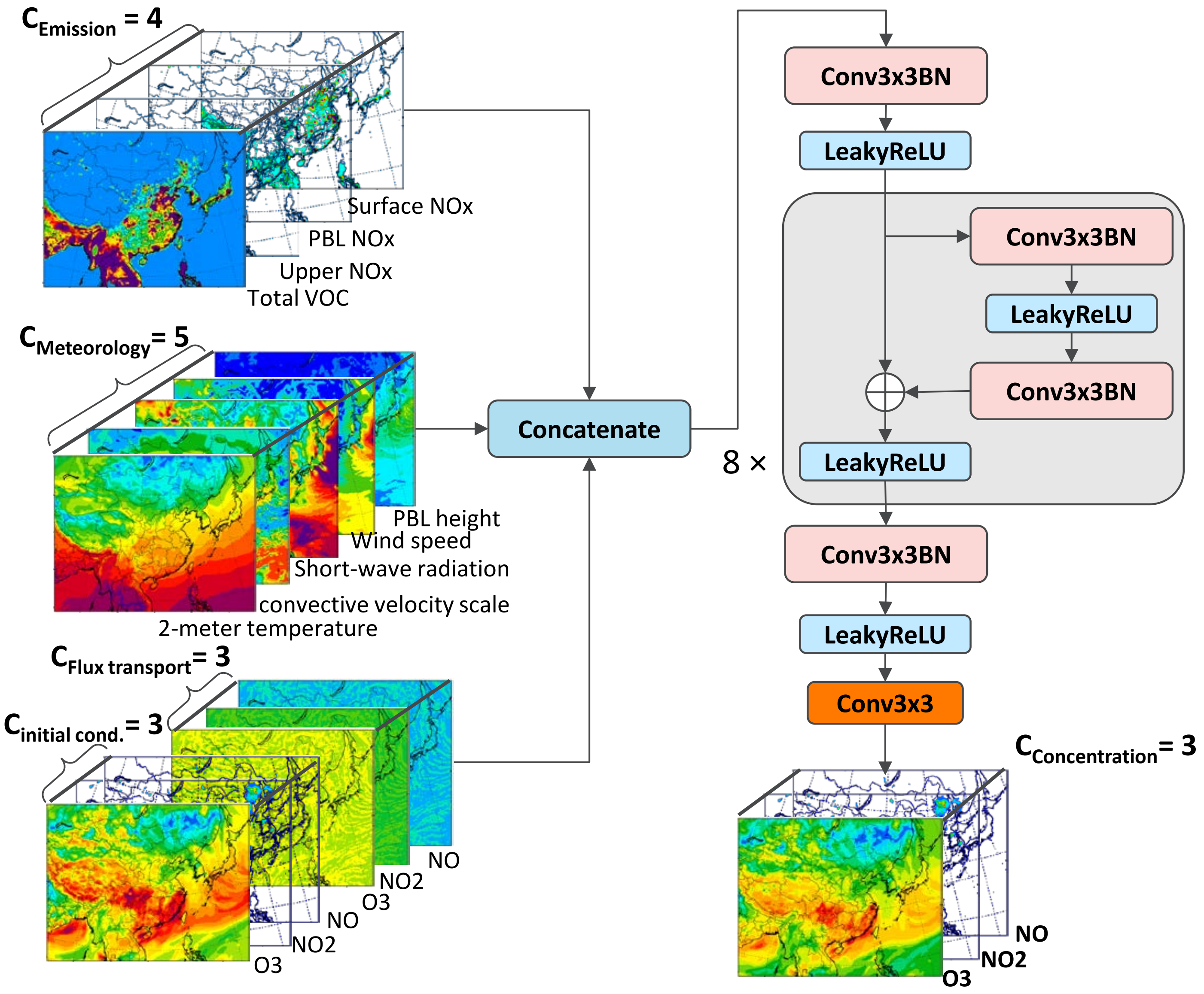
- ✓ T, PBL, SWR, WSP, convective velocity scale
- ✓ NO, NO_2, O_3 flux

Initial condition:

- ✓ previous NO, NO_2, O_3

Label:

- ✓ current NO, NO_2, O_3 conc.

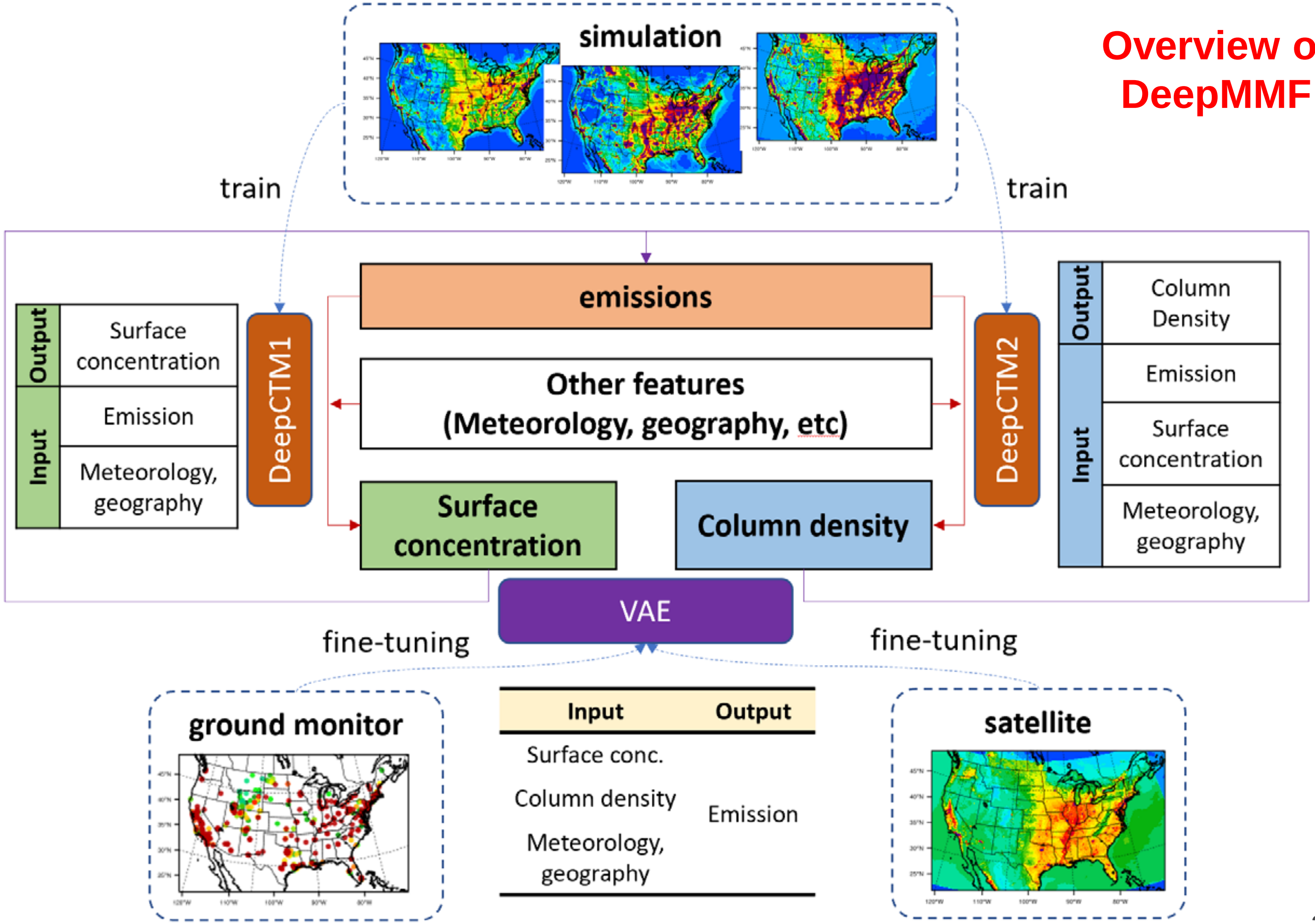


Conv3x3BN: 3x3 convolution followed by batch normalization;
LeakyReLU: leaky rectified linear unit activation function

DeepMMF—Deep-learning Measurement-Model Fusion

Aims to

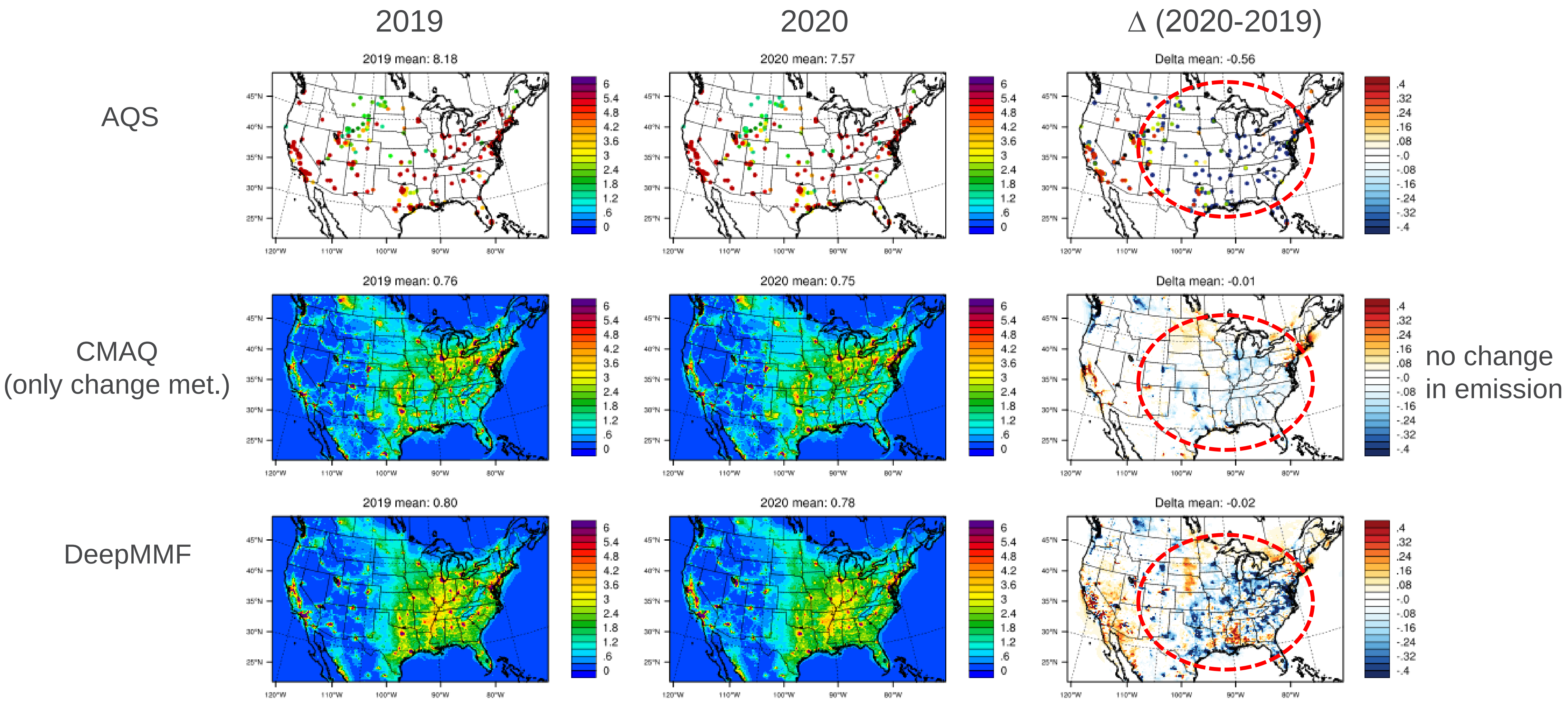
- Effective fusing satellite and ground measurements
- Address sample-imbalance issue
- Provide near real-time update



Overview of DeepMMF

Xing et al., ES&T, 2024

Comparison of observed, simulated, and fused surface NO_2



DeepMMF successfully reflected high concentration and significant reduction

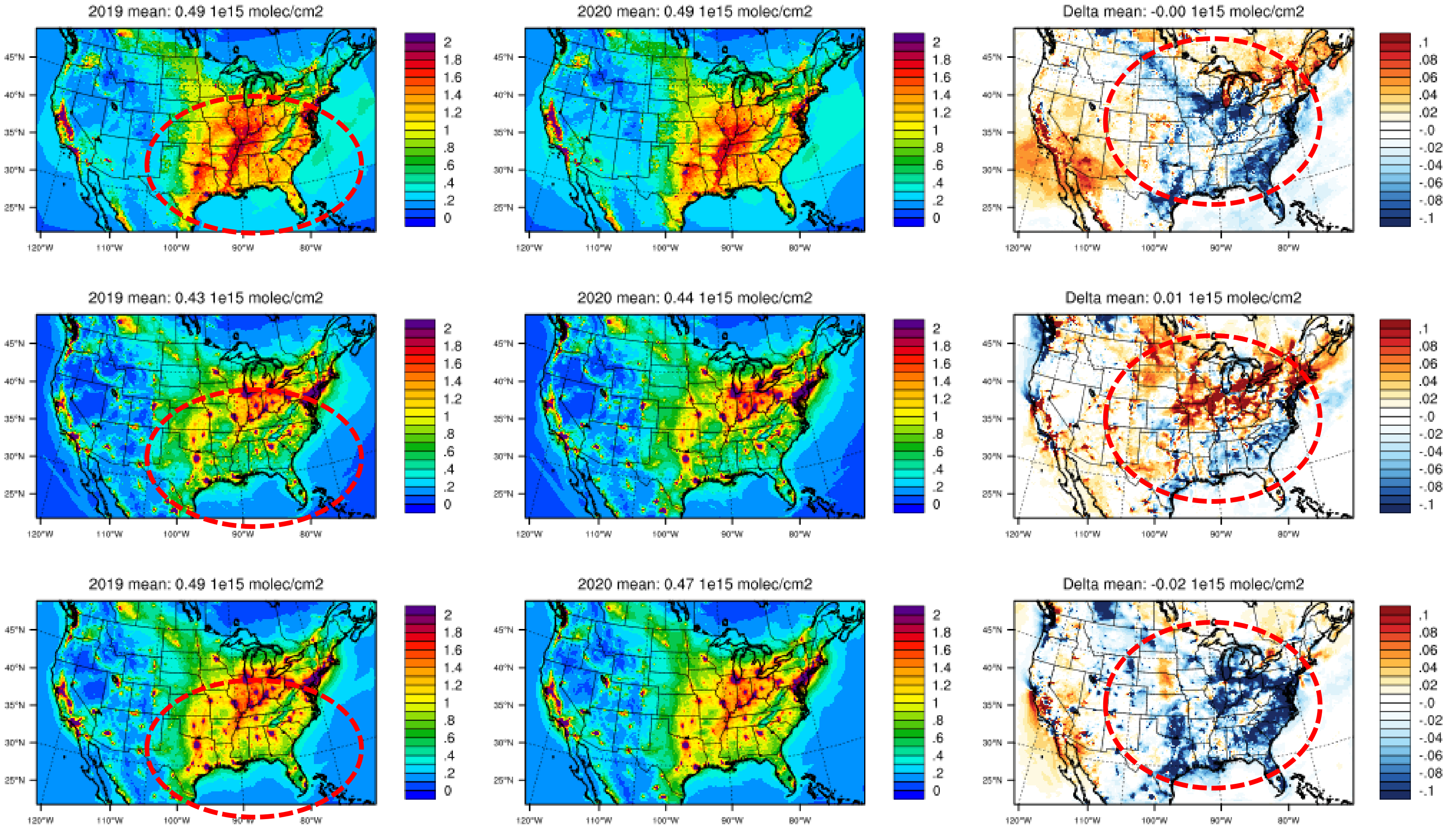
Comparison of observed, simulated, and fused NO_2 column

2019 | 2020 | Δ (2020-2019)

TROPOMI

CMAQ
(only change met.)

DeepMMF



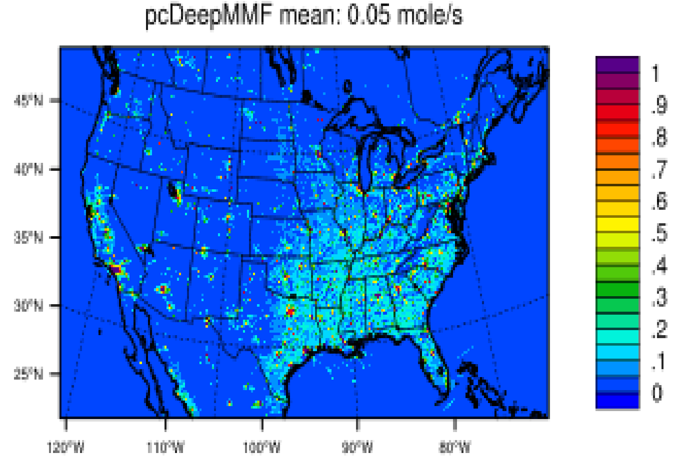
no change in emission

high NO_2 column

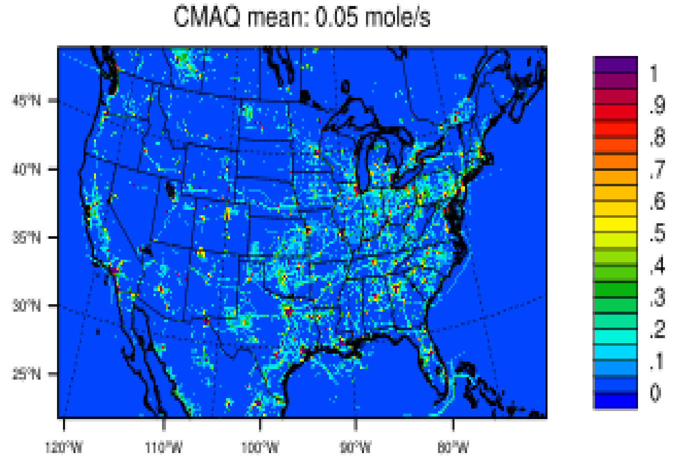
significant reduction

DeepMMF predicts the changes in NOx emission from 2019 to 2020

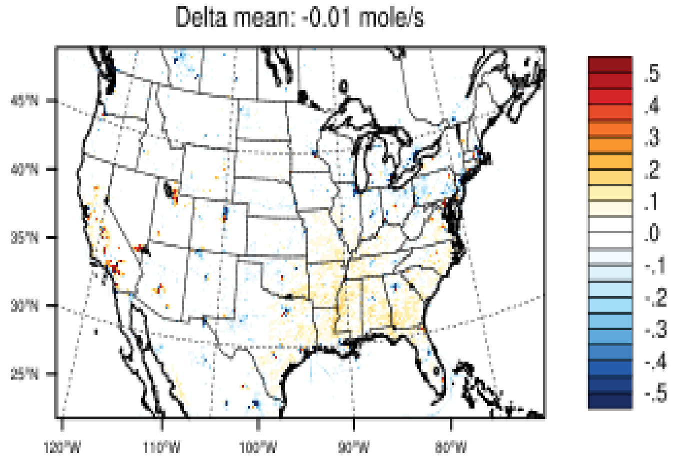
DeepMMF-2019



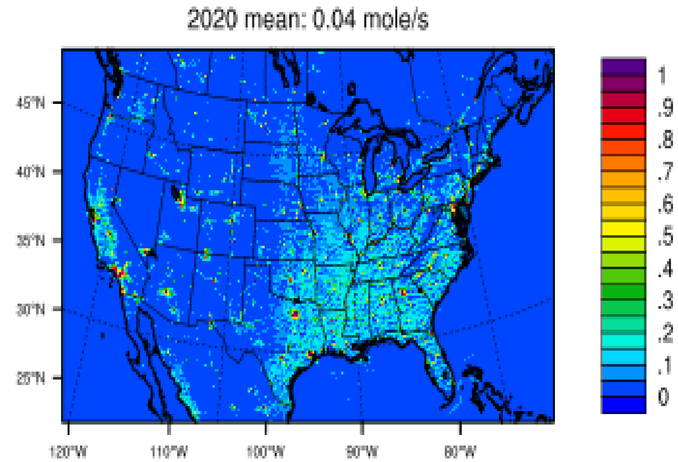
CMAQ-priori



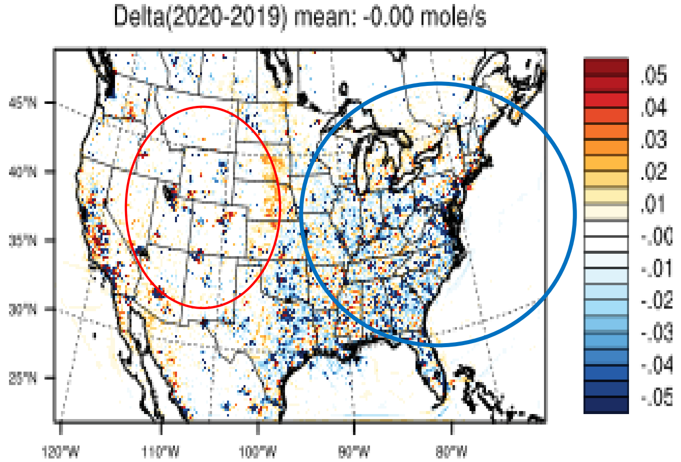
Δ (DeepMMF – CMAQ)



DeepMMF-2020

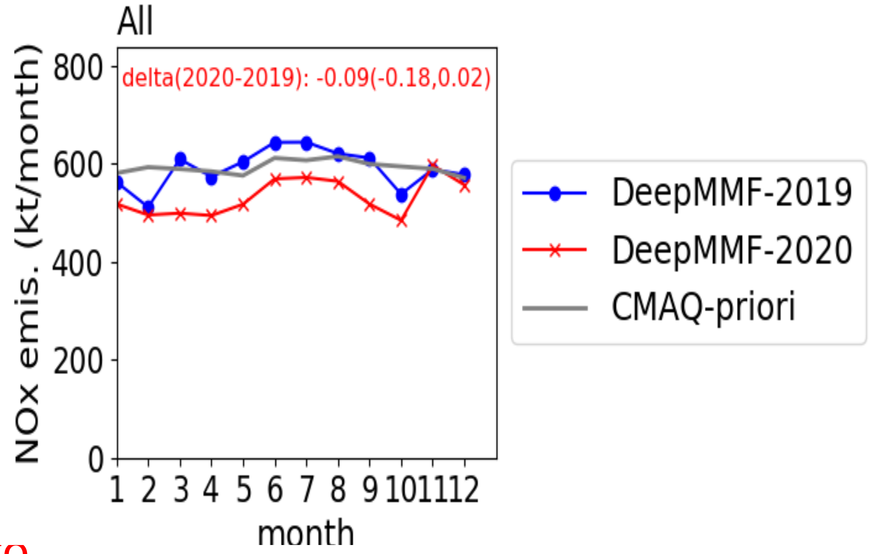


Δ DeepMMF (2020 – 2019)



increase due to the wildfire

reduction due to the pandemic



Xing, et al., *ES&T*, 2024

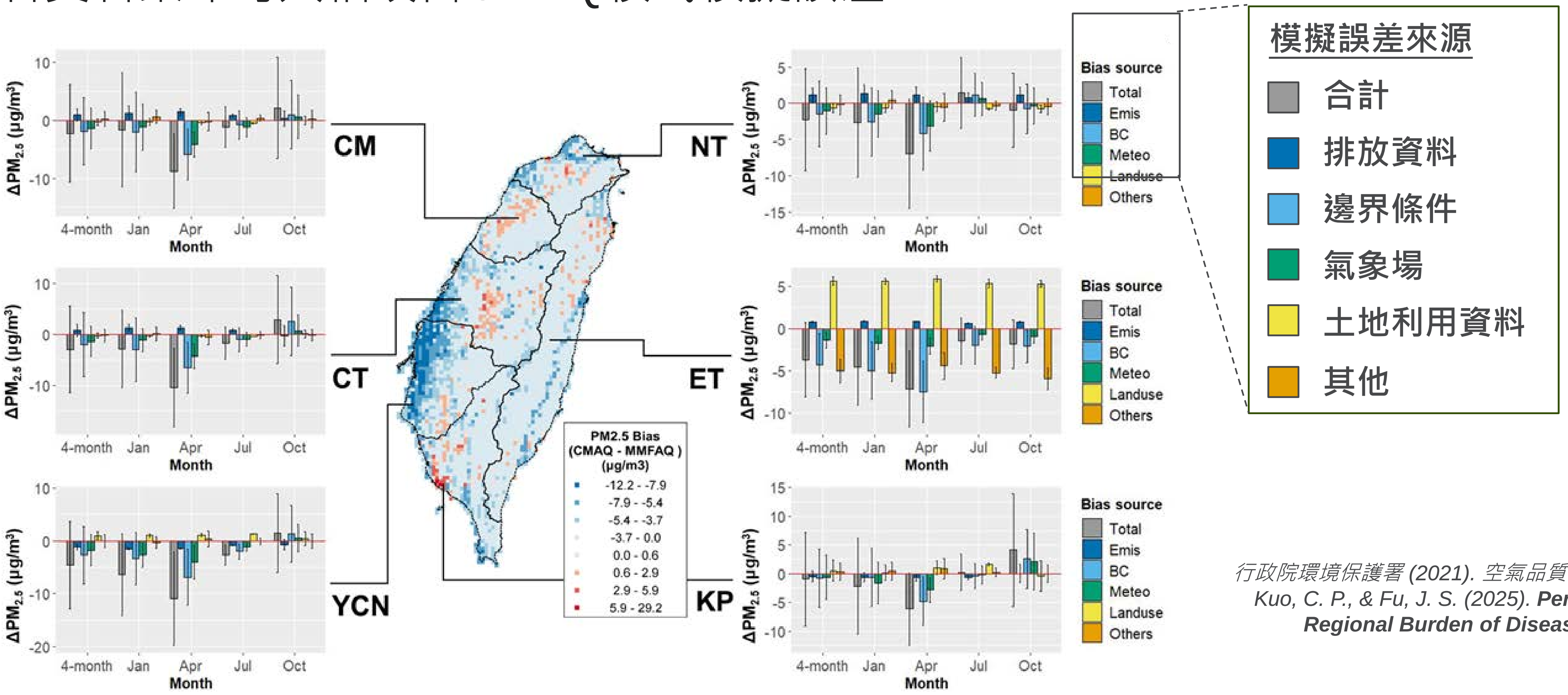
臺灣高密度的空氣品質監測網

- 臺灣具備空氣品質監測站全世界**密度最高**的監測網，亦累積龐大的**數據資料庫 (Big data)**
- **高應用潛力**：以 **AI** 或**機械學習方法 (Machine Learning)** 解決**現有與潛在政策難題**

監測網	測站數量	監測項目	監測頻率	開始監測時間
一般空氣品質測站 (中央)	79	PSNV、O_3、風速風向、溫溼度、雨量	小時	1993
一般空氣品質測站 (地方)	35	PSNV、O_3、風速風向、溫溼度、雨量	小時	-
大型事業測站	64	PSNV、O_3、風速風向、溫溼度、雨量	小時	-
手動測站	32	$PM_{2.5}$	一次24小時/六天	2013
光化測站	15	54種VOCs	小時	2003
河川揚塵監測站	9	PM_{10}、風速風向、溫溼度	小時	2009
特殊性工業區測站	45	PSNV、風速風向、溫溼度、雨量	小時	2015
		$PM_{2.5}$、HAPs	一次24小時/六天	
微型感測器	10,348	$PM_{2.5}$、溫溼度	1-3分鐘	2017

空品模式模擬誤差來源分析

- **CMAQ輸入資料**誤差來源：**排放資料**、**邊界條件**、**氣象場資料**、**土地利用資料**
- **機械學習模型**可評估**輸入資料的不確定性**所導致的模擬誤差，以確認**主要誤差貢獻來源**
- 以下圖為例，**邊界條件 (BC)** 與**氣象場 (Meteo)** 為主要誤差貢獻來源，表示先改善這兩者資料集即可大幅改善CMAQ模式模擬誤差



行政院環境保護署 (2021). 空氣品質惡化防制應變成效提升計畫

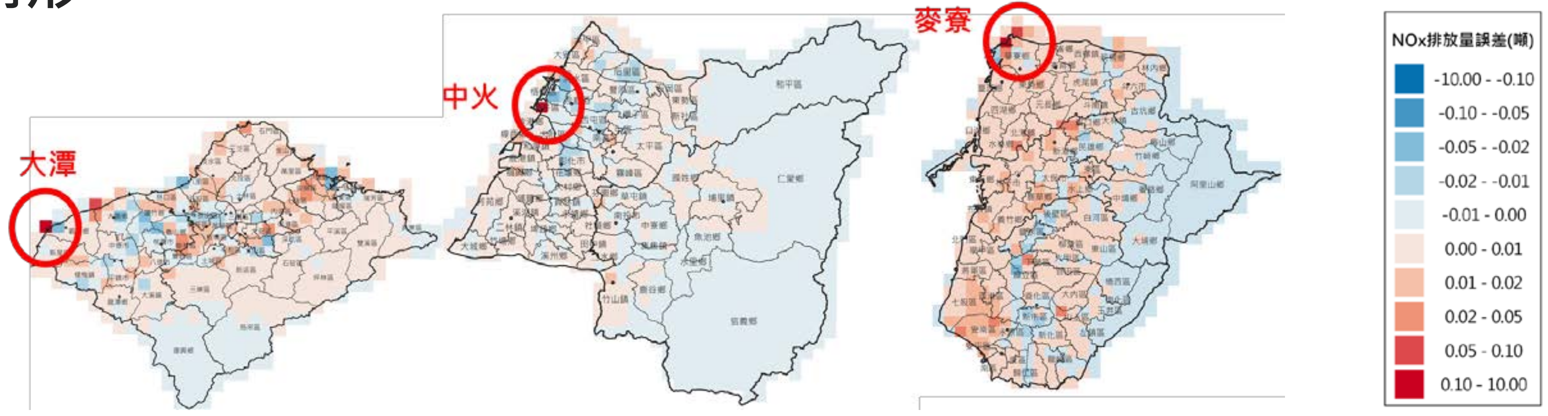
Kuo, C. P., & Fu, J. S. (2025). ***Perspective Improvement of Regional Burden of Disease Estimation by Machine Intelligence***. *(revised)*

空氣污染物排放量之校正

- **空氣污染物排放量**常被認為是**空品模擬誤差**來源之一。由於污染物排放量與環境濃度的**非線性關係**，以及**模擬資源有限**，導致不易掌握**空污排放量時空分布**的誤差。
- 藉由**機械學習模型**掌握污染物排放量與環境濃度的**非線性關係**，可鑑別**未掌握之排放量**與**調整排放源時空分布情形**

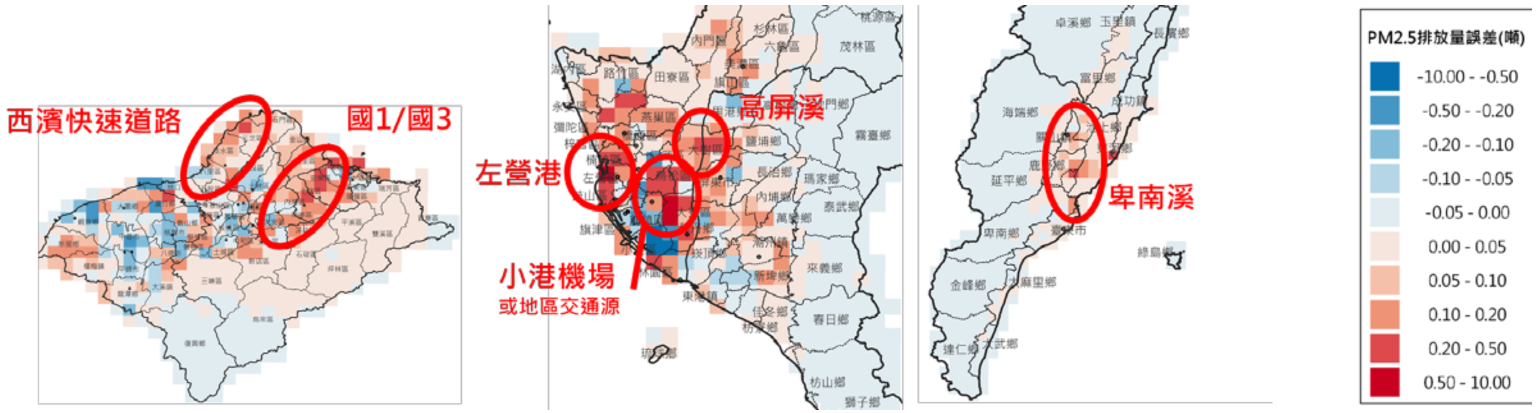
NOx排放量誤差 (kg/day)

紅色表TEDS低估
藍色表TEDS高估



$PM_{2.5}$排放量誤差 (kg/day)

紅色表TEDS低估
藍色表TEDS高估

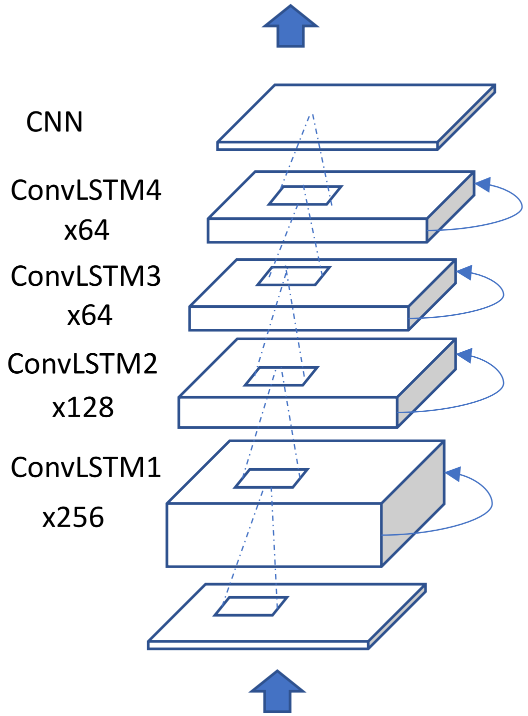


行政院環境保護署 (2022). 空氣品質惡化採取應變措施效益分析計畫

New development of DeepCTM4D (ongoing)

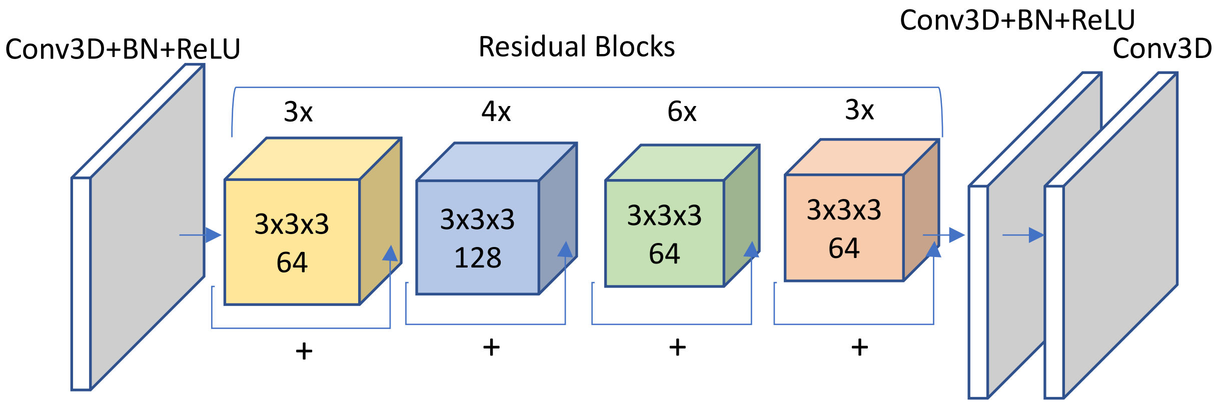
- concentrations

output



input

initial at first hour, and predict the following 24 hours



3D ConvLSTM + ResNet (dealing with spatiotemporal sequence)

- emissions
- meteorology variables

Thank You for your attention!

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