Rutgers University, Environmental Science Department Seminar, 26-April-2024

Earth System Feedbacks on Air Quality Extremes in a Changing Climate

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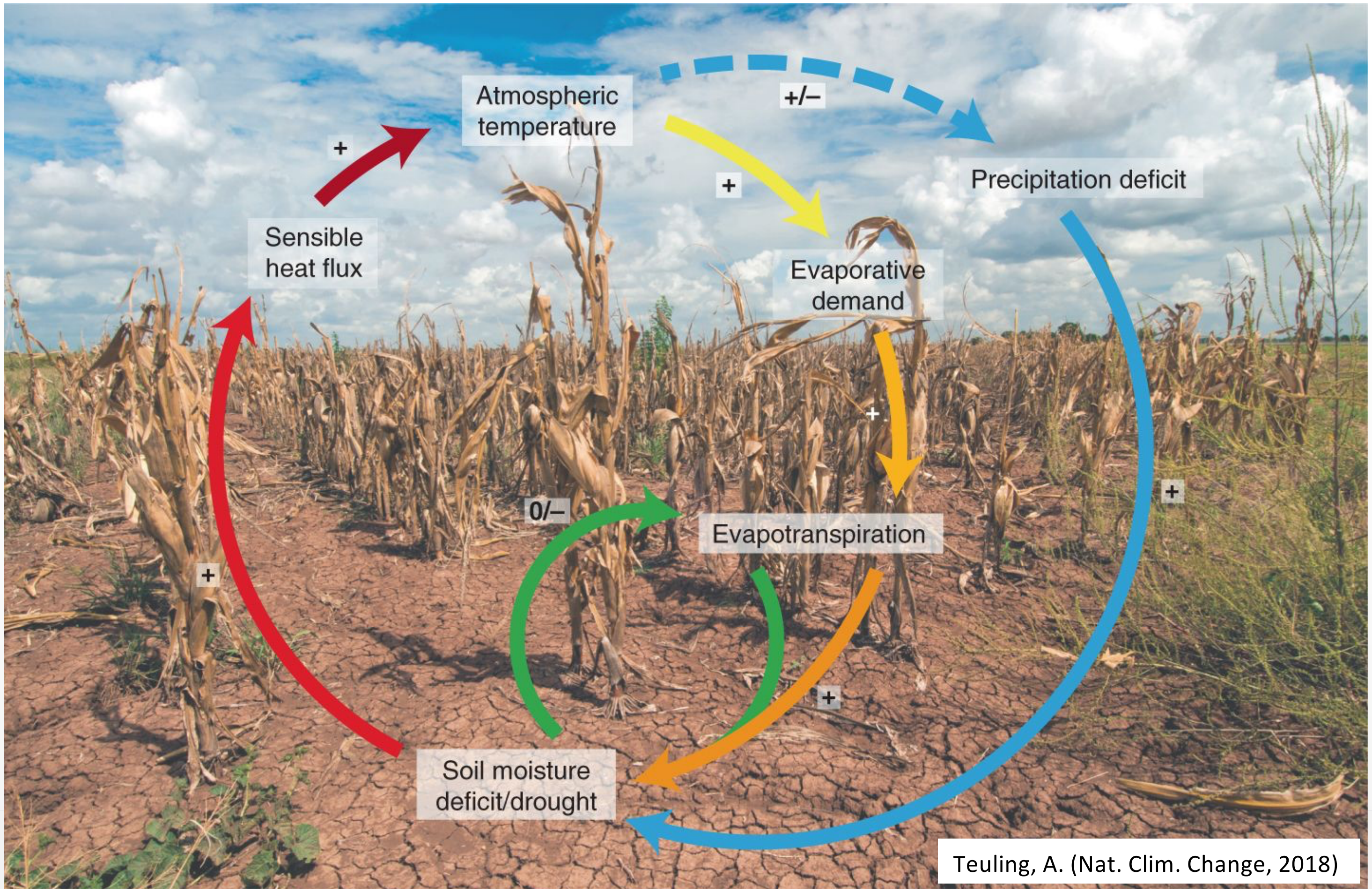
Acknowledgements to: J. Dunne, P. Ginoux, L.W. Horowitz, L. Harris, S. Malyshev, F. Paulot, A. Pouyaei, E. Shevliakova, Y. Xie, N. Zadeh, M. Zhao, and L. Zhou (NOAA GFDL); Lu Hu (U. Montana), S. Smith (DOE/PNNL), Leiming Zhang (Environment Canada); G. Gerosa and A. Finco (Italy), S. Fares (Italy), T. Mikkelsen and K. Pilegaard (Technical U of Denmark), Dagmar Kubistin (Germany)

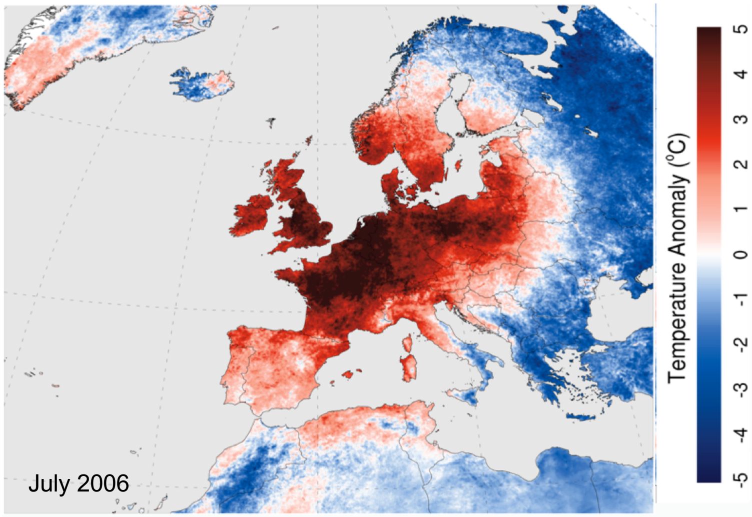
Geophysical Fluid Dynamics Laboratory

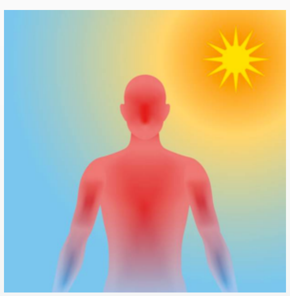
Global climate change is leading to more hot and dry weather



Teuling, A. (Nat. Clim. Change, 2018)

Devastating impacts of "Hot Drought" on natural and human systems

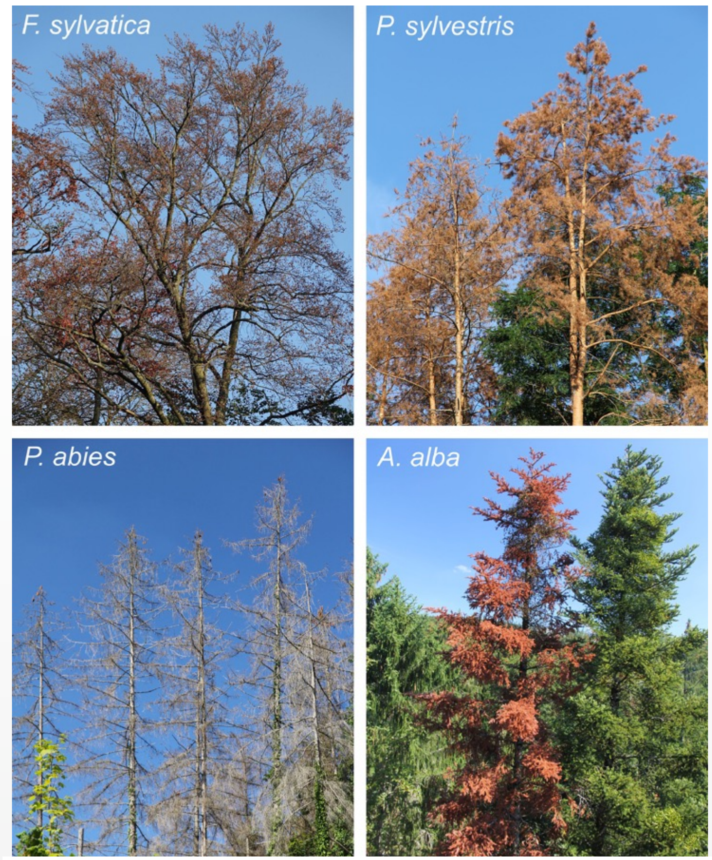




iStock by Getty Image

Human Heatstroke + Air Pollution:

- **70, 000 deaths (2003, W. Europe)**
- **55,000 deaths (2010, Russia)**
- **3418 deaths (2006, W. Europe)**
- **2500 deaths (2018/2019, C. Europe)**



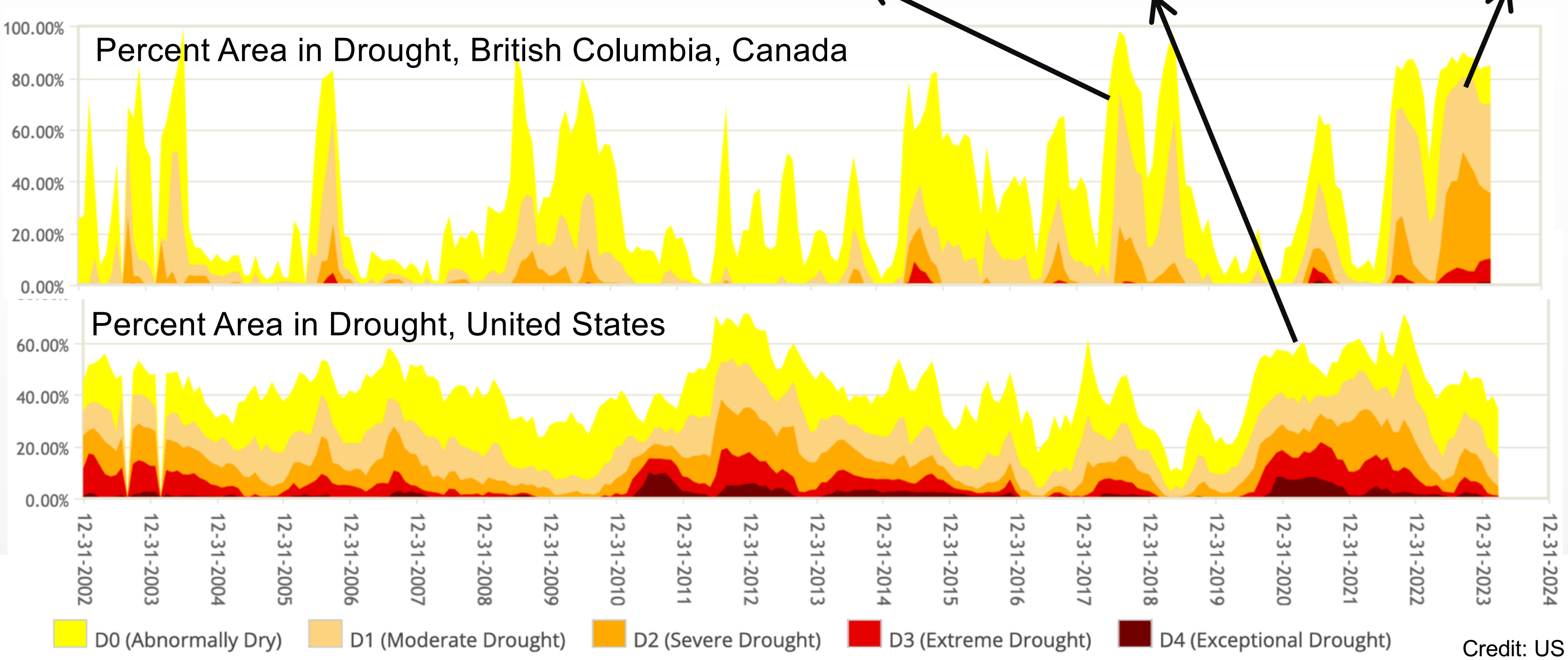
Drought-induced tree mortality
[Schuldt et al., 2020]

Sources: Robine et al. (2008); Barriopedro et al. (2011), BBC News

Western N. American wildfires in a changing climate

2012 2017 2018 2020 2021 2023

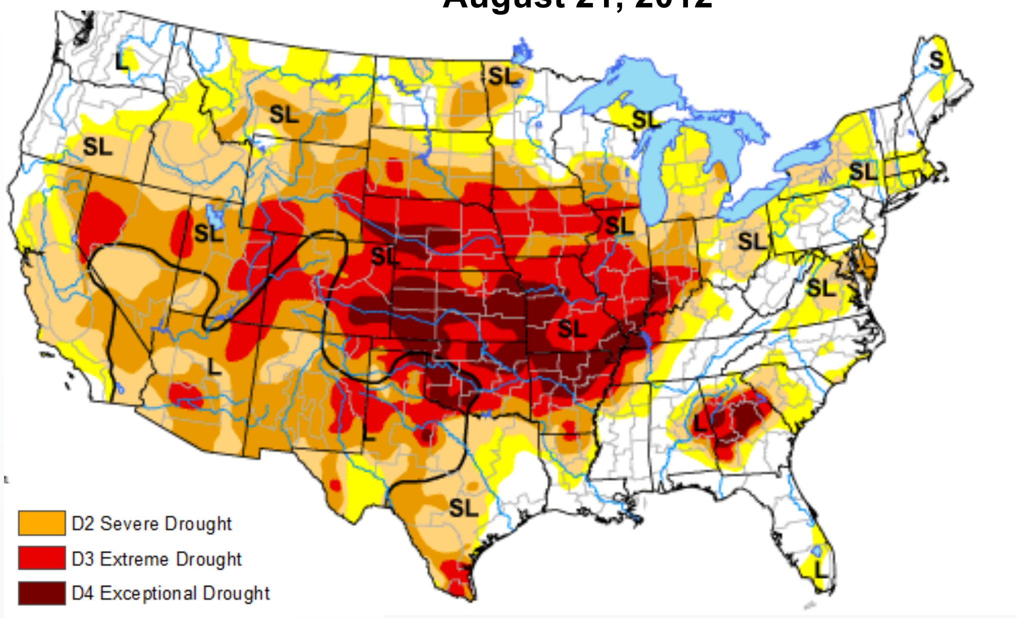
https://www.flickr.com/photos/41284017@N08/7408428768



Credit: US drought monitor

Tens of billions of agricultural losses due to drought

U.S. Drought Monitor
August 21, 2012



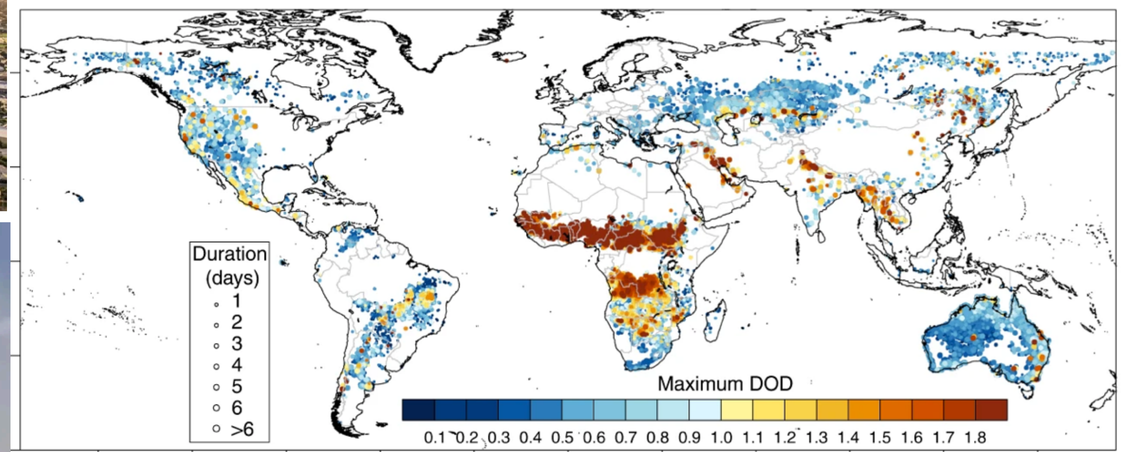
Credit: NBC News; AP Photo

The 2011 Texas drought caused $8 billion agricultural losses

The 2012 Midwest drought caused $35 billion agricultural losses

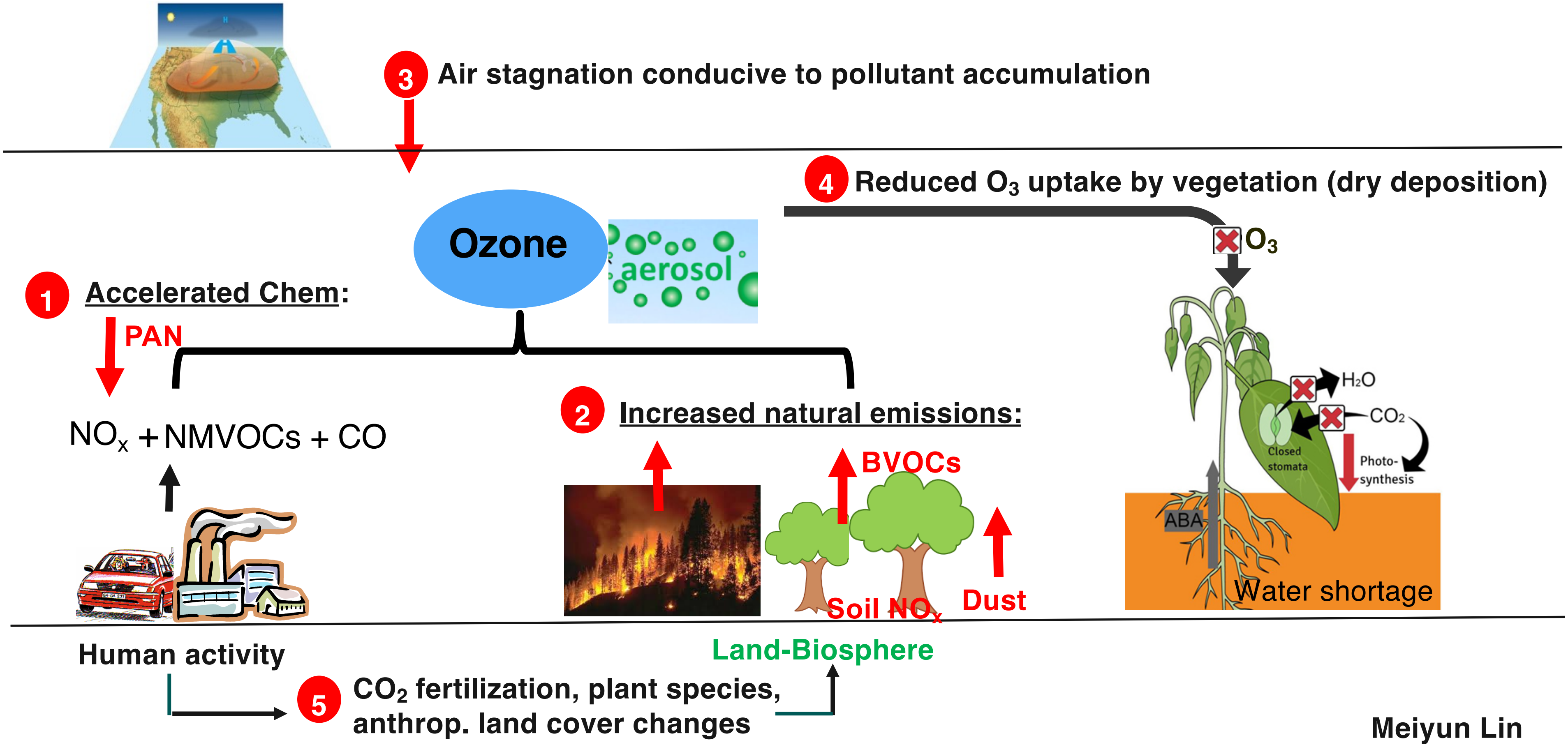
Increasing dust emissions from drier soils, anthropogenic land cover changes, and post-wildfire bare lands

Post-fire dust events detected from satellites



(Y. Yu and P. Ginoux, Nature Geo. 2022)

How does air quality respond to heatwaves, drought, and Earth system feedbacks?

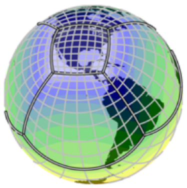


Meiyun Lin

Scientific challenges in understanding Earth system feedbacks

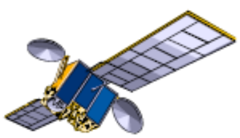
- **The lack of interactivity of atmospheric composition with land-biosphere in current models, e.g.:**
  - Many AQ models rely on prescribed land cover and vegetation characteristics
  - Atmospheric chemistry in CMIP6 climate models are not coupled to interactive wildfire emissions
  - Simulated pollution removal by vegetation does not account for stomatal closure under soil drying or elevated CO_2
- **Large uncertainties in modeling pyrogenic and biogenic emissions, e.g.:**
  - Challenges in representing wildfire occurrence, spread, duration, and emission variability
  - Uncertainties in both empirical and photosynthesis-based BVOC emission models
- **The lack of long-term (i.e., multi years and decades) flux measurements over various types of terrestrial ecosystems**
- **Poor representation of regional hydroclimate extremes in global climate models**
- **Heterogeneity in land-surface-atmosphere coupling**

Addressing the challenges: Process-level understanding across time scales from days to decades and from global to urban spatial scales

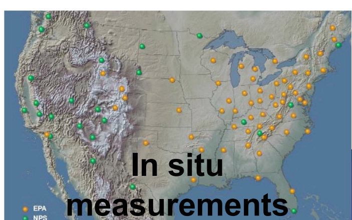


GFDL AM4VR

Field campaigns



Satellites



In situ measurements

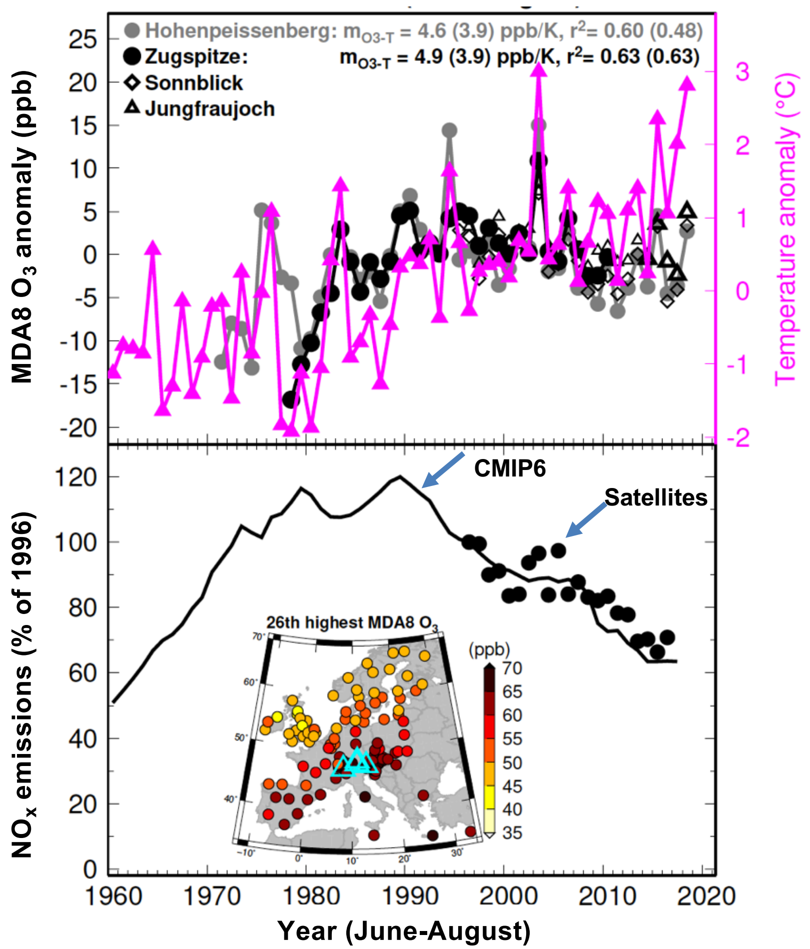
Today's talk:

- How does drought-stress in vegetation affect ozone air pollution extremes and trends during past half-century?
  → Enhanced biosphere-atmosphere coupling under observed climate

- The GFDL variable-resolution global chemistry-climate model for research at the nexus of US climate & air quality extremes
  → The value of increased model resolution in representing natural feedbacks

- Particulate and ozone pollution from western wildfire smoke in present and future climate
  → Uncertainties and future directions

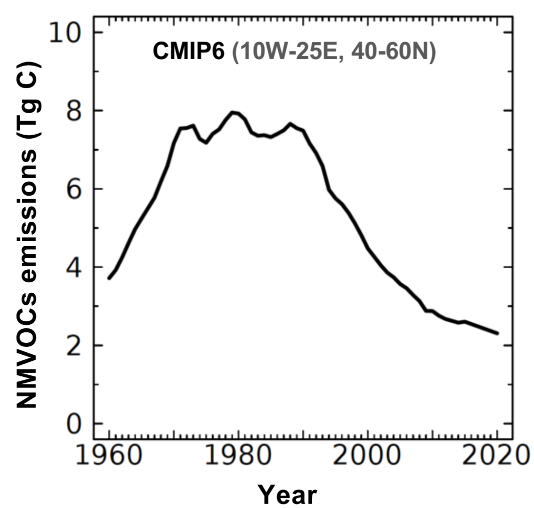
Why is ozone pollution persisting in Europe despite stringent controls on regional precursor emissions?



- The trend of O_3 does not mimic that in NO_x+VOCs emissions
- Observed O_3 increases with rising temperature
- Long-standing challenges in modeling EU O_3 trends

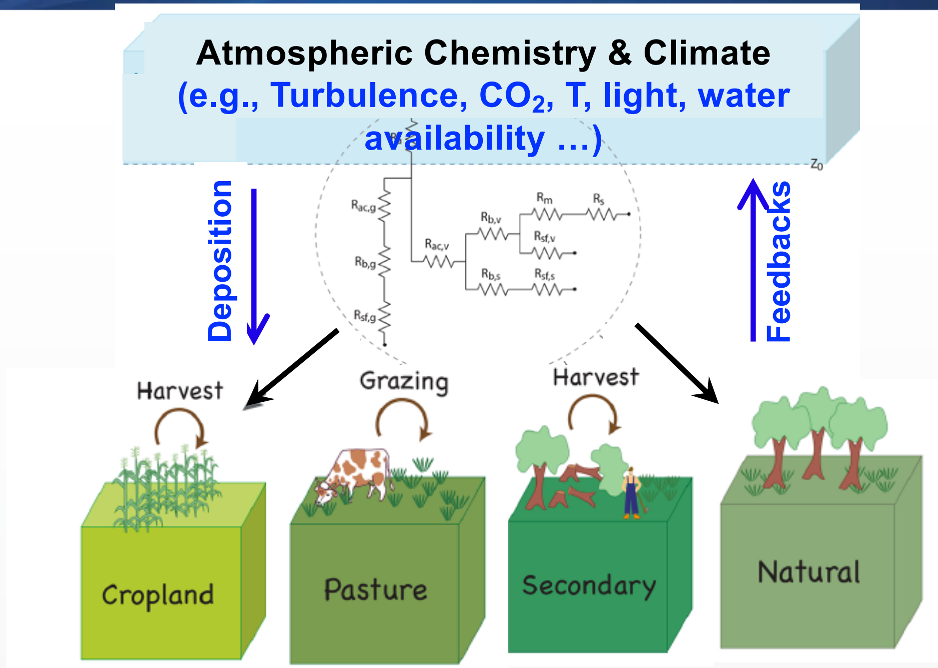
[e.g., Lelieveld2000; Fusco2003; Lamarque2010; Koumoutsaris2012; Parrish2014]

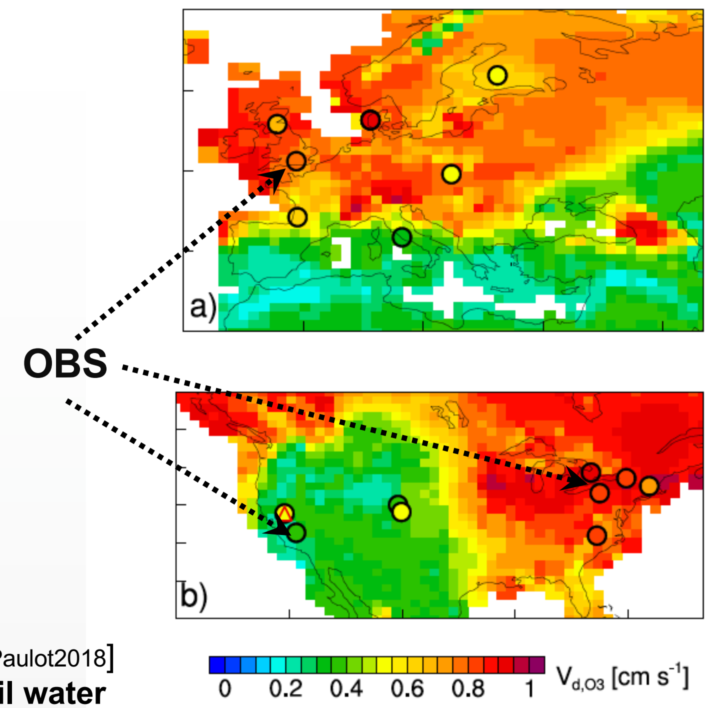
→ Unknown "climate penalty" feedback mechanism?



Lin M. et al. (2020)

New, interactive dry deposition scheme in GFDL Earth System Models



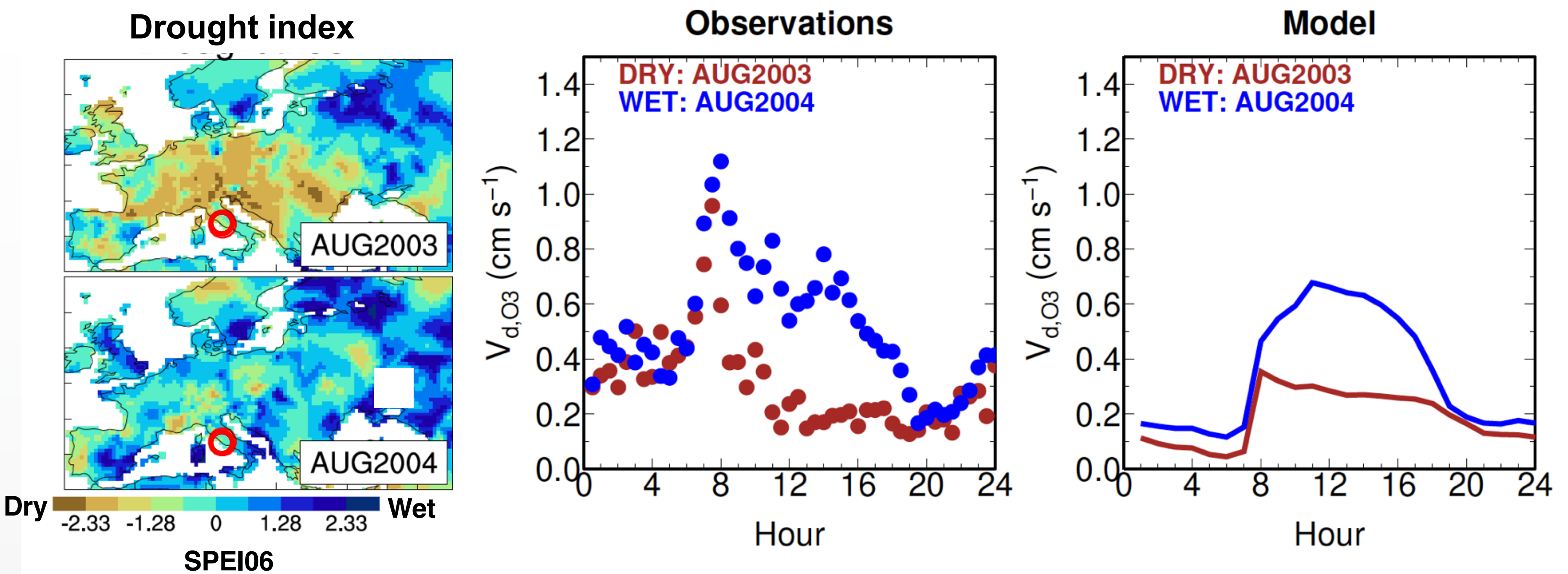


- **Incorporated into GFDL's dynamic vegetation land models** [Shevliakova2009; Paulot2018]
- **Stomatal deposition responds mechanistically to photosynthesis (A_n), soil water availability (φ_w), vapor pressure deficit (D_s), and atmos. CO_2 concentration (C_i).**

$$R_{stom} = \frac{\sqrt{\frac{M(O_3)}{M(H_2O)}}}{g_s(H_2O)}$$

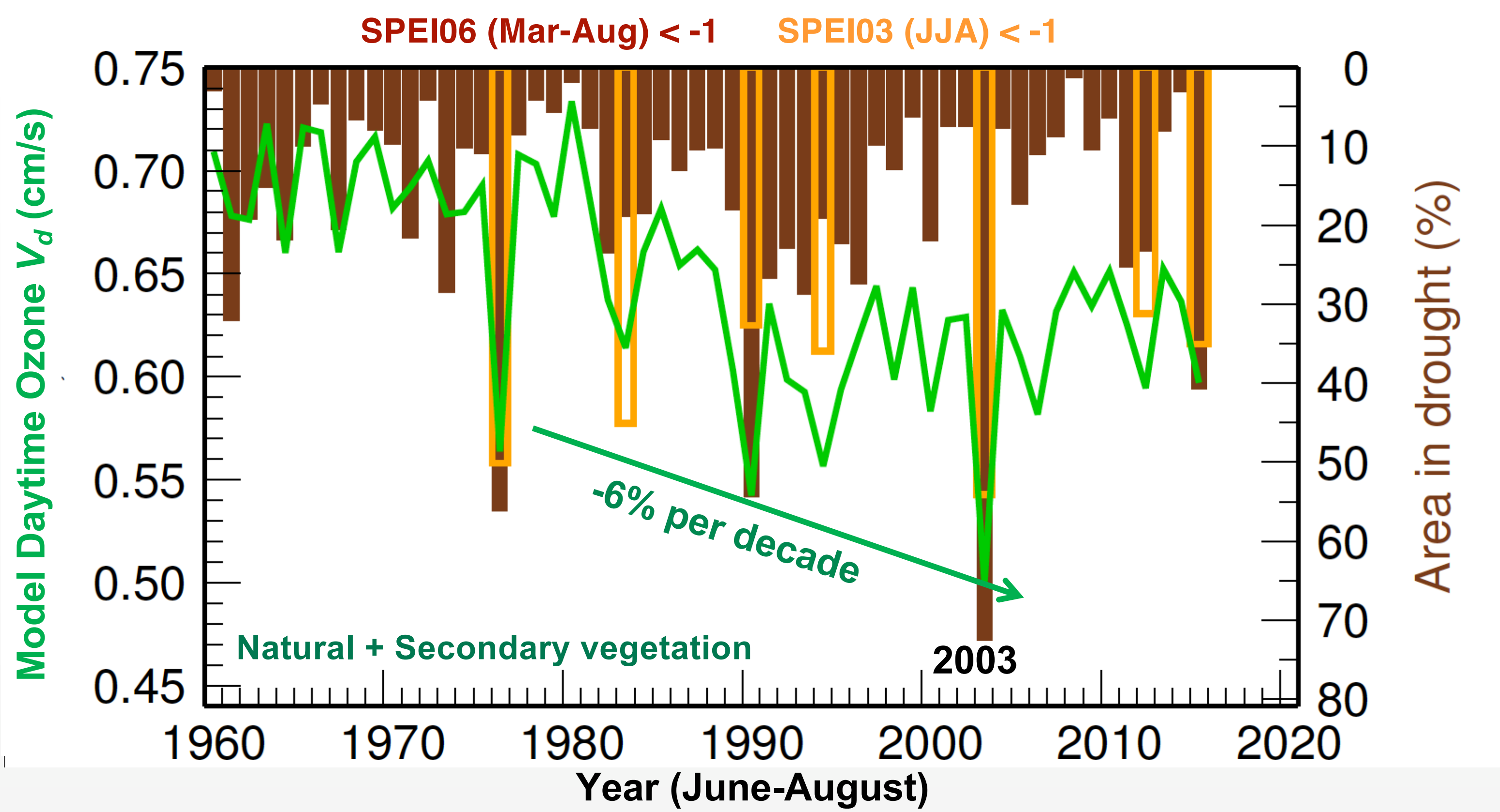
$$g_s(H_2O) = max\left(\frac{m\bar{A}_n}{(C_i - \Gamma_*)(1 + D_s/D_0)}, g_{s,min}\right) \cdot \ \psi_i \cdot \ \psi_w \cdot LAI$$

Observed and modeled reductions in O_3 removal by forests during drought



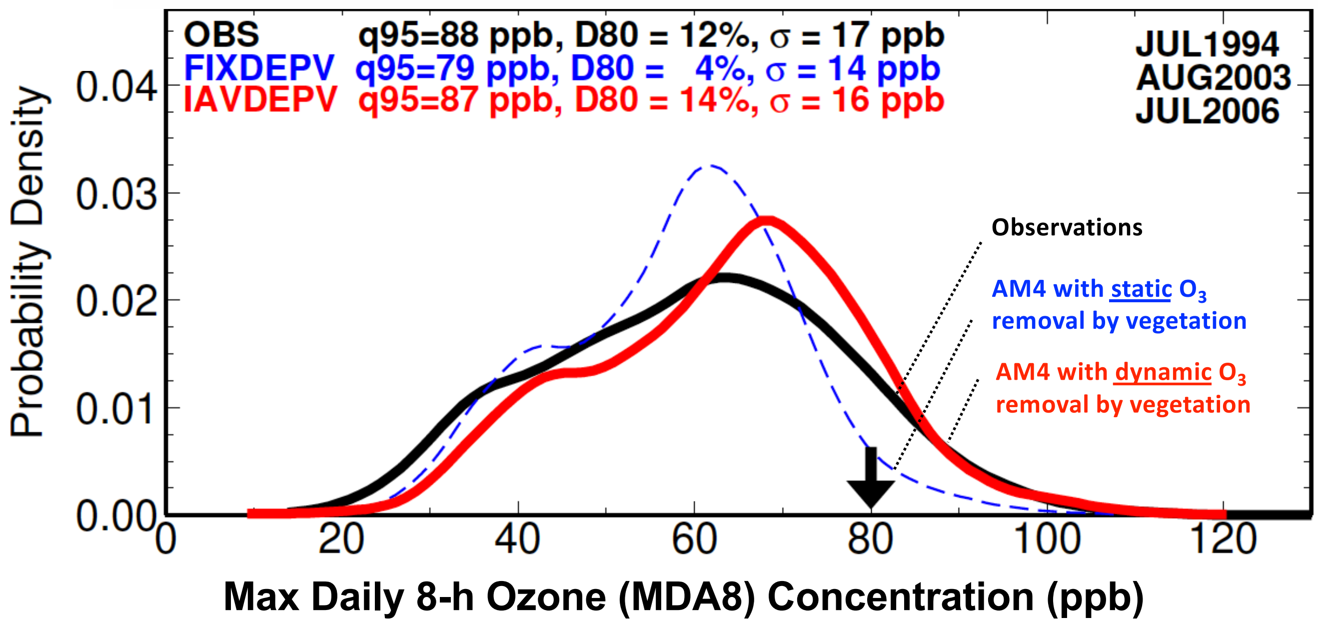
Lin M. et al. (Nature Climate Change, 2020)

Declining ozone removal by vegetation in Europe during past half-century



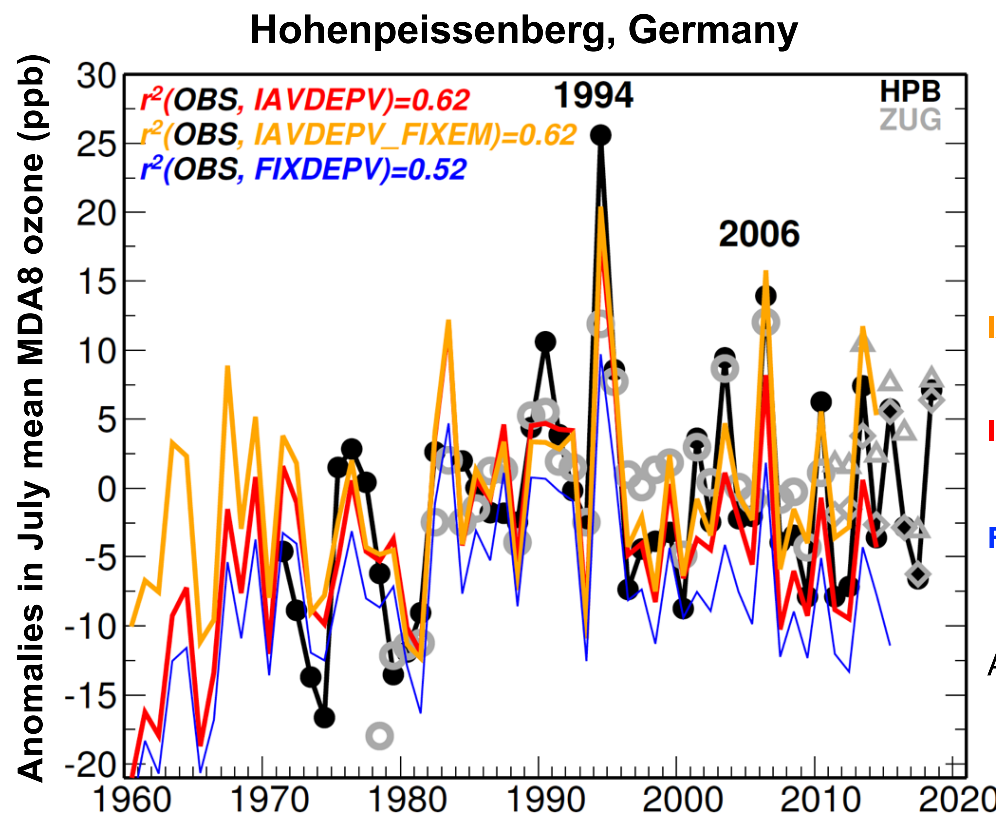
- GFDL Land Model (100 km grid) driven by observation-based atmospheric forcings (incl. precipitation)
- Simulation of soil water availability is dynamic, not depending on any drought index

Reduced ozone removal by drought-stressed vegetation worsens air pollution extremes during heatwaves



Lin M. et al. (Nature Climate Change, 2020)

Increasing ozone air pollution due to reduced removal by vegetation



IAVDEPV_FIXEM: Under 1980 high emission conditions

IAVDEPV: Ozone V_d varying with climate and vegetation state

FIXDEPV: Ozone V_d held constant at 1960 levels;
Varying biogenic isoprene emissions (MEGAN2.1)
Varying anthropogenic emissions

All simulations are forced by reanalysis meteorology

Lin M. et al. (Nature Climate Change, 2020)

→ **Need to include this feedback in coupled CCMs**
→ **First need to improve simulation of precipitation**

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RESEARCH ARTICLE
10.1029/2023MS003984

Key Points:

- A new variable-resolution global chemistry-climate model has been developed for research at the nexus of US climate and air quality extremes
- This model unifies component advances in physics, chemistry and land-atmosphere interactions within a seamless variable-resolution framework
- This model features much improved US regional precipitation, drought, and air quality extremes compared to previous models

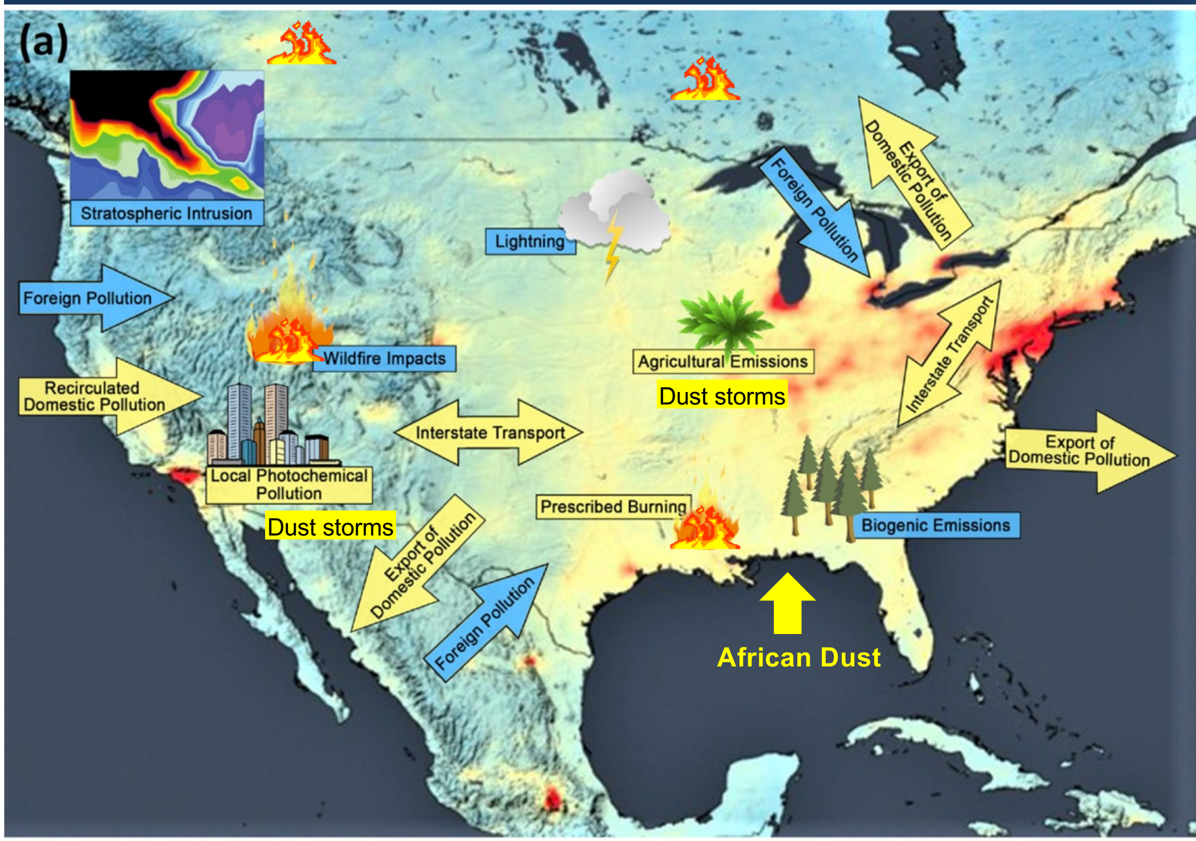
The GFDL Variable-Resolution Global Chemistry-Climate Model for Research at the Nexus of US Climate and Air Quality Extremes

Meiyun Lin[1], Larry W. Horowitz[1], Ming Zhao[1], Lucas Harris[1], Paul Ginoux[1], John Dunne[1], Sergey Malyshev[1], Elena Shevliakova[1], Hamza Ahsan[2], Steve Garner[1], Fabien Paulot[1], Arman Pouyaei[3], Steven J. Smith[2], Yuanyu Xie[4], Niki Zadeh[1], and Linjiong Zhou[3]

[1]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA, [2]Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD, USA, [3]Cooperative Institute for Modeling the Earth System, Princeton University, Princeton, NJ, USA, [4]Princeton School of Public and International Affairs, Princeton University, Princeton, NJ, USA

Selected for AGU Editors' Highlight

Challenges in Predicting U.S. Air Quality in a Changing Climate



Challenges:

- More hot & dry weather
- Large land-biosphere feedbacks
- Transported plus local pollution
- Diverse air basins & complex terrain

Limitations in current tools:

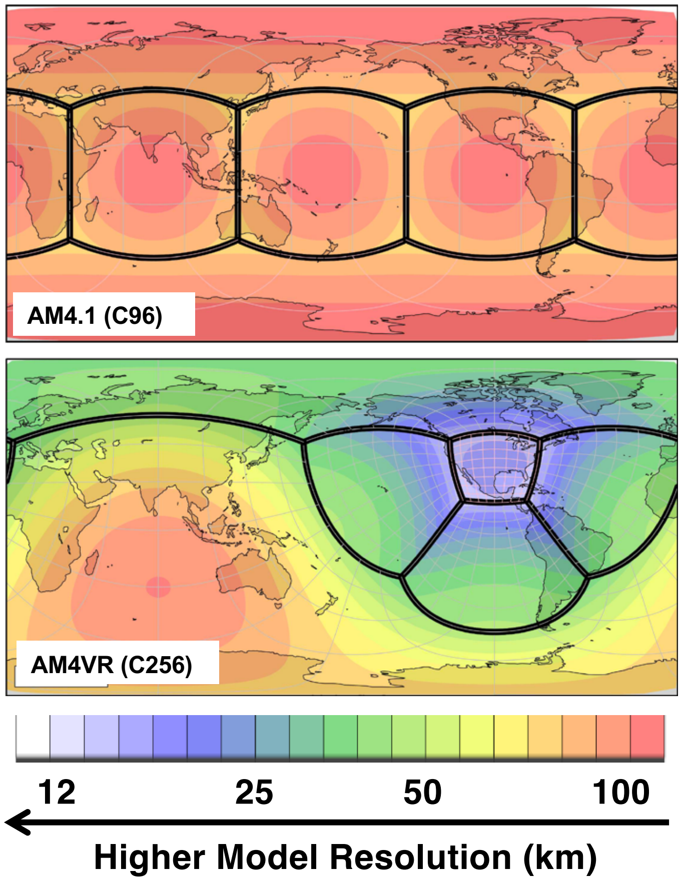
- X Poor representation of precipitation
- X The “stationarity” assumption in statistical downscaling
- X Prescribed vegetation characteristics
- X Issues with imposing global model BCs on regional models

Future:

- ✓ Need a seamless modeling system that can provide detailed info over a targeted region, while still integrating global Earth system components
- ✓ Increased coupling of atmospheric composition with dynamic vegetation

Lin et al. (2012ab, 2015ab, 2017, 2019, 2020); Jaffe et al. (2018, 2020); Ginoux et al. (2012); Xie et al. (2022)

The GFDL Variable-Resolution Global Chemistry-Climate Model (AM4VR)



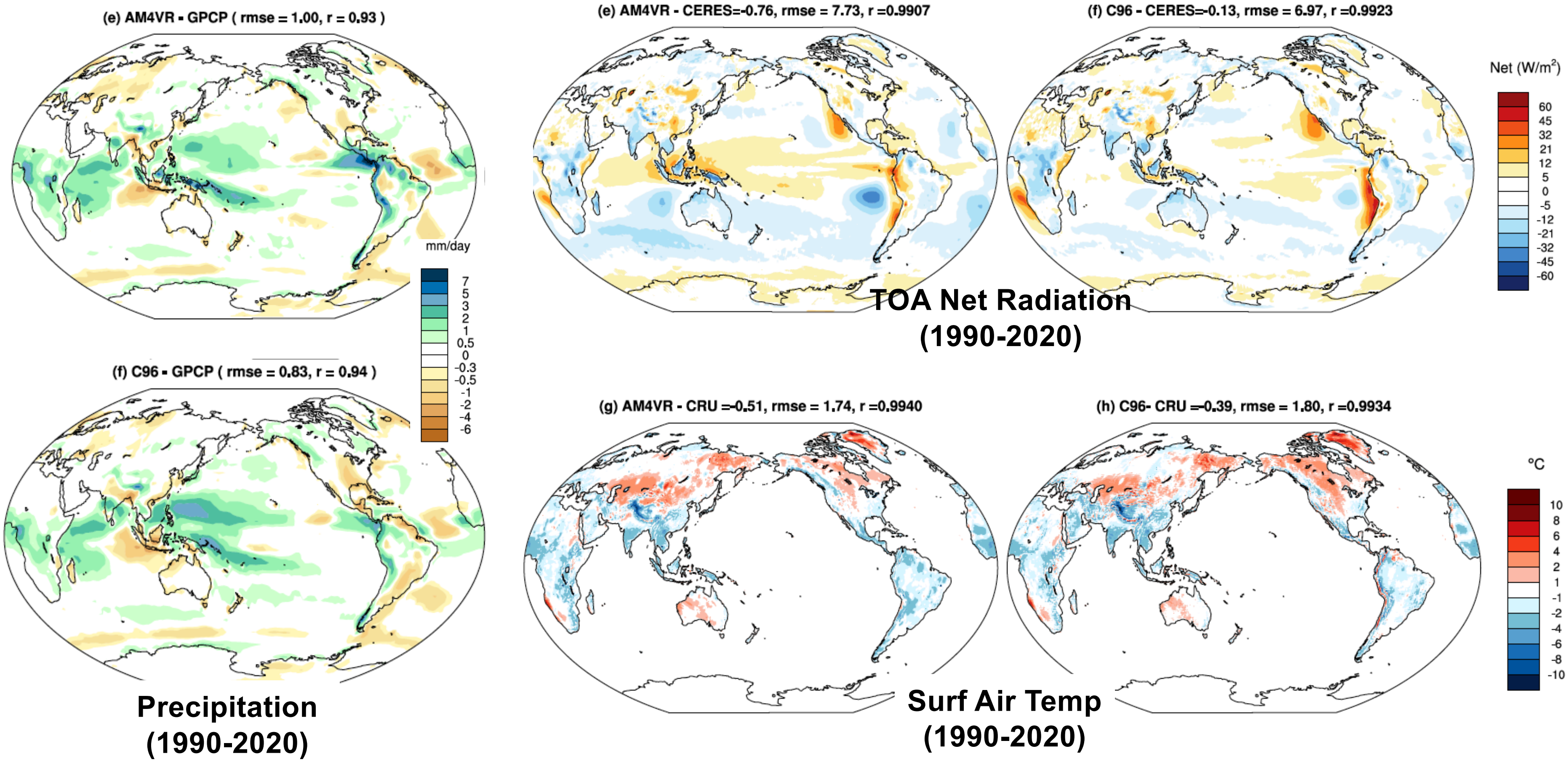
Key Features:

- GFDL FV3 Dynamical Core with regional grid refinement to 13 km over CONUS; sub-grid tiles for land surface heterogeneity
- Retuned moist physics from GFDL AM4.0
- **Comprehensive gas-phase & aerosol chemistry** from AM4.1
- High-resolution anthropogenic emissions from CEDS-2021-04-21 (0.1ºx0.1º), 1980-2020
- **Interactive dust emissions** from a dynamic vegetation land model (LM4.0), with retuned params
- **Interactive dry deposition** of gases, responding to hydroclimate, land cover, and photosynthesis in a **dynamic vegetation** model
- Revised interactive BVOC emissions (MEGAN2.1), with revised hi-res emission potential maps and land cover data
- Revised biomass burning emissions from GFED4s (0.25ºx0.25º), with reactive nitrogen partitioning and increased oxygenated VOCs

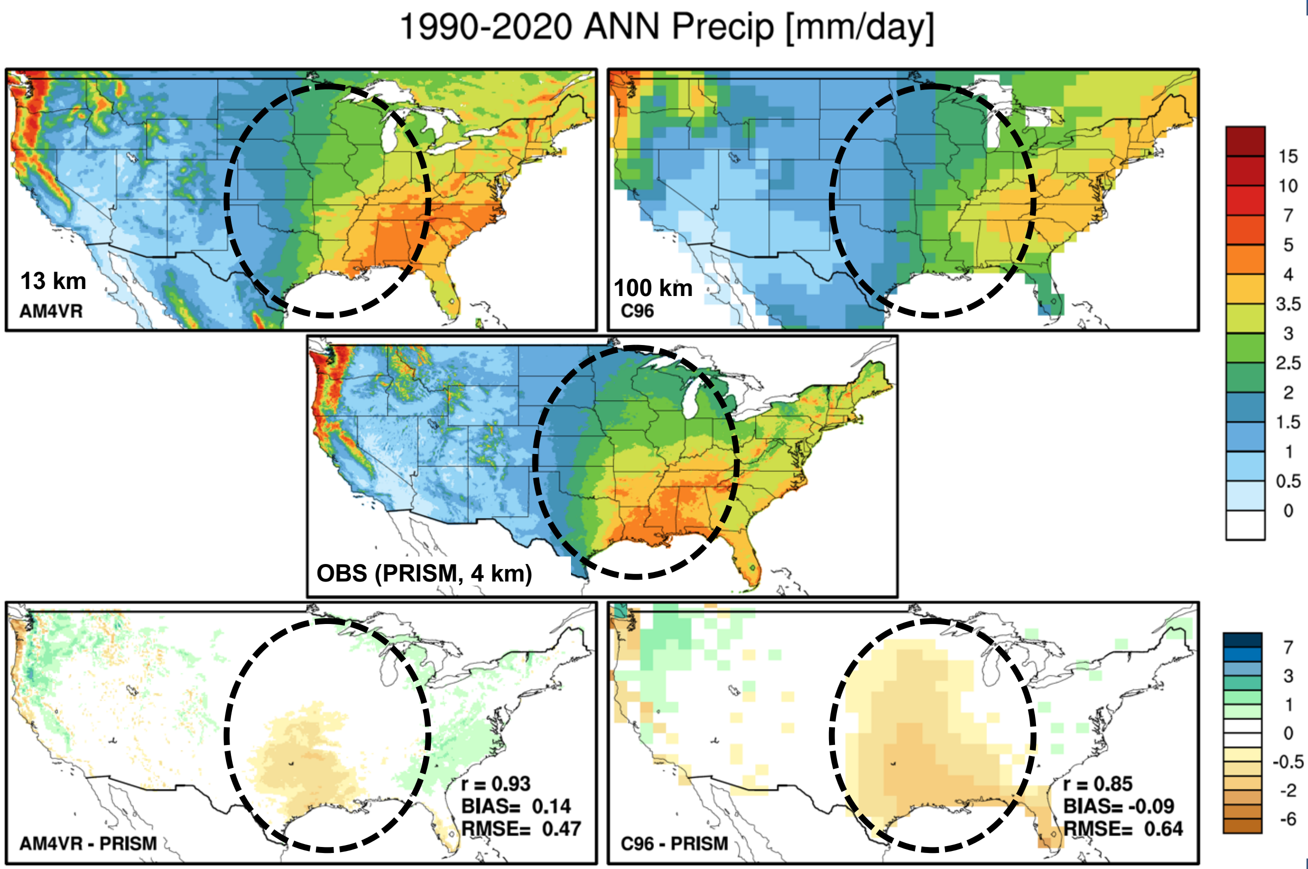
1990-2020 AMIP simulations with prescribed ocean
50% of the computational cost for a 25 km uniform-res grid

Lin M. et al. [JAMES 2024]

AM4VR maintains a good simulation of global-scale circulation and climate comparable to AM4.1 (CMIP6) at uniform 100 km resolution



Marked improvements in U.S. regional precipitation patterns



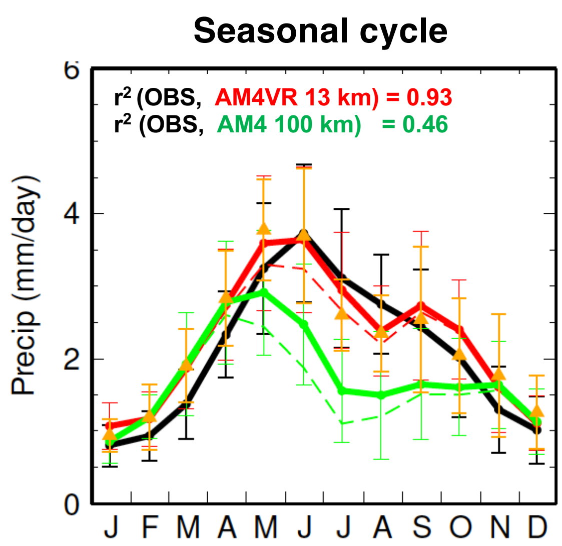
Notably reducing the central US dry bias that has persisted in many generations of weather forecast and climate models

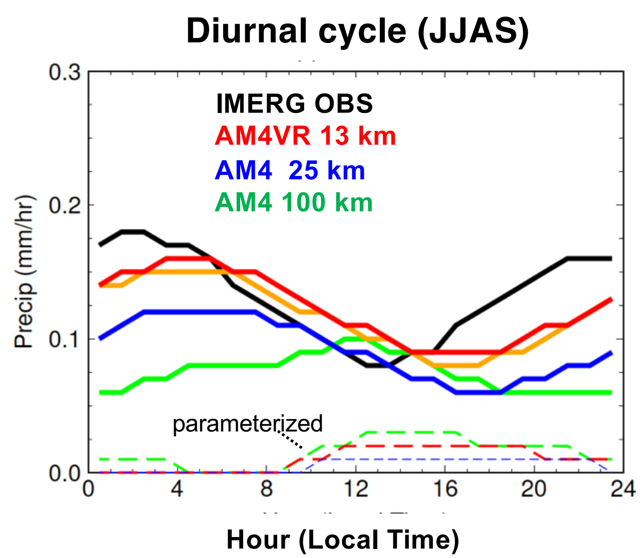
Lin M. et al. [JAMES, 2024]

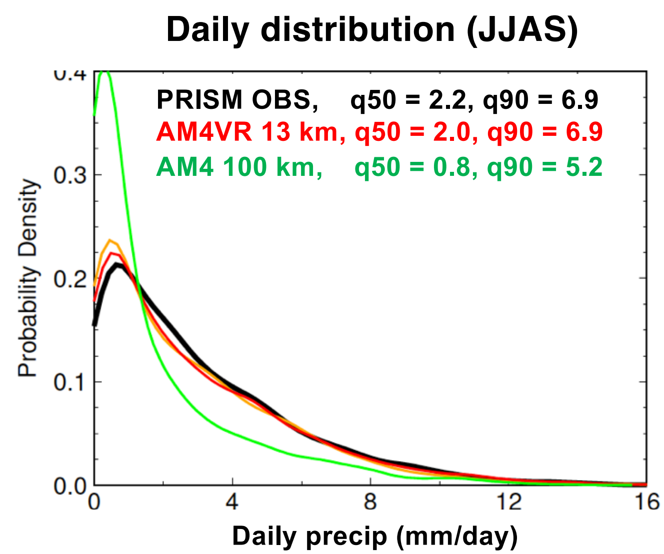
Improved skill in simulating the central US warm-season precipitation from mesoscale convective systems

- Limited skill from recent models at 25 km resolution, e.g. DOE E3SM (Tang et al., 2019; 2023); CMIP6 HiresMIP (Dong et al., 2023)

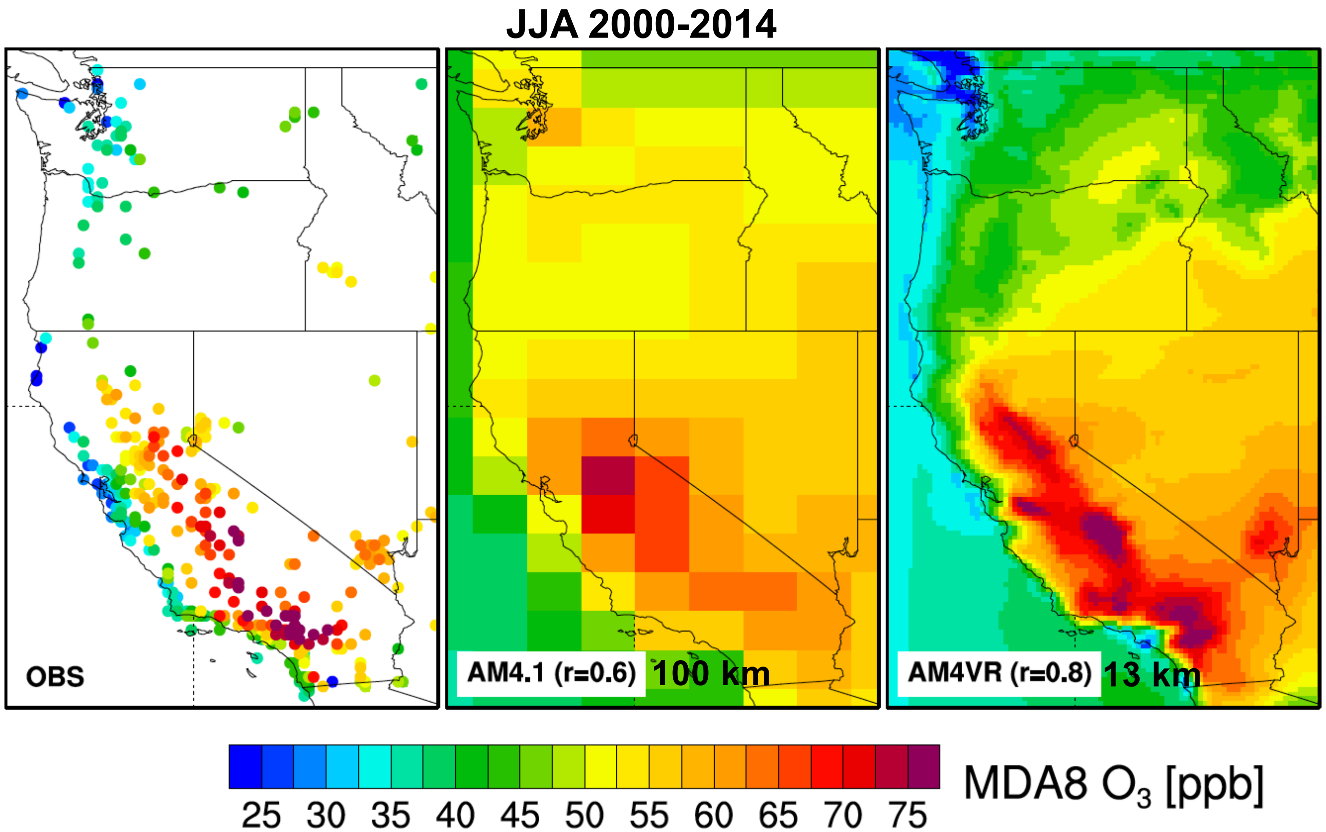
AM4VR at 13 km resolution exhibits:
→ superior fidelity in representing the nocturnal peak of precipitation driven by mesoscale convective systems
→ reduced drizzling bias and increased rainfall extremes







Summer ozone pollution in the western US



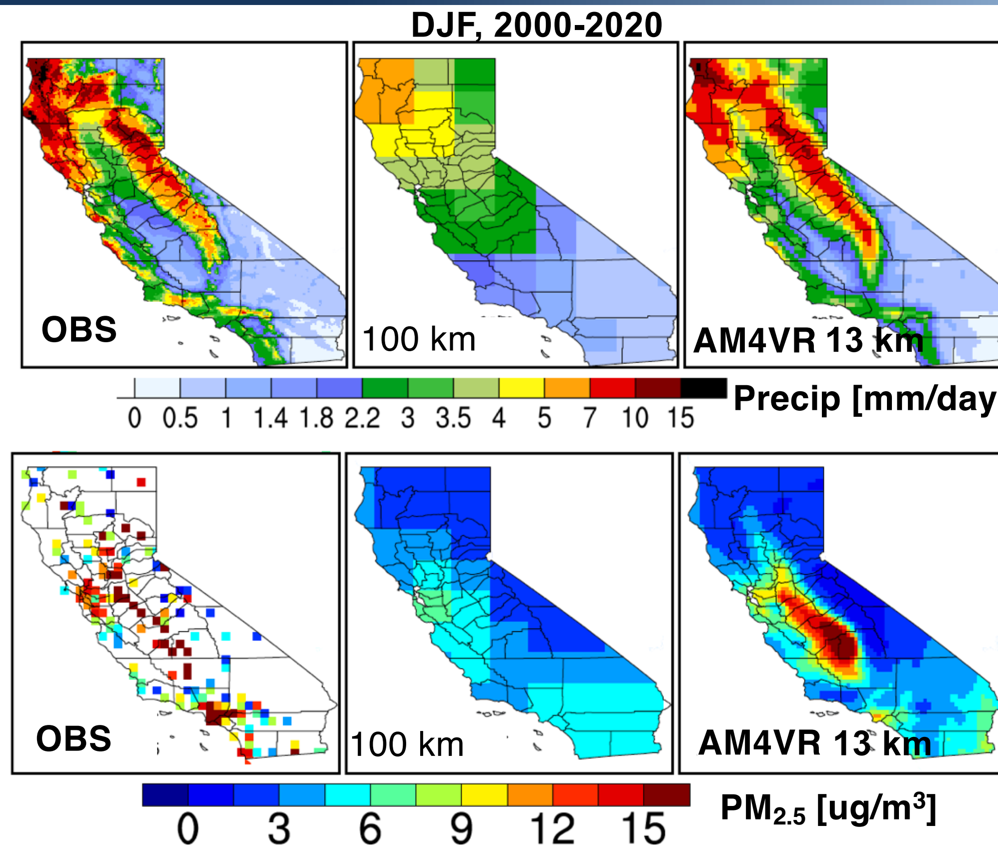
Improved representation of:

1) air pollution meteorology
2) urban-rural chemical regimes
3) BVOC emissions
4) drought
5) ozone removal by vegetation

Lin M. et al. [JAMES, 2024]

Winter Haze and Formation of Tule Fog in the Central Valley

Tule Fog (MODIS)

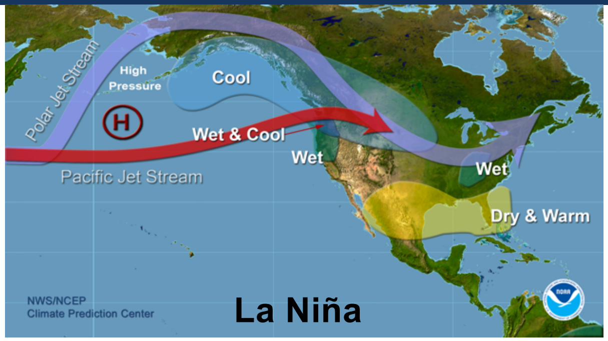


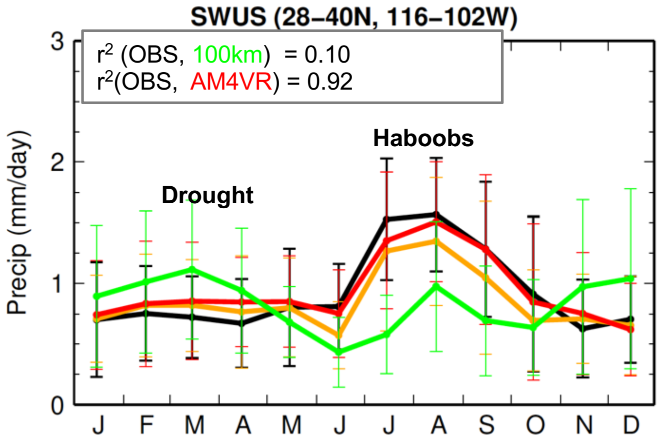
- Strong temperature inversion
- NH_4NO_3 aerosol as an efficient CCN

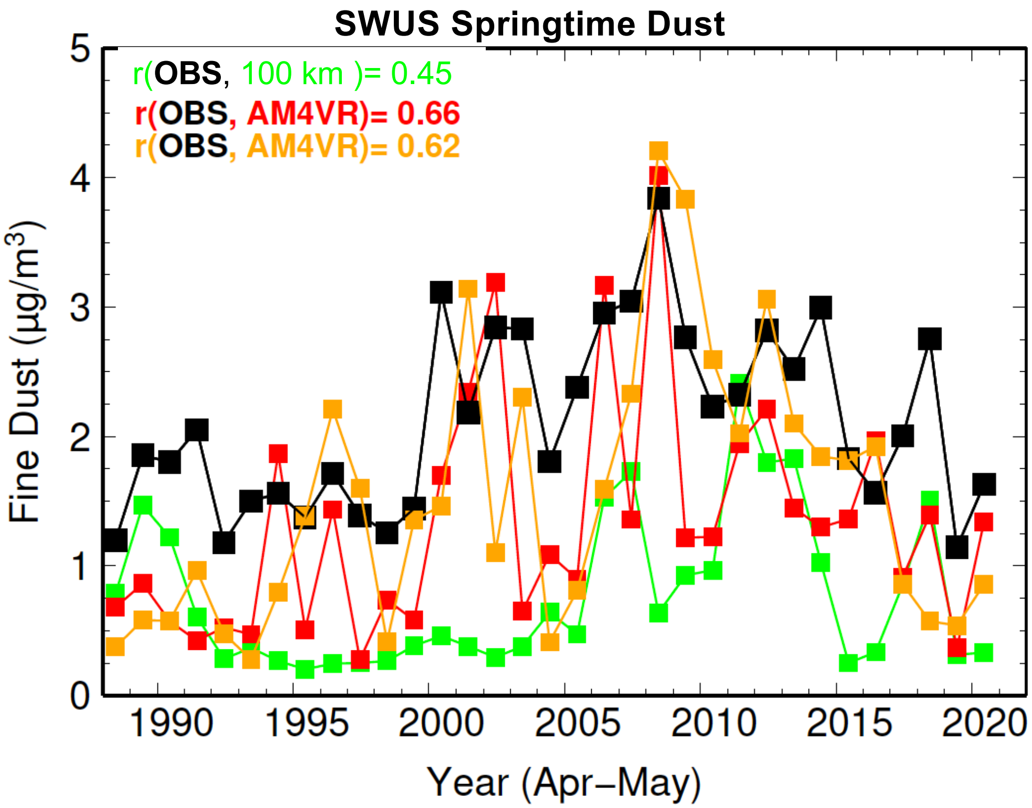
→ Impacts from large-scale circulation and climate change?

Lin M. et al. [JAMES, 2024]

ENSO → Southwest US Hydroclimate and Dustiness





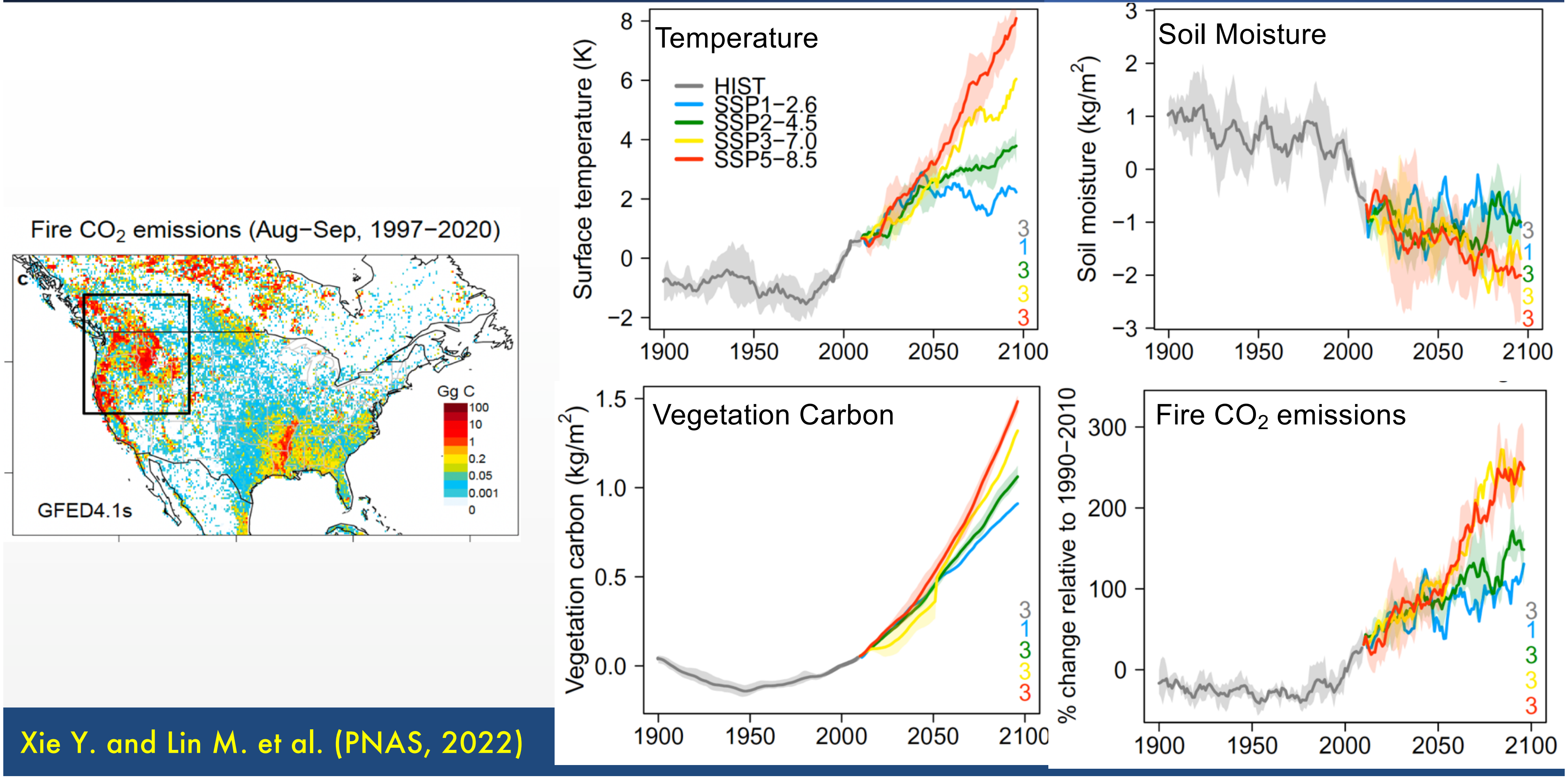


→ AM4VR driven by observed SSTs captures SWUS dust variability, implying seasonal forecast potential

Wildfire Impacts on Air Quality

A man pauses to look at the smoke and haze shrouding One World Trade Center building in New York City, Wednesday, June 7, 2023. Intense Canadian wildfires are blanketing the northeastern U.S. in a haze, turning the air acrid and the sky yellowish gray. (AP Photo/J. David Ake)

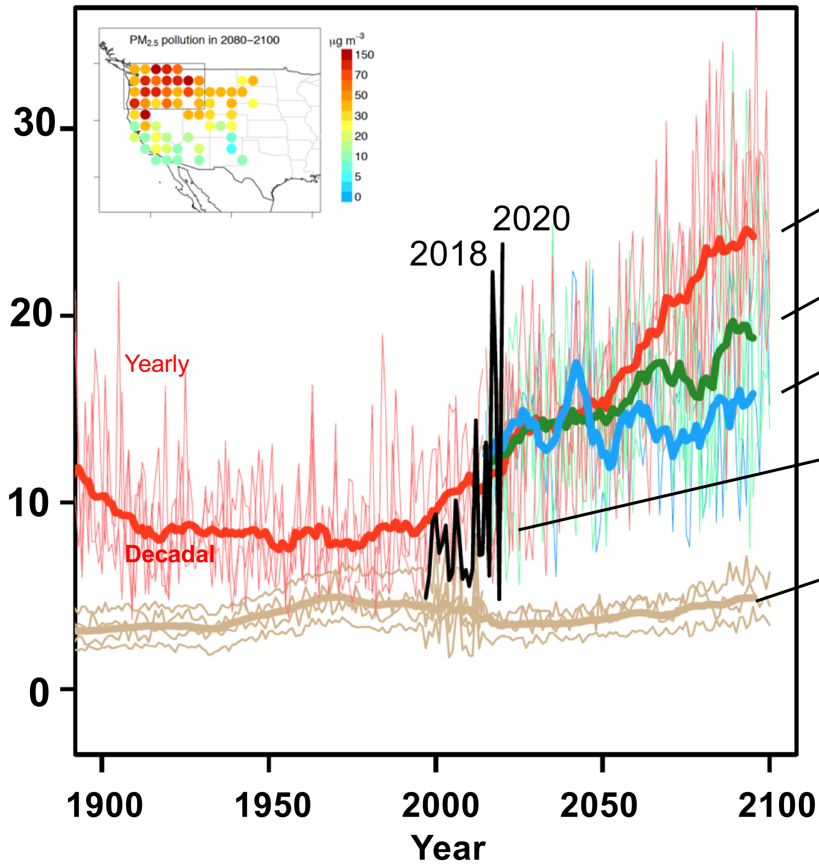
Increasing wildfire activity in US West in future climate



Xie Y. and Lin M. et al. (PNAS, 2022)

Increasing smoke pollution from western wildfires under 21st century climate change

Aug-Sep mean $PM_{2.5}$ (µg/m³) in Pacific Northwest



Applying an empirical statistical model to fires projected by three Earth System Models under a suite of Shared Socioeconomic Pathways (SSPs):

SSP5-8.5: CO_2 emissions tripled by 2075

SSP2-4.5: The world would surpass 2 °C warming by 2050

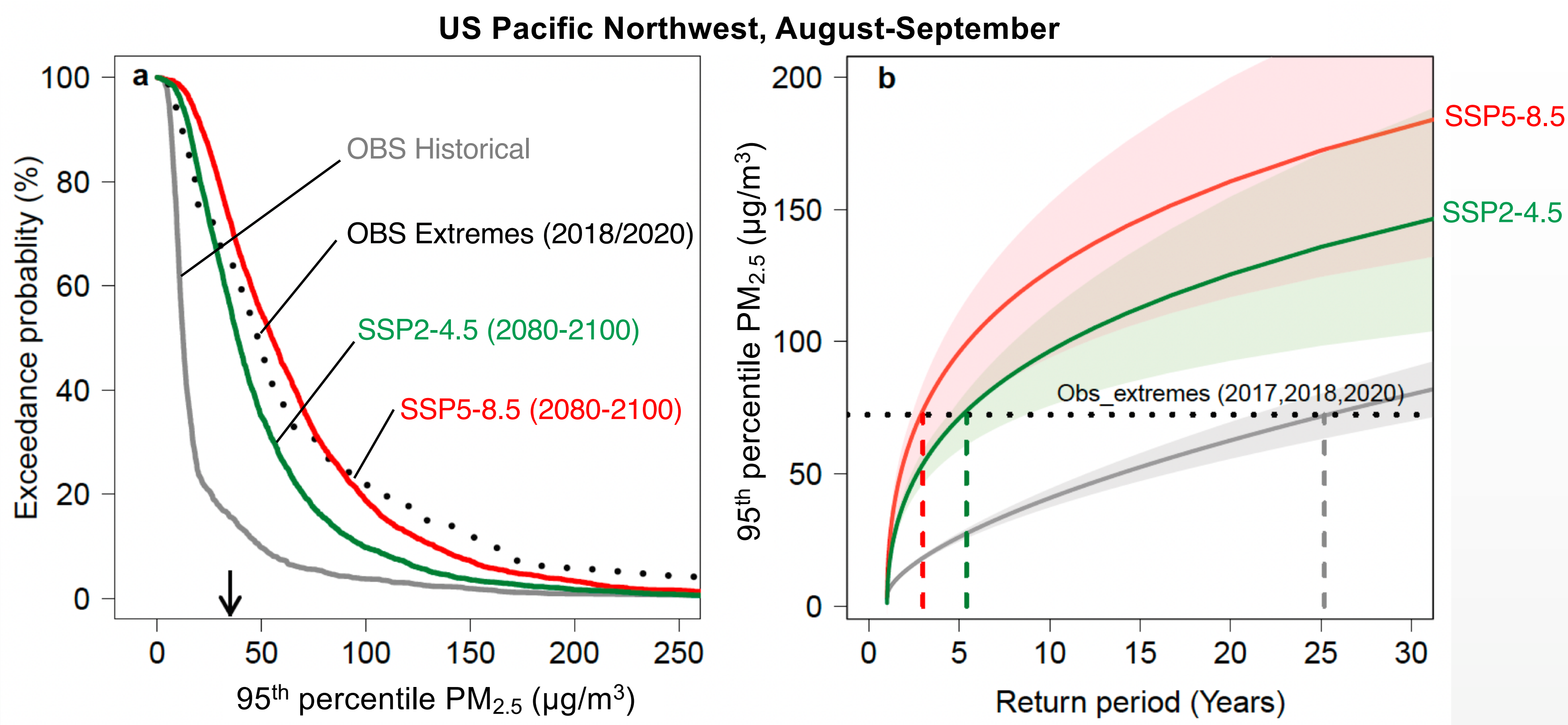
SSP1-2.6: CO_2 emissions cut to net zero by 2075

OBS (EPA)

CMIP6 CCMs w/ prescribed fire emissions of aerosols not accounting for the impacts from climate change

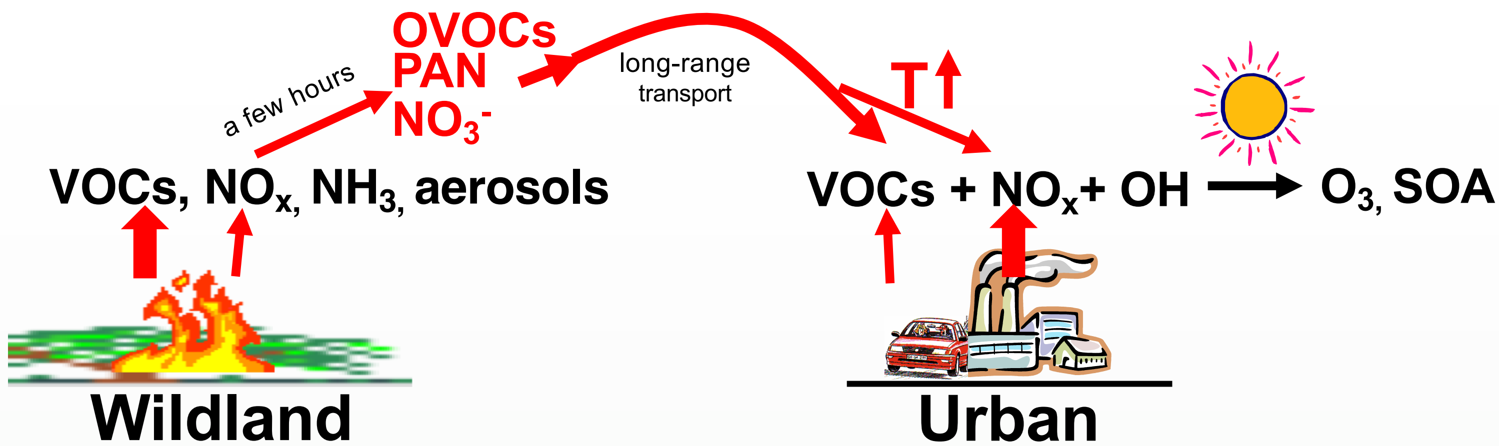
Xie Y. and Lin M. et al. (PNAS, 2022)

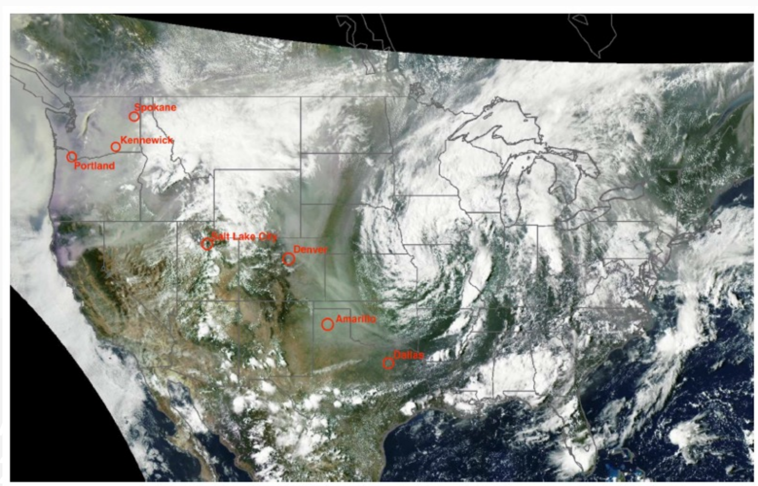
Likelihood of the 2018/2020 smoke extremes in late 21st century



Xie Y. and Lin M. et al. (PNAS, 2022)

The complex impacts of wildfire smoke on ozone formation





Observed:

- Fires emit an enormous diversity of VOCs
- Rapid conversion of NO_x to PAN and NO_3^- in fresh plumes (e.g., Xu et al., 2021)
- Ozone formation is enhanced when VOC-rich smoke plumes mix with NO_x-rich urban pollution (e.g., Jaffe et al., 2020; Jin et al., 2023)

Model problems:

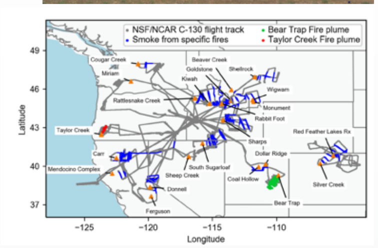
- Underestimation of VOCs, PAN, and aerosols
- Overestimation of NO_x and O_3 close to the fires
- Underestimation of downwind O_3 in aged plumes

Parameterization of NO_y partitioning based on aircraft observations

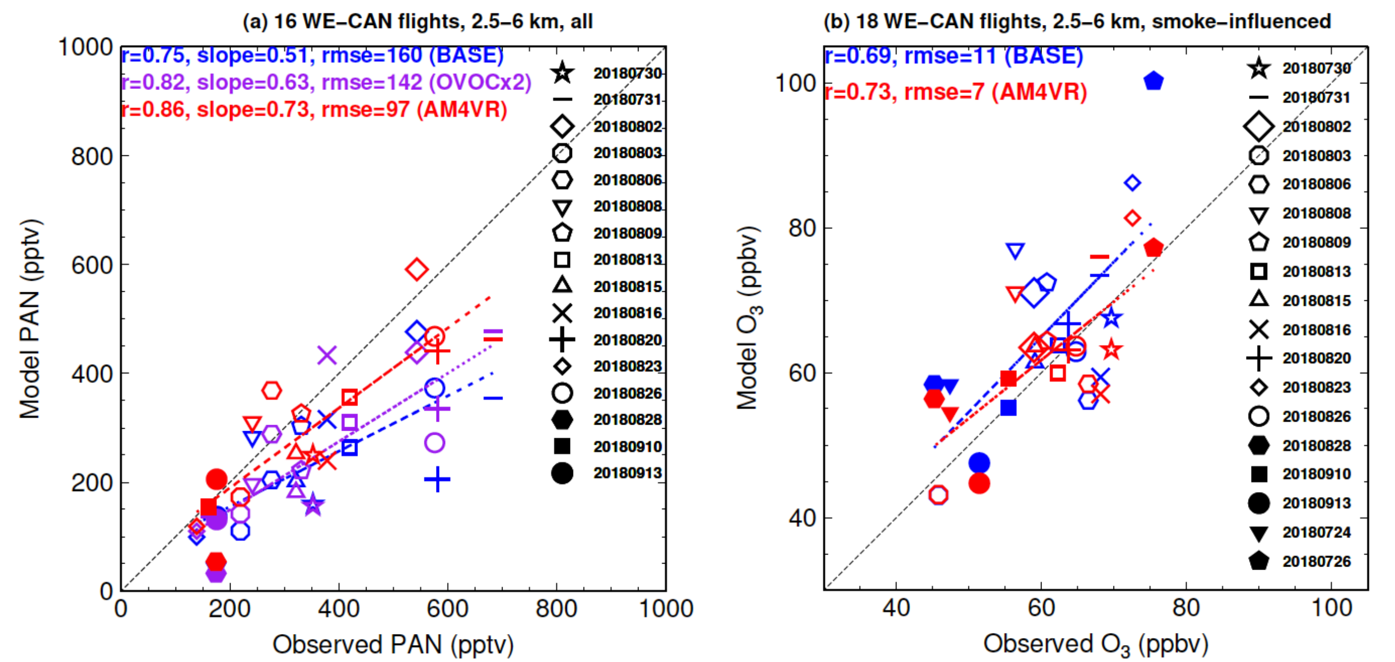
BASE: Fires emitting 100% NO

AM4VR: Fires emitting 37% PAN, 27% NO_3^- and 36% NO

WE-CAN 2018



Juncosa Calahorrano et al., 2021
Lindaas et al. (2021)
Permar et al. (2021)

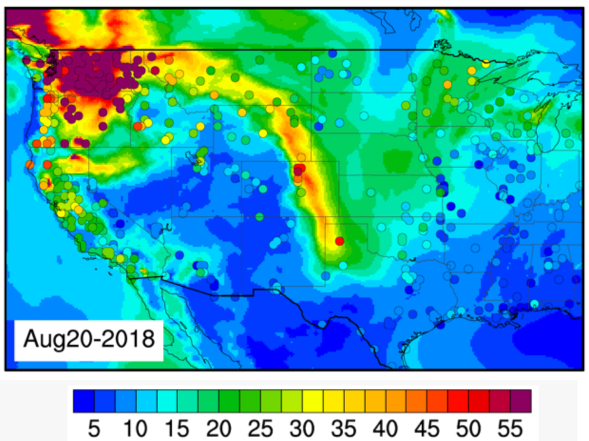


→ Improve simulation of PAN and reduce excessive O_3 production in fresh plumes

Lin M., LW Horowitz, Lu Hu, W. Permar [submitted to GRL, 2024]

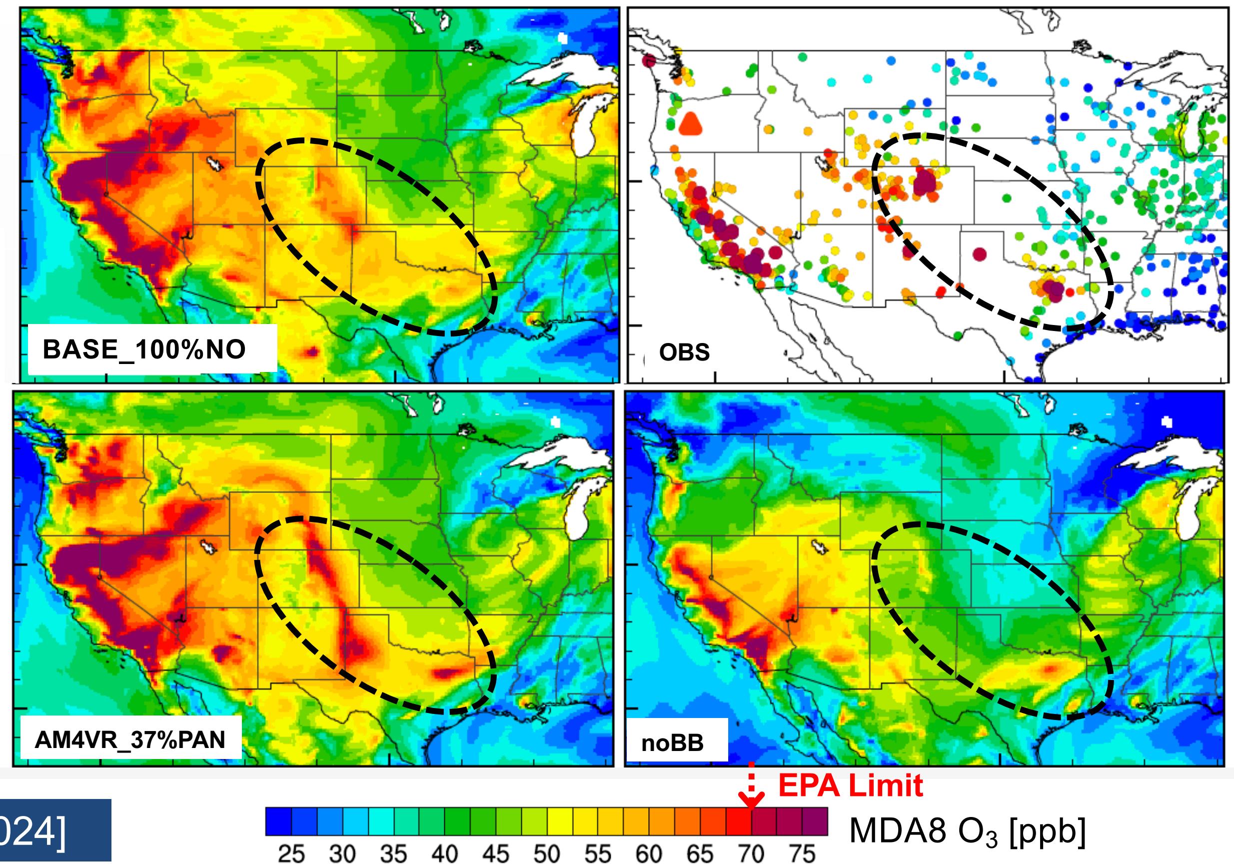
Thermal decomposition of PAN fuels downwind O_3 formation in aged smoke

Surface 24-h $PM_{2.5}$ ($\mu g/m^3$)



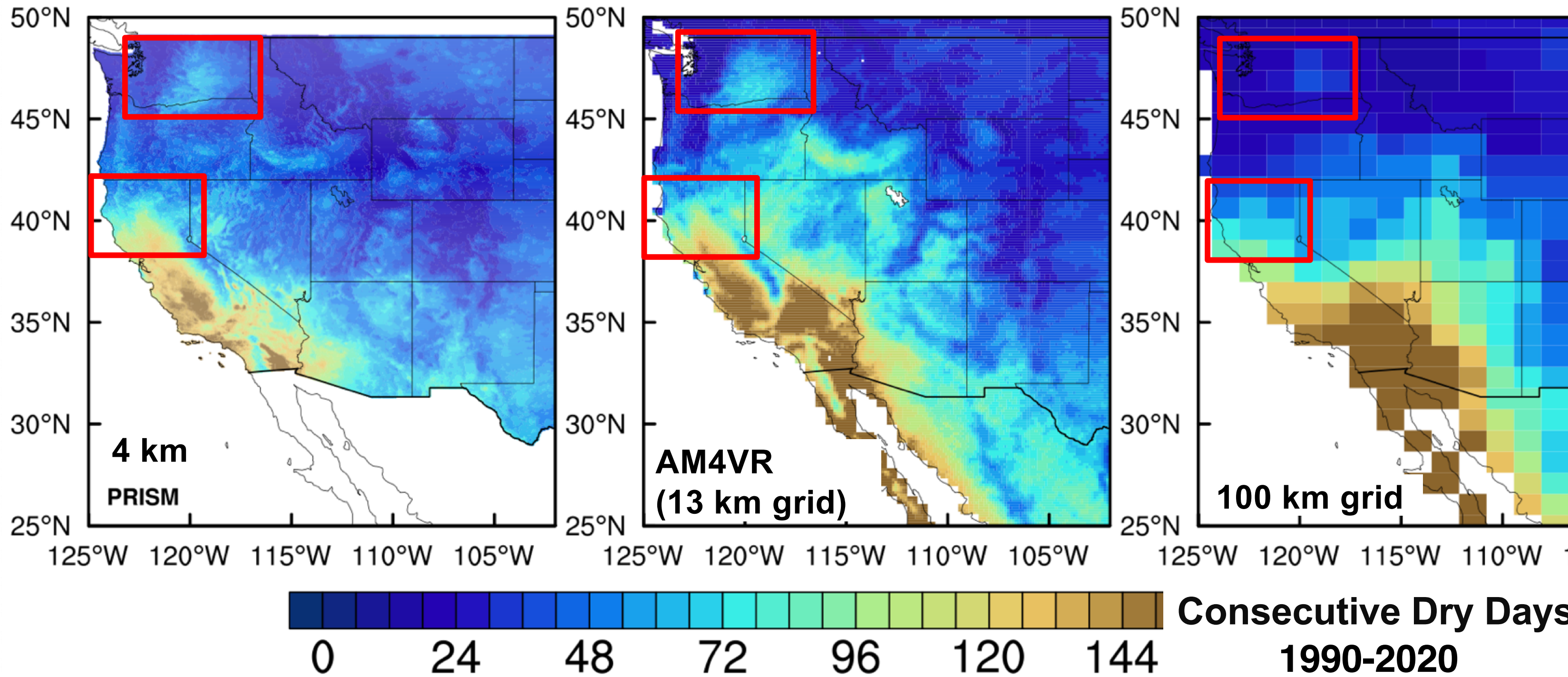
Observations (filled circles)

Surface daily max 8-h ozone on August 20, 2018



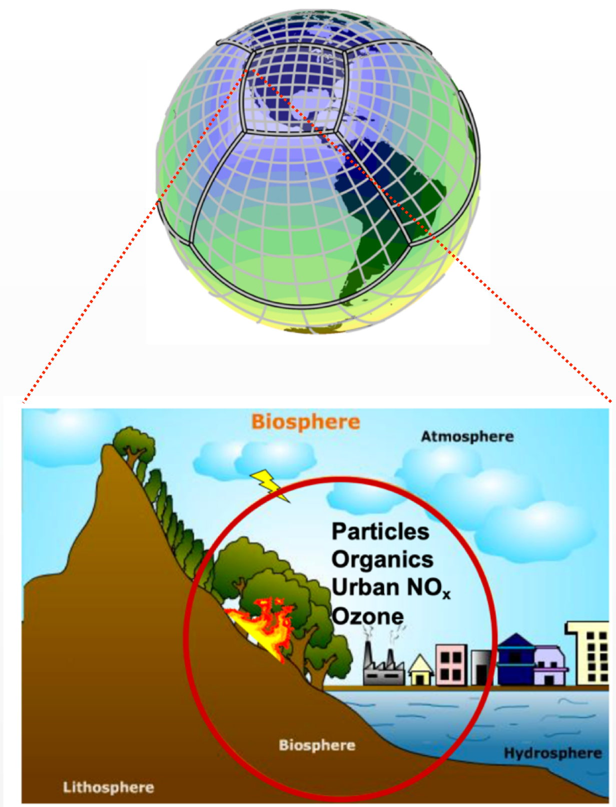
Lin M. et al. [submitted to GRL, 2024]

Towards prognostic daily wildfire emissions coupled to atmospheric chemistry: Improved representation of Western US snowpack and summer drought



Lin M. et al. [JAMES, 2024]

Towards seamless prediction of Earth system feedbacks on air quality extremes in a changing climate



Highlights:

- Increased interactivity of atmos. composition with biosphere
- Integrating global Earth System components within a seamless variable-resolution framework
- Improved representation of hydroclimate and AQ extremes

Applications:

- Develop seasonal air quality forecasting
- Multidecadal projections from global to urban scales
- Impact-oriented research

Future developments:

- Prognostic daily wildfire emissions coupled to atmos. chemistry
- Effects of agricultural irrigation
- Urban heat island effects

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