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Satellite-derived Constraints on the Effect of Drought Stress on Biogenic Isoprene Emissions in the Southeast US

Wei Li, Yuxuan Wang, Nan Lin

Department of Earth and Atmospheric Sciences

University of Houston

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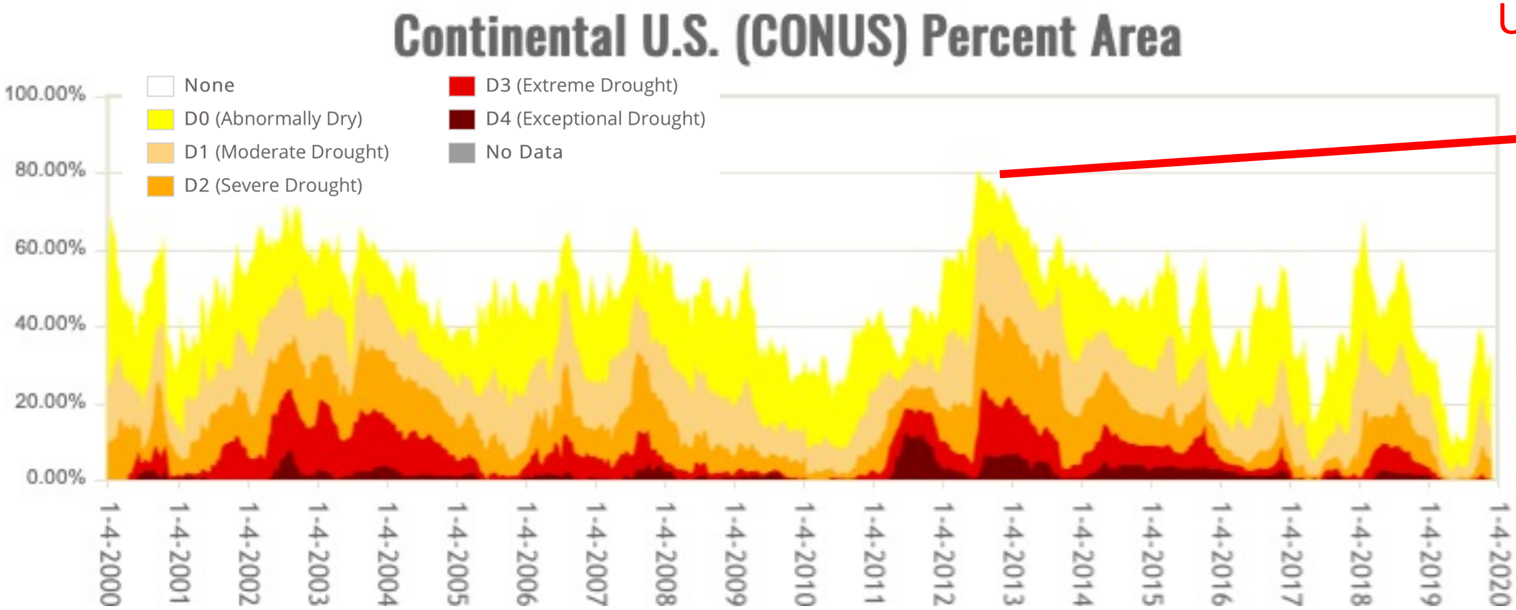
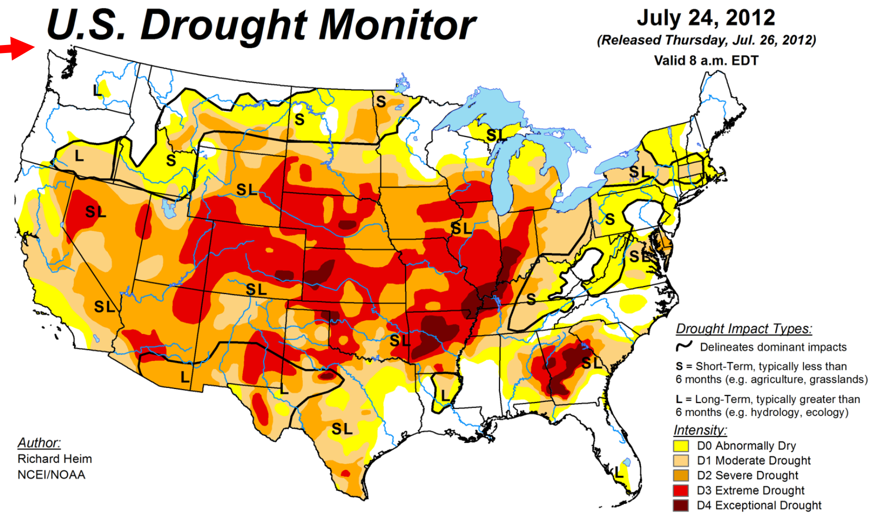
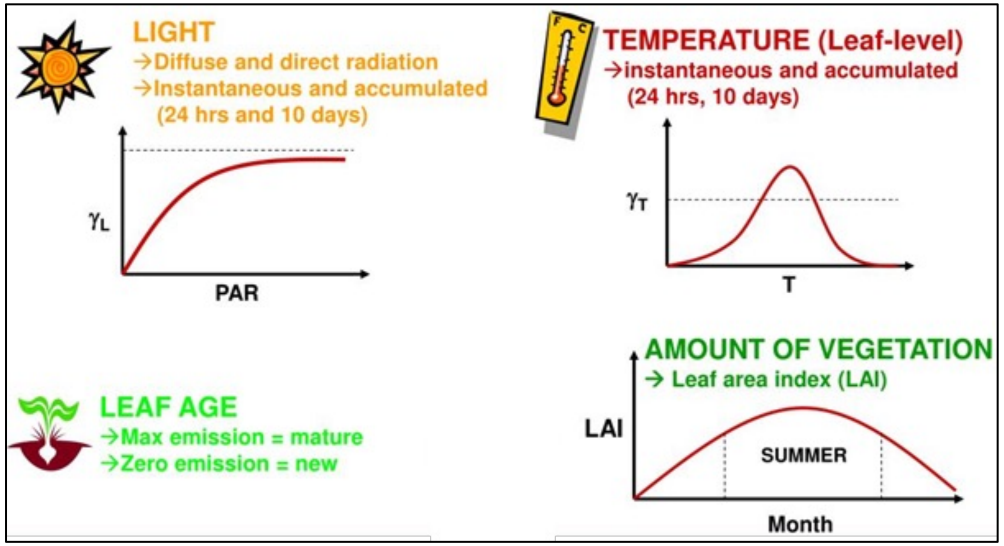
Drought is a common stress on BVOCs emissions in the continental U.S.



US Drought Monitor(USDM) on July 24, 2012



- •Drought occurs every year in the CONUS with different severity levels (e.g., D0-D4 in USDM).
- •Biogenic volatile organic compounds (BVOCs) play a key role in tropospheric chemistry; **isoprene accounts for ~70% of BVOCs, whose emissions depend on physiological status and environmental factors.**
- •These factors are subject to drought conditions (e.g., water deficit, high temperature), which **is not well constrained**.



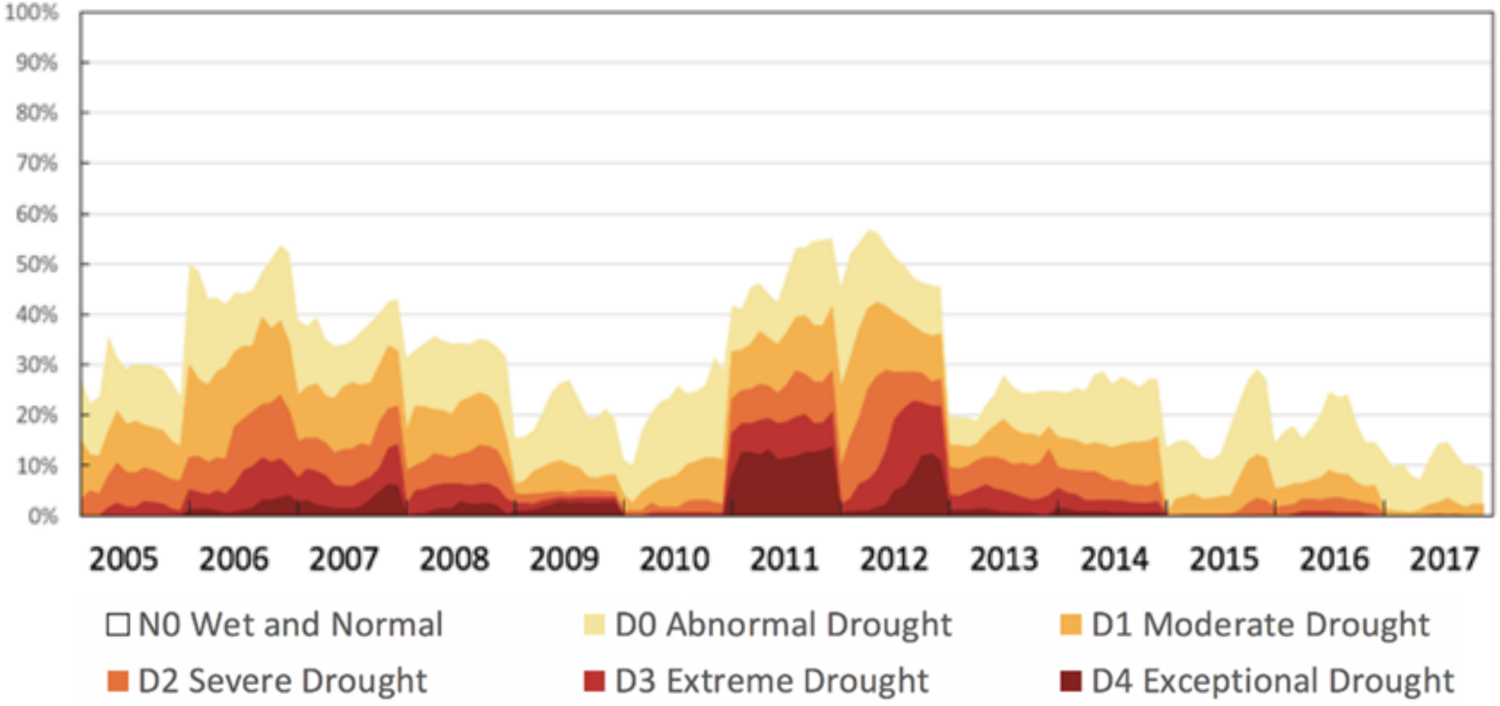
https://droughtmonitor.unl.edu/About/AbouttheData/DroughtClassification.aspx

Guenther et al., 2006

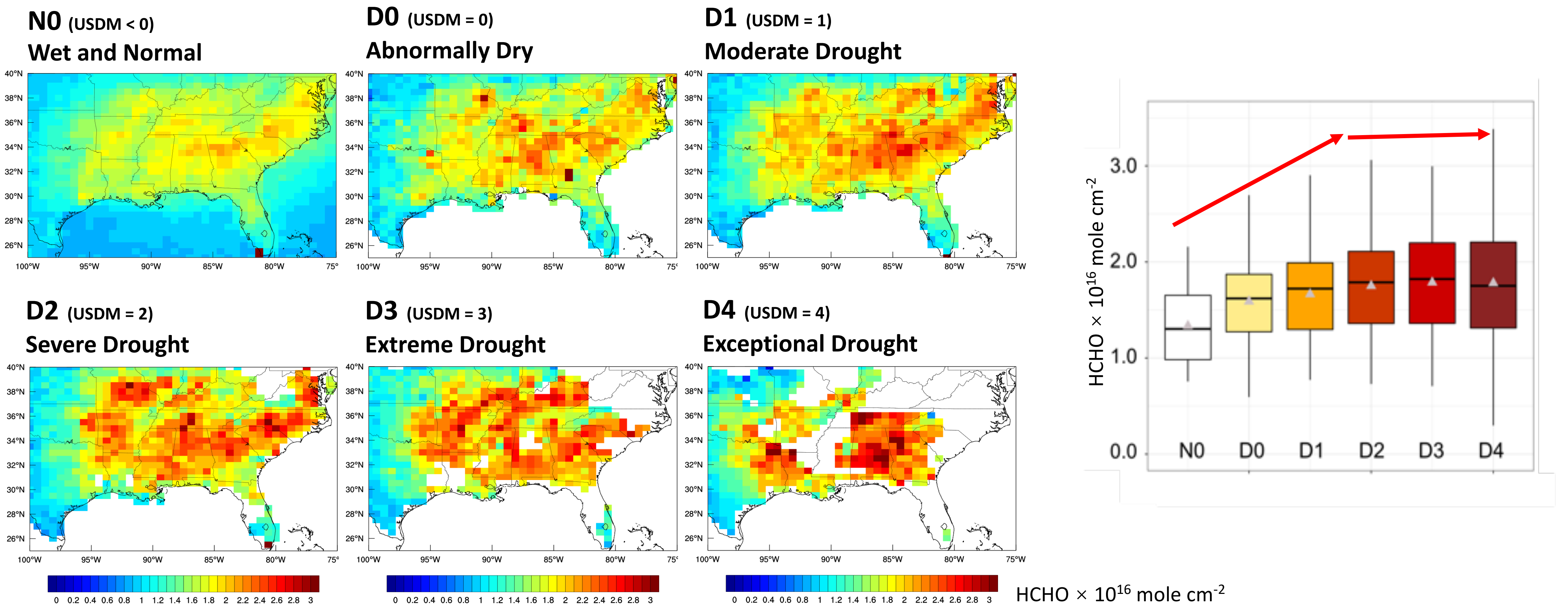
Derive long-term (2005-2017, JJA) constraints using OMI, GEOS-Chem and USDM in the SE US

- **OMI level 3 HCHO column** 0.1° x 0.1° (Chance, 2019); widely used as isoprene proxy (e.g., Kaiser et al., 2018); **scaled uniformly by 1.59** to match with aircraft measurements (Zhu et al., 2016).
- Nested-grid **GEOS-Chem v12.2.0** driven by MERRA2 at 0.5° × 0.625° with **MEGAN2.1 for BVOC** emissions (no soil moisture factor).
- OMI and GC HCHO columns are spatially and temporally matched onto **USDM categories (gridded onto 0.5° x 0.5°)** with **N0** representing normal conditions.

Time series of USDM weekly drought index in the SE US

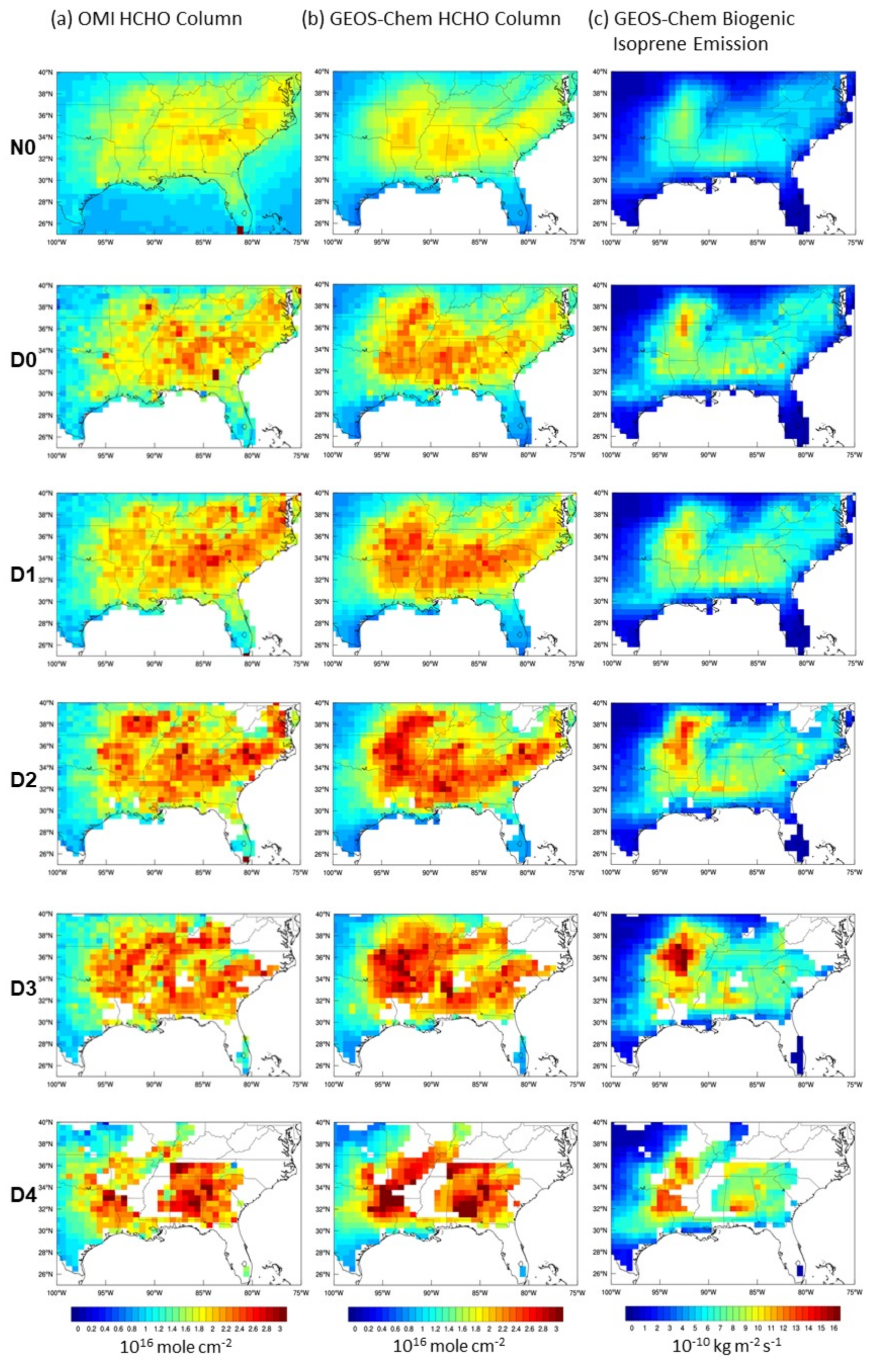


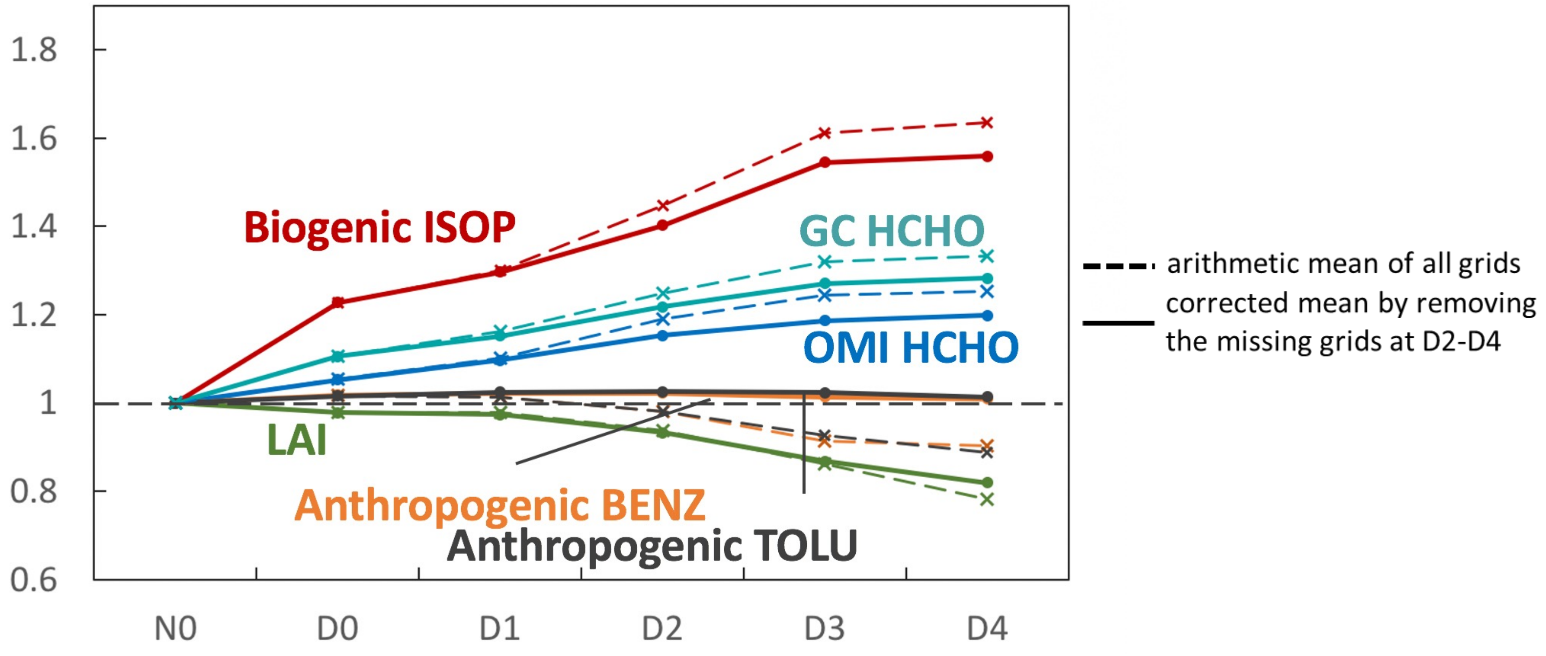
OMI HCHO columns mapped onto different drought levels



- OMI HCHO increases as drought intensity increases. HCHO under D0-D4 is 5.3%, 9.7%, 15.3%, 18.7% and 19.8% higher than the non-drought state (N0).
- The increase is not linear, peaking at D2 and flattening at D3 and D4

Modeled drought responses compared to OMI





- Model HCHO under D0-D4 is 10.5%, 15.7%, 21.7%, 25.8%, and 28.9% higher than the non-drought state (N0); these changes are **40-100% higher than that from OMI**.
- Modeled isoprene emissions are 22.7%, 29.6%, 40.3%, 54.5%, and 56.0% higher in D0-D4 than N0, which drive the increase of HCHO as drought intensifies.
- Model overestimates isoprene emissions under drought conditions and **a drought stress factor is needed in MEGAN 2.1**.

OMI-based drought stress algorithm using temperature and water stress

- We found GC overestimates HCHO sensitives to high temperatures (> 300 K) at D0-D4; consistent with observed evidence (Geron et al., 2016).
- The algorithm is to minimize the differences in HCHO column sensitivities to high temperatures between OMI and GC.
- Isoprene emission factor ($\gamma_{2.1}$) in MEGAGAN 2.1:

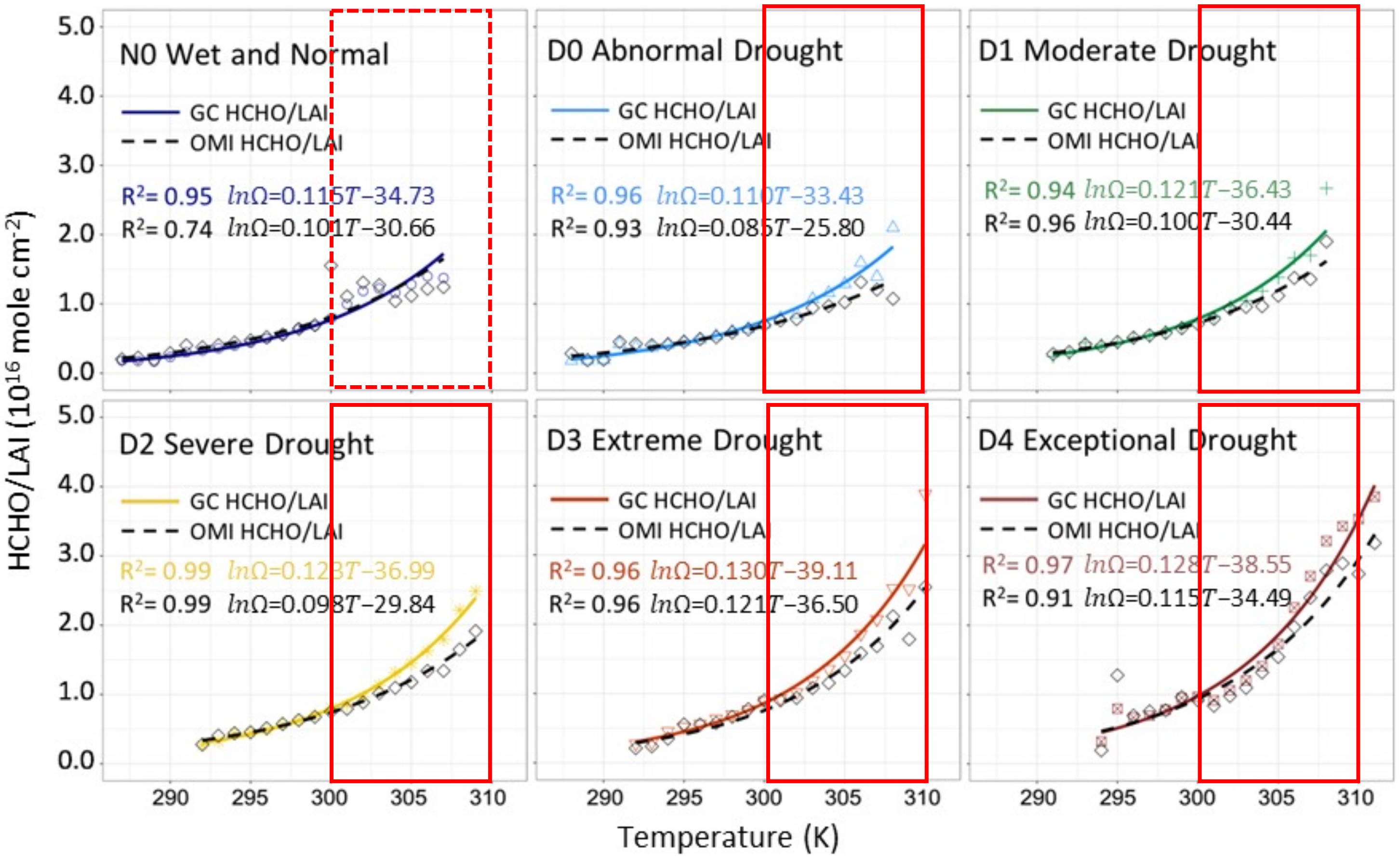
$$\gamma_{2.1} = C_{FAC}\gamma_{PAR}\gamma_{T}\gamma_{AGE}\gamma_{LAI}\gamma_{CO2}\gamma_{SM} = \gamma_0\, \gamma_{SM}$$

Replace $\boldsymbol{\gamma_{SM}}$ **=1** in $\gamma_{2.1}$ with a drought stress factor $\boldsymbol{\gamma_{d\_isoprene}}$:

$$\gamma_{d\_isoprene} = \frac{\Omega_{OMI}}{\Omega_{GC}} = \frac{e^{k_{OMI}T + b_{OMI}}}{e^{k_{GC}T + b_{GC}}} = e^{(k_{OMI} - k_{GC})T}\, e^{(b_{OMI} - b_{GC})}$$

Average (b_{OMI}-b_{GC}) and (k_{OMI}-k_{GC}) from D0 to D4 using fitted formulas

$$\gamma_{d\_isoprene} = \frac{\Omega_{OMI}}{\Omega_{GC}} = 383.38e^{-0.02T}$$



HCHO column to LAI ratio (Ω) to normalize the drought response

OMI-based drought stress algorithm using temperature and water stress

The final OMI-based isoprene drought stress factor $\boldsymbol{\gamma_{d\_OMI}}$:

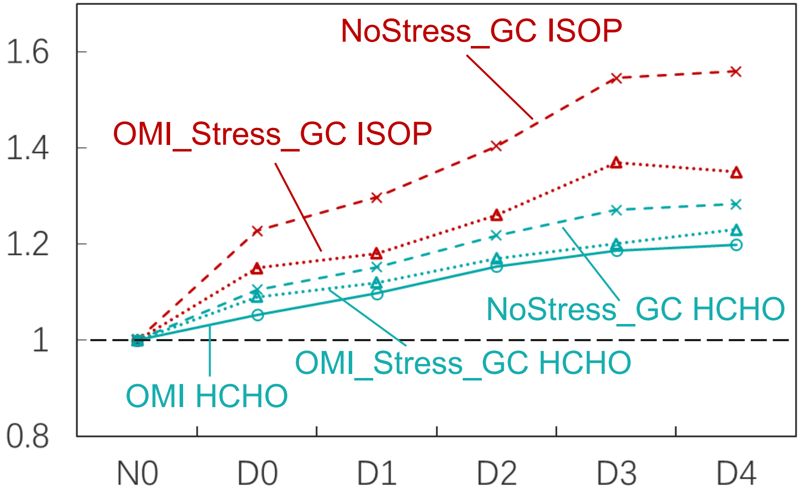
$$\gamma_{d\_OMI} = \gamma_0 \gamma_{d\_isoprene} \begin{cases} \gamma_{d\_isoprene} = 1 \ (\beta_t \geq 0.6 \text{ or } \mathrm{T} \leq 300\mathrm{K}) \\ \gamma_{d\_isoprene} = \dfrac{\Omega_{OMI}}{\Omega_{GC}} = 383.38e^{-0.02T} \ (\beta_t < 0.6, T > 300K) \end{cases}$$

The drought stress is triggerd when :

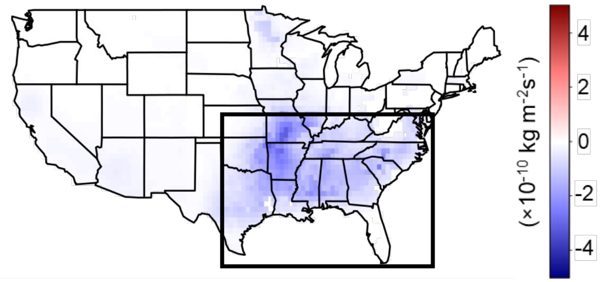
- **T > 300K:** when overestimation is found.
- **β_t (soil water stress; 0 ≤ βt ≤ 1) < 0.6**: 75% quantile under D0-D4 to capture most of the drought conditions.
- β_t is passed to MEGAN 2.1 from **the ecophysiology module** (Lam and Amos, 2019), which simulates photosynthesis rate and bulk stomatal conductance as an online component; the module uses soil parameters from the Hadley Centre Global Environment Model version 2 – Earth System Model (HadGEM2-ES).

Atmospheric compositions changes from the drought stress algorithm in SE US

Biogenic ISOP Emission & HCHO column

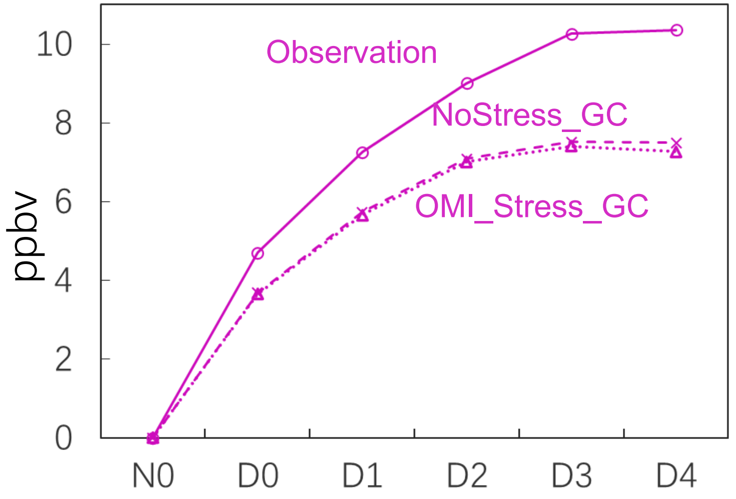


Biogenic ISOP OMI_Stress_GC - NoStress_GC **at D2**

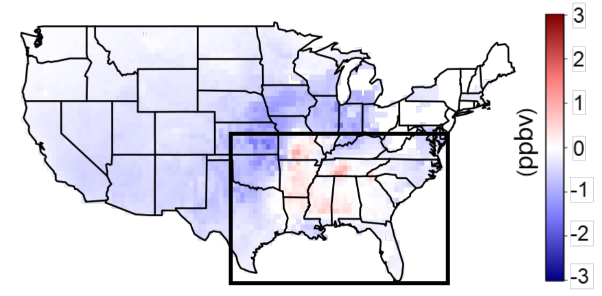


- ISOP emissions reduce by 9%-21%; **peak at D3 followed by a decrease at D4** consistent with observed non-linear changes.
- Stressed HCHO column has a better agreement with OMI than non-stressed GC.

MDA8 O_3

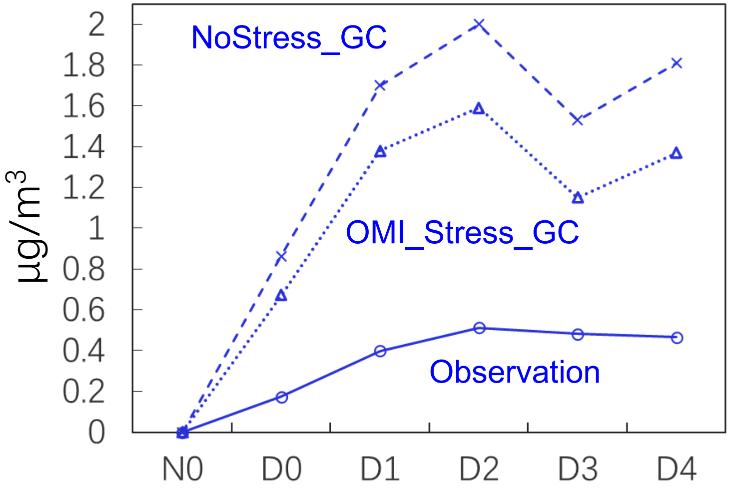


OMI_Stress_GC - NoStress_GC **at D2**

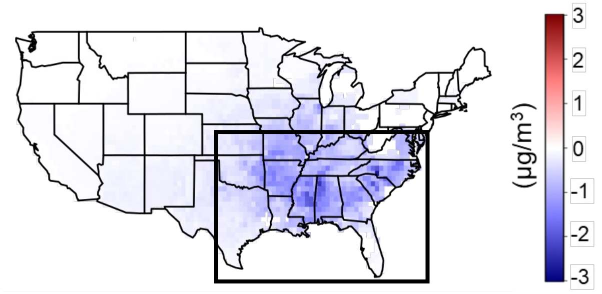


- Observed MDA8 O_3 increases by 11%-25% (Li et al., JGR, 2022); **GC underestimates such increments**.
- Overall small changes due to the O_3 increase over low-NO_x regions.

Organic Aerosol (OA)



OMI_Stress_GC - NoStress_GC **at D2**



- Observed OA increases by 4%-15% **peaking at D2**; GC overpredicts such increments by more than 50%.
- The **drought stress reduces such high bias by 7%-12%.**

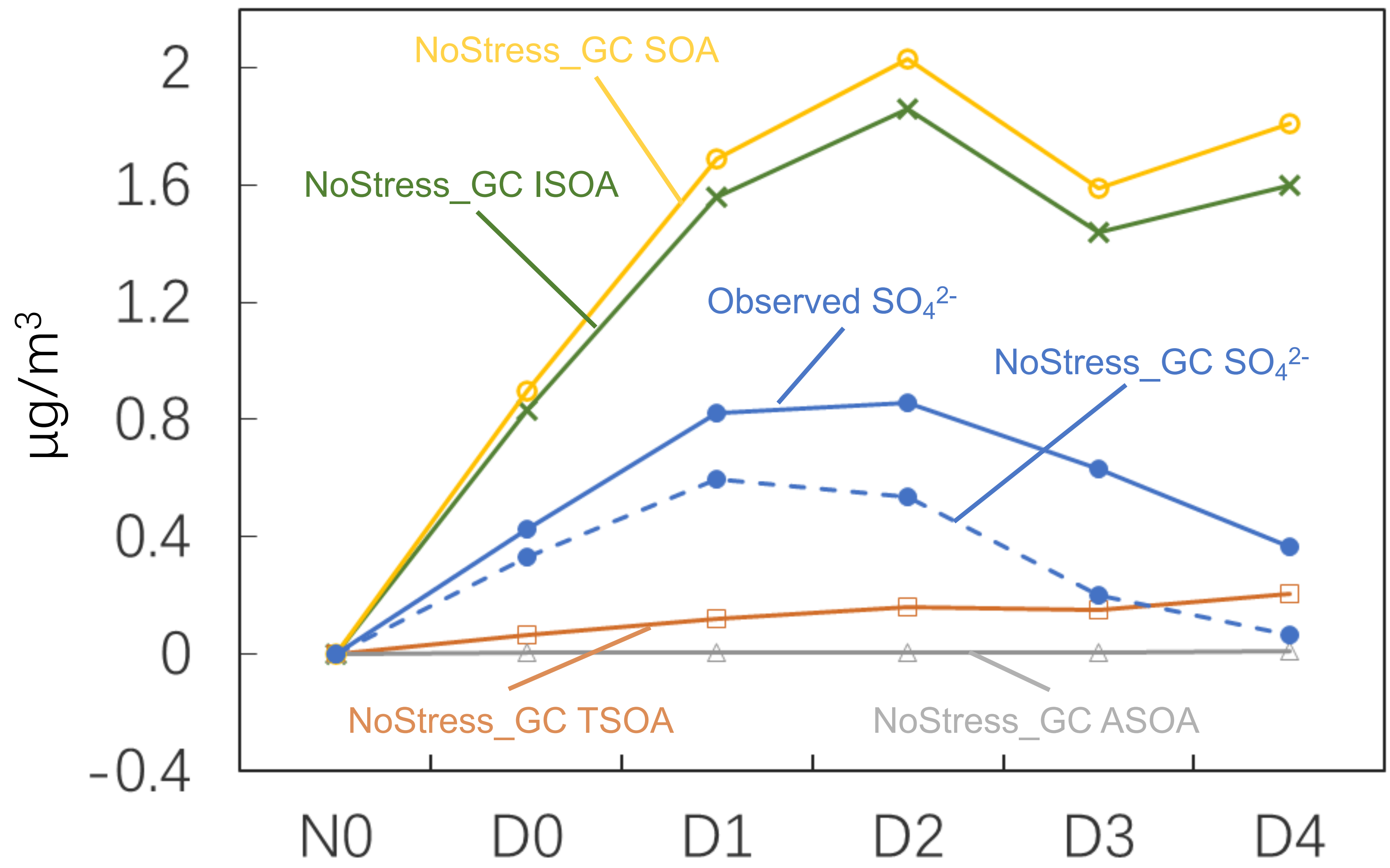
Conclusions and References

Conclusions:

- OMI HCHO column is found to be 5.3% (mild drought) - 19.8% (severe drought) higher than that under no-drought conditions; GEOS-Chem simulated increases are 1.4-2.0 times higher.
- We derived a top-down drought stress factor (γ_{d_OMI}) in GEOS-Chem that parameterizes using water stress and temperature. The factor led to an 8.6% (mild drought) - 20.7% (severe drought) reduction in isoprene emissions in the SE US, thus improving the simulation of HCHO, O_3 and OA response to drought.
- This study demonstrates the unique values of exploiting long-term satellite observations to develop empirical stress algorithms on biogenic emissions where in situ flux measurements are limited.

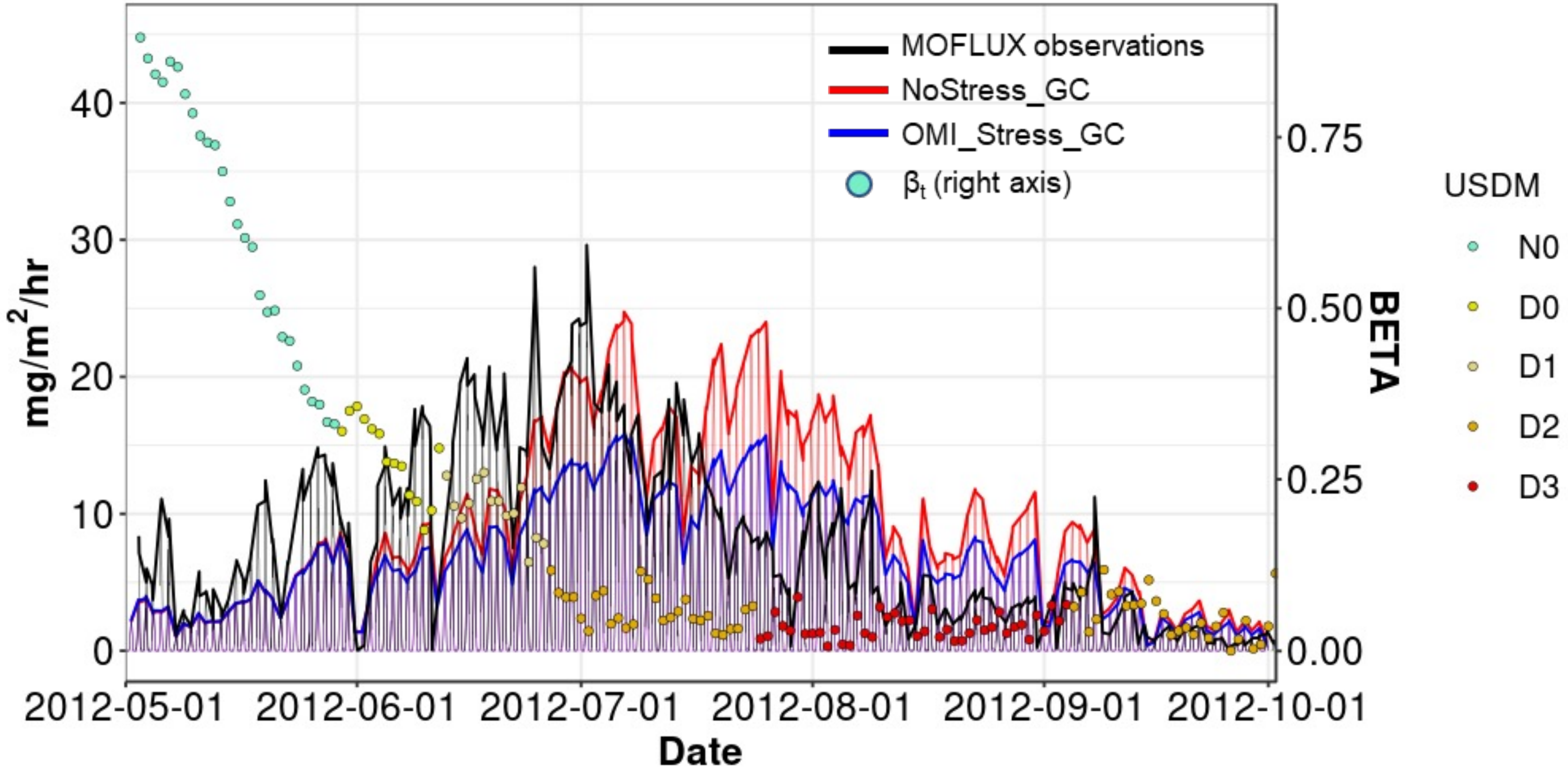
References:

- Wang Yuxuan, Nan Lin, Wei Li, Alex, Guenther, Joey C. Y. Lam, Amos P. K. Tai, Mark J. Potosnak & Roger Seco (2022). **Satellite-derived Constraints on the Effect of Drought Stress on Biogenic Isoprene Emissions in the Southeast US**. EGUsphere [preprint].
- Li Wei, Wang Yuxuan, Flynn, J., Griffin, R. J., Guo, F., & Schnell, J. L. (2022). Spatial variation of surface O3 responses to drought over the contiguous United States during summertime: role of precursor emissions and ozone chemistry. *Journal of Geophysical Research: Atmospheres*, e2021JD035607.



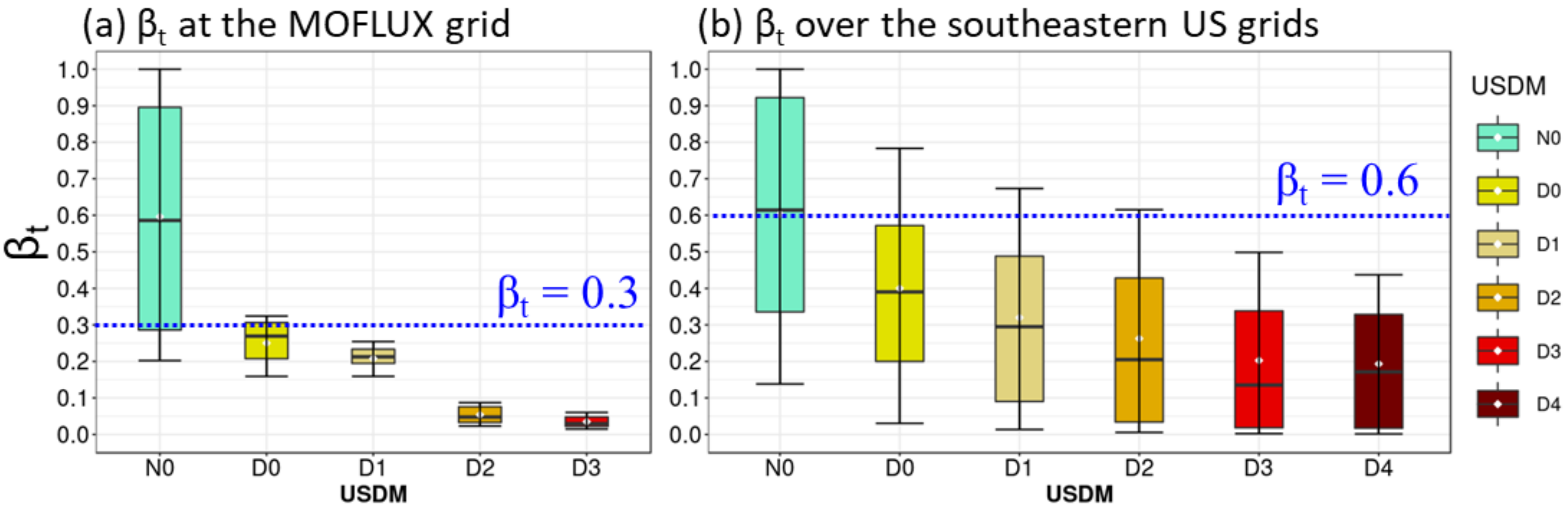
NoStress_GC SOA
NoStress_GC ISOA
Observed SO_4^{2-}
NoStress_GC SO_4^{2-}
NoStress_GC TSOA
NoStress_GC ASOA
μg/m3
2
1.6
1.2
0.8
0.4
0
-0.4
N0
D0
D1
D2
D3
D4

Comparison with the MOFLUX observations in 2012 May-Sep.



Mean bias: 2.05	γ_{d_OMI} →	Mean bias: 0.20
IOA: 0.80		IOA: 0.89
R:0.77**		R:0.80**

βt (soil water stress) distributions by USDM levels

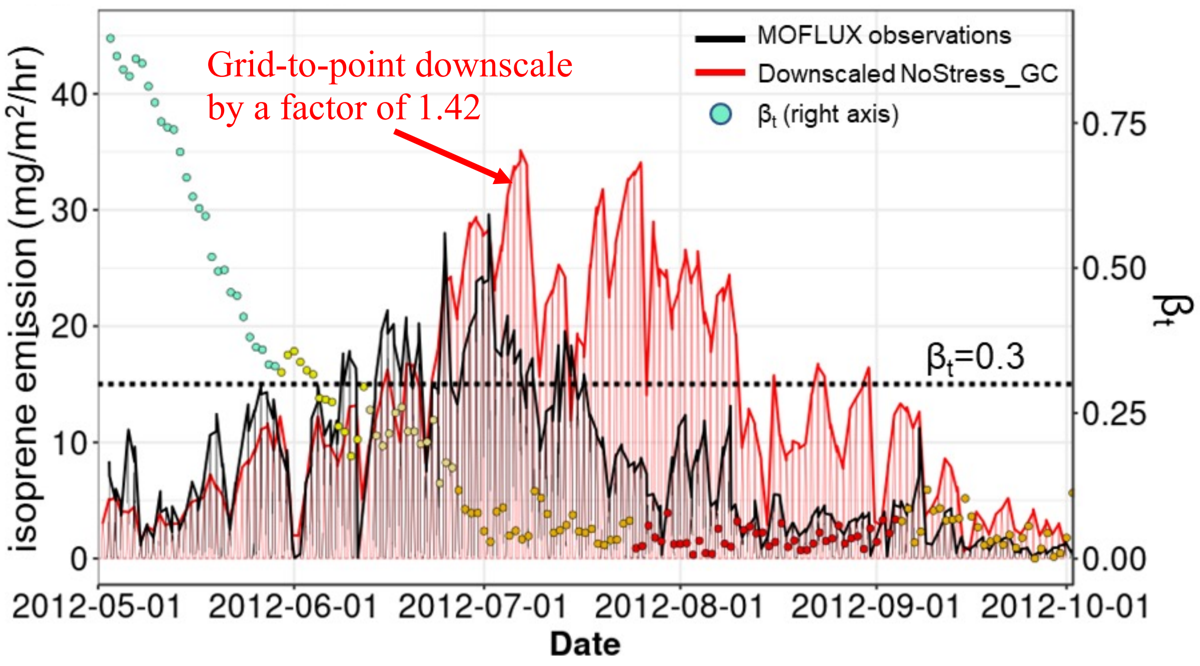


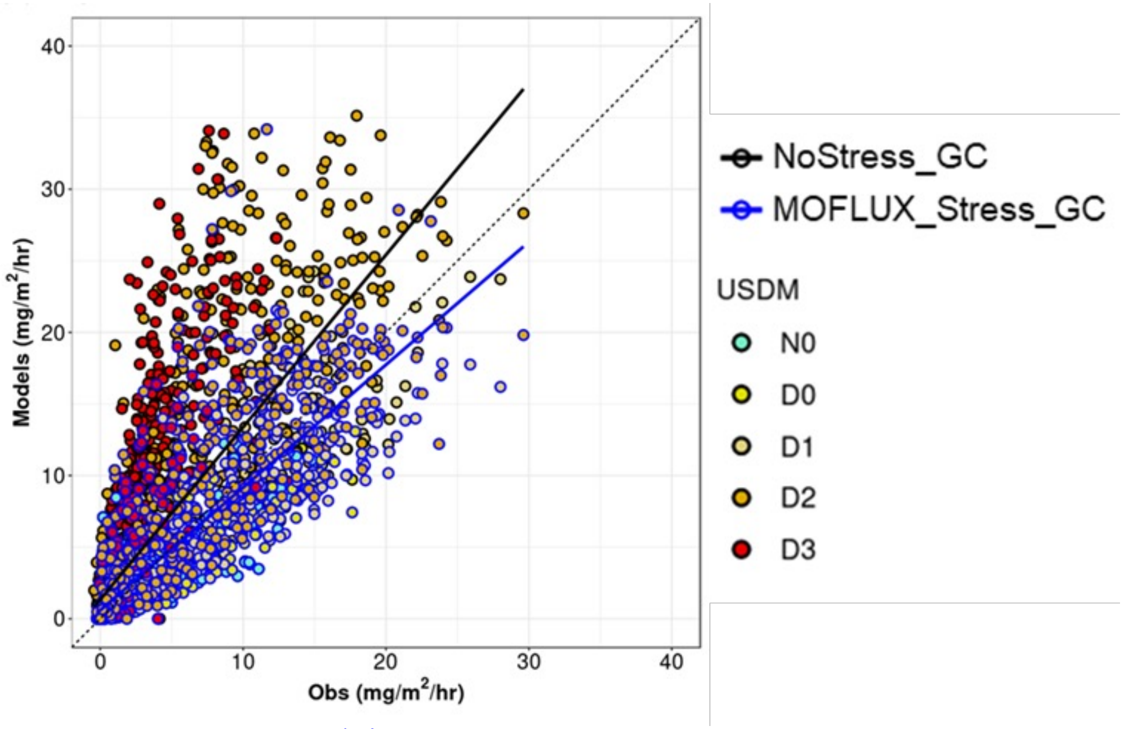
MOFLUX-based drought stress algorithm using the ecophysiology module

Based on May-Sep 2012 following Jiang et al., (2018):

$$\gamma_{d\_MOFLUX} = \gamma_0 \gamma_{d\_isoprene} \begin{cases} \gamma_{d\_isoprene} = 1 \ (\beta_t \geq 0.3) \\ \gamma_{d\_isoprene} = V_{cmax}/\alpha \ (\beta_t < 0.3, \alpha = 77) \end{cases}$$

- **V_{cmax} (maximum carboxylation rate)**: indicates ability of plant to convert CO_2 into carbon substrates for BVOC production.
- **βt** < 0.3: 75% quantile under D0-D3 at a single grid
- **α:** empirical value when minimum mean bias is reached.





Mean bias: 2.05
IOA: 0.85
R:0.77**

γ_{d_MOFLUX} →

Mean bias: 0.01
IOA: 0.93
R:0.80**

MOFLUX-based drought stress algorithm using an ecophysiology module

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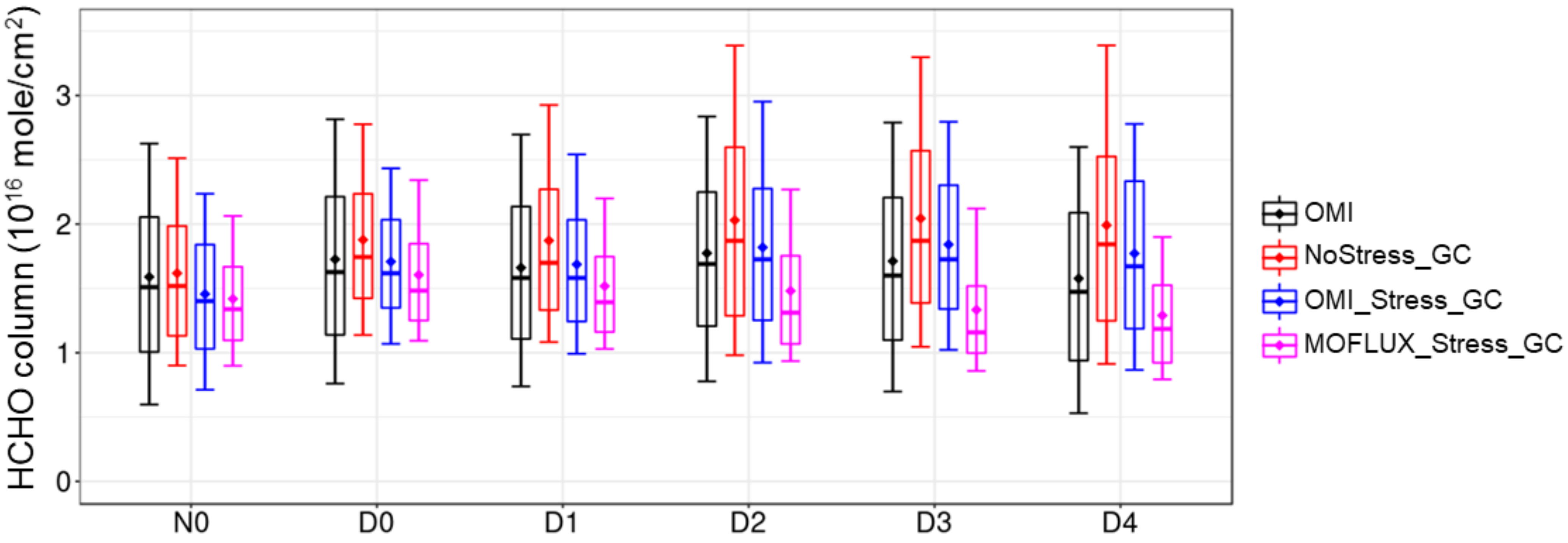

γ_{d_OMI} outperforms γ_{d_MOFLUX} over the SE US in JJA 2012