# Constituent data assimilation plans of the GMAO at NASA Goddard

**Brad Weir** (Morgan State & NASA GMAO) <brad.weir@nasa.gov>
*Responsible for controversial views, mistakes, and bad ideas*

N Balashov, S Basu, S Cohn, B Karpowicz, C Keller, K E Knowland, L Ott, S Pawson, V Shah, R Todling, P Wales, and K Wargan

*Aerosols (barely included):* Arlindo, V Buchard, A Collow, P Castellanos

Banff, 20th March 2023

# Historical digression


Nonlin. Processes Geophys., 20, 1047–1060, 2013
www.nonlin-processes-geophys.net/20/1047/2013/
doi:10.5194/npg-20-1047-2013


Nonlinear Processes in Geophysics
Open Access

## A potential implicit particle method for high-dimensional systems

**B. Weir, R. N. Miller, and Y. H. Spitz**

College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA

*Correspondence to:* B. Weir (bweir@oce.orst.edu)

Received: 9 May 2013 – Revised: 9 September 2013 – Accepted: 21 October 2013 – Published: 28 November 2013

# R21C-Chem

- NASA's first "all-atmosphere" chemical reanalysis
- Roughly: Retrospective GEOS CF w/ constituent assimilation (CoDAS)

- Meteorology: GEOS GCM replayed to reanalysis (maybe R21C)
- Resolution: 25km horiz., 72 eta levels to 0.01 hPa; 12km DAS and 3km sim capabilities for carbon
- Chemistry: GEOS-Chem
- Aerosols: AOD assimilation as before (GAAS), coupling TBD

# CoDAS (Constituent Data Assimilation System)

- Generalization of legacy $O_3$ state estimation from NWP systems
- Tracer agnostic: Assimilates any point sample (MLS) or averaging kernel obs (TROPOMI/OCO) of any trace gas
- Available to the public as part of GEOS ADAS: https://github.com/GEOS-ESM/GEOSadas
- Whatever Ens/Var/Hybrid combo you like
- Backbone of several existing and upcoming products

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2020JD033335

**The Anomalous 2019 Antarctic Ozone Hole in the GEOS Constituent Data Assimilation System With MLS Observations**

Krzysztof Wargan[1,2], Brad Weir[3,2], Gloria L. Manney[4,5], Stephen E. Cohn[2], and Nathaniel J. Livesey[6]

[1]Science Systems and Applications, Inc., Lanham, MD, USA, [2]Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [3]Universities Space Research Association, Columbia, MD, USA, [4]NorthWest Research Associates, Socorro, NM, USA, [5]Department of Physics, New Mexico Institute of Mining and Technology, Socorro, NM, USA, [6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Key Points:
- The 2019 ozone hole area was about $10 \times 10^6$ km$^2$ or less, compared to over $20 \times 10^6$ km$^2$ typical for Septembers 2005–2018
- The anomalously high Antarctic total ozone resulted from an unusual polar vortex size and geometry rather than from chemistry
- Even a minor sudden stratospheric warming in the Southern Hemisphere can have a big impact

SCIENCE ADVANCES | RESEARCH ARTICLE

CORONAVIRUS

**Regional impacts of COVID-19 on carbon dioxide detected worldwide from space**

Brad Weir[1,2]*, David Crisp[3], Christopher W. O'Dell[4], Sourish Basu[2,5], Abhishek Chatterjee[1,2], Jana Kolassa[2,6], Tomohiro Oda[1,2,7,8,9], Steven Pawson[2], Benjamin Poulter[10], Zhen Zhang[11], Philippe Ciais[12], Steven J. Davis[13], Zhu Liu[14], Lesley E. Ott[2]



Activity reductions in early 2020 due to the coronavirus disease 2019 pandemic led to unprecedented decreases in carbon dioxide ($CO_2$) emissions. Despite their record size, the resulting atmospheric signals are smaller than and obscured by climate variability in atmospheric transport and biospheric fluxes, notably that related to the

Earth and Space Science

RESEARCH ARTICLE
10.1029/2022EA002632

**M2-SCREAM: A Stratospheric Composition Reanalysis of Aura MLS Data With MERRA-2 Transport**

Krzysztof Wargan[1,2], Brad Weir[2,3,4], Gloria L. Manney[5,6], Stephen E. Cohn[2], K. Emma Knowland[2,3,4], Pamela A. Wales[2,3,4], and Nathaniel J. Livesey[7]

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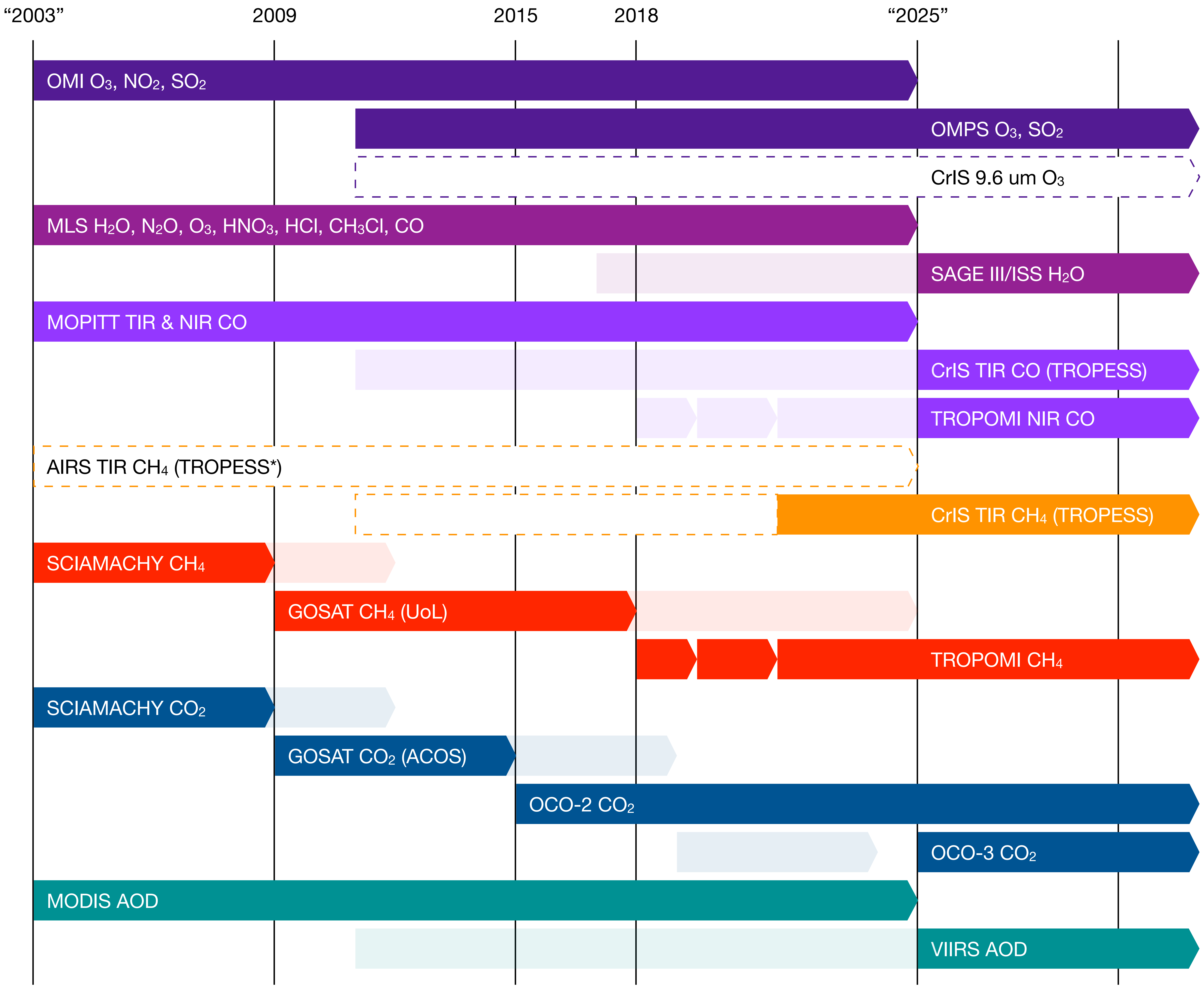
Key Points:
- A new composition reanalysis of the stratosphere is introduced
- Microwave Limb Sounder ozone, $H_2O$, $HNO_3$, HCl, and $N_2O$ are assimilated for 2004–2021 and will be extended to the present
- The reanalysis is useful for studies of chemical and transport variability on time scales from hours to decades

# R21C-Chem: Heritage

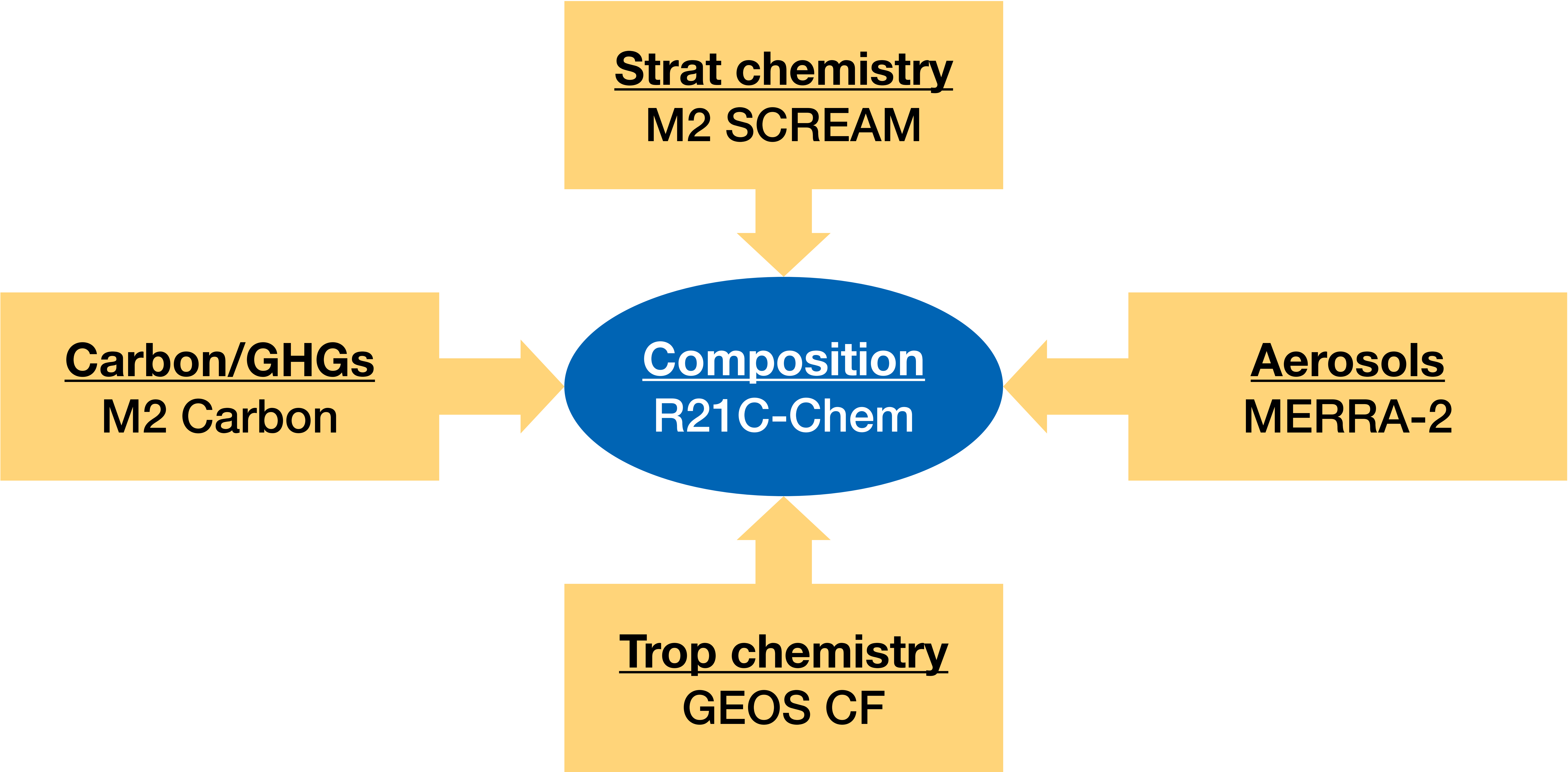
- Previously
  - MERRA-2 met: Strat ozone, **trop** water vapor ($H_2O$), and aerosols
  - M2 Carbon: $CO_2$, $CH_4$, CO
  - M2 SCREAM strat: **Strat** $H_2O$, $N_2O$, $HNO_3$, HCl, CO, $CH_3Cl$
  - GEOS CF trop: $NO_2$, $SO_2$, 9.6 um $O_3$
- R21C-Chem: Everything together in one system




Light shading: Overlap used for tuning & bias correction
Dashed borders: Contingent/TBD

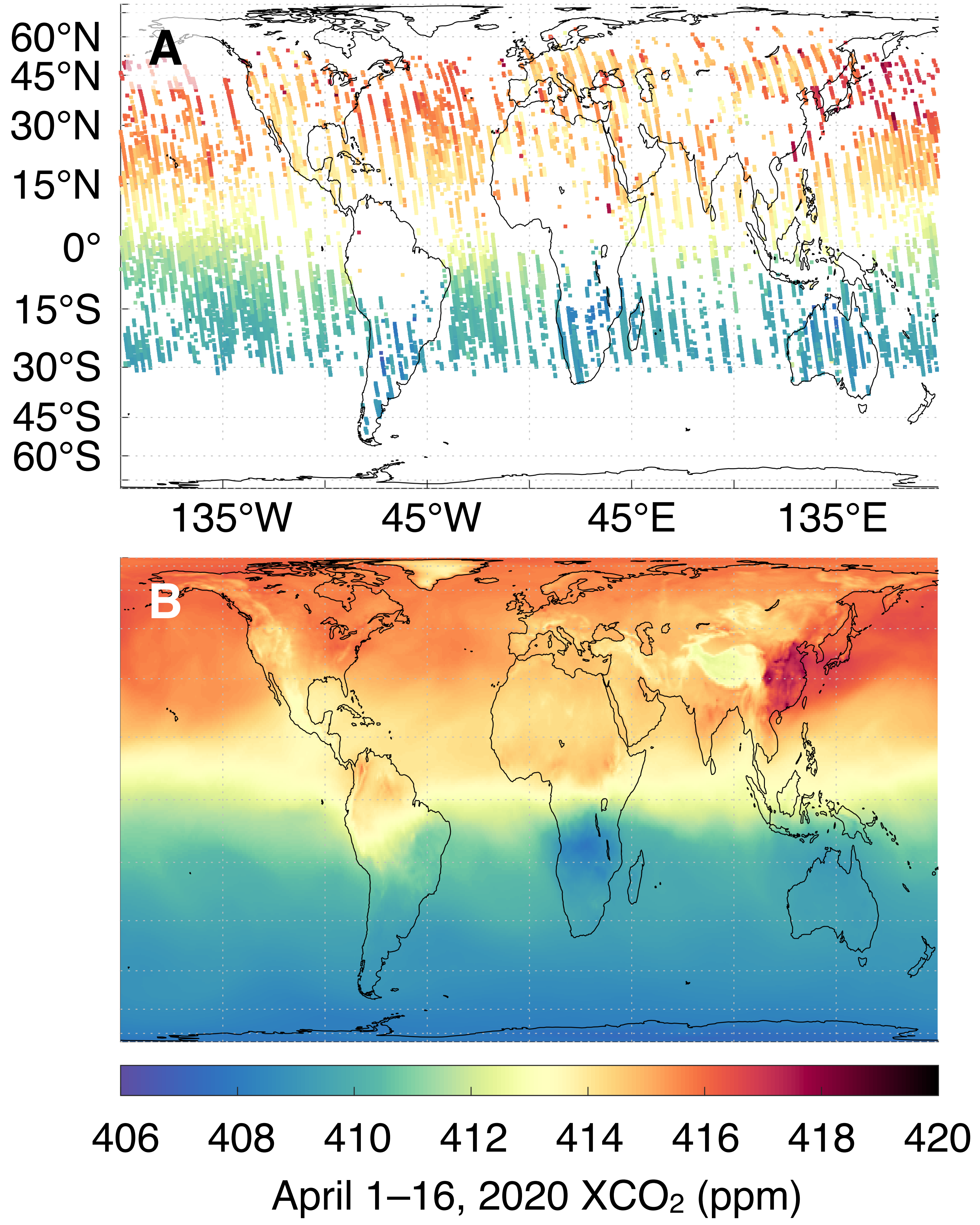
* Unprocessed to date, will use if available

# R21C-Chem: Putting it all together

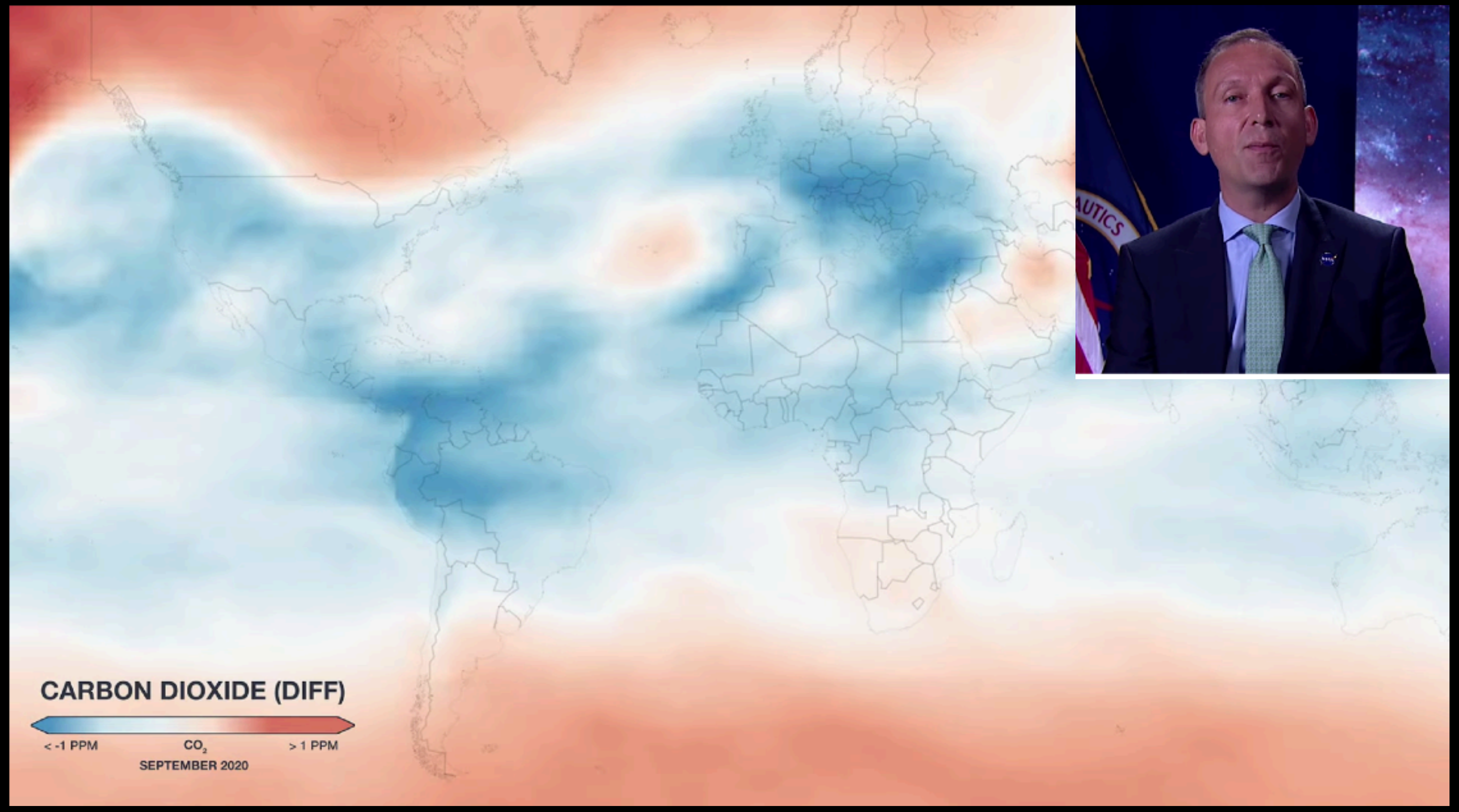


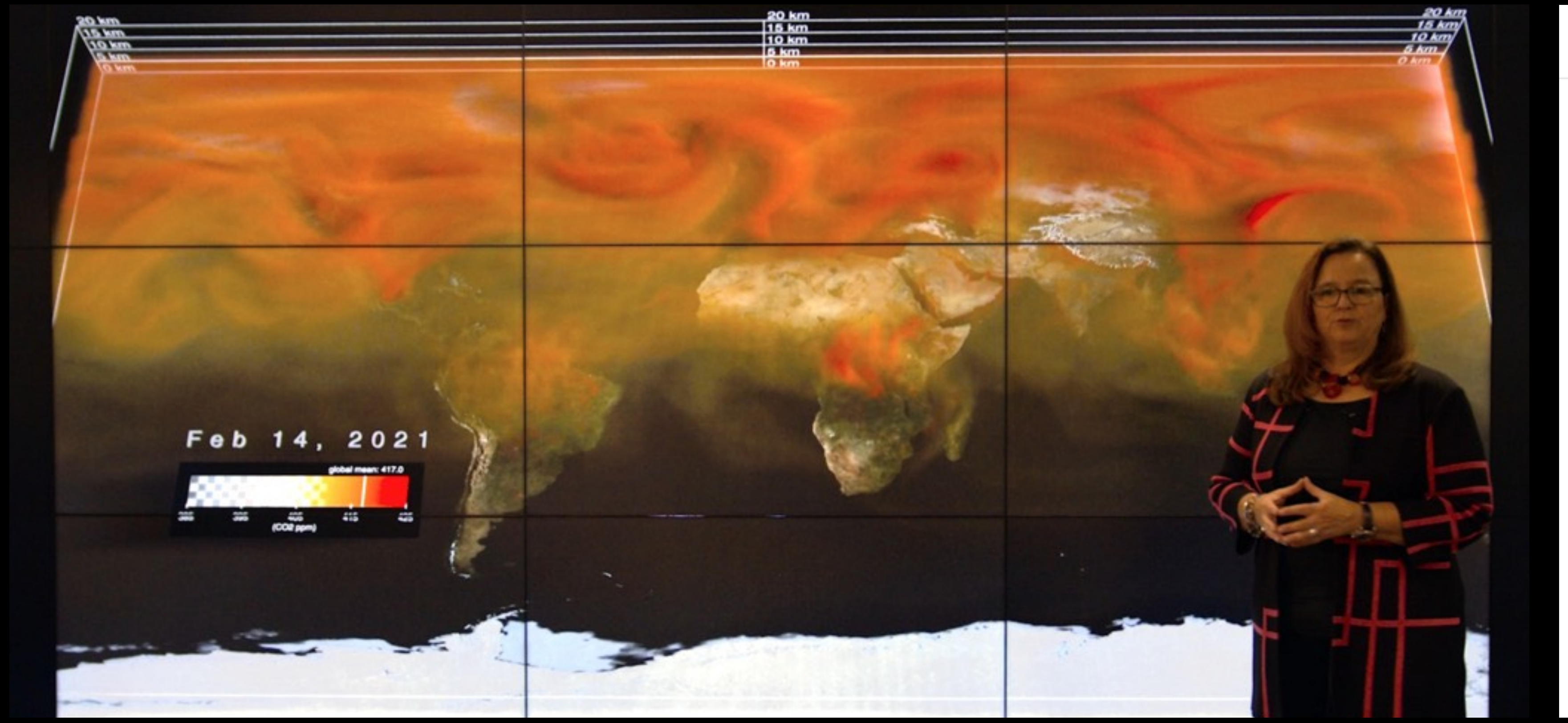
# Carbon assimilation

- Assimilate satellite column $CO_2$, $CH_4$, and CO obs to produce time-varying, 3D fields (M2CC)
- 50km replay to MERRA-2 met, 12km run in progress
- Observationally-informed flux package (e.g. night lights, NDVI, FRP, surface growth rate)
- $CO_2$ is OCO-2 L3 product (OCO-2/GEOS) available on GES DISC & visualizations at https://fluid.nccs.nasa.gov/carbon
- … still doing flux inversions (Sourish)



# Supporting climate action




The New York Times

## *Satellites Could Help Track if Nations Keep Their Carbon Pledges*

Scientists used satellite measurements of carbon dioxide to detect small atmospheric reductions over areas under coronavirus lockdowns. The approach could help track emissions more quickly in the future.

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Al Gore, COP27

SCIENCE ADVANCES | RESEARCH ARTICLE

CORONAVIRUS

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20 June 2022

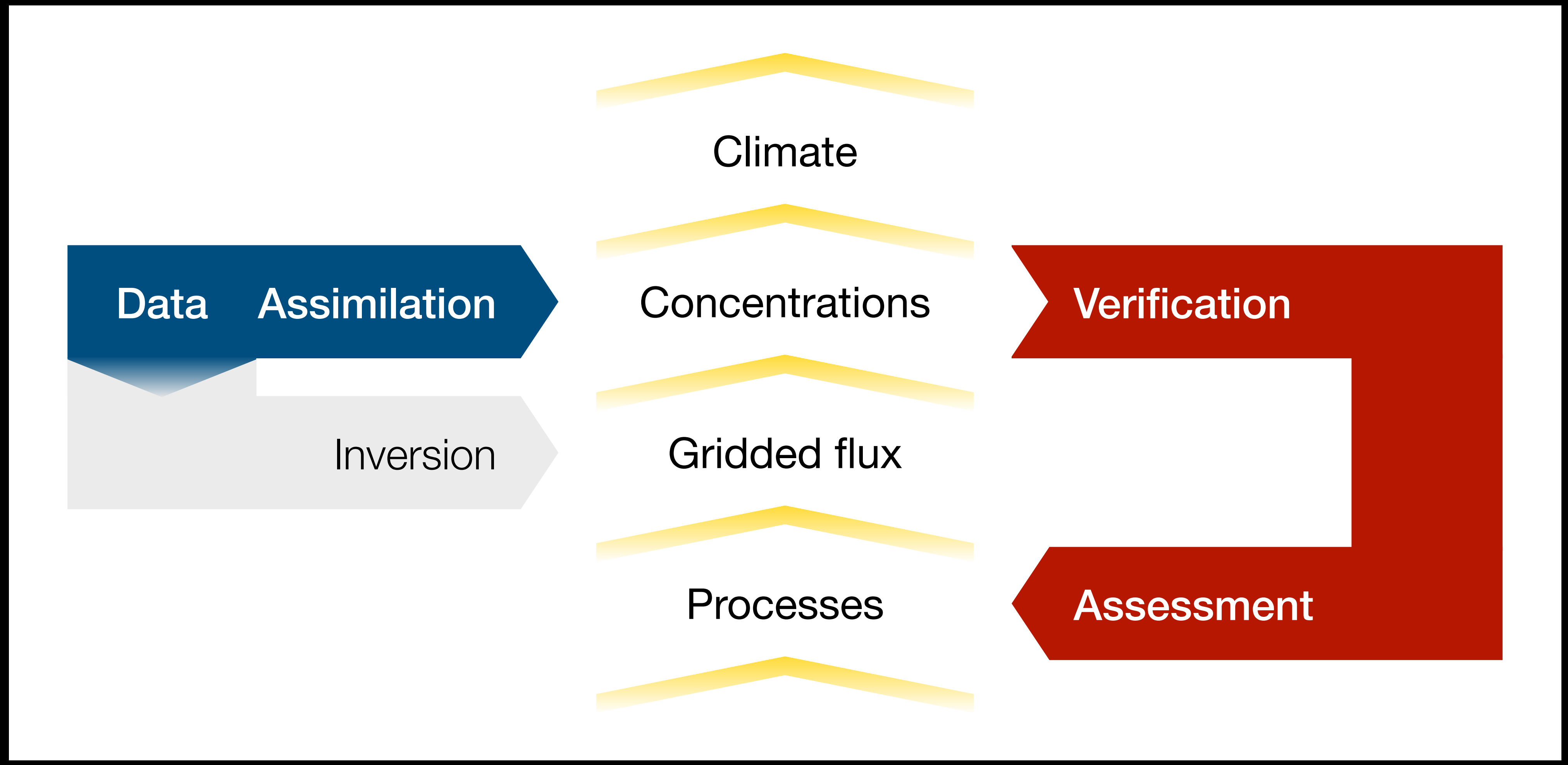
PERSPECTIVE

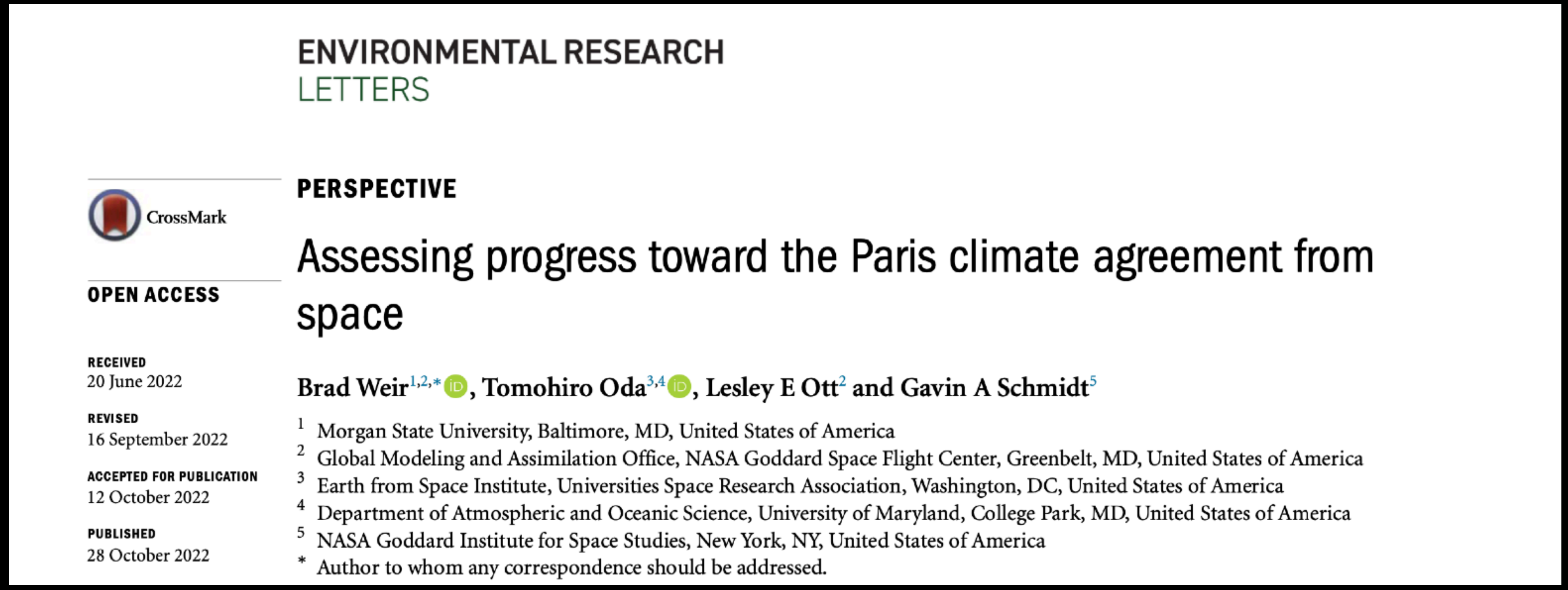
## Assessing progress toward the Paris climate agreement from space

Brad Weir[1,2,*], Tomohiro Oda[3,4], Lesley E Ott[2] and Gavin A Schmidt[5]

# Processes and concentrations

- Fluxes are unverifiable except within a few km of a few hundred sites
- Indirect verification thru concentrations
- "Priors" already skillful and data constrained
- Fluxes don't matter: processes do (e.g., "soil vs trees")
- Knowing exact fluxes everywhere is only halfway toward mitigation goals (how)
- Assess processes w/ concentrations
- Increase resolution

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12 October 2022

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28 October 2022

PERSPECTIVE

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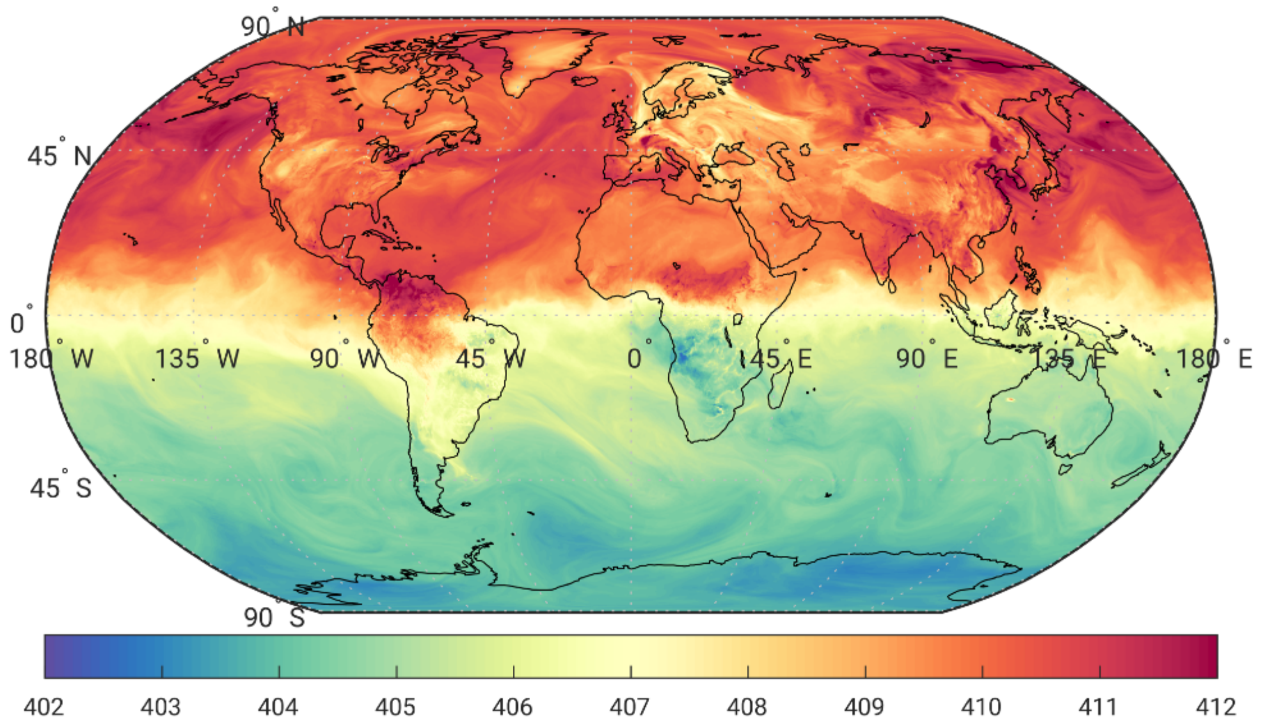
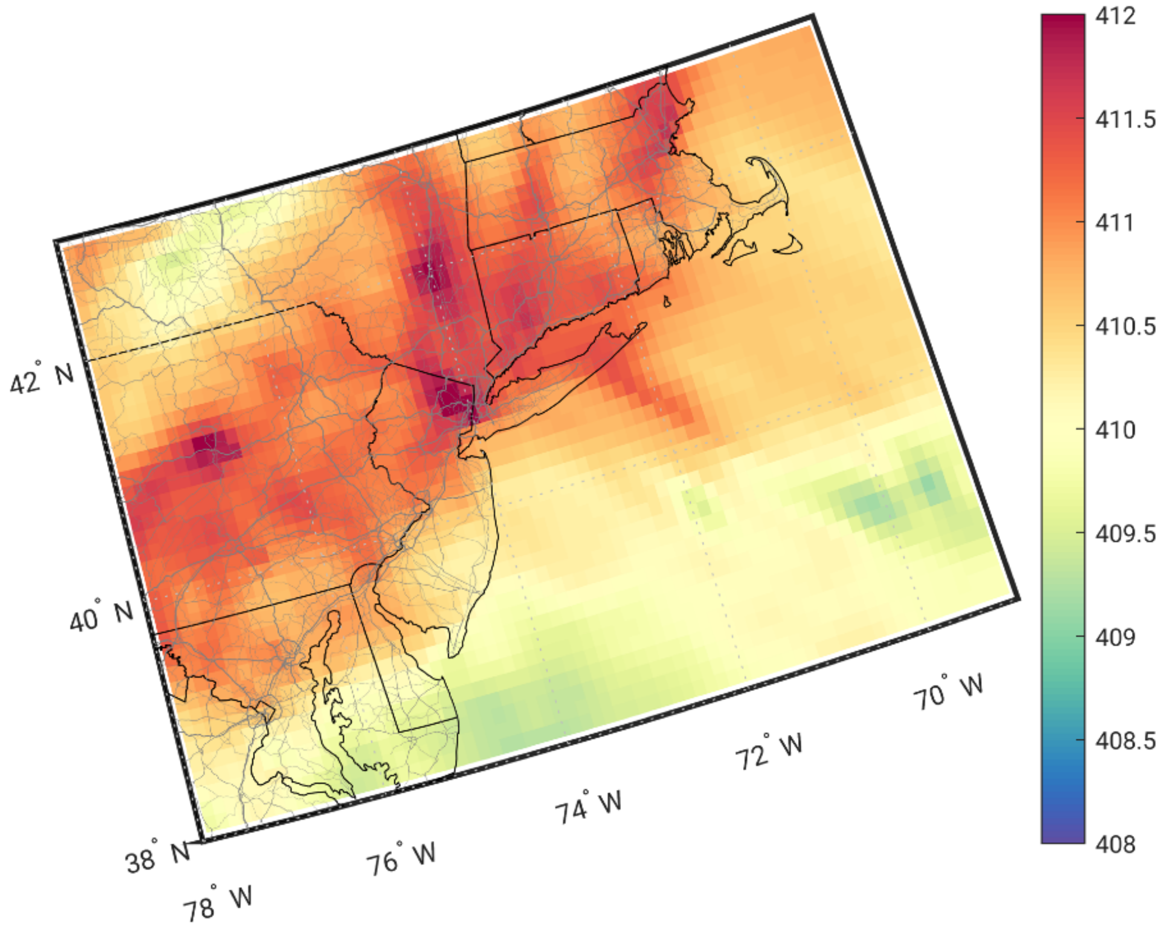
[3] Earth from Space Institute, Universities Space Research Association, Washington, DC, United States of America
[4] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, United States of America
[5] NASA Goddard Institute for Space Studies, New York, NY, United States of America
[*] Author to whom any correspondence should be addressed.

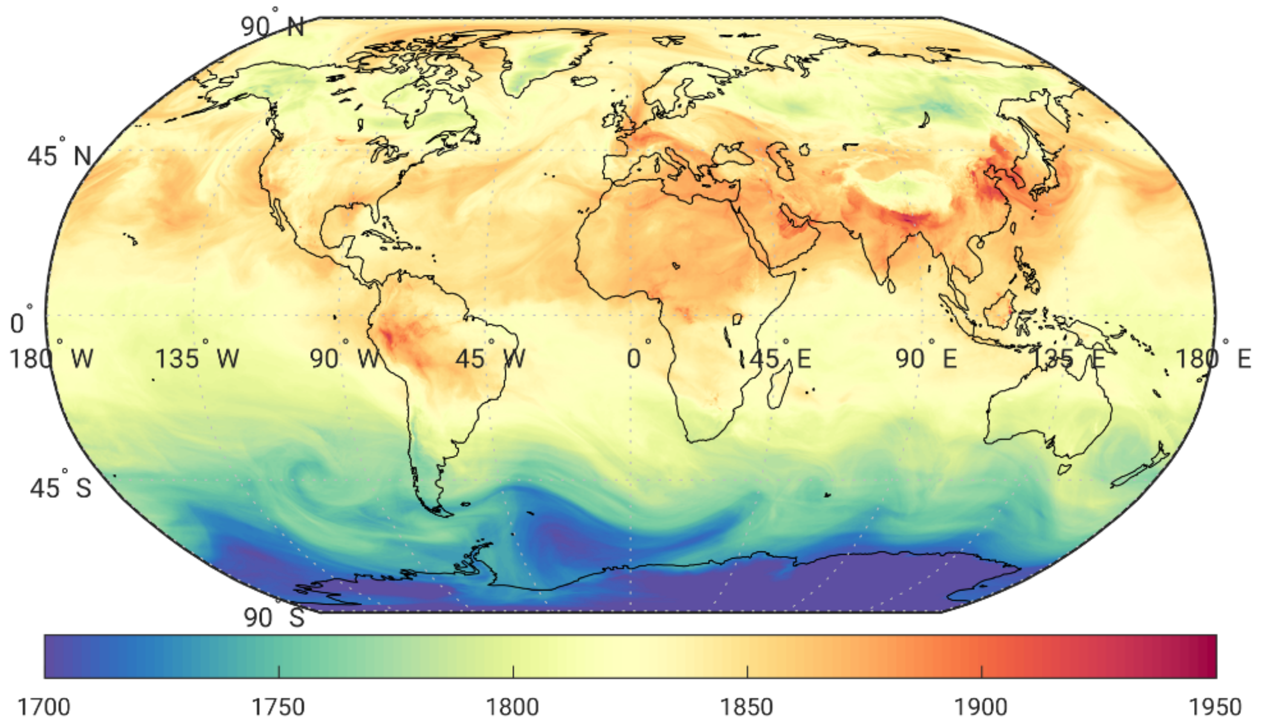
# 12km carbon DA

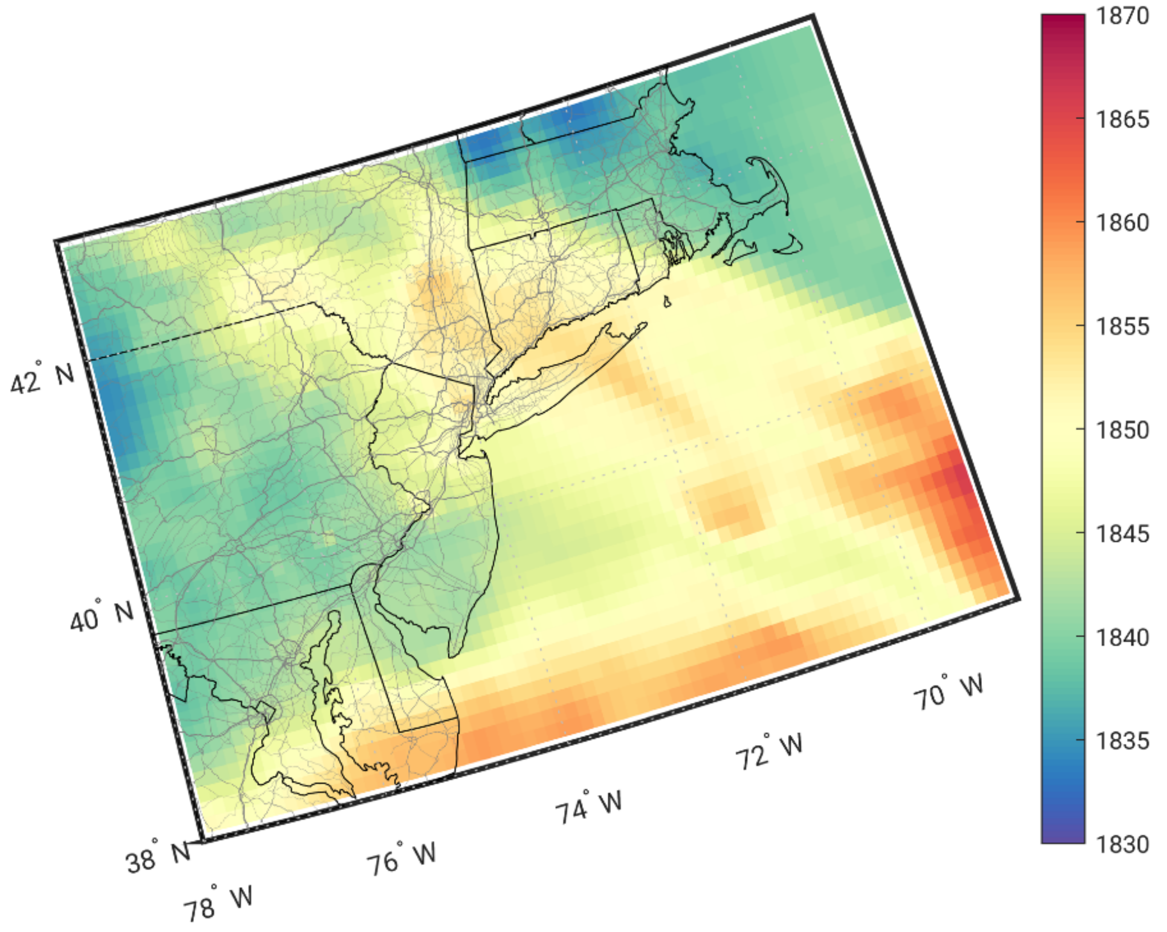
## OCO-2 $XCO_2$ [ppm]



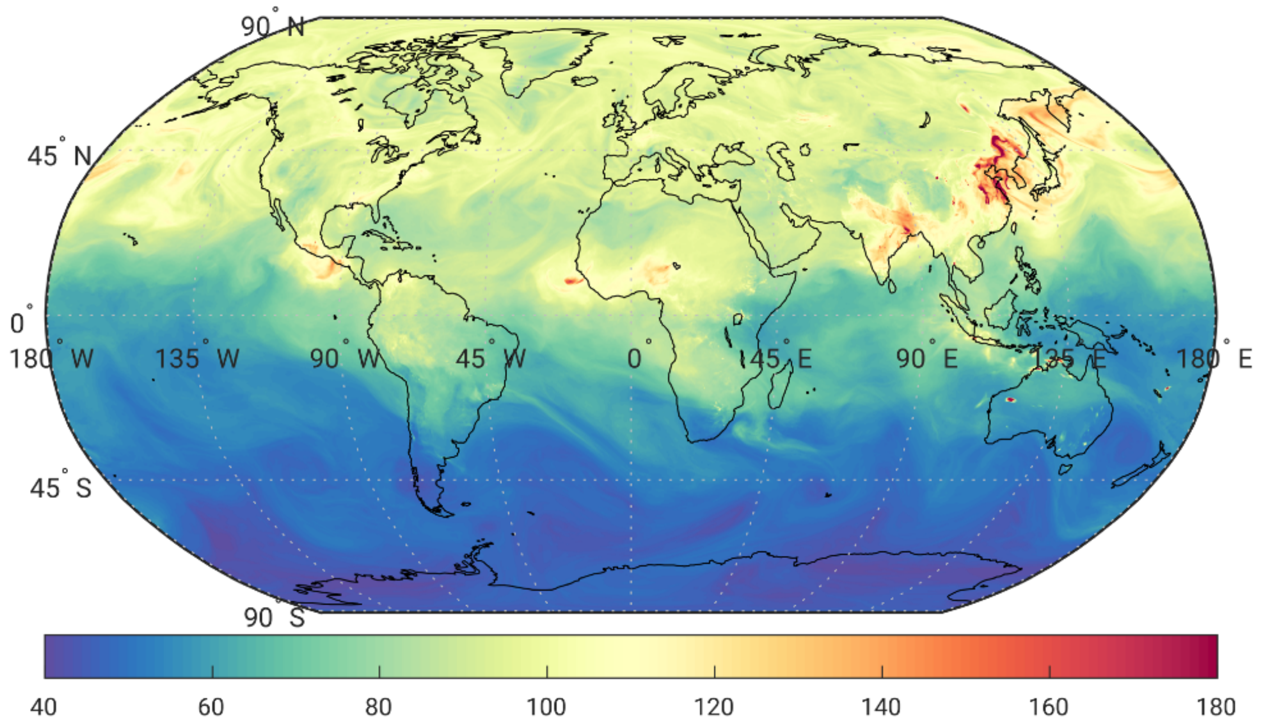



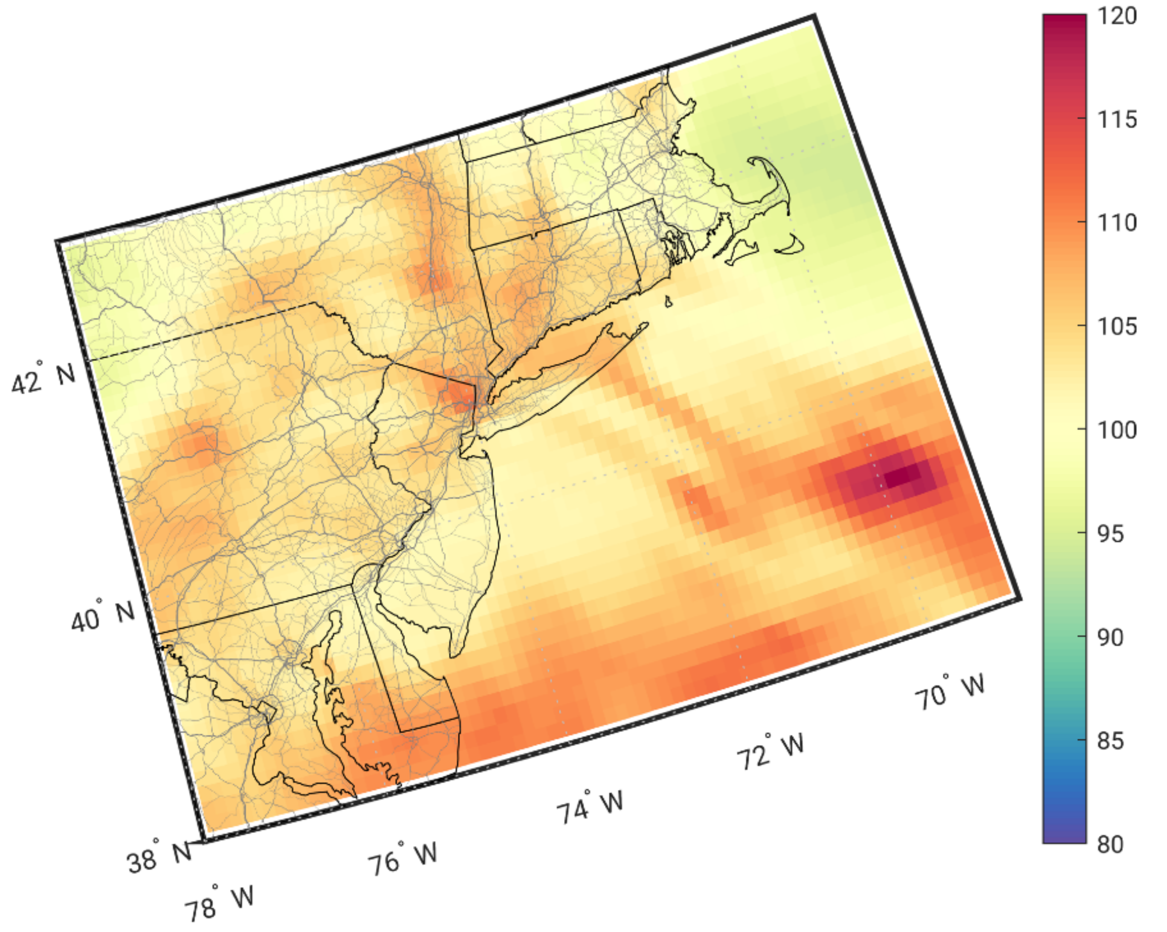

## TROPOMI $XCH_4$ [ppb]




## TROPOMI XCO [ppb]



# M2 SCREAM

**MERRA-2 Stratospheric Composition Reanalysis of Aura MLS**

- 50 km replay to MERRA-2 met (except strat $H_2O$)
- Assimilates $O_3$, HCl, $HNO_3$, $N_2O$, and **strat** $H_2O$ profiles from MLS & OMI column $O_3$
- Realistic, data-constrained, high-resolution **strat** and **trop** $H_2O$
- Publicly available: 2004 – now(ish) on GES DISC

Earth and Space Science

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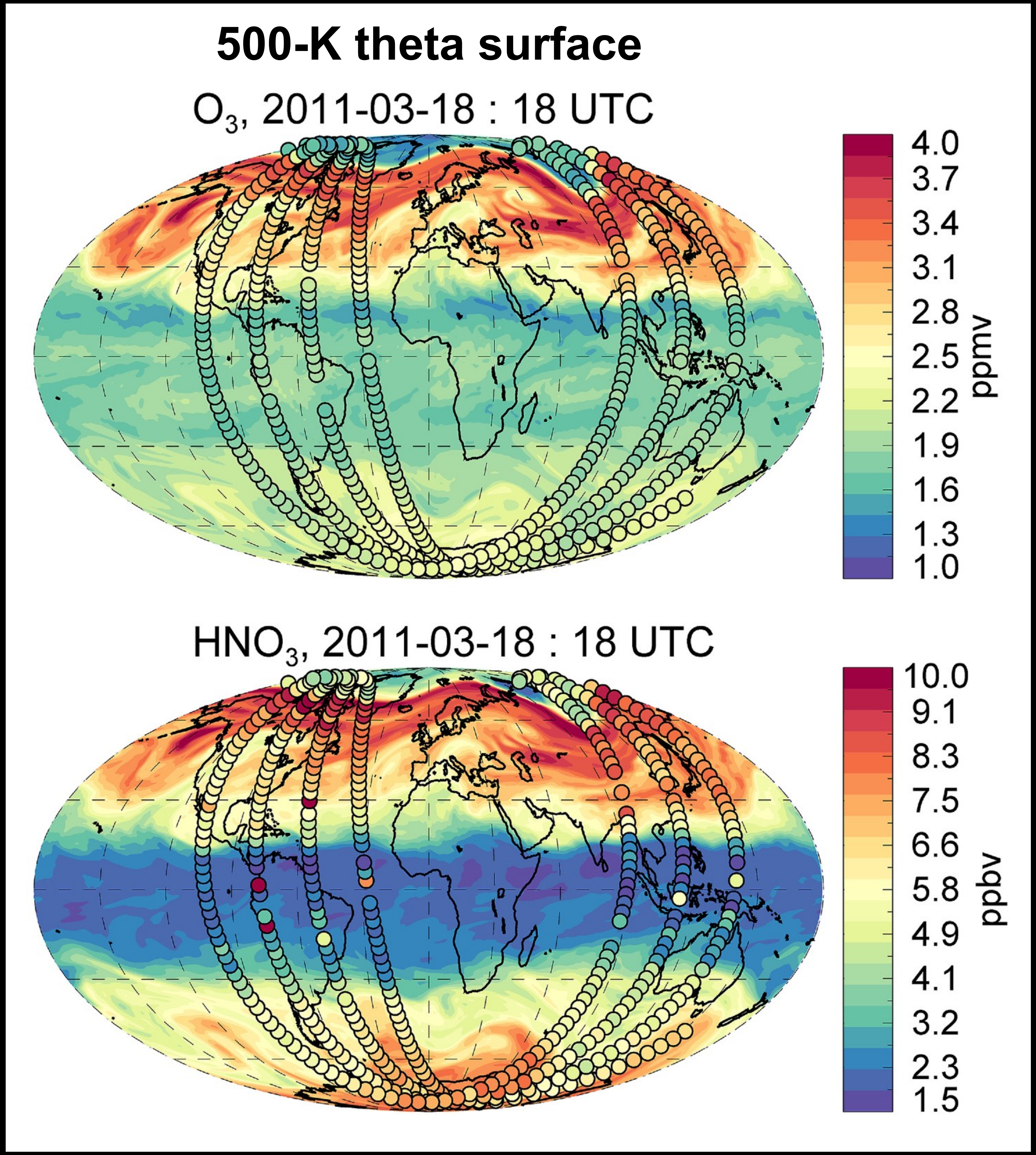


*from K Wargan*

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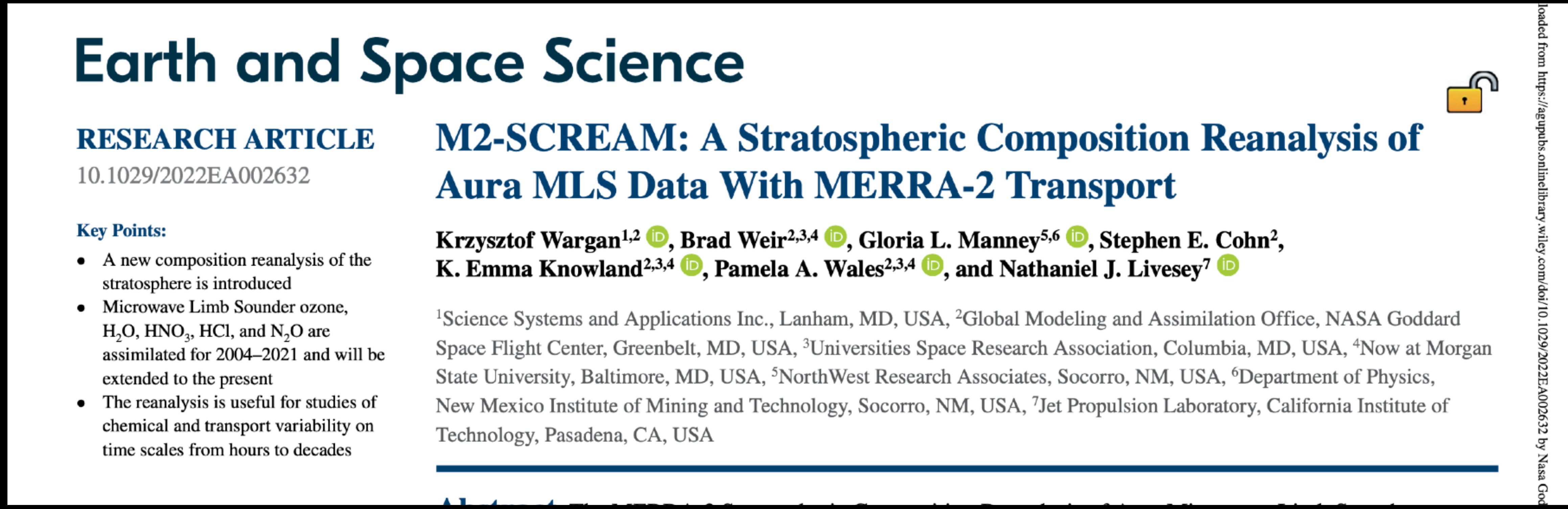
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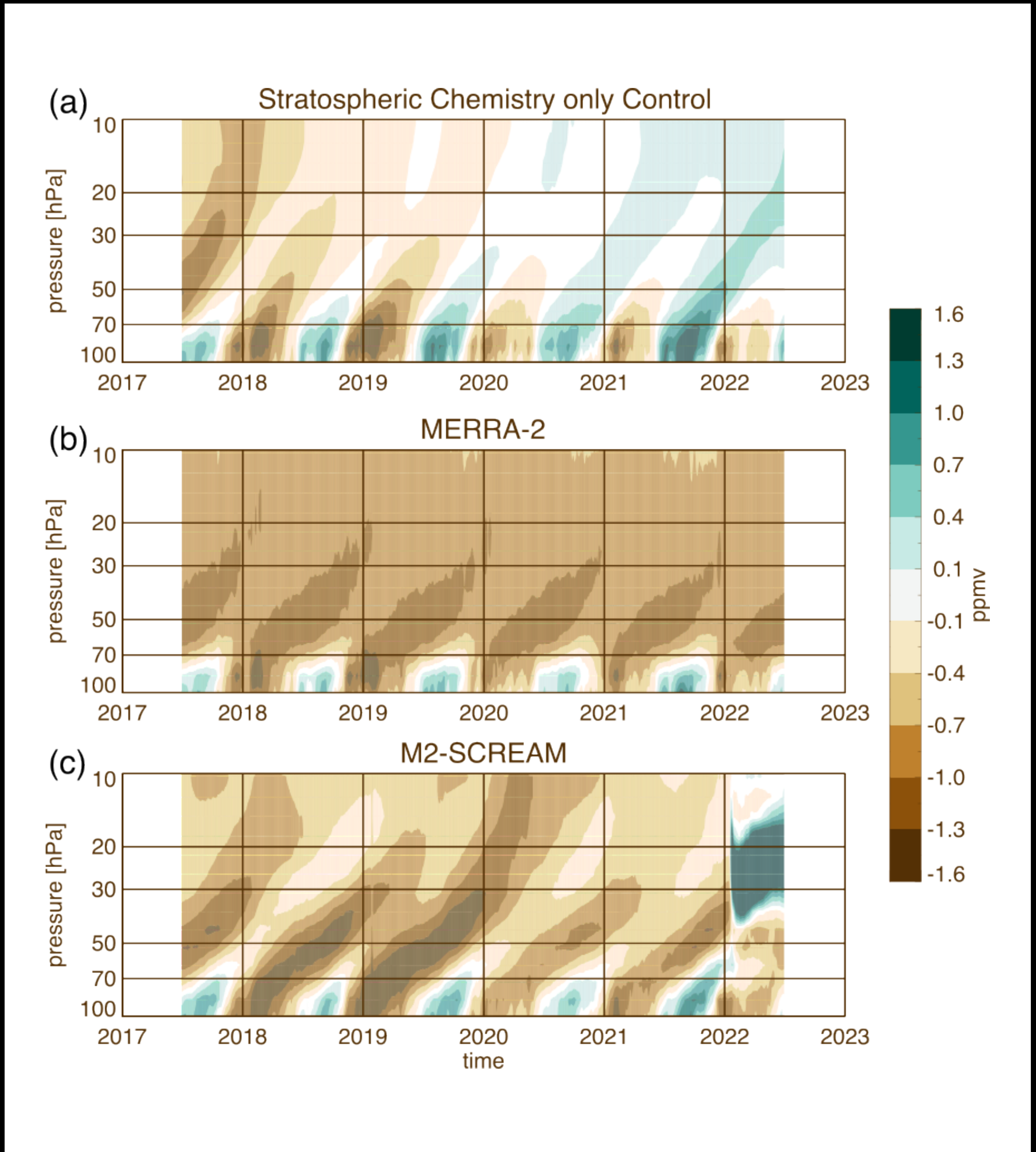
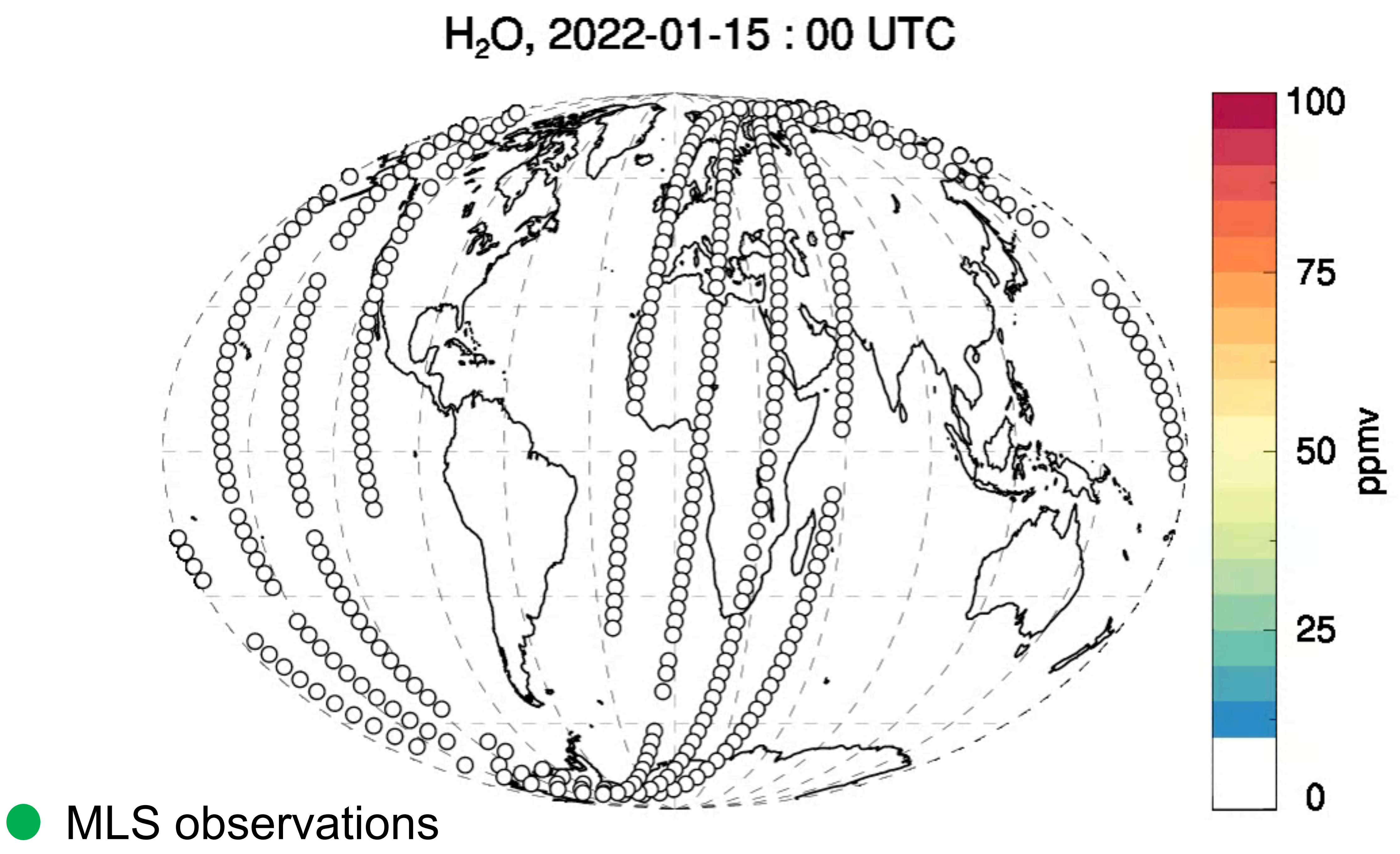
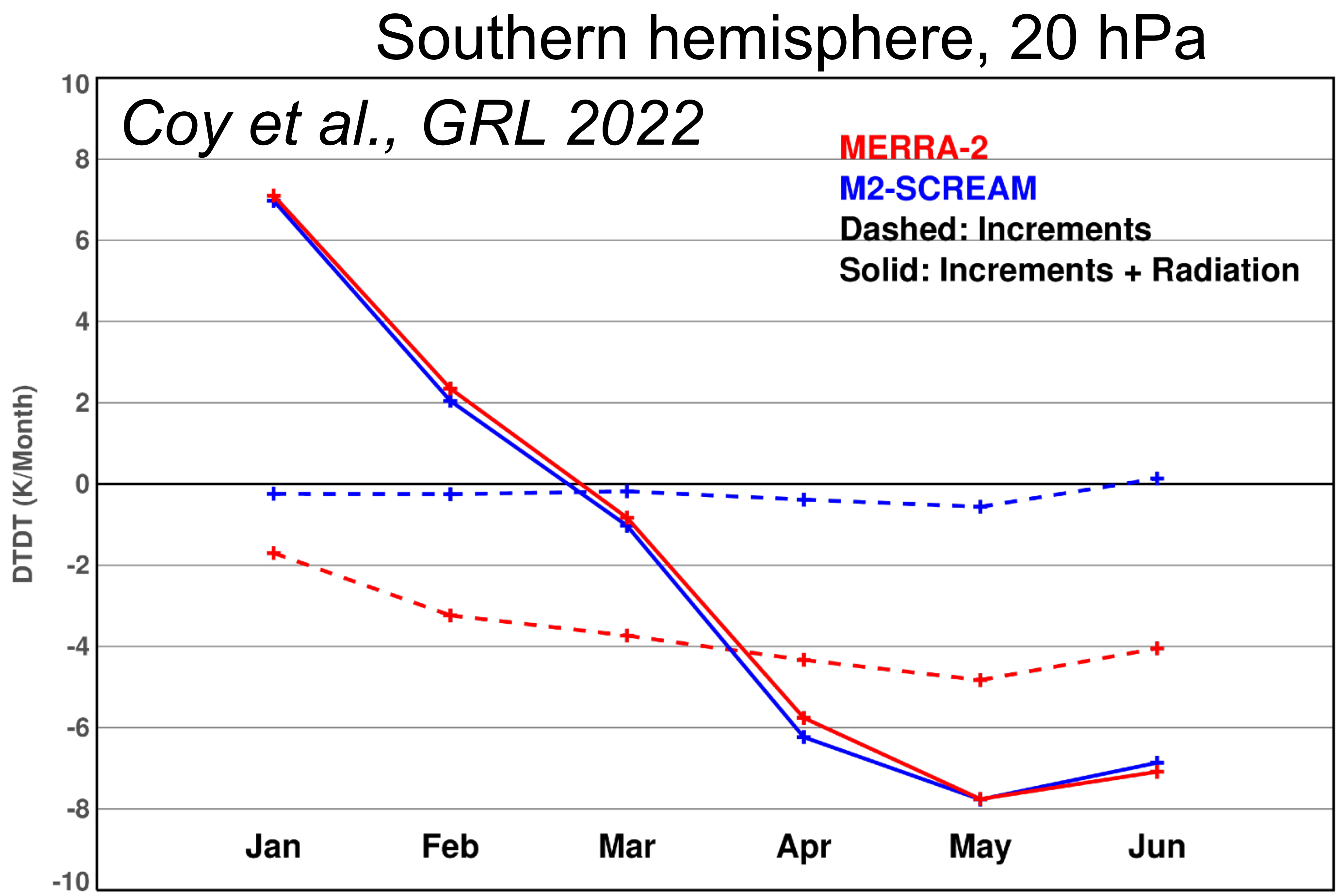



*from K Wargan and K E Knowland*

# Hunga Tonga–Hunga Ha’apai



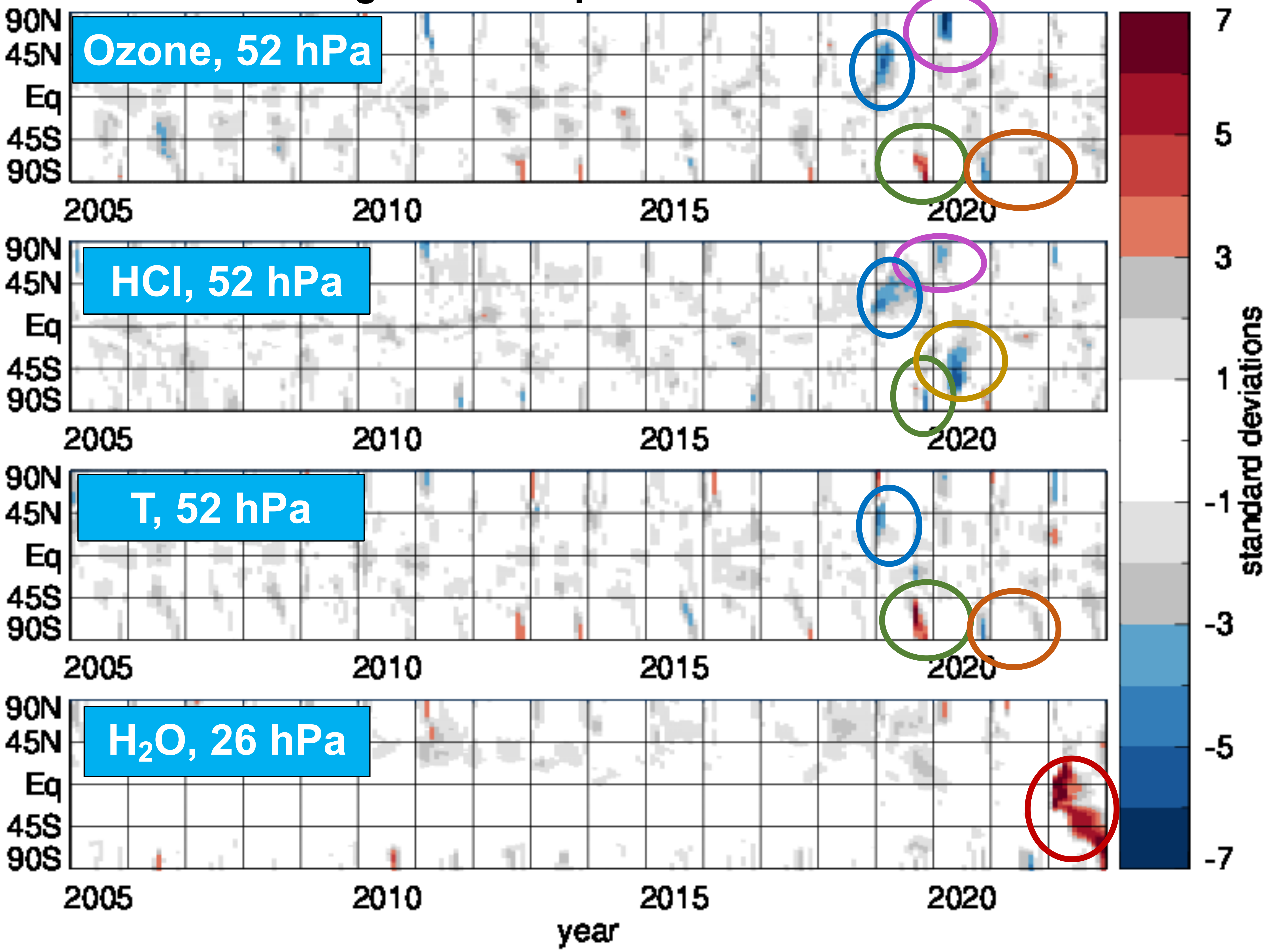

Water vapor at 650 K potential temperature (~26 km) from M2-SCREAM




The extra water vapor induces radiative cooling and dynamical perturbations consistent w/ M2 analysis tendency

*from K Wargan*

## Trace gas and temperature anomalies




**Early 2019: Dynamically-driven anomaly**

**Late 2019: Rare sudden stratospheric warming over Antarctica**

**2020: Exceptionally strong Arctic polar vortex**

**2020: Australian New Year's wildfires**

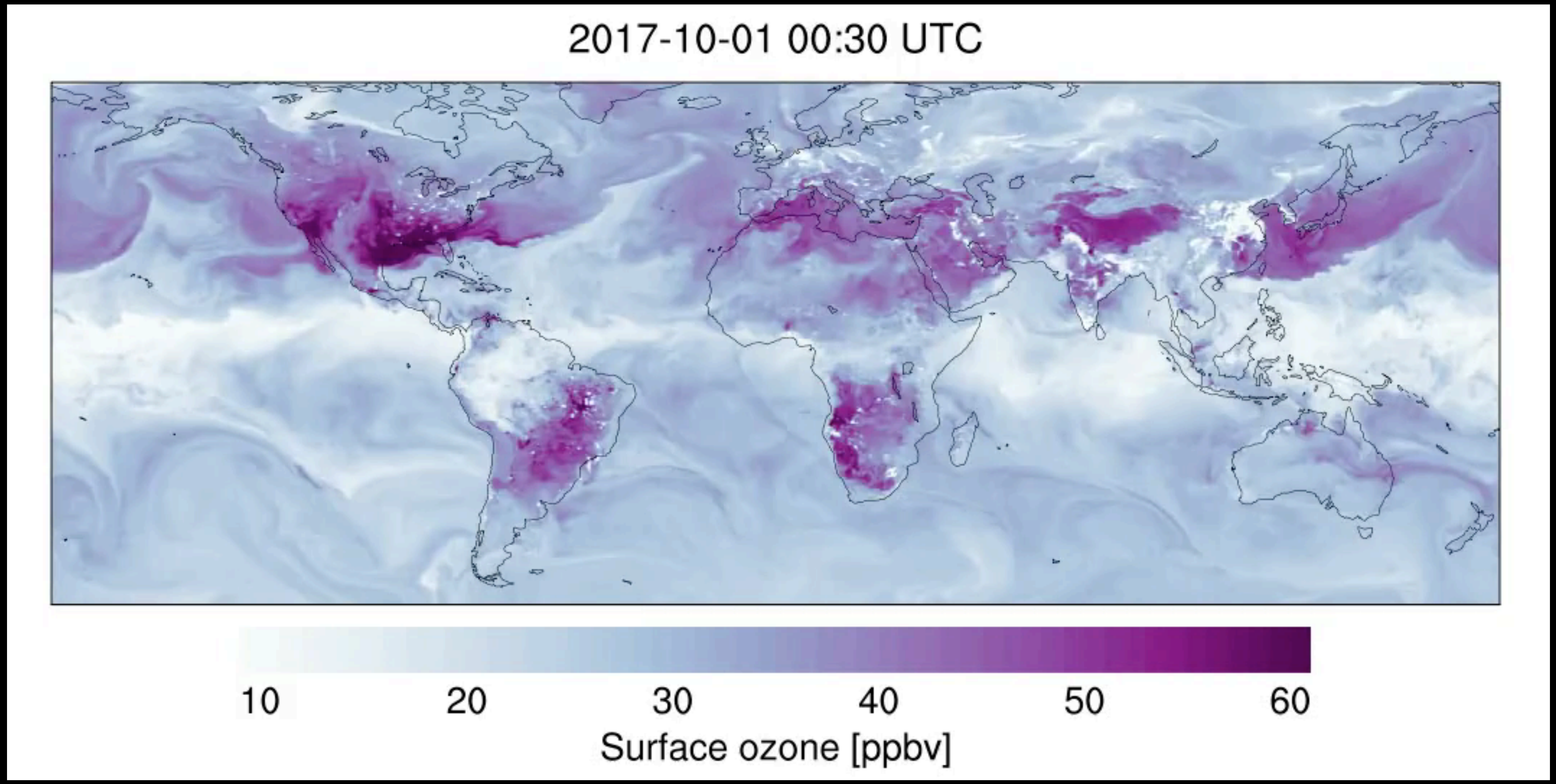
**2020 and 2021: Long-lasting Antarctic polar vortices**

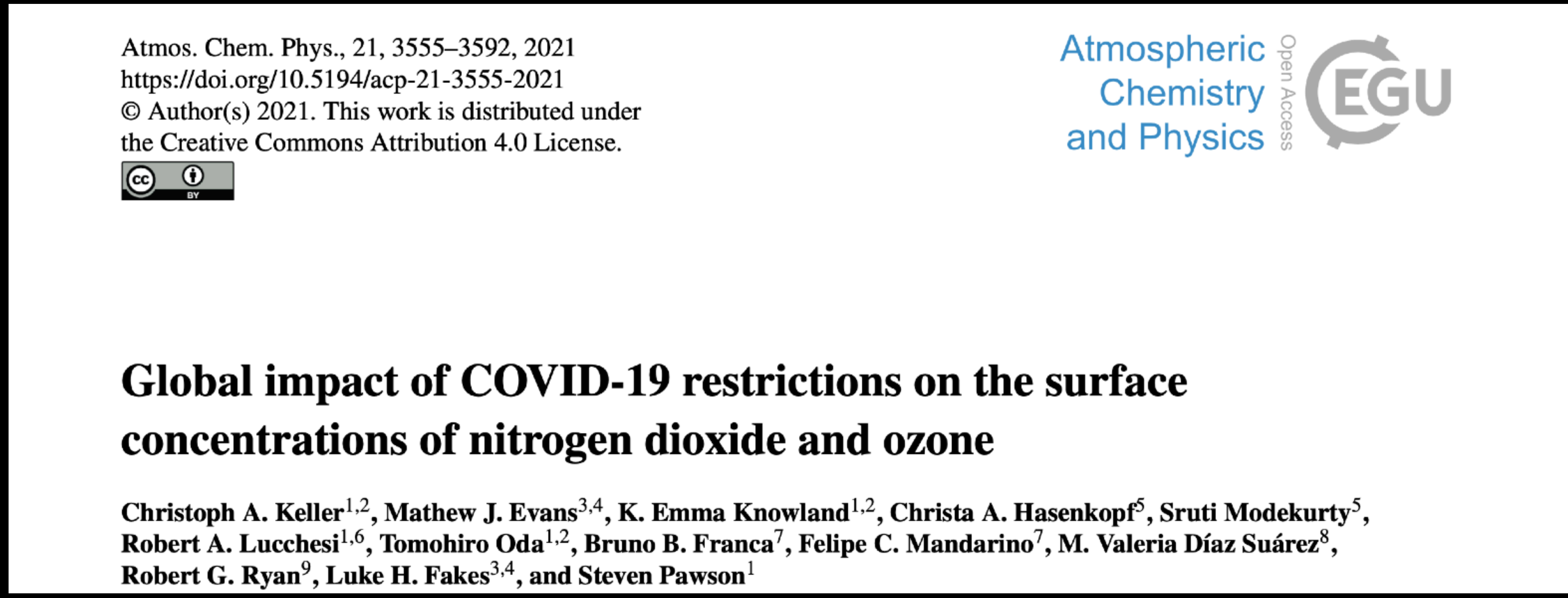
**2022: Hunga Tonga eruption**

*from K Wargan*

# GEOS CF

- GEOS-Chem chemistry: 250 gas-phase species, 725 reactions
- 25km replay to GEOS IT met
- Coupling w/ aerosol chemistry
- https://fluid.nccs.nasa.gov/cf



Atmos. Chem. Phys., 21, 3555–3592, 2021
https://doi.org/10.5194/acp-21-3555-2021
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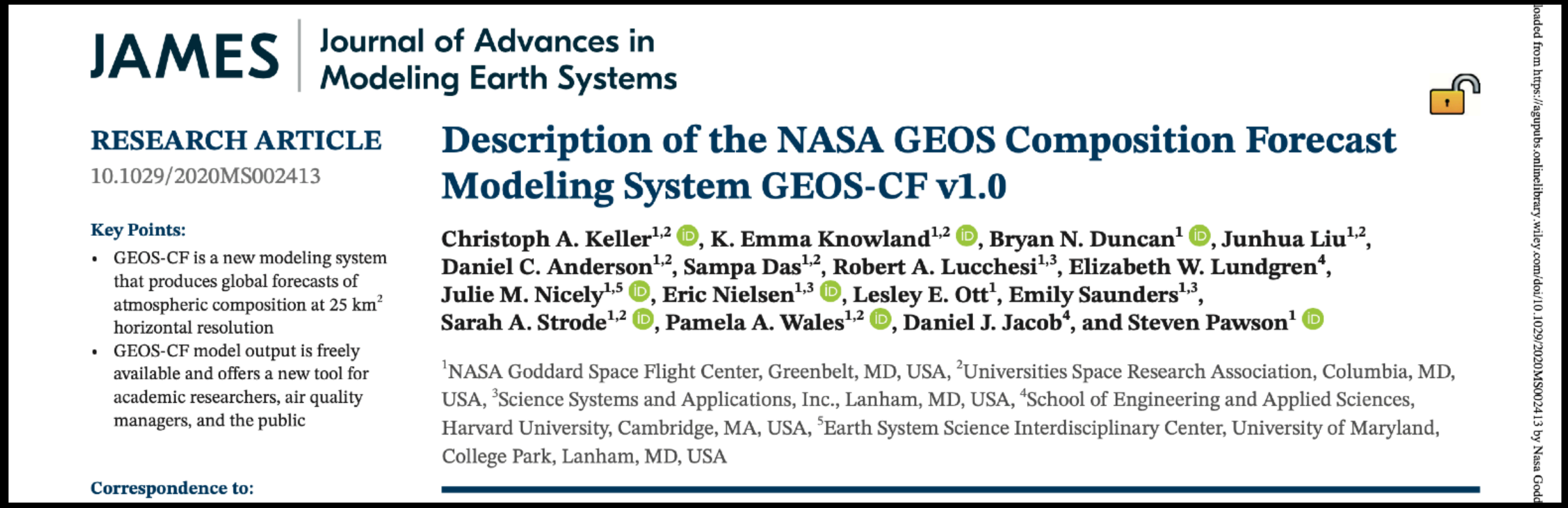
Atmospheric Chemistry and Physics | Open Access | EGU

**Global impact of COVID-19 restrictions on the surface concentrations of nitrogen dioxide and ozone**

Christoph A. Keller[1,2], Mathew J. Evans[3,4], K. Emma Knowland[1,2], Christa A. Hasenkopf[5], Sruti Modekurty[5], Robert A. Lucchesi[1,6], Tomohiro Oda[1,2], Bruno B. Franca[7], Felipe C. Mandarino[7], M. Valeria Díaz Suárez[8], Robert G. Ryan[9], Luke H. Fakes[3,4], and Steven Pawson[1]



JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2020MS002413

**Description of the NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0**

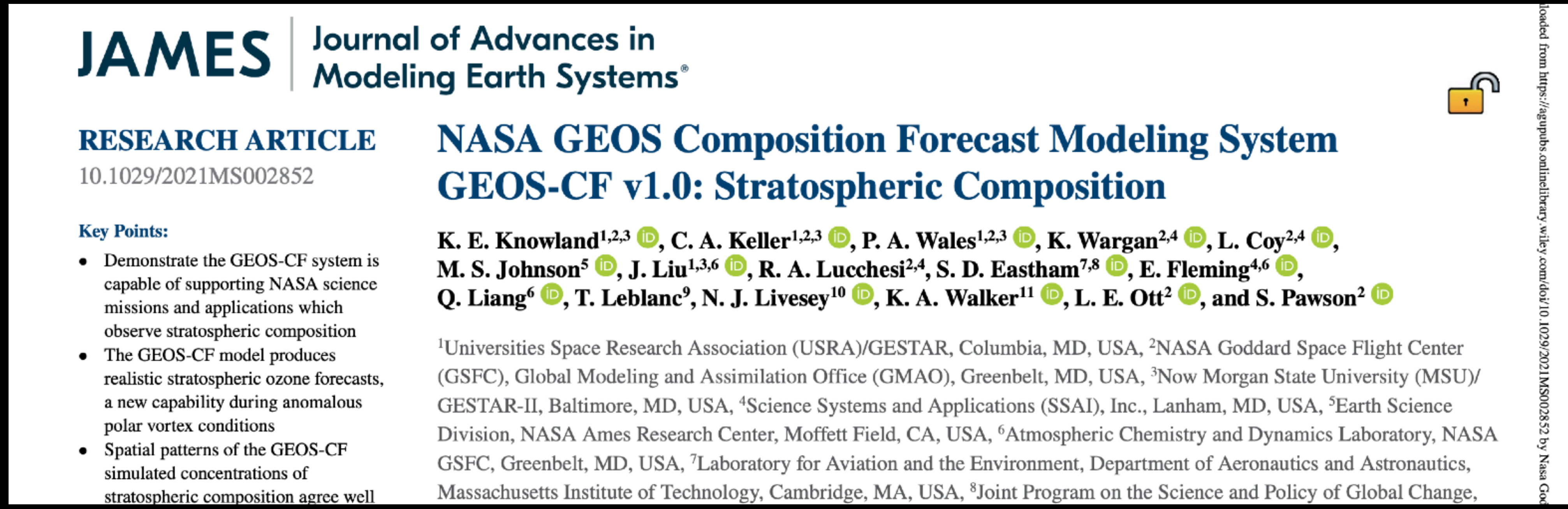
Christoph A. Keller[1,2], K. Emma Knowland[1,2], Bryan N. Duncan[1], Junhua Liu[1,2], Daniel C. Anderson[1,2], Sampa Das[1,2], Robert A. Lucchesi[1,3], Elizabeth W. Lundgren[4], Julie M. Nicely[1,5], Eric Nielsen[1,3], Lesley E. Ott[1], Emily Saunders[1,3], Sarah A. Strode[1,2], Pamela A. Wales[1,2], Daniel J. Jacob[4], and Steven Pawson[1]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [2]Universities Space Research Association, Columbia, MD, USA, [3]Science Systems and Applications, Inc., Lanham, MD, USA, [4]School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA, [5]Earth System Science Interdisciplinary Center, University of Maryland, College Park, Lanham, MD, USA

Key Points:

- GEOS-CF is a new modeling system that produces global forecasts of atmospheric composition at 25 $km^2$ horizontal resolution
- GEOS-CF model output is freely available and offers a new tool for academic researchers, air quality managers, and the public

Correspondence to:



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RESEARCH ARTICLE
10.1029/2021MS002852

**NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0: Stratospheric Composition**

K. E. Knowland[1,2,3], C. A. Keller[1,2,3], P. A. Wales[1,2,3], K. Wargan[2,4], L. Coy[2,4], M. S. Johnson[5], J. Liu[1,3,6], R. A. Lucchesi[2,4], S. D. Eastham[7,8], E. Fleming[4,6], Q. Liang[6], T. Leblanc[9], N. J. Livesey[10], K. A. Walker[11], L. E. Ott[2], and S. Pawson[2]

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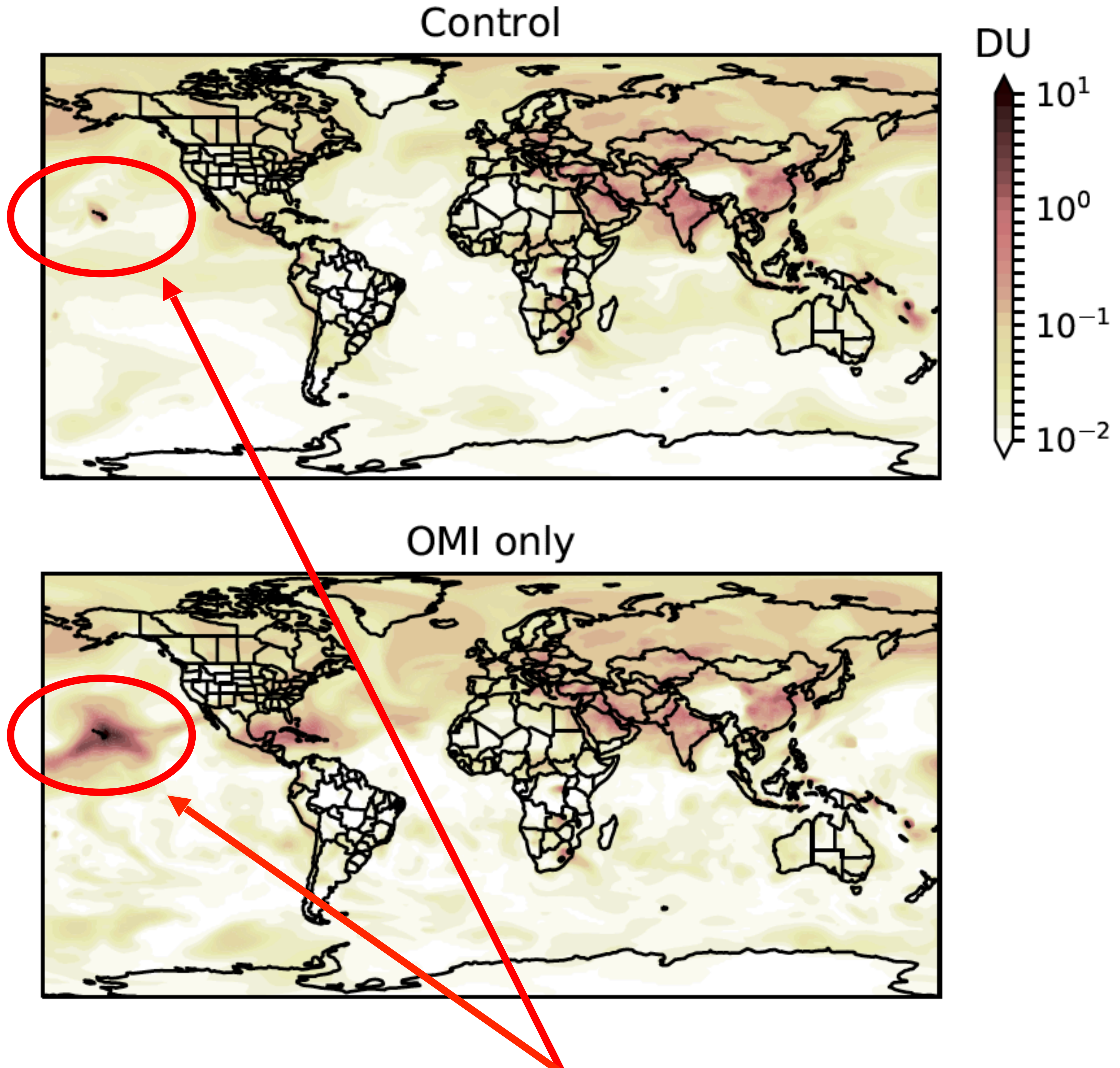
Key Points:

- Demonstrate the GEOS-CF system is capable of supporting NASA science missions and applications which observe stratospheric composition
- The GEOS-CF model produces realistic stratospheric ozone forecasts, a new capability during anomalous polar vortex conditions
- Spatial patterns of the GEOS-CF simulated concentrations of stratospheric composition agree well

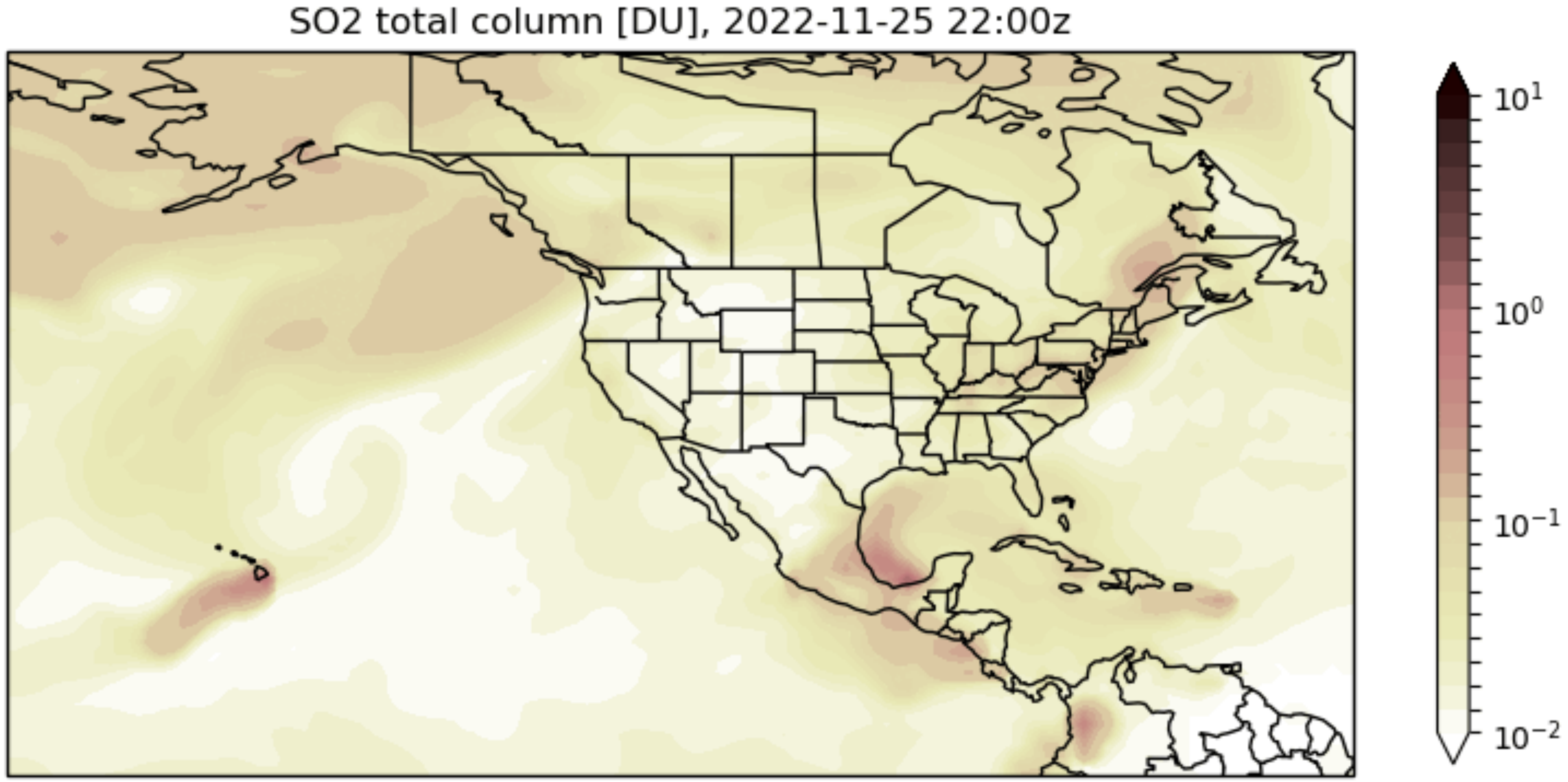
*from C Keller and K E Knowland*

# $SO_2$ assimilation: Mauna Loa eruption

**$SO_2$ total column, 6 Dec 2022**

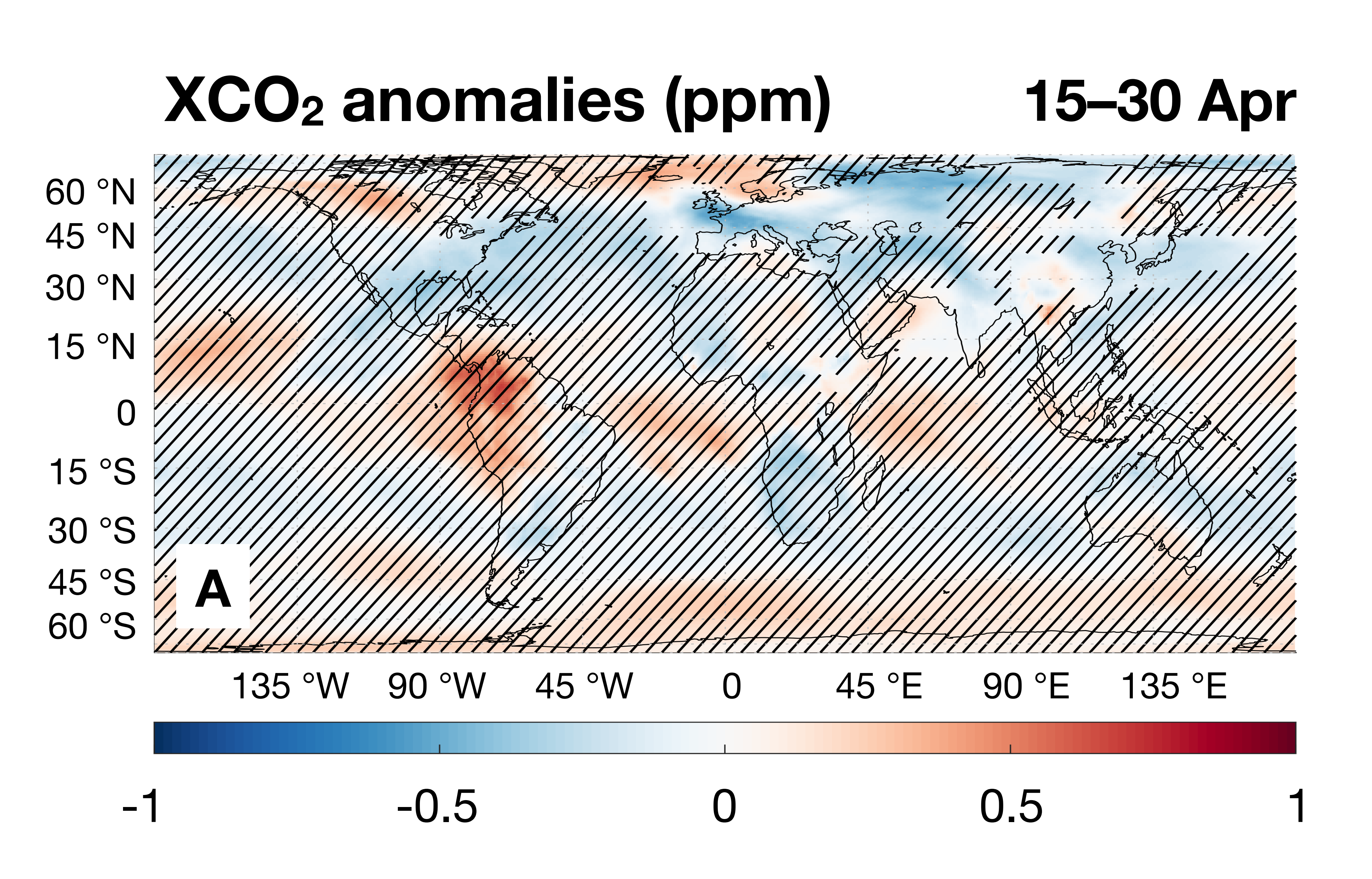


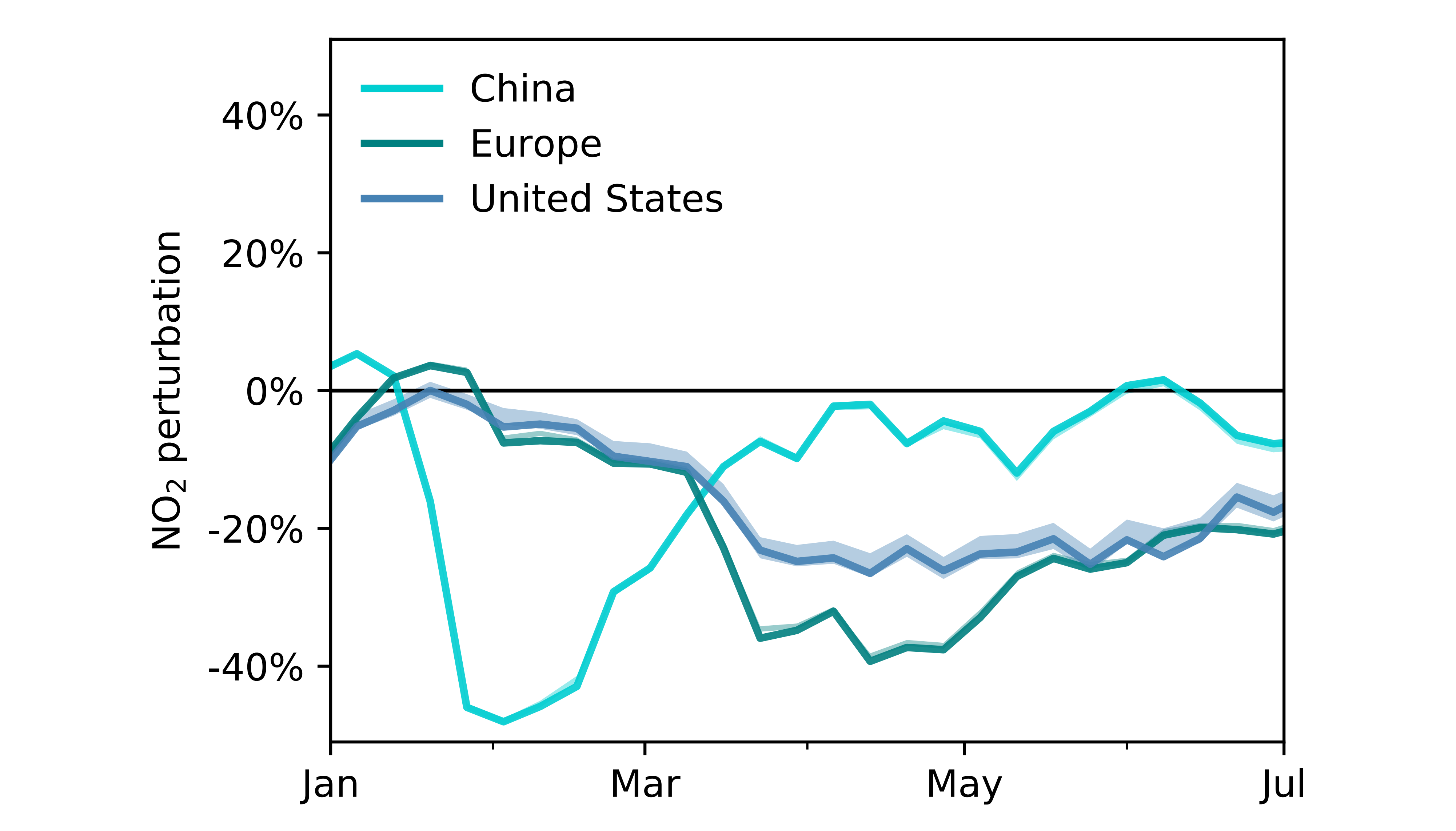

Mauna Loa eruption not simulated (top), yet still captured by assimilation (bottom)




*from C Keller*

# COVID-19 $CO_2$, $NO_2$, and $O_3$




SCIENCE ADVANCES | RESEARCH ARTICLE

CORONAVIRUS

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EGU

## Global impact of COVID-19 restrictions on the surface concentrations of nitrogen dioxide and ozone

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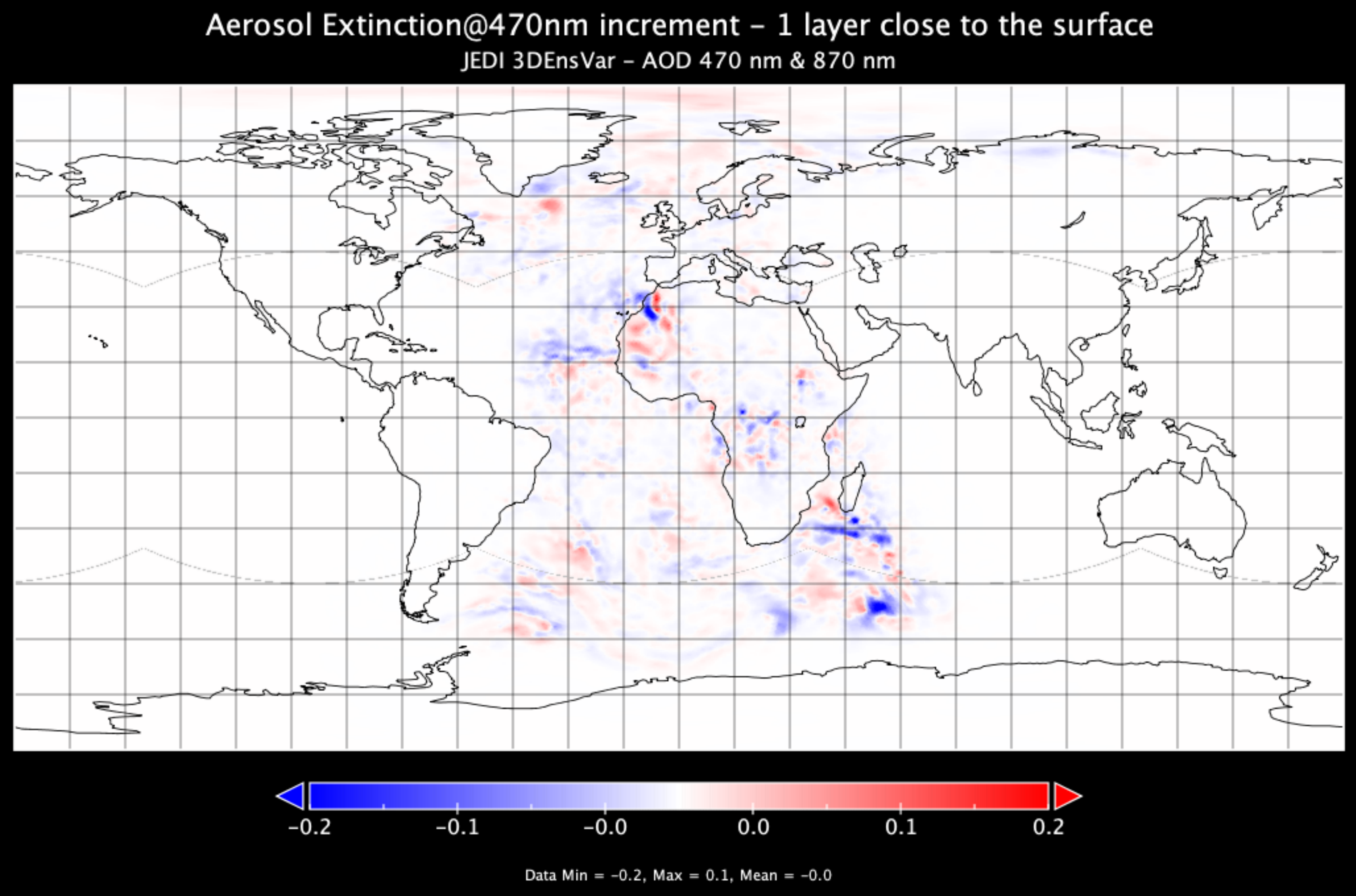
*from C Keller*

# Tomorrow’s Enterprise

- State estimation systems transitioning to Joint Effort for Data assimilation Integration (JEDI)
- Joint effort of GMAO, NOAA EMC & PSL, NCAR, Navy, Air Force, and UK Met Office managed through JCSDA
- Will be the basis of future coupled ocean-atmosphere (and more) analyses, e.g., MERRA-3
- Interoperable “all-DAS” system

# Aerosol data assimilation system

- JEDI-based aerosol data assimilation scheme transitioning to a hybrid ensemble-variational scheme
- Upgrade from 2D Aerosol Optical Depth (AOD) to vertically resolved aerosol extinction
- Permits assimilation of multi-spectral passive and active aerosol measurements, e.g., lidar, aerosol optical centroid height, and radiances
- Prognostic model underlying this data assimilation system (GOCART) undergoing refactor to GOCART2G: https://github.com/GEOS-ESM/GOCART




JEDI 3DEnVar: Aerosol extinction increments at 470 nm (for one model layer) after one analysis cycle at C90
Observing System: AOD at 470 & 870 nm

*from V Buchard, Arlindo, and D Holdaway*

# Conclusions

- GMAO maintains state-of-the-art Earth System modeling and data assimilation systems
- Code (GitHub), products (GES DISC), etc. publicly available and documented in literature
- Increased coupling, resolution, fidelity of constituent analyses
- R21C-Chem coming soon
- Further inter-center interoperability, coordination, and collaboration w/ JEDI