



NASA's High-Resolution GEOS Forecasting and Reanalysis Products: Impact of Stratospheric Intrusions on Surface Ozone Air Quality

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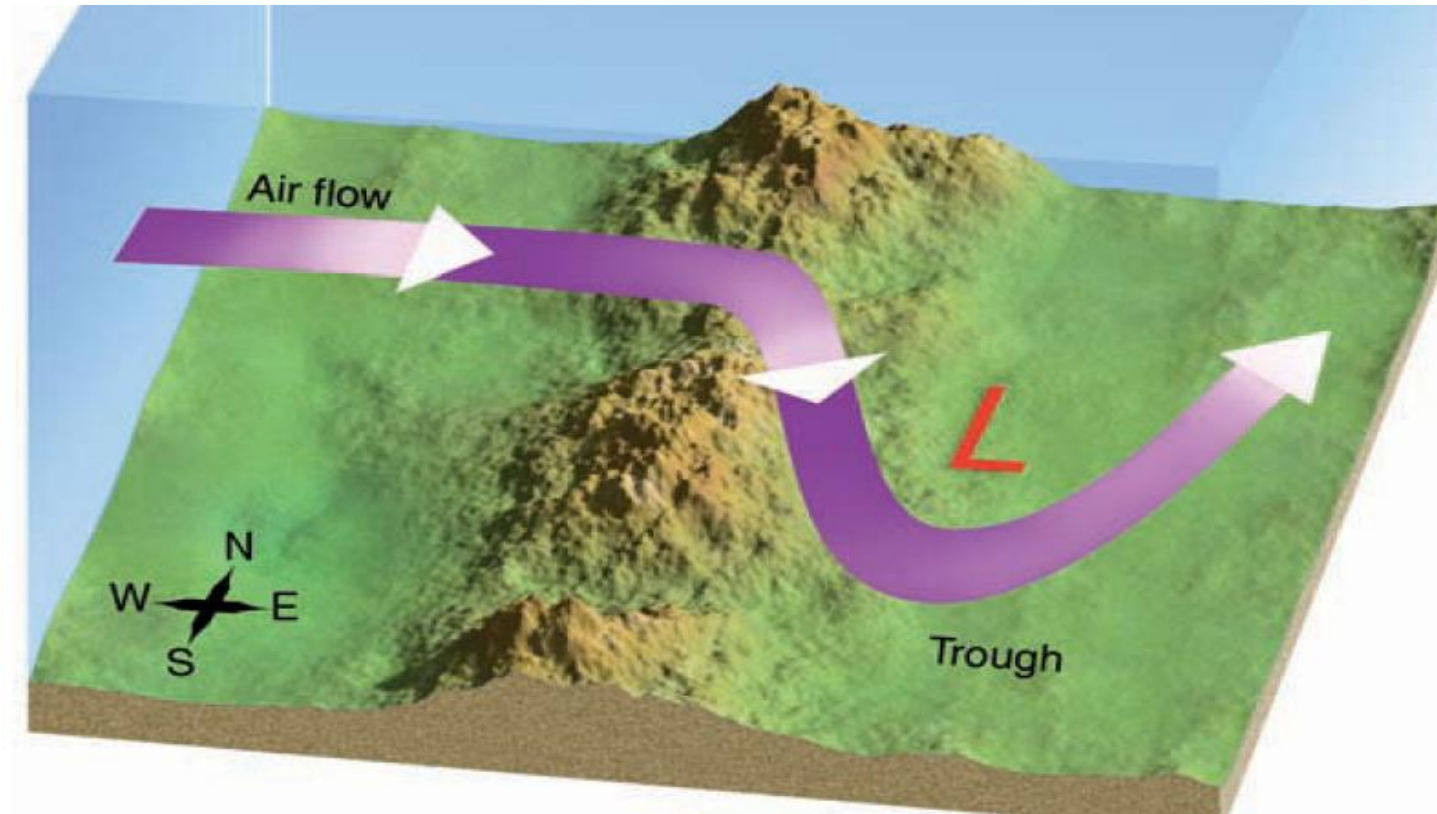
NASA LaRC: Tim Berkoff, Guillaume Gronoff

University of Reading, UK: Kevin Hodges

6 March 2020

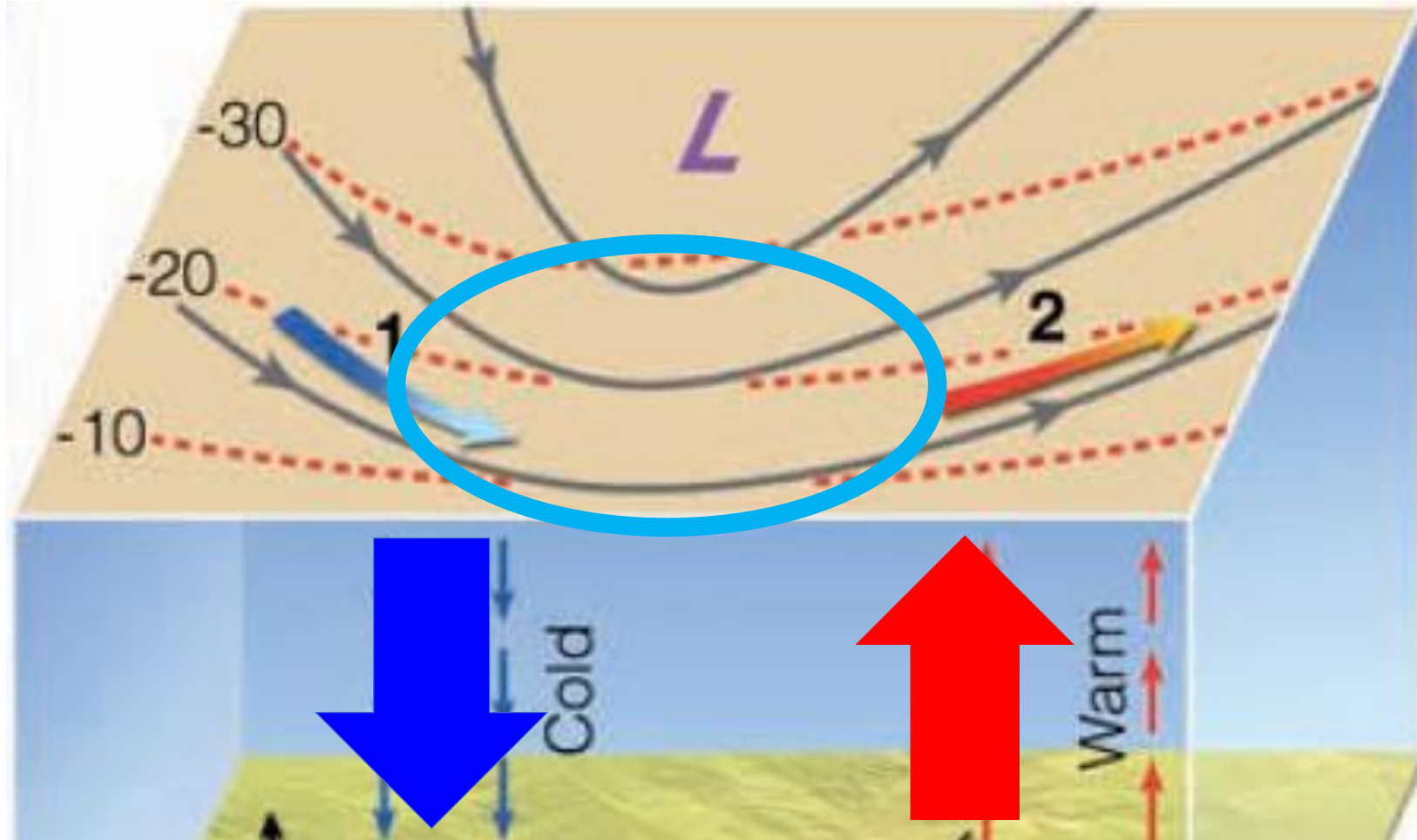


Introduction to Upper-level flow



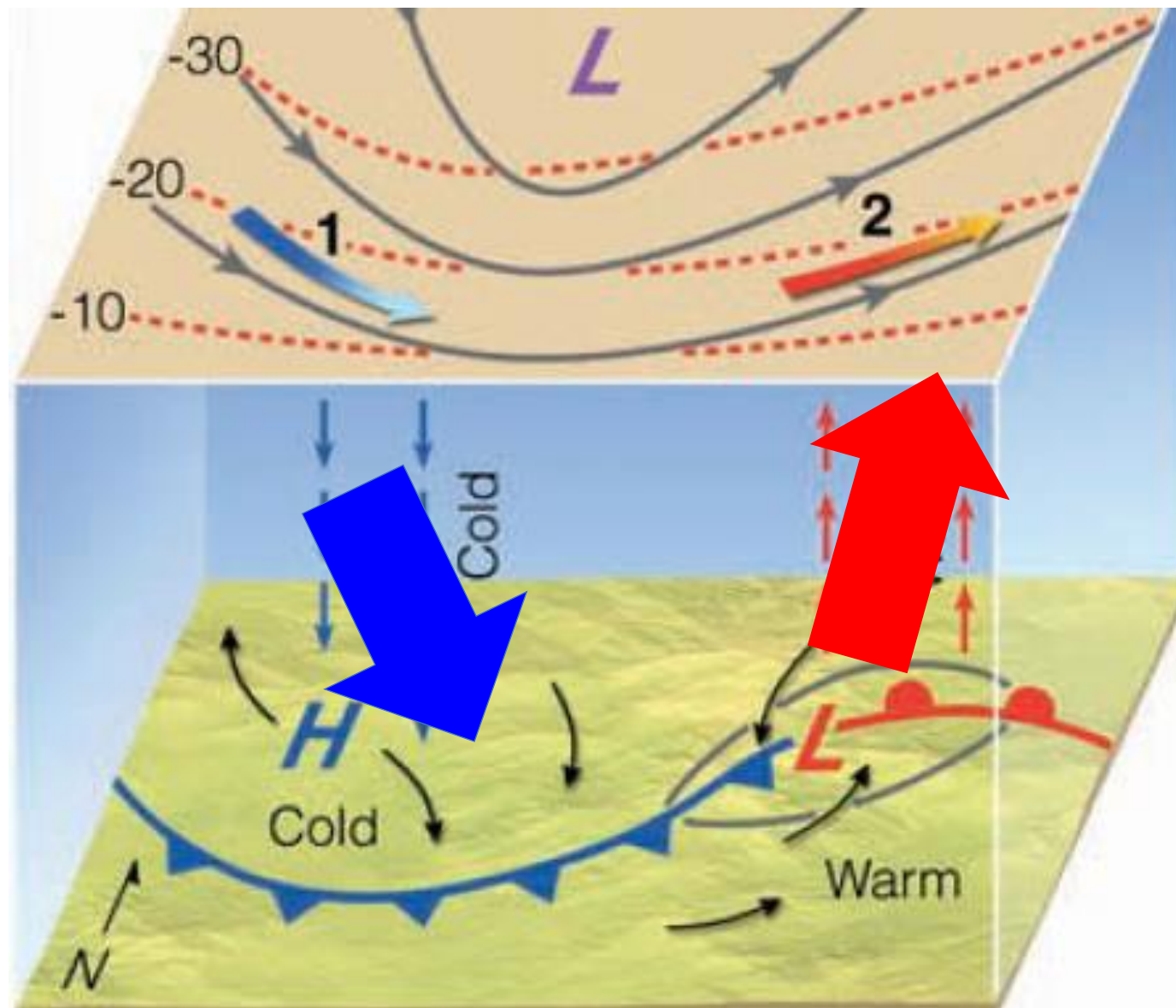
Upper-level wave trains exist, with troughs often forming as the flow is disturbed by mountains

- Converging air accumulates and **subsides**
- Diverging air draws air **upwards** from the surface



- As air enters the trough, wind speeds increase resulting in a jet maximum at the base of the trough.

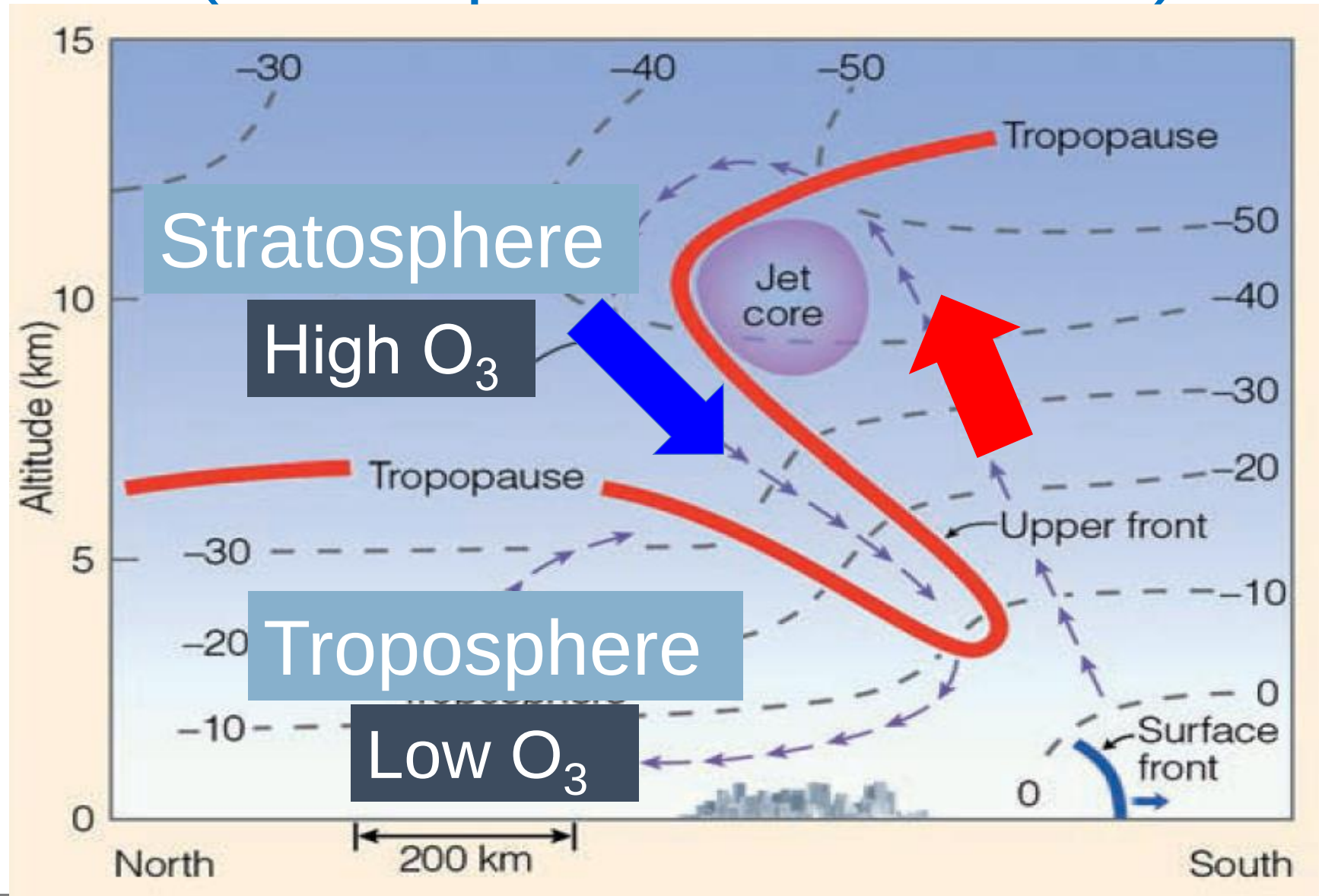
- Upper-level trough supports development of a mid-latitude cyclone
- **Descent** behind cold front



Tropopause Fold (Stratospheric Intrusions: SI)

SIs are associated with:

- High O_3 , PV
- Low CO , moisture (“dry intrusion”)



O_3 is a regulated air pollutant

- SIs can lead to concentrations of ground-level O_3 exceeding the national ambient air quality standard (NAAQS) set by the EPA, especially at high elevations
- In October 2015, the EPA revised the U.S. NAAQS for daily maximum 8 h average (MDA8) O_3 from 75 parts per billion by volume (ppbv) to 70 ppbv

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➤ **Critical to accurately forecast these events!**



Previously, SIs misrepresented in models

- SIs are fine-scale features, resolution needs to be high enough to capture the filaments



Previously, SIs misrepresented in models

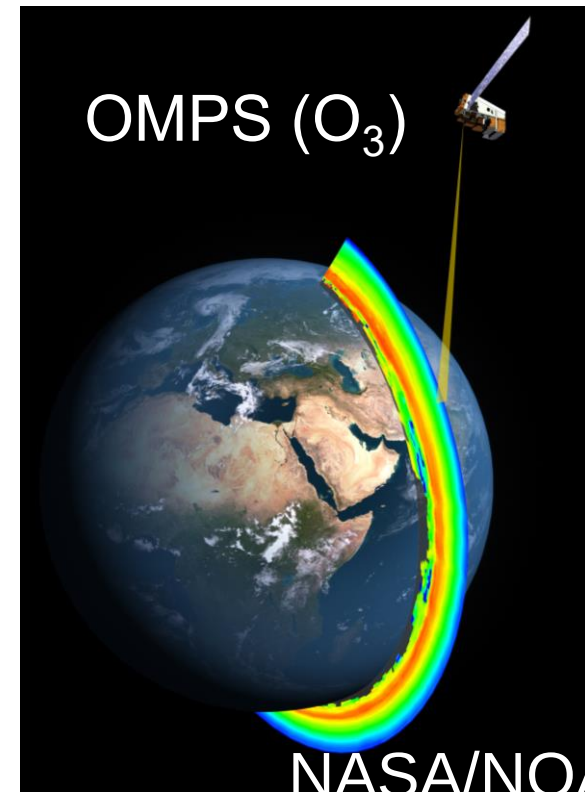
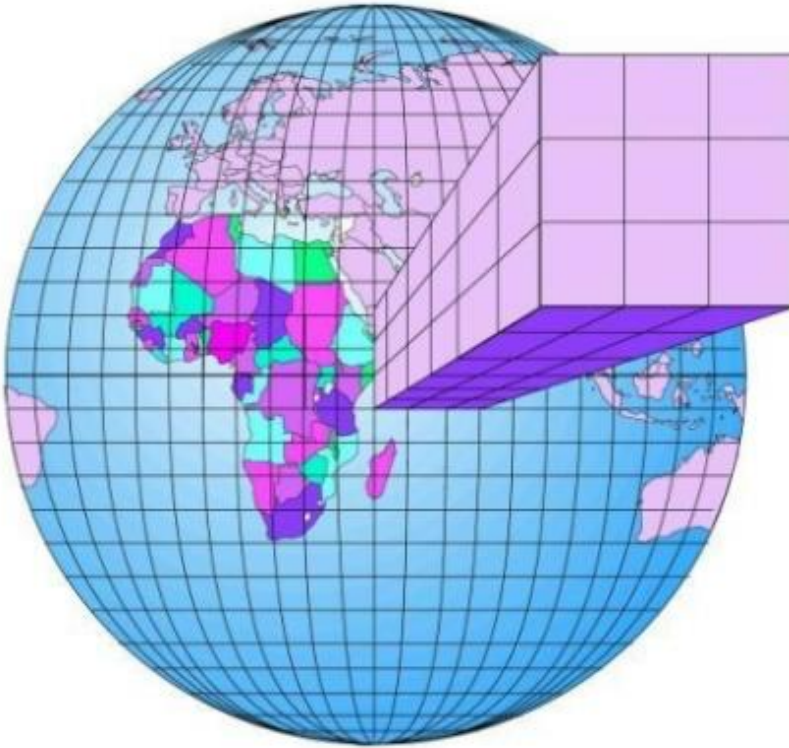
- SIs are fine-scale features, resolution needs to be high enough to capture the filaments
- Simulating and predicting such events remains challenging

Previously, SIs misrepresented in models

- SIs are fine-scale features, resolution needs to be high enough to capture the filaments
- Simulating and predicting such events remains challenging
- Need horizontal resolution of 50 km or less
(Büker et al., 2005; Lin et al., 2012; Ott et al., 2016)

NASA GMAO global meteorology and chemistry products

GEOS

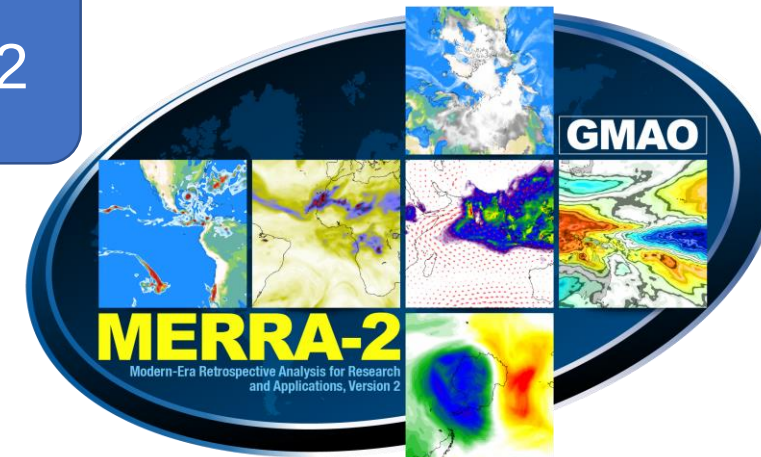
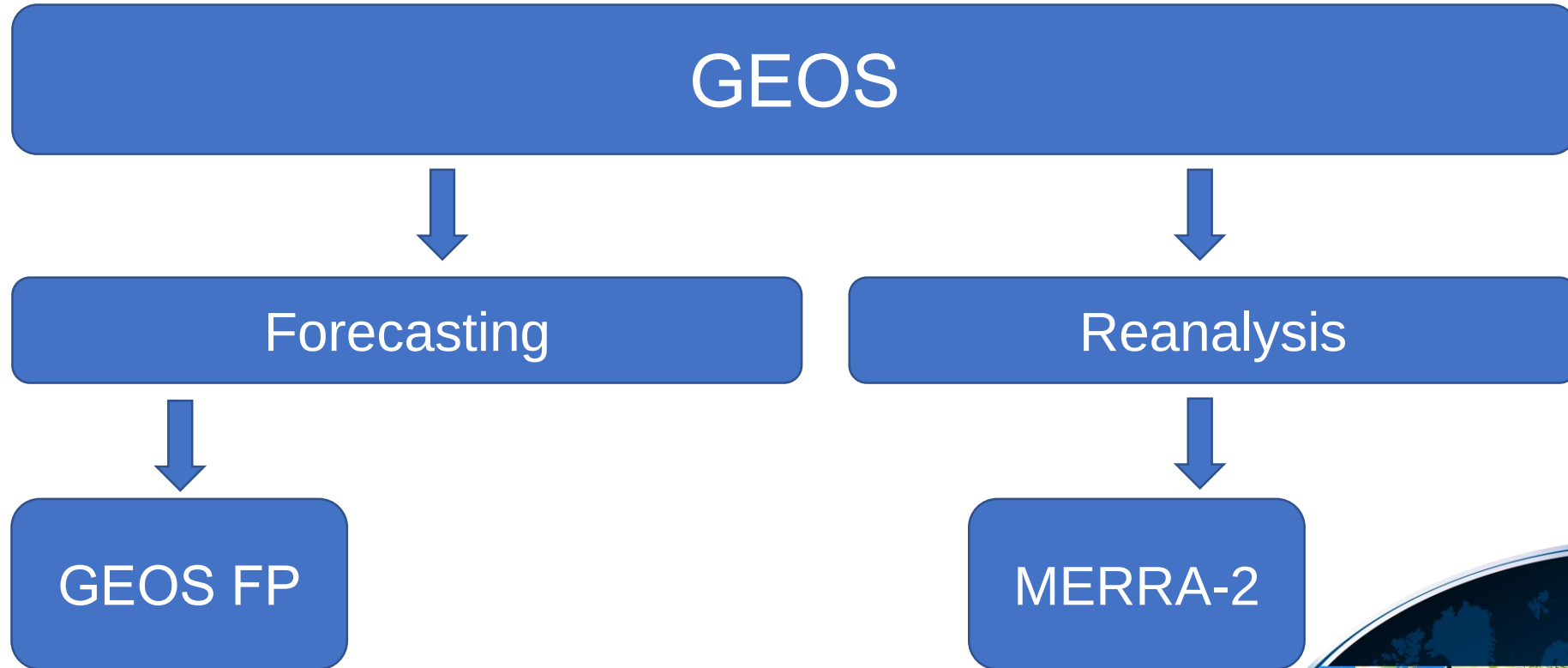


www.nasa.gov

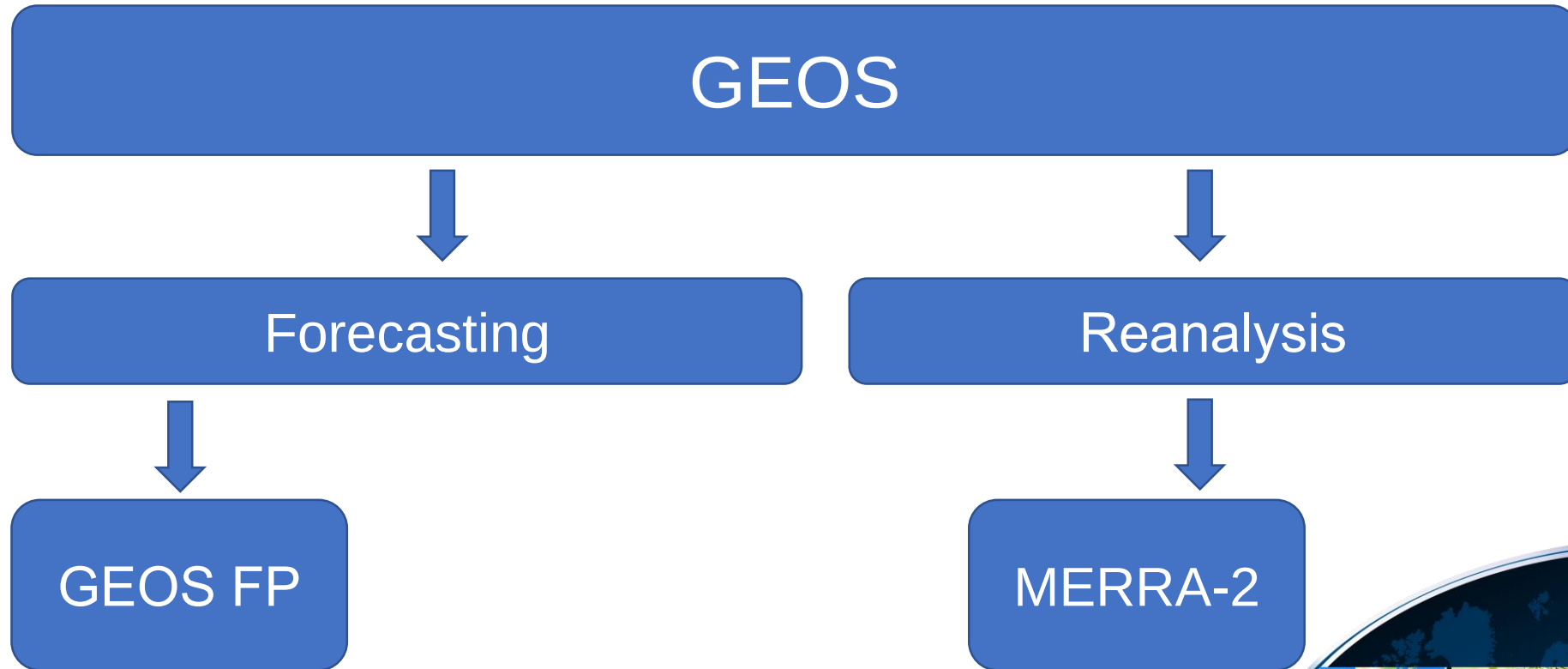
NASA GMAO global meteorology and chemistry products



NASA GMAO global meteorology and chemistry products

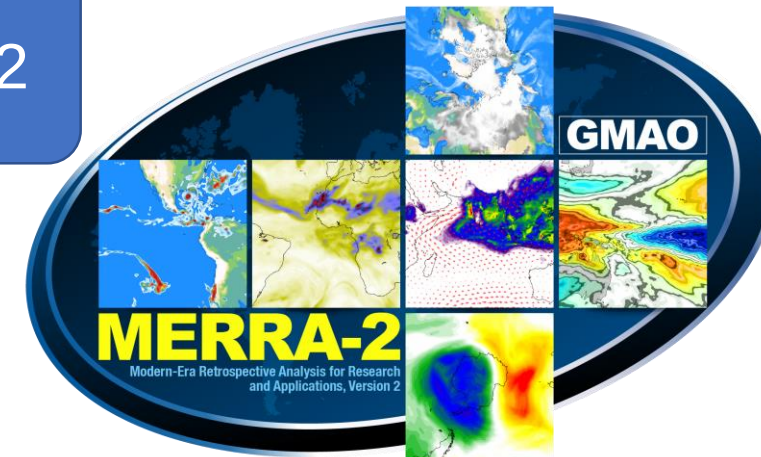


NASA GMAO global meteorology and chemistry products



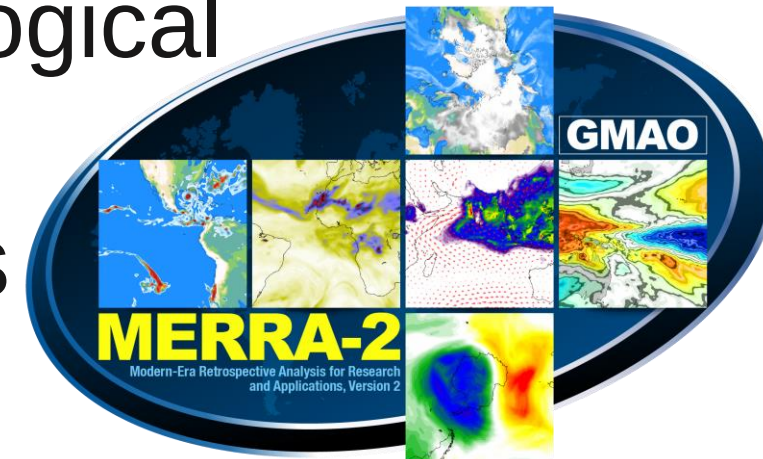
GEOS 5.17	11/01/2017 - 7/11/2018
5.21	7/11/2018 - 3/13/2019
5.22	3/13/2019 - 1/30/2020
5.25	1/30/2020 - on-going

GEOS 5.12.4



NASA's MERRA-2 Reanalysis

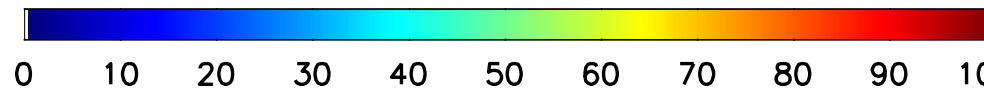
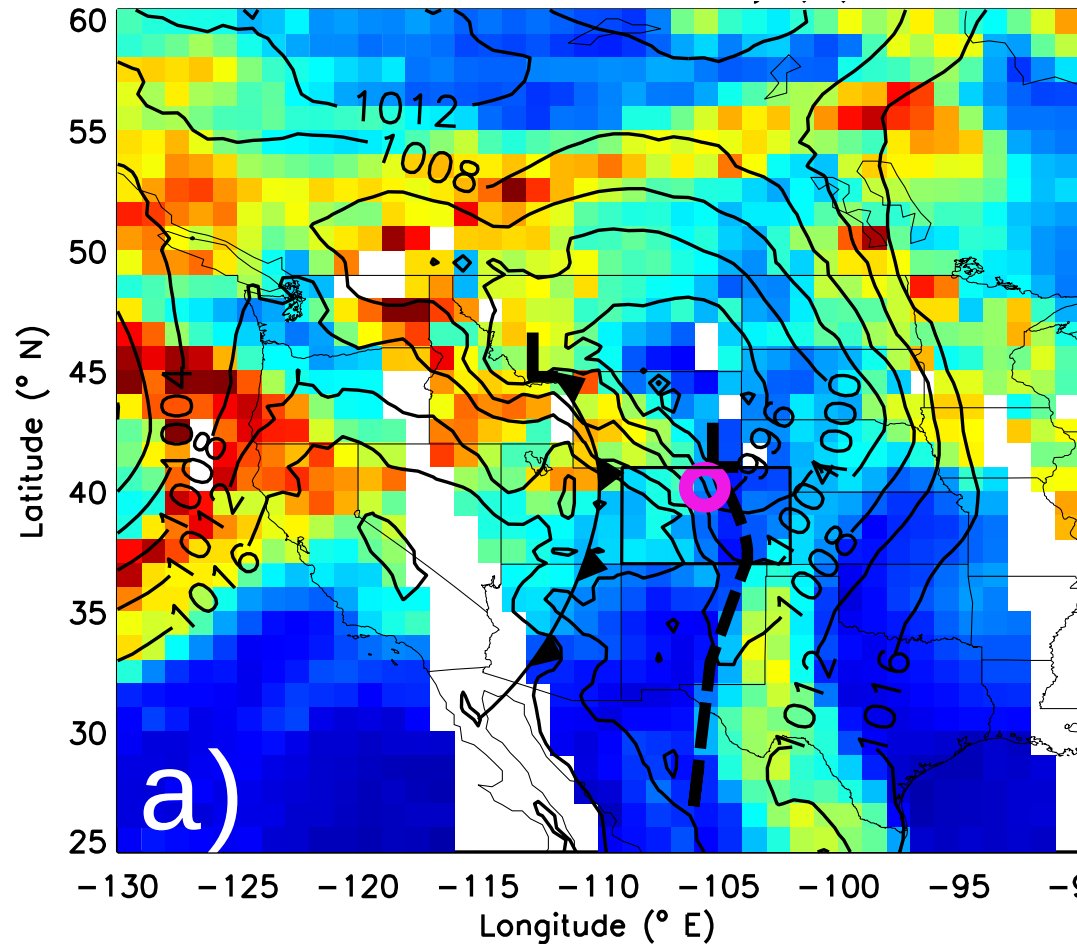
- High resolution global data set
 - 50 km horizontal
0.5° latitude x 0.625° longitude
 - 72 levels up to 0.01 hPa
- Product of GEOS data assimilation system
 - Assimilates conventional meteorological observations, aerosols and ozone
- Available since 1980 to a few weeks behind present



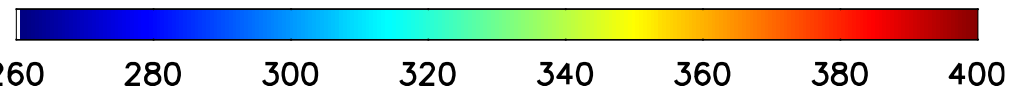
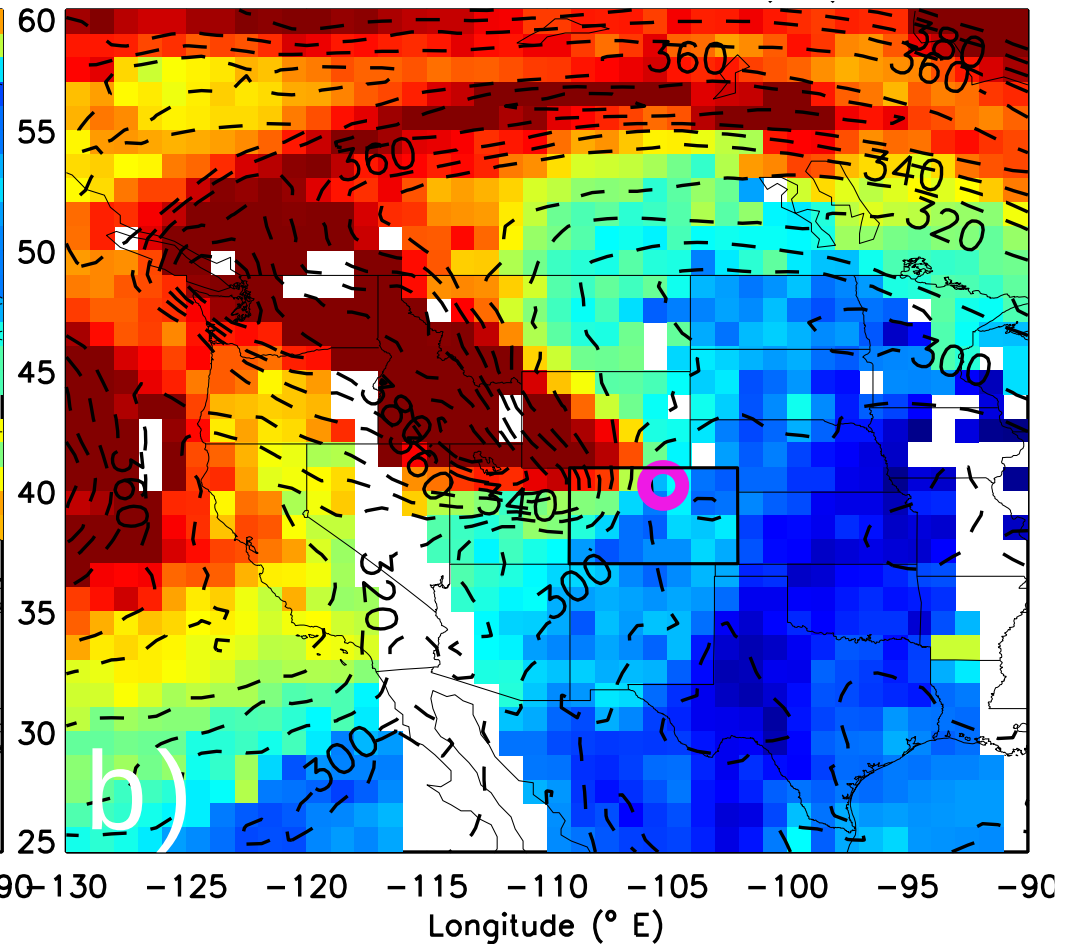
Question 1

Can MERRA-2 capture the dynamical features of a stratospheric intrusion?

AIRS 700 hPa RH (%)

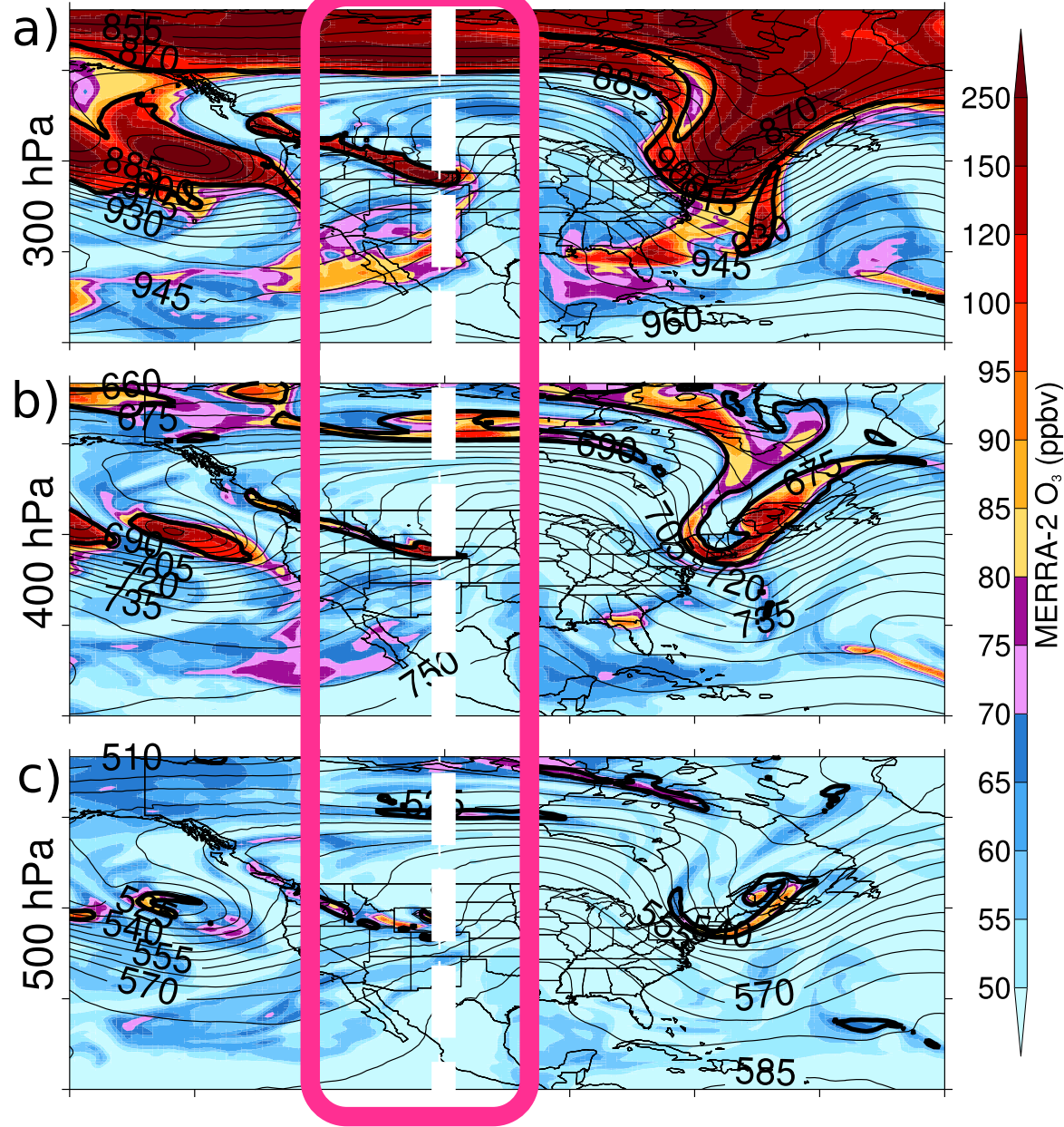


AIRS vs M2 TCO (DU)



Knowland et al., 2017, GRL

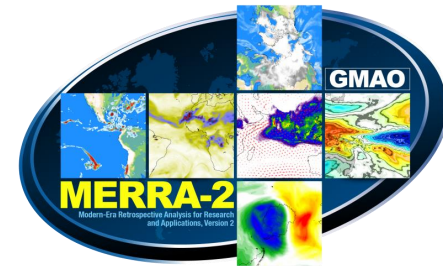
March 27, 2012 0UTC



MERRA-2

Fine-scale filaments of stratospheric air at 300 to 500 hPa with high values of PV (> 2 PVU)

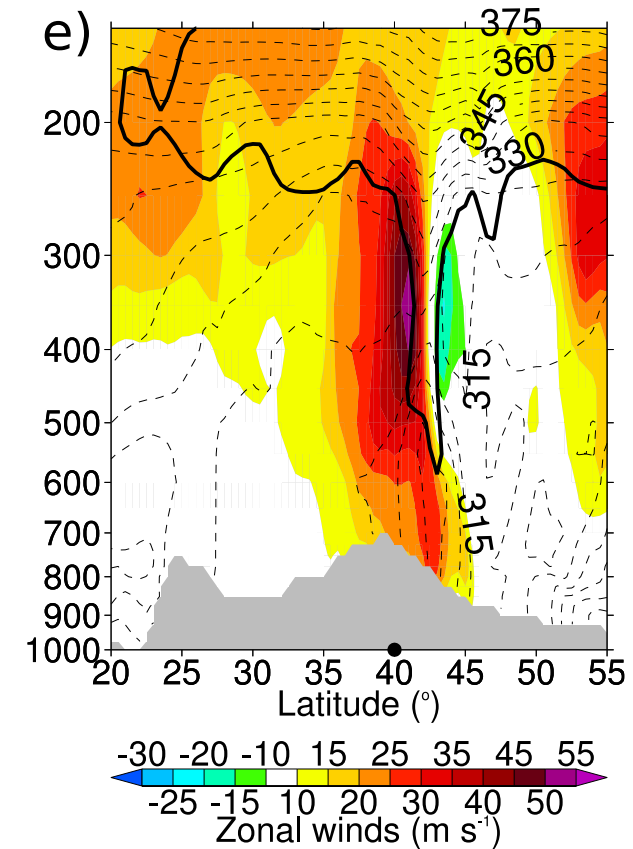
- distinguish the SI from background tropospheric O₃



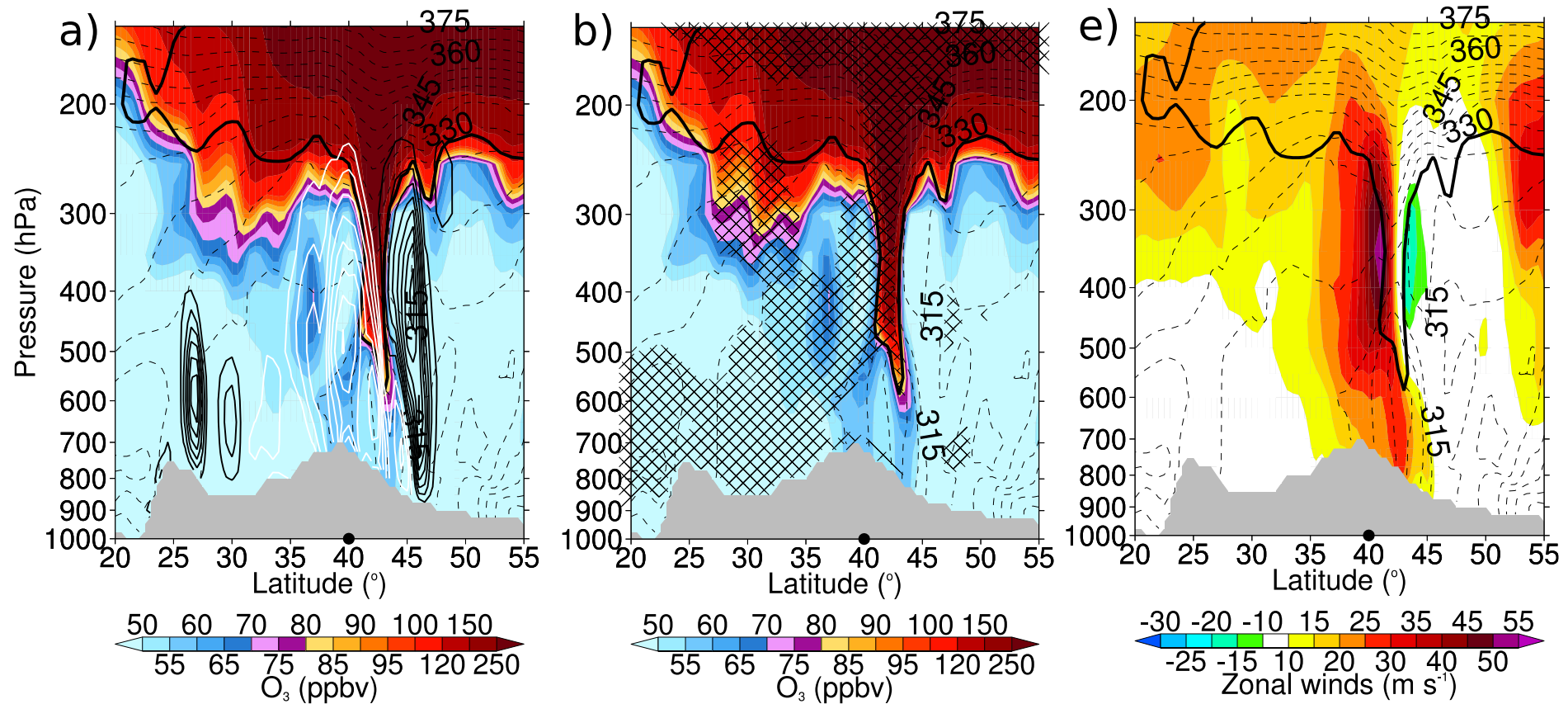
Knowland et al., 2017, GRL

Atmospheric dynamics

- ✓ Tropopause descends to ~600 hPa
- ✓ Wrapped around jet core

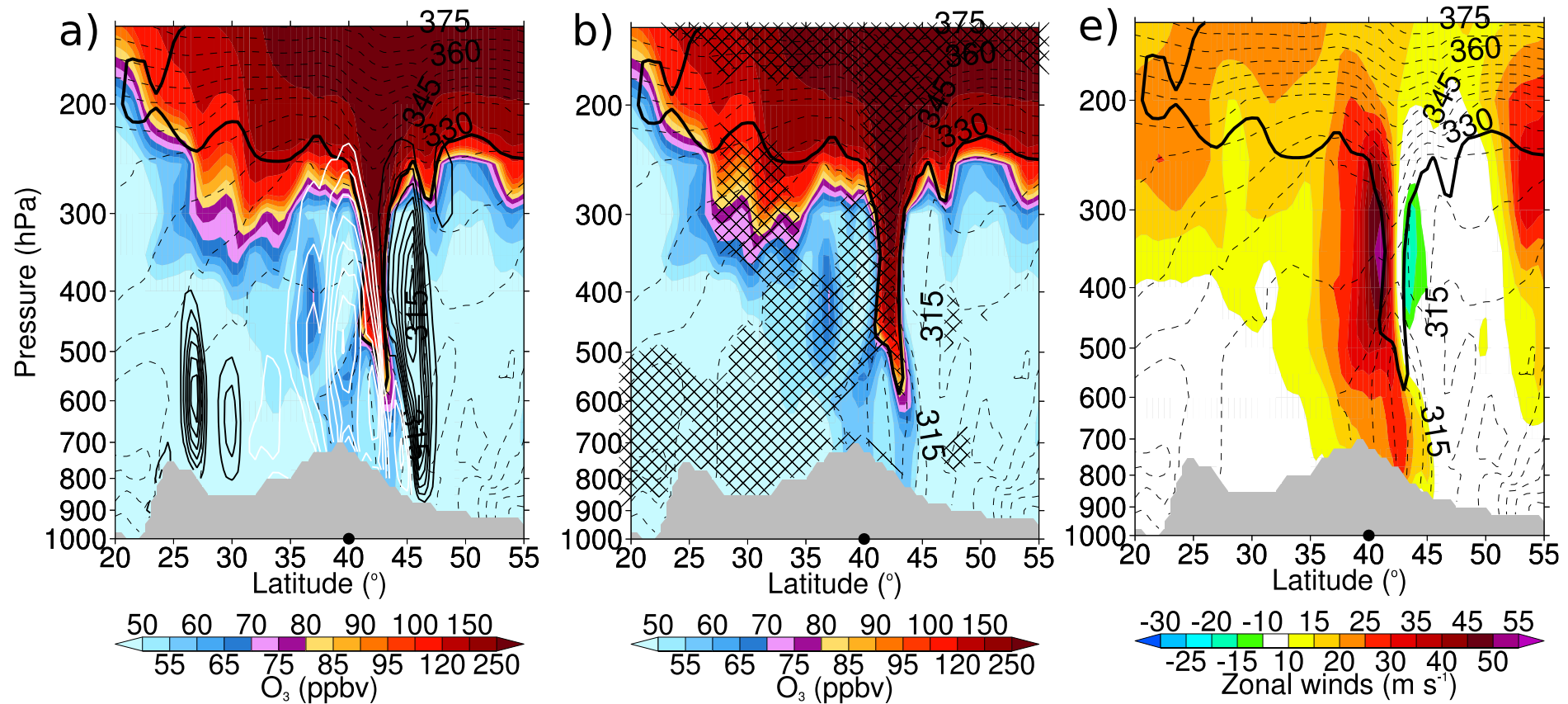


Knowland et al., 2017, GRL



- Tropopause folds are associated with:
 - High O₃, PV (2PVU thick line)
 - Low RH (hatching), CO (not shown)

Knowland et al., 2017, GRL



- Since assimilated O₃ is mainly stratospheric, MERRA-2 O₃ is realistic within the SIs, however biased elsewhere in the troposphere. Knowland et al., 2017, GRL

Question 2

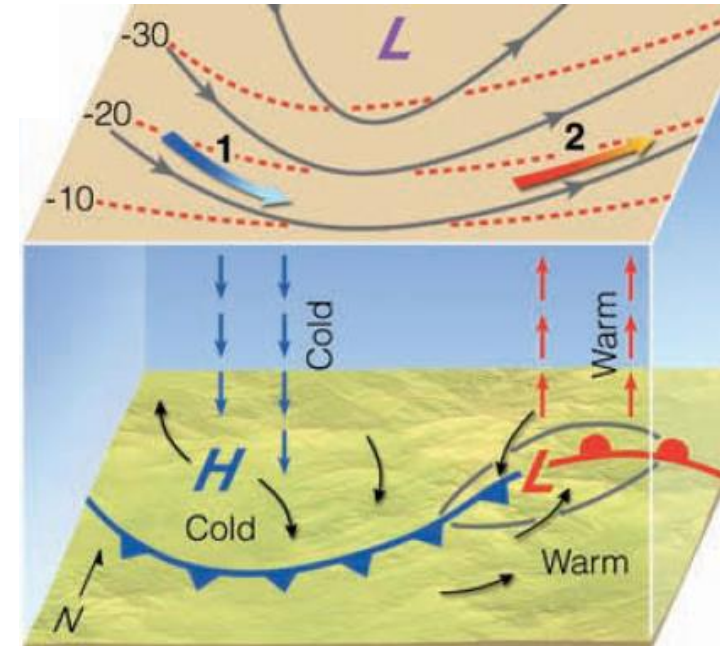


Can we build a catalogue of SI events using the MERRA-2 Reanalysis?

Construct Upper-level Tracks

Use TRACK (Hodges 1995, 1999) to identify cyclones in MERRA-2 by maxima in 850-hPa relative vorticity ($\zeta_{850 \text{ hPa}}$)

1. Smaller scale systems are more easily identified
2. Not strongly influenced by the large scale background field
3. Less extrapolation below orography



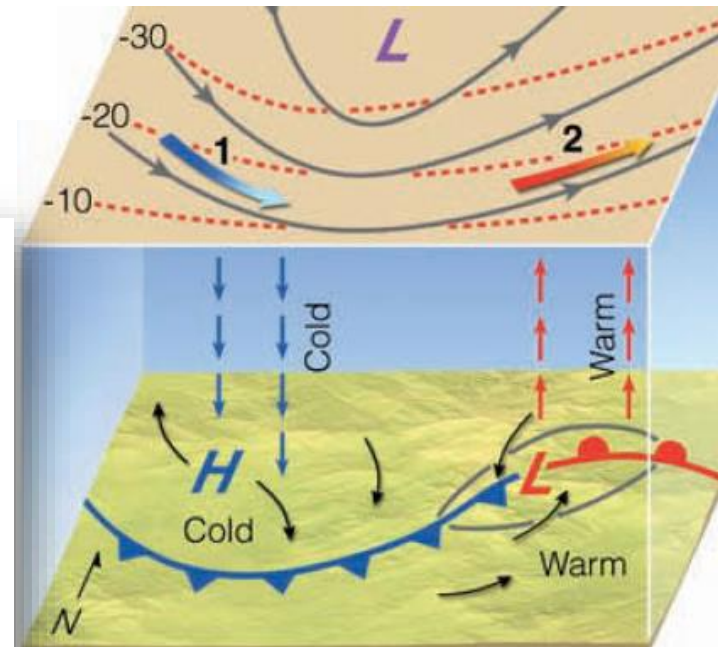
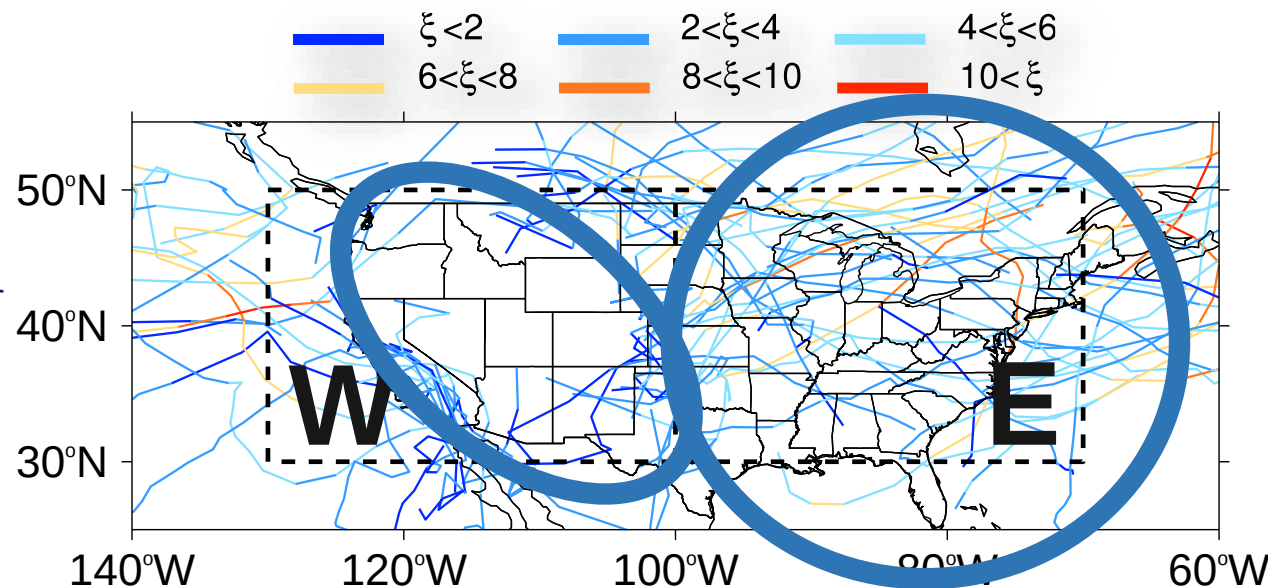
Knowland et al., in prep.

Construct Upper-level Tracks

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MAM 2012

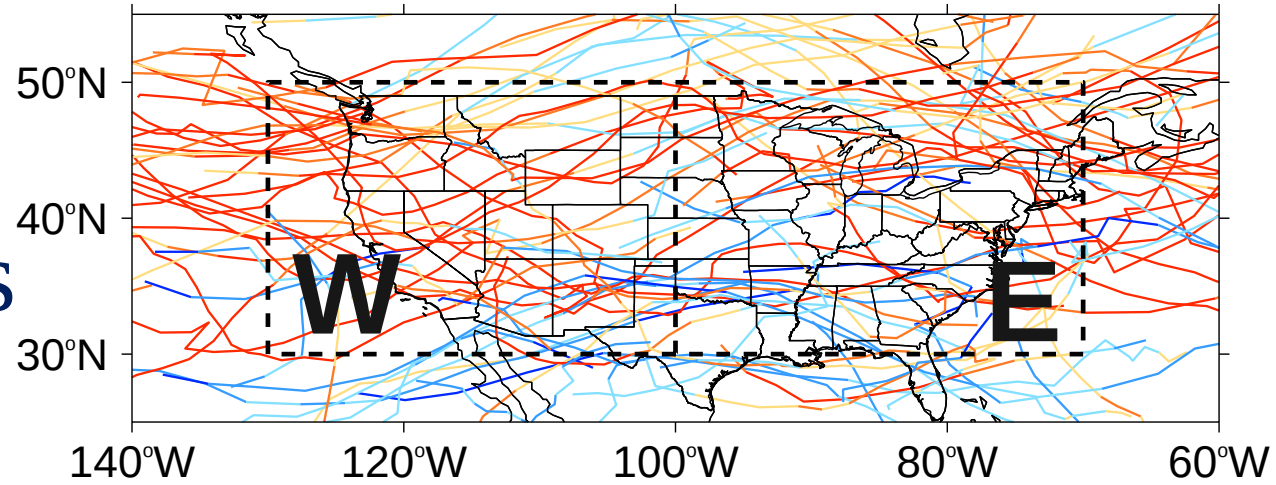
$\zeta_{850 \text{ hPa}}$ storm tracks



Knowland et al., in prep.

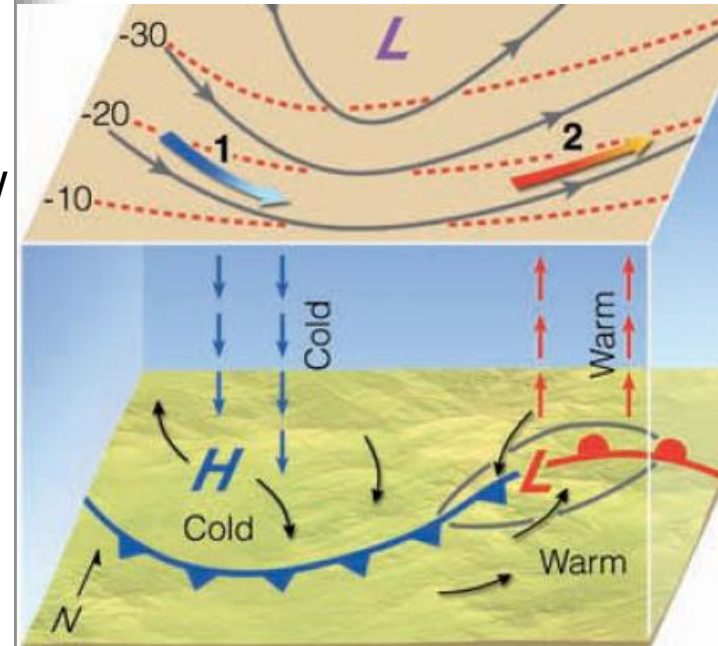
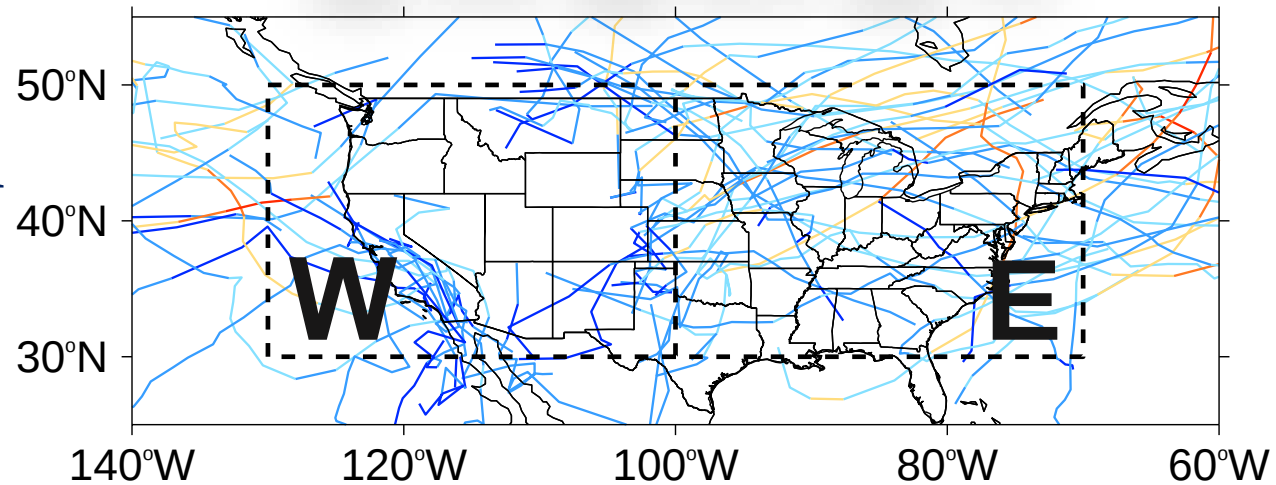
Construct Upper-level Tracks

$\zeta_{300 \text{ hPa}}$ tracks



MAM 2012

$\zeta_{850 \text{ hPa}}$ storm tracks



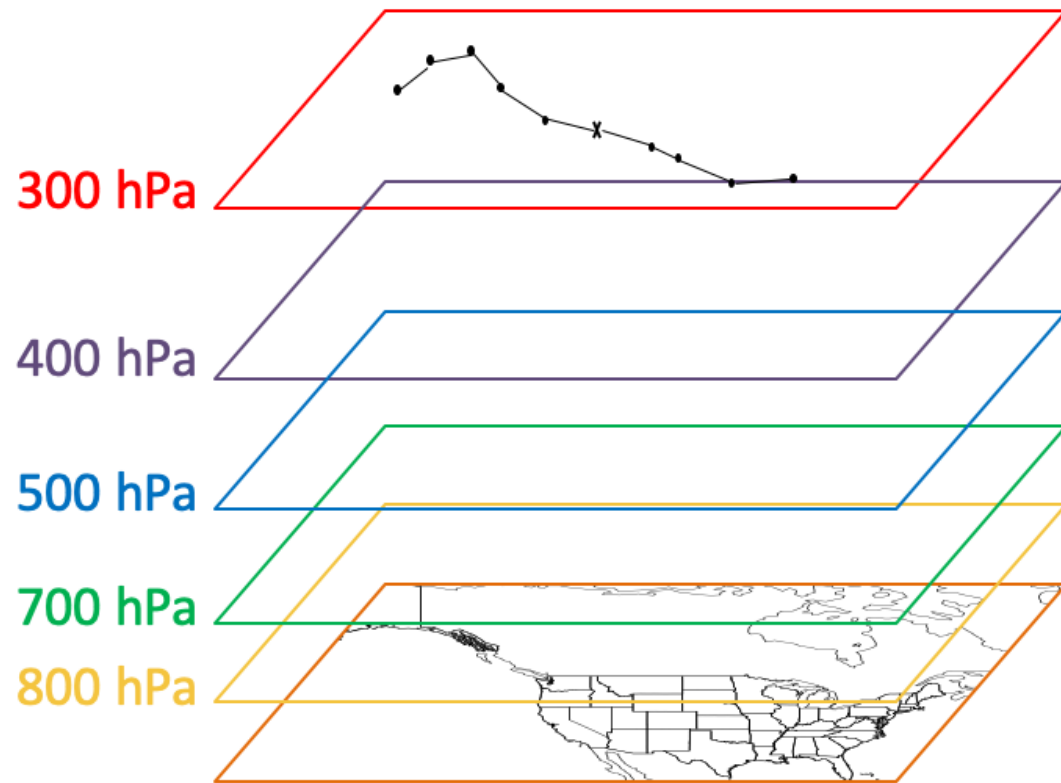
Knowland et al., in prep.

1. Construct “Storm tracks”

TRACK output has the form

DATE LONGITUDE LATITUDE VARIABLE

where VARIABLE is $\zeta_{300 \text{ hPa}}$



2. SI Filtering Methodology

The $\zeta_{300 \text{ hPa}}$ tracks for the ten-year period from 2005-2014 were selected for most consistent O3 observing system:

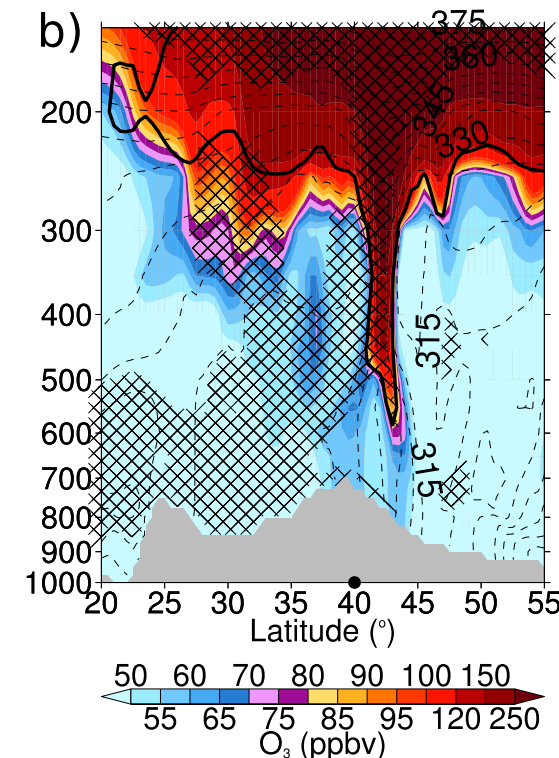
- Since October 2004, high vertical resolution stratospheric O₃ profiles from MLS and total column ozone from OMI constrain the model ozone.
- In 2015, change in MLS from v2.2 to v4.2 resulted in anomalously higher ozone in upper troposphere. In 2016, MLS 261-hPa level was turned off in the DAS.

Knowland et al., in prep.

2. SI Filtering Methodology

In order to select tracks which are likely associated with SIs, the $\zeta_{300 \text{ hPa}}$ tracks for

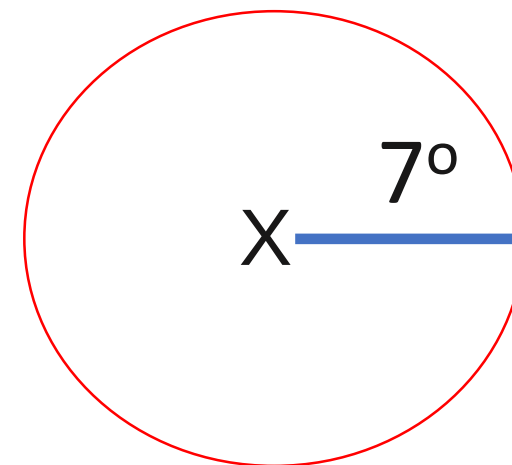
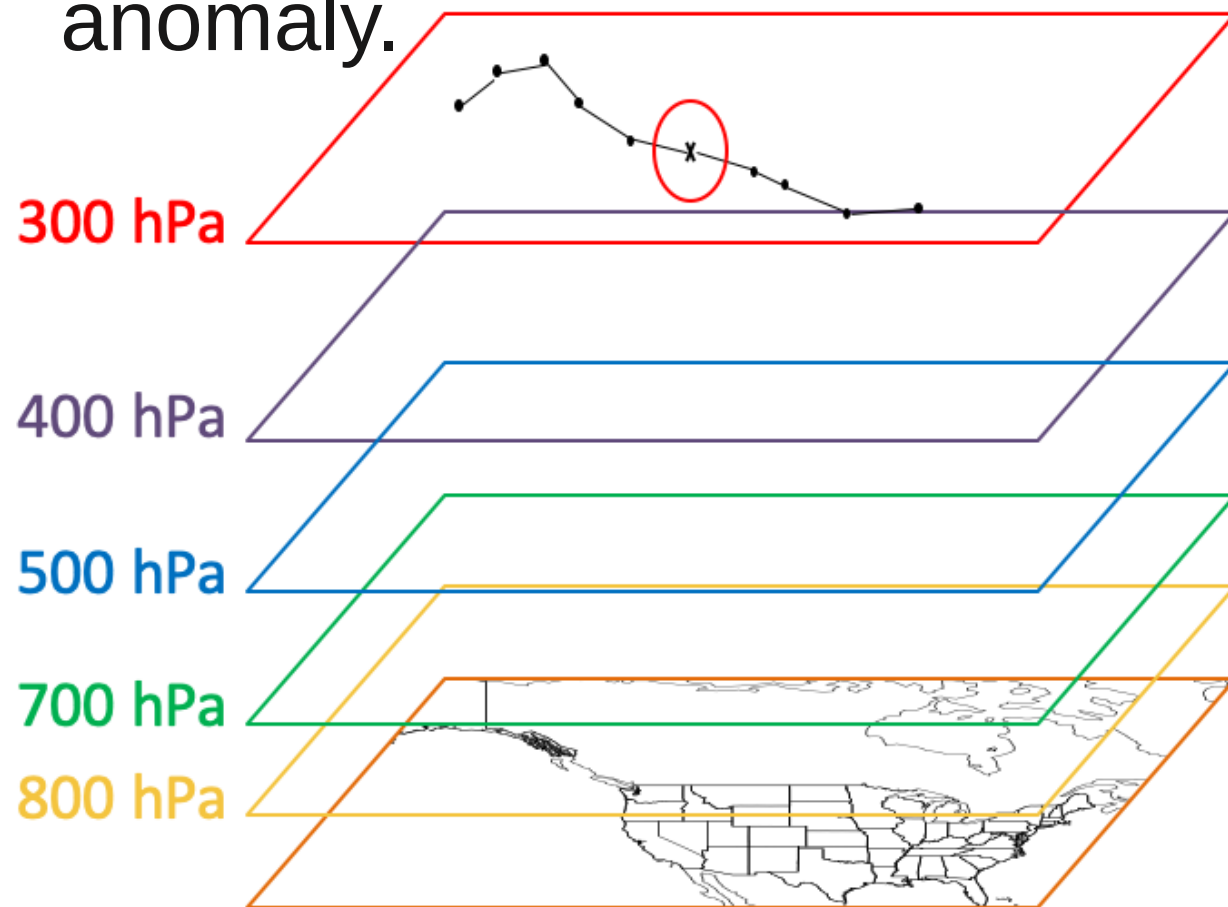
1. 2005-2014 were selected.
2. Set filtering thresholds based on anomalies
 1. max EPV > 2 PVU,
 2. min RH < 10 %,
 3. max O_3 > 25 ppbv, > 50 ppbv, > 100 ppbv,within 7° search radius



Knowland et al., in prep.

2. SI Filtering Methodology

- Search radius around the “track point” for the maximum anomaly.

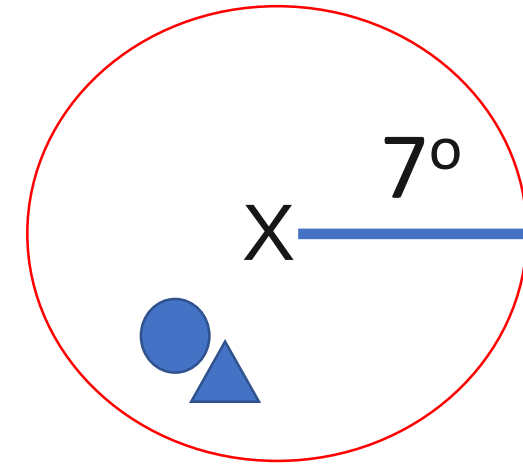
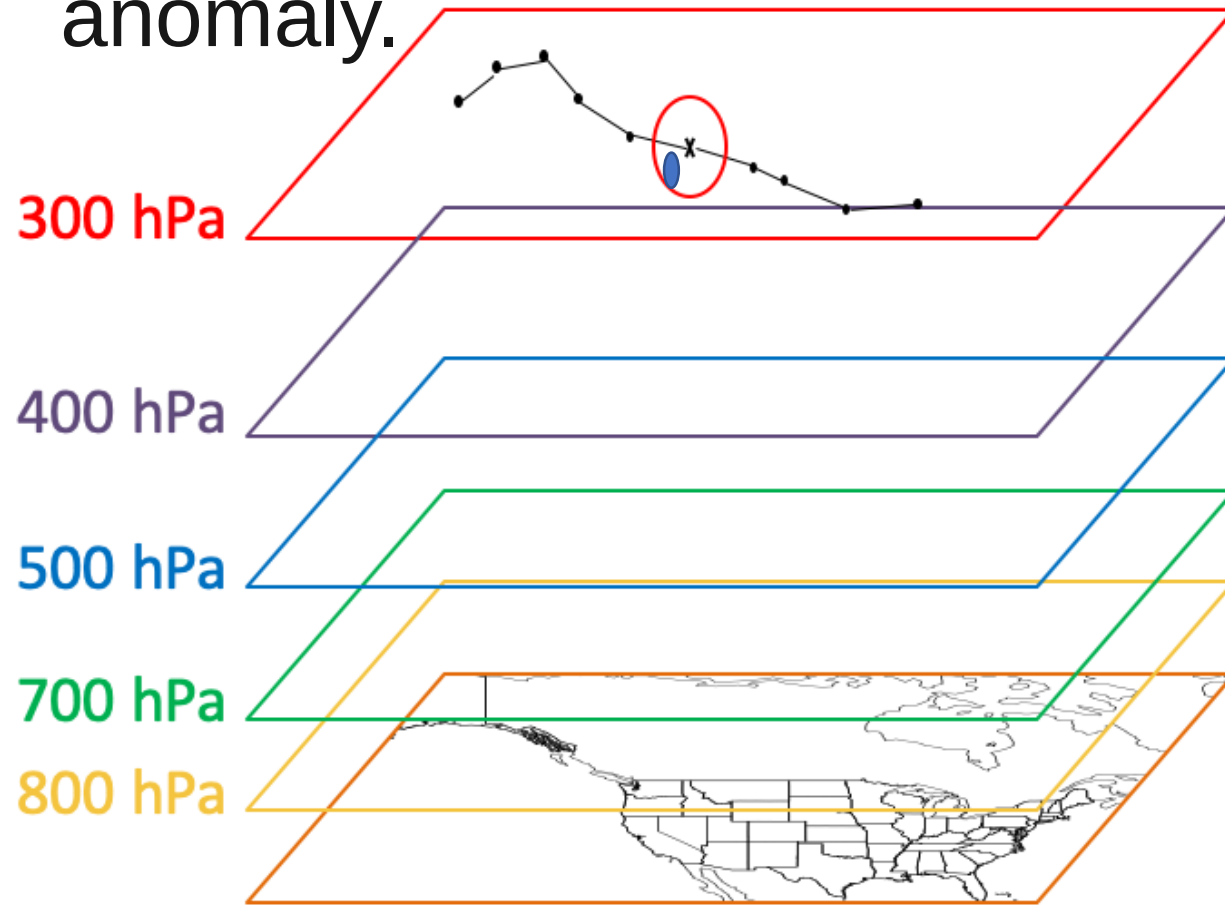


Radial coordinate system for a given radius is chosen

Knowland et al., in prep.

2. SI Filtering Methodology

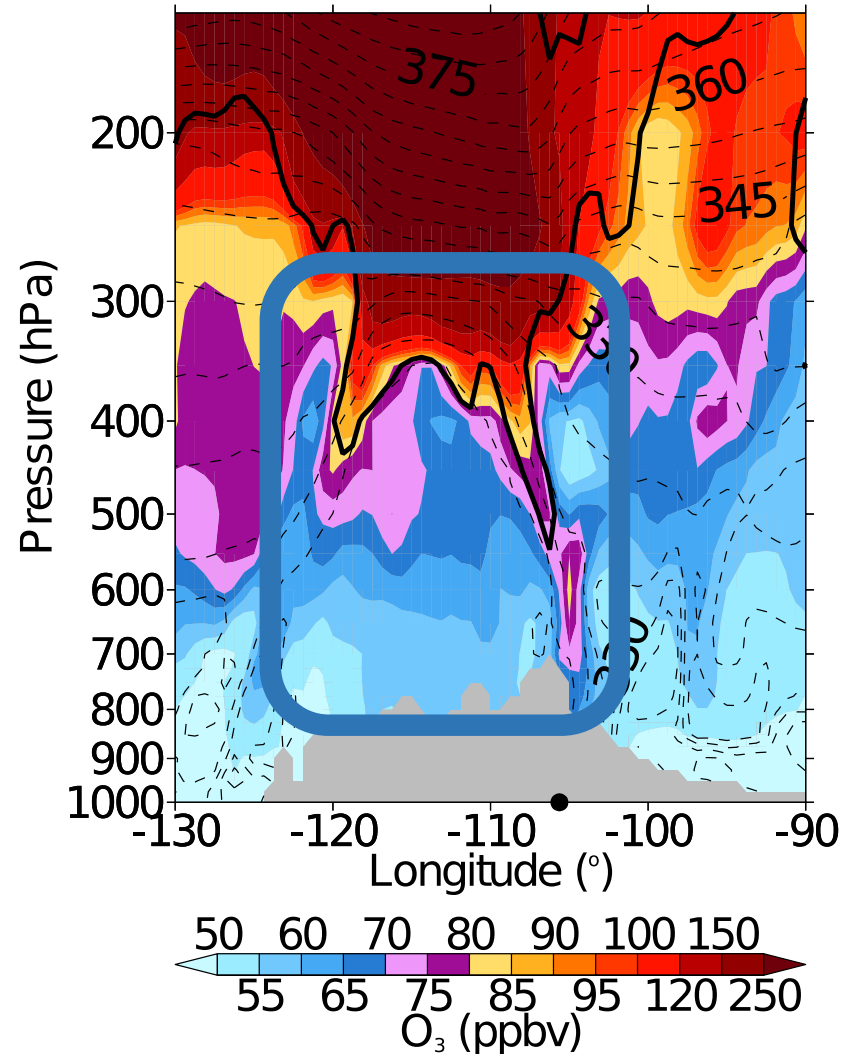
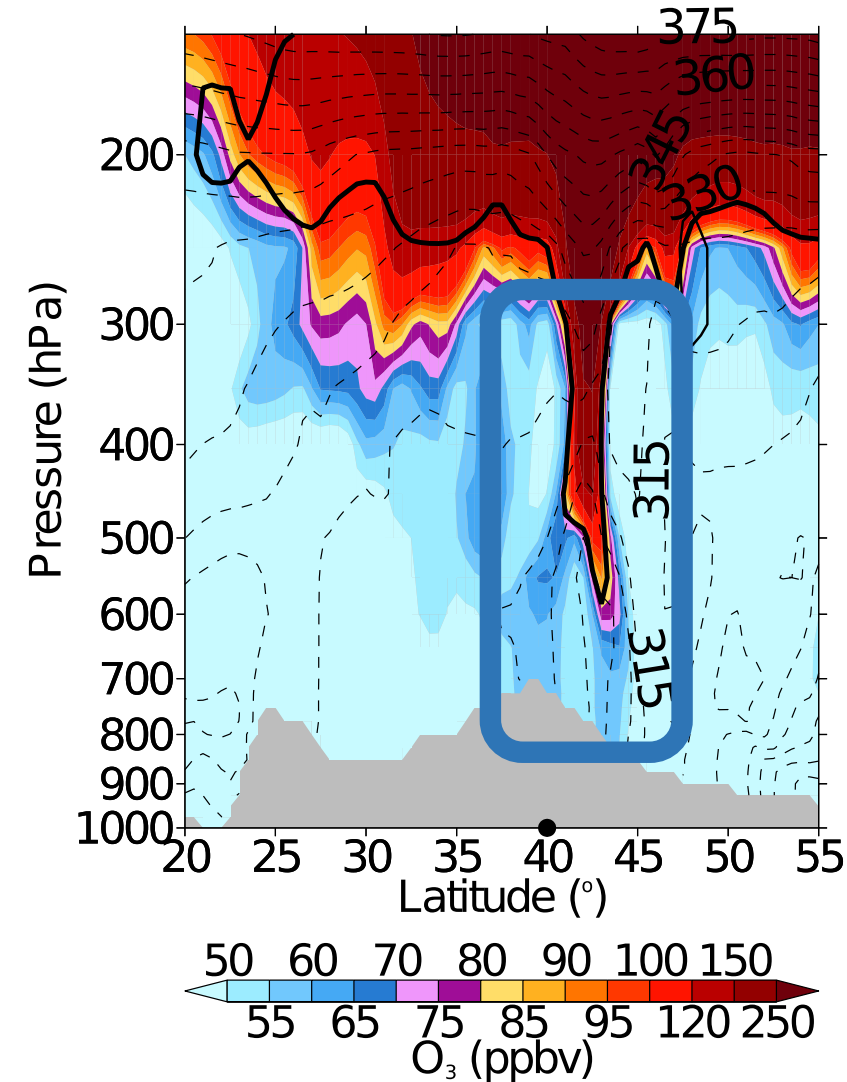
- Search radius around the “track point” for the maximum anomaly.



- Location of Max EPV anomaly
- ▲ Location of Max O₃ anomaly

Knowland et al., in prep.

2. SI Filtering Methodology



Sensitivities tests were done for radii from 2° to 15°

2. SI Filtering Methodology

- Attach to each “track point”, the max (or min) anomaly of MERRA-2 fields known to be associated with intrusions:

- Max EPV,

- Min RH,

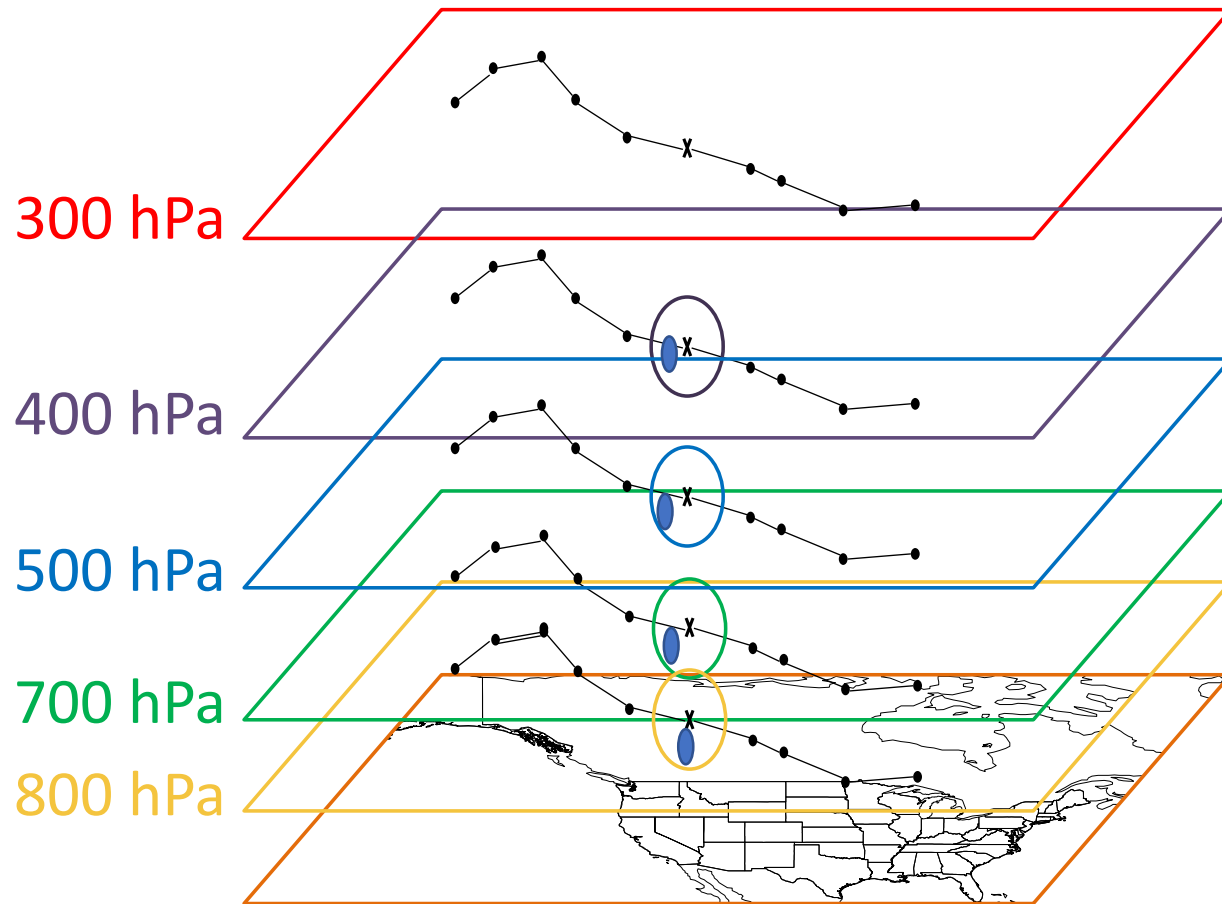
- Max O_3 ,

- Max ω ,

e.g., DATE LON LAT $\zeta_{300 \text{ hPa}}$ LON LAT EPV anomaly_{400 hPa}

2. SI Filtering Methodology

- Working toward the surface, check that at least one point along the track has max EPV anomaly $> 2\text{PVU}$.



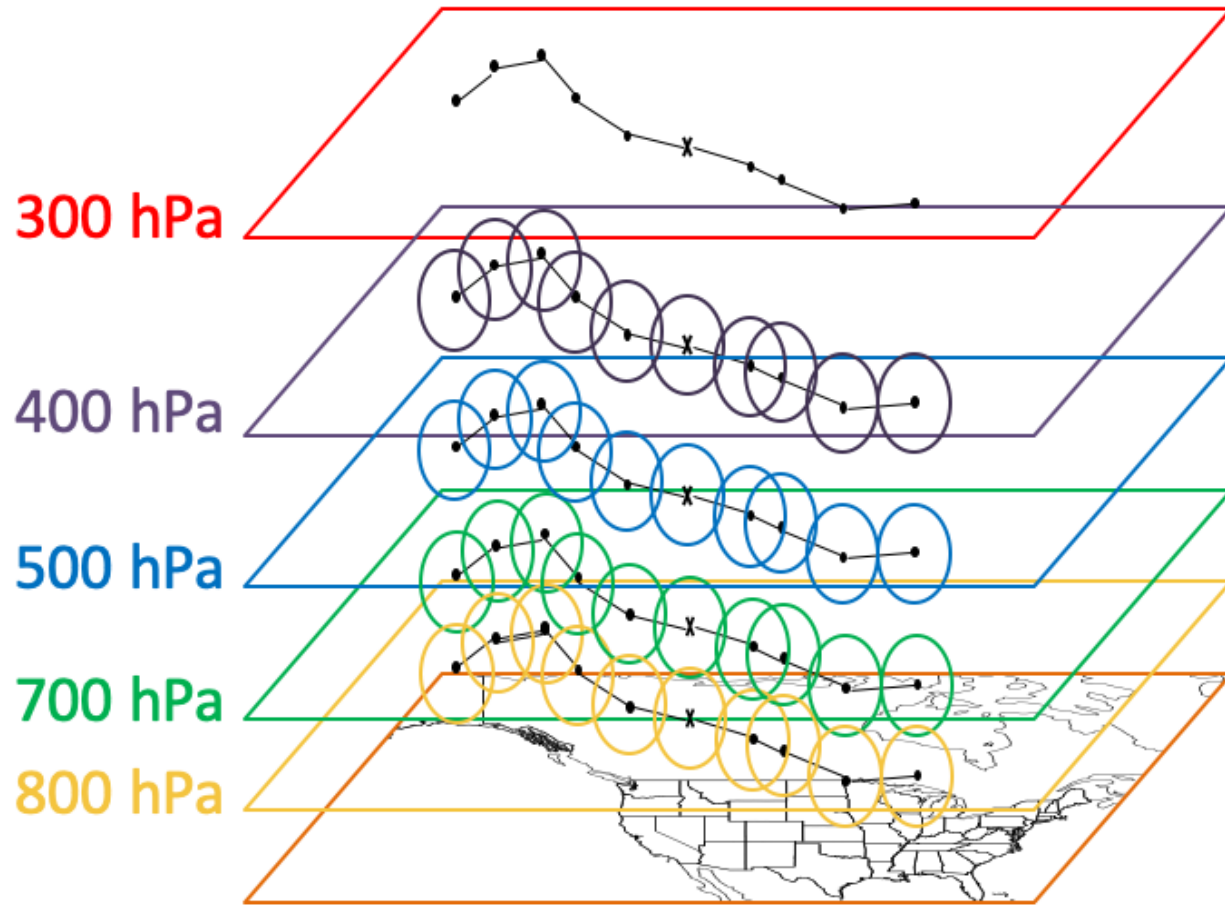
➤ Apply to multiple levels at same track point

e.g., DATE LON LAT $\zeta_{300 \text{ hPa}}$
 LON LAT EPV_{anom}₄₀₀
 hPa LON LAT
 EPV_{anom}_{500 hPa} LON
 LAT EPV_{anom}_{600 hPa}
 LON LAT EPV_{anom}_{700 hPa}

Knowland et al., in prep.

2. SI Filtering Methodology

- Working toward the surface, check that at least one point along the track has max EPV anomaly $> 2\text{PVU}$.



- Apply to multiple levels at same track point
- Apply to all points along the track

Knowland et al., in prep.

2. SI Filtering Methodology

In order to select tracks which are likely associated with SIs, the $\zeta_{300 \text{ hPa}}$ tracks were filtered for at least 1 timestep and within 7° search radius:

1. At each pressure level filter tracks with max EPV anomaly > 2 PVU.
 - a. Subset tracks further where EPV > 2 PVU for 4 timesteps
 - b. Filter tracks for min RH anomaly $< 10 \%$,
 - c. Filter tracks for max O_3 anomaly > 25 ppbv, > 50 ppbv, > 100 ppbv

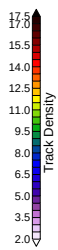
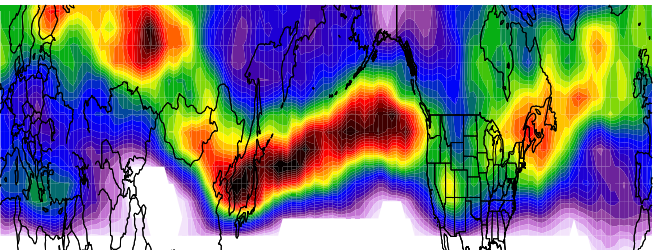
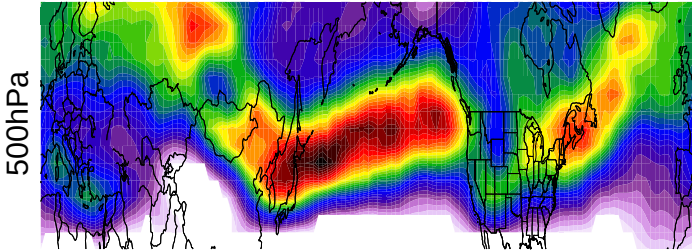
Knowland et al., in prep.



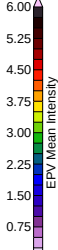
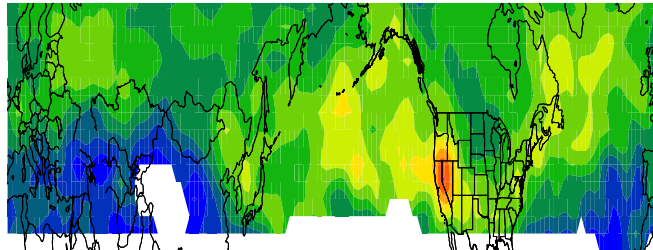
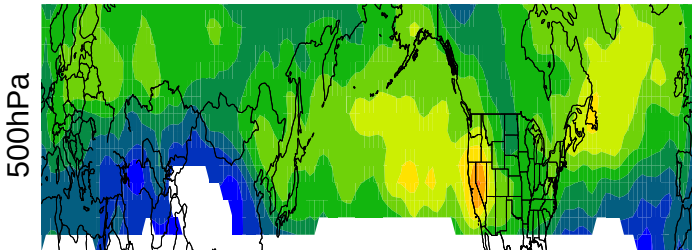
MAM 1980-2014

MAM 2005-2014

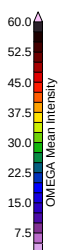
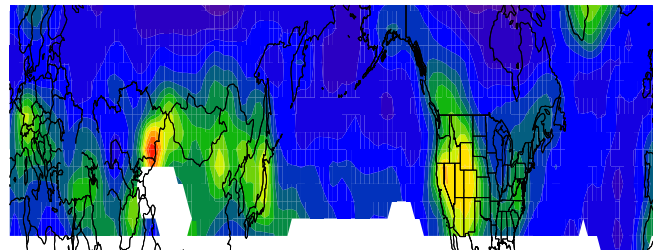
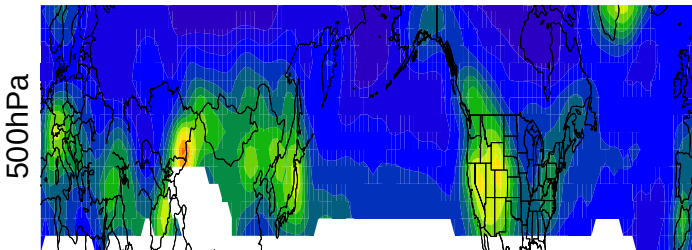
ζ_{300}



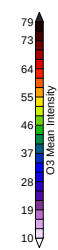
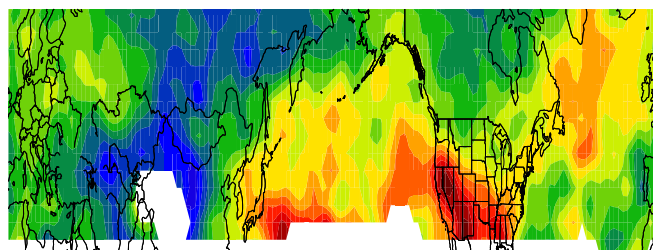
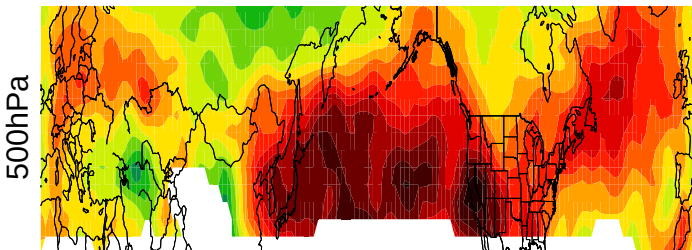
PV



ω

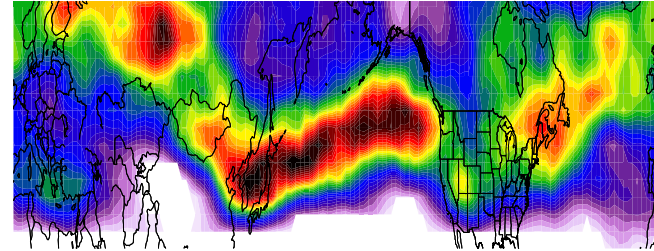
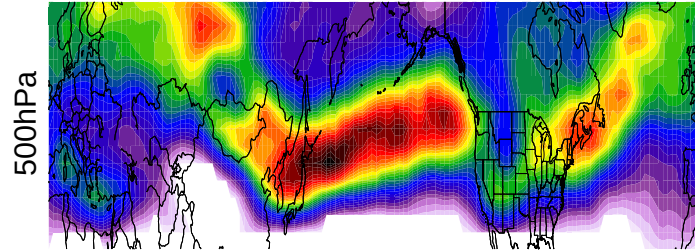


O_3

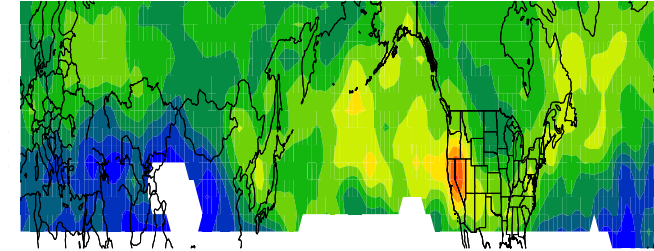
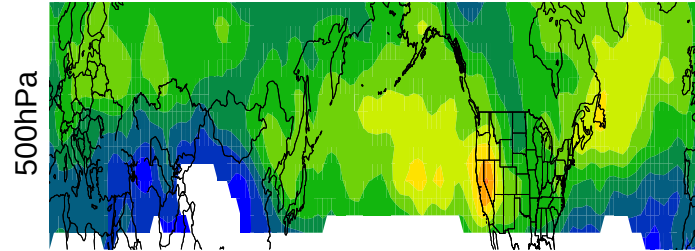


MAM 1980-2014

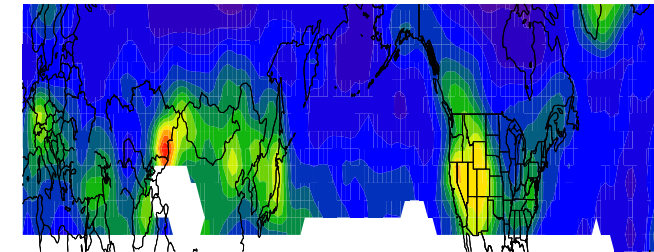
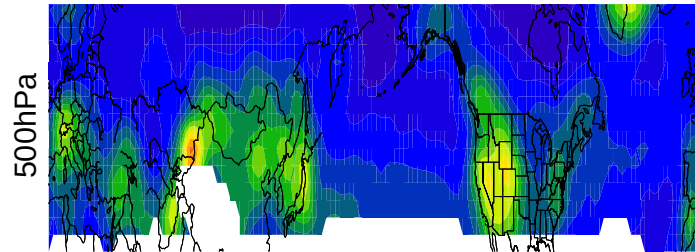
MAM 2005-2014

 ζ_{300} 

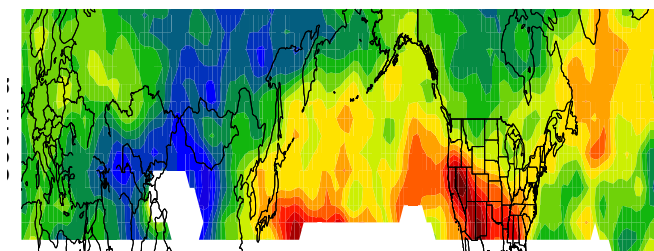
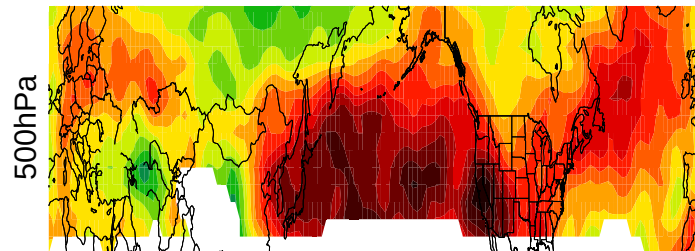
Track Density

 PV 

EPV Mean Intensity

 ω 

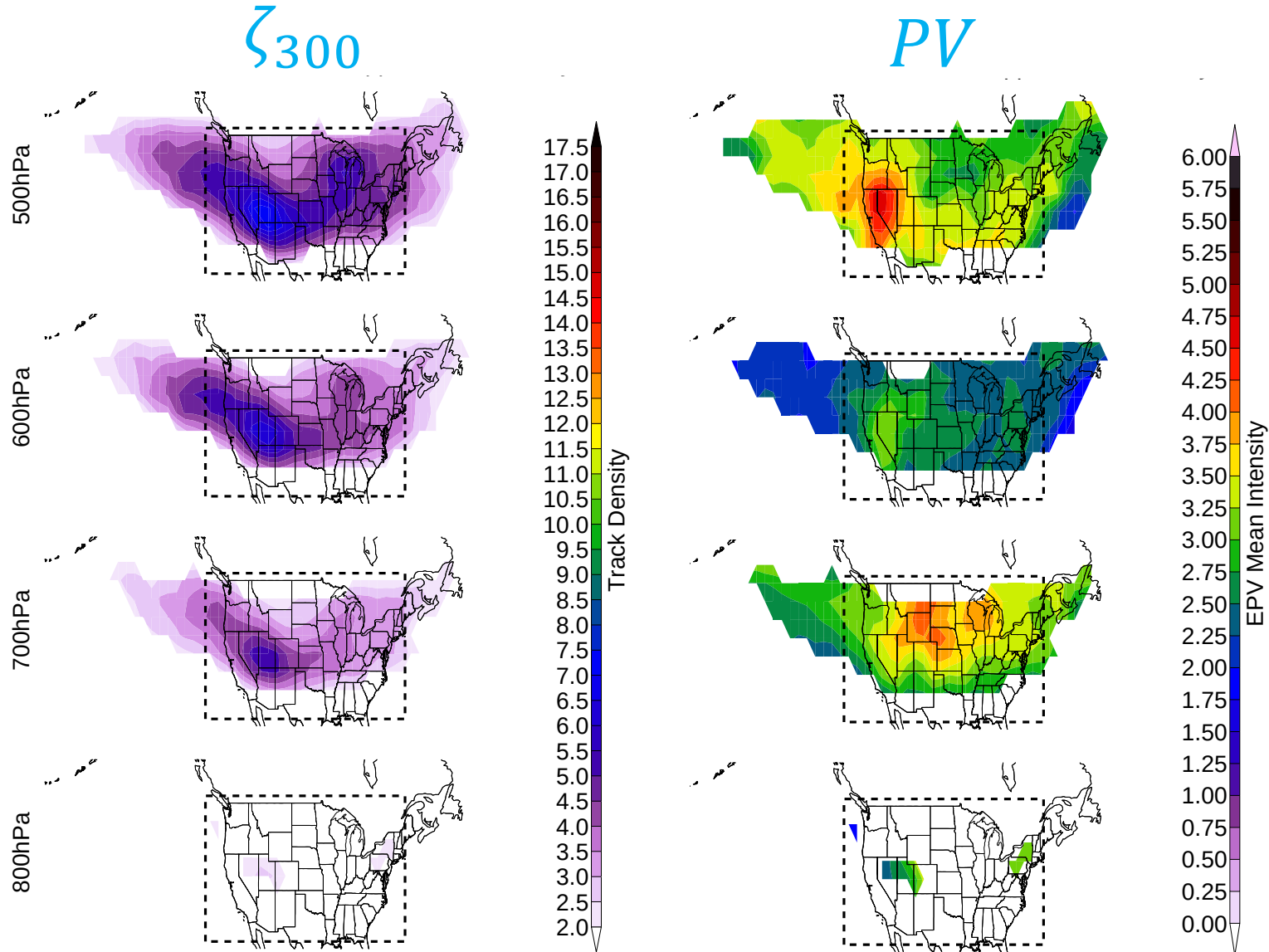
OMEGA Mean Intensity

 O_3 

O3 Mean Intensity

Clearly, we can see the impact of the change in the ozone observing system!

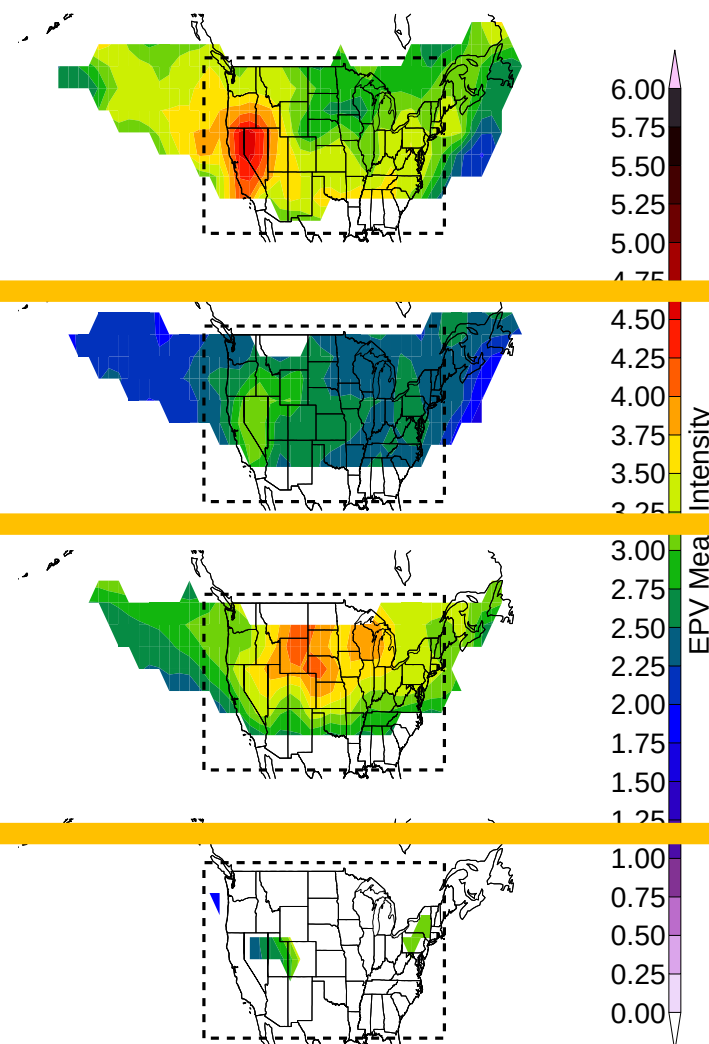
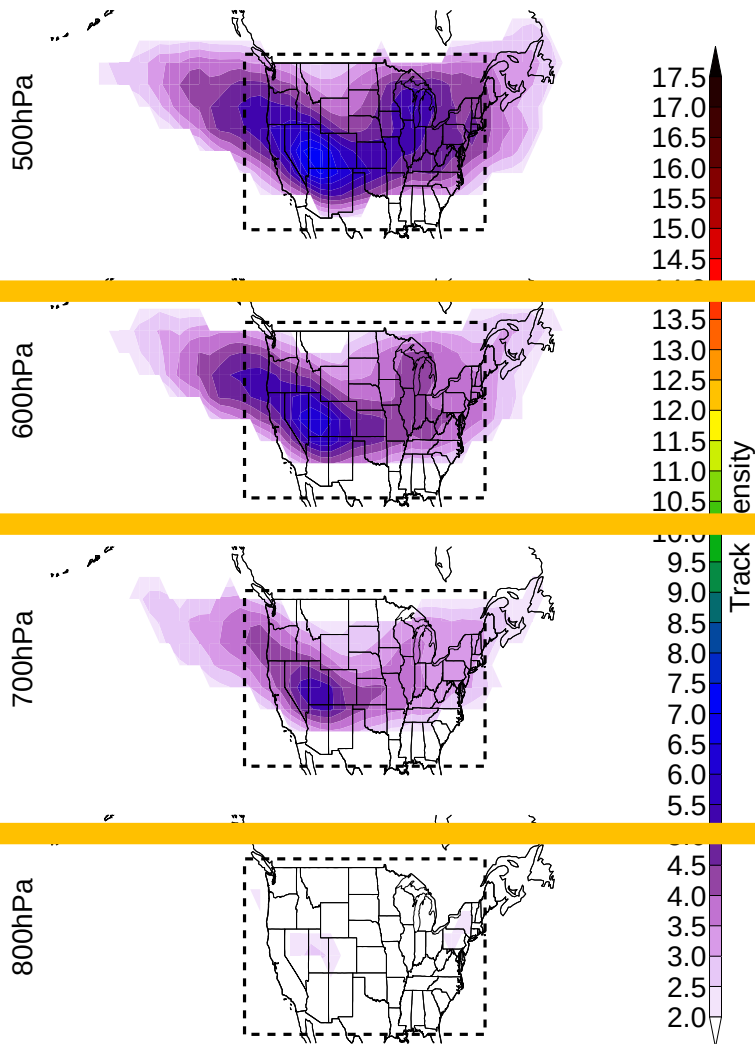
SI Filtered tracks: MERRA2 MAM 2005-2014 USA



SI Filtered tracks: MERRA2 MAM 2005-2014 USA

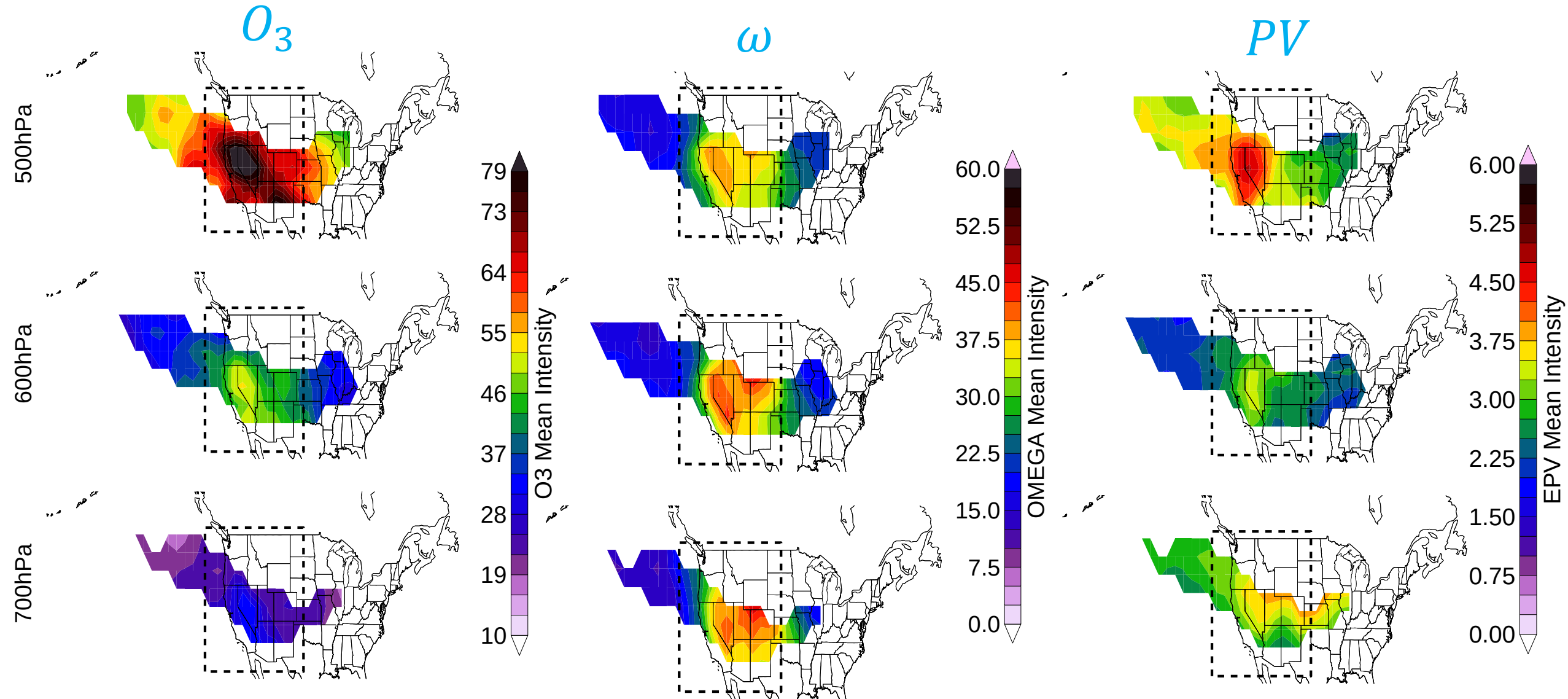
 ζ_{300}

PV



Max PV
anomalies
at 700 hPa
are
northeast
of max
track
density

SI Filtered tracks: Western USA MAM 2005-2014

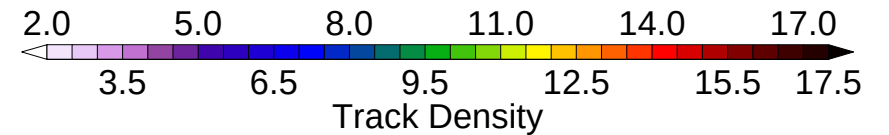
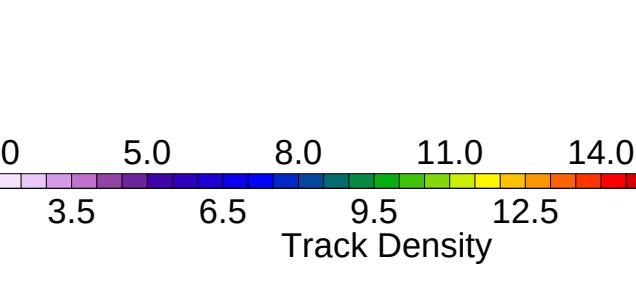
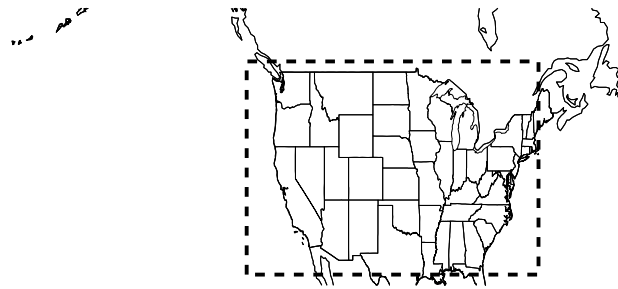
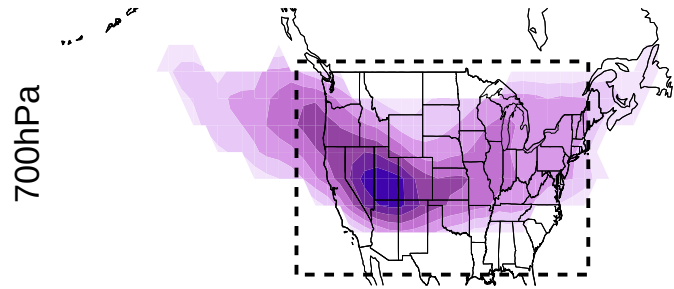
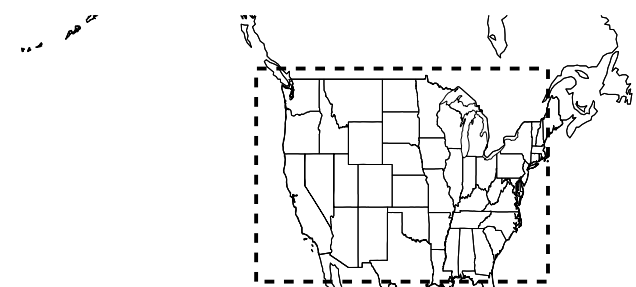
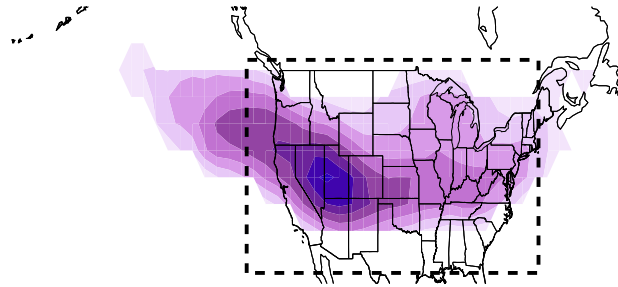
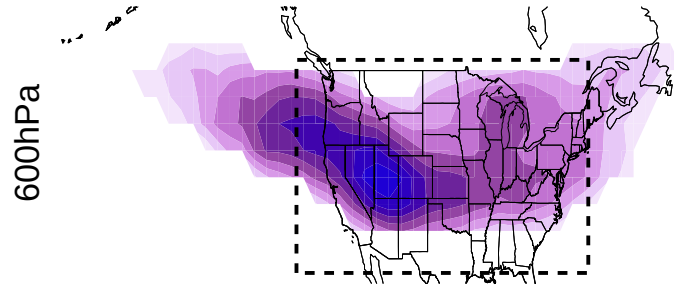
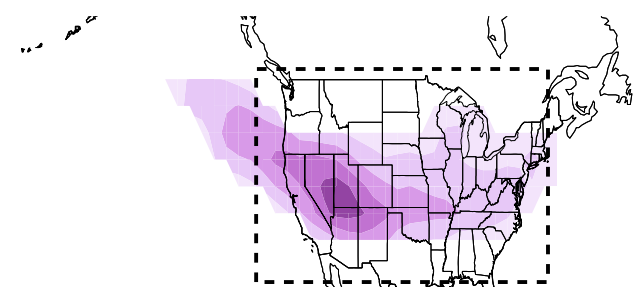
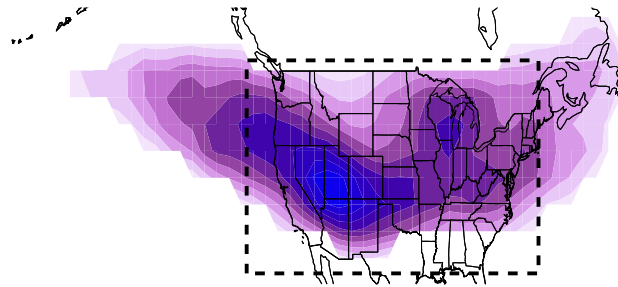
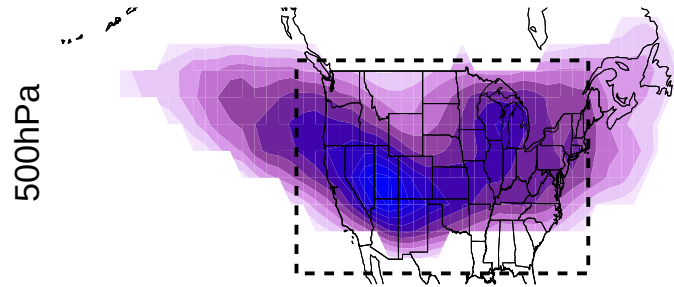


Track Density: USA MAM 2005-2014

$O_3 > 25 \text{ ppb}$

$O_3 > 50 \text{ ppb}$

$O_3 > 100 \text{ ppb}$

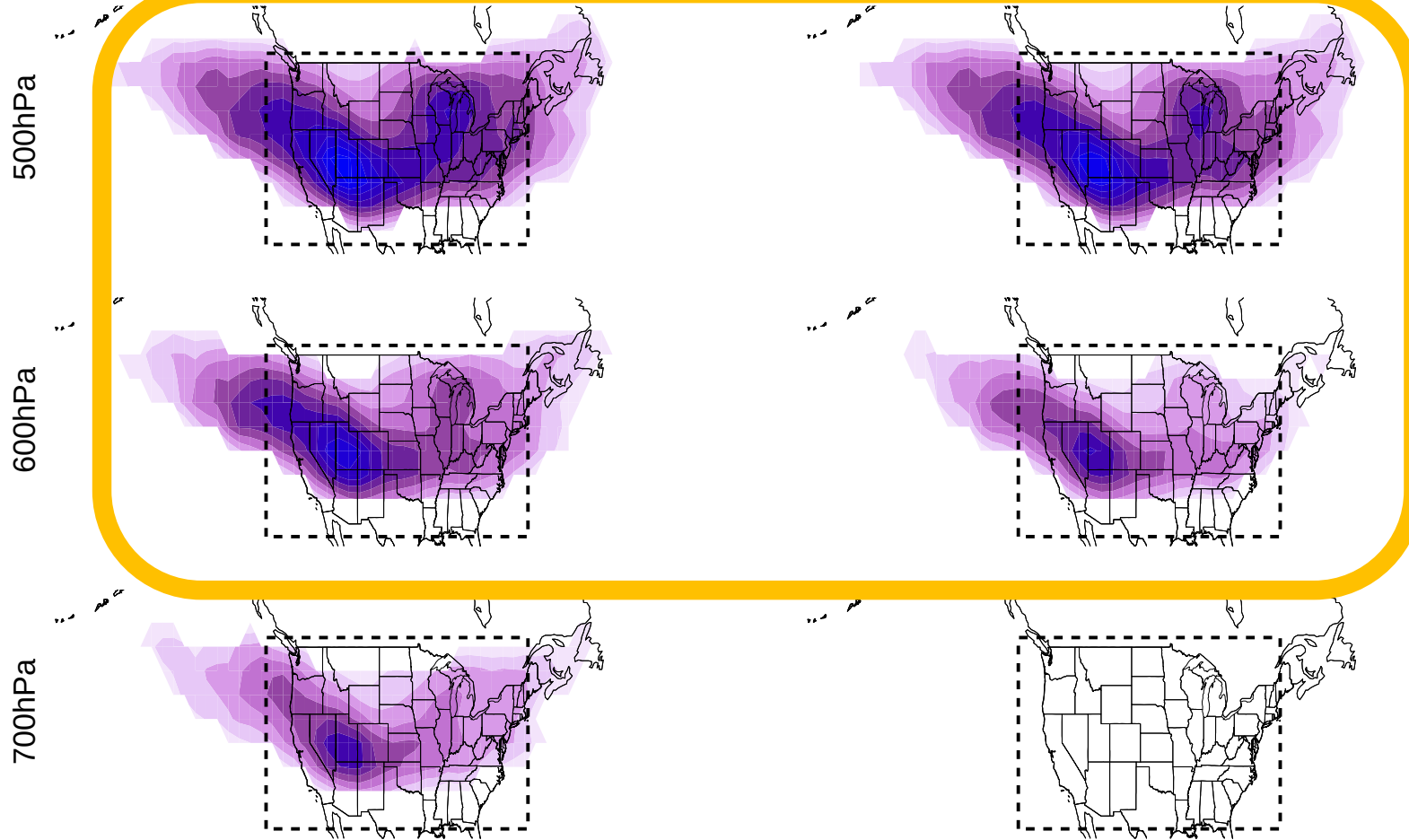


Track Density: USA MAM 2005-2014

$O_3 > 25 \text{ ppb}$

$O_3 > 50 \text{ ppb}$

$O_3 > 100 \text{ ppb}$



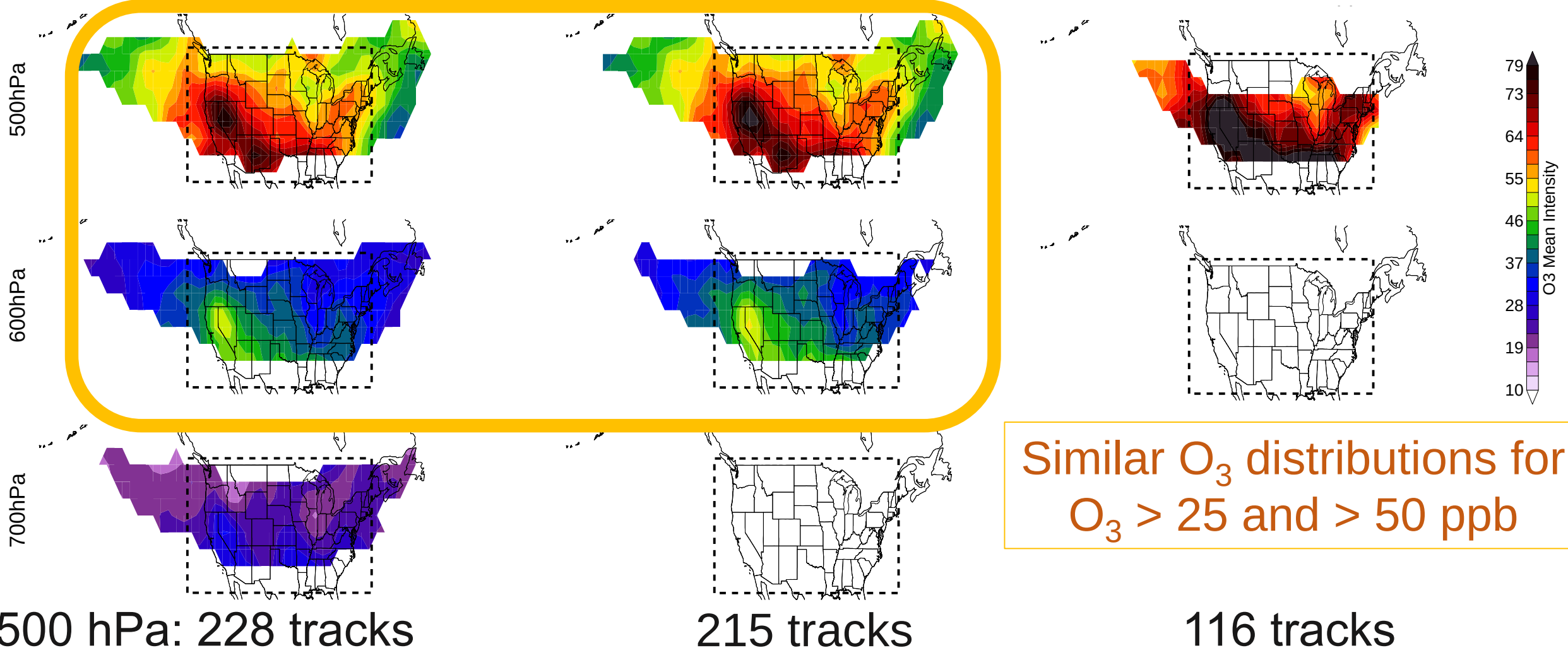
Similar track pattern for lower thresholds, though less dense for $O_3 > 50 \text{ ppb}$

Anomalous Ozone: USA MAM 2005-2014

$O_3 > 25 \text{ ppb}$

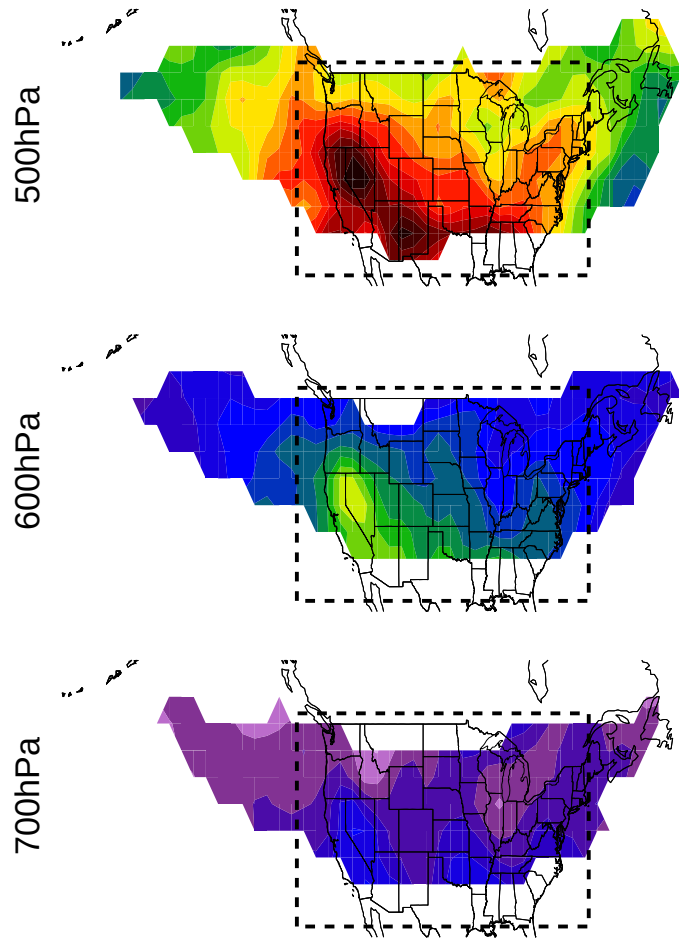
$O_3 > 50 \text{ ppb}$

$O_3 > 100 \text{ ppb}$



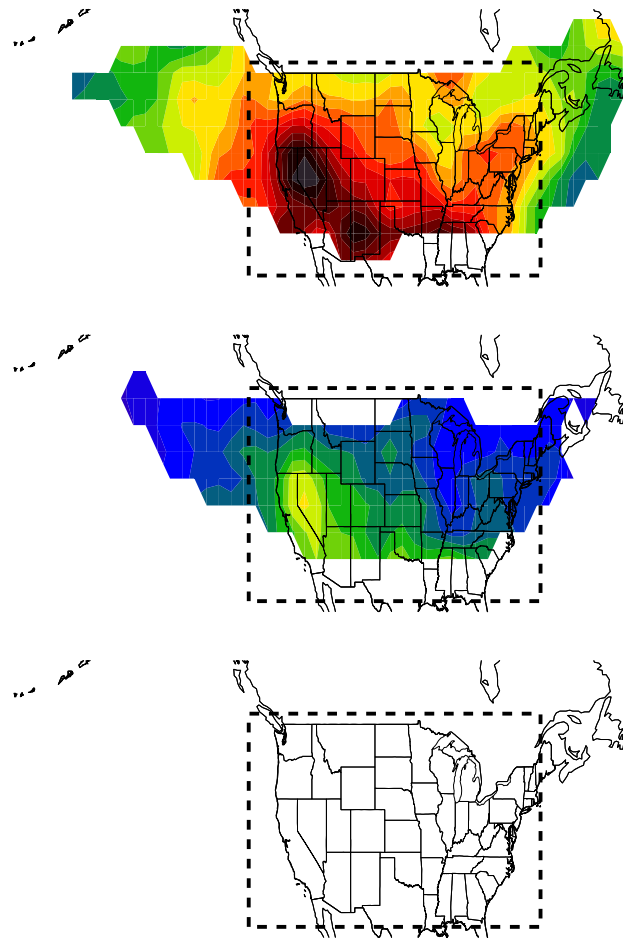
Anomalous Ozone: USA MAM 2005-2014

$O_3 > 25 \text{ ppb}$



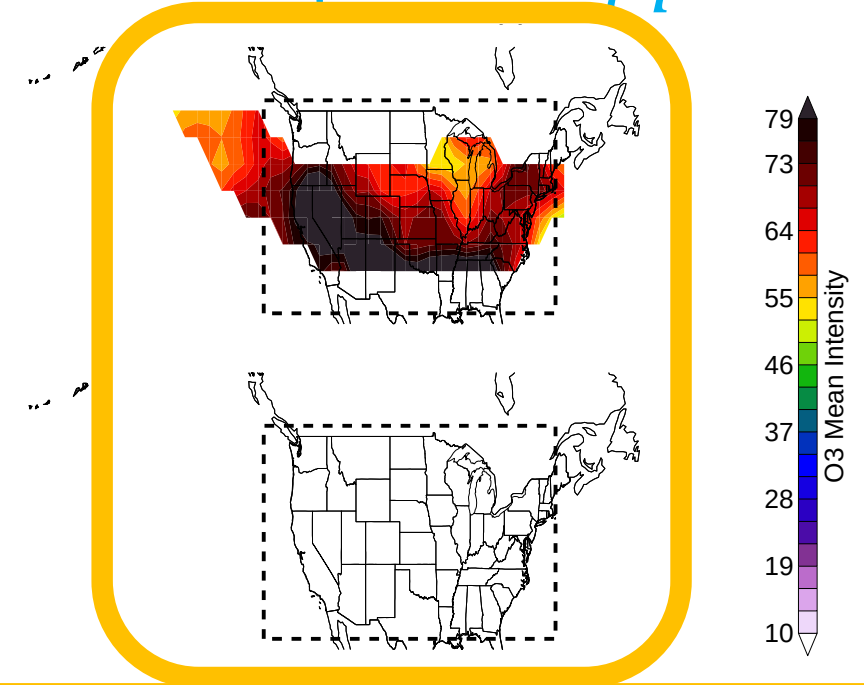
500 hPa: 228 tracks

$O_3 > 50 \text{ ppb}$



215 tracks

$O_3 > 100 \text{ ppb}$



116 tracks at 500 hPa
22 tracks at 600 hPa

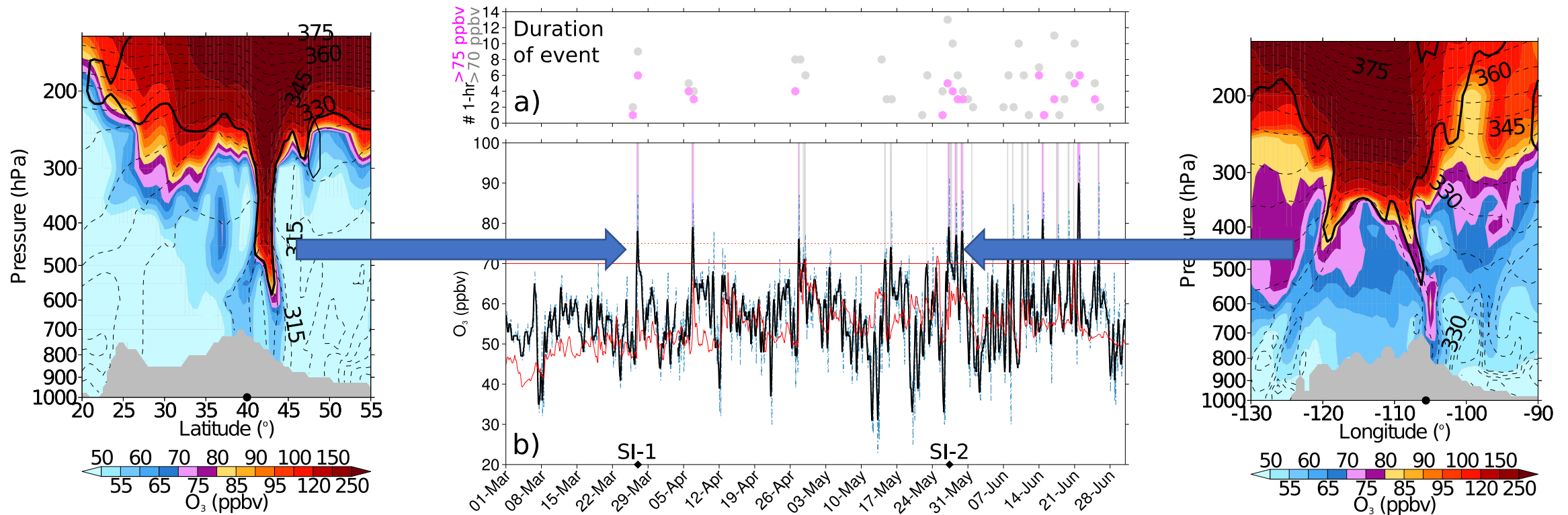
116 tracks

Question 3

- Can we link stratospheric intrusions seen in MERRA-2 with observed ozone exceedences?

Question 3

- Can we link stratospheric intrusions seen in MERRA-2 with observed ozone exceedences?



EPA Stratospheric Ozone flags

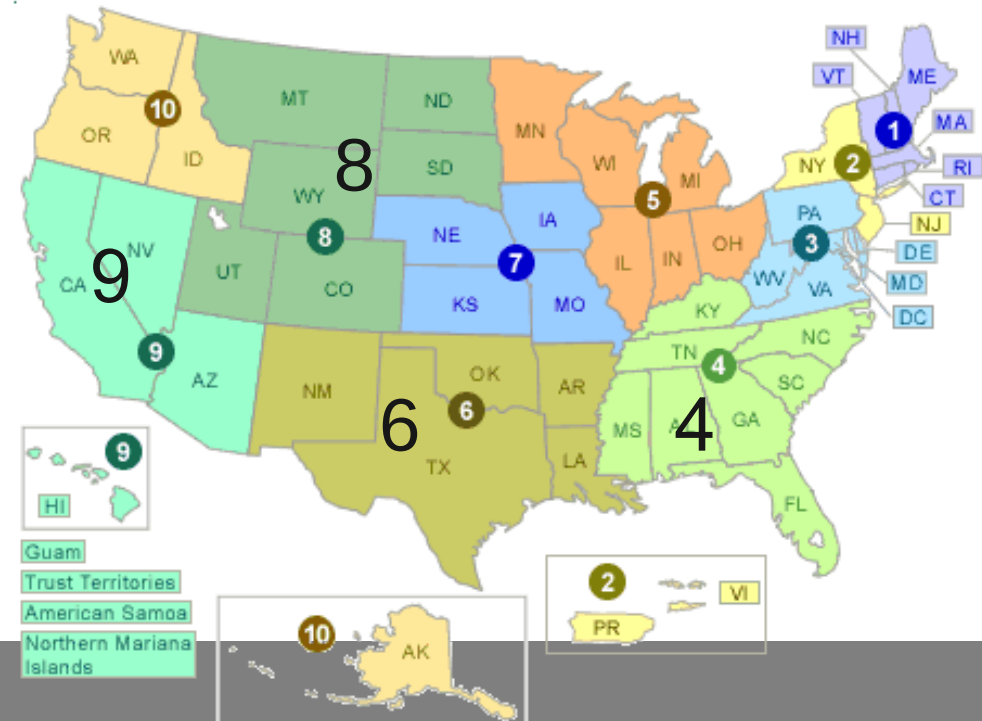
Richard Payton at the EPA compiled the list of stratospheric ozone flags, both IO (information) or RO (request exclusion), from their Air Quality System from 2005 to 2015.

- Stratospheric ozone flags were found in EPA regions 4, 6, 8 and 9.

- February 2009

- MAM 2007-2015

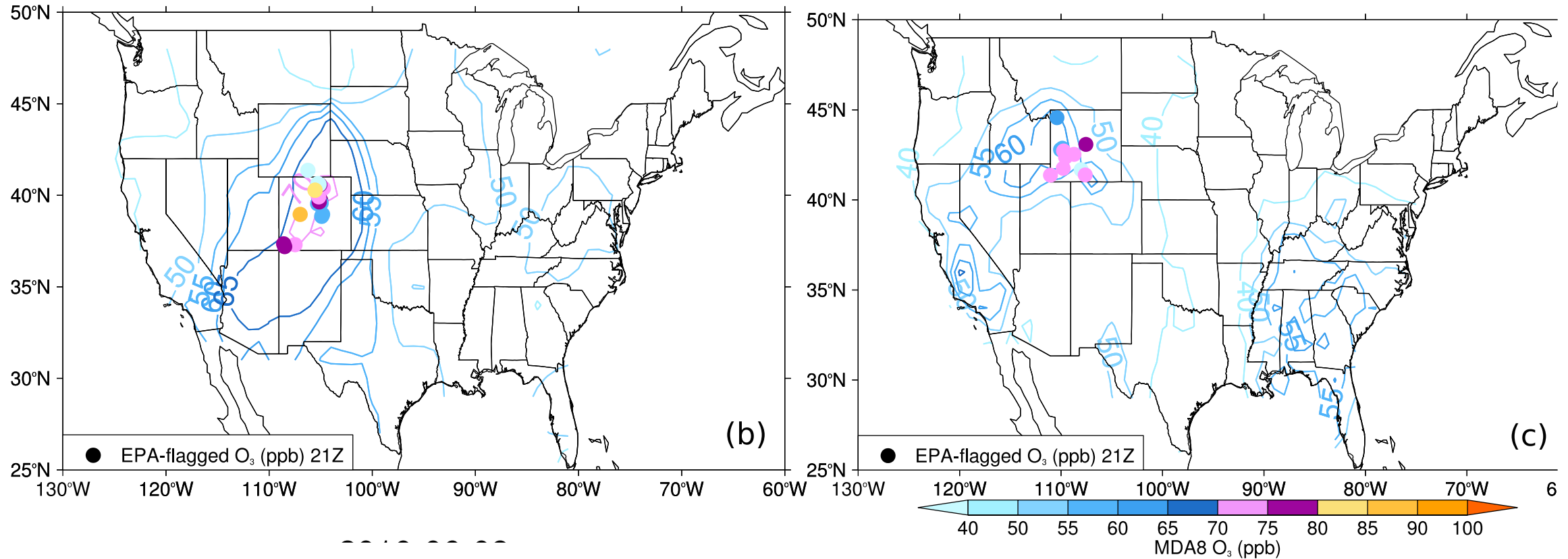
- June 2010-2015



EPA-flagged O_3 vs MDA8 O_3

2012-04-06

2010-06-08



Comparison between observed O_3 during an exceedance (dots) and the maximum daily 8-hour average (MDA8) O_3 (contours) $1^\circ \times 1^\circ$ gridded data set by Jordan Schnell (Schnell et al., 2014 ACP)

1. Construct “Storm tracks”

- Use the objective feature tracking algorithm, TRACK (Hodges 1995, 1999)

➤ TRACK output has the form

DATE LONGITUDE LATITUDE VARIABLE

➤ Construct “tracks” using the EPA surface ozone data where exceedences are flagged for stratospheric influence

DATE LONGITUDE LATITUDE OZONE

2. Sample for anomalies

- Attach to each “track point”, the max (or min) anomaly of MERRA-2 fields known to be associated with intrusions:
 - Max EPV, O_3 , ω , wind speed, PBL, TROPPB
 - Min RH, H
- e.g., DATE LON LAT O_3 LON LAT EPV anomaly_{500 hPa}

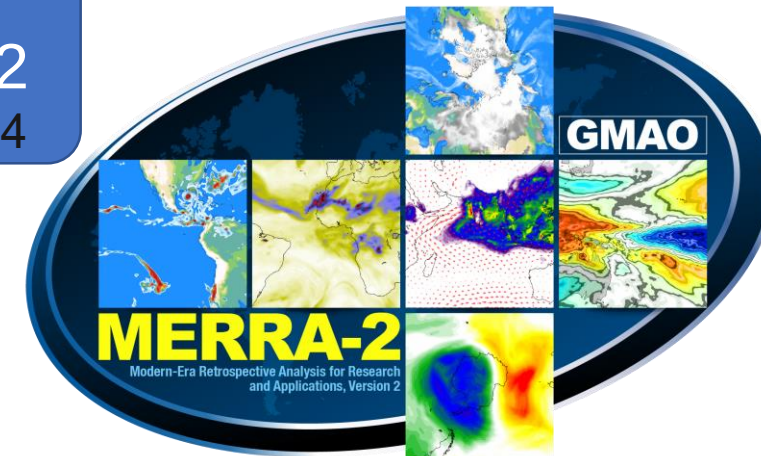
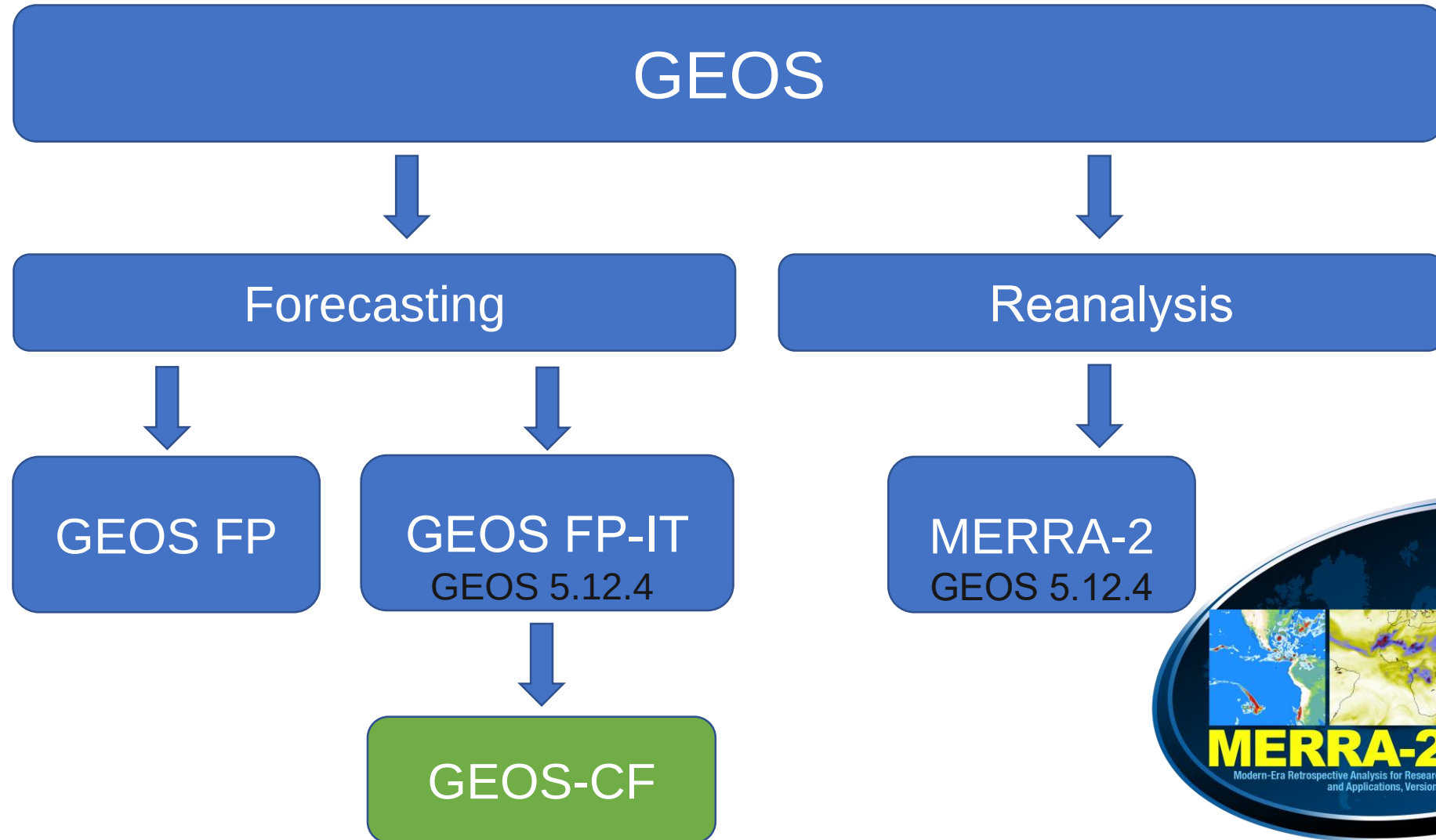
Stay Tuned....

Question 4

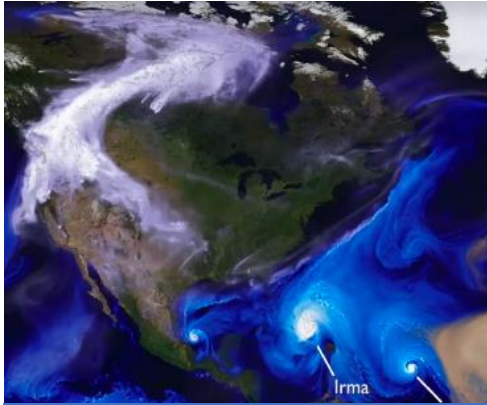


Can we forecast SI events in GEOS
forecasting products?

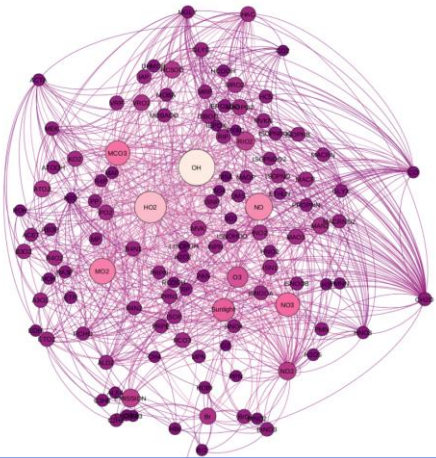
NASA GMAO global meteorology and chemistry products



NASA's composition forecast (GEOS-CF)



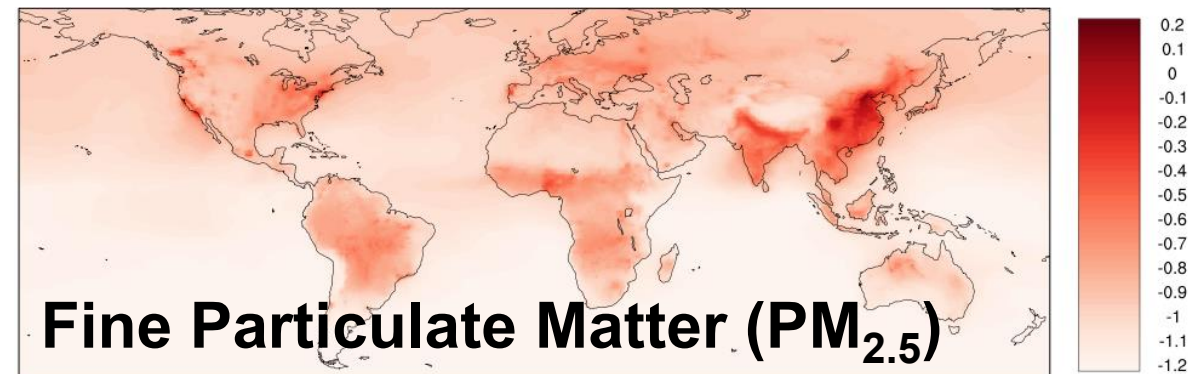
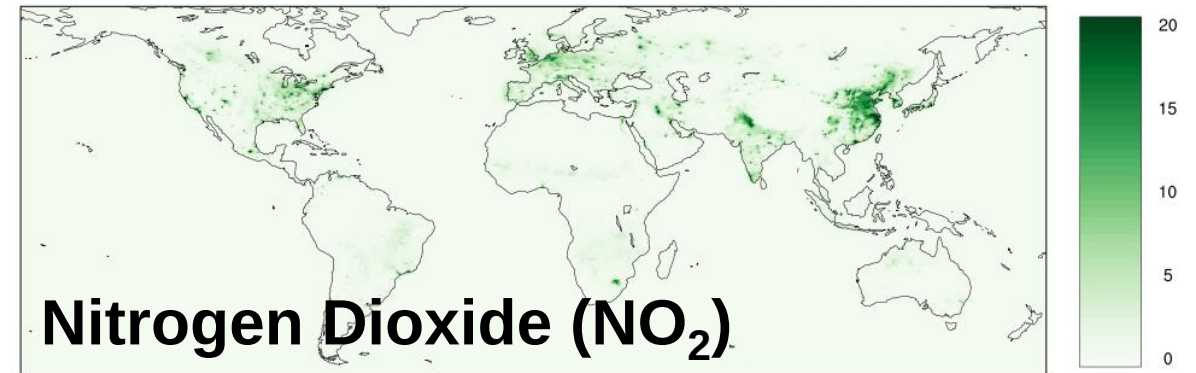
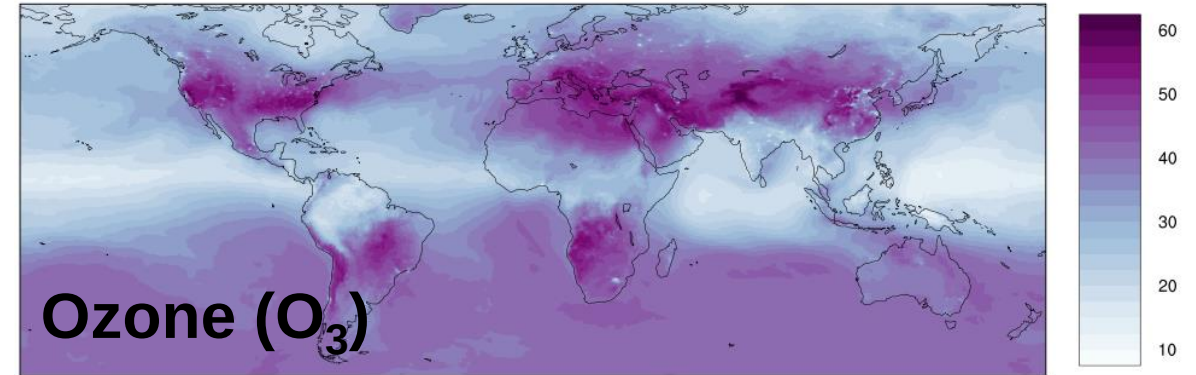
GEOS FP-IT



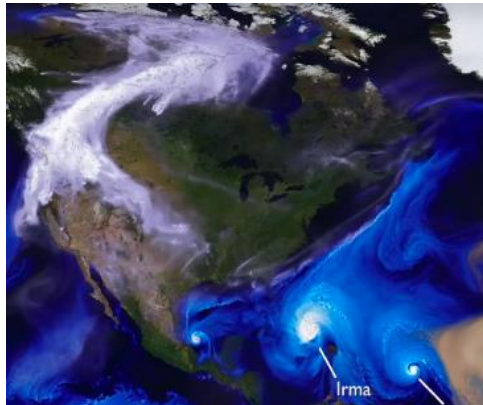
GEOS - Chem

- ❖ 250 Chemical Species
- ❖ 725 Chemical Reactions

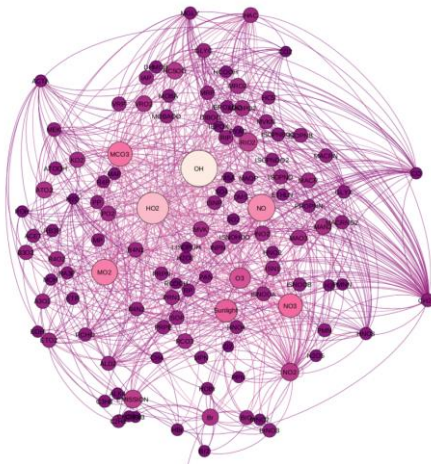
GEOS-Chem



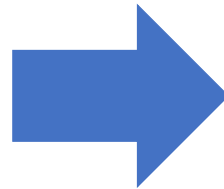
Daily composition forecast



GEOS FP-IT



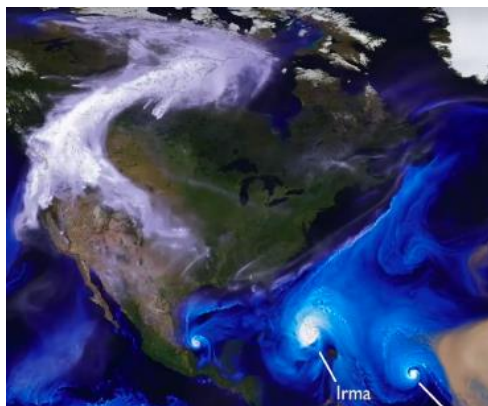
GEOS - Chem



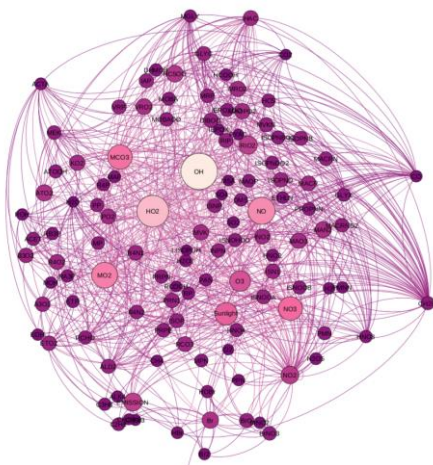
GEOS - CF

- Currently no direct data assimilation of constituents in GEOS-CF

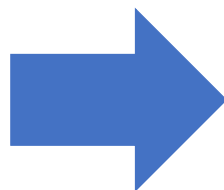
Daily composition forecast



GEOS FP-IT



GEOS - Chem



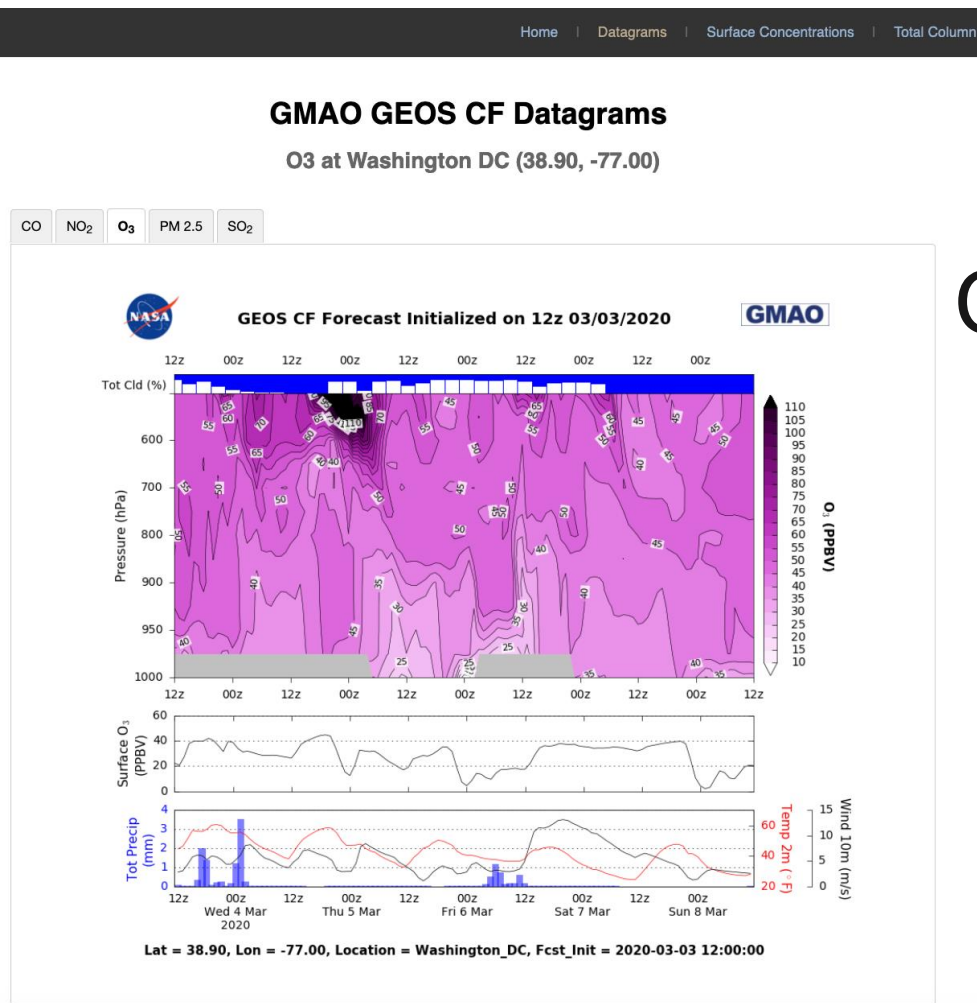
GEOS - CF

- GOCART aerosols constrained by satellite measurements of AOD
- Biomass burning emissions from QFED
- Stratospheric O_3 (above ~75hPa) nudged to GEOS-FP ($\Rightarrow$ MLS) O_3

Forecasting and validating SI events

GEOS - CF

- One **5-day forecast** per day
- 1-day replay
 - 5-day forecast
 - c360 (0.25° , $\sim 25 \times 25 \text{ km}^2$)
 - Chemistry and Meteorology fields
 - Available since Jan 2018



www.fluid.nccs.nasa.gov/cf

Composition Forecast

CF Datagrams

NATIONAL

Select a Station

WORLD

Select a Station

AERONET

NORTH AMERICA

LMOL

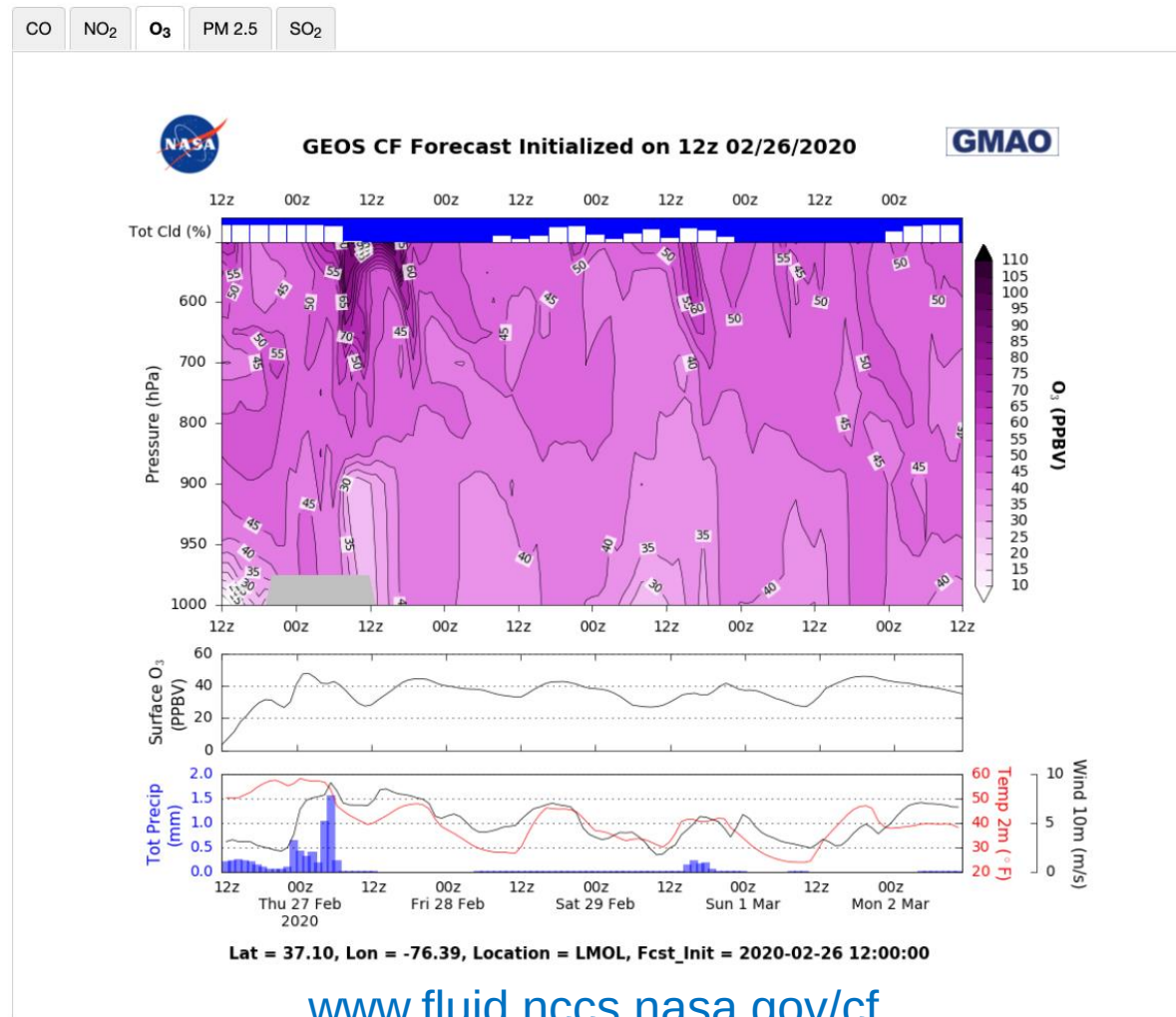
MEGACITIES

Select a Station

ACTIVE CAMPAIGNS

Select a Station

GMAO GEOS CF Datagrams

O₃ at LMOL (37.10, -76.39)


Next step:

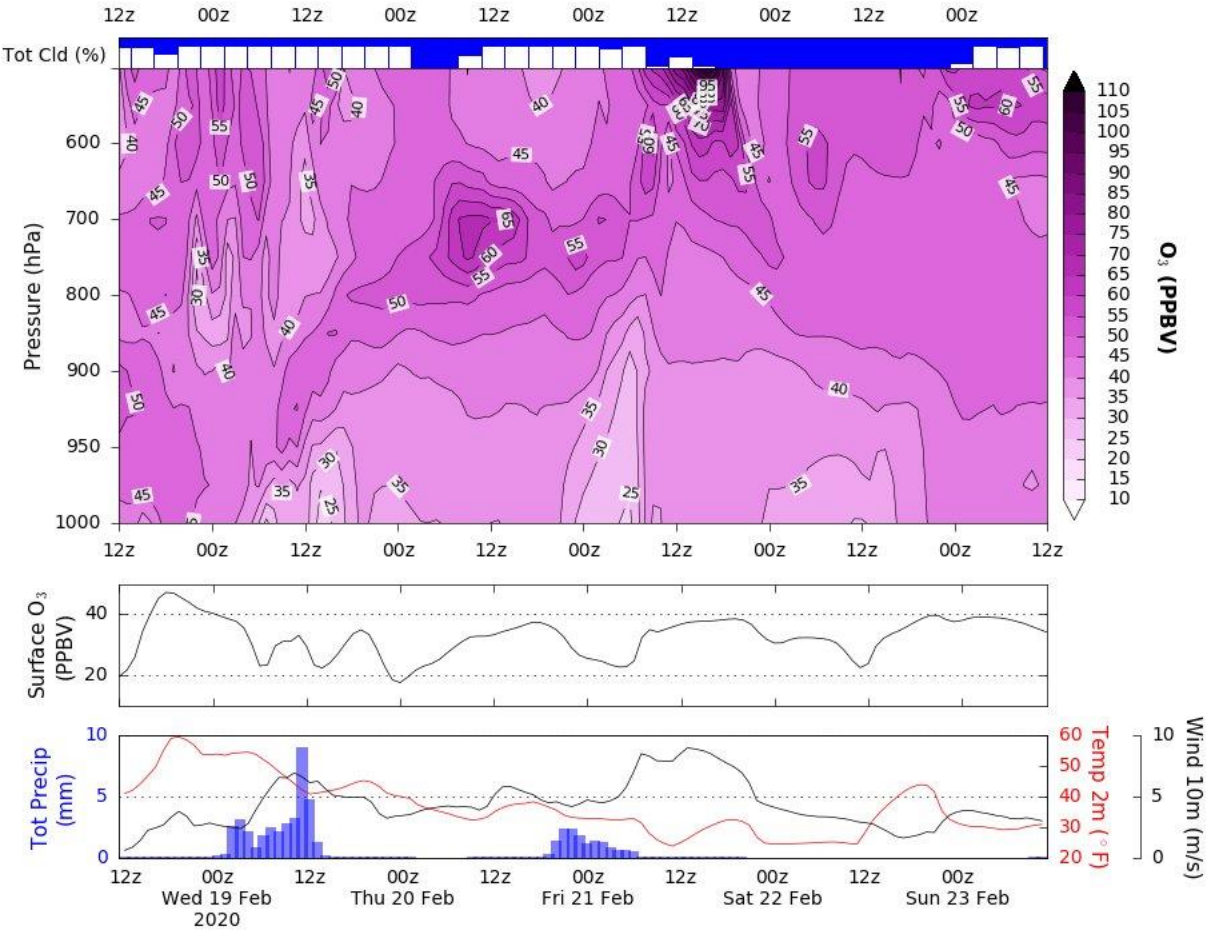
Can we provide a flag or alert to indicate to end-users that a stratospheric intrusion is likely in their area?

GEOS-CF Forecasts for NASA Langley: "LMOL"



GEOS CF Forecast Initialized on 12z 02/18/2020

GMAO

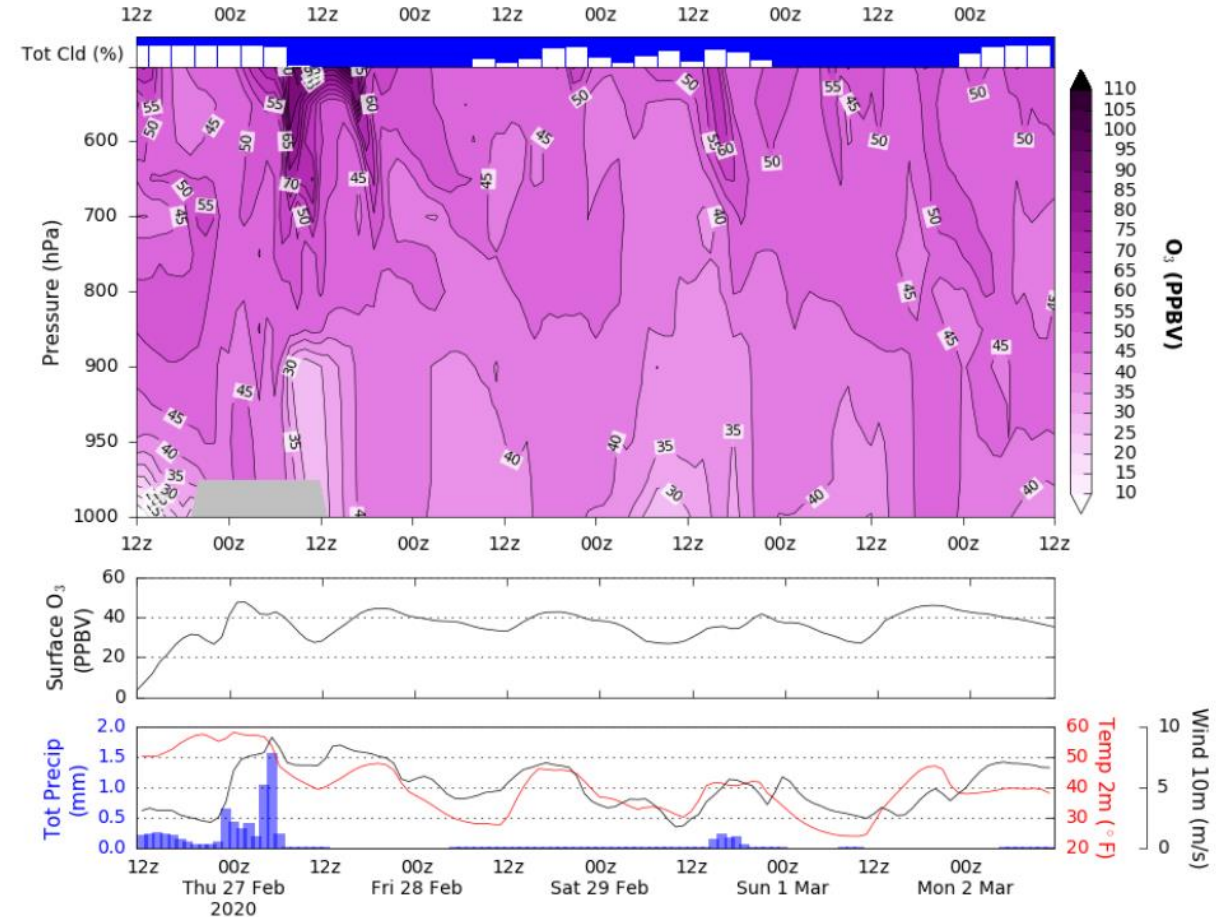


Lat = 37.10, Lon = -76.39, Location = LMOL, Fcst_Init = 2020-02-18 12:00:00



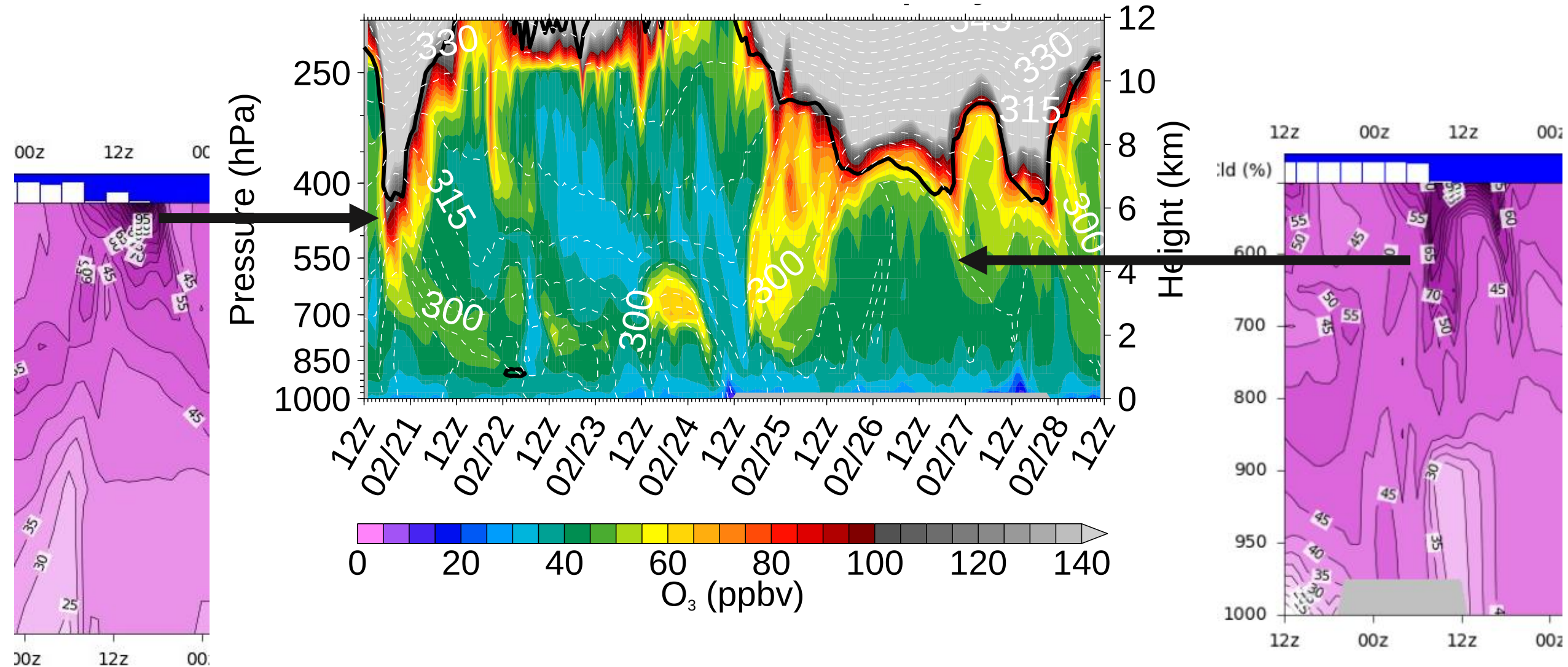
GEOS CF Forecast Initialized on 12z 02/26/2020

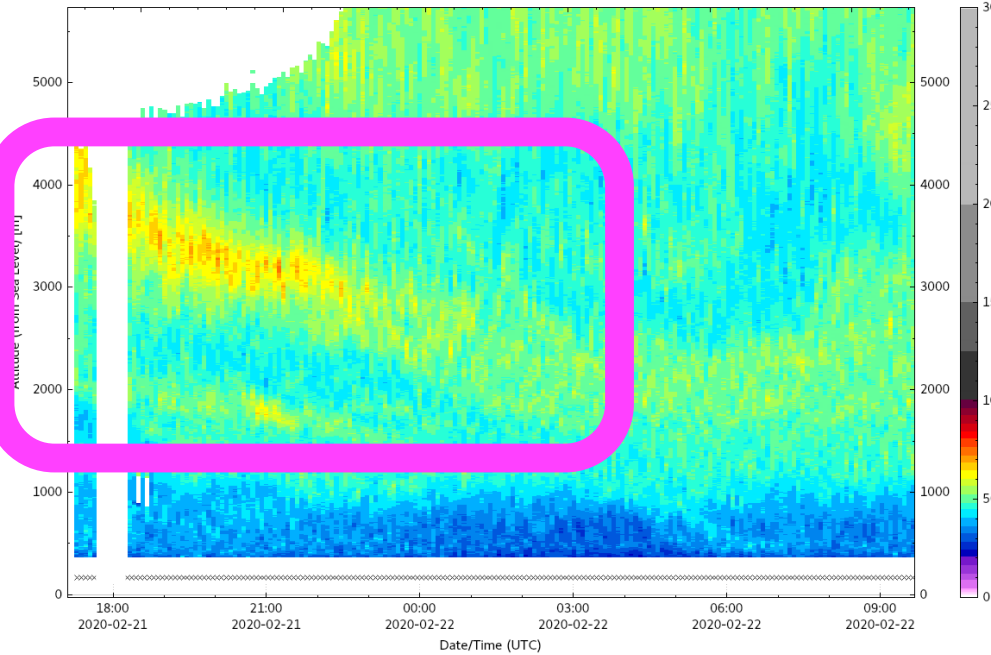
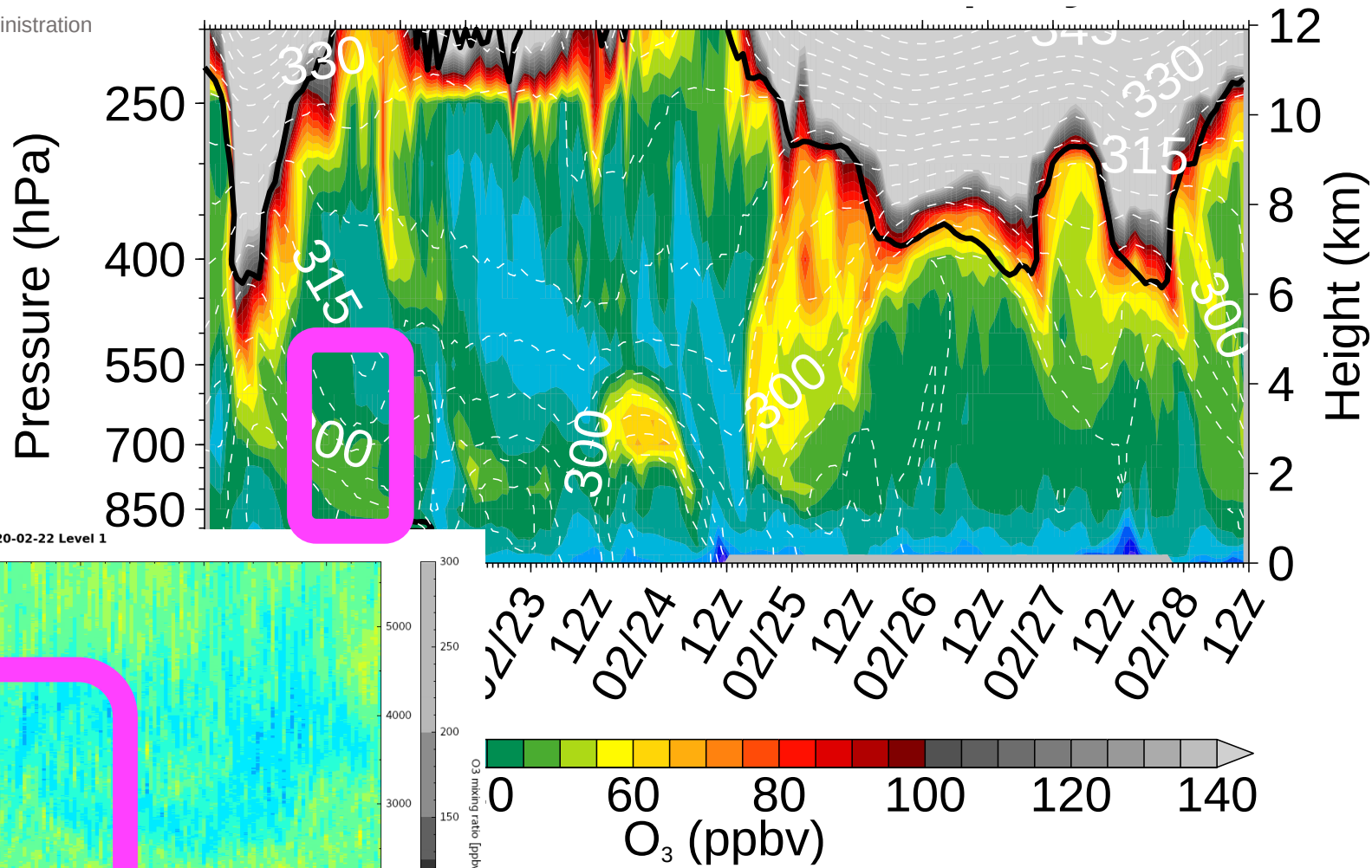
GMAO



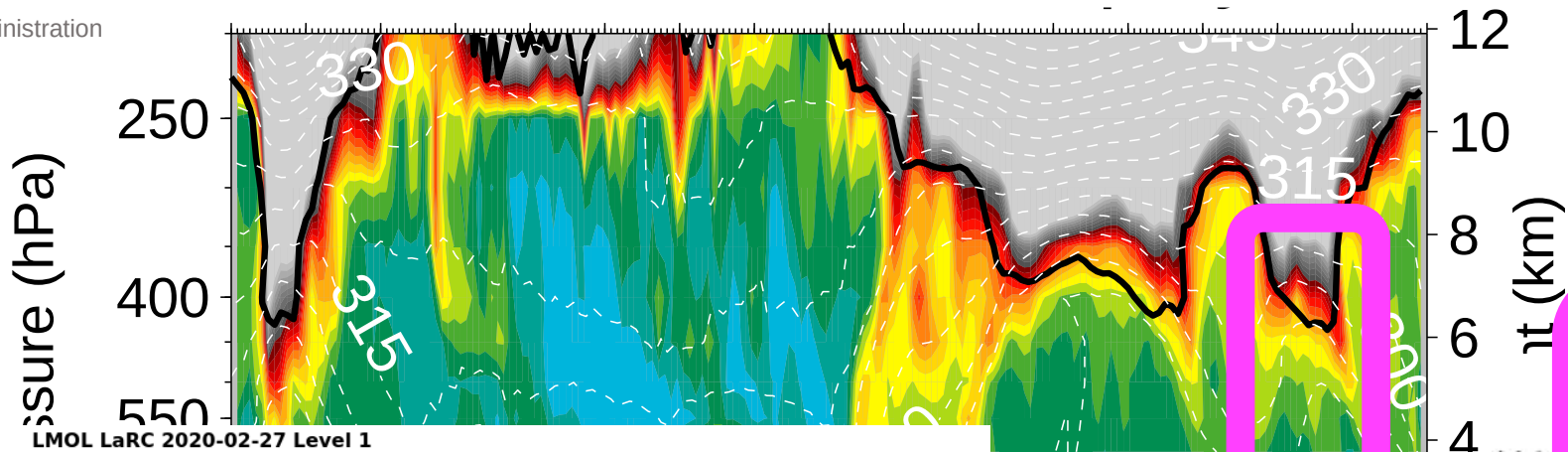
Lat = 37.10, Lon = -76.39, Location = LMOL, Fcst_Init = 2020-02-26 12:00:00

GEOS-CF 'analysis' at Langley (12z Feb 20 – 12z Feb 28, 2020)

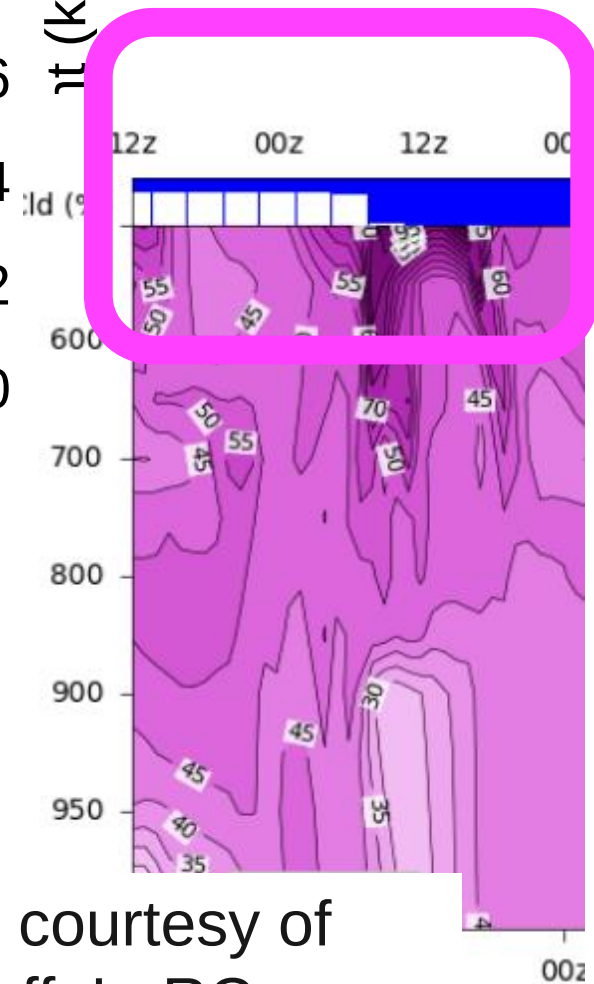
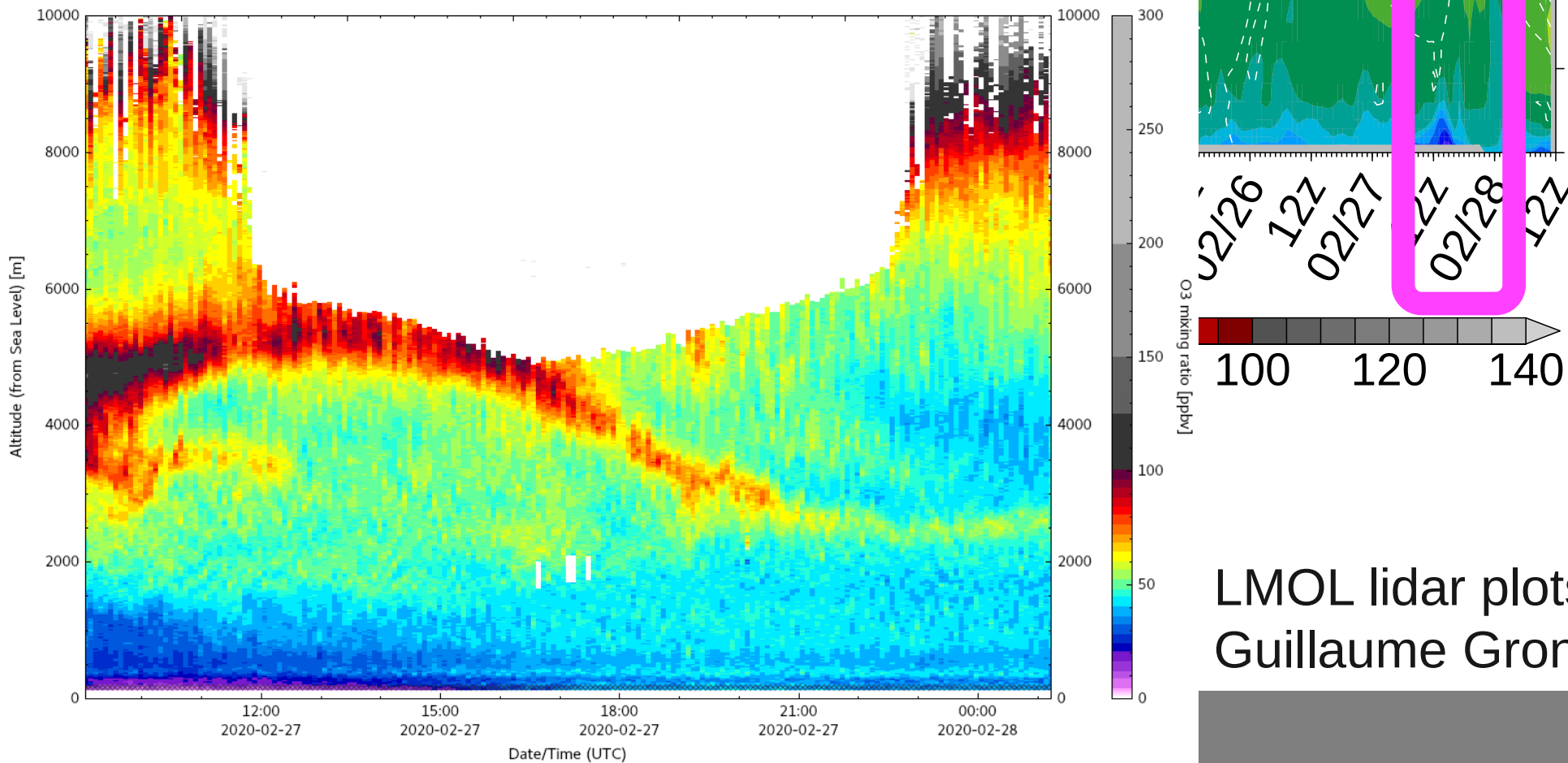




LMOL lidar plots courtesy of
Guillaume Gronoff, LaRC



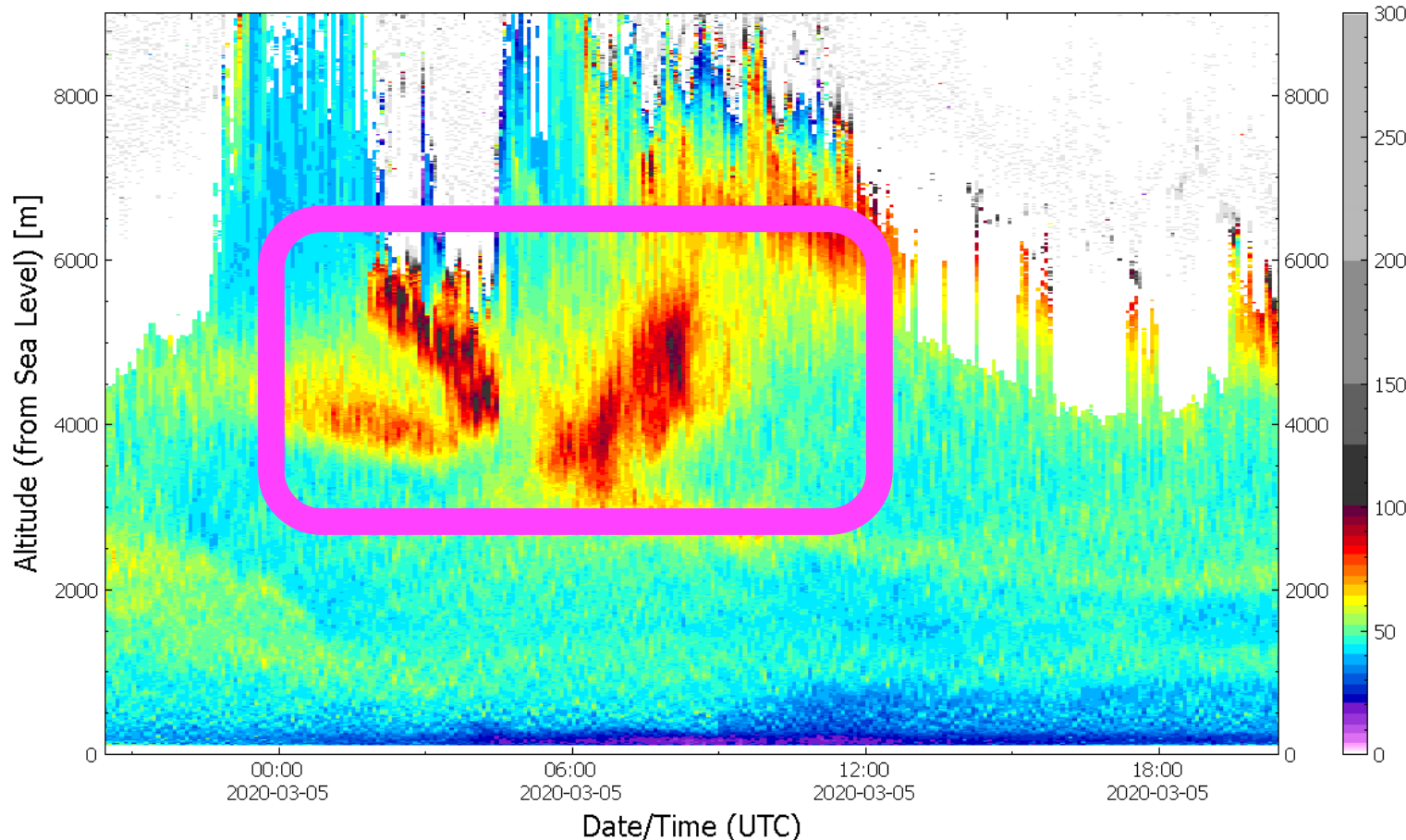
LMOL LaRC 2020-02-27 Level 1



LMOL lidar plots courtesy of
Guillaume Gronoff, LaRC

John Sullivan (GSFC) and Guillaume Gronoff (LaRC) are set to measure yesterday ☺

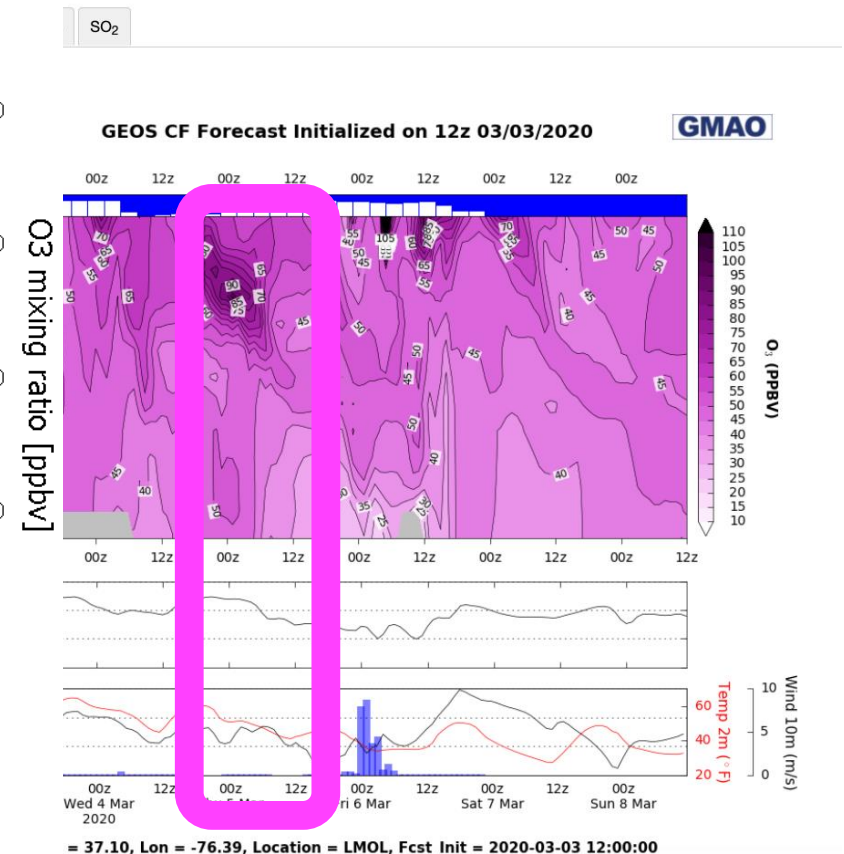
Ozone curtain plot. -- WARNING QUICKLOOK -- Latest data at UTC: 2020-03-05T20:26:39Z
Langley Mobile Ozone Lidar. Location: Hampton Latitude: 37.095 Longitude -76.389



Date/Time (UTC)
Processing time (LT):2020-03-05T15:26:56

GMAO GEOS CF Datagrams

O3 at LMOL (37.10, -76.39)

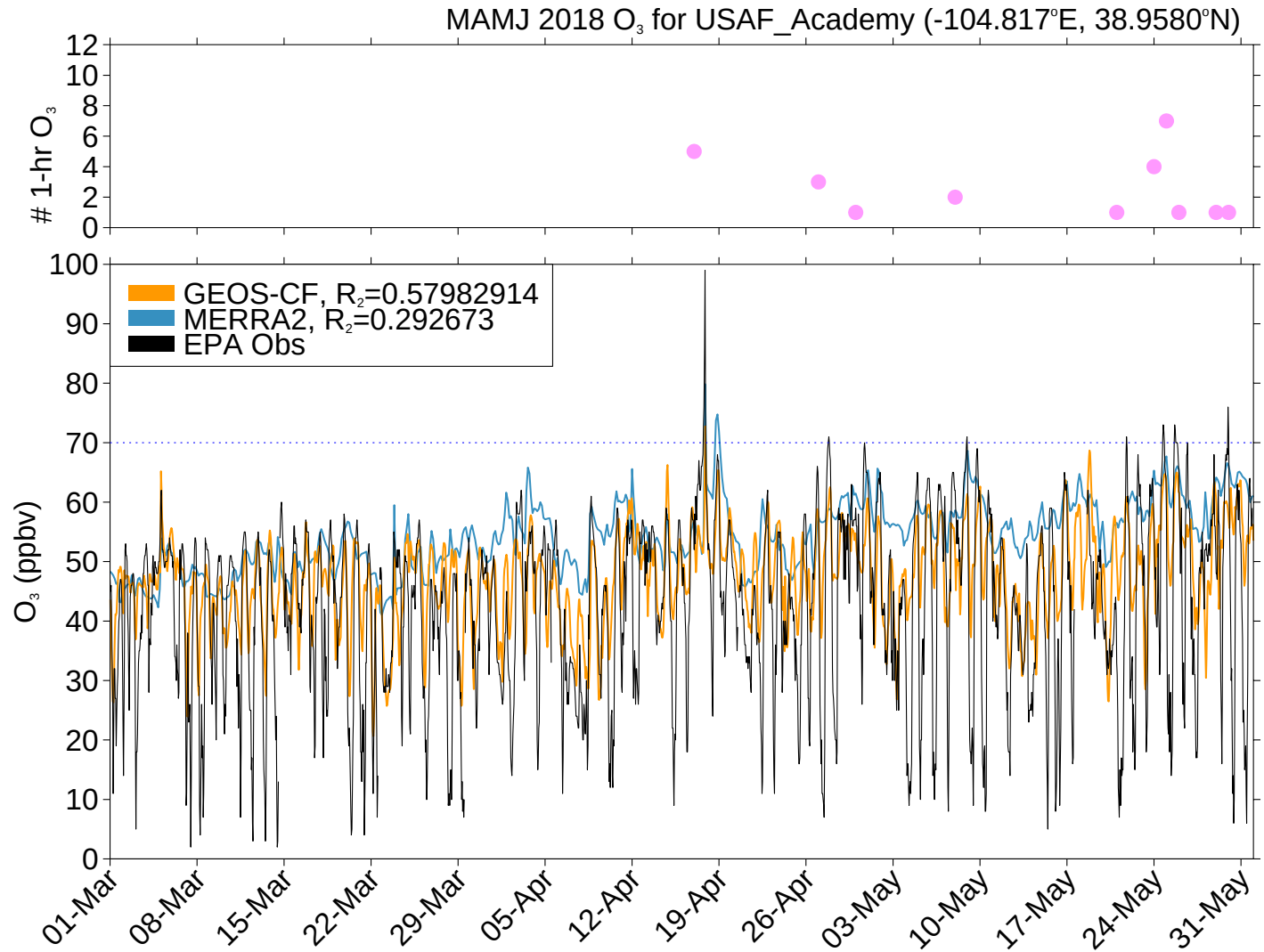
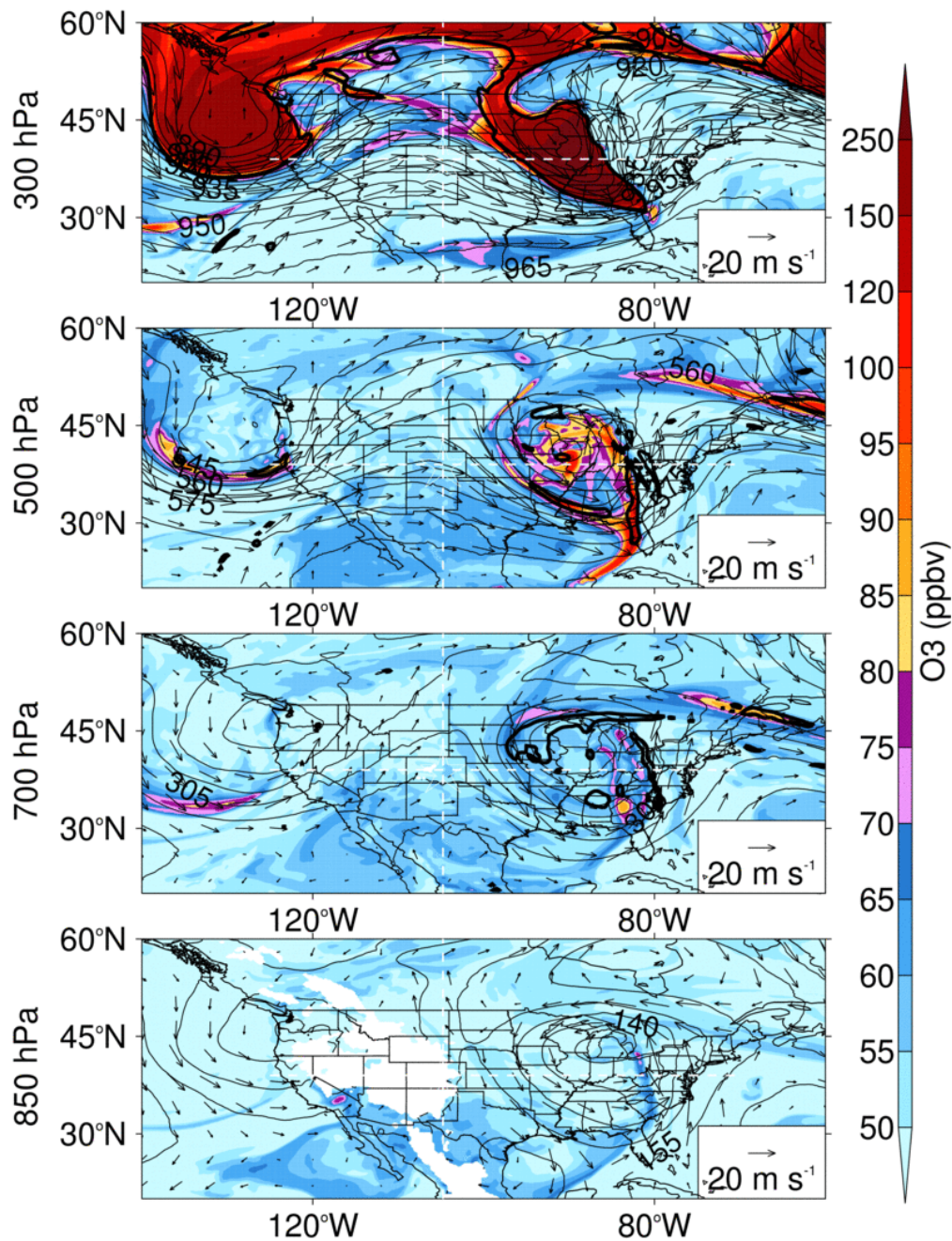


Question 5



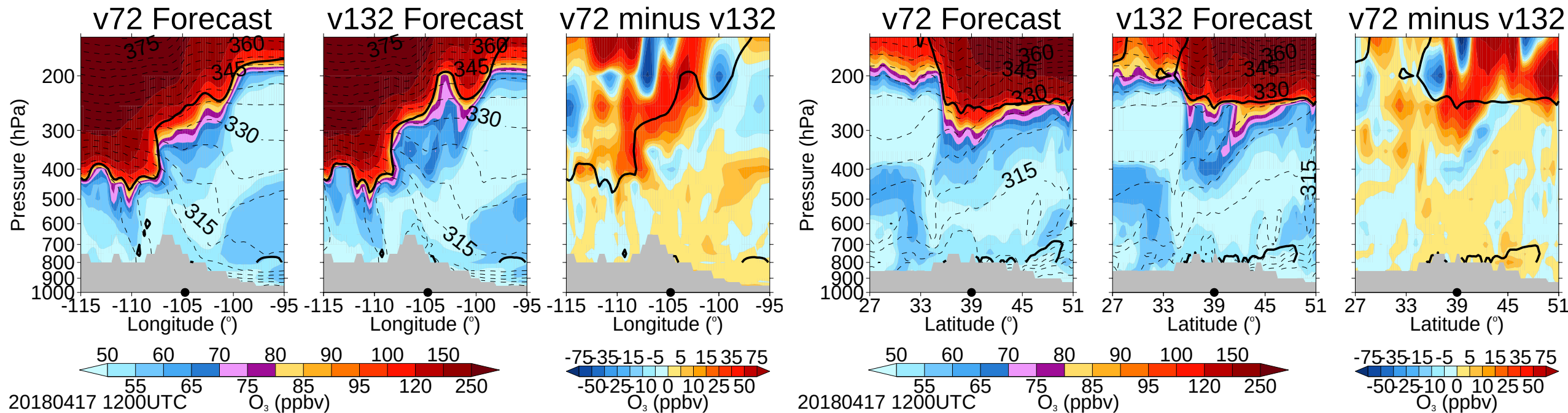
How can we improve the representation of
SIs in GEOS?

17 April 2018 SI event

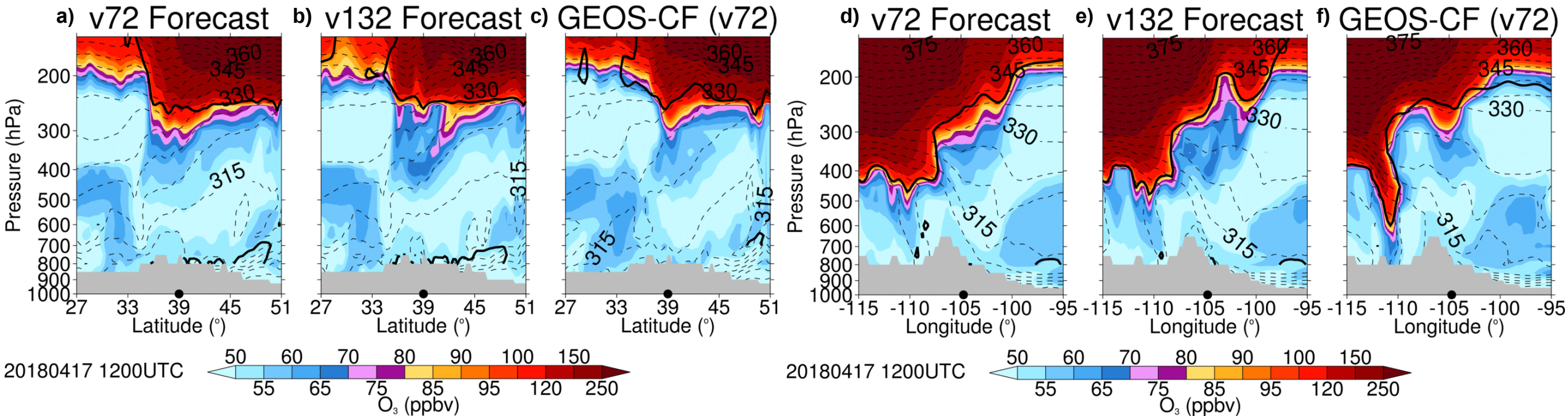


Increased vertical resolution in GEOS

- The purpose of these experiments was to investigate how increasing the model's vertical resolution would affect transfer of constituents in and between the troposphere and stratosphere.
- GEOS-CF forecast simulation of April 2018 SI event.
 - Current GEOS grid: 72 model layers
 - Future GEOS grid: 132 model layers
- Both simulations were initialized with the GEOS-CF one day before the event (runs performed by Elliot Sherman).



Increased vertical resolution in GEOS



The high concentration of ozone in the v72 Forecast descends to lower pressure levels (a) than in the v132 Forecast (b), however the tropopause in the v132 Forecast remains near 550 hPa, similar to the GEOS-CF replay, for longer.

Summary

- ✓ MERRA-2 is a high-resolution global reanalysis which can be used in scientific studies to identify SIs by both atmospheric dynamics and O_3
- ✓ GEOS-CF is suitable tool to support instrument teams measuring tropospheric and lower stratosphere composition
- Working on best approach to communicate SI potential to interested end-user groups.

Knowland, et al (2017). Stratospheric intrusion-influenced ozone air quality exceedances investigated in the NASA MERRA-2 reanalysis. GRL <https://doi.org/10.1002/2017GL074532>