Integration of Satellite, NEXRAD and *In Situ* Aircraft Observations Addressing Deep Stratospheric Convective Injection Over the US in Summer

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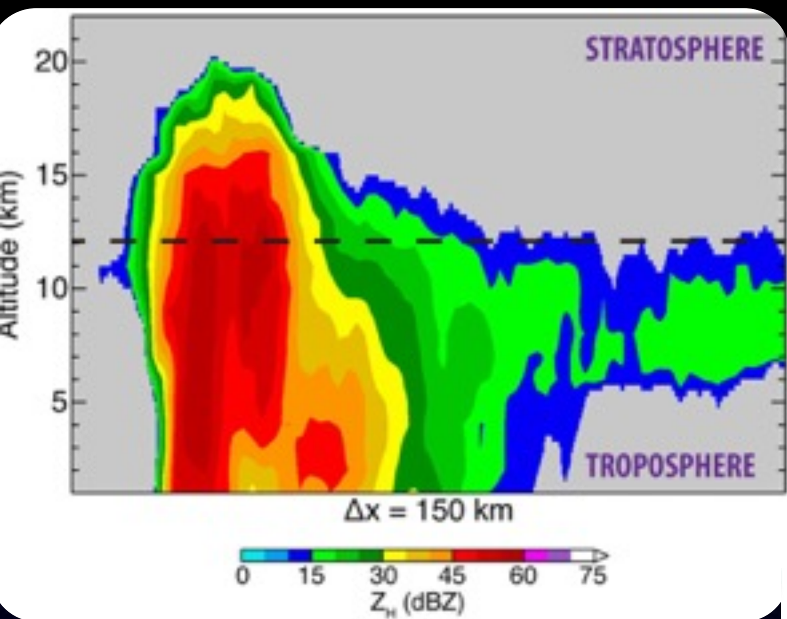
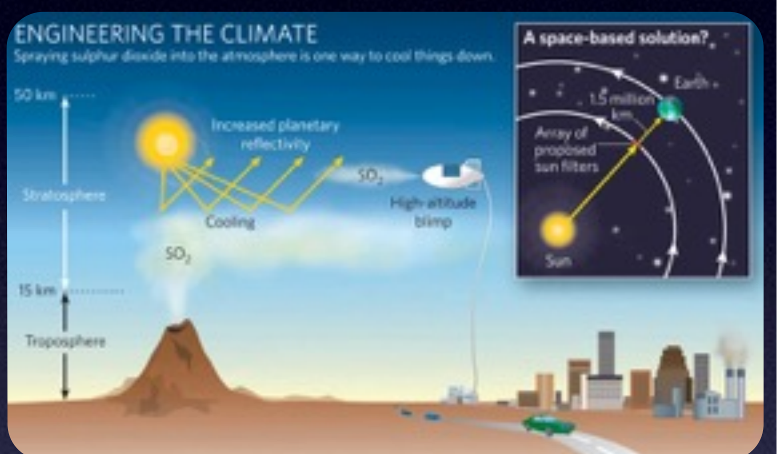
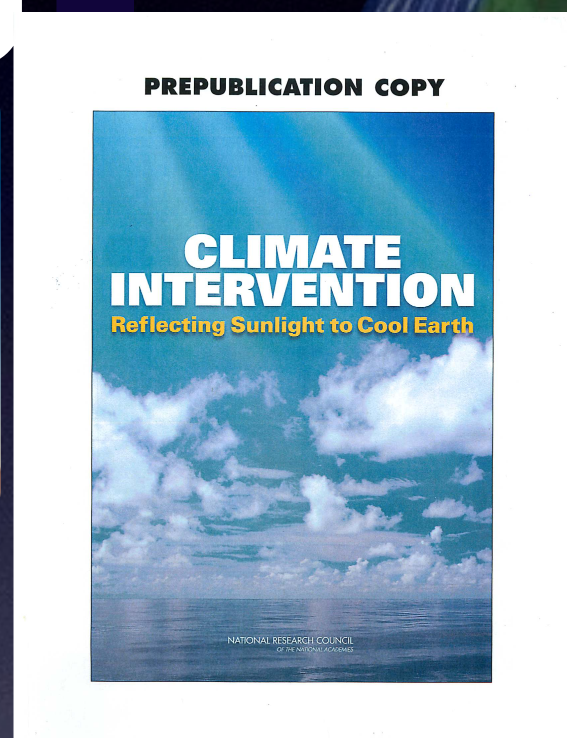
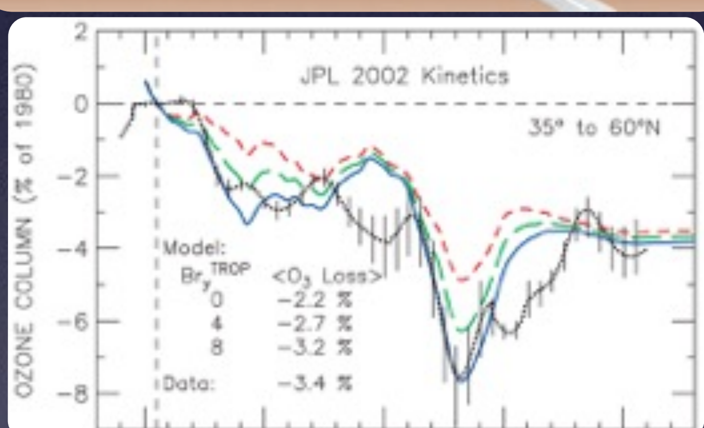
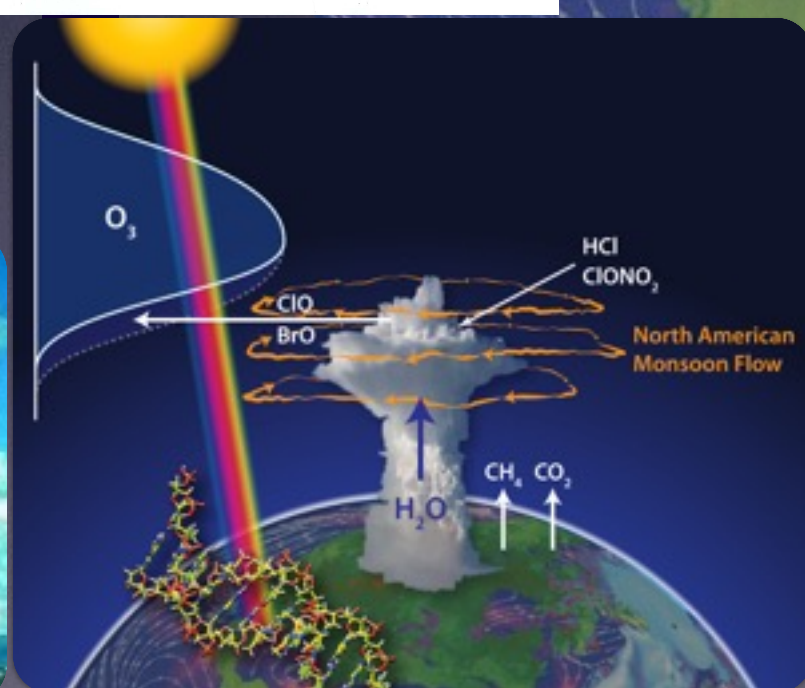
Harvard University
Cambridge, MA 02138

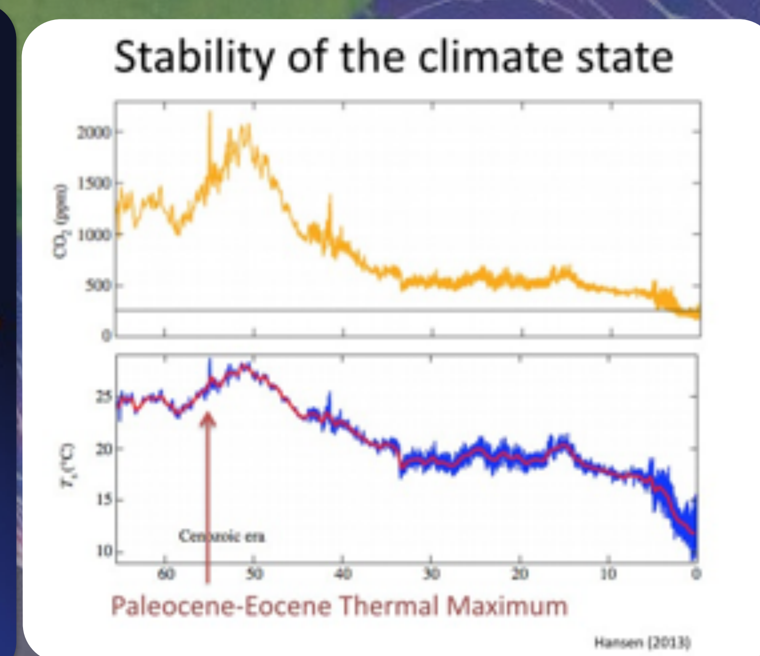




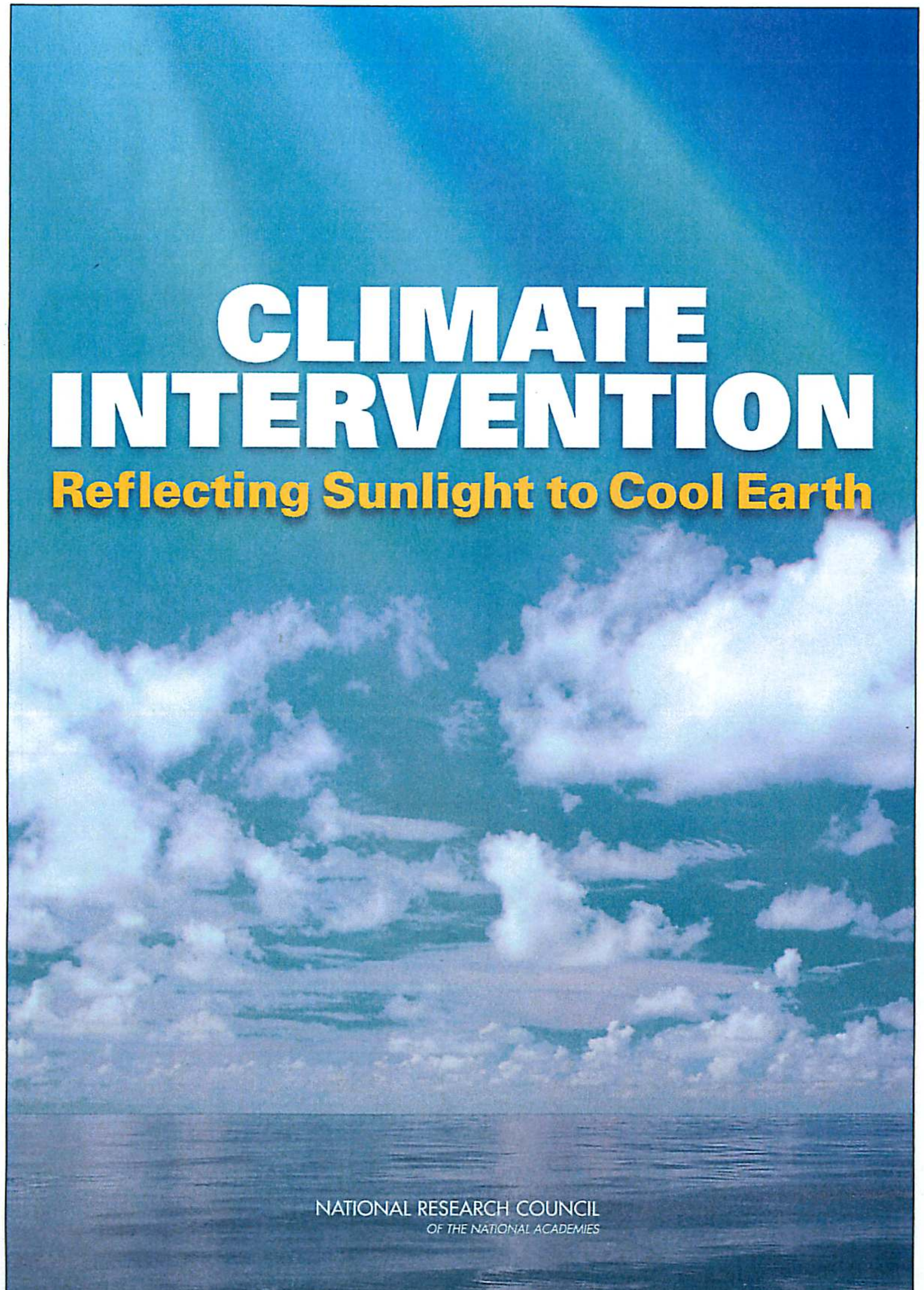






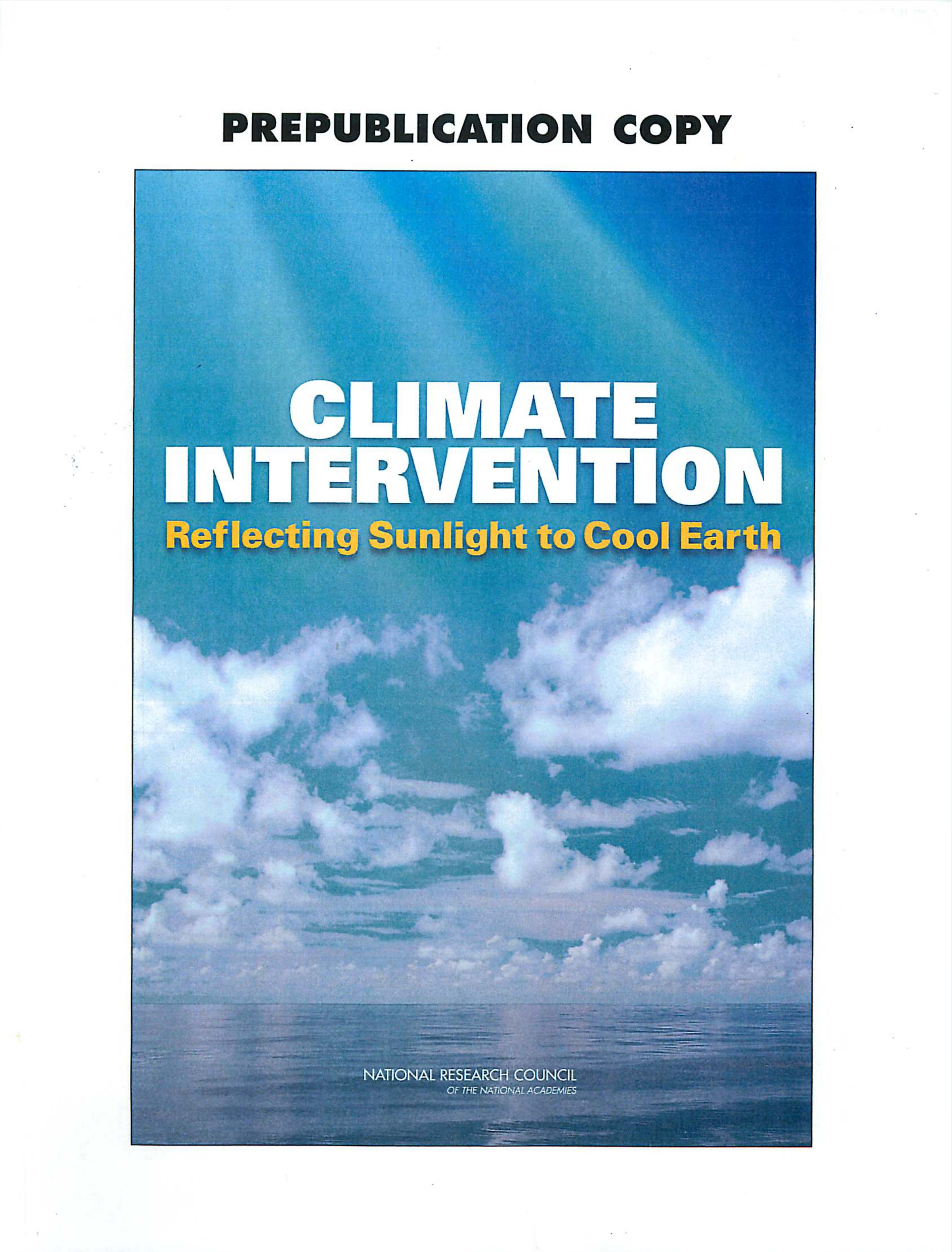


PREPUBLICATION COPY



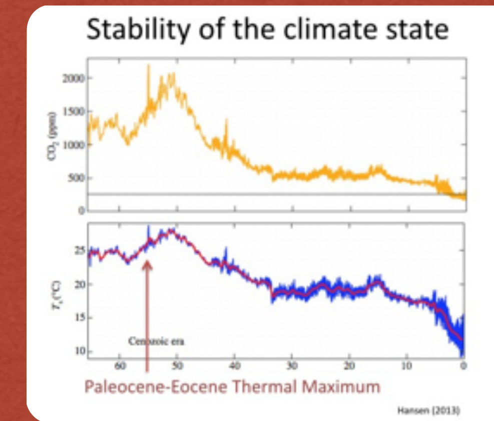
NRC Report: "Climate Intervention: Reflecting Sunlight to Cool the Earth"

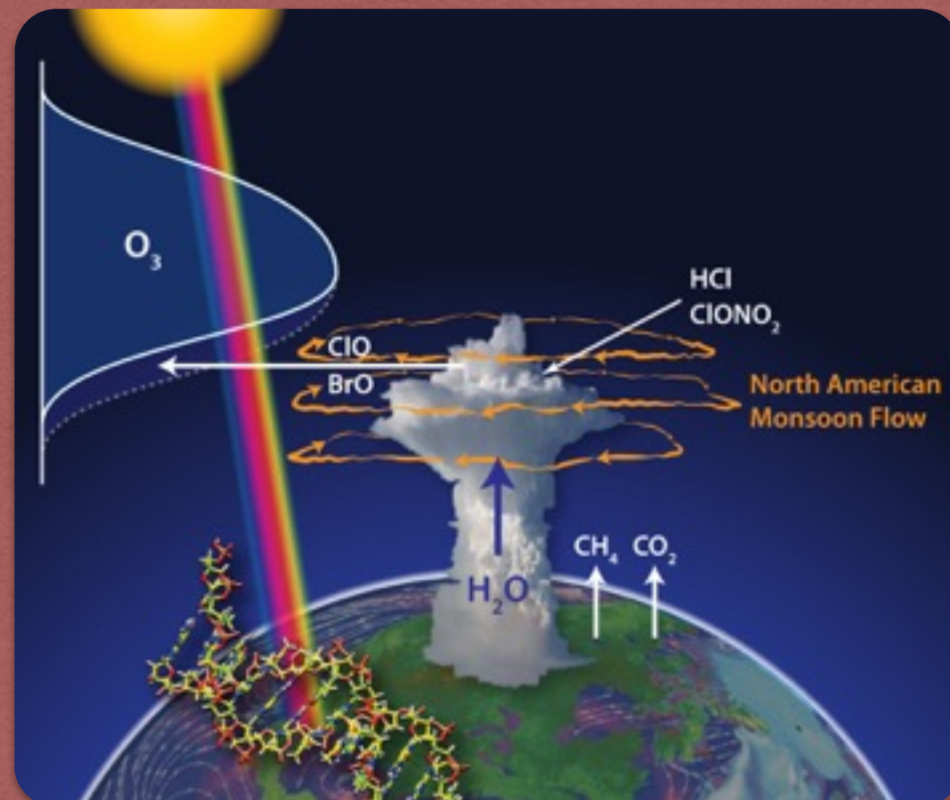
"The Committee recommends an albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers basic understanding of the climate system and its human dimensions."



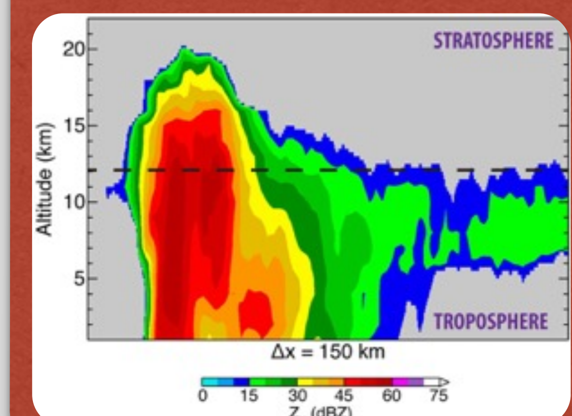
Deep Convection

Climate Forcing

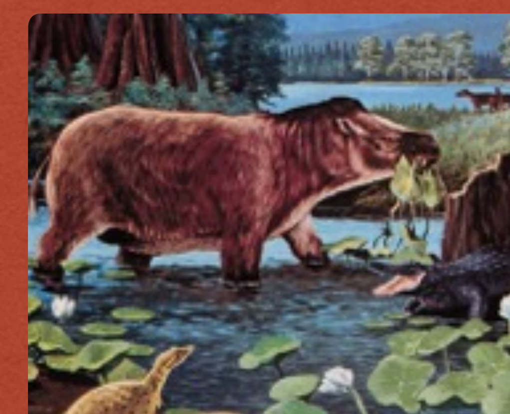




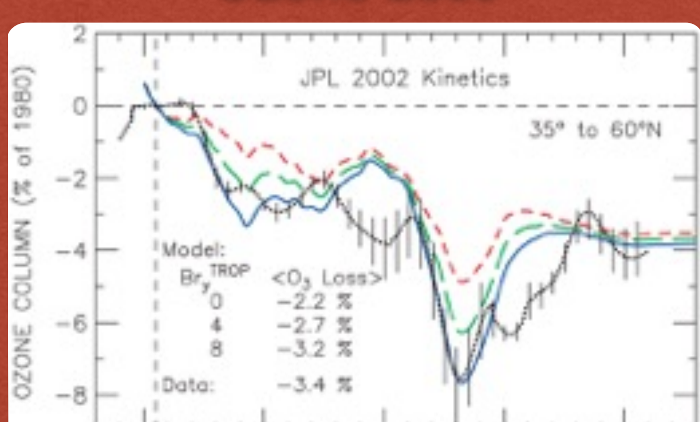
NEXRAD



Eocene

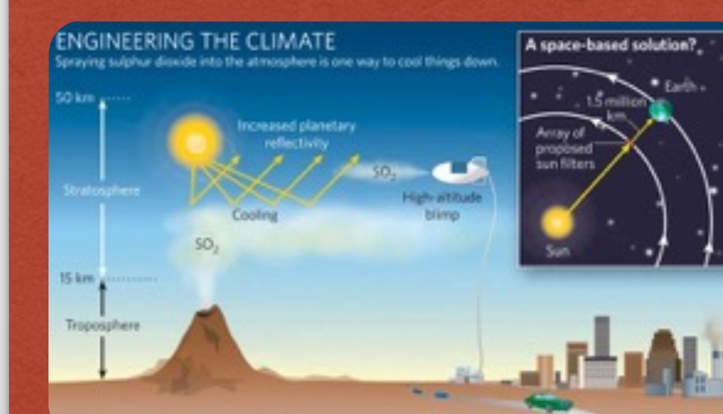


Ozone Loss



Volcanic Injection

Solar Radiation Management



Why is overshooting convection interesting?

- North of the Sub-tropical jet, deep stratospheric convection can be an important mechanism for irreversibly moistening the stratosphere
- The physics of deep stratospheric convection is not understood - nor is its response to continued forcing of the climate.
- Overshooting convection can transport water and other tropospheric boundary layer constituents into the lower stratosphere that are normally removed in the troposphere.
- Deep stratospheric convection with entrapment in the anti-cyclonic flow over the US mechanistically links ozone catalytic chemistry, SRM, volcanic injection and emerging evidence from paleoclimate studies.
- Measuring the occurrence of overshooting tops is a first step toward a bottom-up estimate of irreversible troposphere-to-stratosphere transport by convection

Model Simulation of Overshooting Top

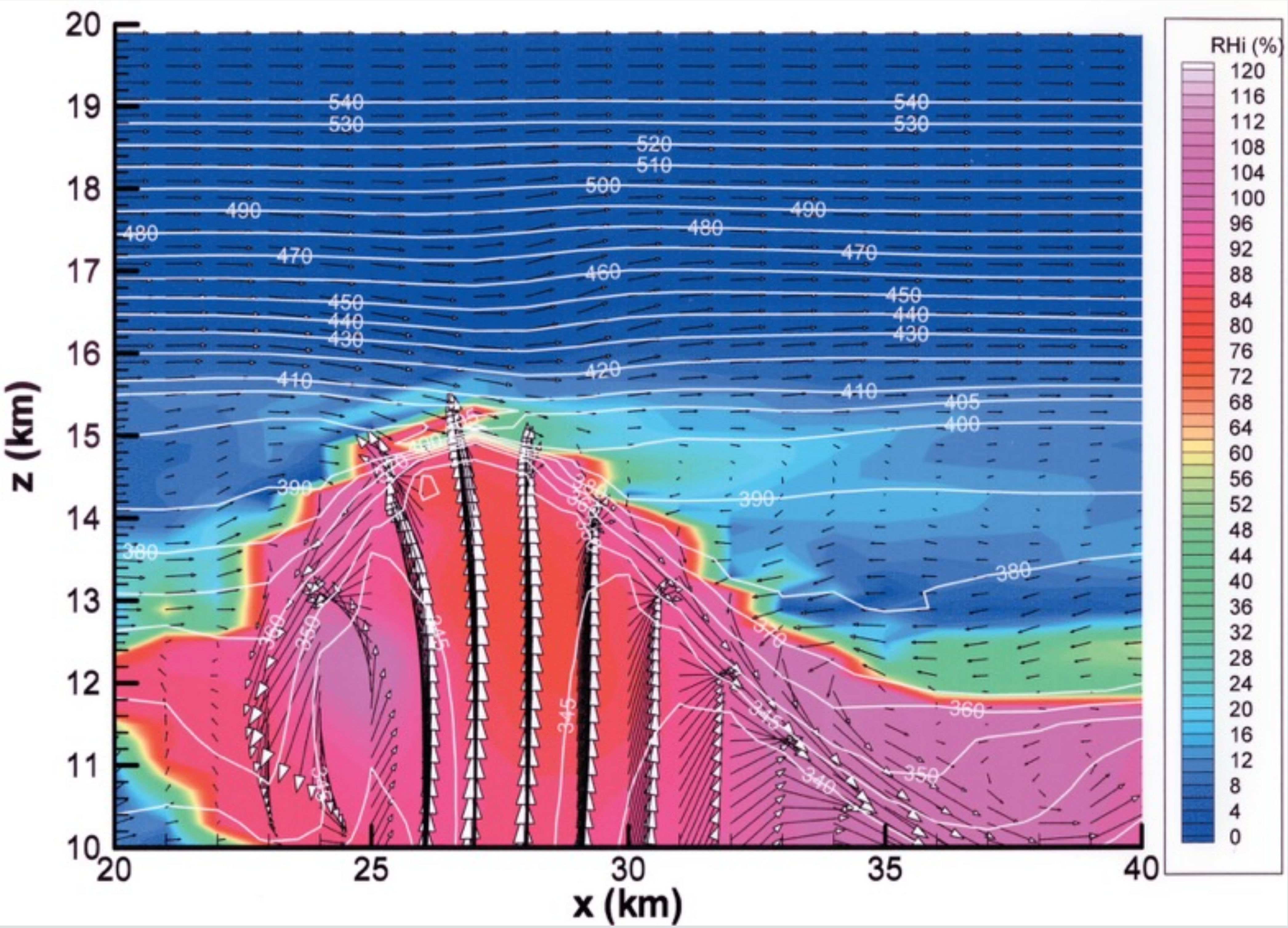


Figure 8. Central east-west cross-section of the simulated storm at t = 73 min 10 sec, showing the overlapped RHi, wind vector (projected on the x-z plane) and θ fields. The wave breaking is obvious in the region where x ~28 km and z ~15 km.

Wang, 2003, *JGR*

Journal of Geophysical Research: Atmospheres
Volume 108, Issue D6, 4194, 28 MAR 2003 DOI: 10.1029/2002JD002581
http://onlinelibrary.wiley.com/doi/10.1029/2002JD002581/full#jgrd9978-fig-0008

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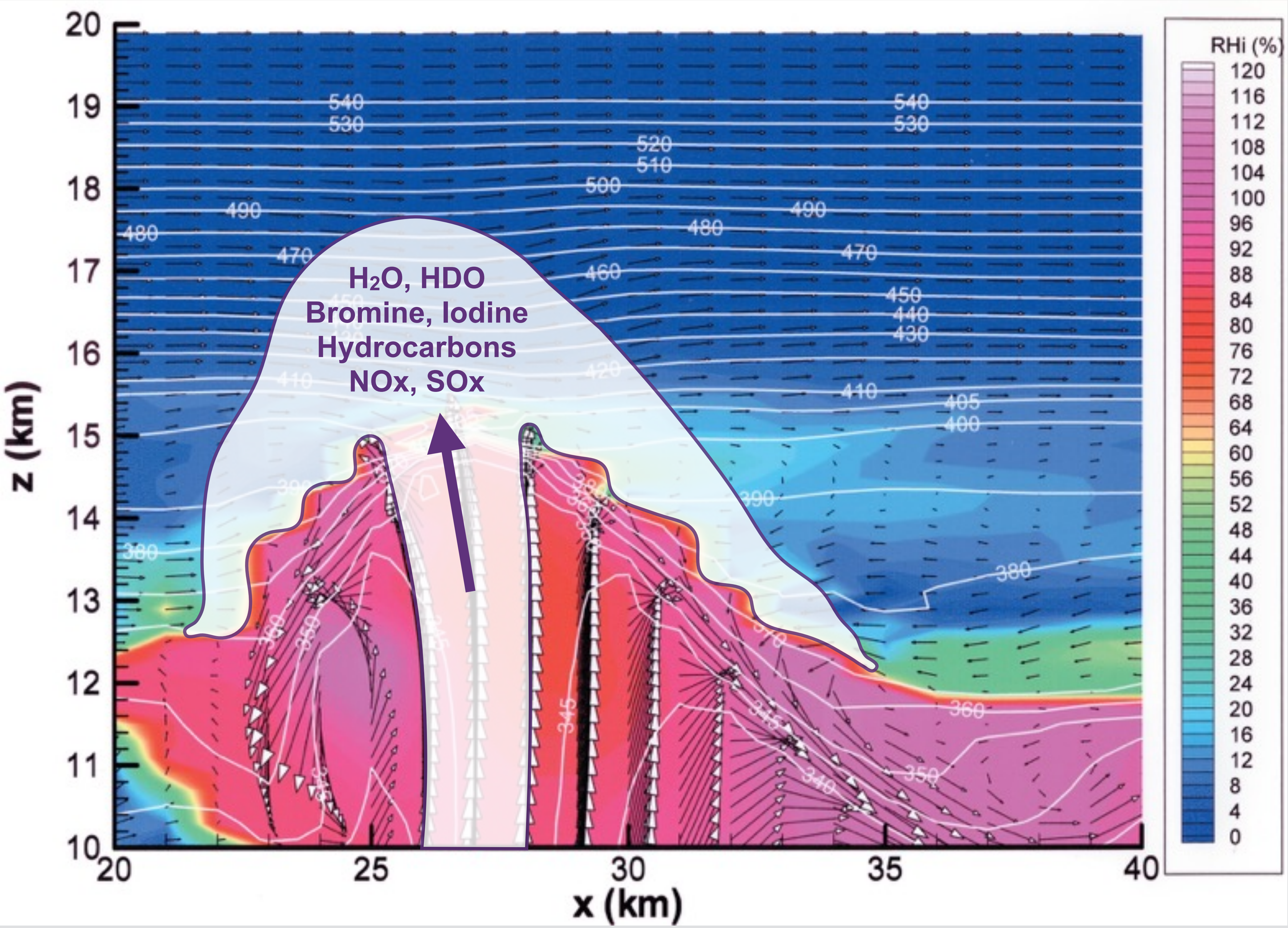

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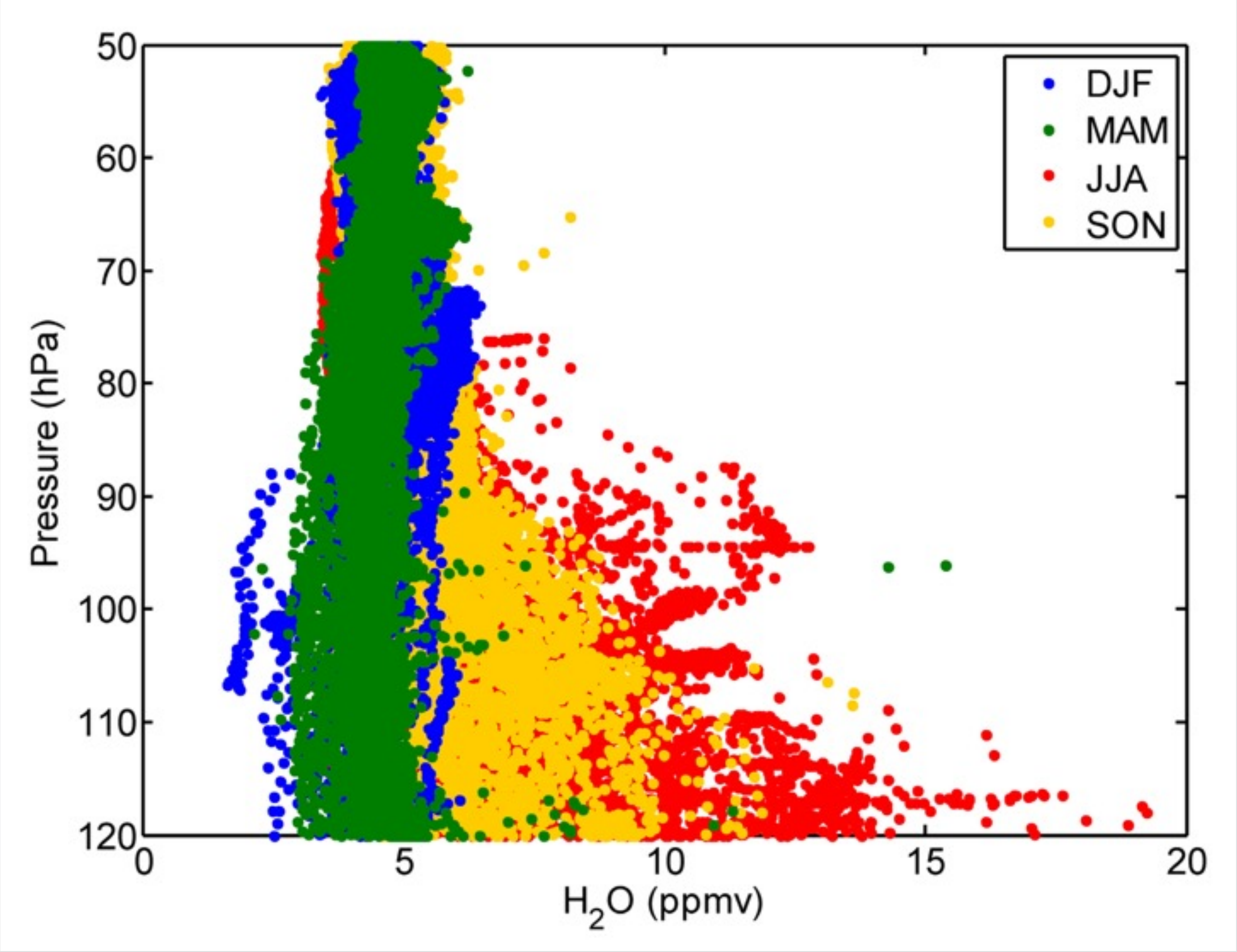
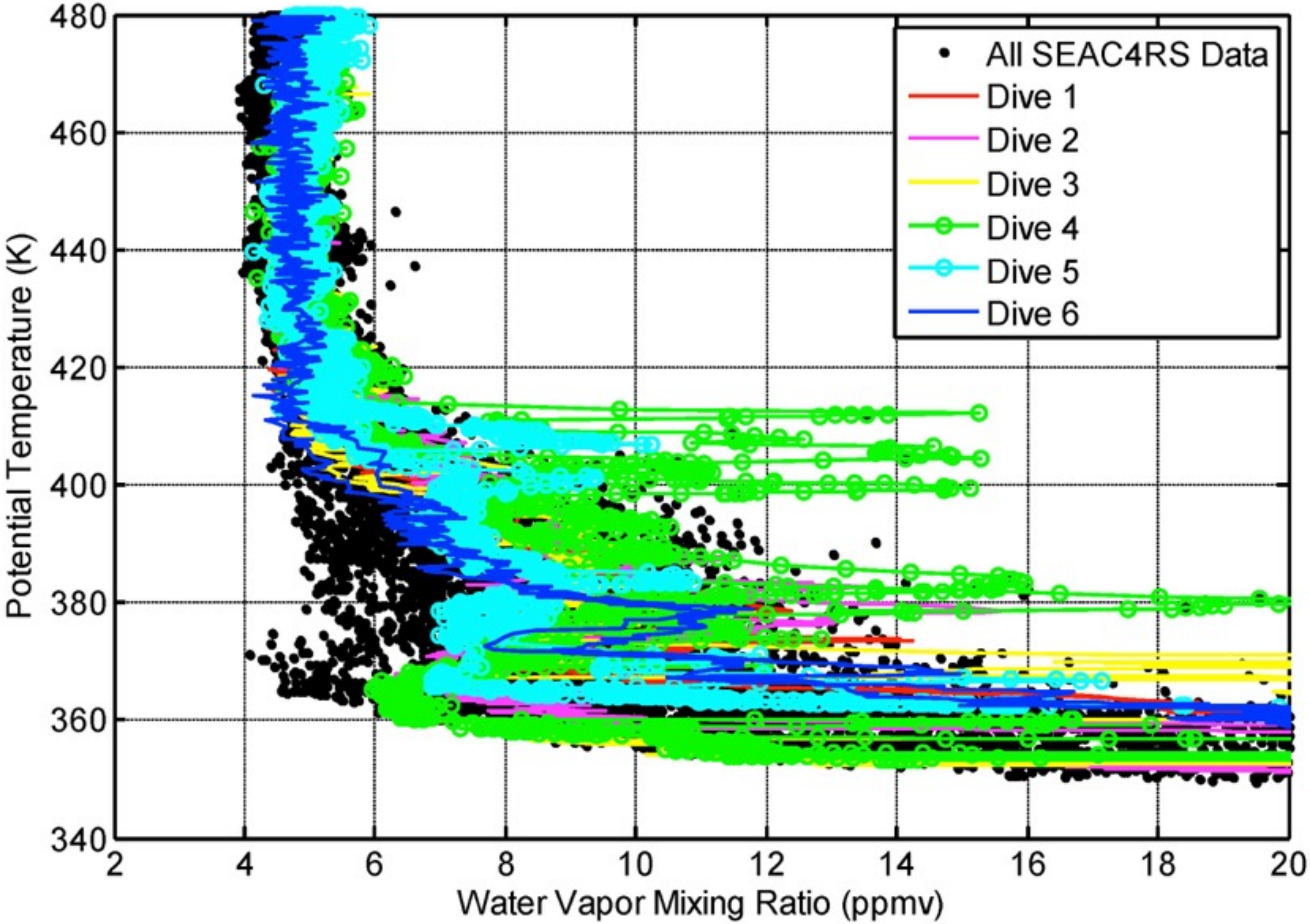
In Situ H_2O Observations over the US in Summer

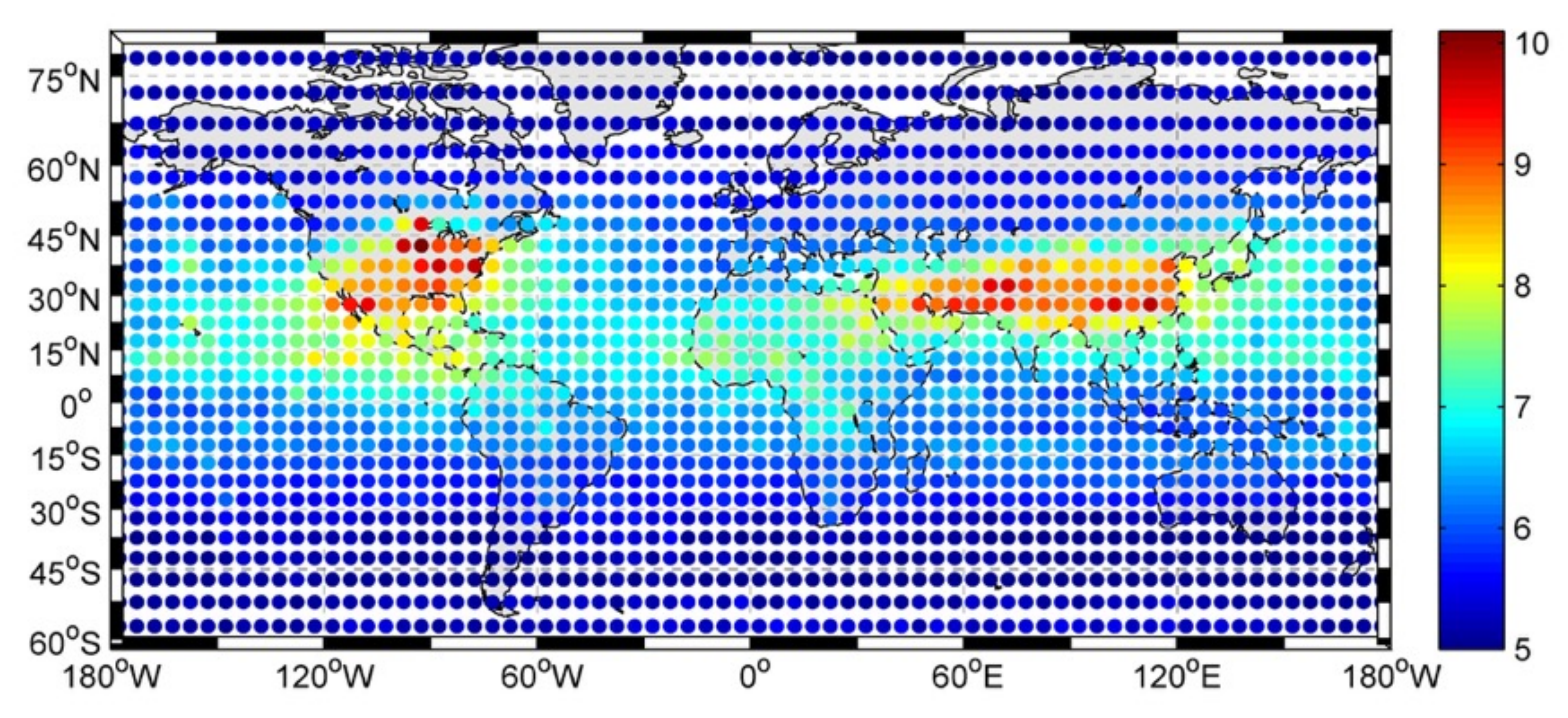


In situ aircraft measurements of water vapor in the summertime over the United States show numerous occurrences of elevated concentrations reaching pressure altitudes deep into the stratosphere.

Convectively Sourced Plume in SEAC4RS

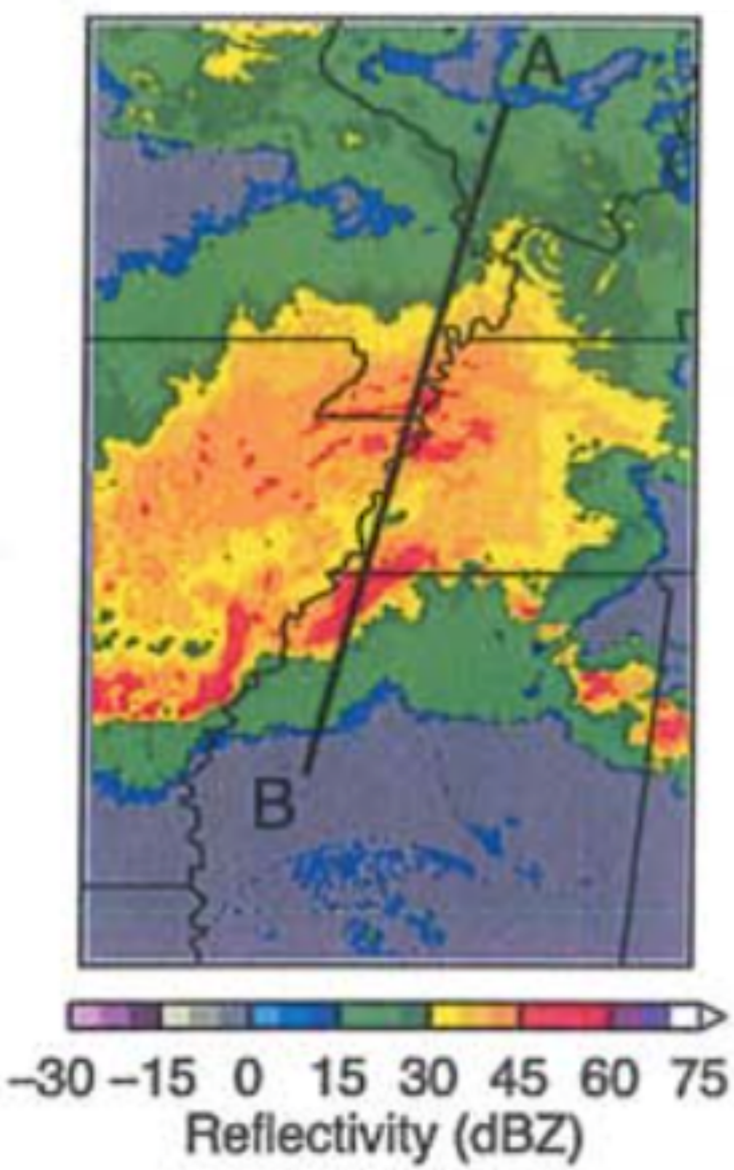
Plume in Overworld Stratosphere Observed on Aug. 27, 2013

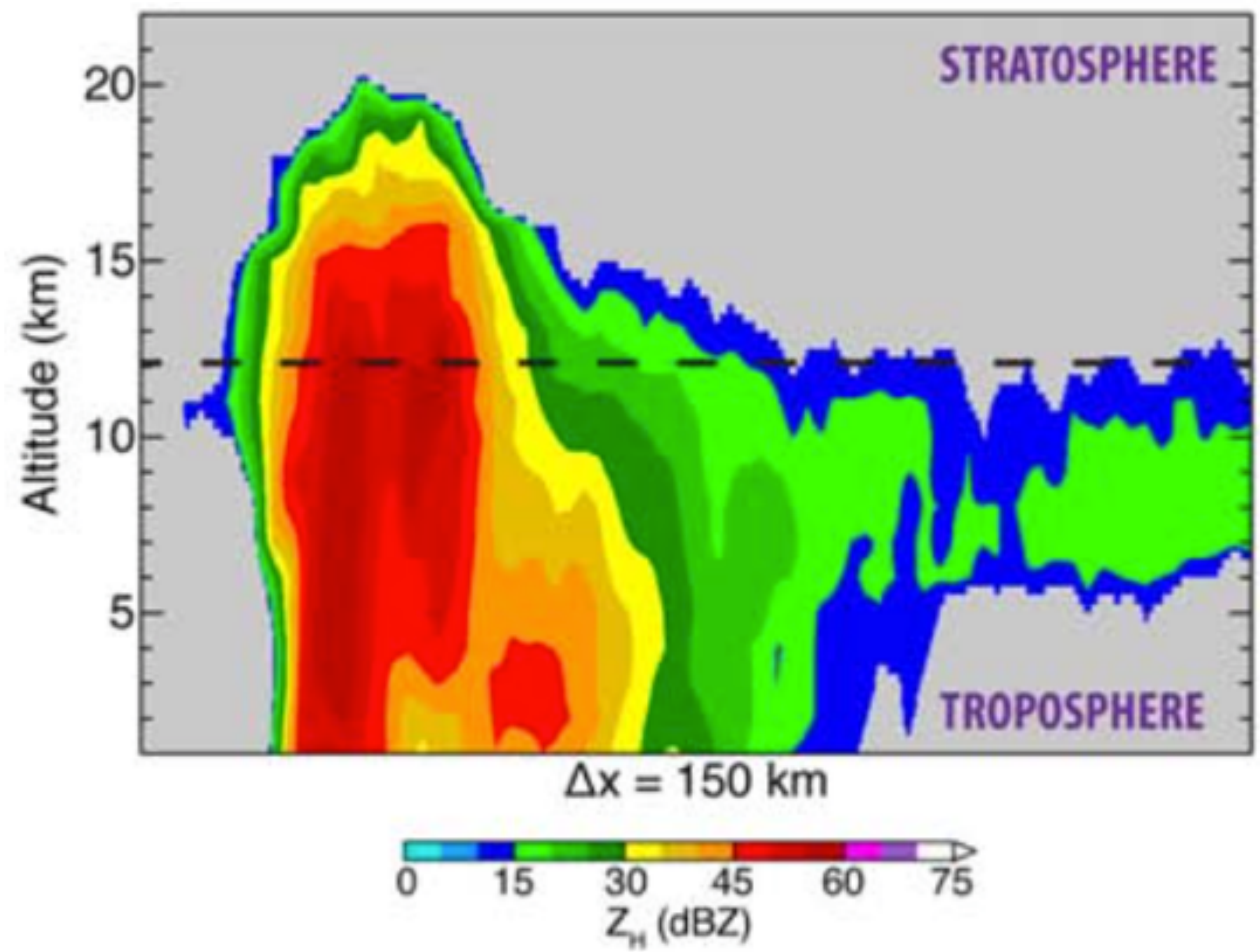




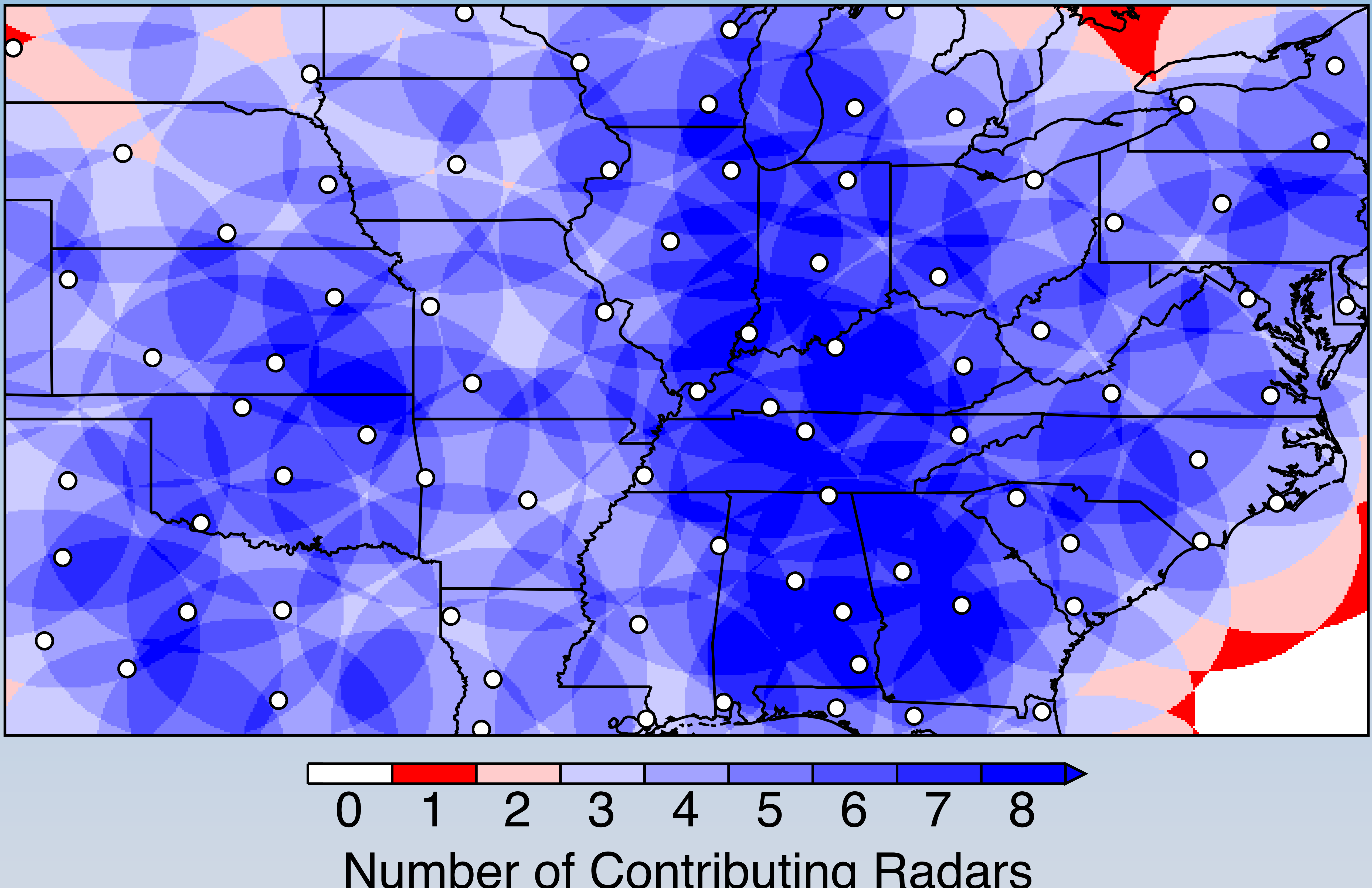
75°N
60°N
45°N
30°N
15°N
0°
15°S
30°S
45°S
60°S
180°W
120°W
60°W
0°
60°E
120°E
180°W
10
9
8
7
6
5

NEXRAD observations

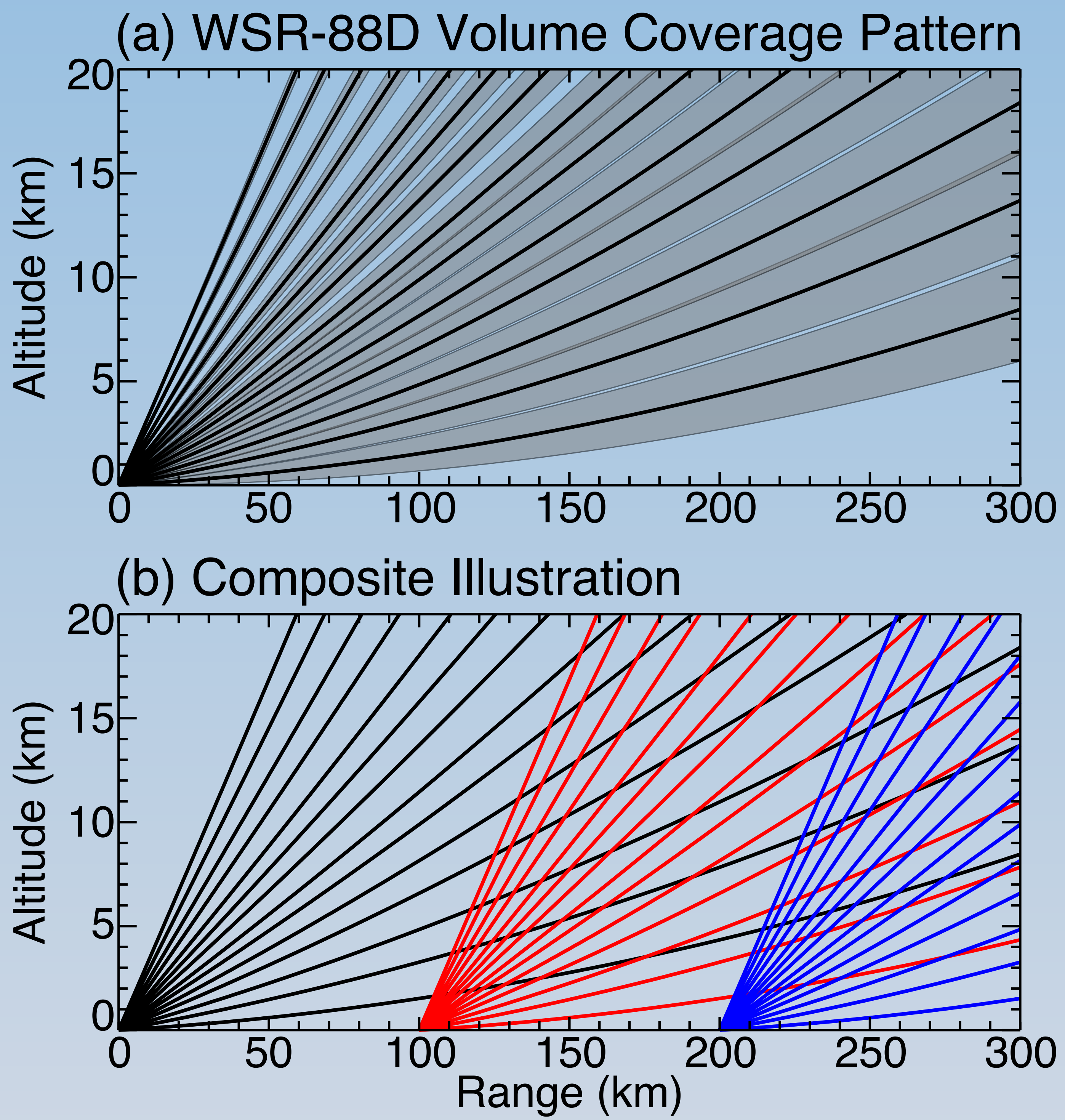


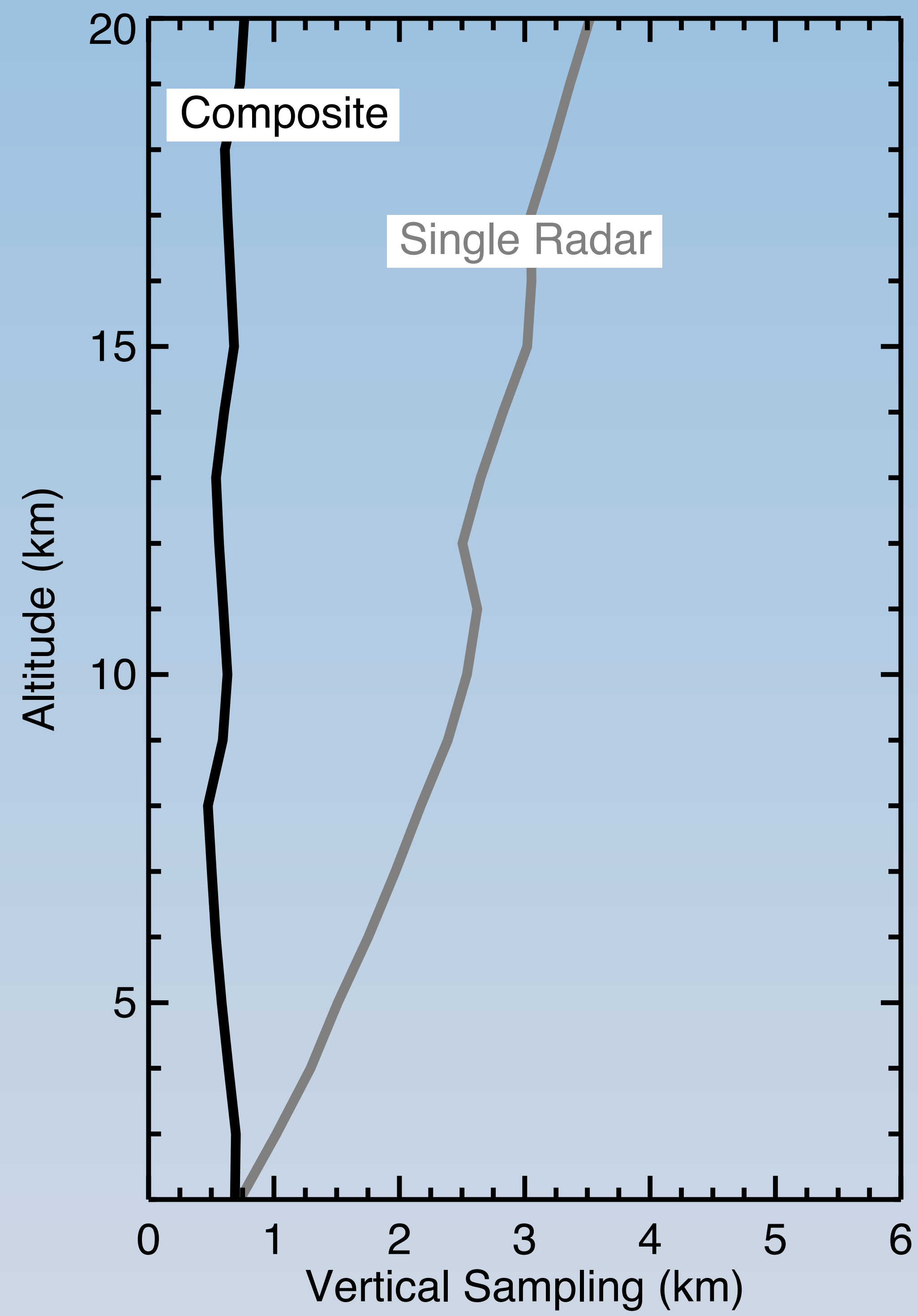


Study Area and NEXRAD Radar Locations



Combining Multiple Radars





Homeyer, 2014, *JAS*

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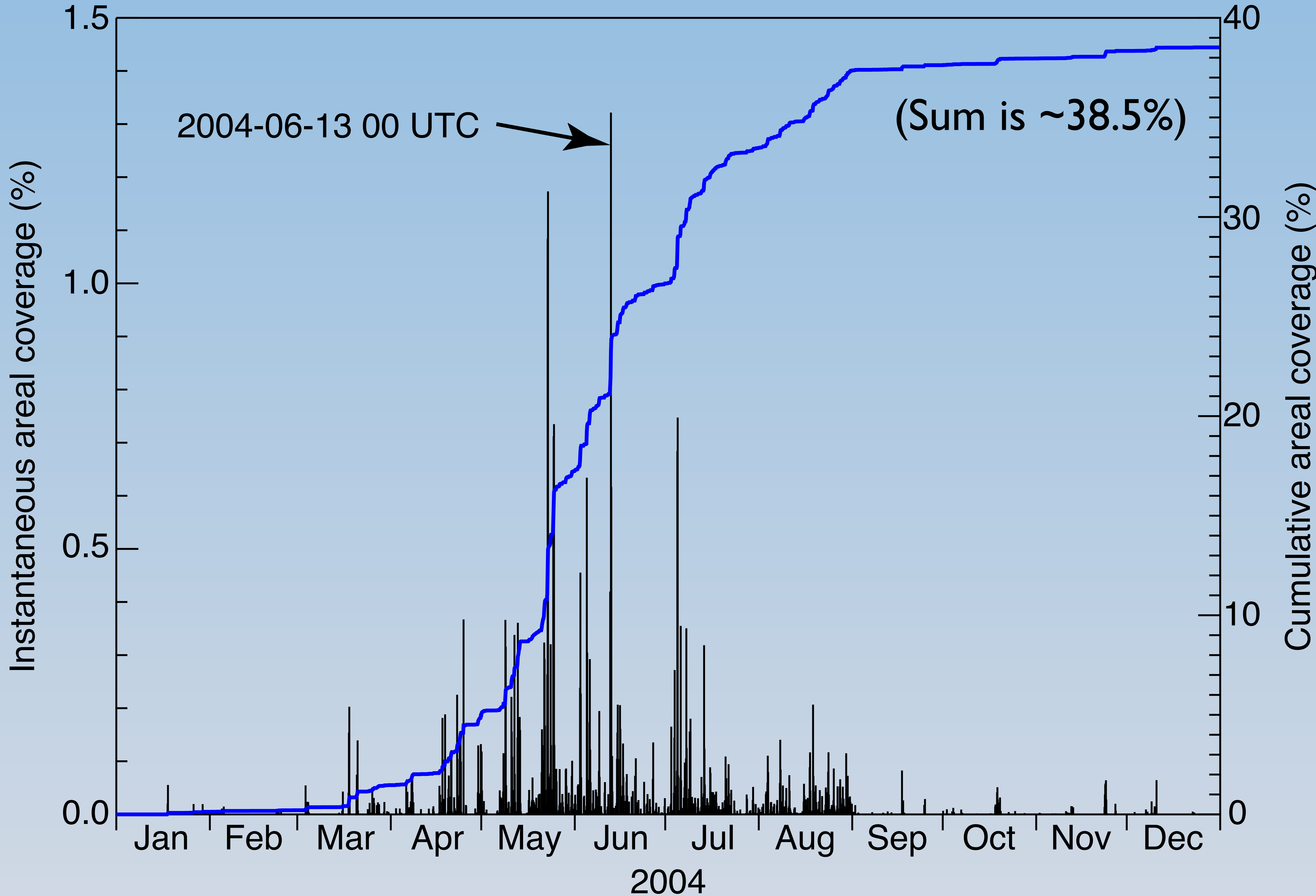
3-Hourly Time Series of Overshooting Area



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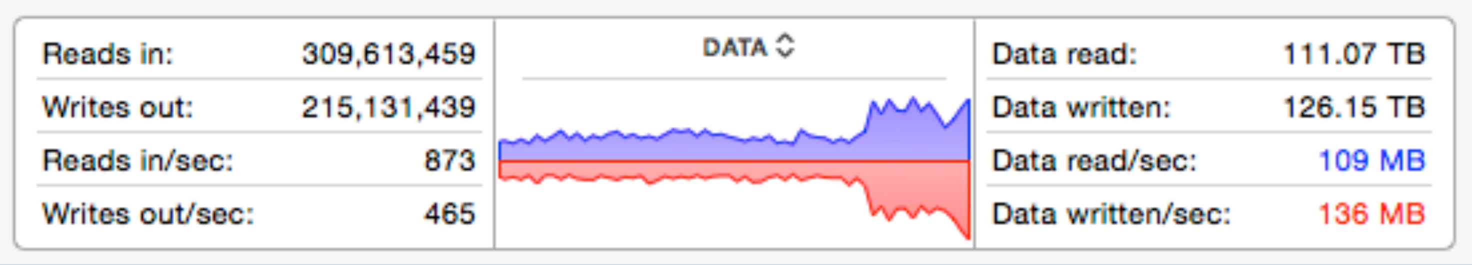
Current Status and Research Topics

- Currently have 9 years of data
  - Full year for 2004 – 2010
  - May – August for 2011 – 2012
- Approximately 65 TB of compressed Level 2 files
- Research topics
  - Improve radar compositing algorithms
  - Comparison with satellite overshooting retrievals
  - Interannual variability of overshooting occurrence
  - Relationship of overshooting to environmental factors
  - Transport of overshooting air in the lower stratospheric anticyclone



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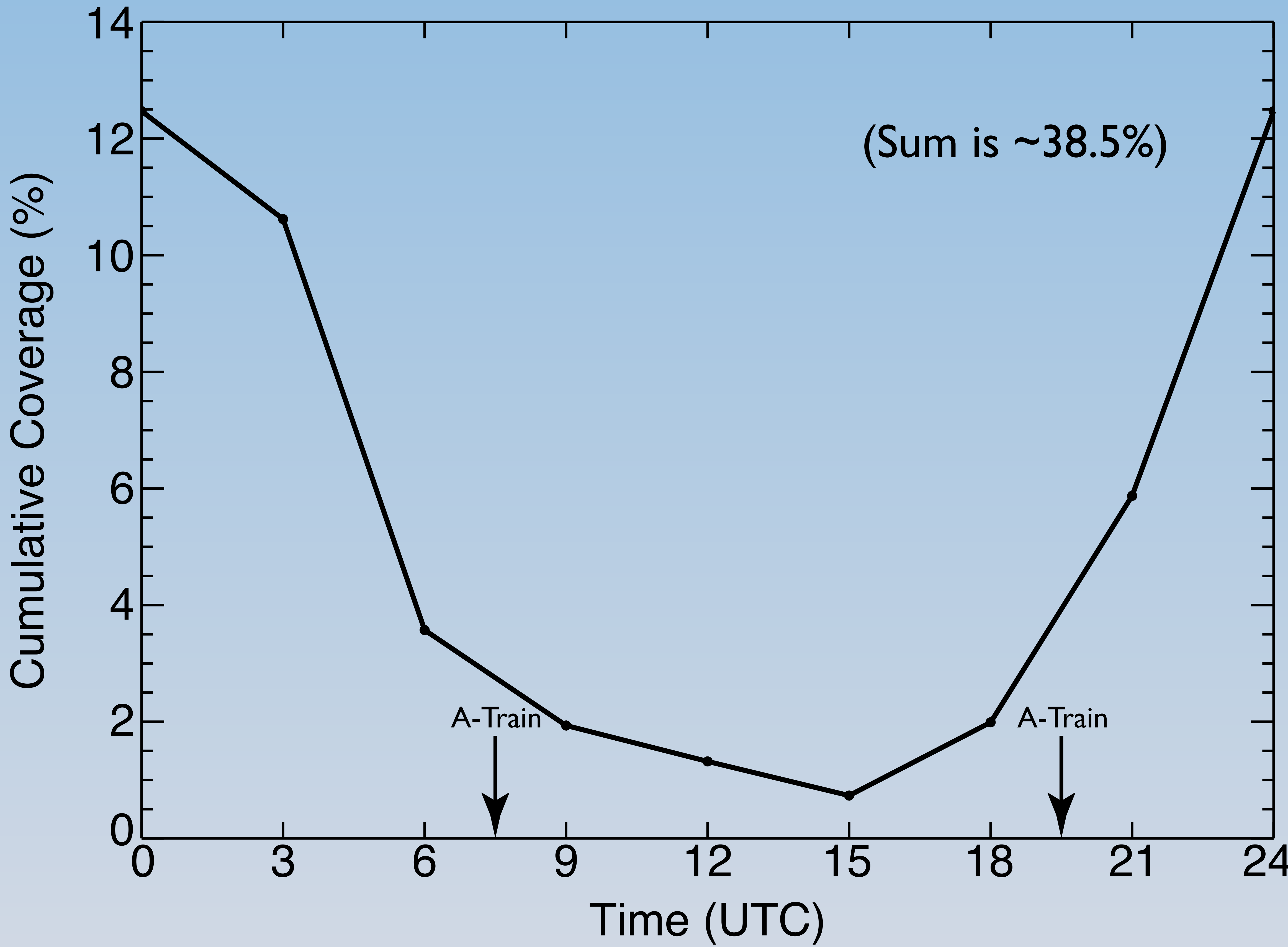
Diurnal Distribution of Overshoots



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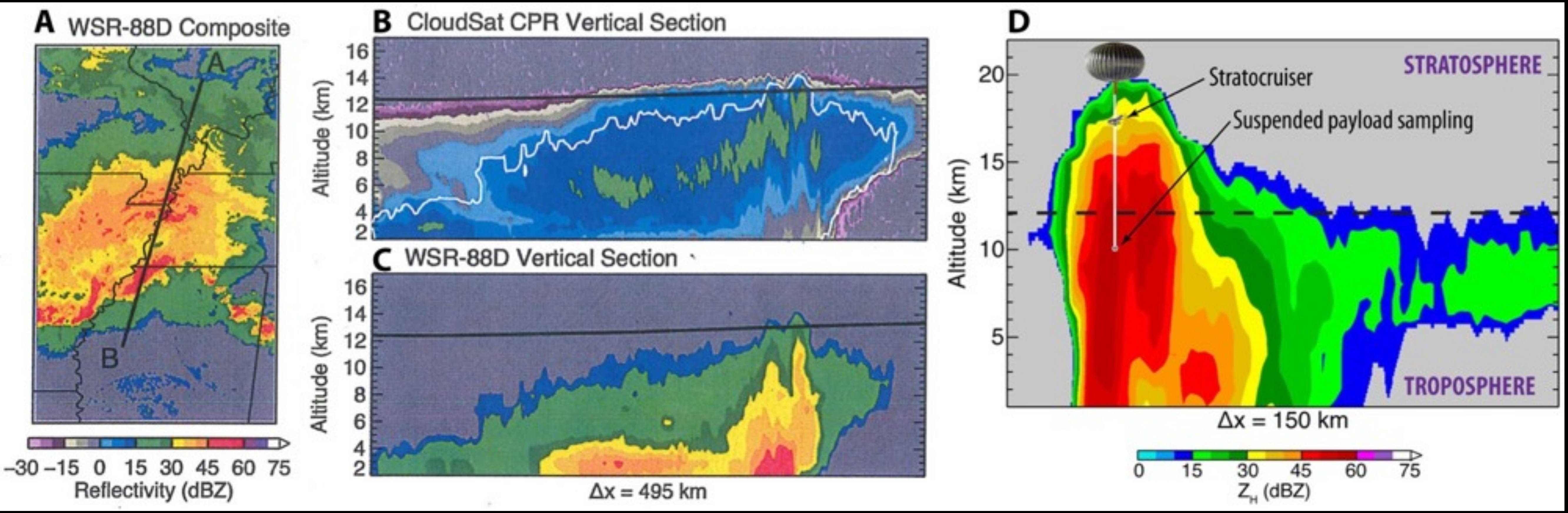
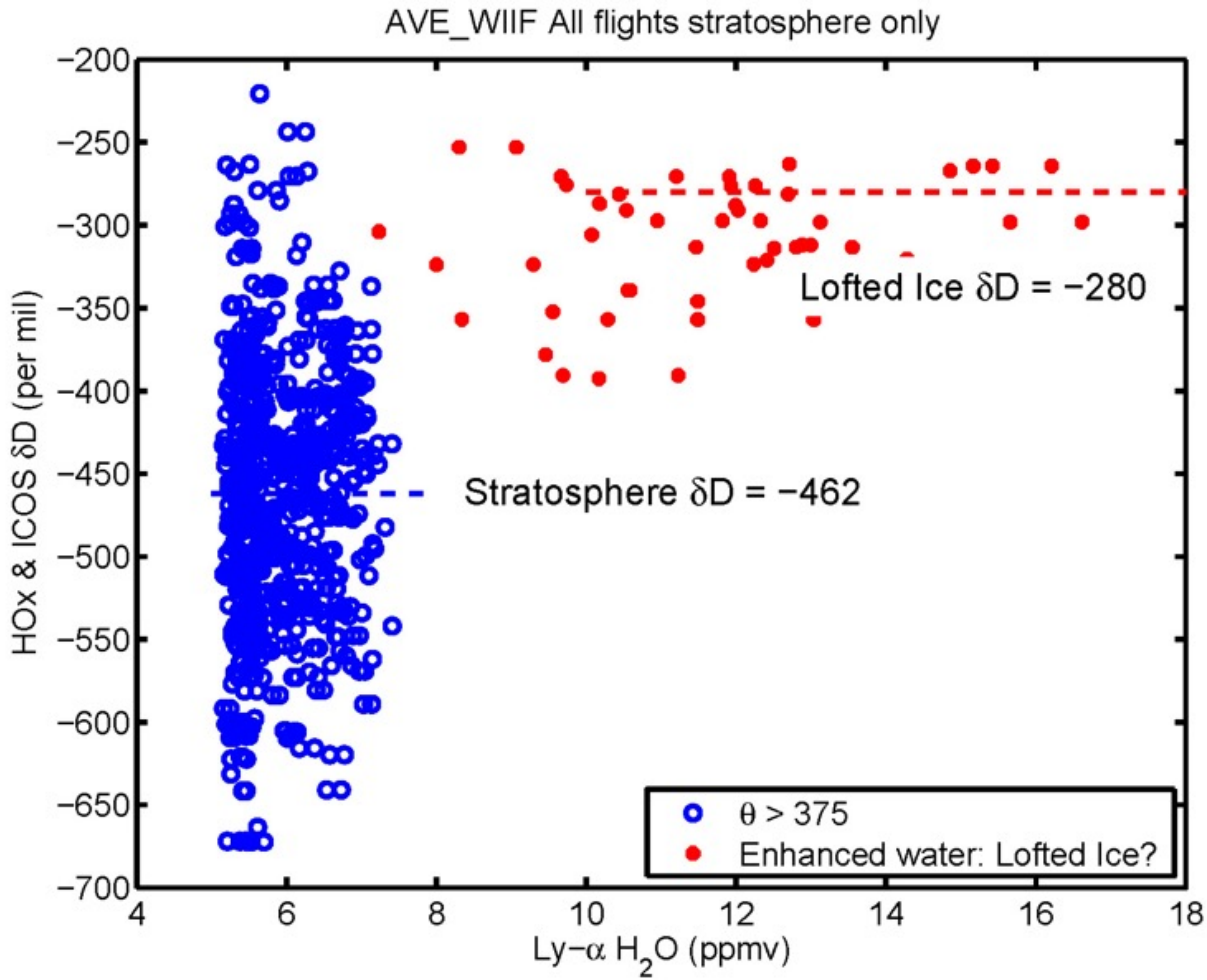


A WSR-88D Composite
A
B
−30 −15 0 15 30 45 60 75
Reflectivity (dBZ)
B CloudSat CPR Vertical Section
Altitude (km)
16
14
12
10
8
6
4
2
C WSR-88D Vertical Section
Altitude (km)
16
14
12
10
8
6
4
2
Δx = 495 km
D
STRATOSPHERE
Stratocruiser
Suspended payload sampling
TROPOSPHERE
Altitude (km)
20
15
10
5
Δx = 150 km
0 15 30 45 60 75
Z_H (dBZ)

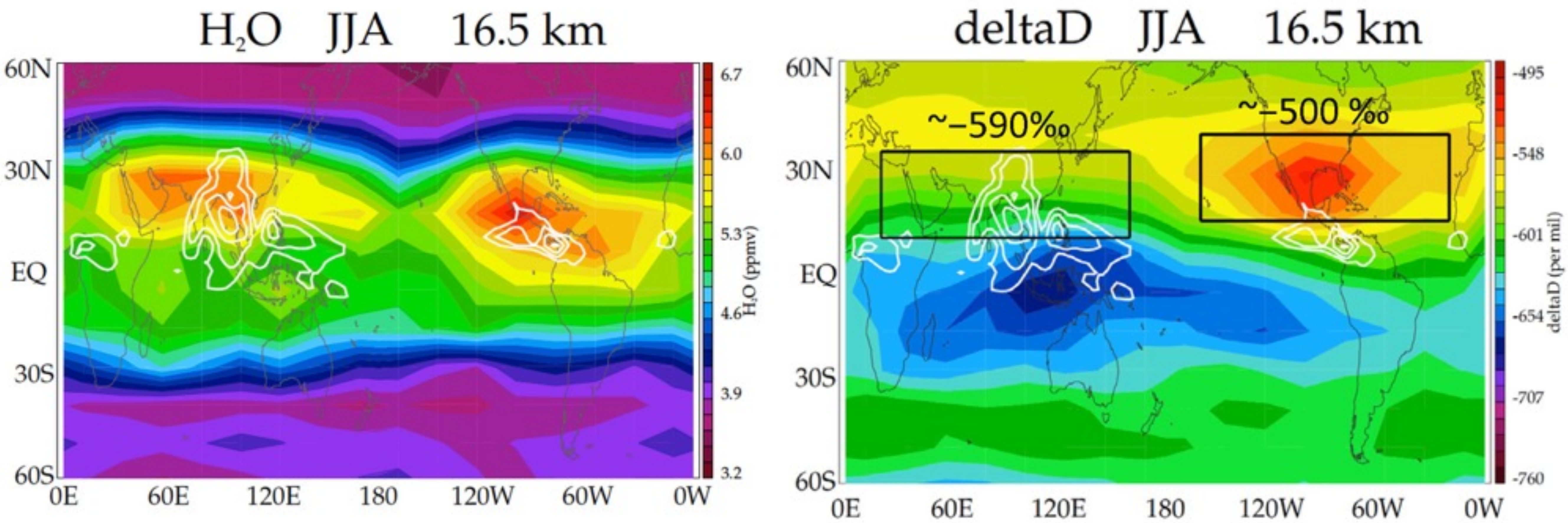


AVE_WIIF All flights stratosphere only
HOx & ICOS δD (per mil)
Ly−α H2O (ppmv)
Lofted Ice δD = −280
Stratosphere δD = −462
θ > 375
Enhanced water: Lofted Ice?
−200
−250
−300
−350
−400
−450
−500
−550
−600
−650
−700
4
6
8
10
12
14
16
18

Evidence of Direct Convective Injection

Analysis of ACE Satellite Data

Figure 12 from Randel et al., 2012

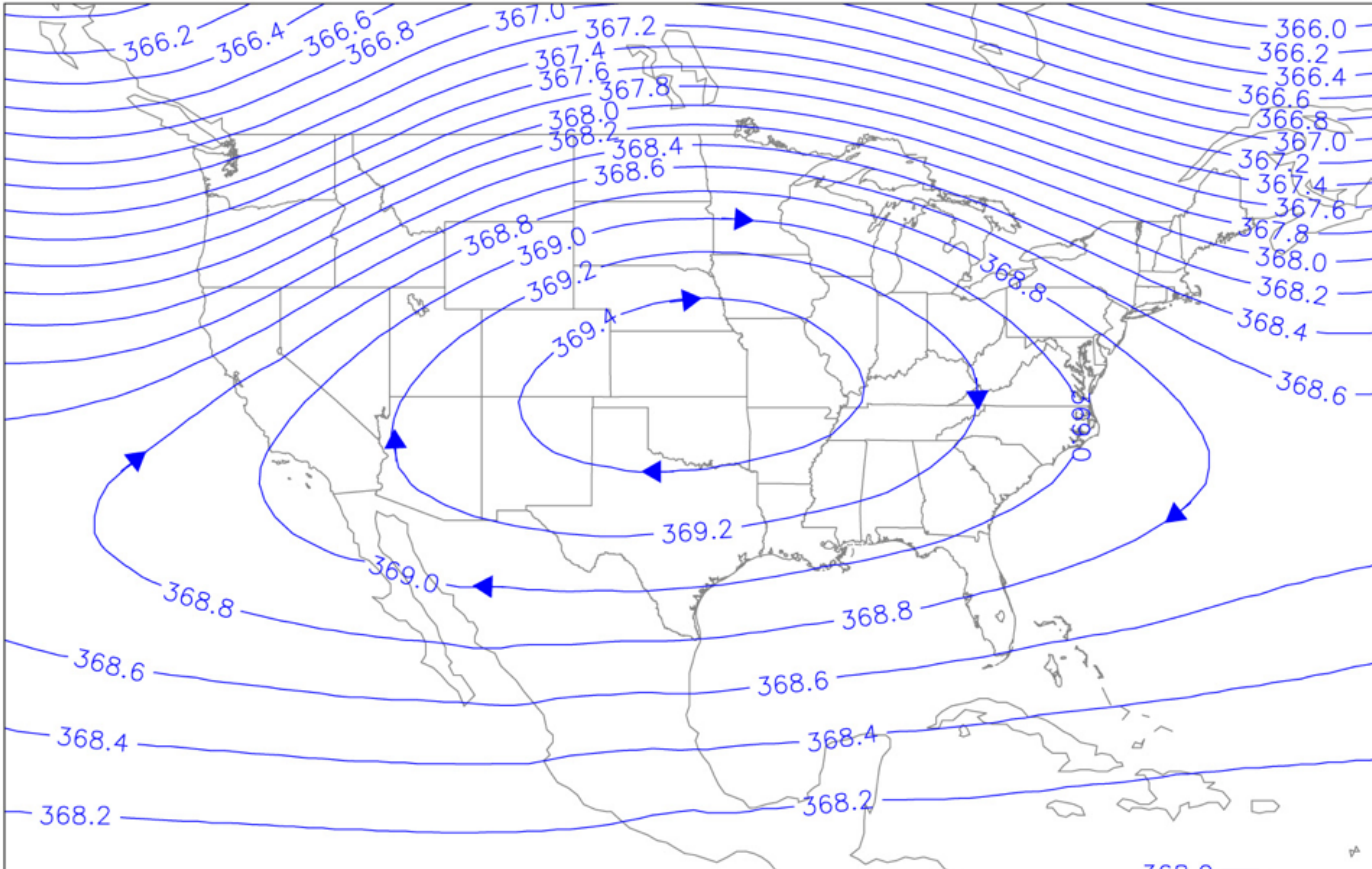


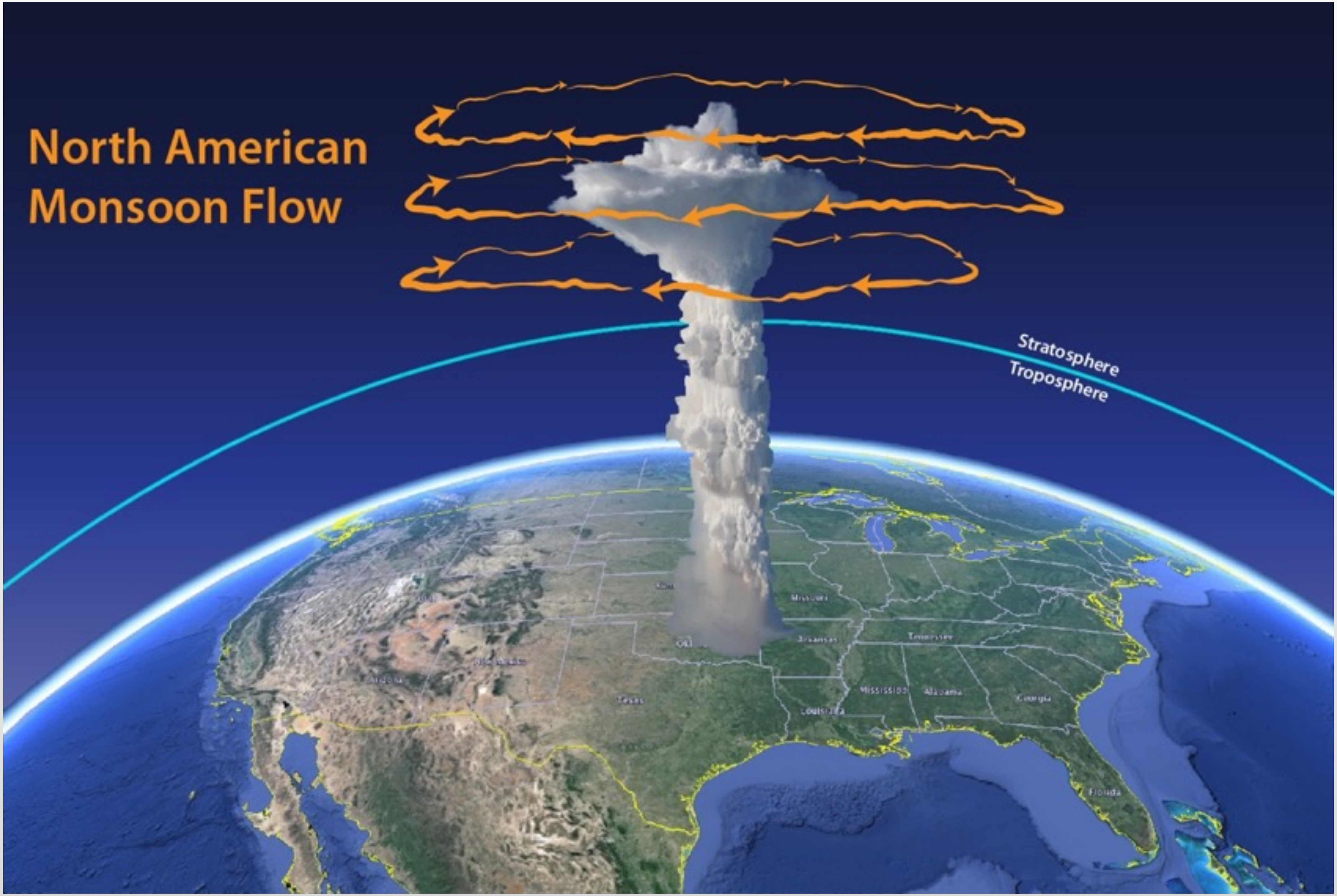
(16.5 km ~ 100 hPa ~ 380 K)

- White contours denote strongest tropical convection
- Water vapor enrichments evident near monsoon regions

Randel et al., JGR, 2012

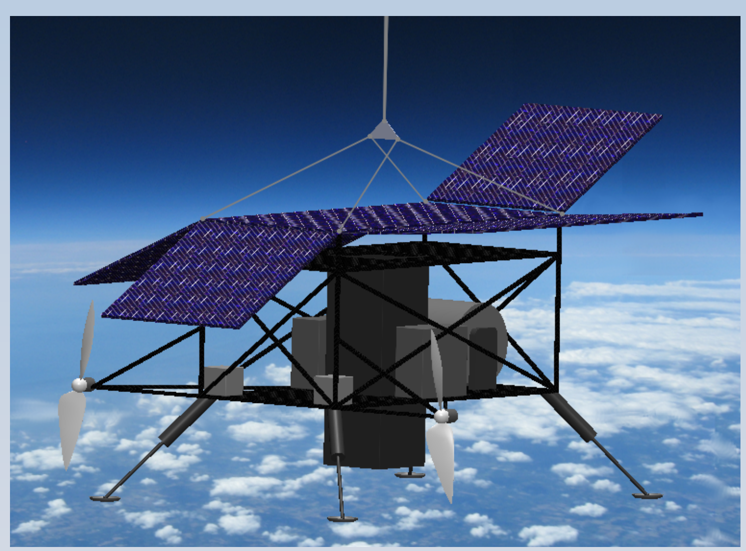
Montgomery Potential [kJ/kg], θ = 395 K July, 2011

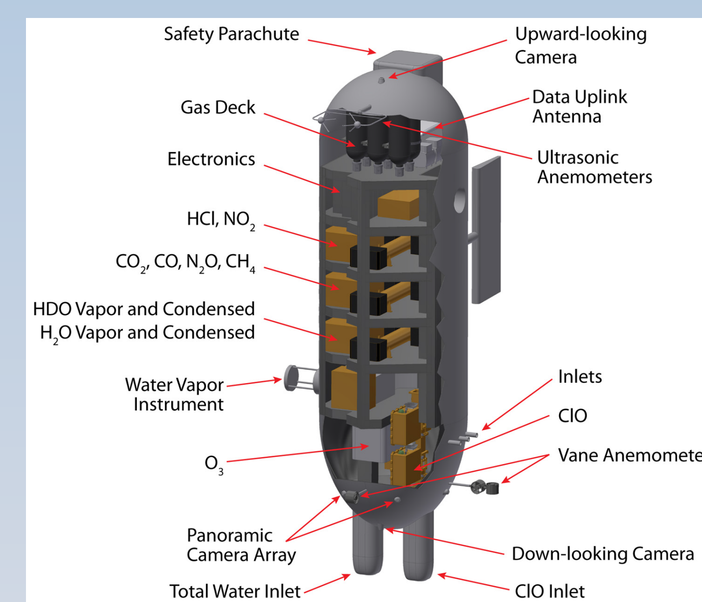



North American
Monsoon Flow
Stratosphere
Troposphere
Texas
Tennessee
Georgia
Florida

Stratocruiser

- Long-duration pressurized balloon floats near summertime zero-wind line (~20 km, 50-70 hPa)
- ~6-week lifetime
- Gondola w/batteries, solar panels, and electrically powered propulsion system (8 kts cruise speed)
- 200 kg instrument package on 10 km winch line, 5-10 m/s
- Maneuverable to target convective systems and environment





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Model Simulation of Overshooting Top

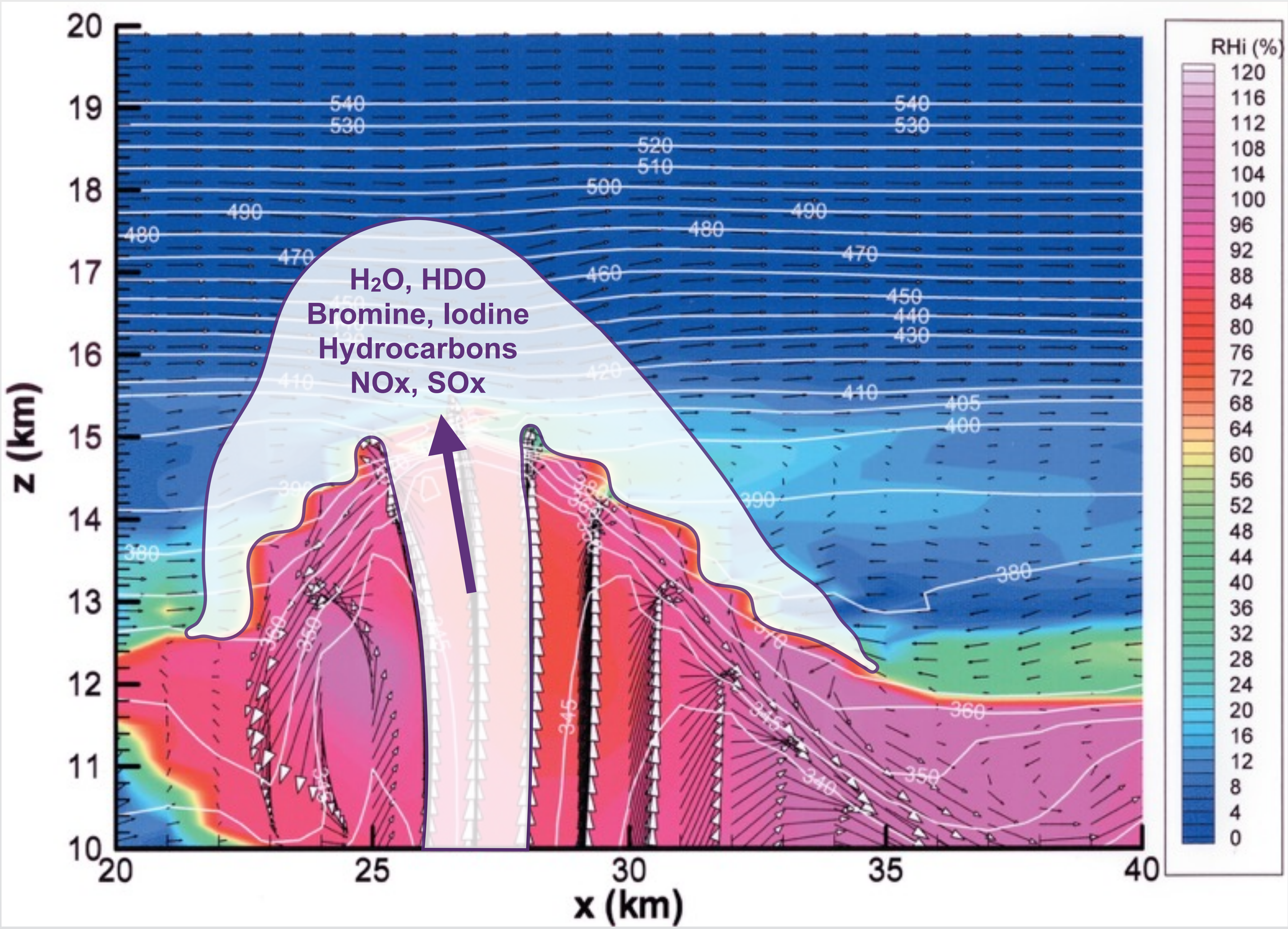

Figure 8. Central east-west cross-section of the simulated storm at t = 73 min 10 sec, showing the overlapped RHi, wind vector (projected on the x-z plane) and θ fields. The wave breaking is obvious in the region where x ~28 km and z ~15 km.

Wang, 2003, *JGR*

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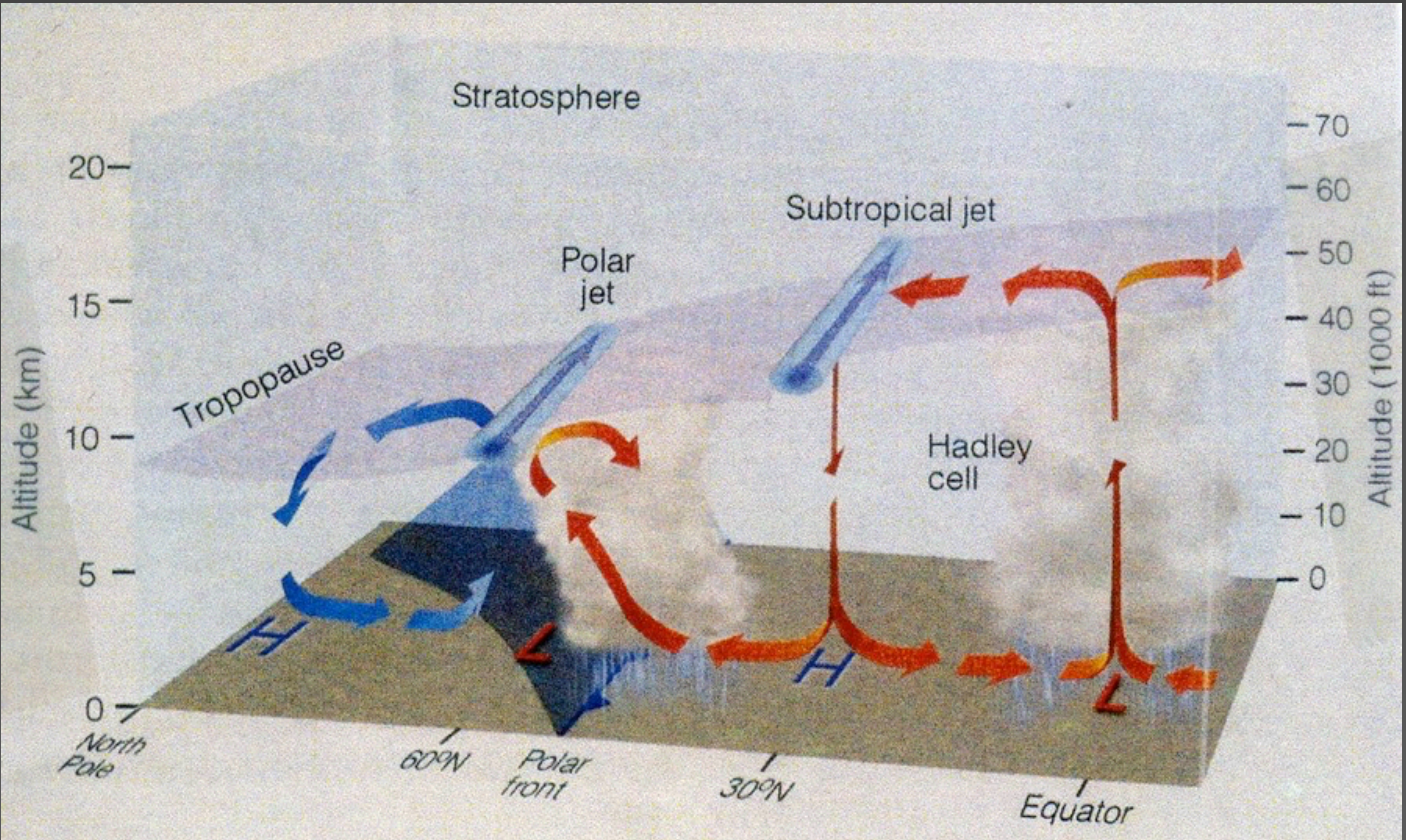
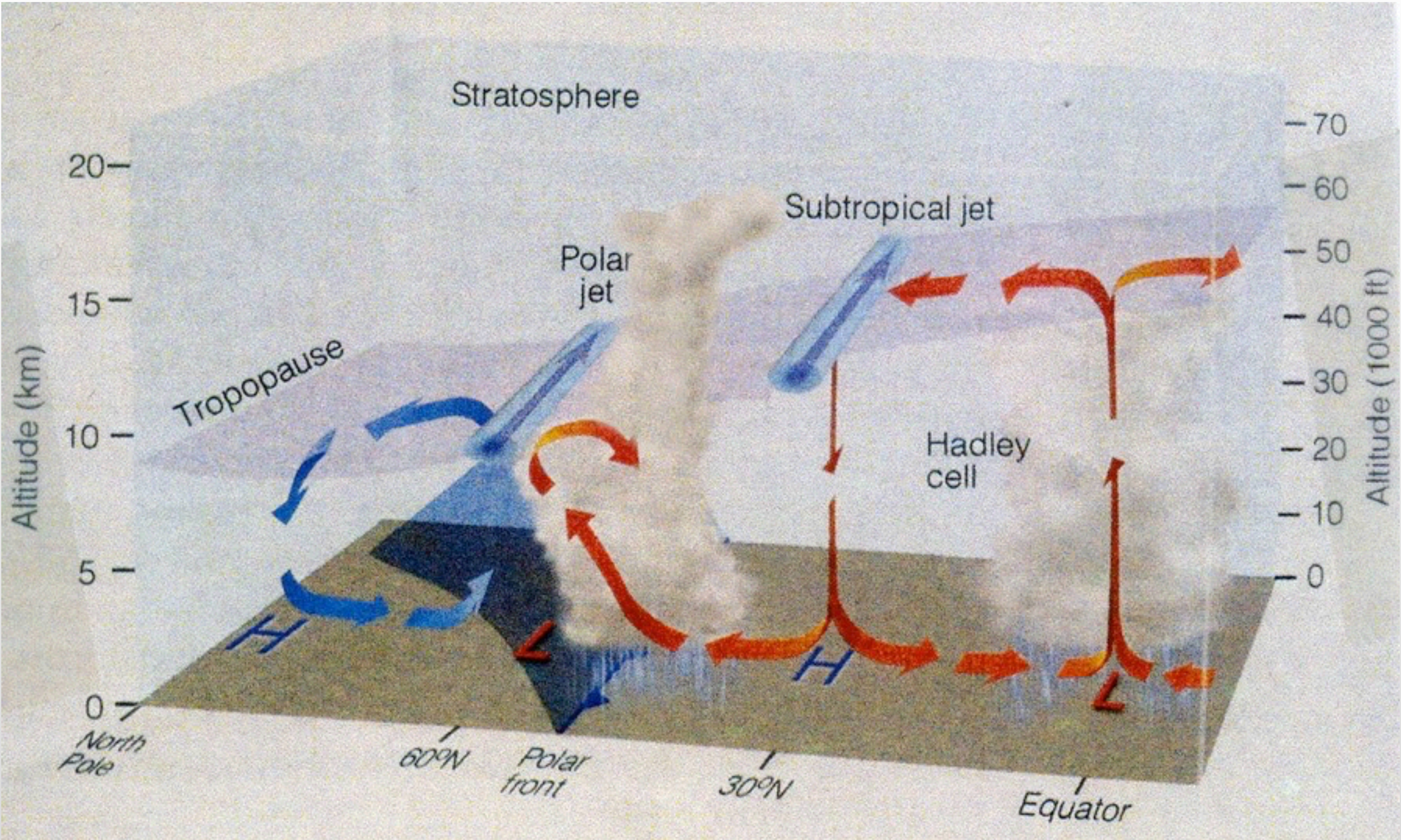
http://onlinelibrary.wiley.com/doi/10.1029/2002JD002581/full#jgrd9978-fig-0008

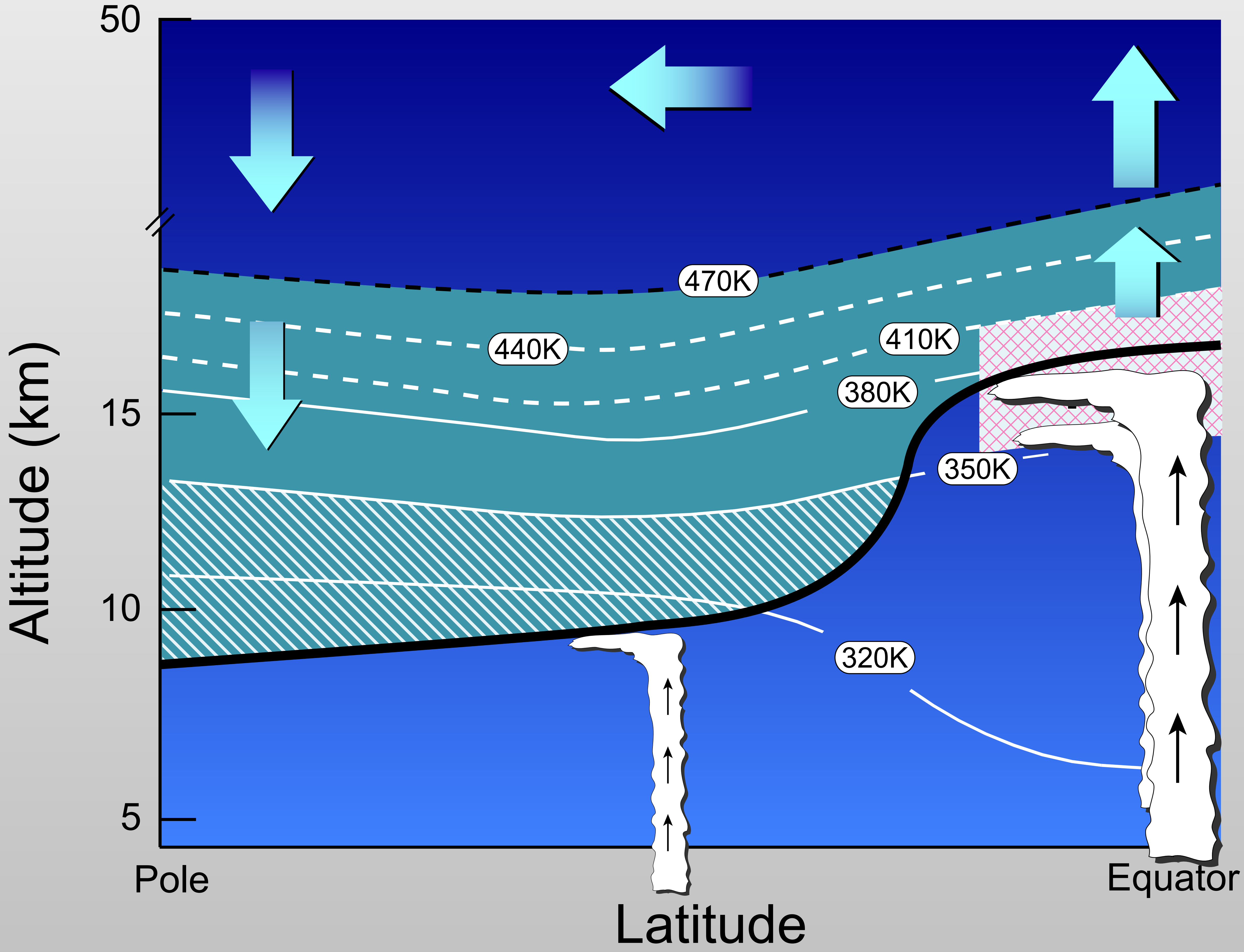
Summary: The Key Points to Emphasize

- NEXRAD, Aircraft and Satellite Observations Make it Clear that Convection Can Deliver Large Quantities of Water Directly (i.e. limited entrainment) to the Lowermost Stratosphere and the Overworld Stratosphere at least to 440K.
- Convective Injection North of the Subtropical Jet Bypasses the Thermal Control Mechanism and Inject H2O Irreversibly into the Overworld.
- Trajectories Demonstrate that there is a Persistent Anti-Cyclonic Flow Over the Central US in July and August.

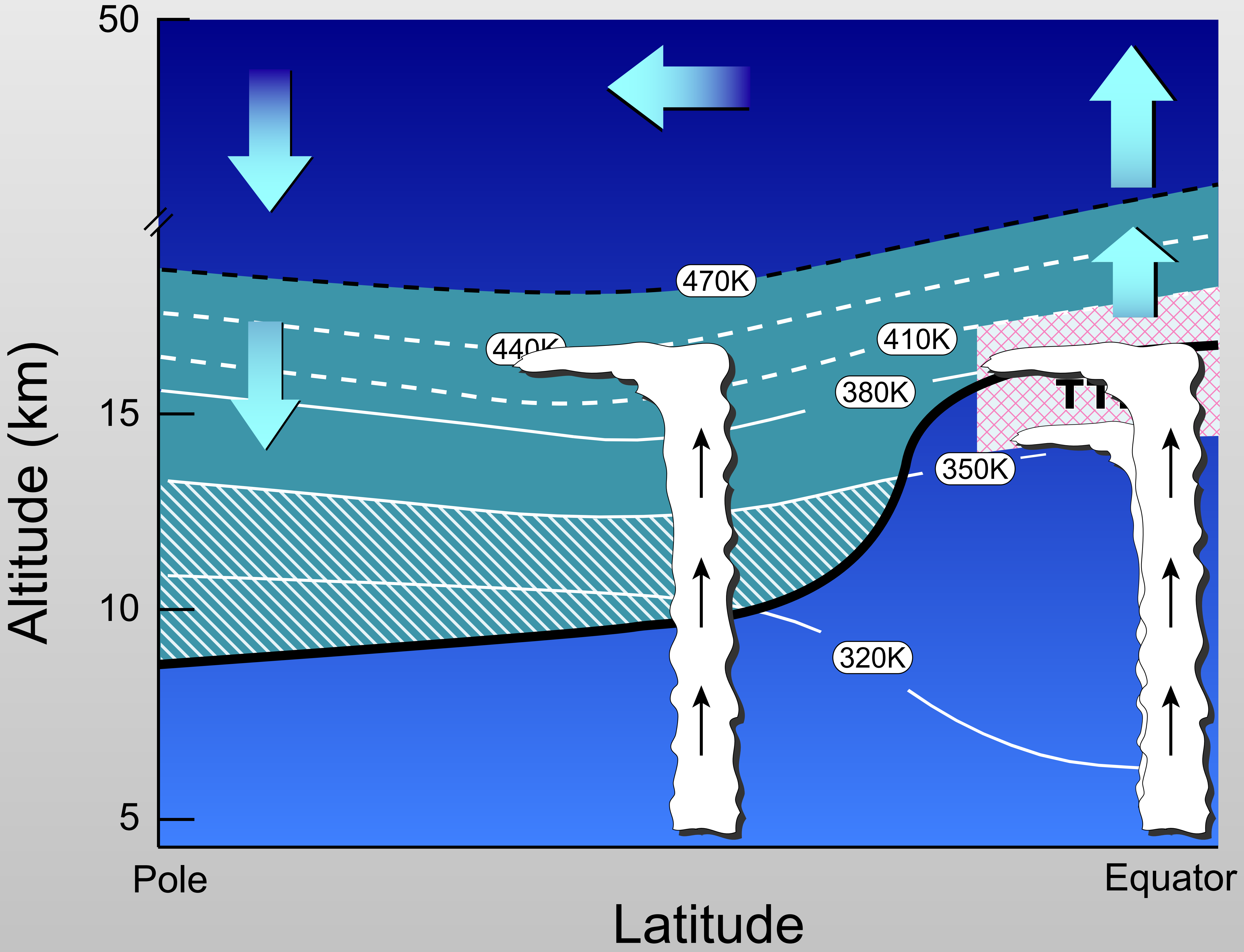


Stratosphere
Subtropical jet
Polar
jet
Tropopause
Hadley
cell
H
L
H
L
20
15
10
5
0
Altitude (km)
70
60
50
40
30
20
10
0
Altitude (1000 ft)
North
Pole
60°N
Polar
front
30°N
Equator


Stratosphere
Subtropical jet
Polar jet
Tropopause
Hadley cell
Altitude (km)
20
15
10
5
0
Altitude (1000 ft)
70
60
50
40
30
20
10
0
H
L
H
L
North Pole
60°N
Polar front
30°N
Equator

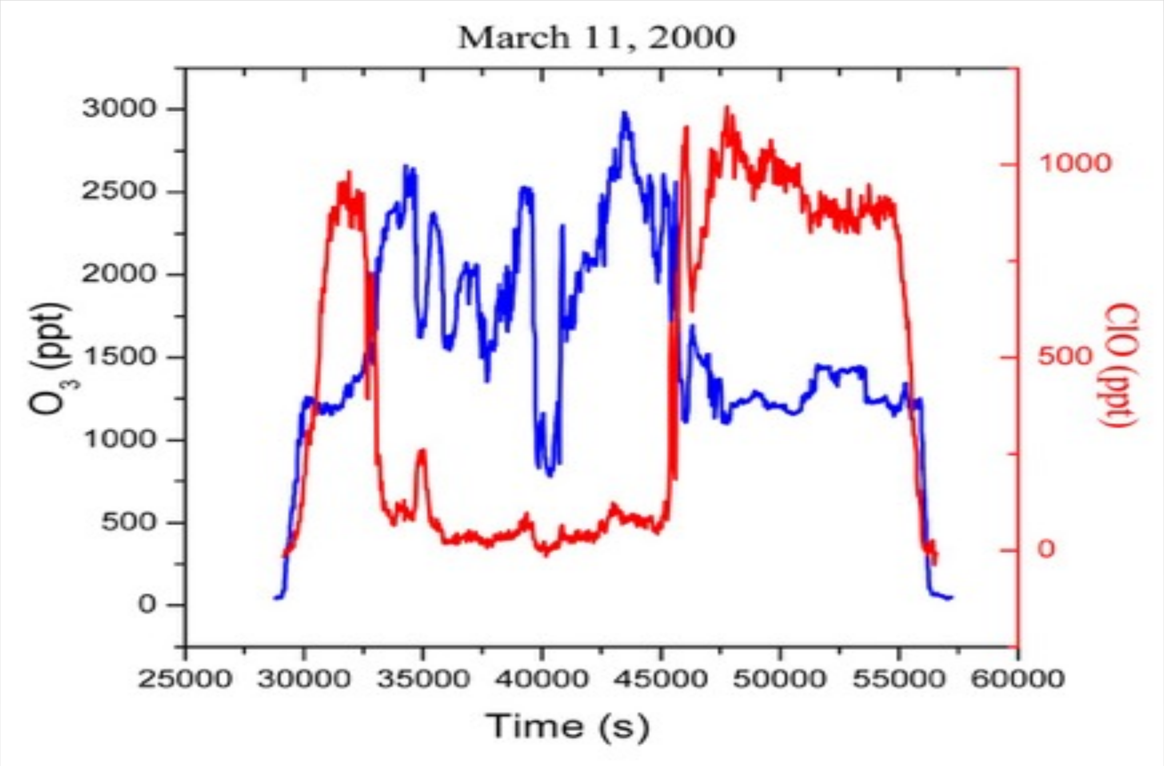


50
15
10
5
Altitude (km)
470K
440K
410K
380K
350K
320K
Pole
Equator
Latitude

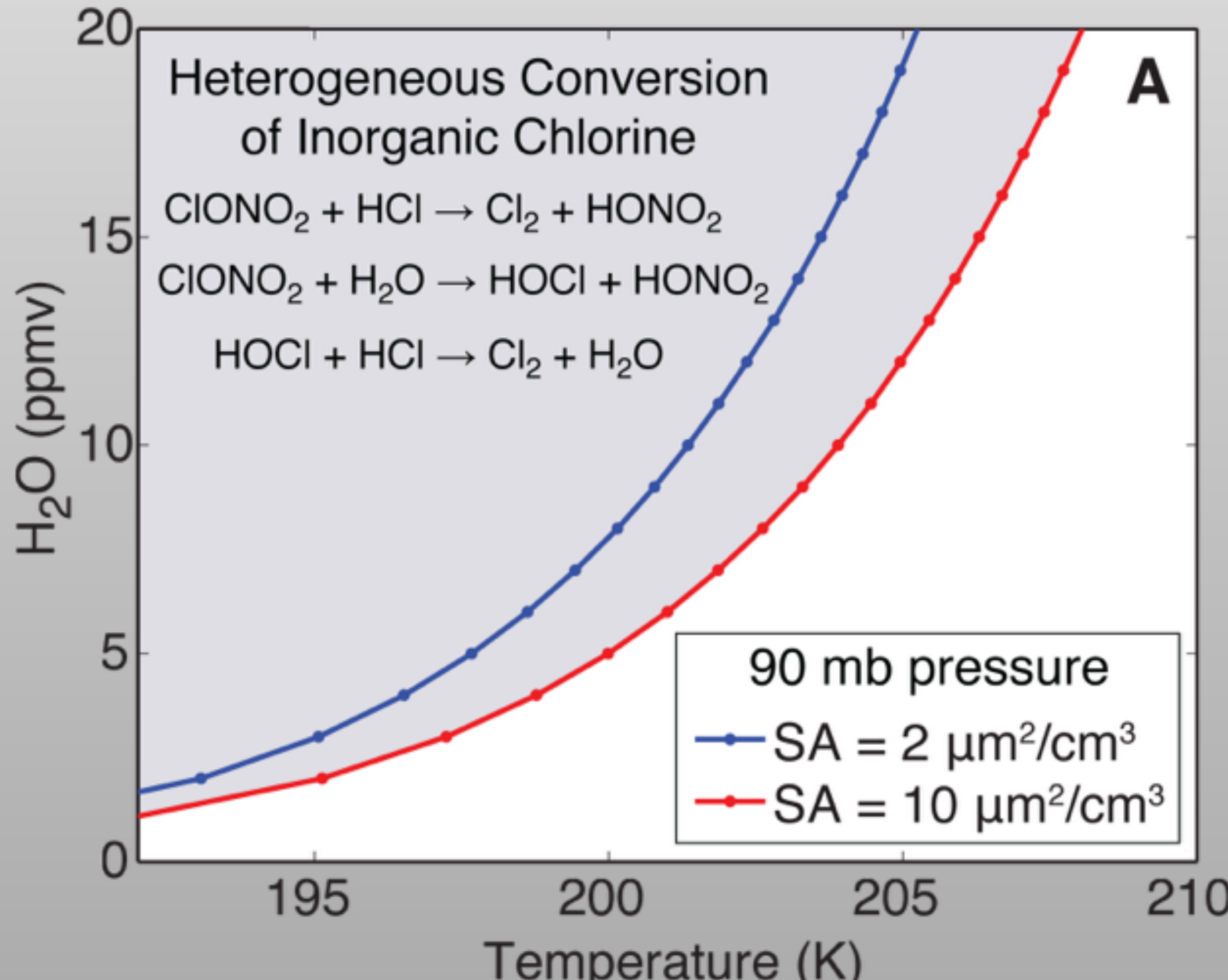


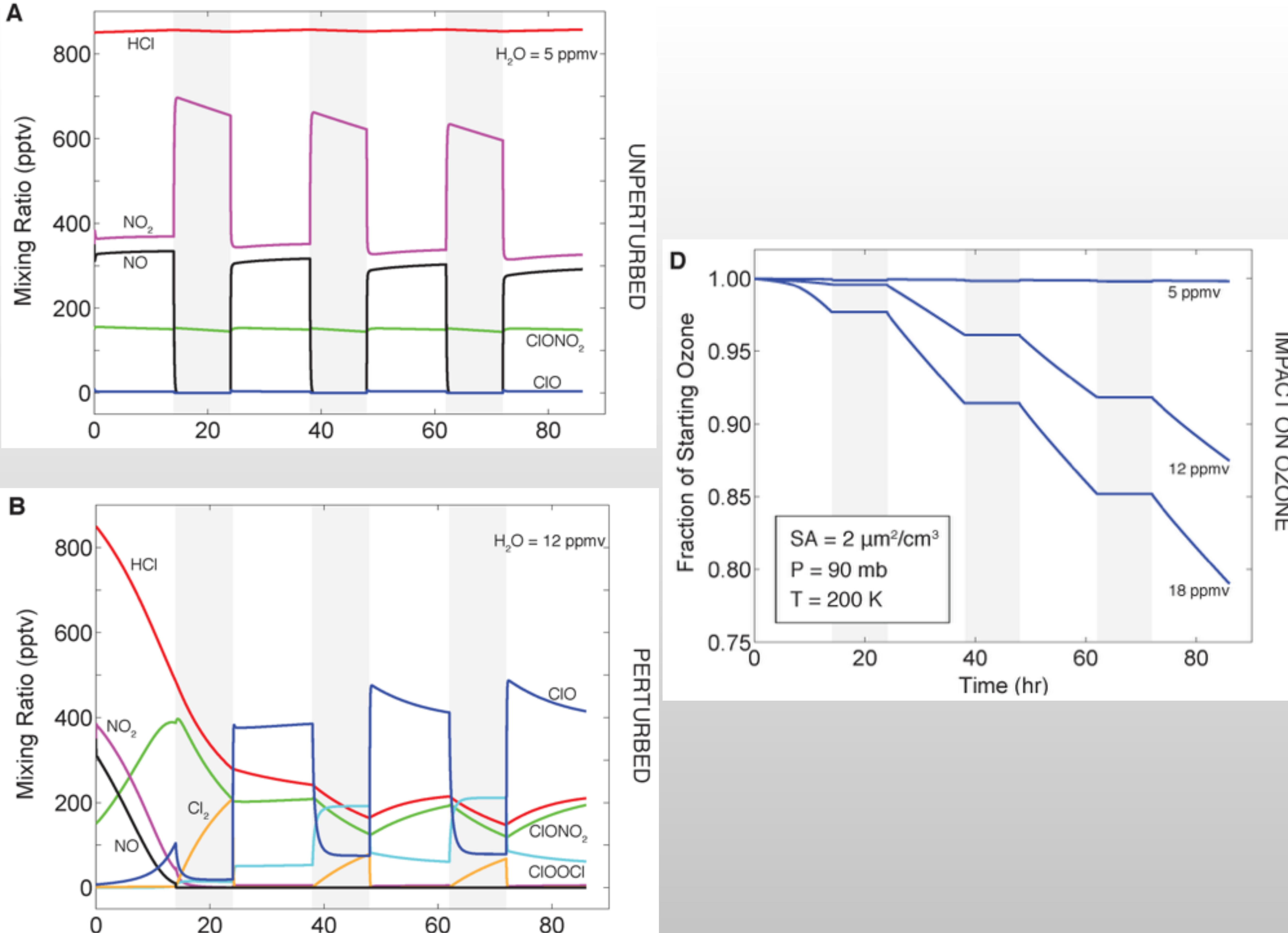
50
15
10
5
Altitude (km)
470K
440K
410K
380K
350K
320K
Pole
Equator
Latitude

What About the Catalytic Photochemical Implications?



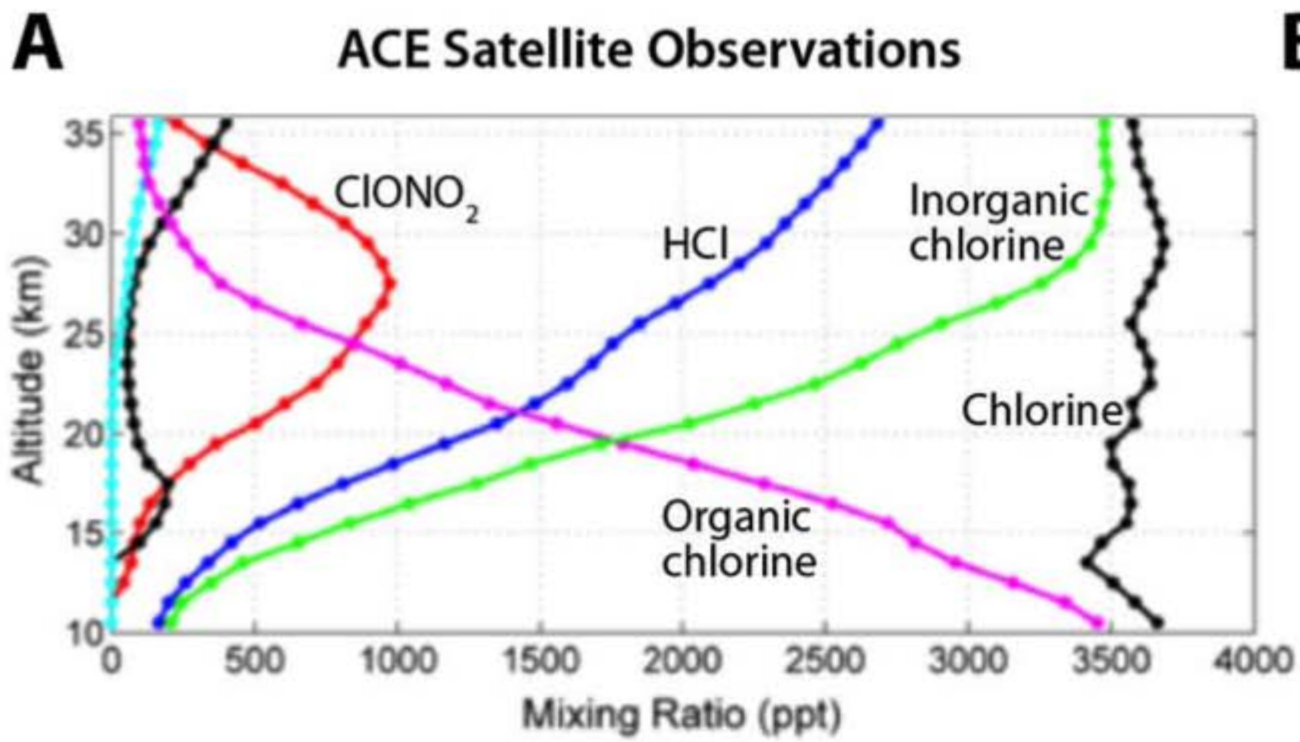
Major Transition in Our Perspective on the Mechanism for Heterogeneous Catalytic Conversion of Inorganic Chlorine to Free Radical Form: Not PSCs But *Simple Binary Sulfate-Water Aerosols*

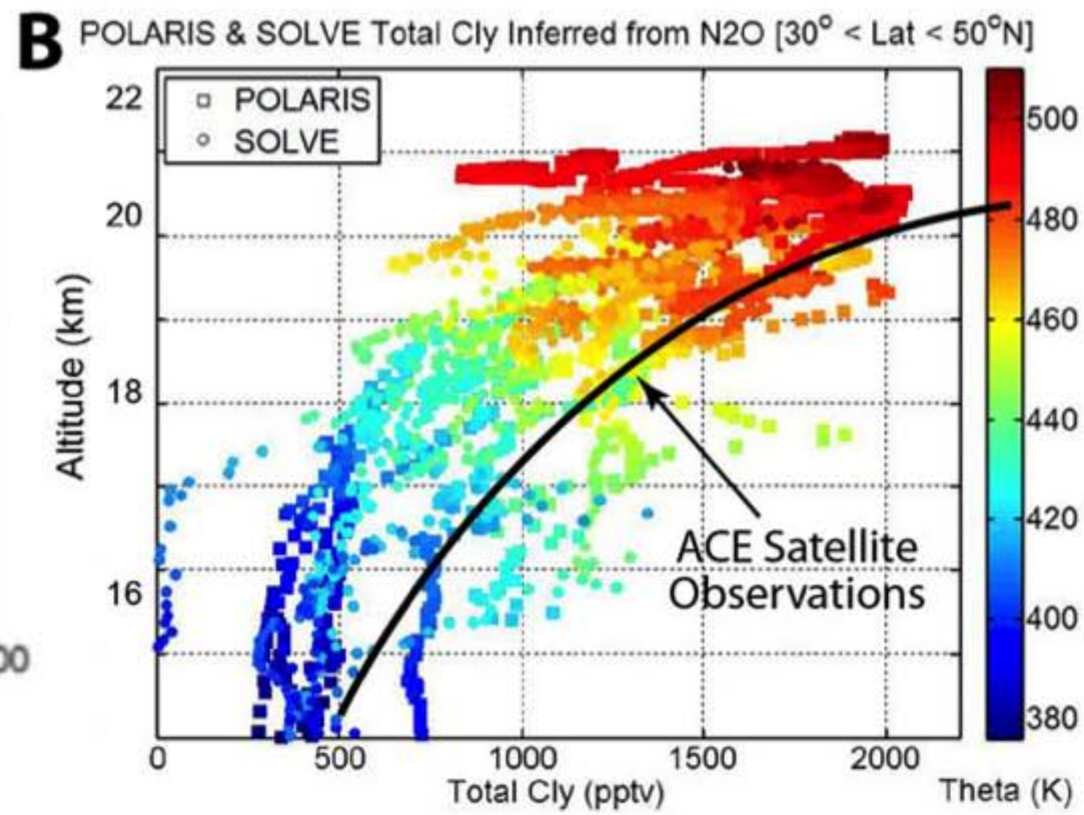


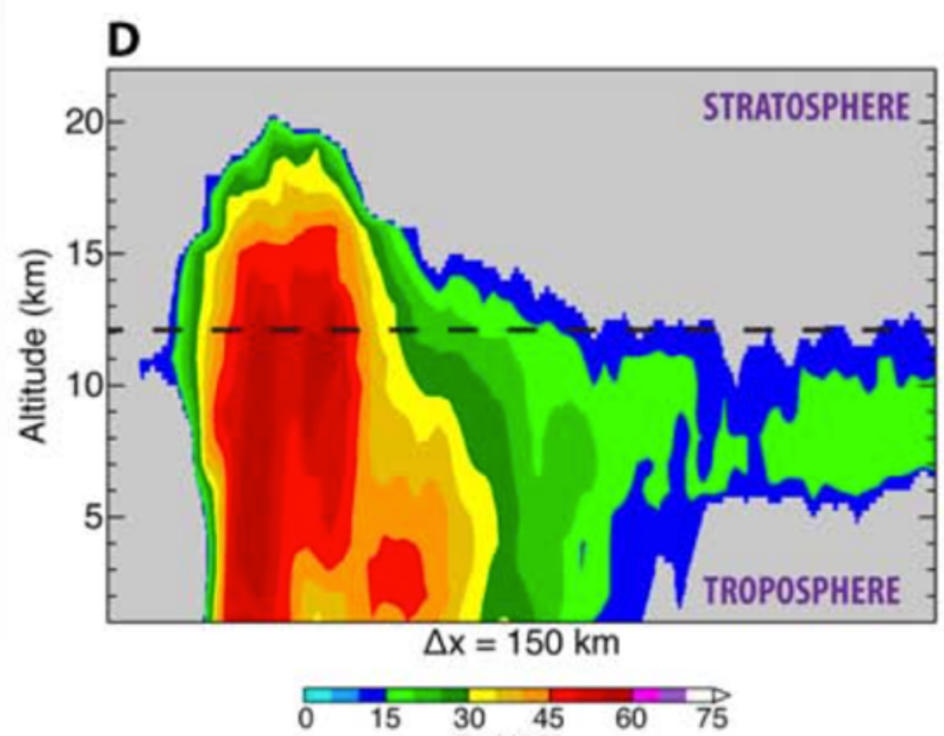


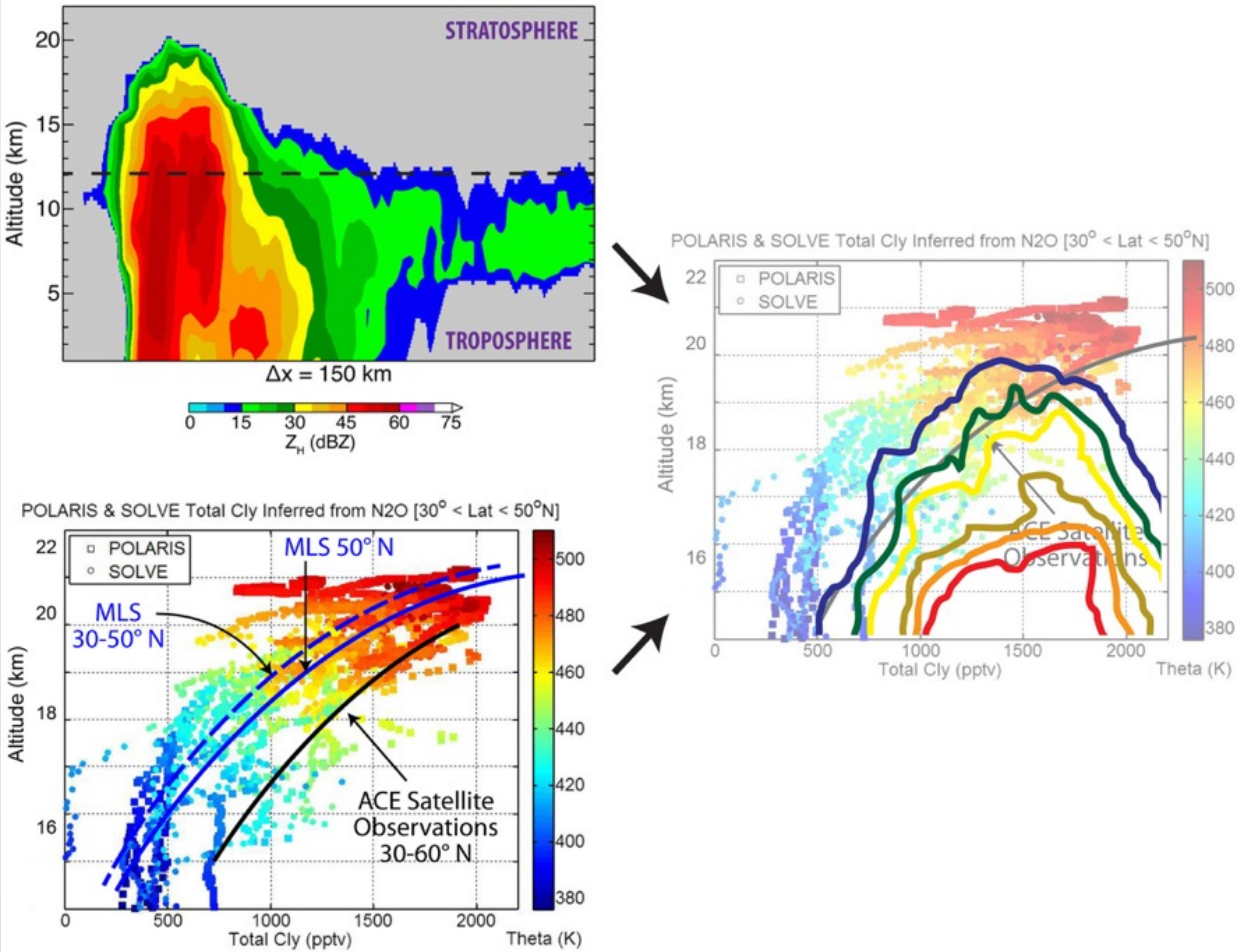
A
HCl
H_2O = 5 ppmv
NO_2
NO
$ClONO_2$
ClO
Mixing Ratio (pptv)
UNPERTURBED
B
H_2O = 12 ppmv
HCl
NO_2
Cl_2
NO
ClO
$ClONO_2$
ClOOCl
Mixing Ratio (pptv)
PERTURBED
D
5 ppmv
12 ppmv
18 ppmv
SA = 2 μm²/cm³
P = 90 mb
T = 200 K
Fraction of Starting Ozone
Time (hr)
IMPACT ON OZONE

Comparing ACE Satellite Inorganic Chlorine with *In Situ* Aircraft Observations

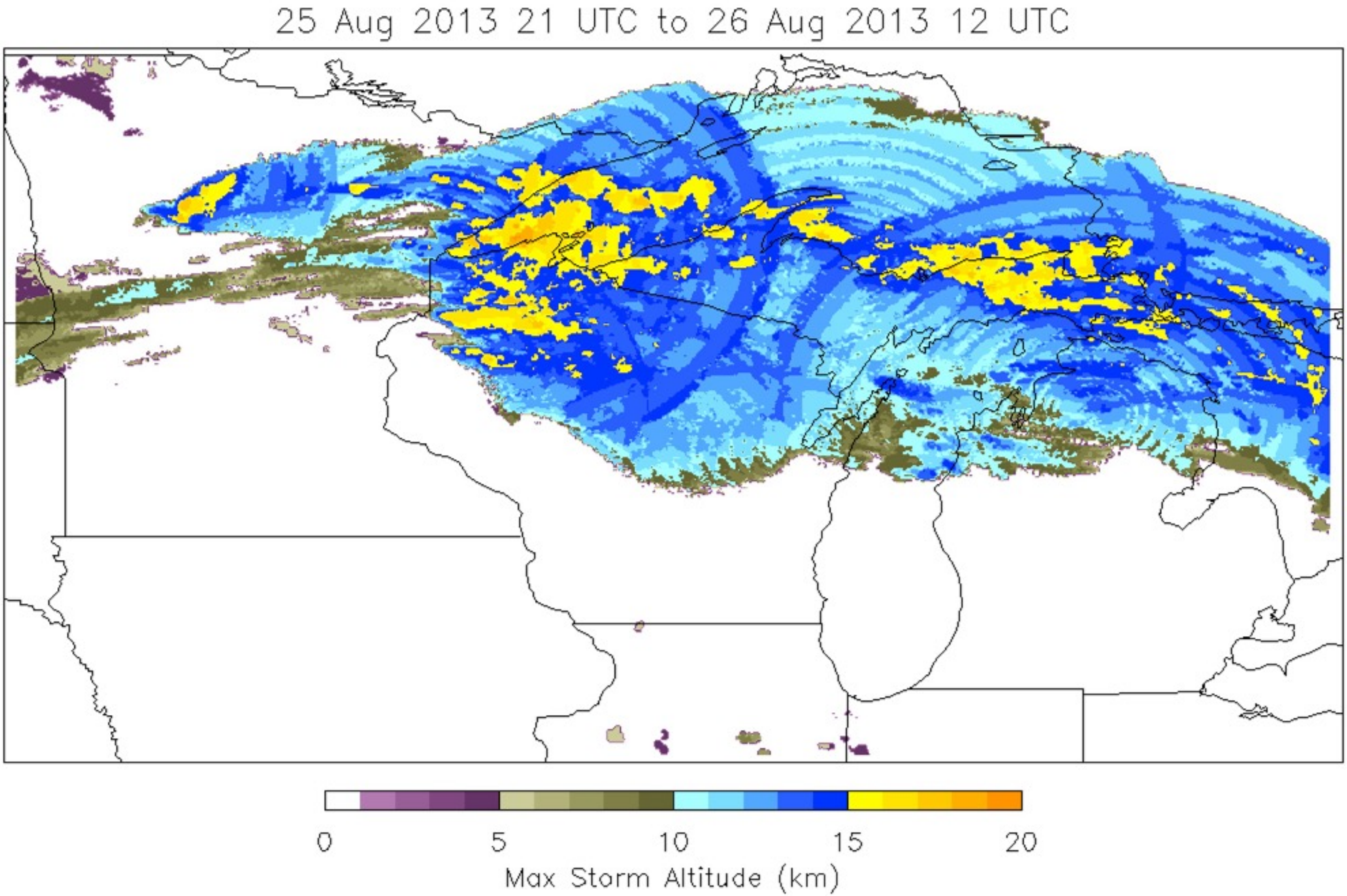




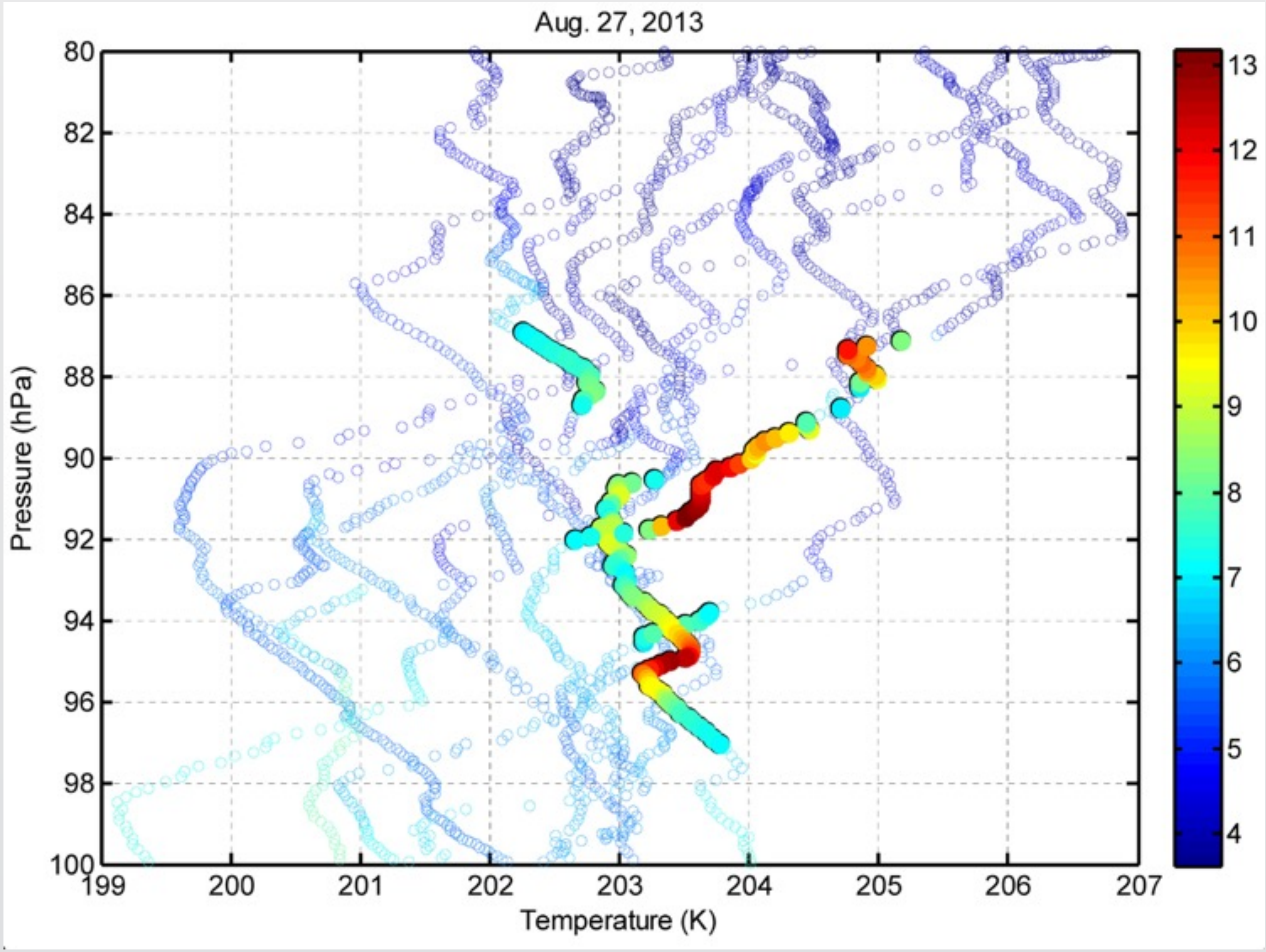




STRATOSPHERE
TROPOSPHERE
Altitude (km)
Δx = 150 km
Z_H (dBZ)
0 15 30 45 60 75
POLARIS & SOLVE Total Cly Inferred from N2O [30° < Lat < 50°N]
POLARIS
SOLVE
MLS 50° N
MLS 30-50° N
ACE Satellite Observations 30-60° N
Altitude (km)
Total Cly (pptv)
Theta (K)
POLARIS & SOLVE Total Cly Inferred from N2O [30° < Lat < 50°N]
POLARIS
SOLVE
ACE Satellite Observations
Altitude (km)
Total Cly (pptv)
Theta (K)

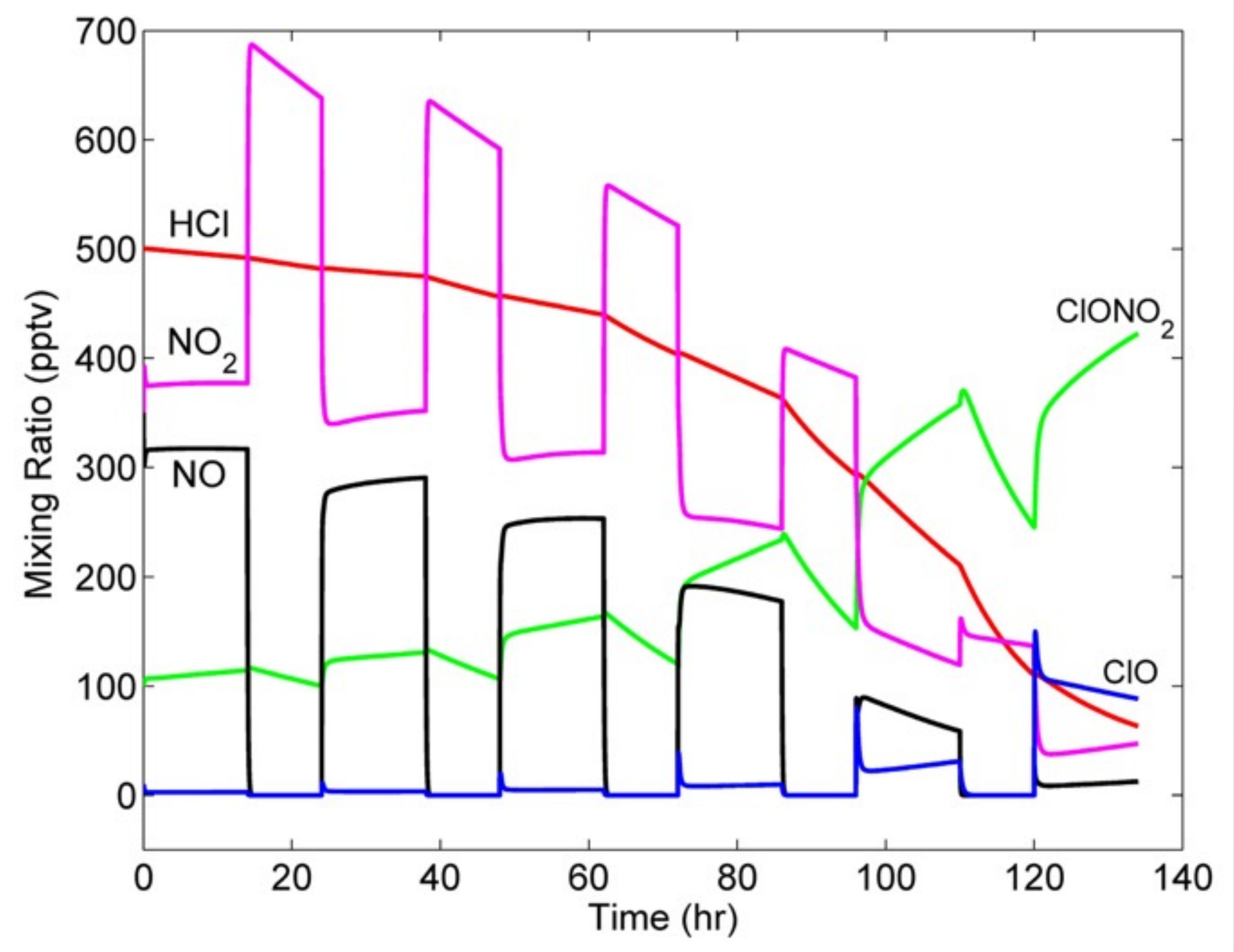

25 Aug 2013 21 UTC to 26 Aug 2013 12 UTC
0
5
10
15
20
Max Storm Altitude (km)

Case Study: in Situ Water Vapor - Aug 27, 2013



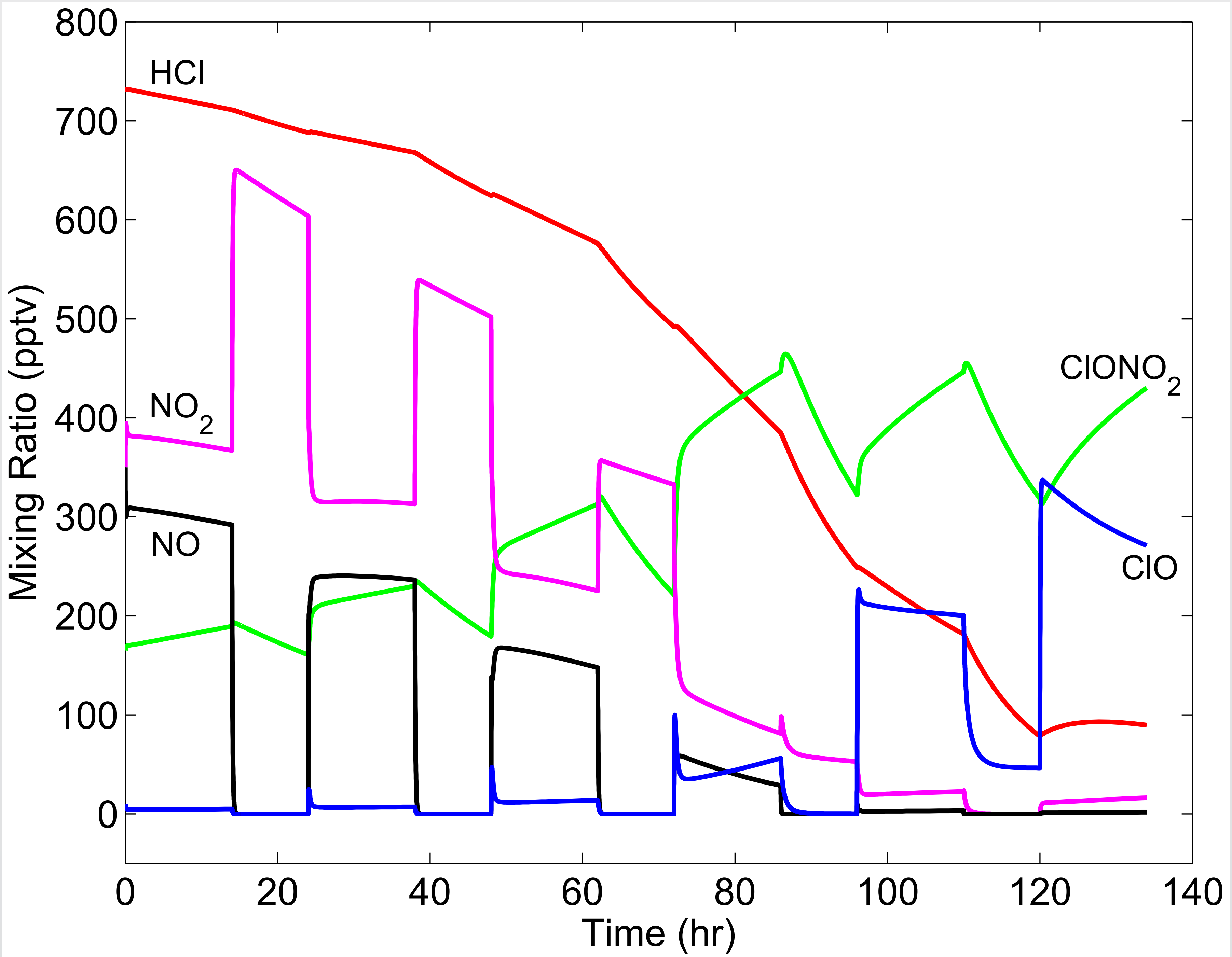
Water vapor in excess of 13 ppm at ~410 K was observed in situ on- board the ER-2 during the SEAC^{4}RS flight of Aug 27, 2013.

Case Study: Kinetic Model - late Aug 2013



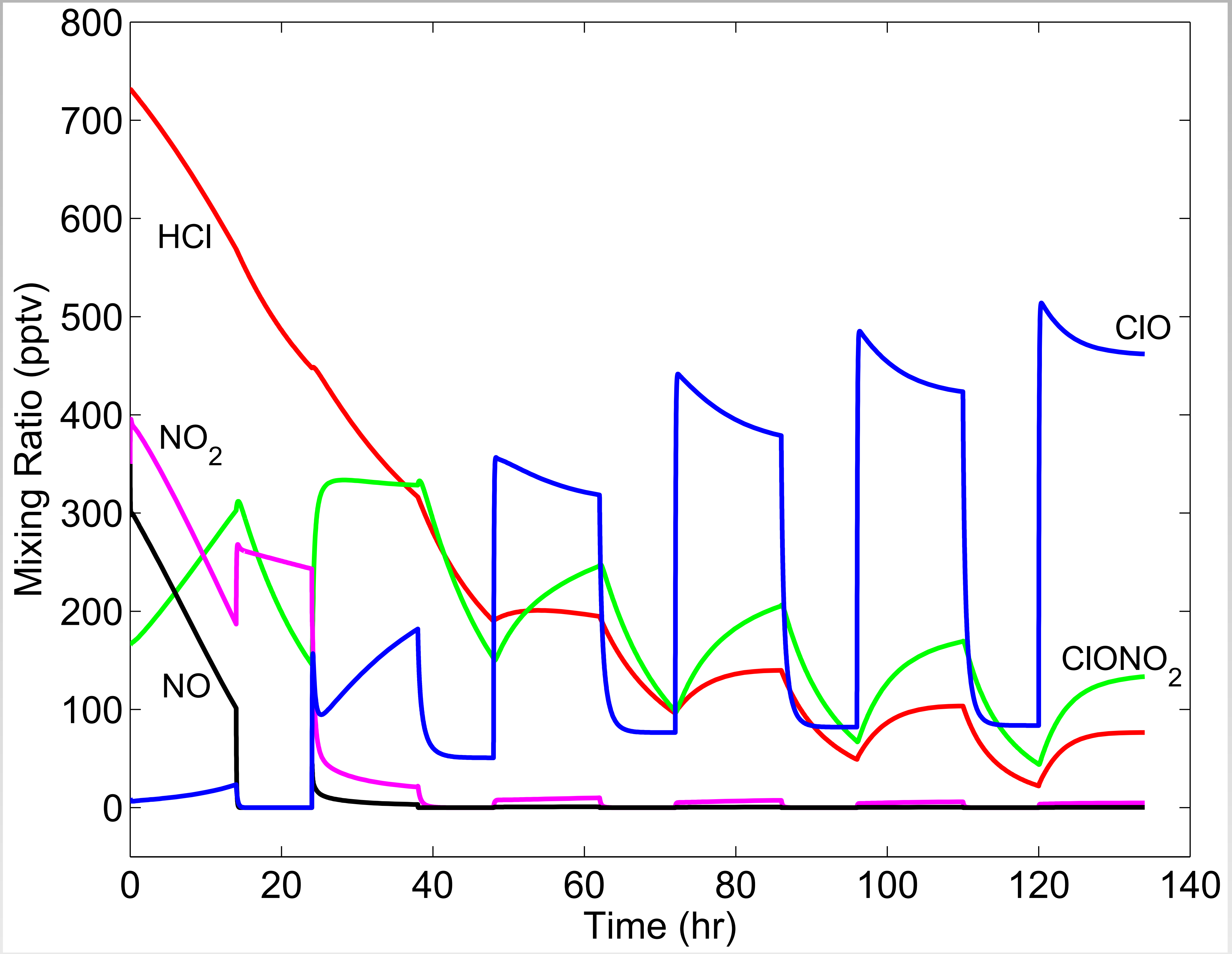
Calculated chemical impact of elevated water vapor for conditions representative of late August 2013. P = 90 mb, SA = 2 $\mu m^2/cm^3$, H_2O = 13 ppm, T = 203 K with radiative cooling of 0.05 K day^{-1} ppm^{-1} (Maycock et al, *QJRMS* 2011; Dykema, in prep 2015), HCl interpolated from MLS, duration of elevated stratospheric water vapor = 5 days.

Case Study: Kinetic Model - late Aug 2013

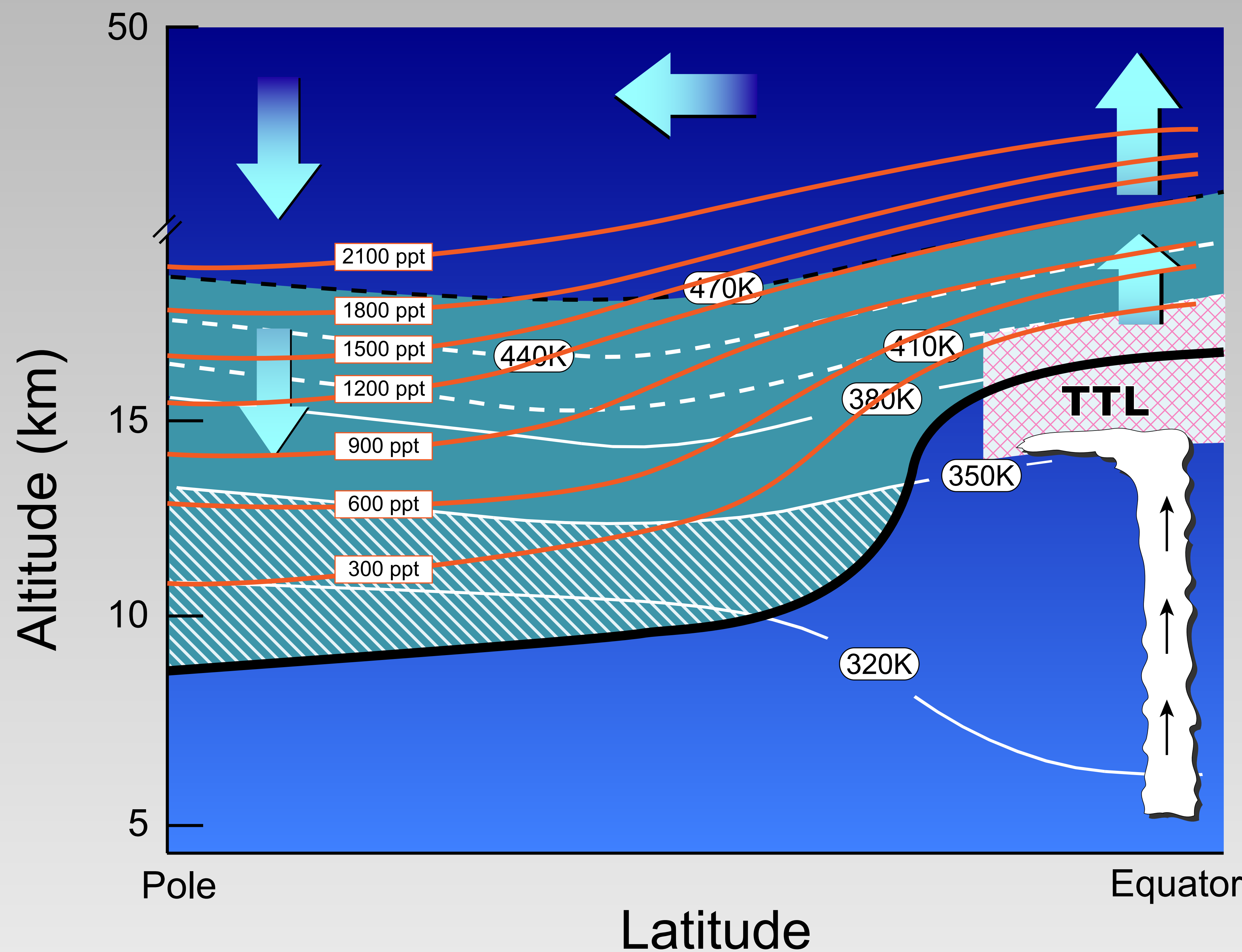


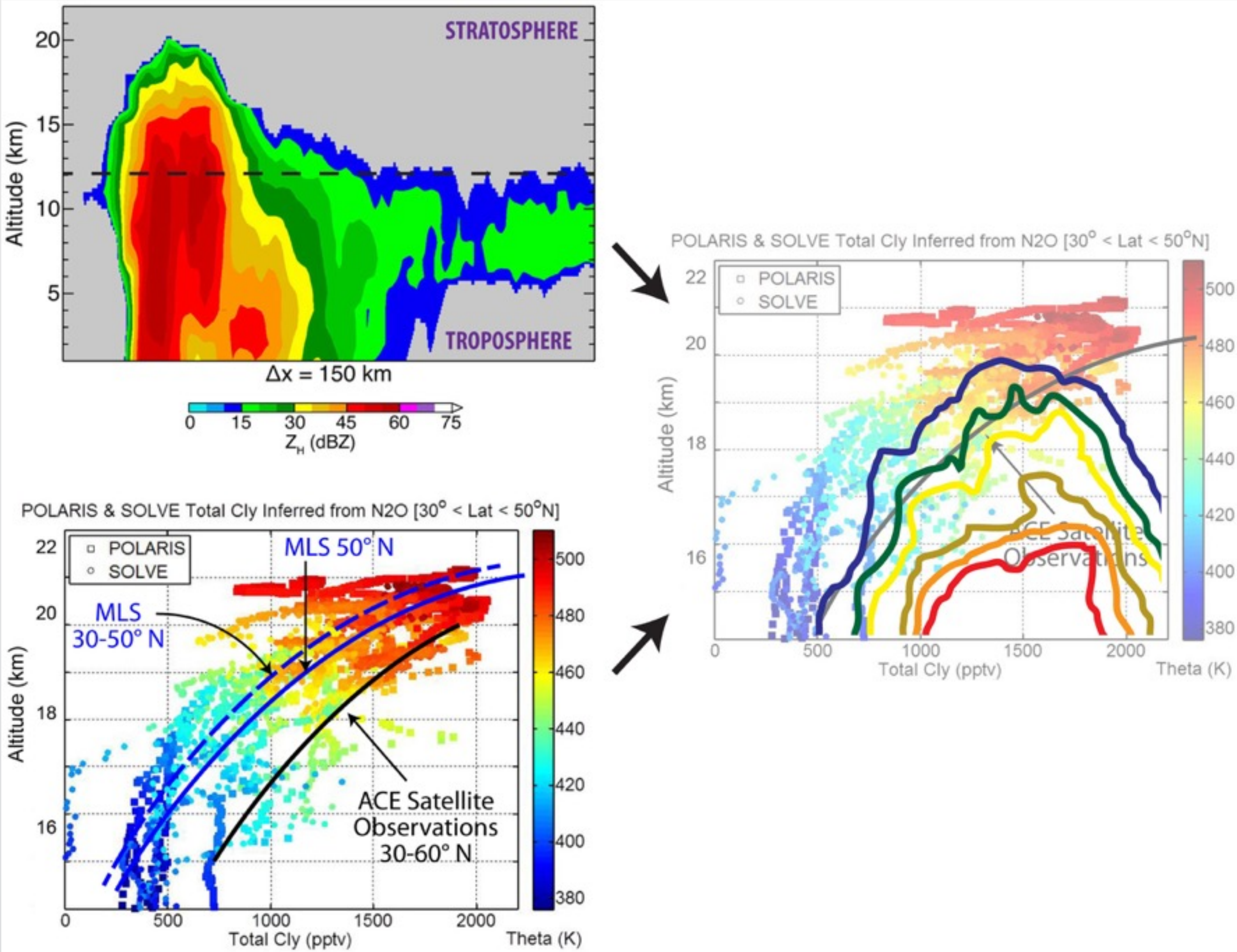
Calculated chemical impact of elevated water vapor for conditions representative of late August 2013. P = 90 mb, SA = 2 $\mu m^2/cm^3$, H_2O = 13 ppm, T = 203 K with radiative cooling of 0.05 K day^{-1} ppm^{-1} (Maycock et al, *QJRMS* 2011; Dykema, in prep 2015), HCl interpolated from ACE, duration of elevated stratospheric water vapor = 5 days.

SRM Conditions, ACE and *In Situ* Cly:

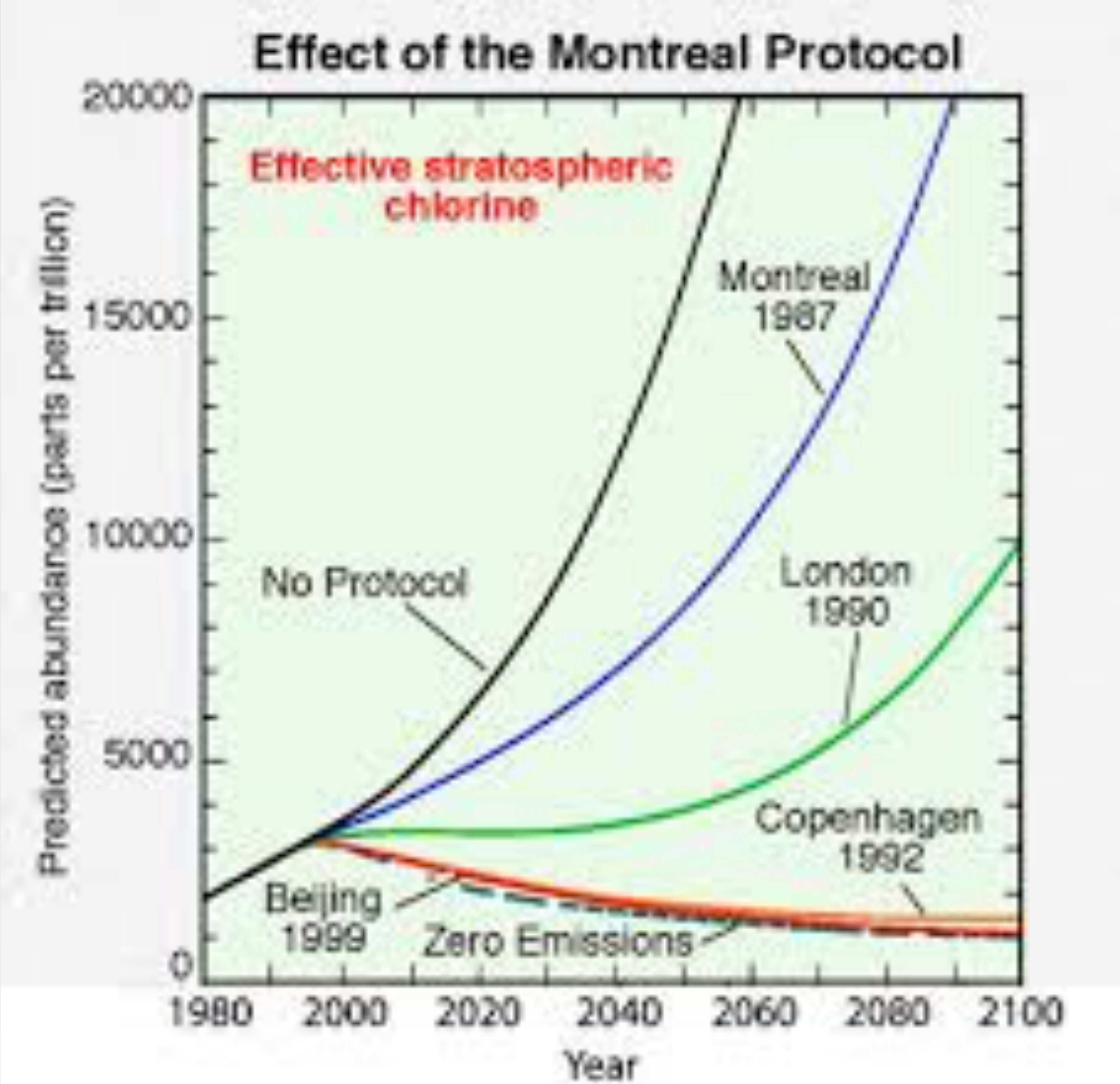


What Specifically is the Structure of Inorganic Chlorine and Available NOX in the Summertime Lower Stratosphere Over the US?

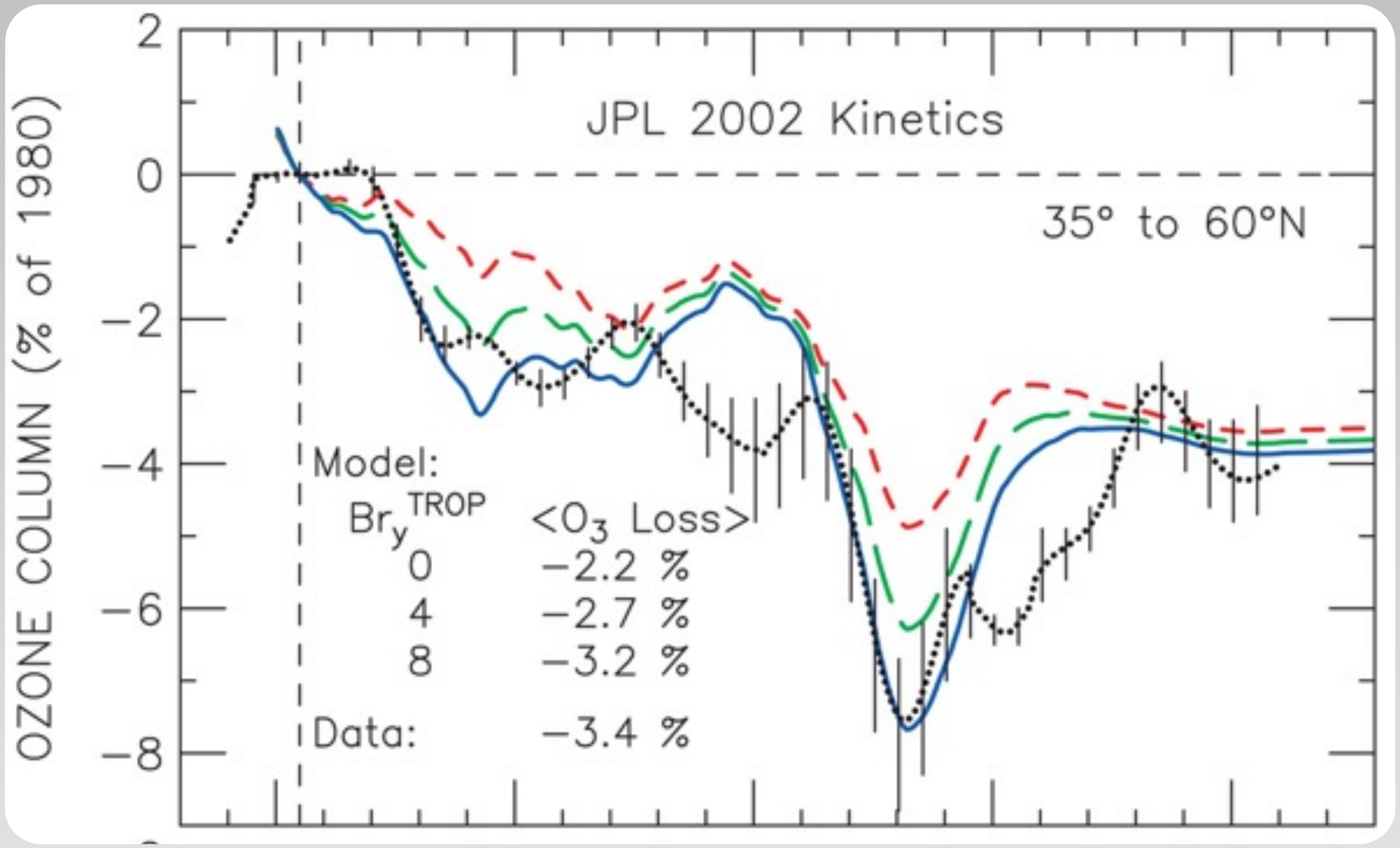


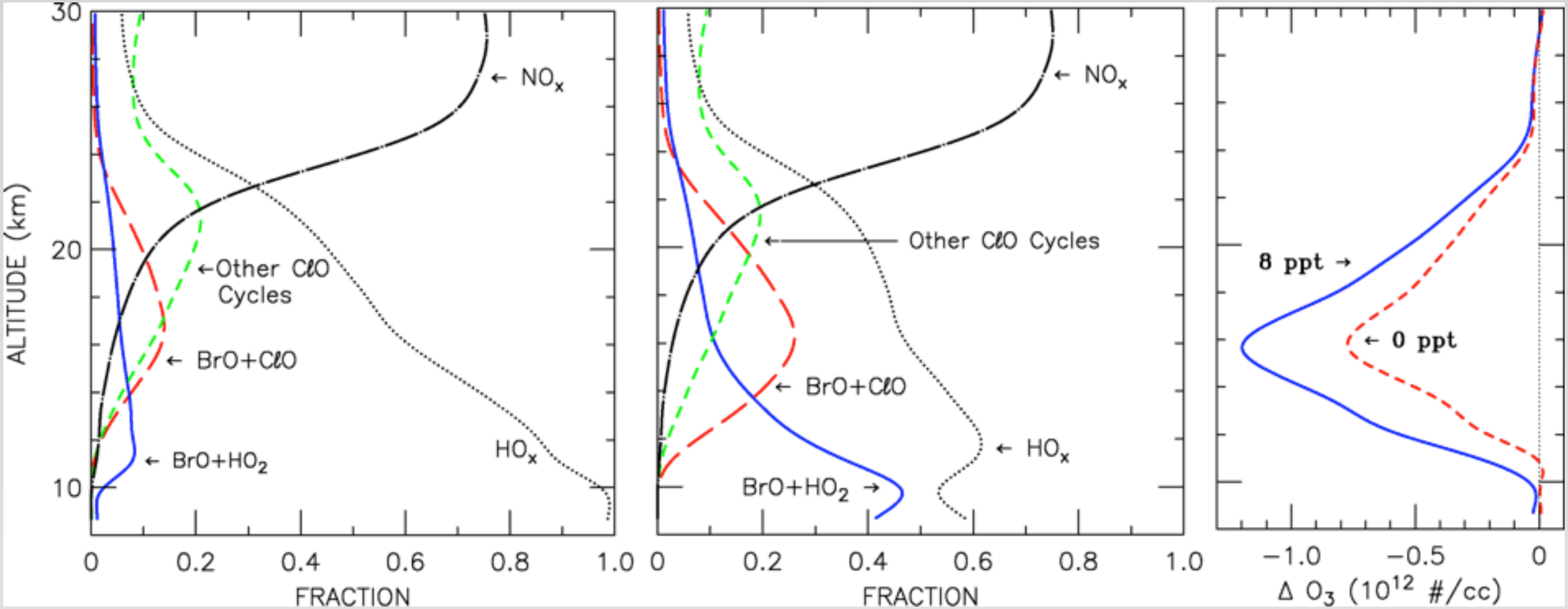


STRATOSPHERE
TROPOSPHERE
Altitude (km)
Δx = 150 km
Z_H (dBZ)
POLARIS & SOLVE Total Cly Inferred from N2O [30° < Lat < 50°N]
POLARIS
SOLVE
MLS 50° N
MLS 30-50° N
ACE Satellite Observations 30-60° N
Altitude (km)
Total Cly (pptv)
Theta (K)
POLARIS & SOLVE Total Cly Inferred from N2O [30° < Lat < 50°N]
POLARIS
SOLVE
ACE Satellite Observations
Altitude (km)
Total Cly (pptv)
Theta (K)


Effect of the Montreal Protocol
Effective stratospheric chlorine
Predicted abundance (parts per trillion)
20000
15000
10000
5000
0
No Protocol
Montreal 1987
London 1990
Copenhagen 1992
Beijing 1999
Zero Emissions
1980
2000
2020
2040
2060
2080
2100
Year

What *is* the Mechanism Responsible for Ozone Column Loss From Pinatubo?





Ozone Photochemistry. Enhanced Bromine: Increased ozone depletion due mainly to BrO + ClO cycle. BrO + HO_2 cycle becomes a significant O_3 sink below 16 km (BrO + HO_2 does not drive O_3 depletion if Br_y^{Trop} is constant over time.)

$Br_y^{Trop} = 0$ ppt $\qquad$ $Br_y^{Trop} = 8$ ppt

Model Simulation of Overshooting Top

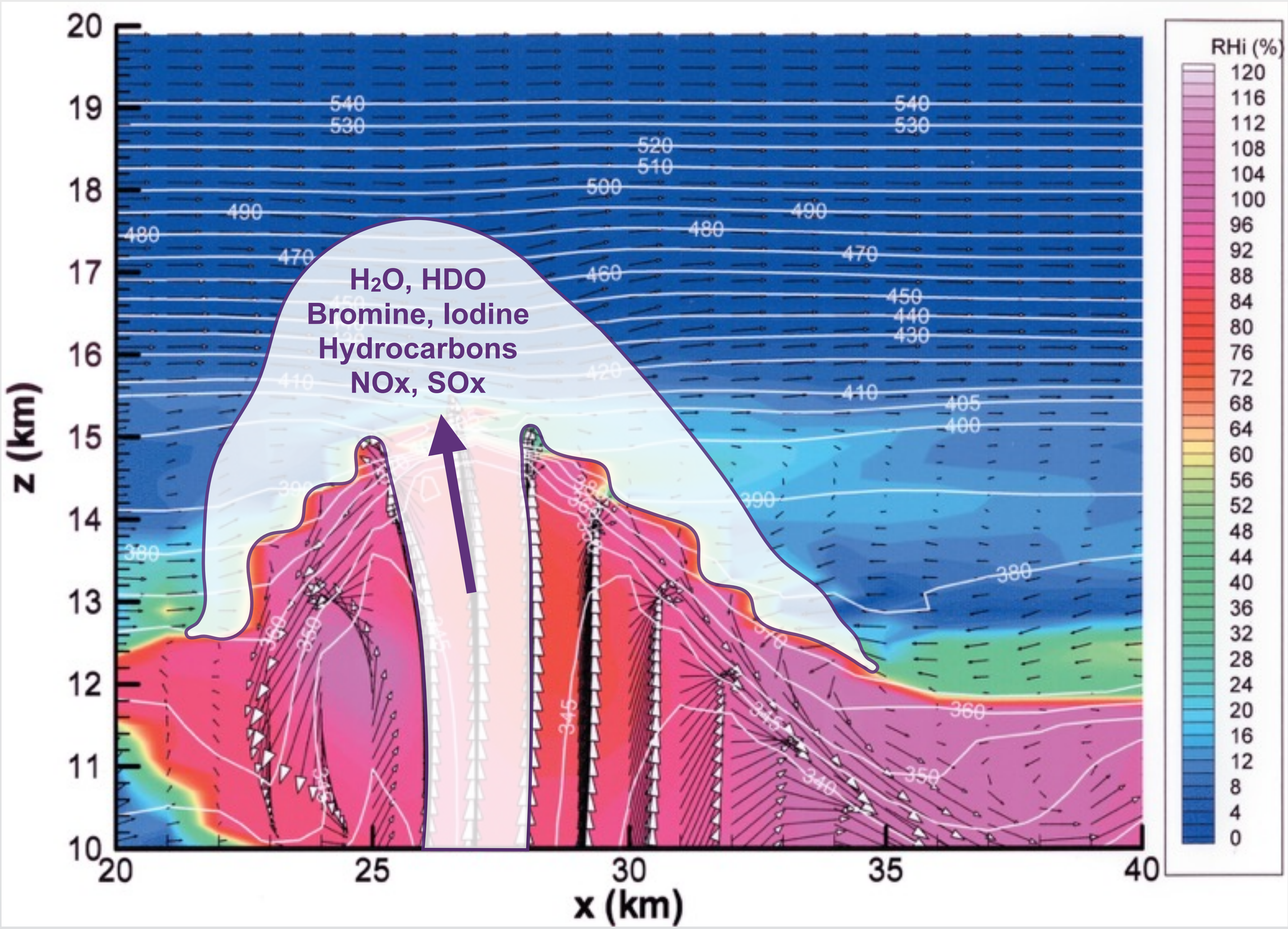


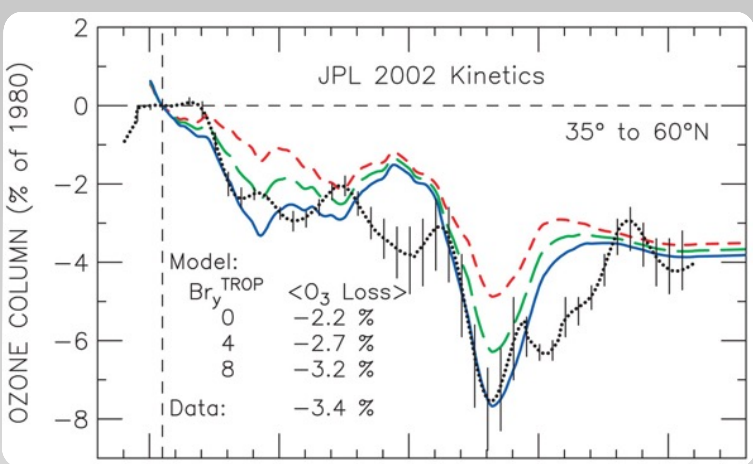
Figure 8. Central east-west cross-section of the simulated storm at t = 73 min 10 sec, showing the overlapped RHi, wind vector (projected on the x-z plane) and θ fields. The wave breaking is obvious in the region where x ~28 km and z ~15 km.

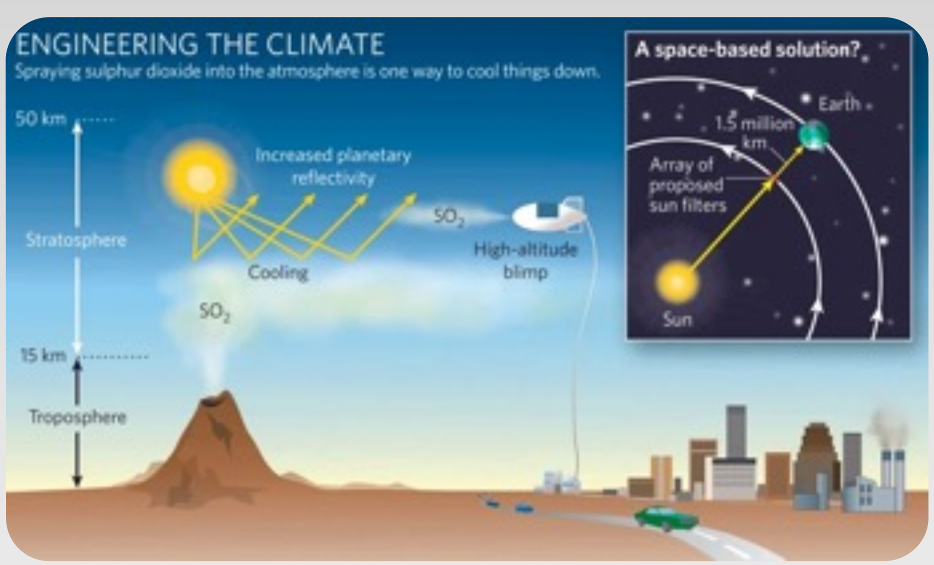
Wang, 2003, *JGR*

Journal of Geophysical Research: Atmospheres
Volume 108, Issue D6, 4194, 28 MAR 2003 DOI: 10.1029/2002JD002581
http://onlinelibrary.wiley.com/doi/10.1029/2002JD002581/full#jgrd9978-fig-0008

The Questions:

- What was the chemical mechanism that resulted in a ~ 6% decrease in ozone column for two years following Pinatubo?
- What is the impact on the ozone column concentration over the US in summer when one or more convection events injects into either a volcanic background or an SRM background?

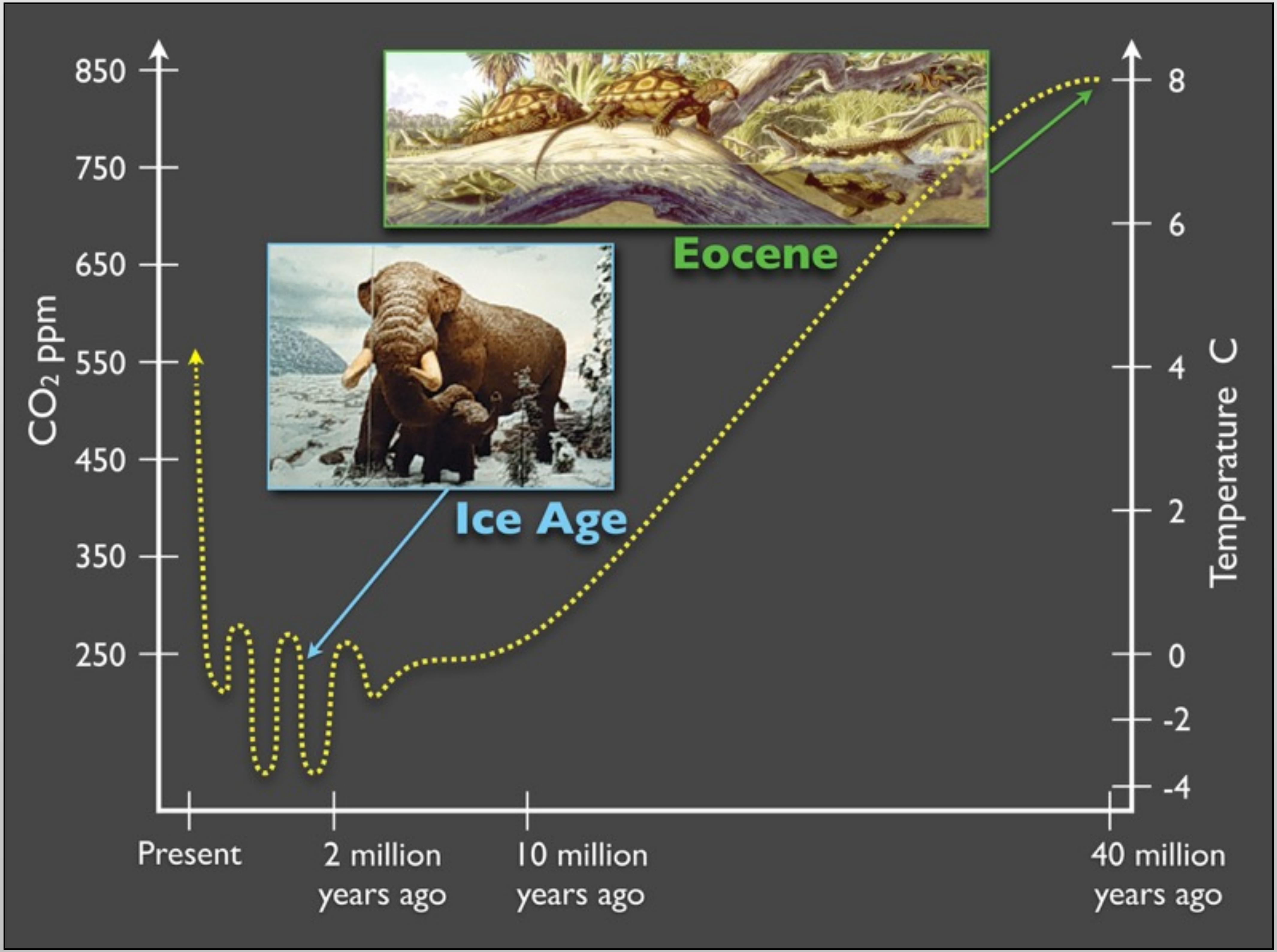




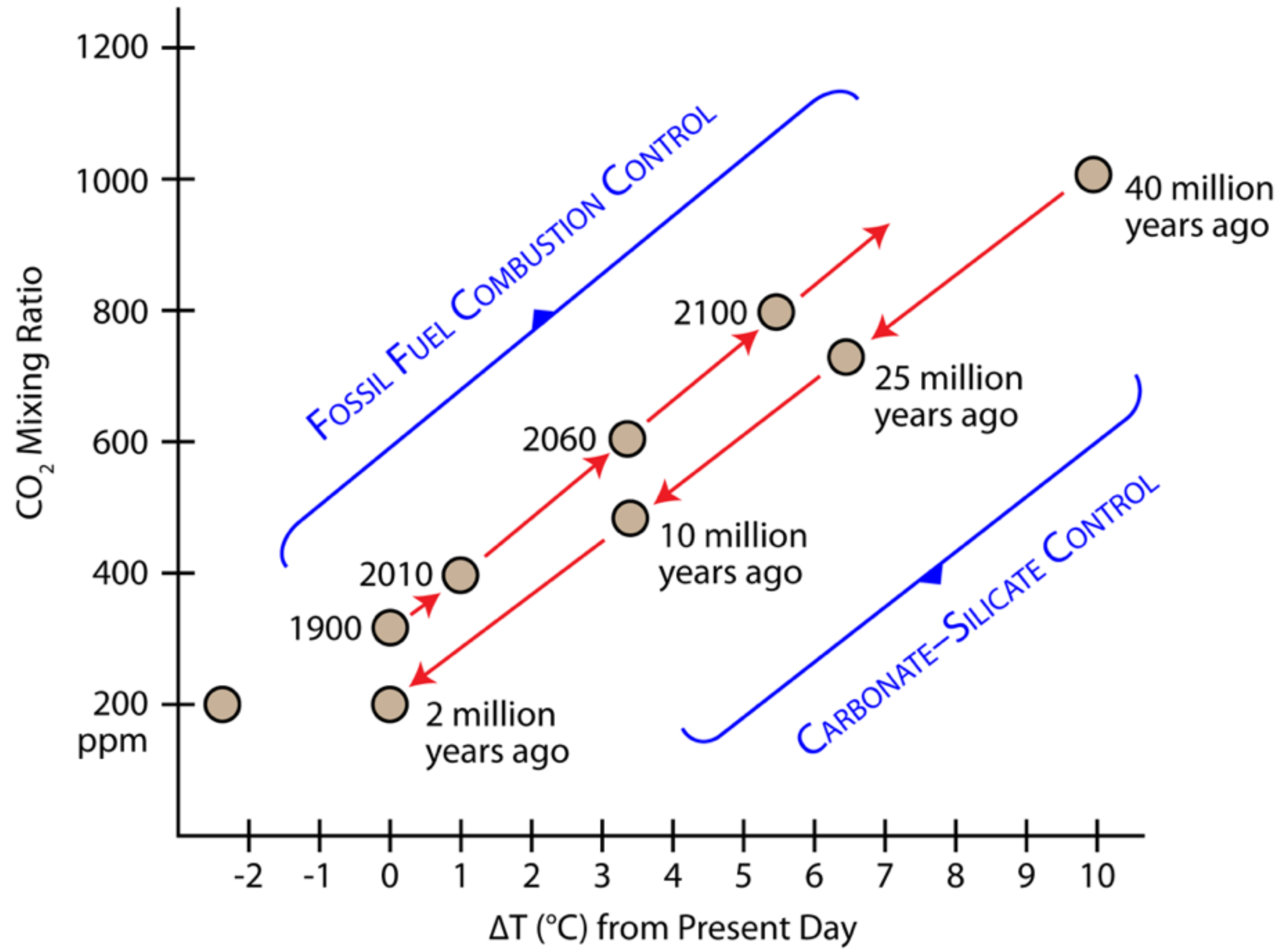
How Does This Relate to Paleoclimate Evidence?

An artist's picture of the Arctic coast during the Eocene epoch, about 40 million years ago.

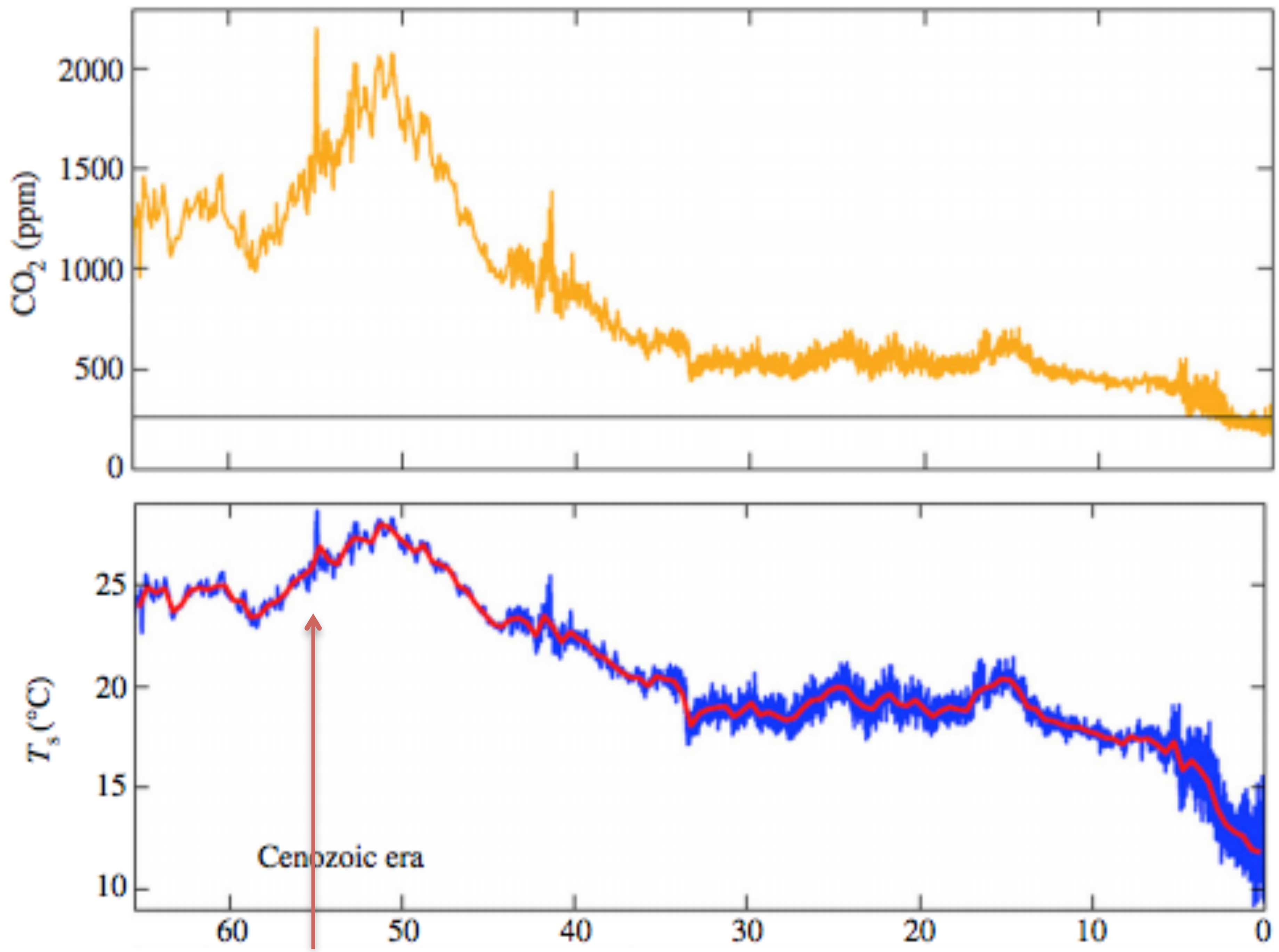
What do we know from past climate stages?



Measured in CO_2 Years



Stability of the climate state



Paleocene-Eocene Thermal Maximum

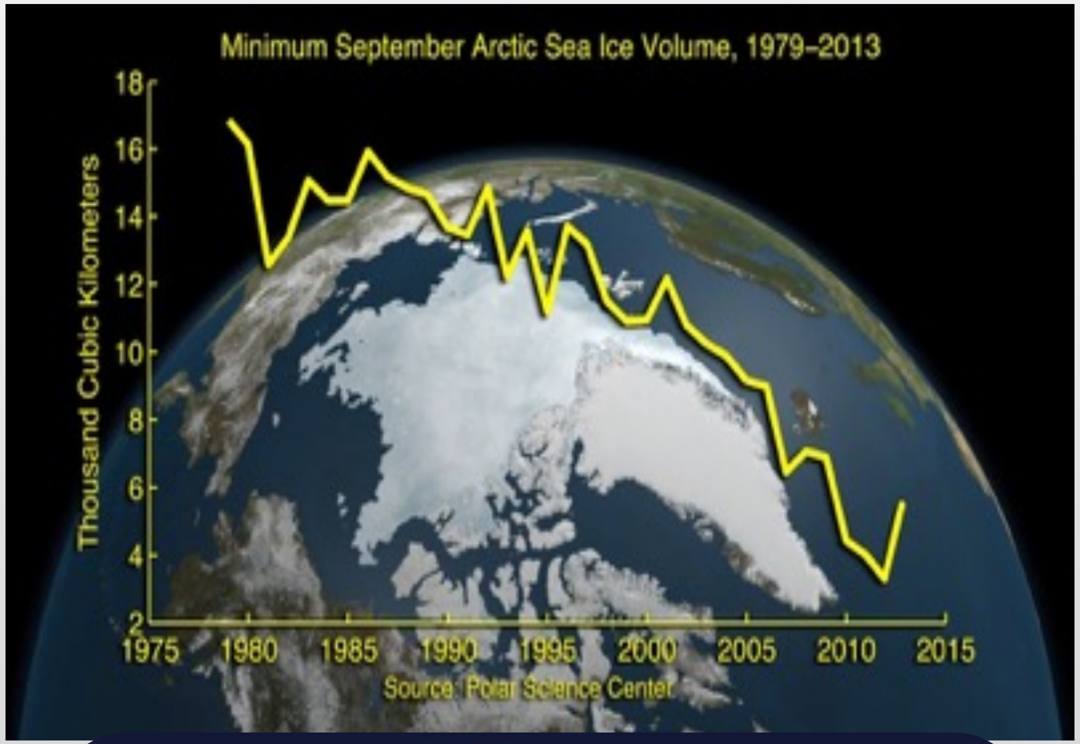
Hansen (2013)

Key Question: How Will the Current Climate Structure Revert Back to the Eocene Structure?

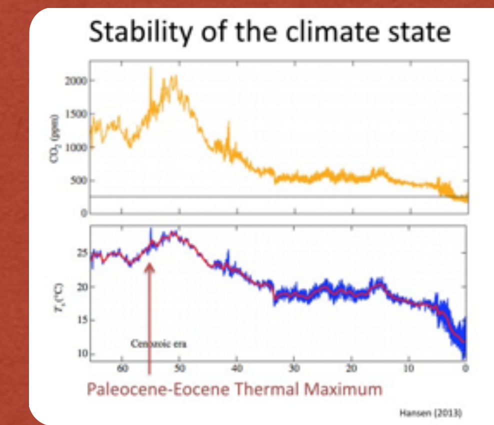
- The Period From the End of the Eocene to the Pleistocene was Characterized by an Ice-Free NH - This Existed at CO2 levels ~ 550-600 ppm

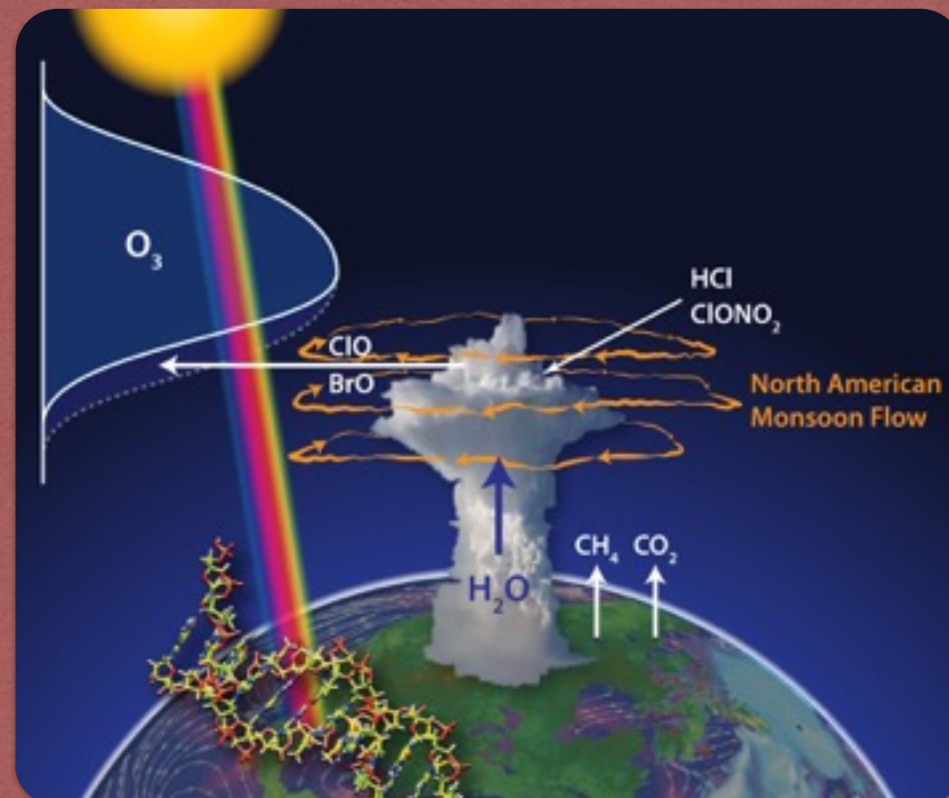
- What Was the Structure of the Stratosphere-Troposphere Interface? How Moist was the Stratosphere?

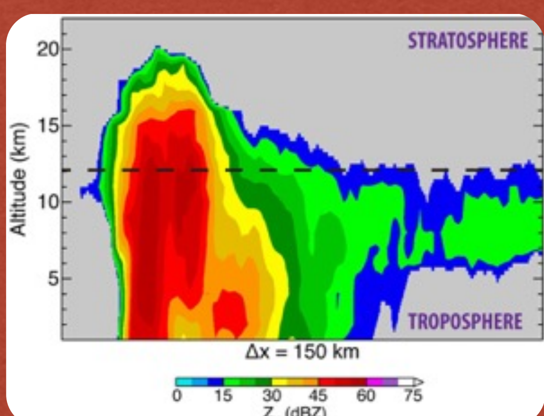
- Does the System Transition From Today's Structure Via a Combination of Convective Injection North of the Sub-Tropical Jet Combined With a Reduction in the Equator-to-Pole Temperature Gradient? Or one or the other?

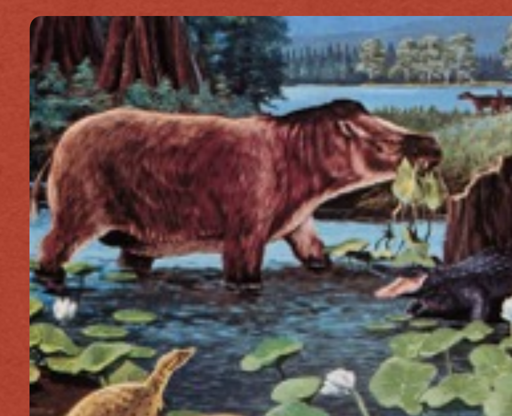


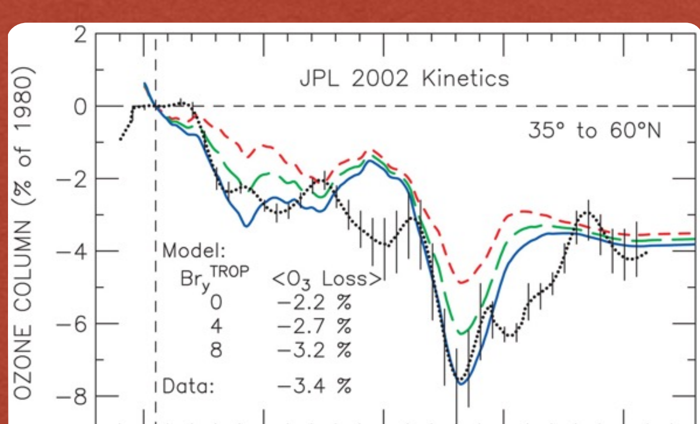
So We Have a Closely Coupled Set of Problems

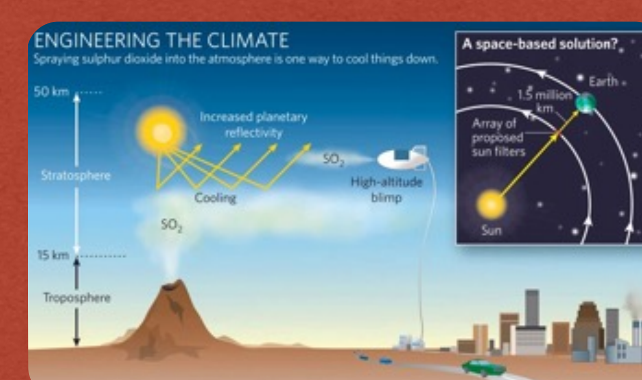






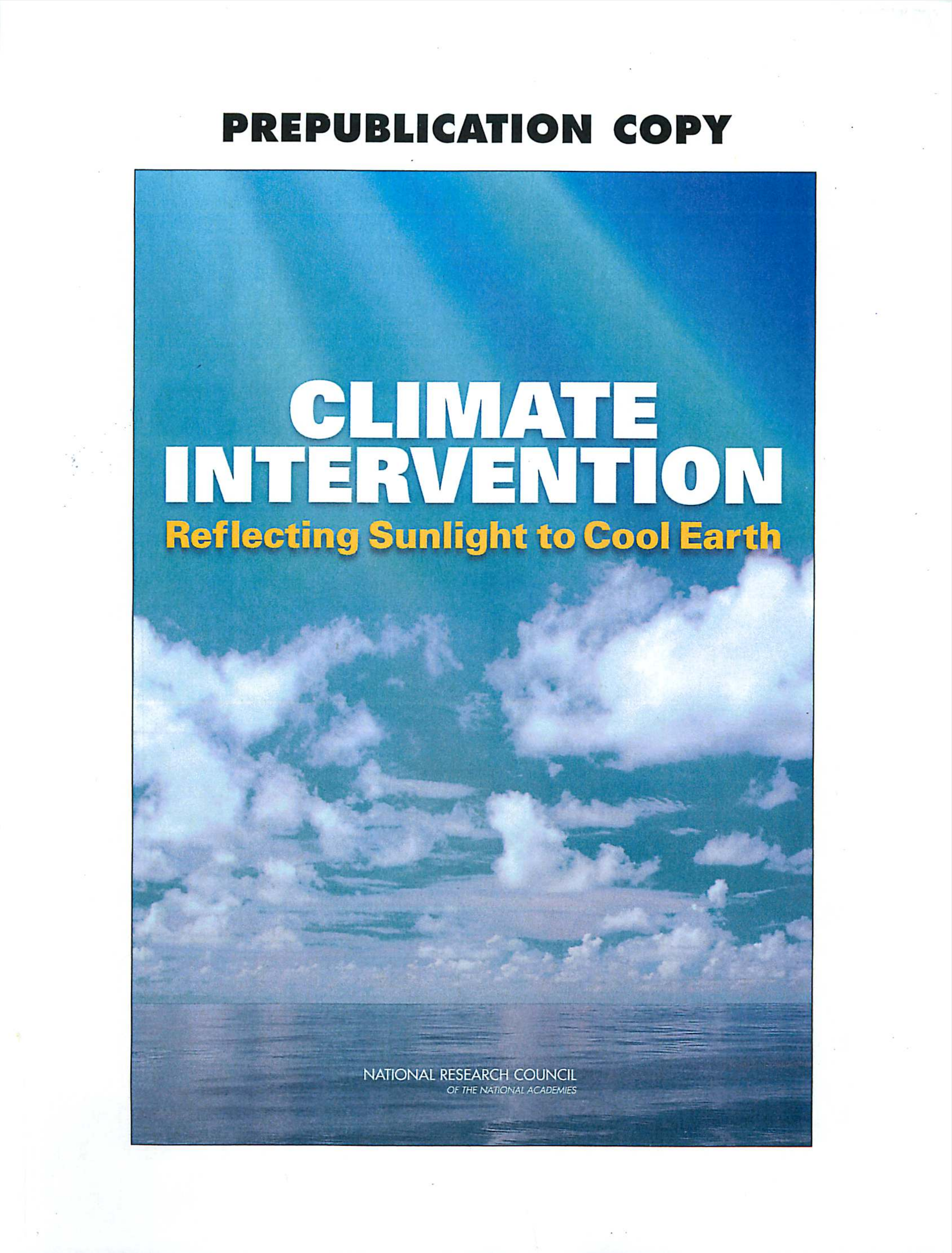






NRC Report: "Climate Intervention: Reflecting Sunlight to Cool the Earth"

"The Committee recommends an albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers basic understanding of the climate system and its human dimensions."



The Committee was more explicit on page 79 in "Summary and Statement of Research Needs for SAAM (Albedo Modification by Increasing Stratospheric Aerosols):"

"There are many component processes that are not sufficiently well understood to produce quantitative characterization of processes important to SAAM, and statements about how intervention by SAAM would affect the planet are thus not possible. Several processes are particularly deserving of attention from both a modeling and measurement point of view because they are critical to any implementation of SAAM and are unique to SAAM strategies of climate intervention:

- Stratospheric aerosol microphysics (formation, growth, coalescence, dispersion);
- Impacts on chemistry (particularly ozone);
- Impacts on water vapor in the upper troposphere and lower stratosphere; and
- Effects of additional aerosol on upper tropospheric clouds.

END