Water Vapor in the Stratospheric Overworld

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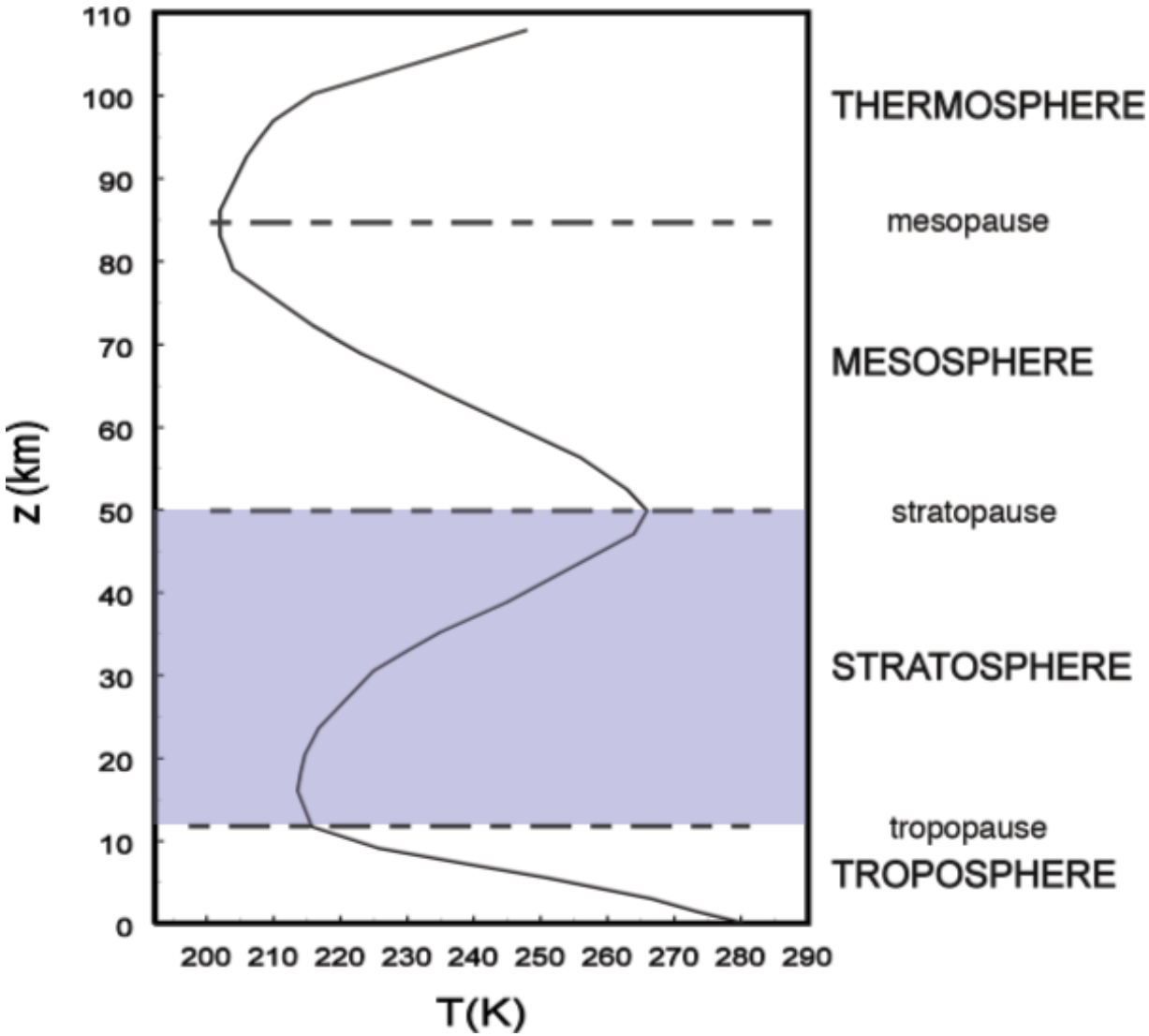
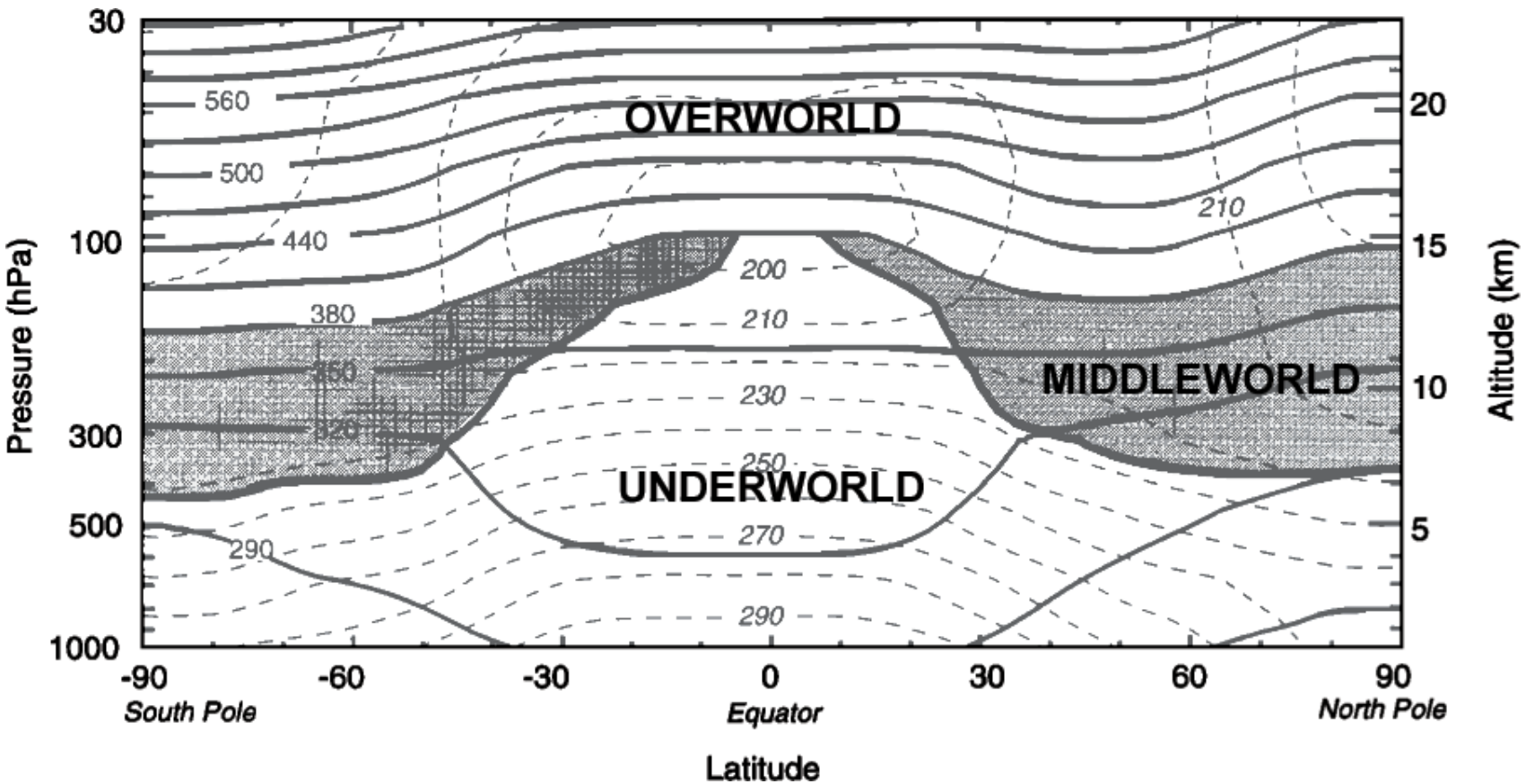
Center for Earth System Science

March 12, 2012

1. What is the stratospheric overworld?
2. The importance of stratospheric water vapor
   - Radiation and climate
   - Stratospheric ozone chemistry
3. What controls stratospheric water vapor?
   - An historical perspective
   - The tropical tape recorder
   - The stratospheric hydrogen budget
4. Interannual variability and trends
5. Burning questions
6. My current work

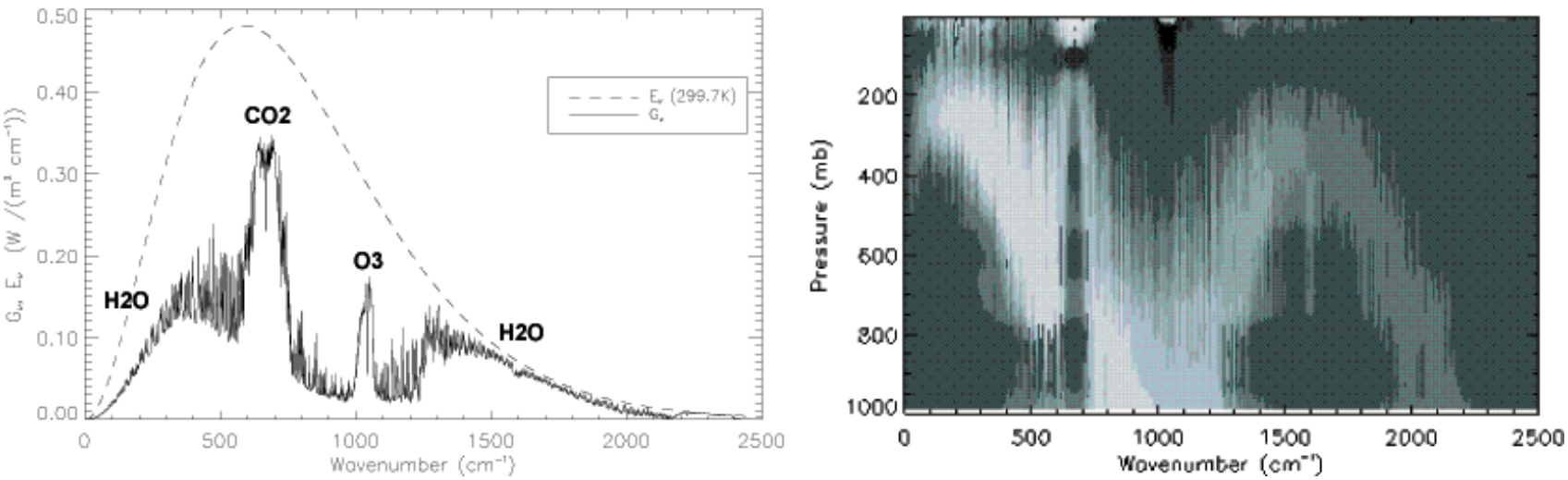

110
100
90
80
70
60
50
40
30
20
10
0
z (km)
200 210 220 230 240 250 260 270 280 290
T(K)
THERMOSPHERE
mesopause
MESOSPHERE
stratopause
STRATOSPHERE
tropopause
TROPOSPHERE

The "overworld" is the part of the stratosphere for which potential temperature surfaces are everywhere above the tropopause.



From *Holton et al.* 1995.

Water vapor is the most abundant greenhouse gas, with strong absorption and emission in the infrared part of the spectrum.



From *Brindley and Harries* 1998

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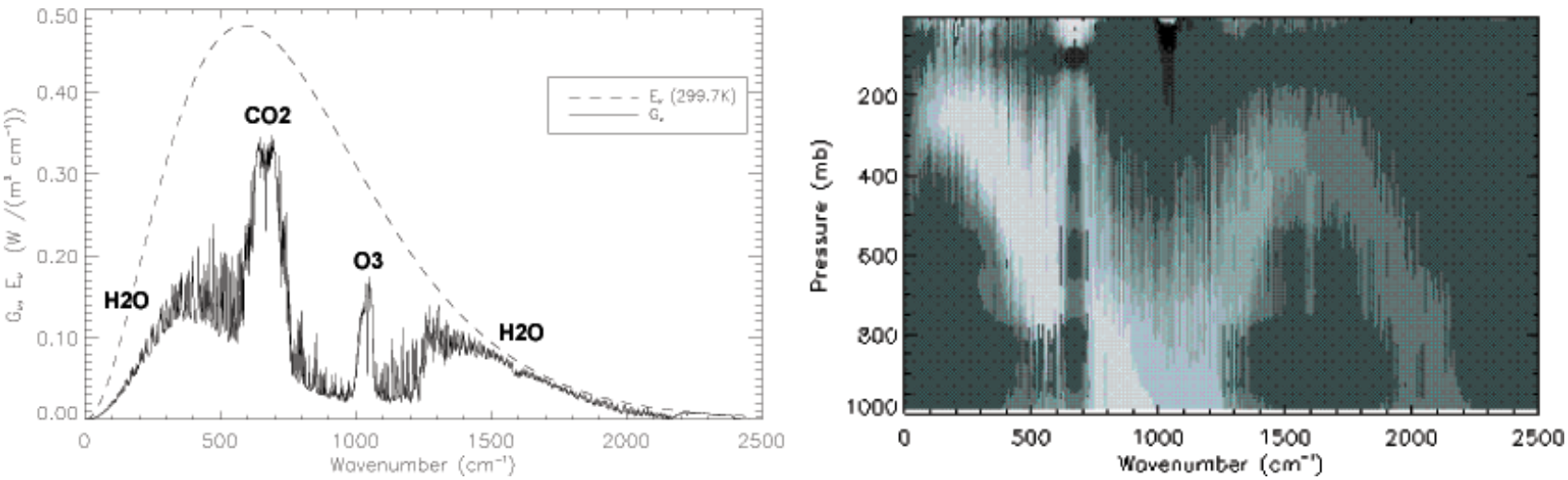

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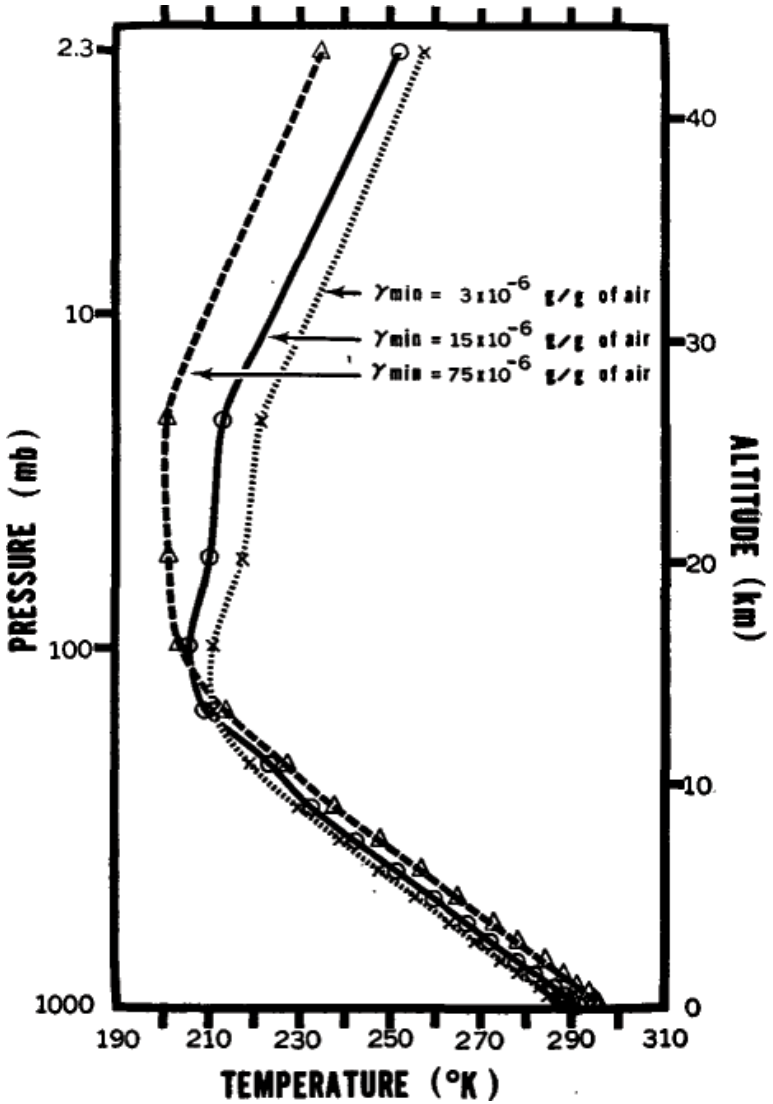
An increase in stratospheric water vapor would be expected to cool the stratosphere and warm the surface.



From *Manabe and Wetherald* 1967

Water vapor is the primary source of OH in the stratosphere. The abundance of OH plays a key role in regulating the HO_x, ClO_x, and NO_x catalytic ozone destruction cycles.

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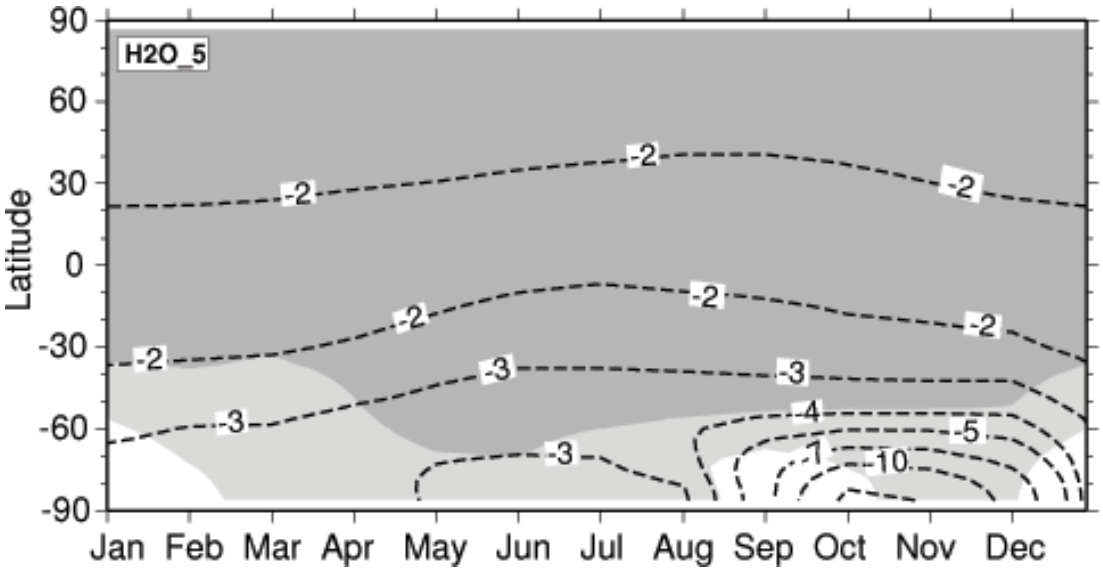
Models indicate that an increase in stratospheric water vapor significantly enhances ozone loss due to gas-phase chemistry.



From *Stenke and Grewe* 2005

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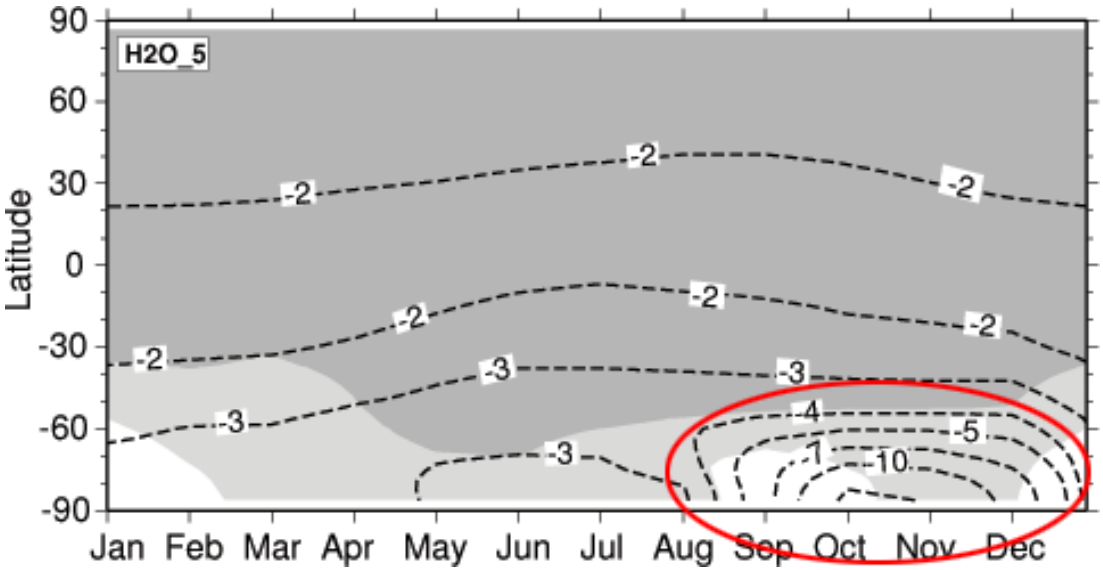
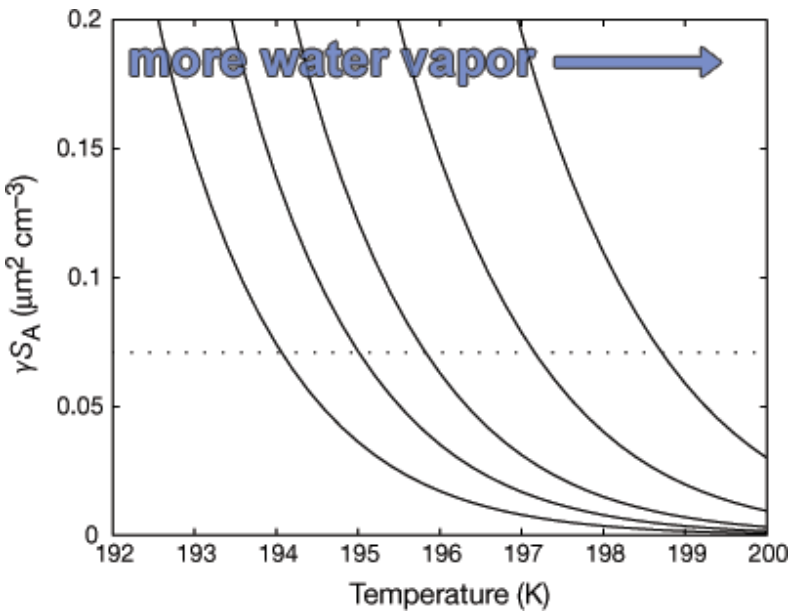


From *Stenke and Grewe* 2005

The abundance of water vapor also regulates the saturation temperature of for polar stratospheric cloud formation.



From *Kirk-Davidoff et al.* 1999

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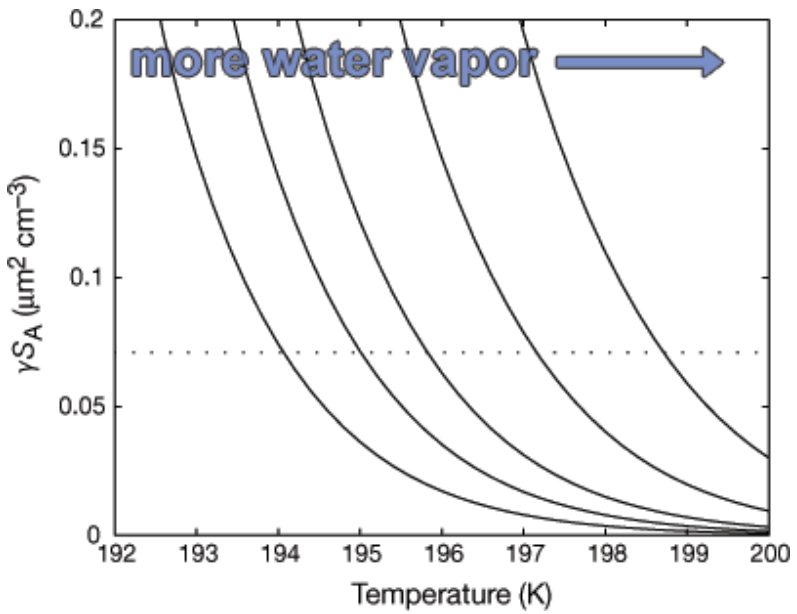

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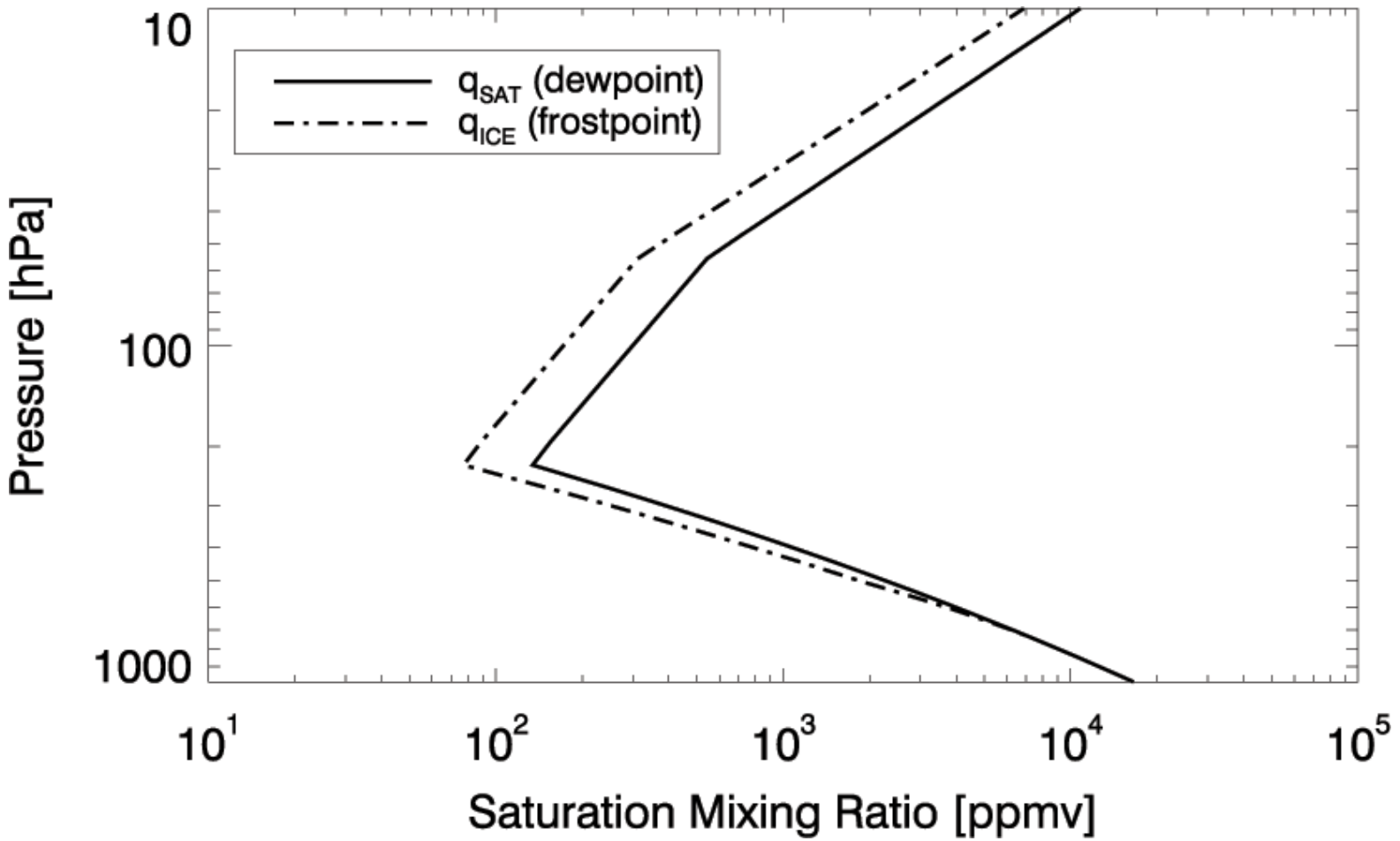
An increase in water vapor also enhances ozone loss due to heterogeneous chemistry.

The water vapor content of the atmosphere is limited and to a large extent determined by the Clausius–Clapeyron relation.



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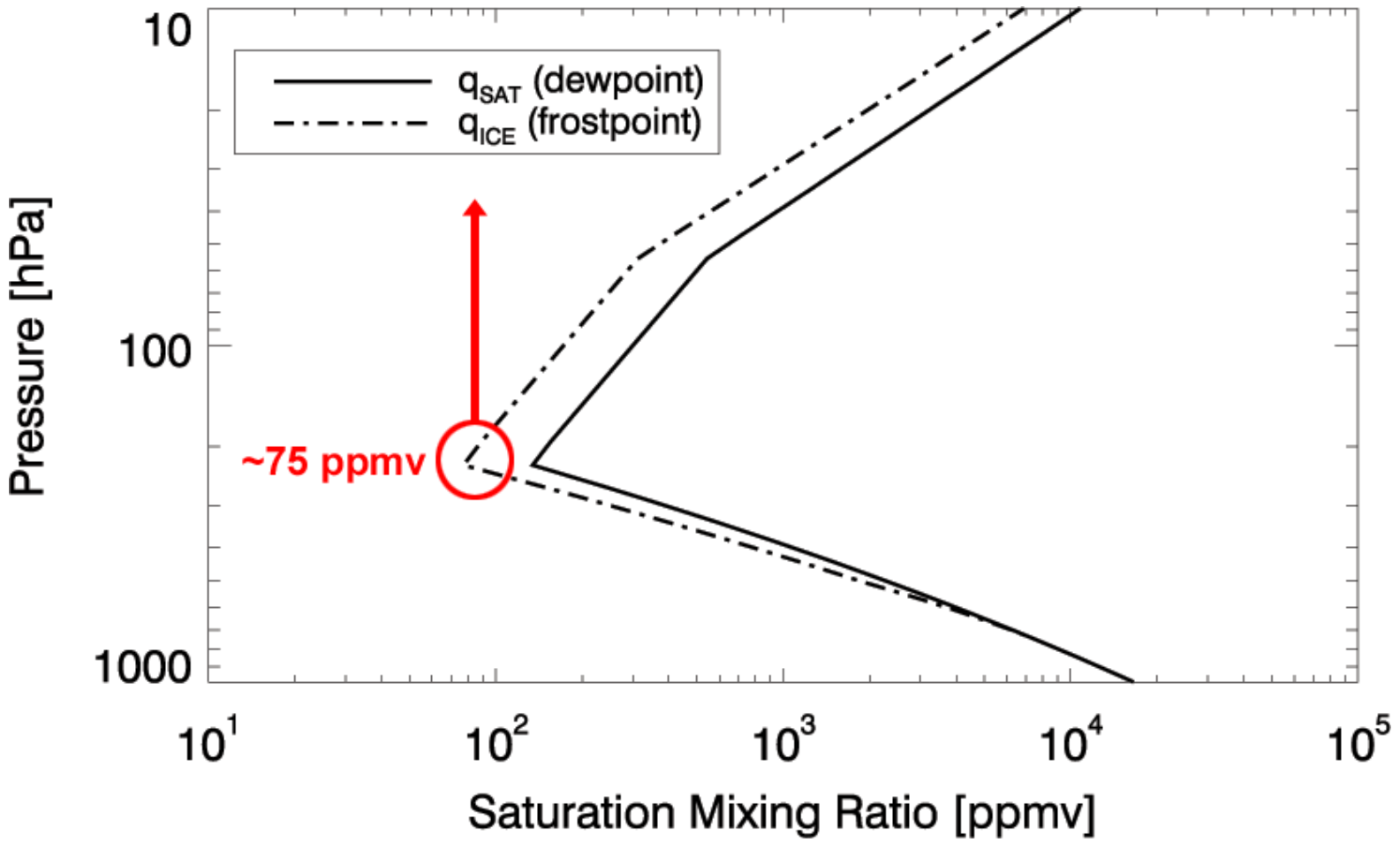
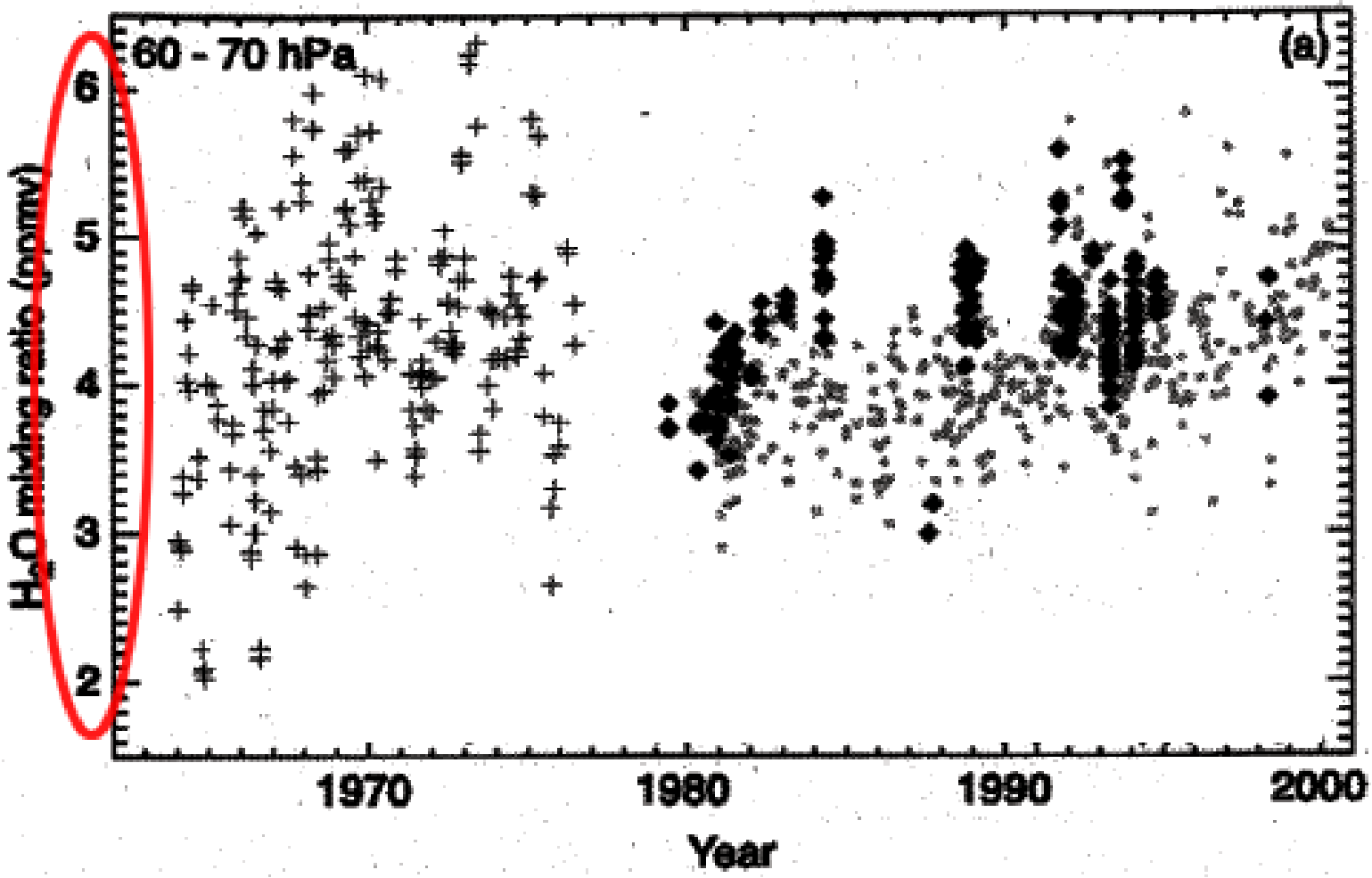
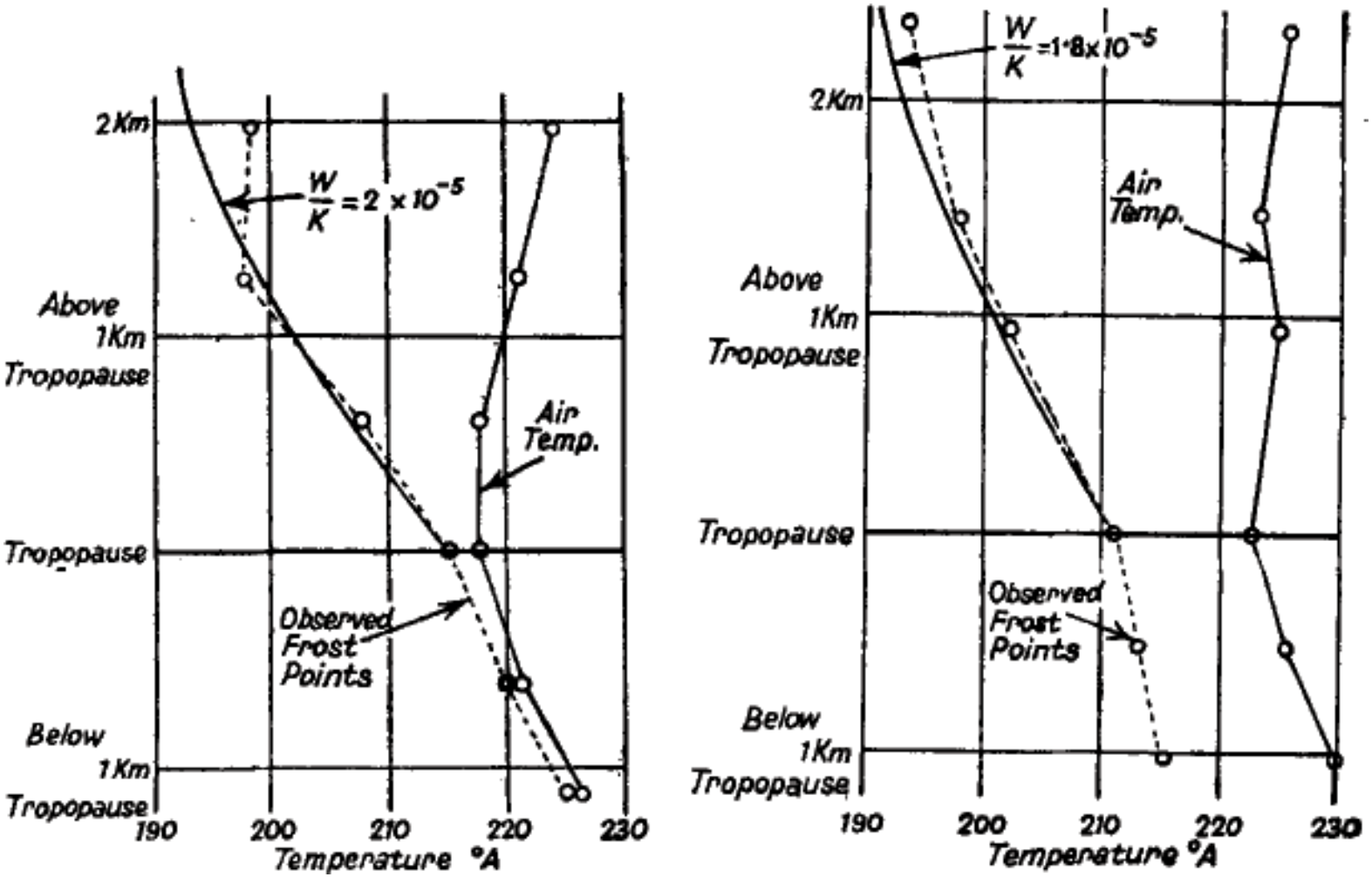


But the stratosphere is much drier than this.



From *Rosenlof et al.* 2001



From *Brewer* 1949

Contradictory observations:

1. Temperature distribution suggests radiative equilibrium;
2. Helium and carbon dioxide are nearly constant with height, suggesting turbulence;
3. Water vapor is much lower than expected, suggesting gravitational settling without turbulence.

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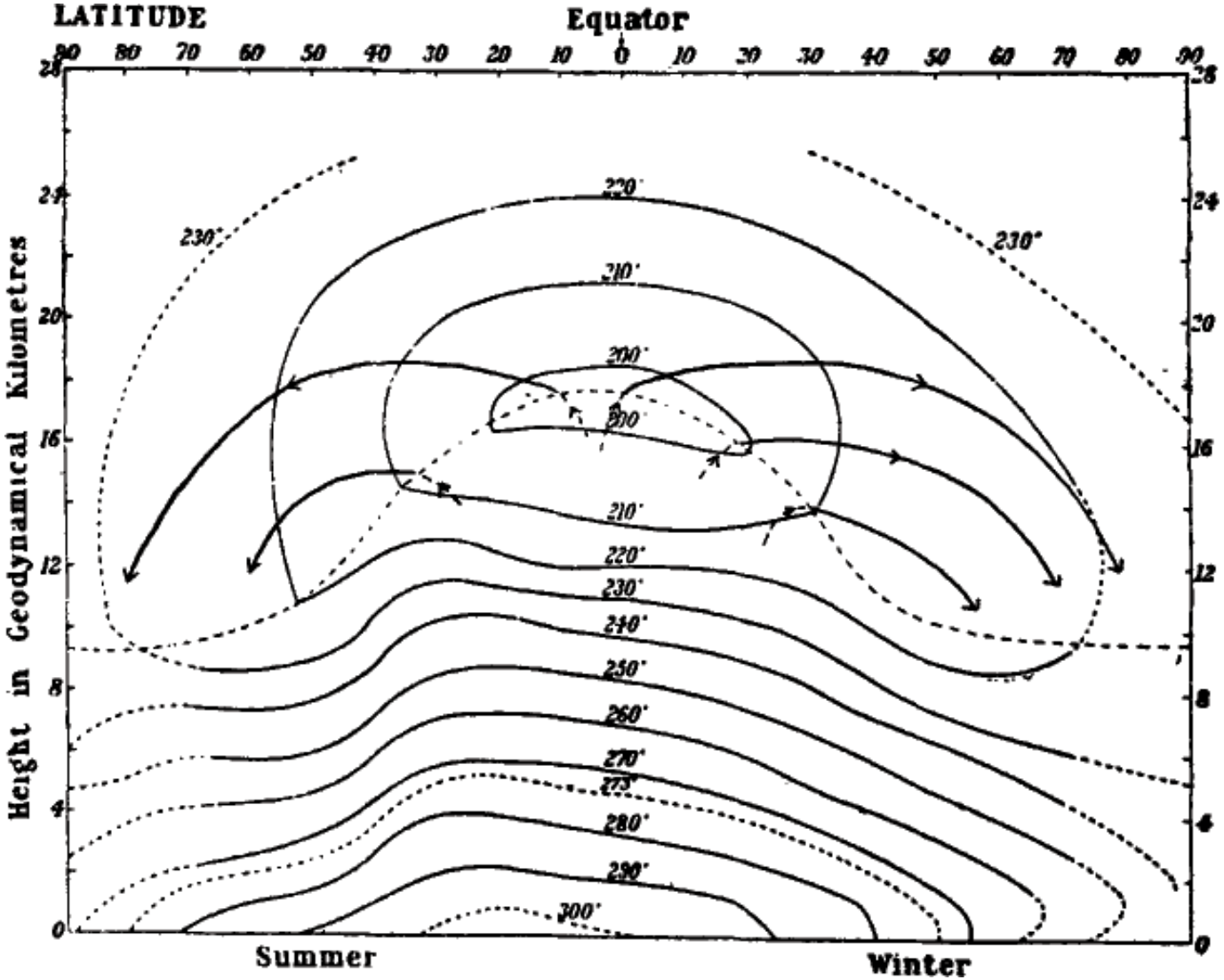

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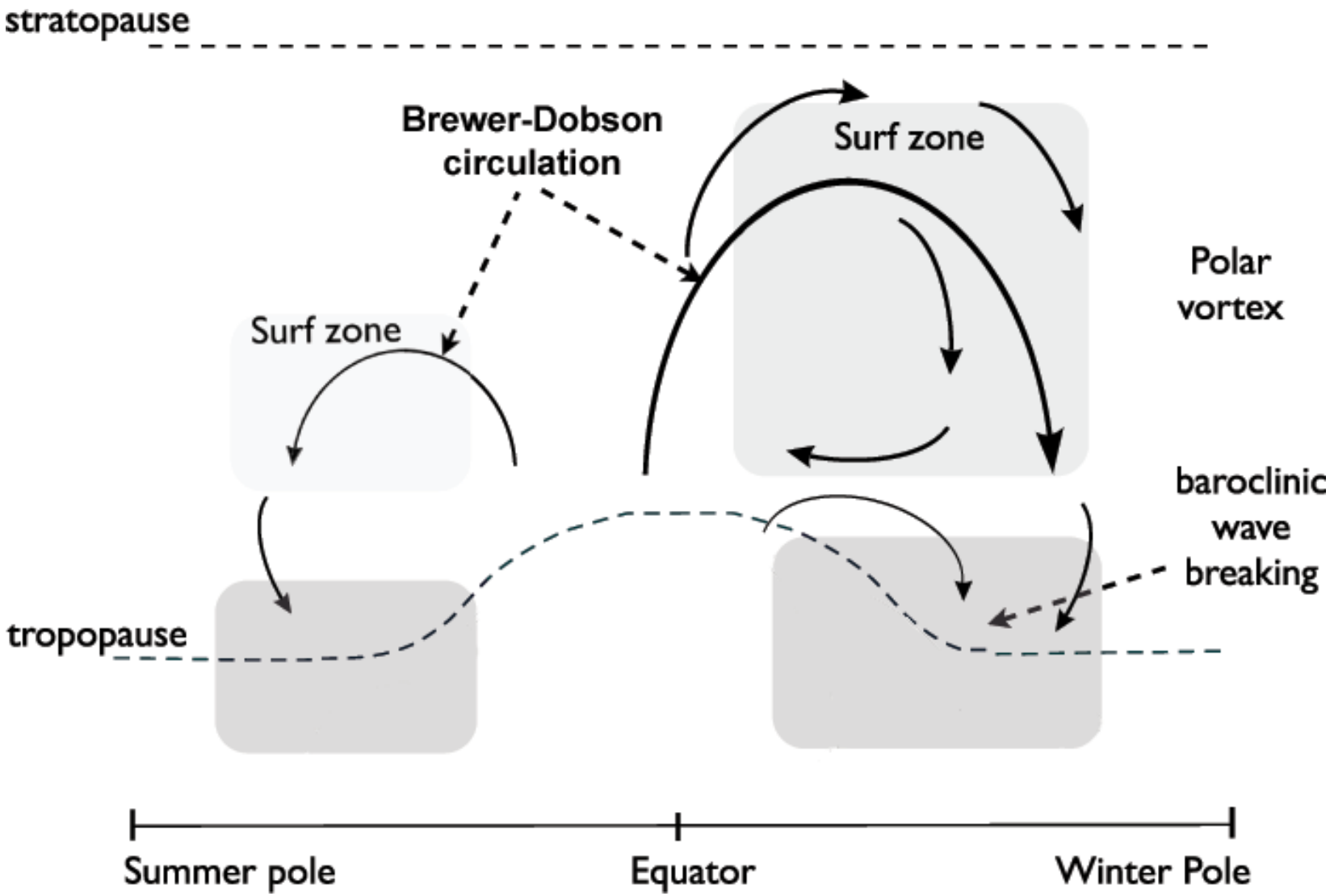
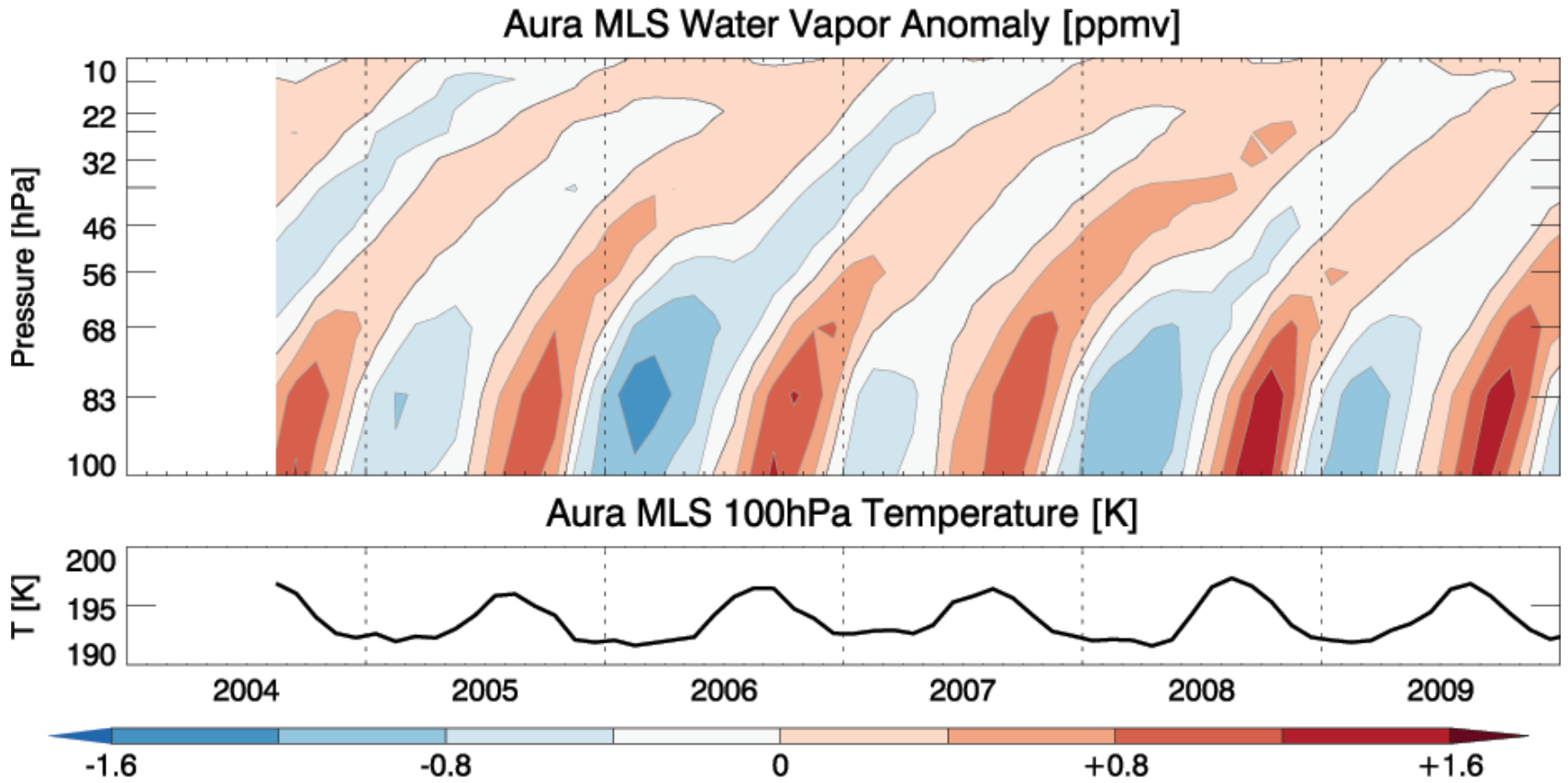
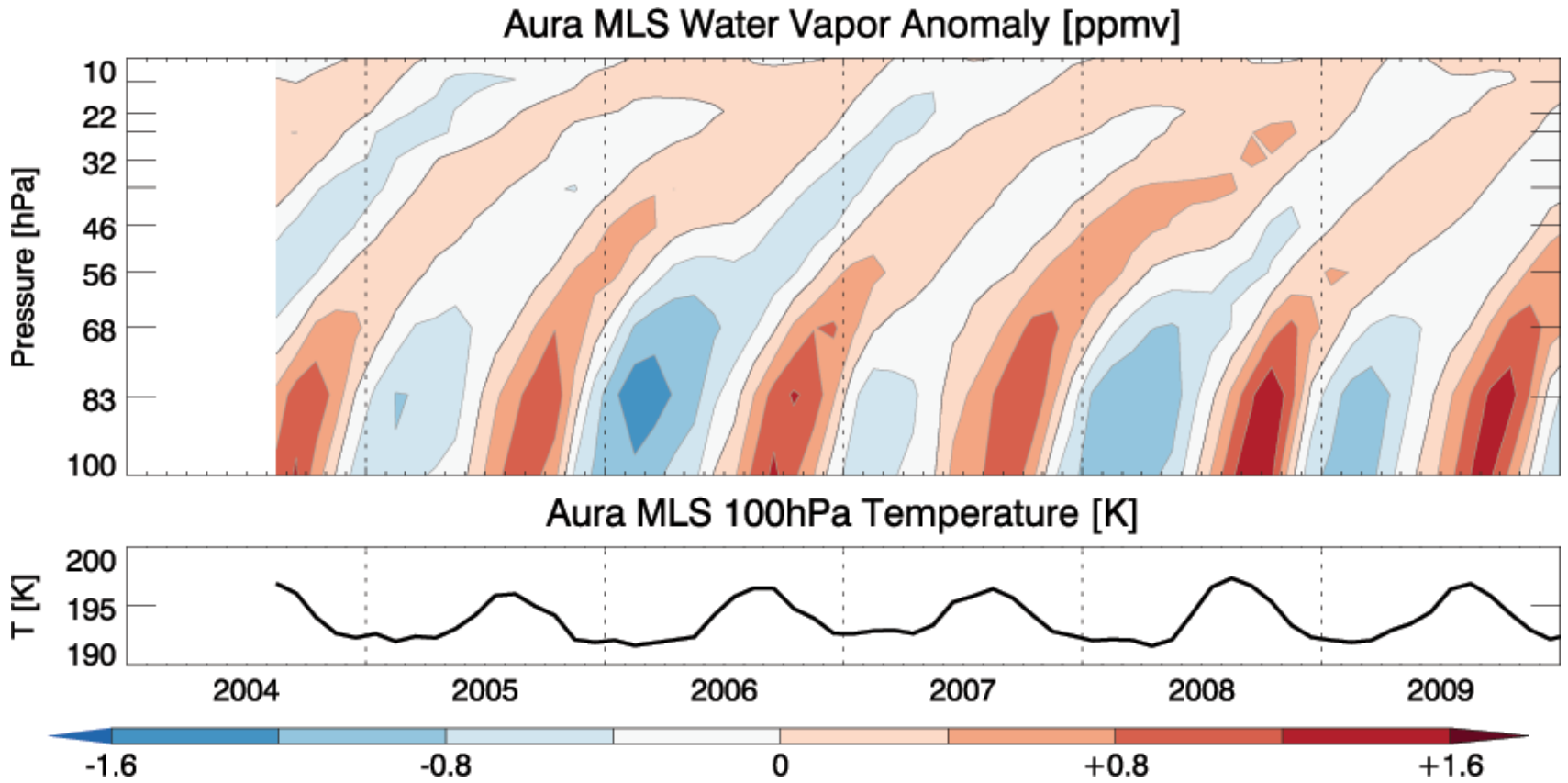


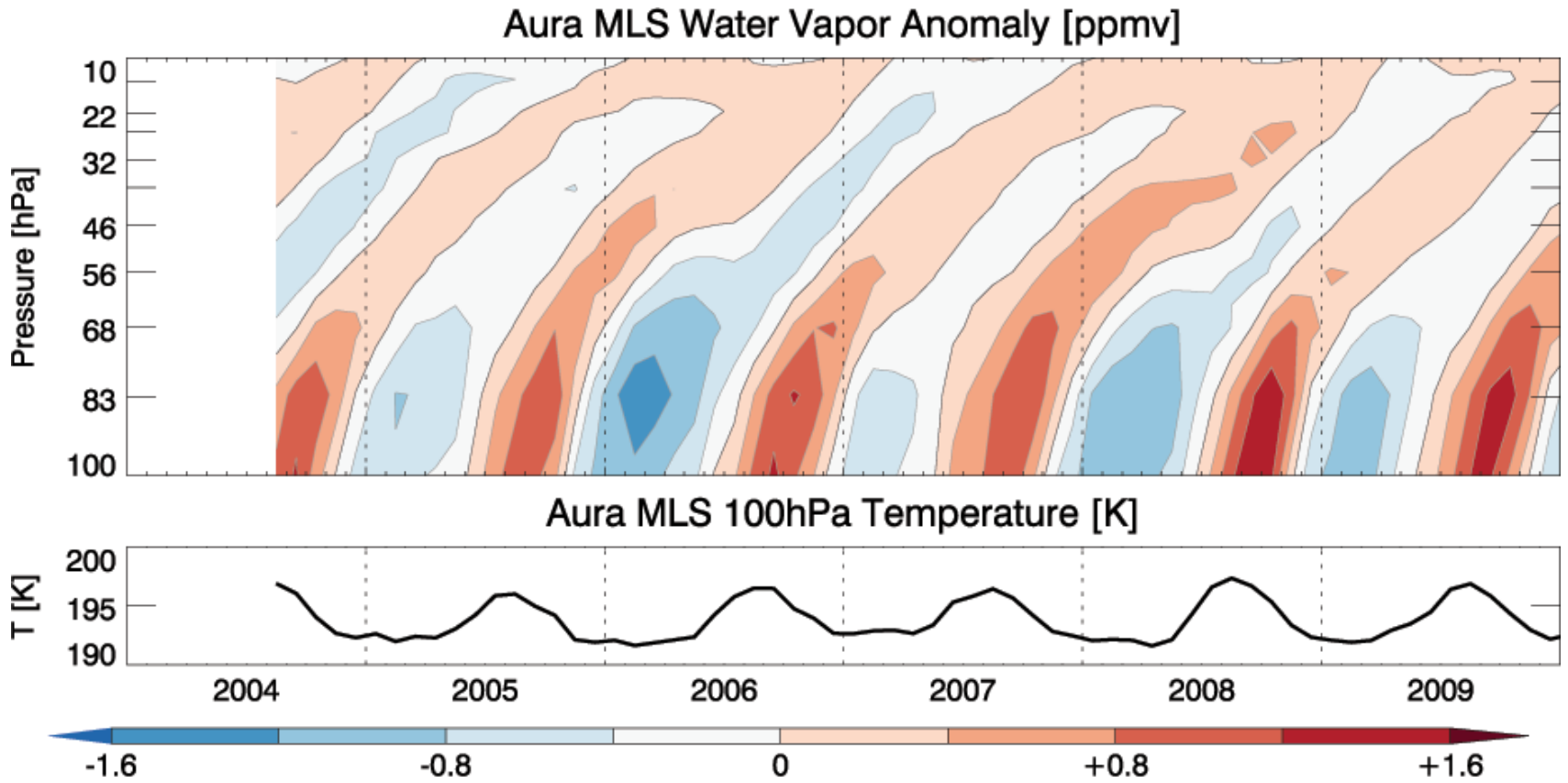
From *Vallis* 2006



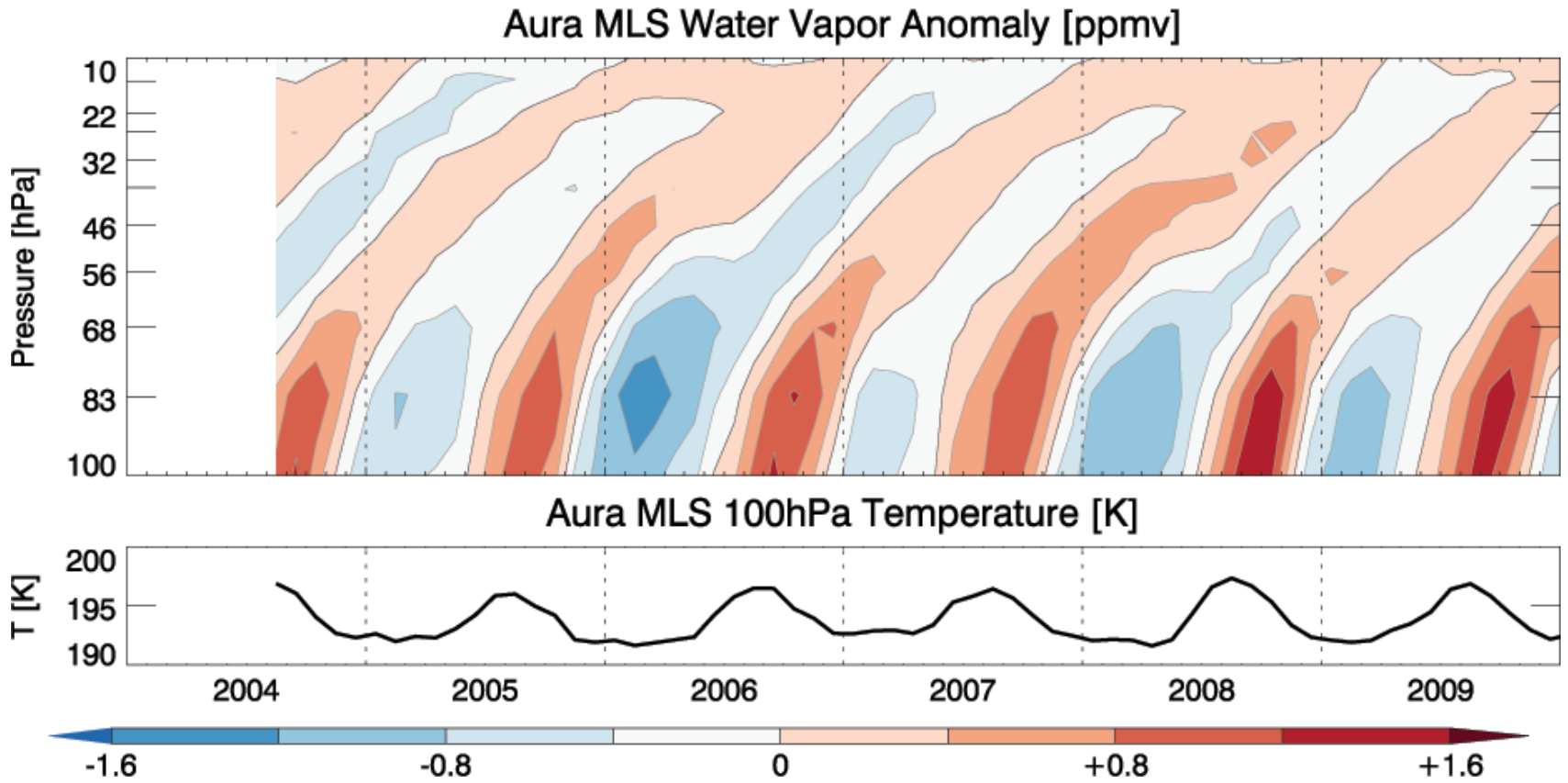
The seasonal cycle of water vapor at the tropopause propagates upward over time (*Mote et al.* 1996).



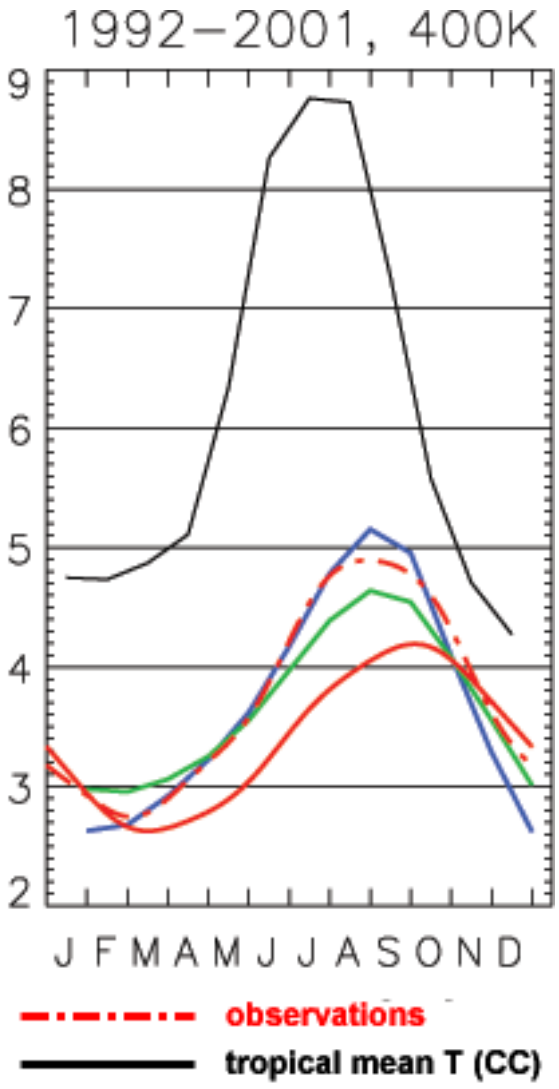
Stratospheric water is determined by tropical tropopause temperatures



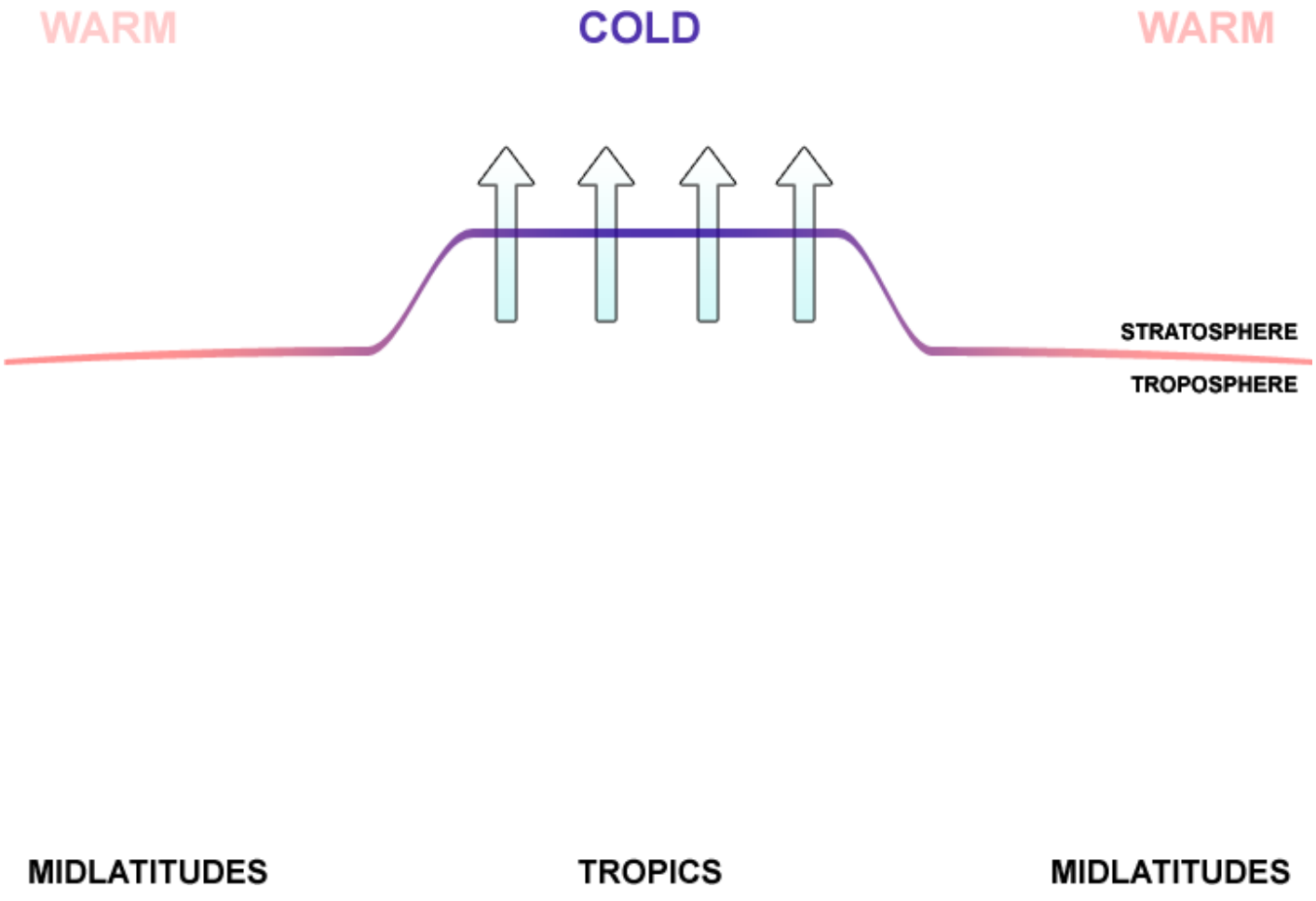
Stratospheric water is determined by tropical tropopause temperatures – right?



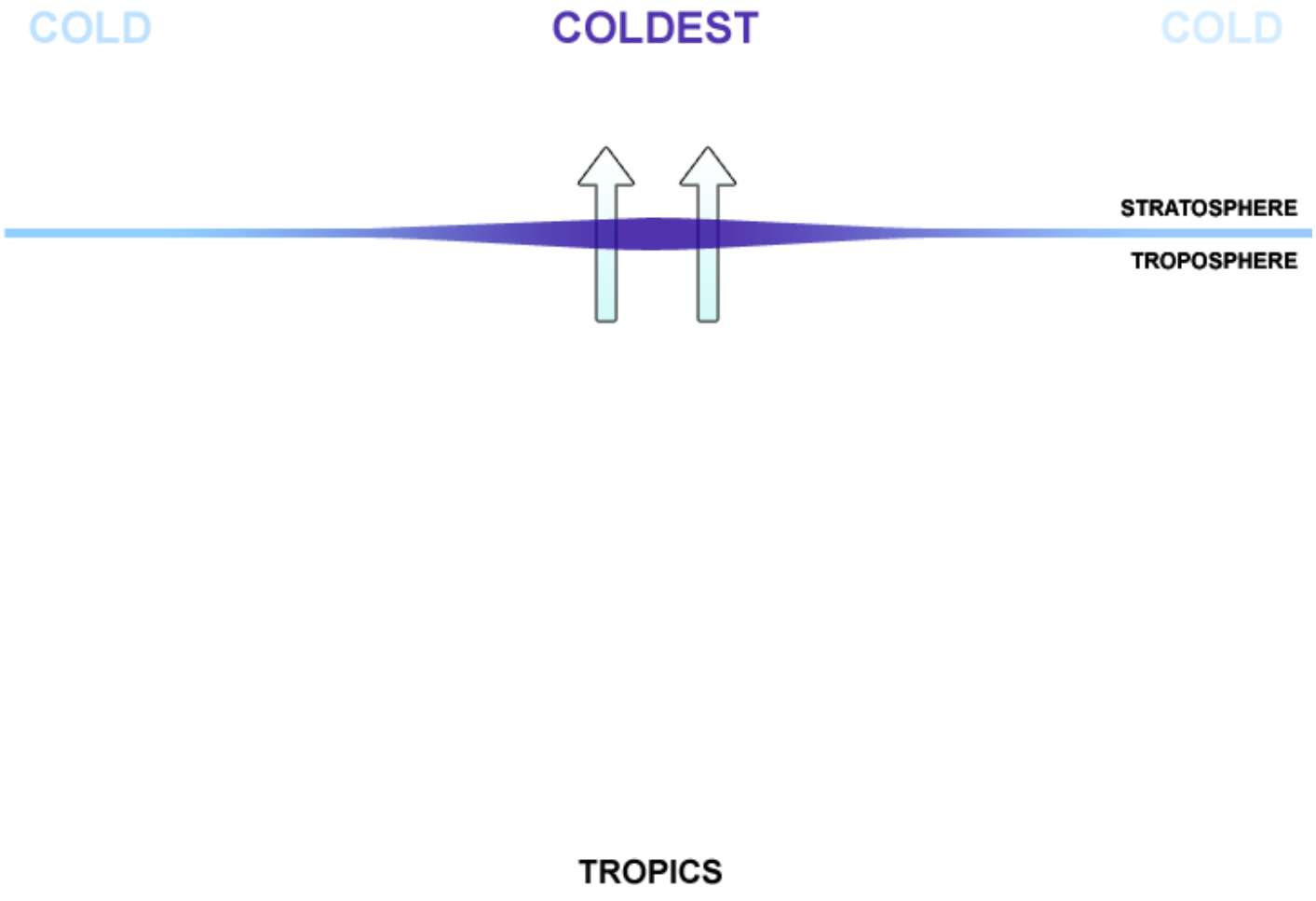
The stratosphere is drier and the seasonal cycle is smaller than mean tropical tropopause temperatures suggest.



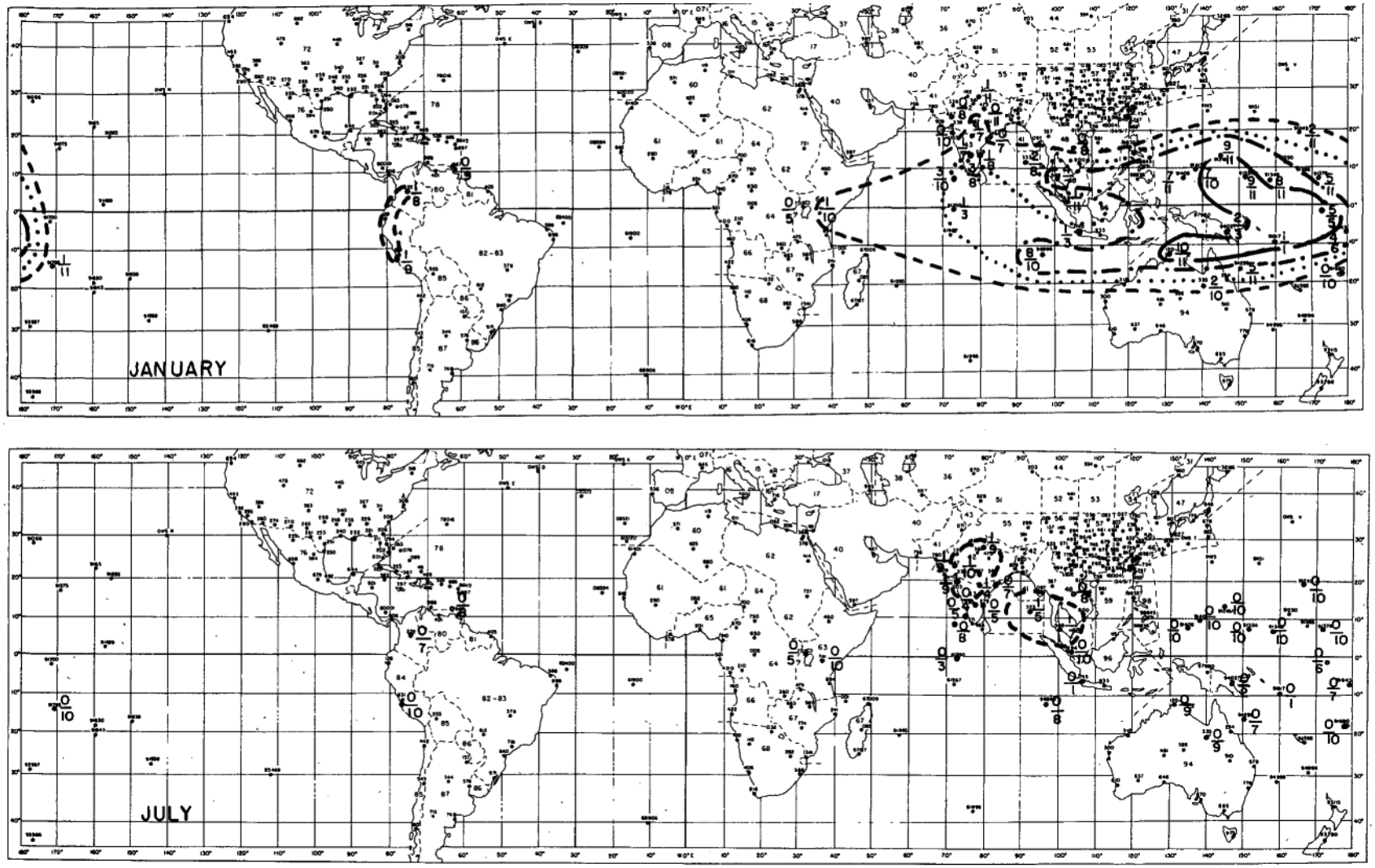
From *Fueglistaler et al.* 2005



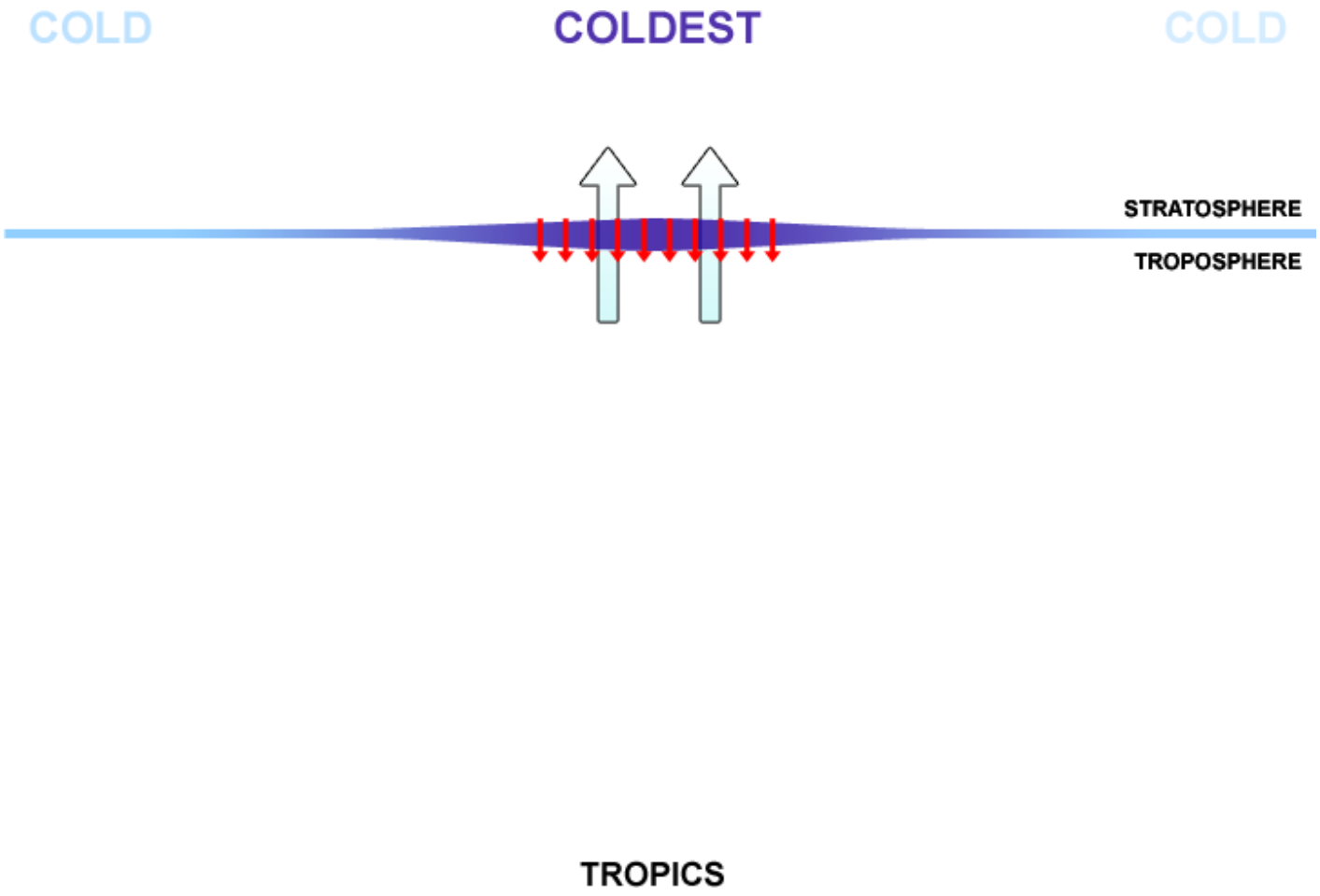
Entry through the tropical tropopause (*Brewer* 1949).



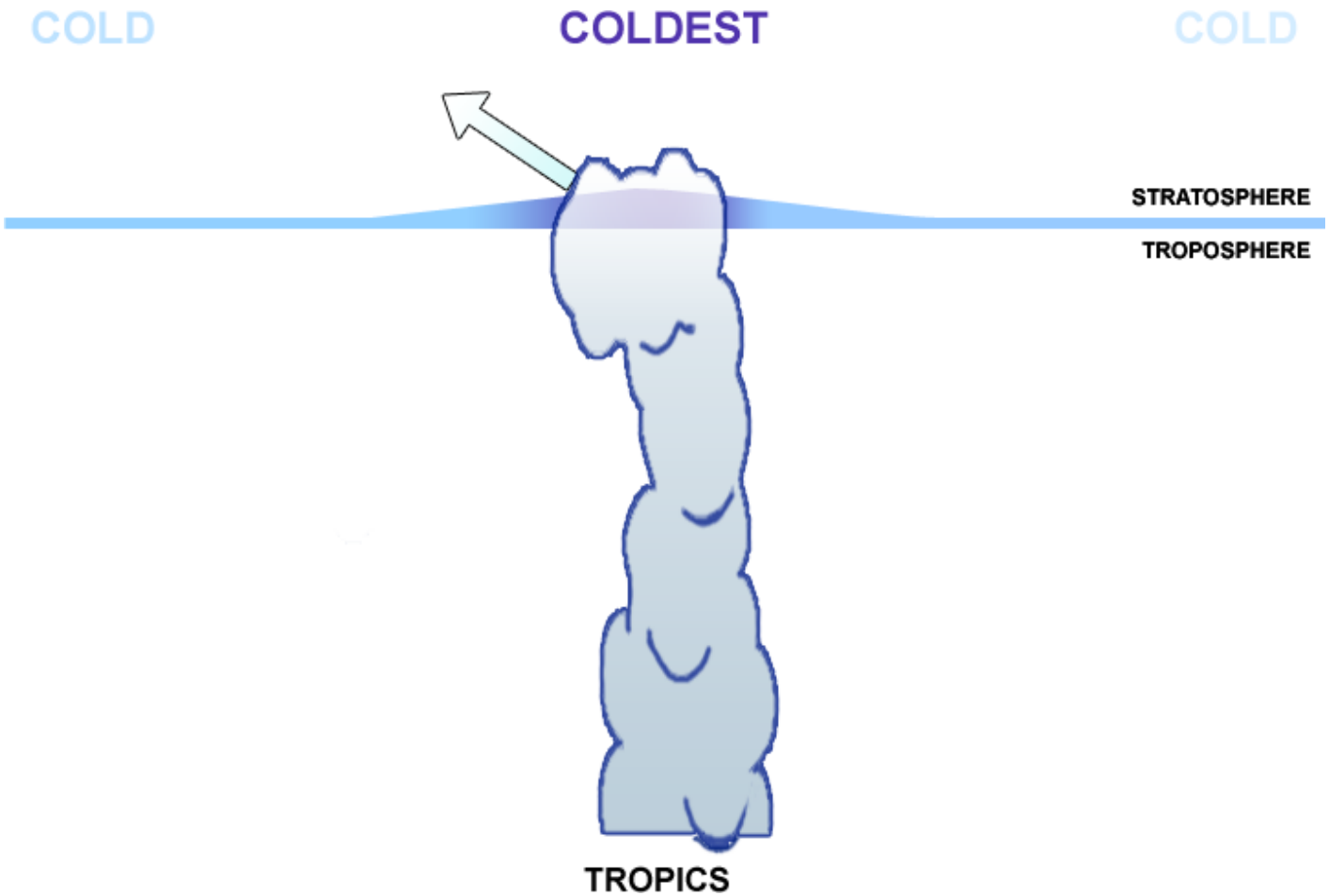
The "stratospheric fountain" (*Newell and Gould-Stewart* 1981).



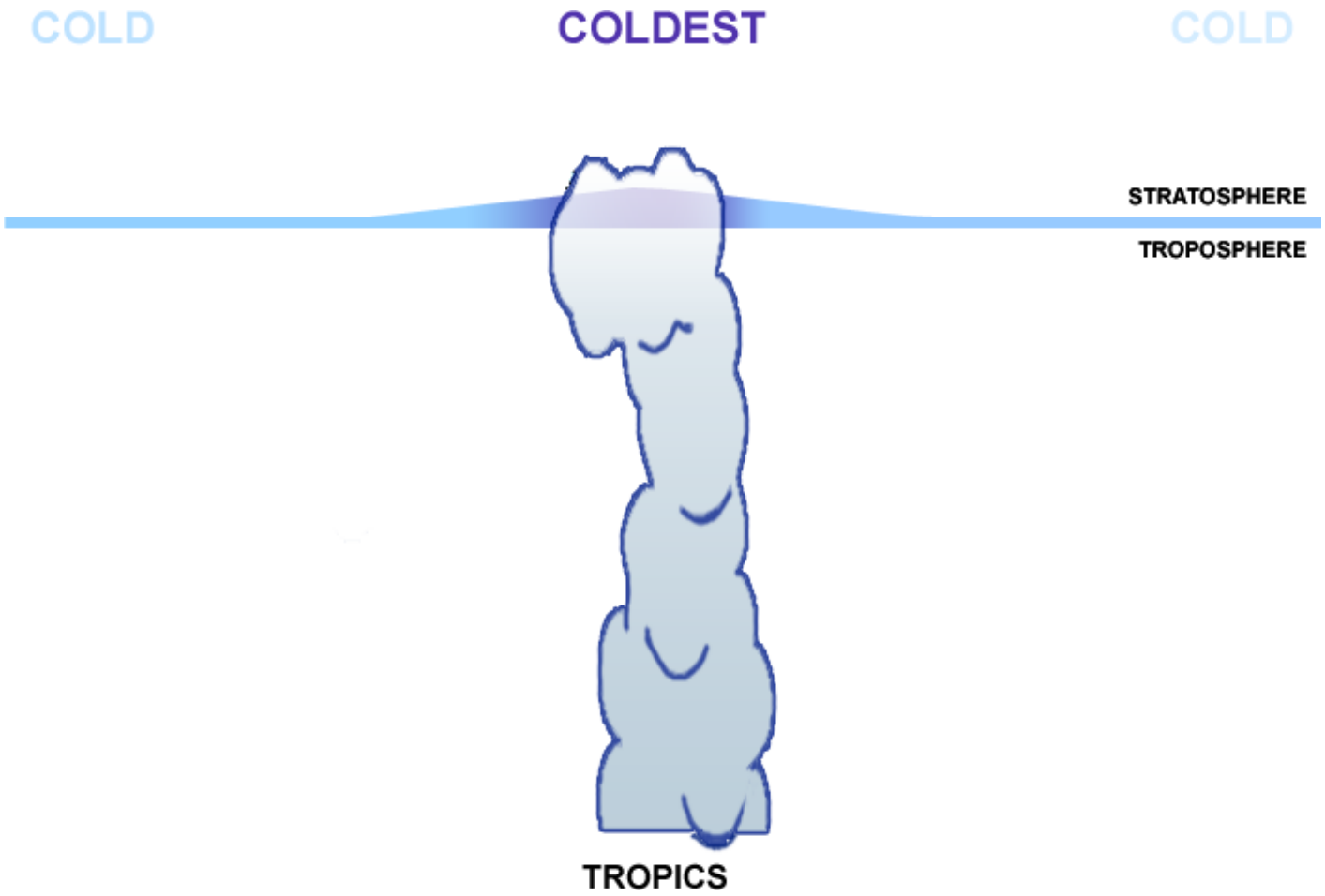
From *Newell and Gould-Stewart* 1981



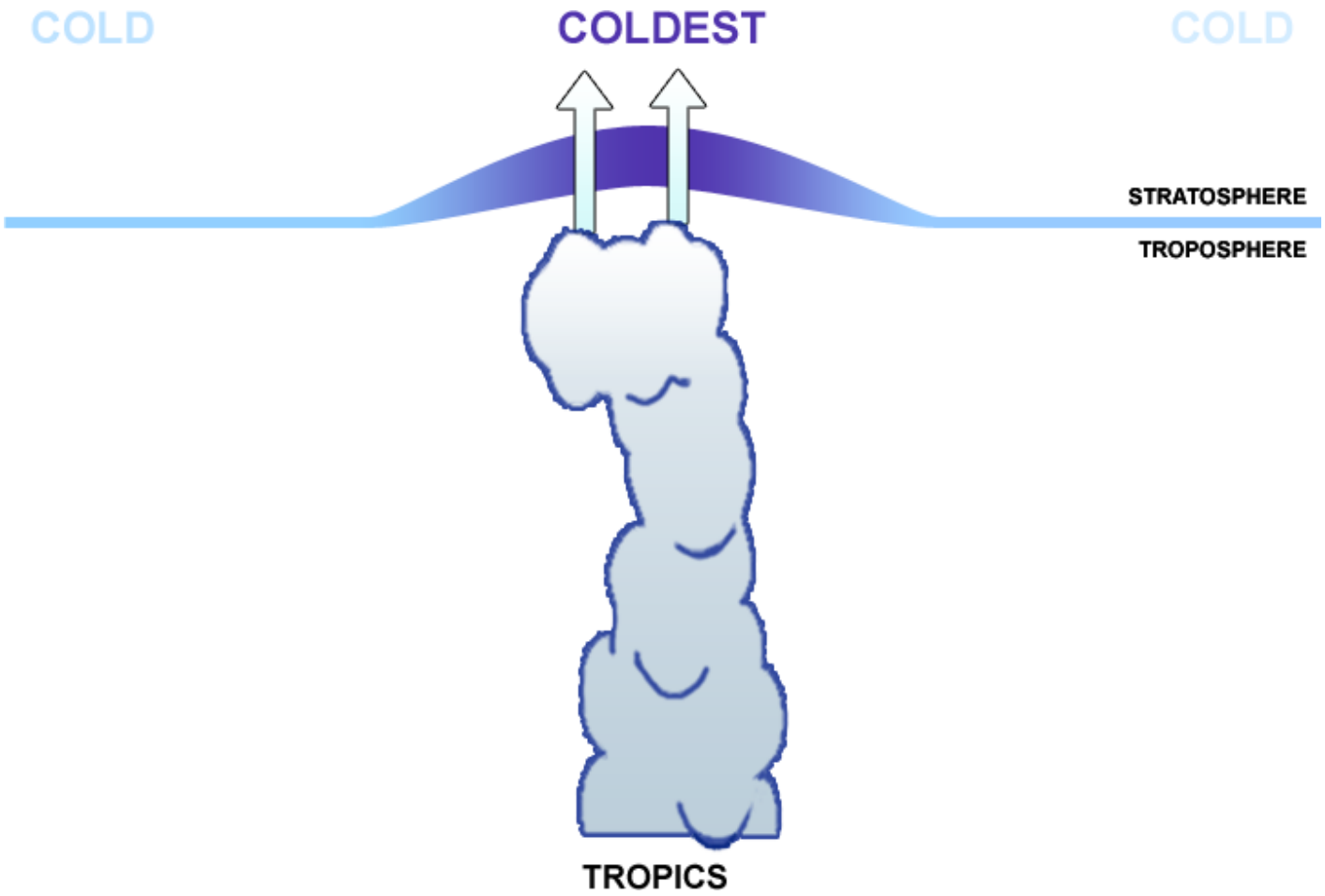
Downward motion observed over fountain region (*Sherwood* 2000).



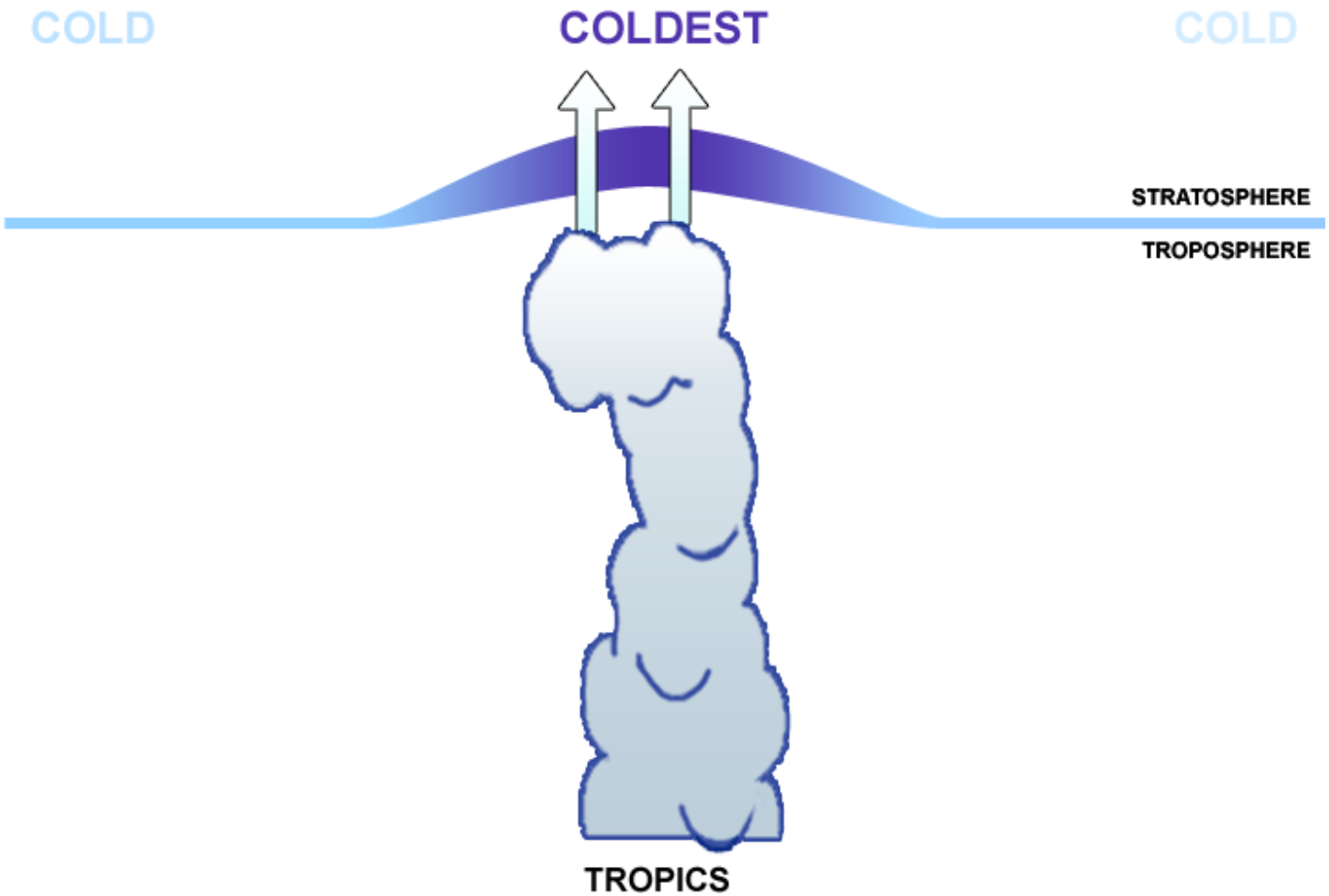
Overshooting convection "dehydration engines" (*Danielsen* 1982).



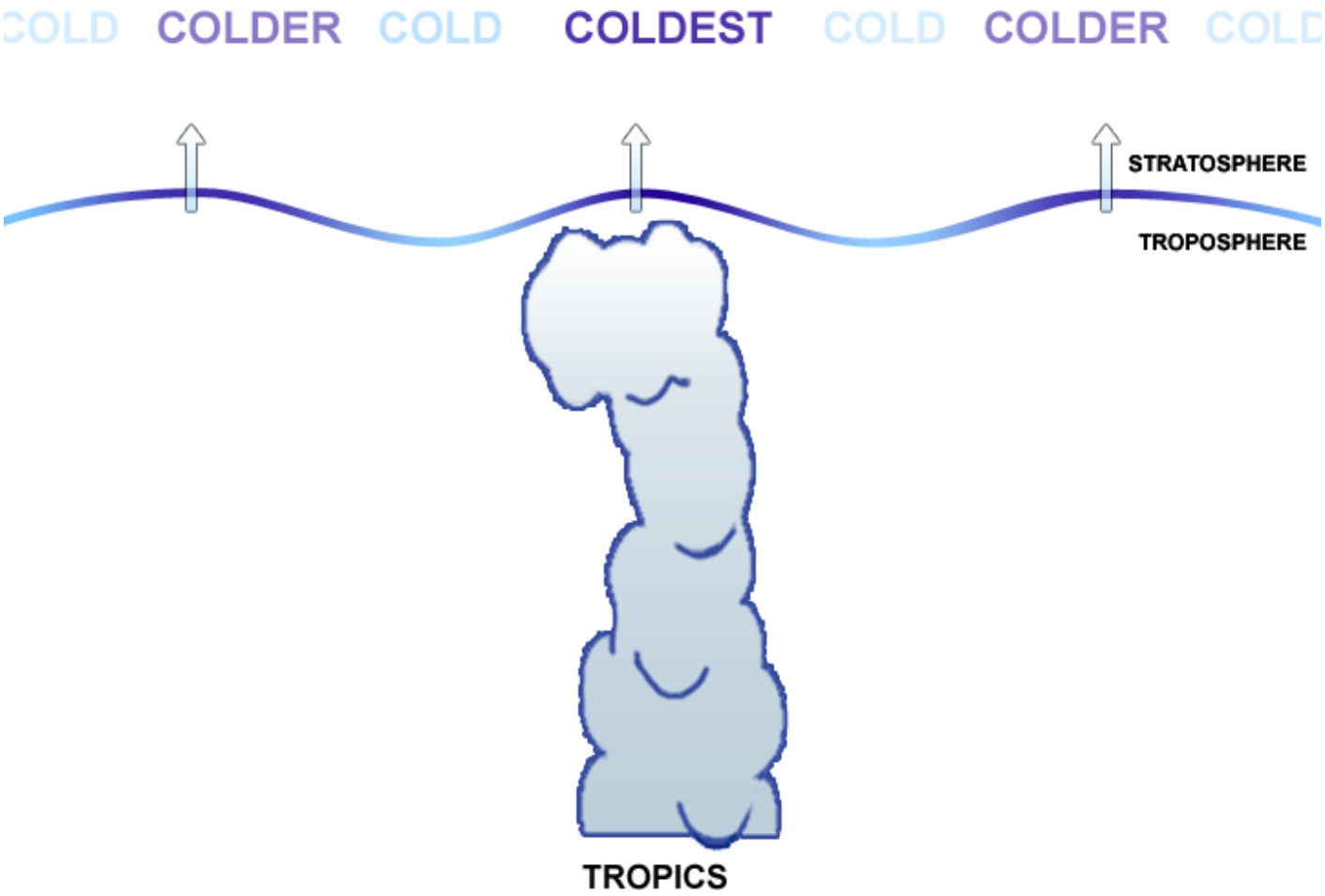
Suitable convective events occur only rarely.



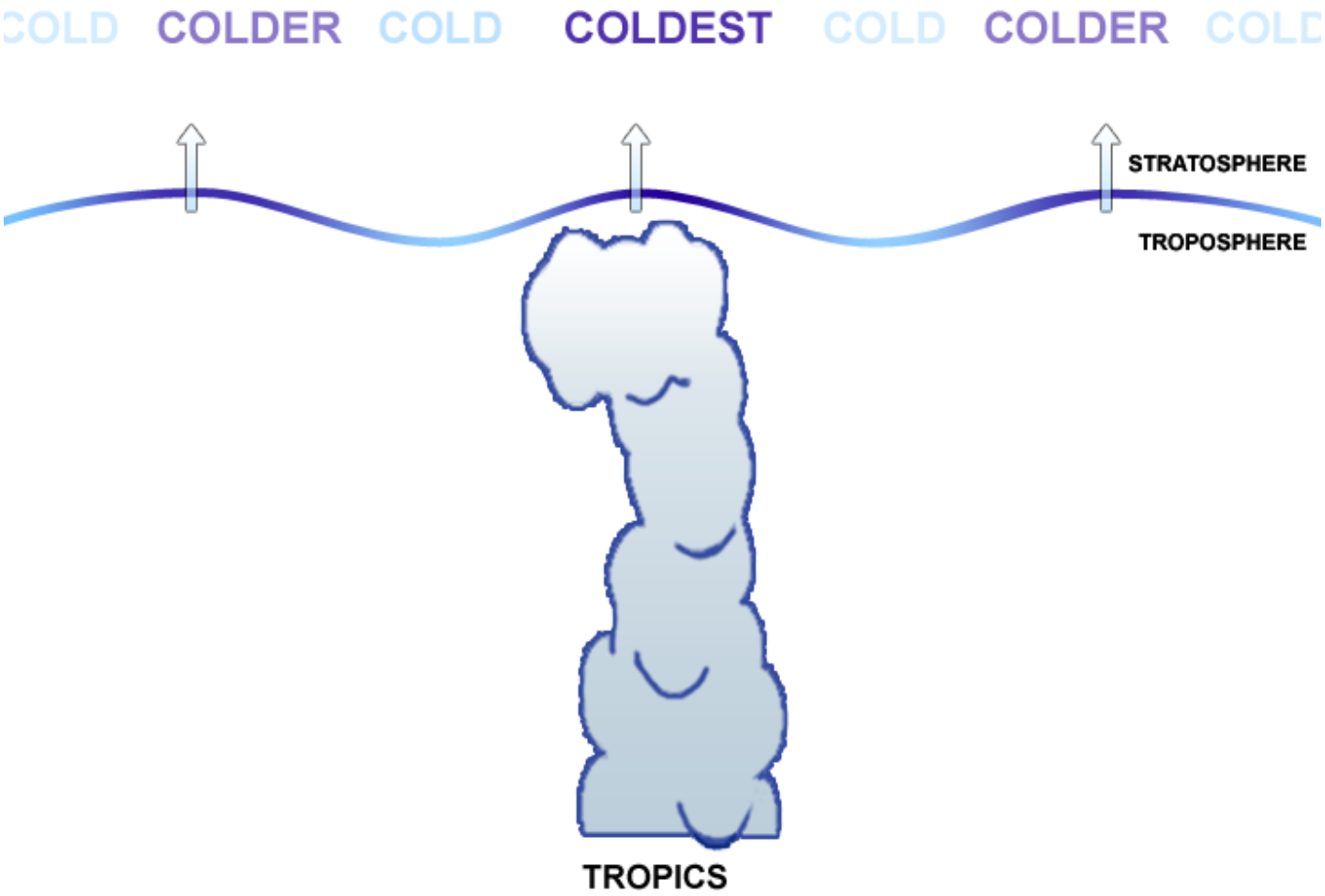
Mesoscale systems lift the stratosphere (*Fritsch and Brown* 1982).



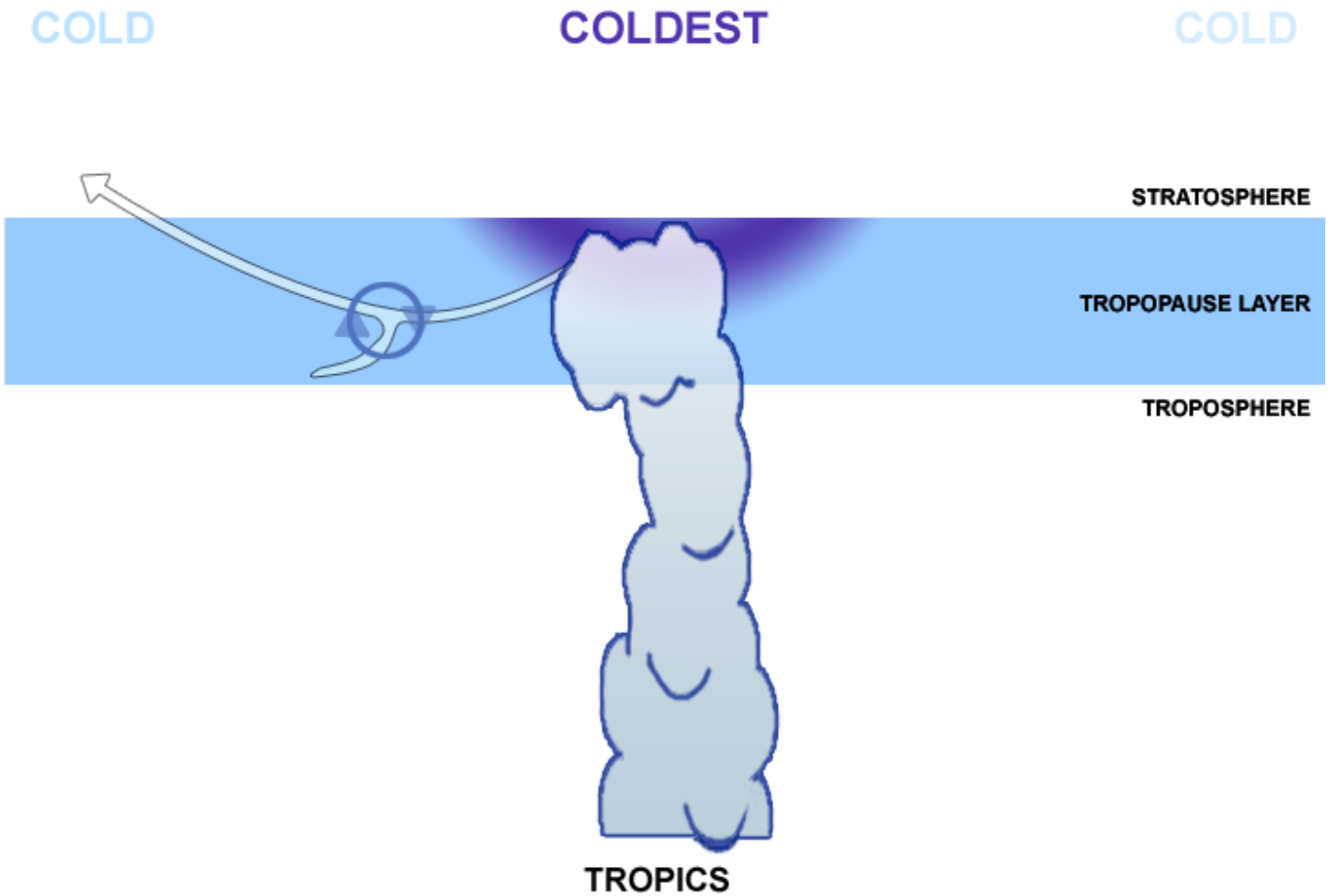
Could it explain the scale of the drying or the seasonal cycle?



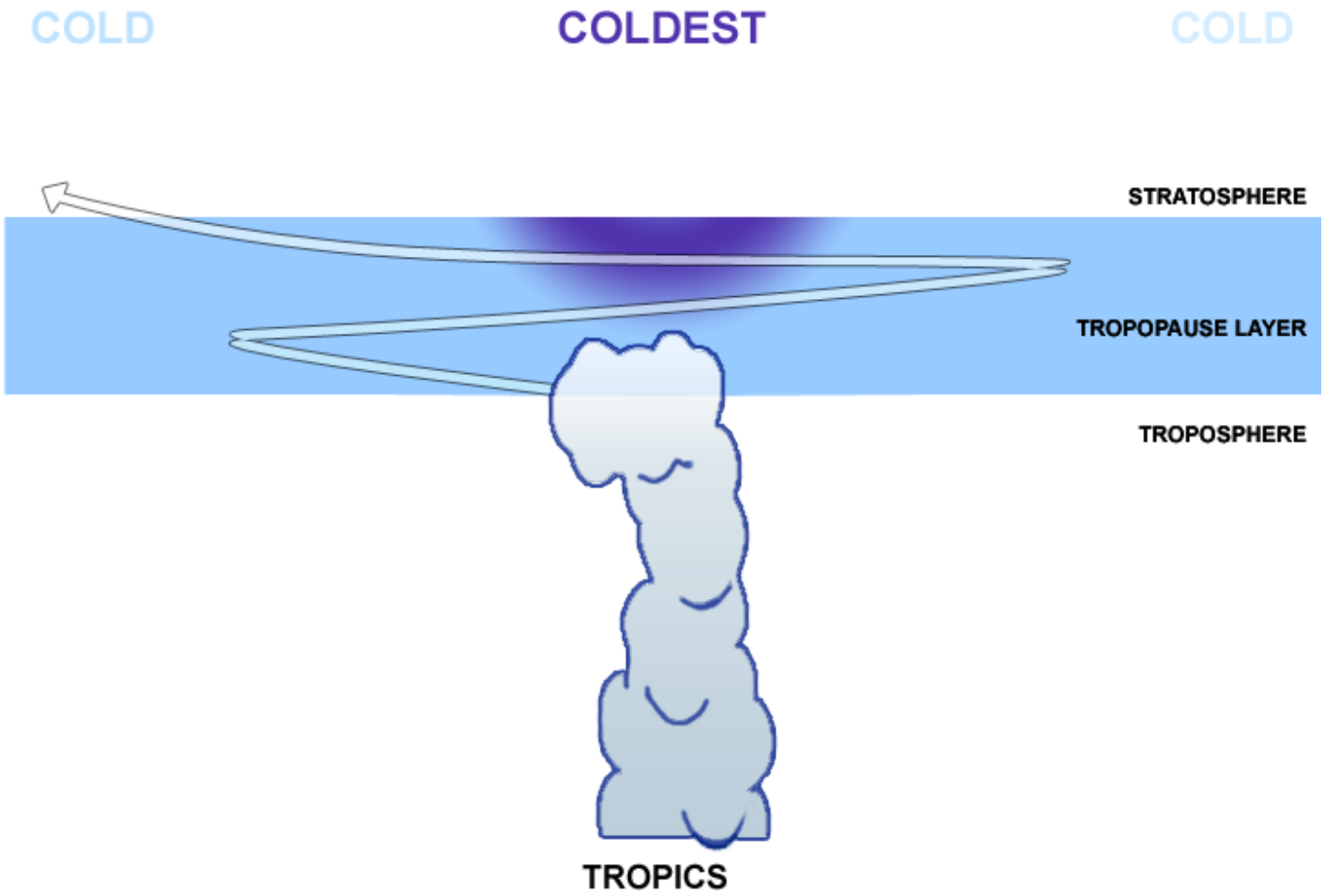
Dehydration by gravity waves (*Potter and Holton* 1995).



Relatively short time scales for dehydration – does ice fall out?

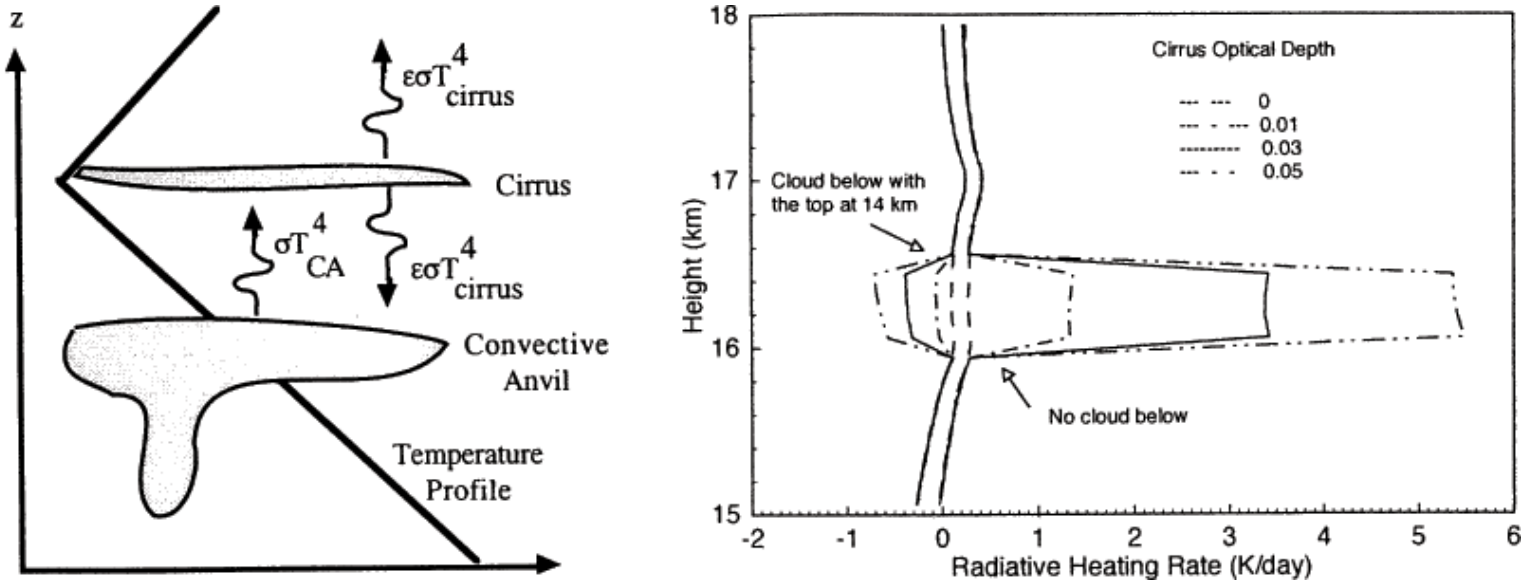


"Convective dehydration" (*Sherwood and Dessler* 2000).



"Cold trap dehydration" (*Holton and Gettelman* 2001).

Thin ice clouds above deep convective anvils can promote radiative cooling and subsidence, as opposed to radiative heating and ascent.

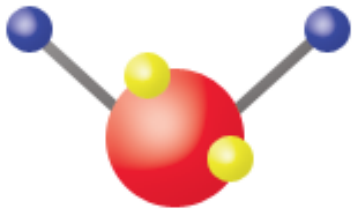


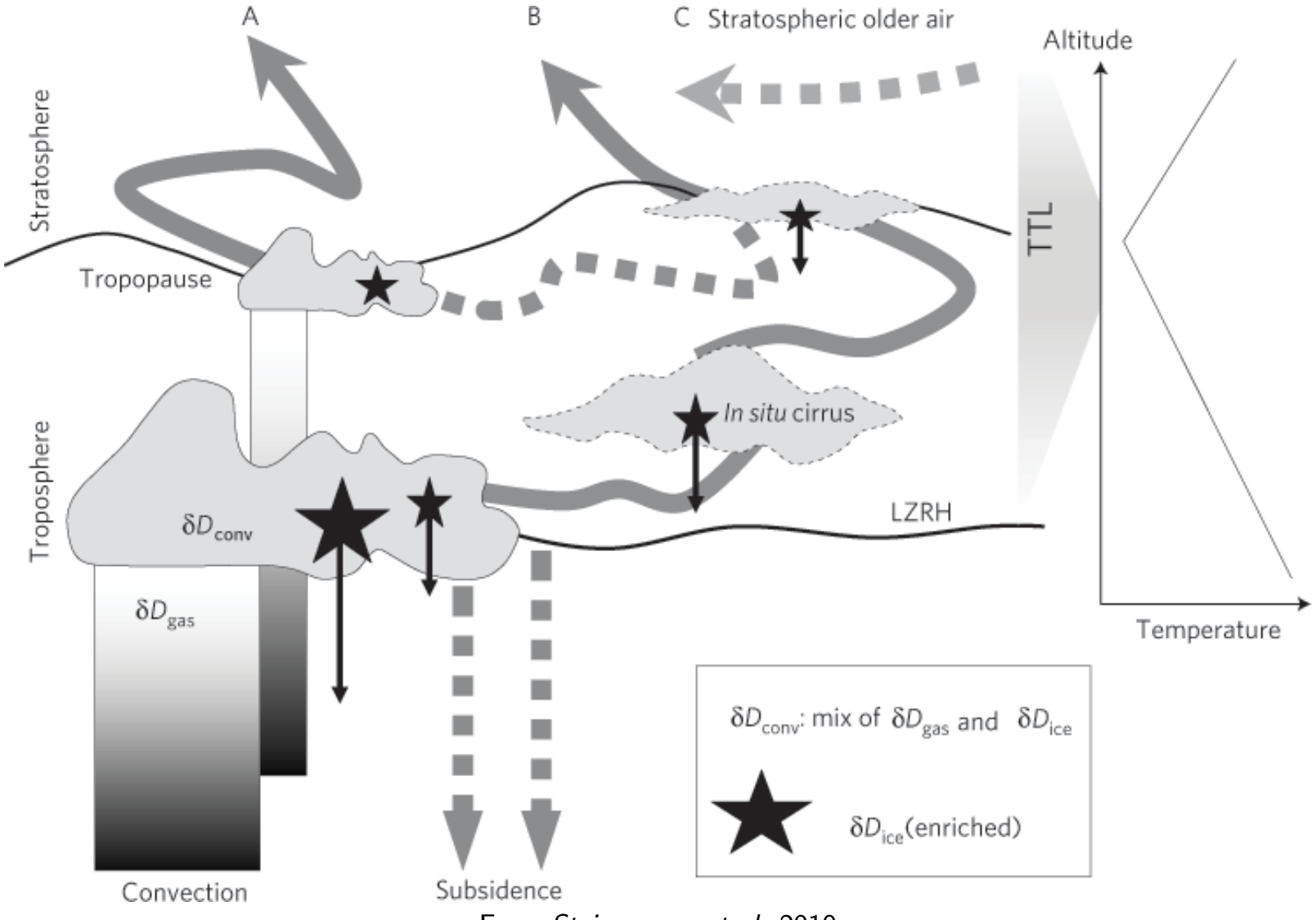
From *Hartmann et al.* 2001

$$\epsilon\sigma T_{\mathrm{CA}}^4 = 2\epsilon\sigma T_{\mathrm{cirrus}}^4$$

$$T_{\mathrm{cirrus}} = \frac{1}{\sqrt[4]{2}} T_{\mathrm{CA}}$$

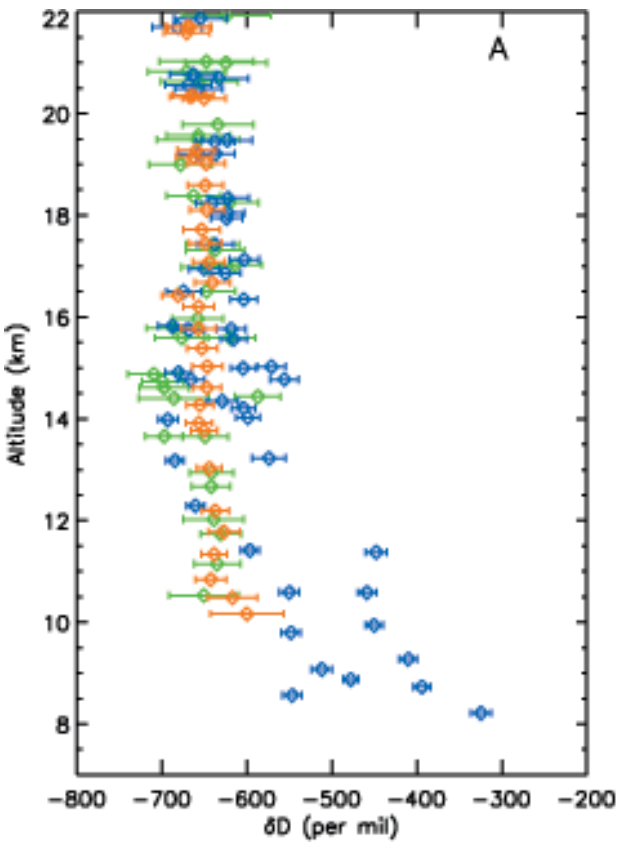
convective dehydration vs. cold trap dehydration

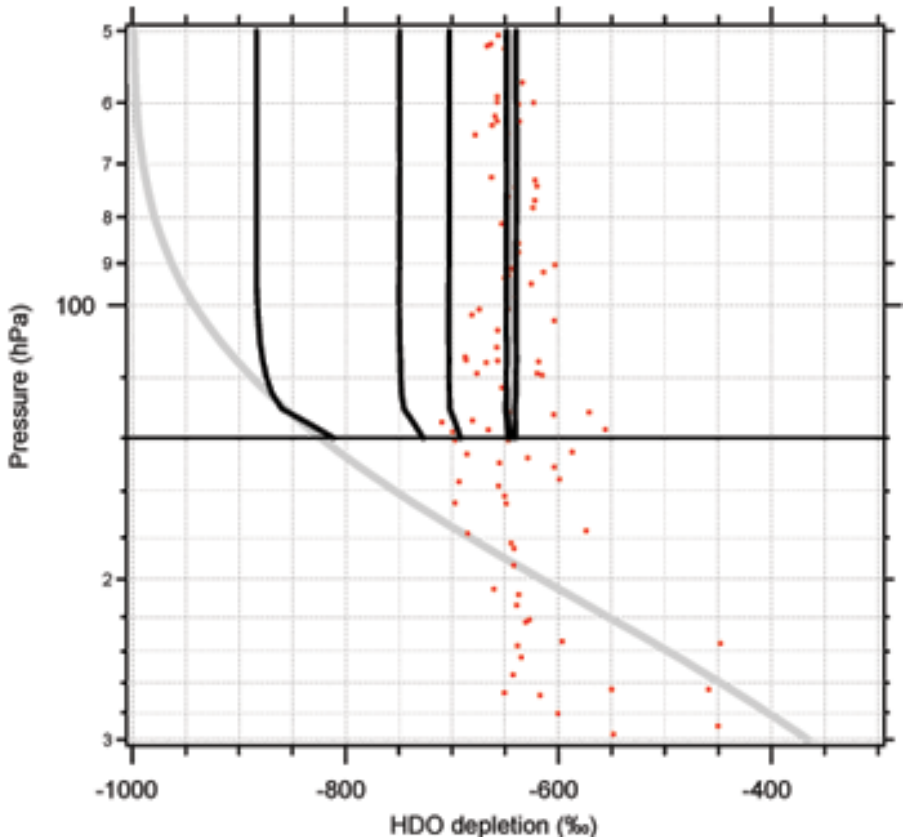
Water		1,000,000
Deuterated Water		311
^{18}O Water		2,005



From *Steinwagner et al.* 2010

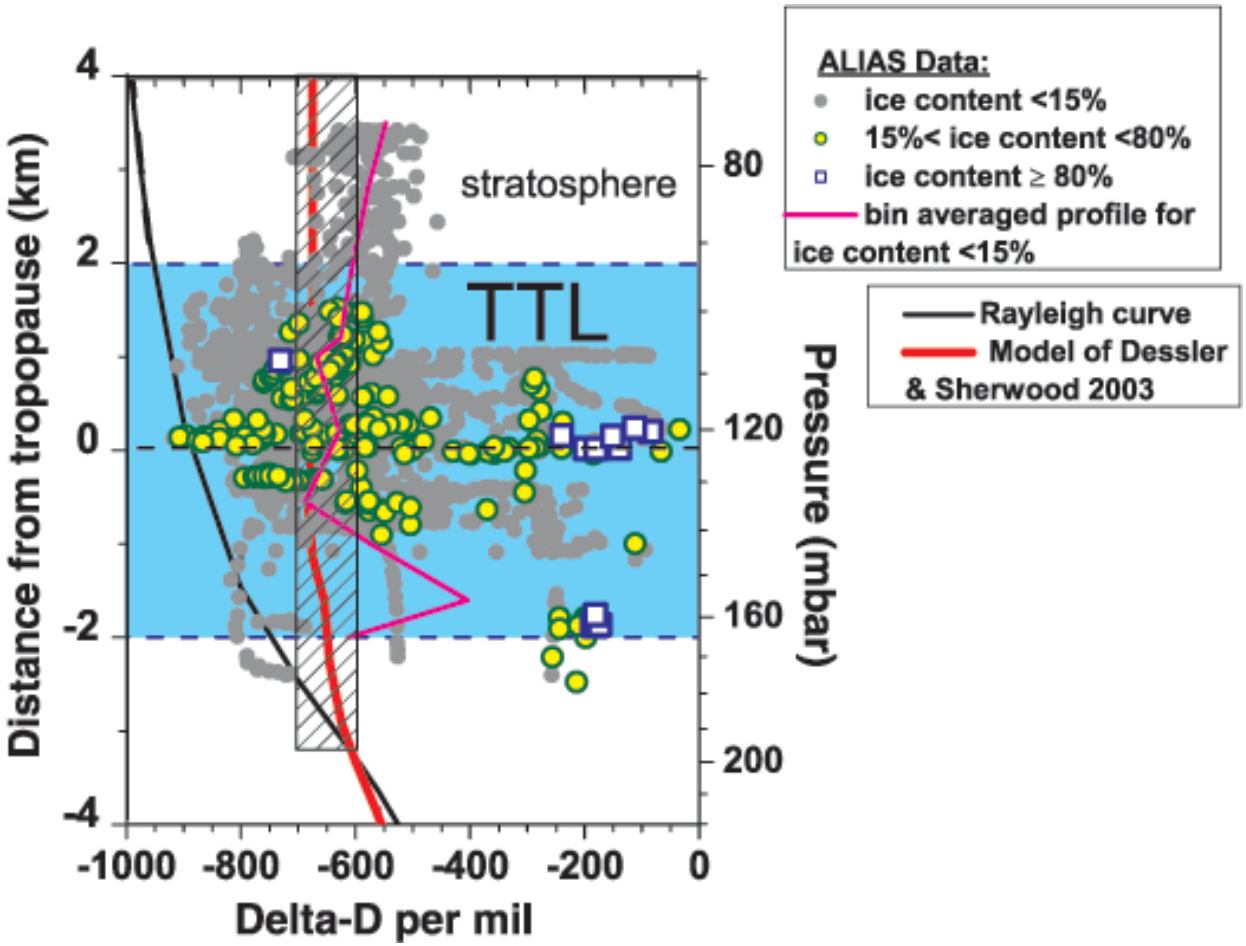
Isotopic observations from the space shuttle supported the convective dehydration hypothesis...



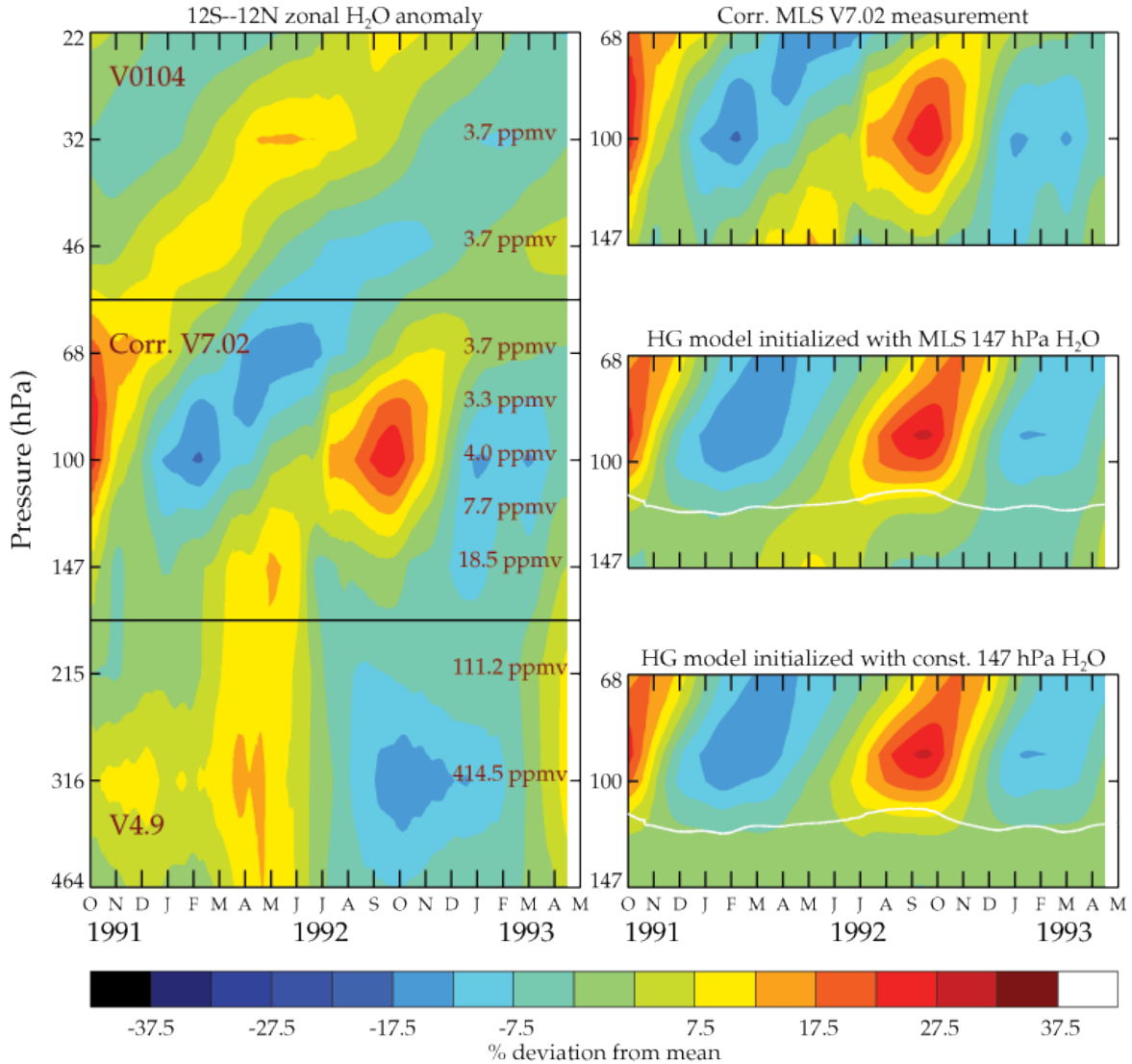


From *Kuang et al.* 2003 and *Dessler and Sherwood* 2003

...but in situ observations presented a more nuanced view.



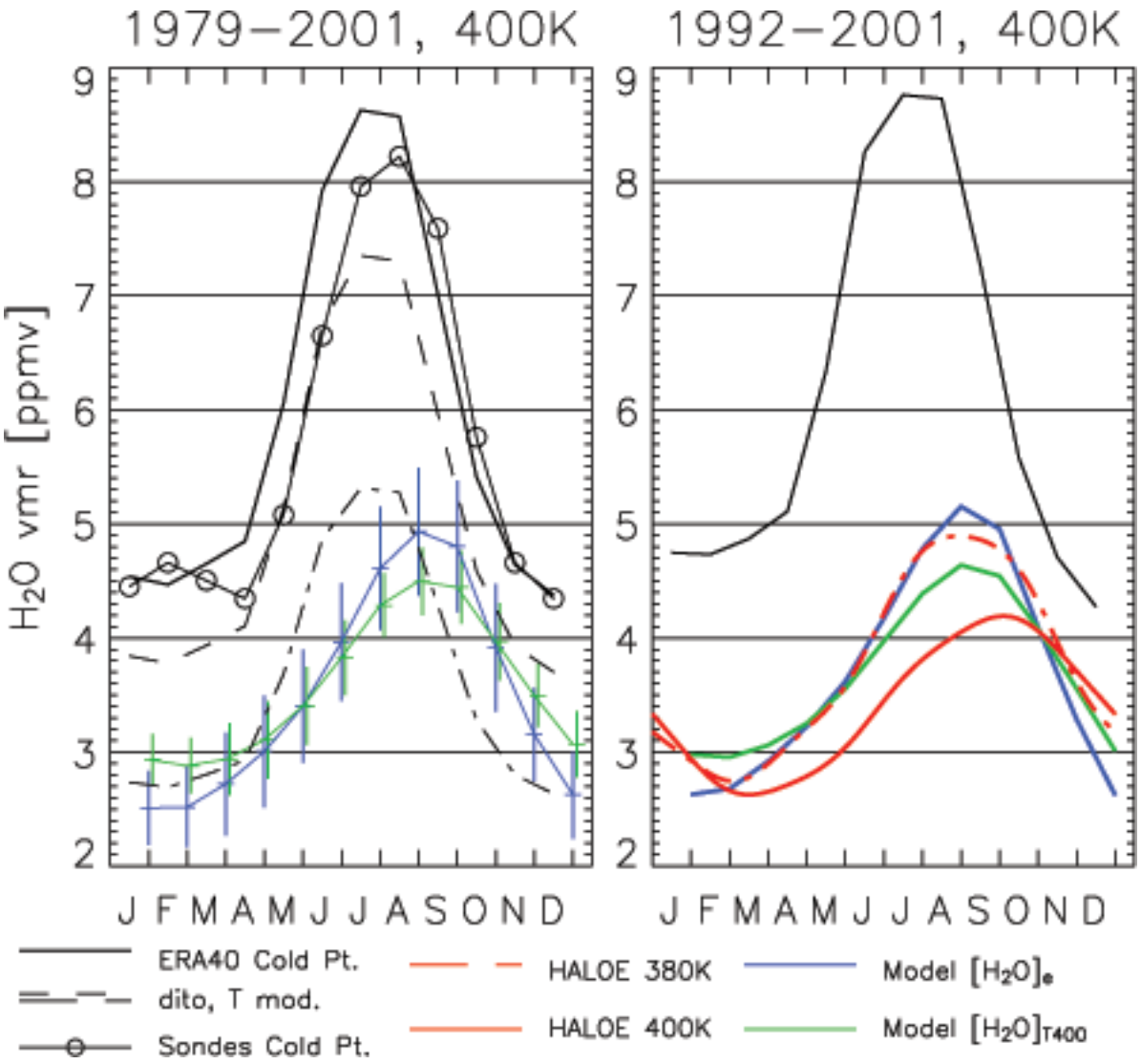
From *Webster and Heymsfield* 2003



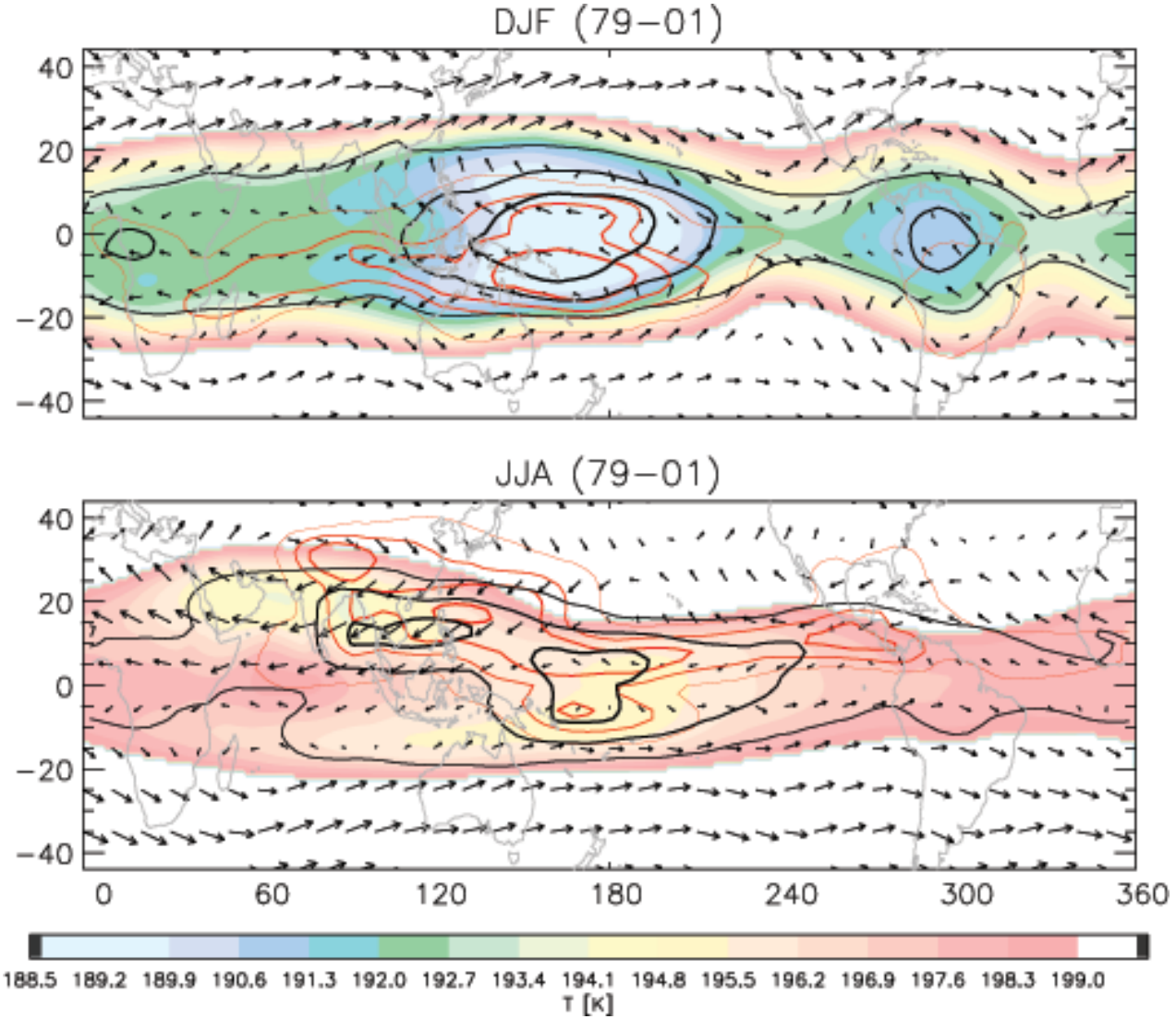
From *Read et al.* 2004

Advection–Condensation Model

Identify the transport of water vapor into the tropical lower stratosphere according to its Lagrangian dry point.



From *Fueglistaler et al.* 2005



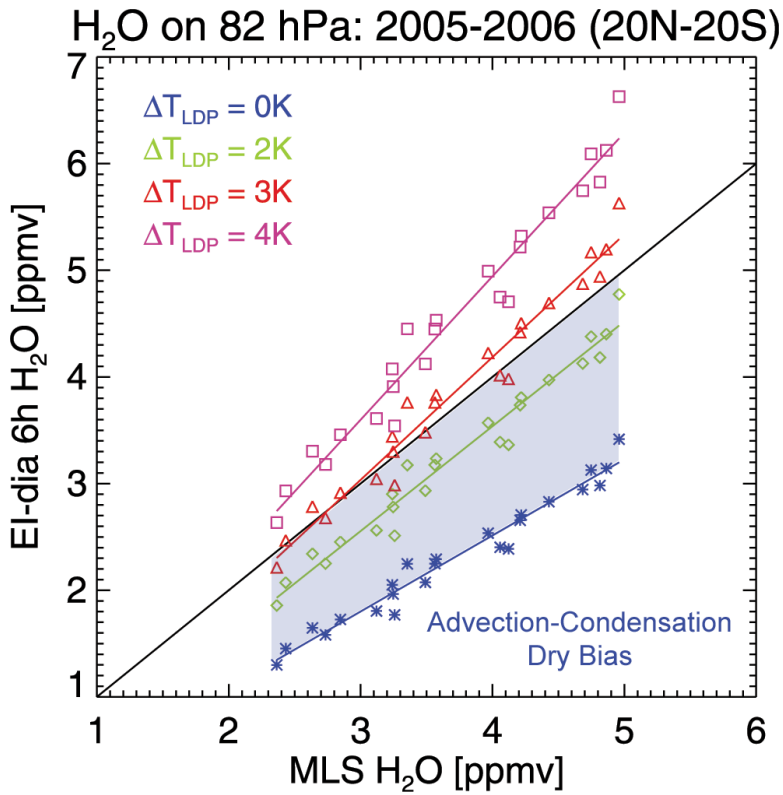
From *Fueglistaler et al.* 2005

Advection–Condensation Model

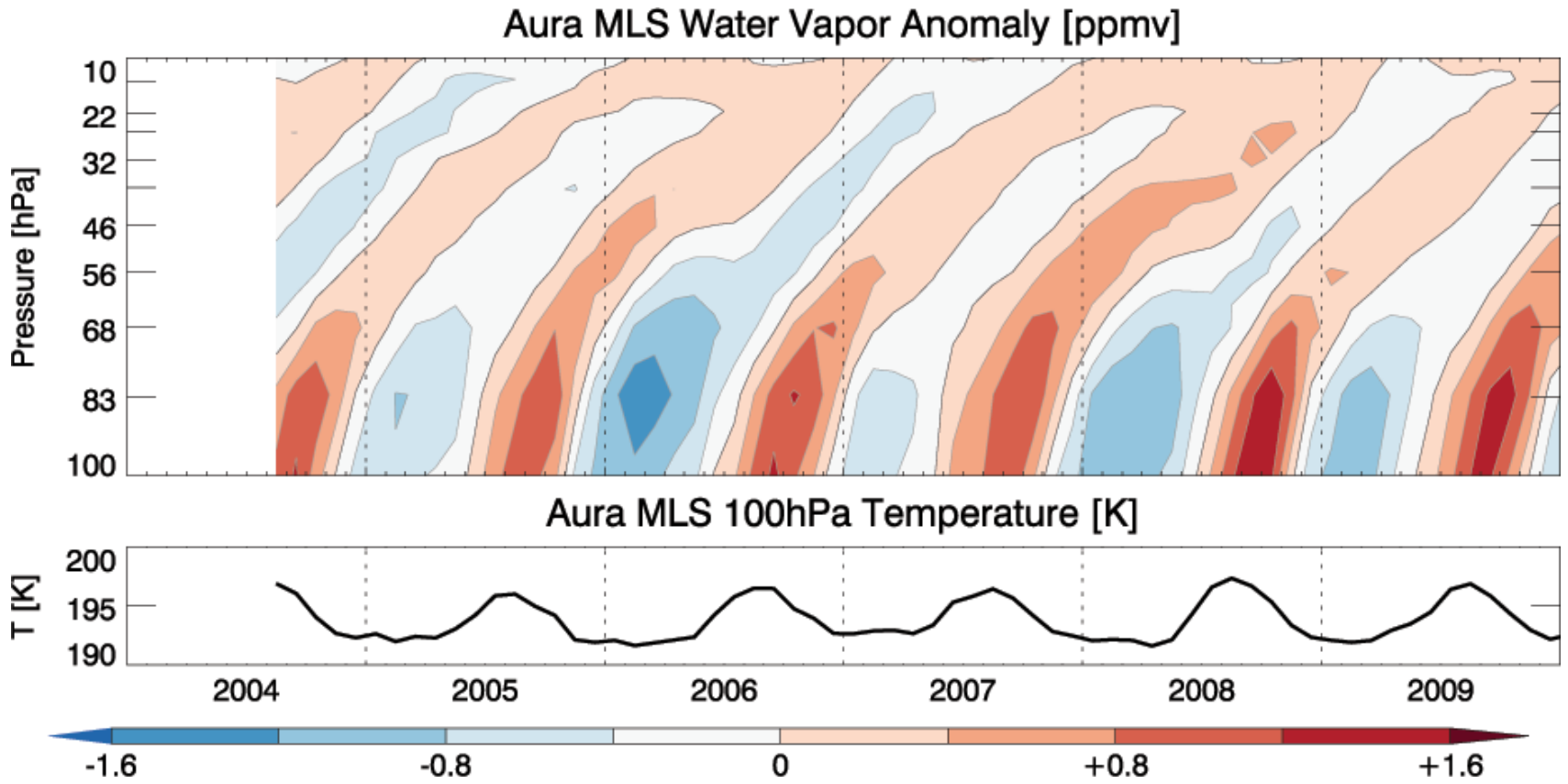
Identify the transport of water vapor into the tropical lower stratosphere according to its Lagrangian dry point.

The success of this type of model suggests that convective and cirrus cloud processes are not important.

Recent results indicate that advection–condensation simulations of water vapor are biased dry, especially during boreal summer.



From *Liu et al.* 2010



The amplitude of the tape recorder is substantially reduced in the middle and upper troposphere.

Methane and molecular hydrogen are oxidized in the middle and upper stratosphere to form water.

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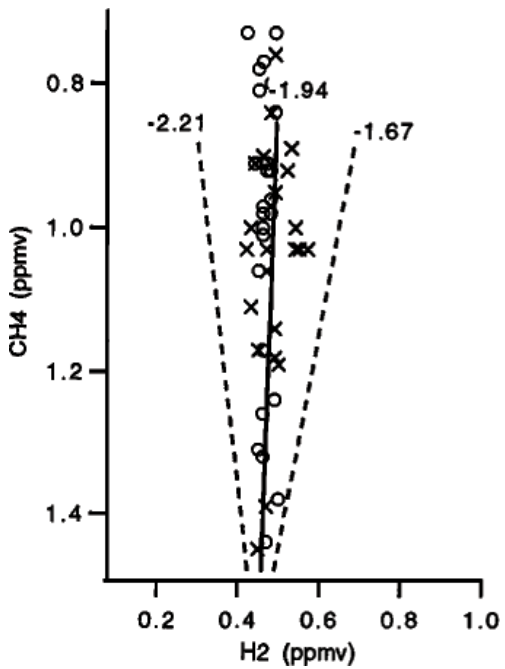
Methane oxidation also produces molecular hydrogen at a rate that roughly balances loss due to oxidation.



From *Dessler et al.* 1994

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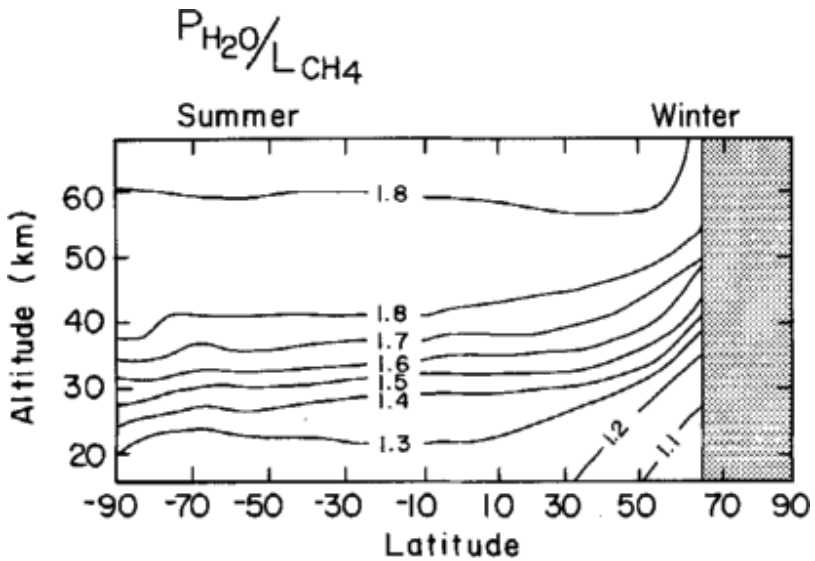
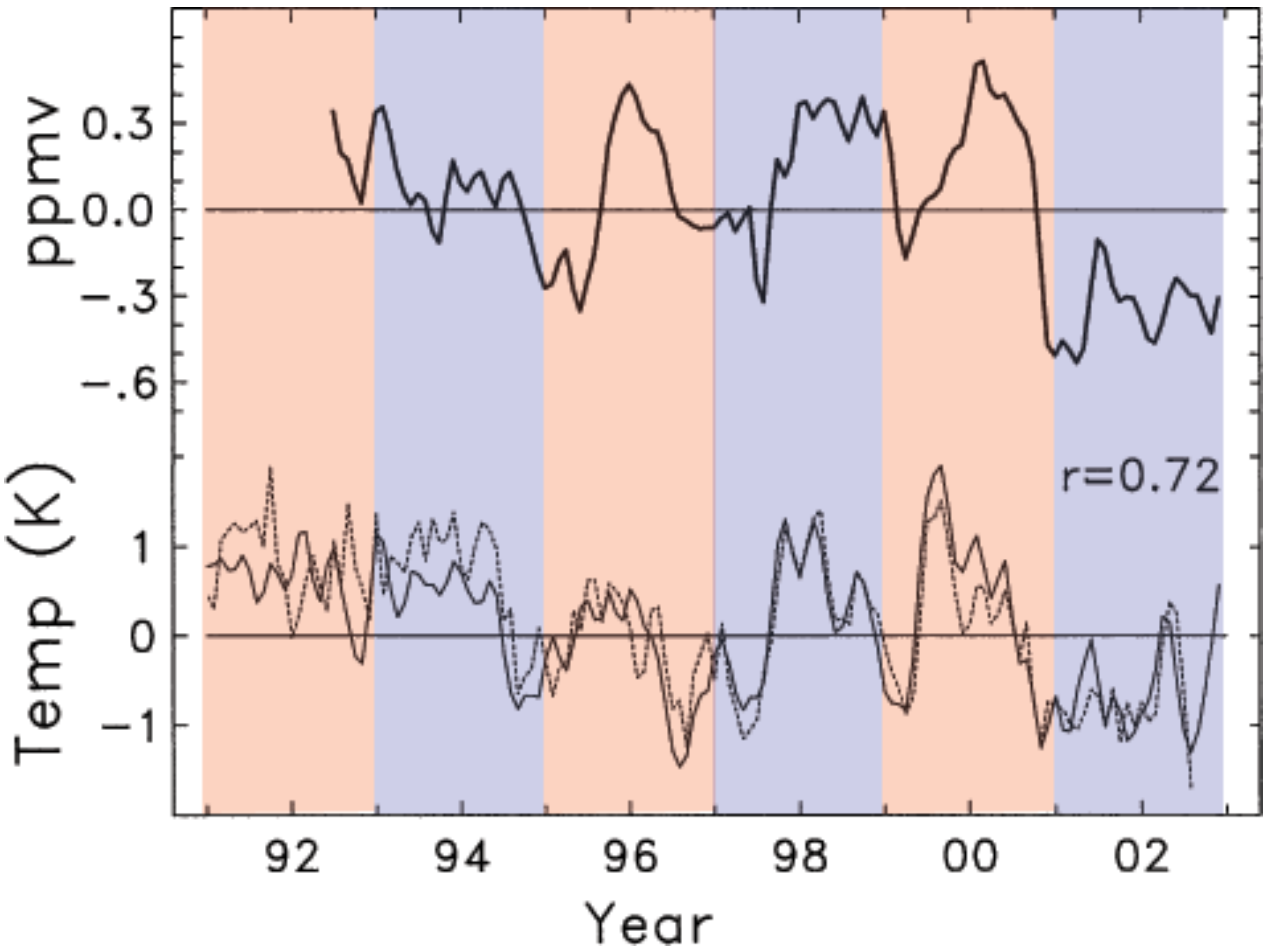


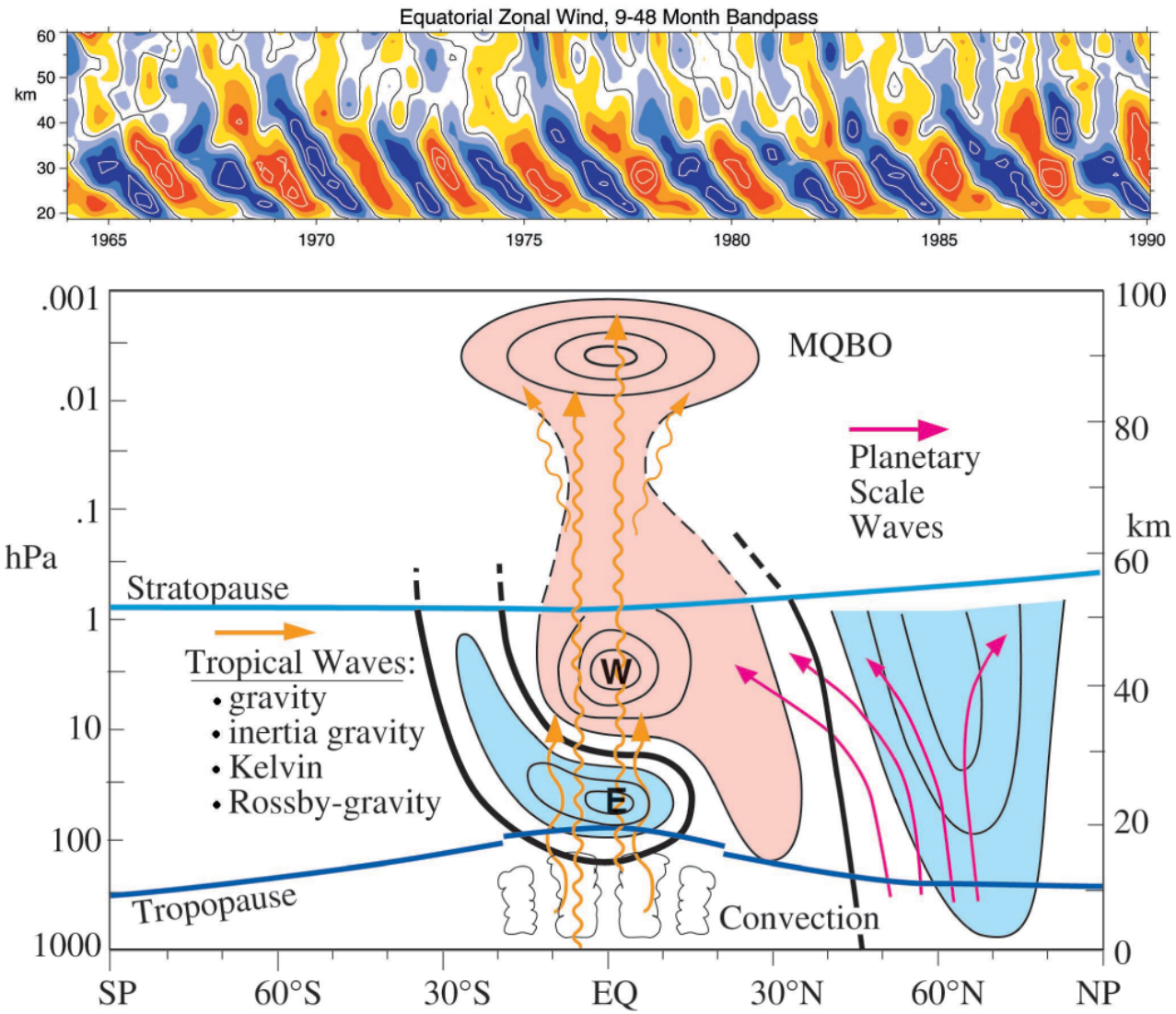
From *le Texier et al.* 1988

Each methane molecule that enters the stratosphere is converted into approximately two molecules of water vapor, gradually overwhelming the seasonal cycle.

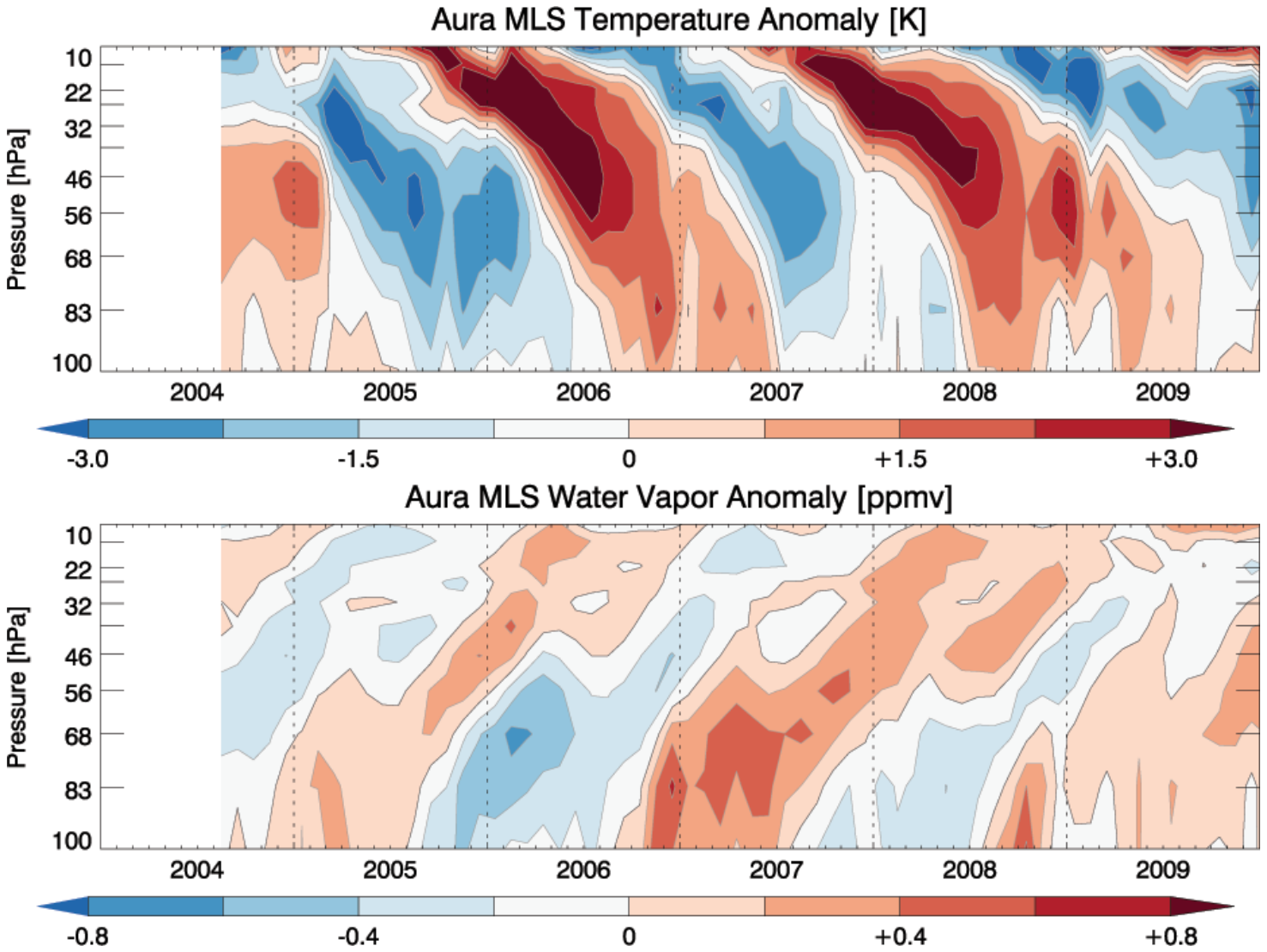
Deseasonalized stratospheric water vapor varies on an approximate two year cycle.

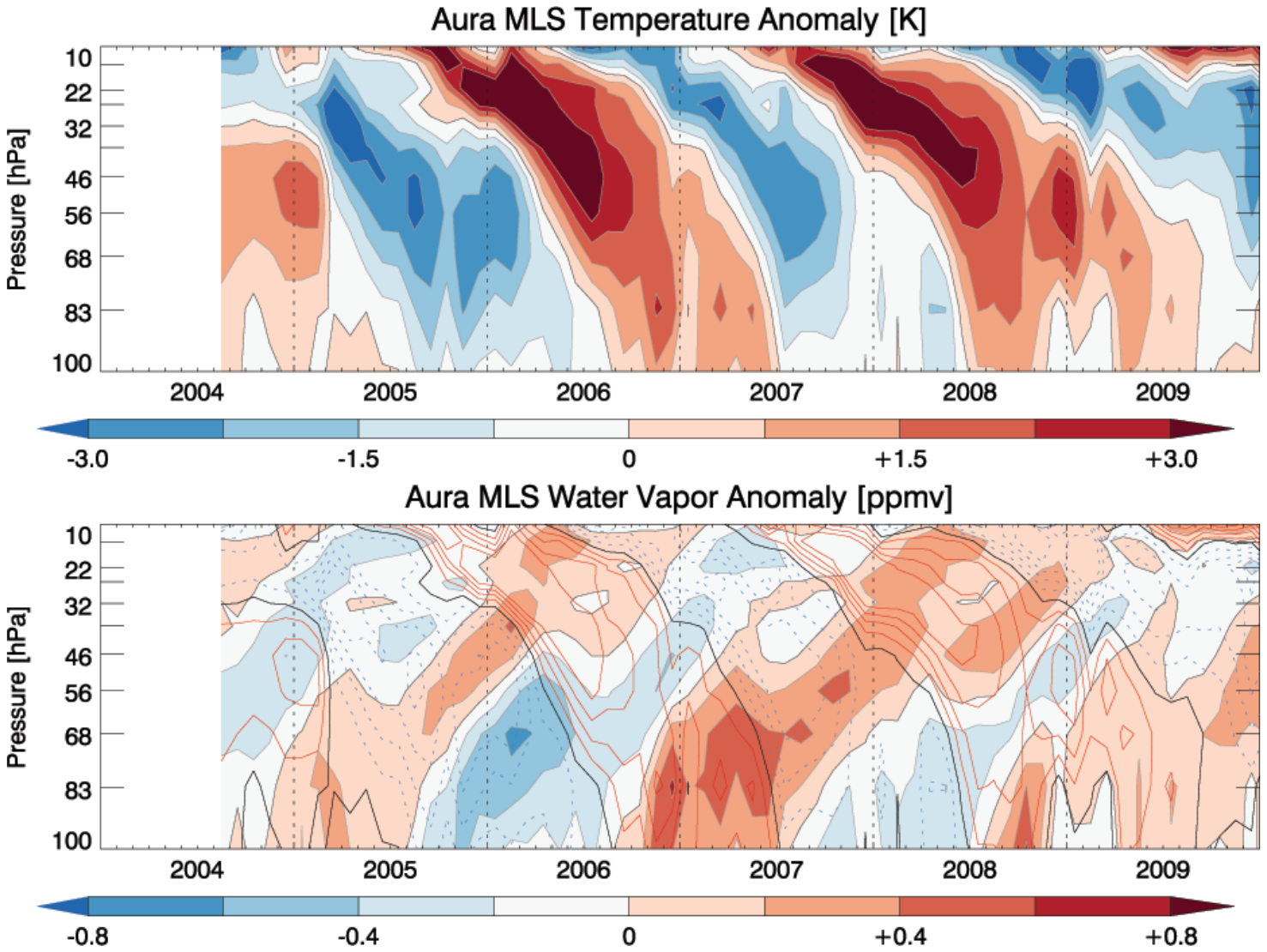


From *Randel et al.* 2004



From *Baldwin et al.* 2001


Aura MLS Temperature Anomaly [K]
Pressure [hPa]
10
22
32
46
56
68
83
100
2004
2005
2006
2007
2008
2009
-3.0
-1.5
0
+1.5
+3.0
Aura MLS Water Vapor Anomaly [ppmv]
Pressure [hPa]
10
22
32
46
56
68
83
100
2004
2005
2006
2007
2008
2009
-0.8
-0.4
0
+0.4
+0.8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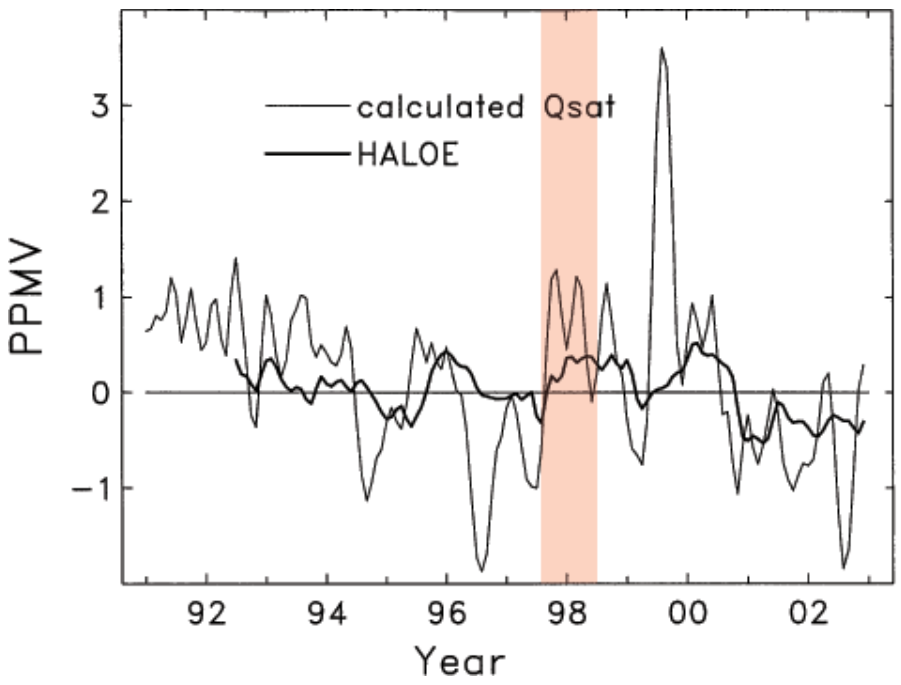
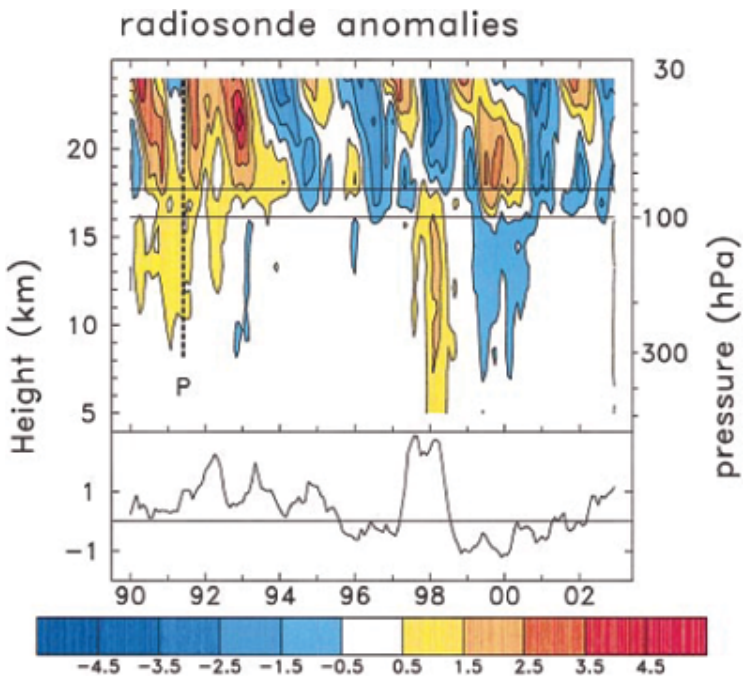
2007
2008
2009
-0.8
-0.4
0
+0.4
+0.8

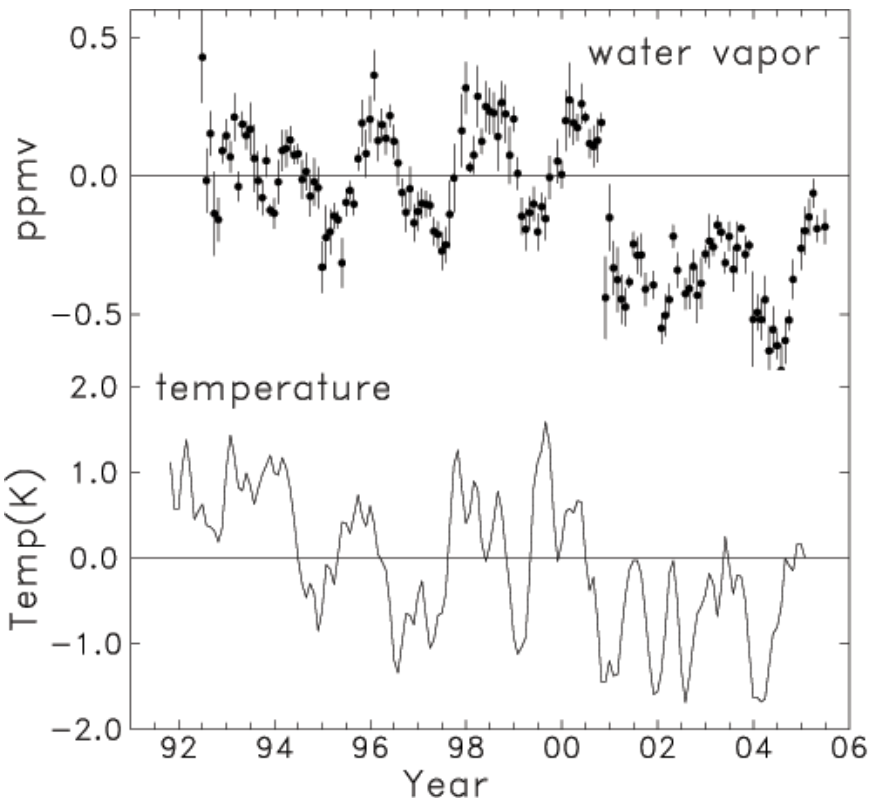
Strong ENSO fluctuations can also drive changes in tropical tropopause temperatures and stratospheric water vapor.

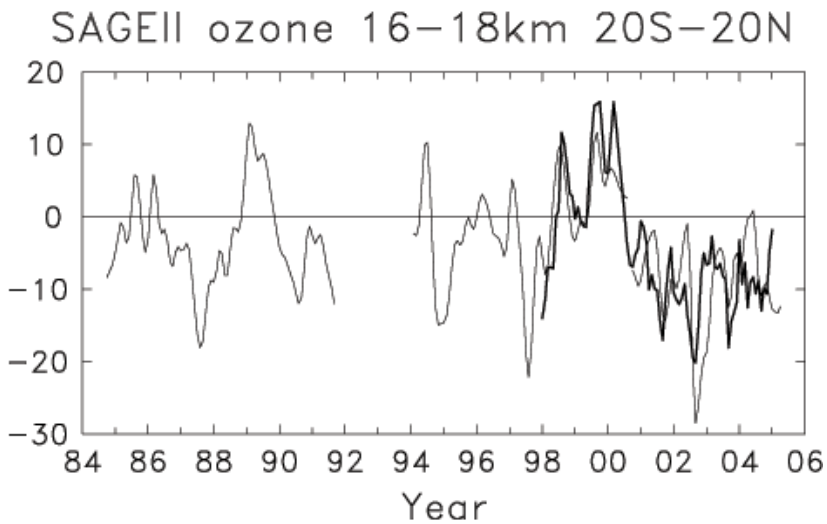




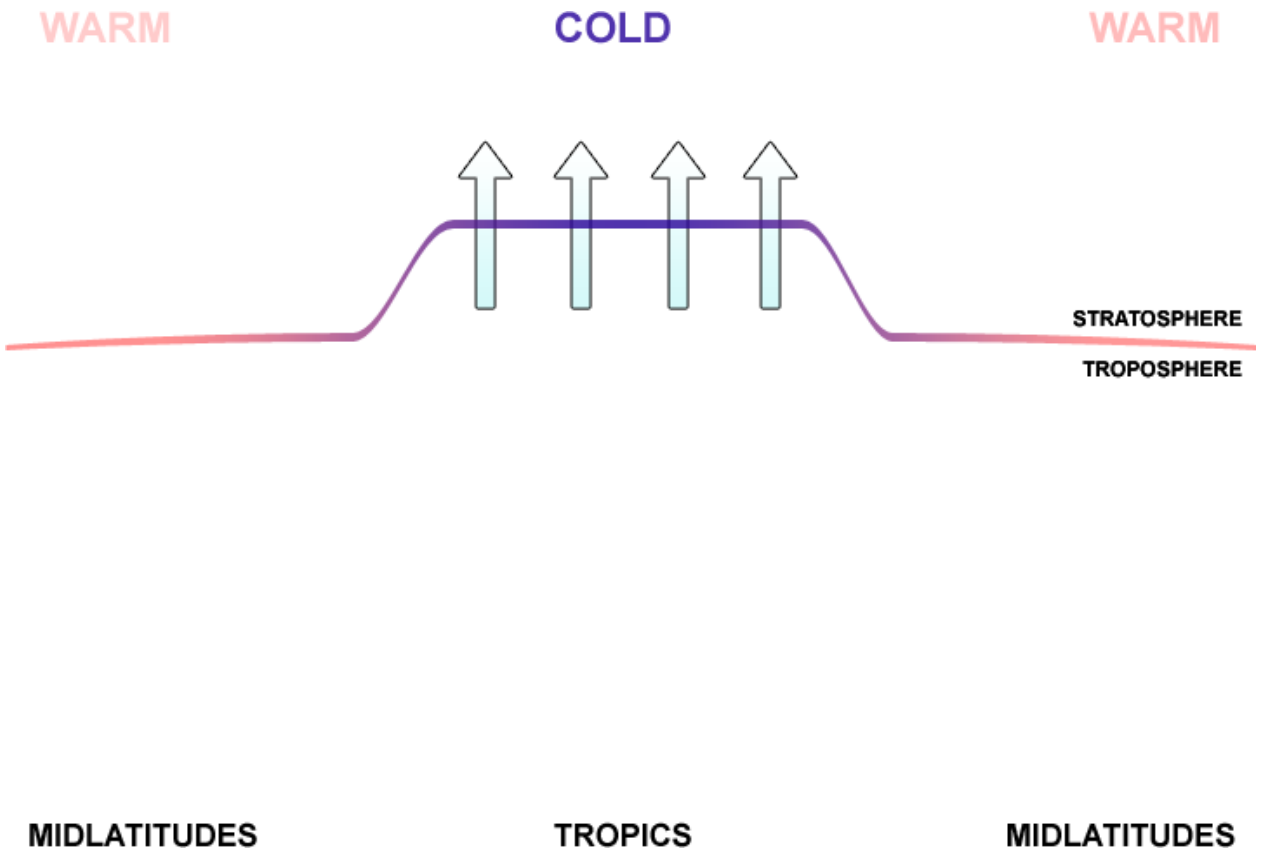
From *Randel et al.* 2004

Global stratospheric water vapor concentrations dropped abruptly in 2001, as did temperature and ozone in the tropics.

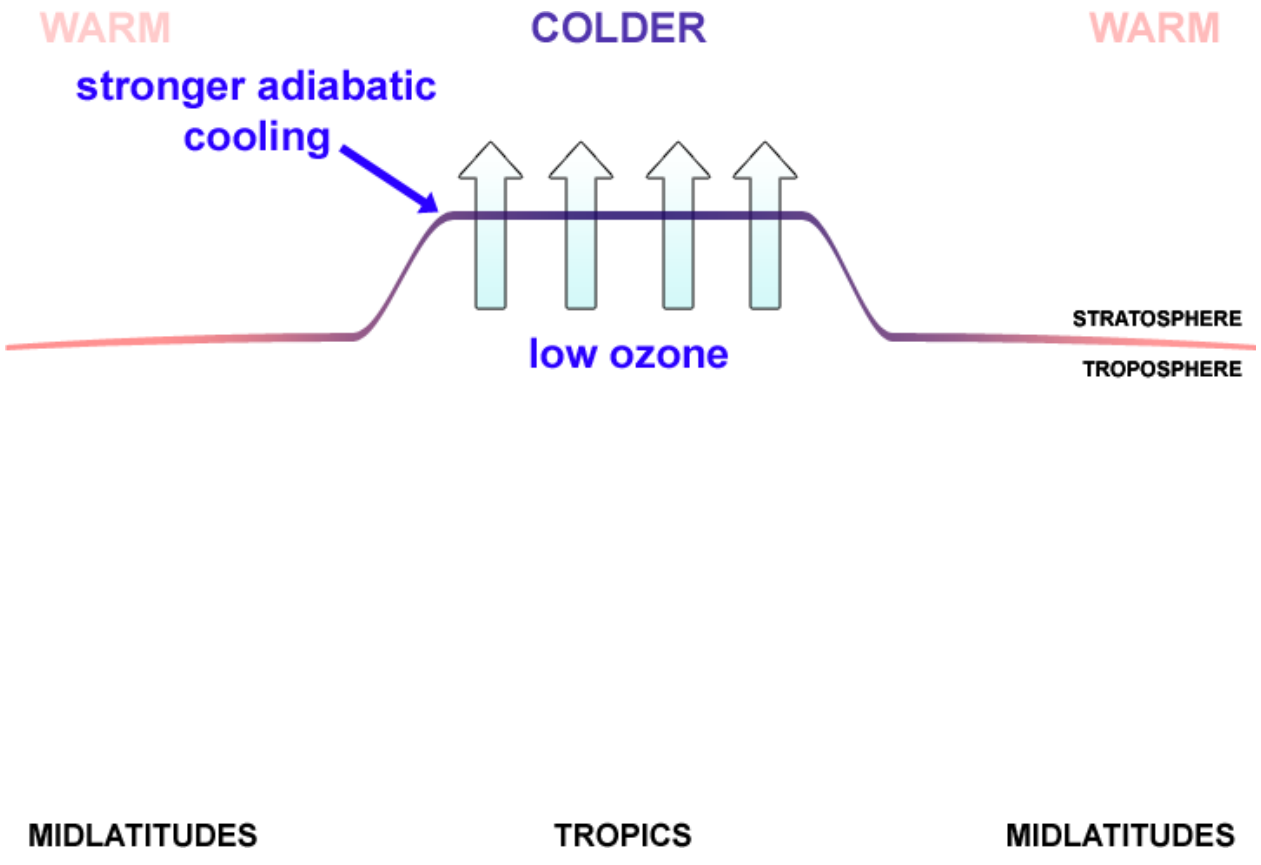




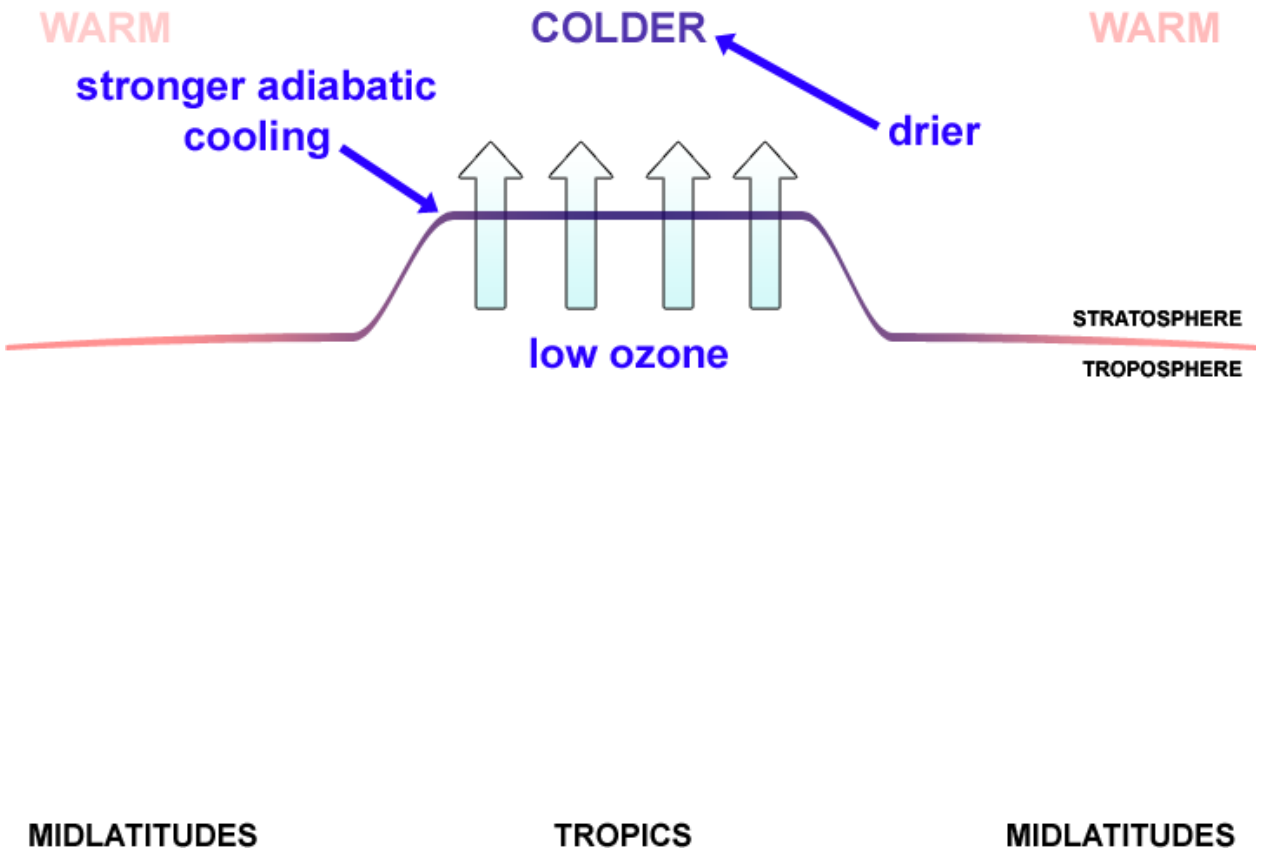
From *Randel et al.* 2006



All of these changes are consistent with an increase in upwelling at the tropical tropopause.

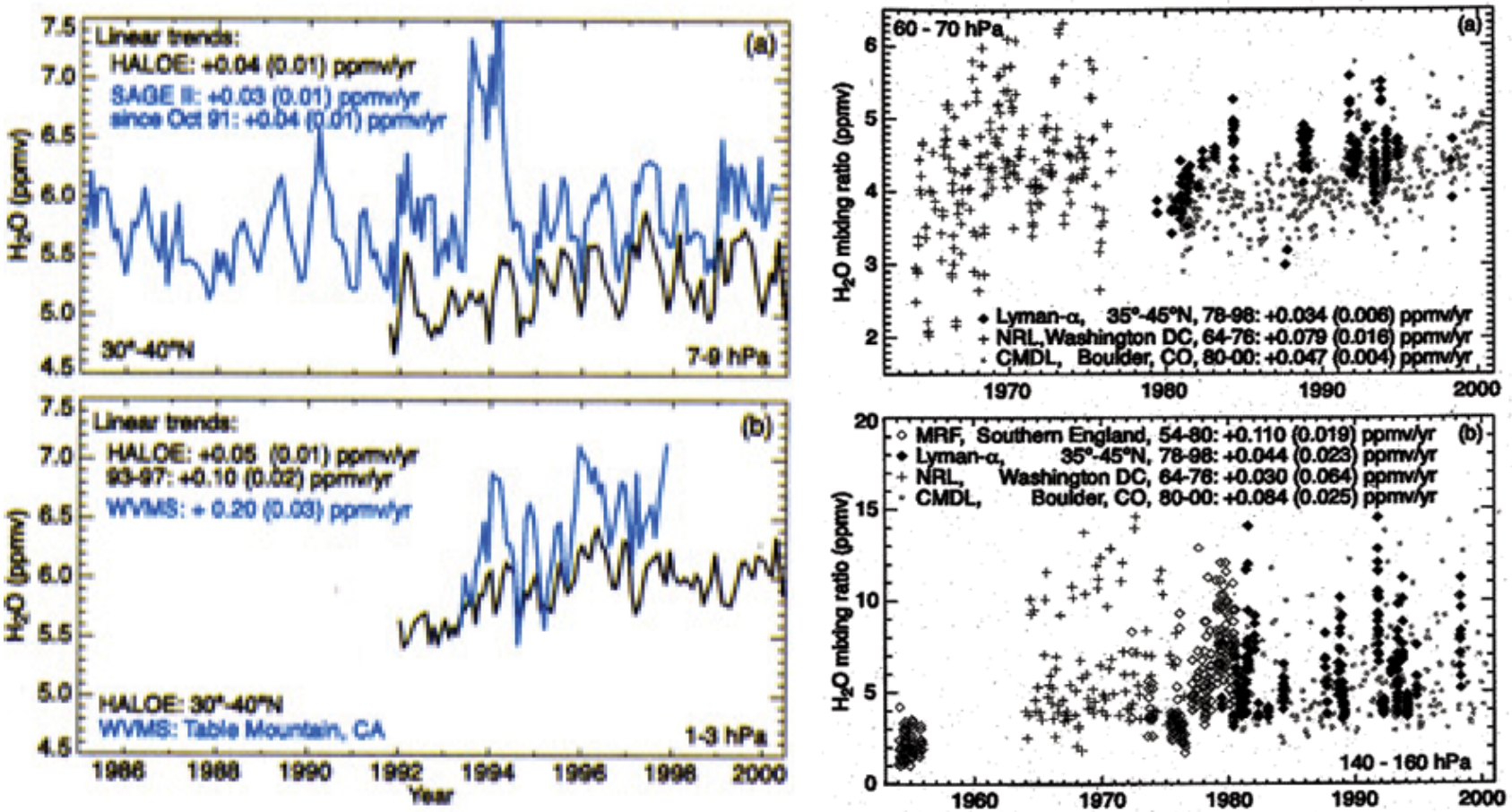


Enhanced upwelling at the tropical tropopause would lead to lower ozone and colder temperatures.



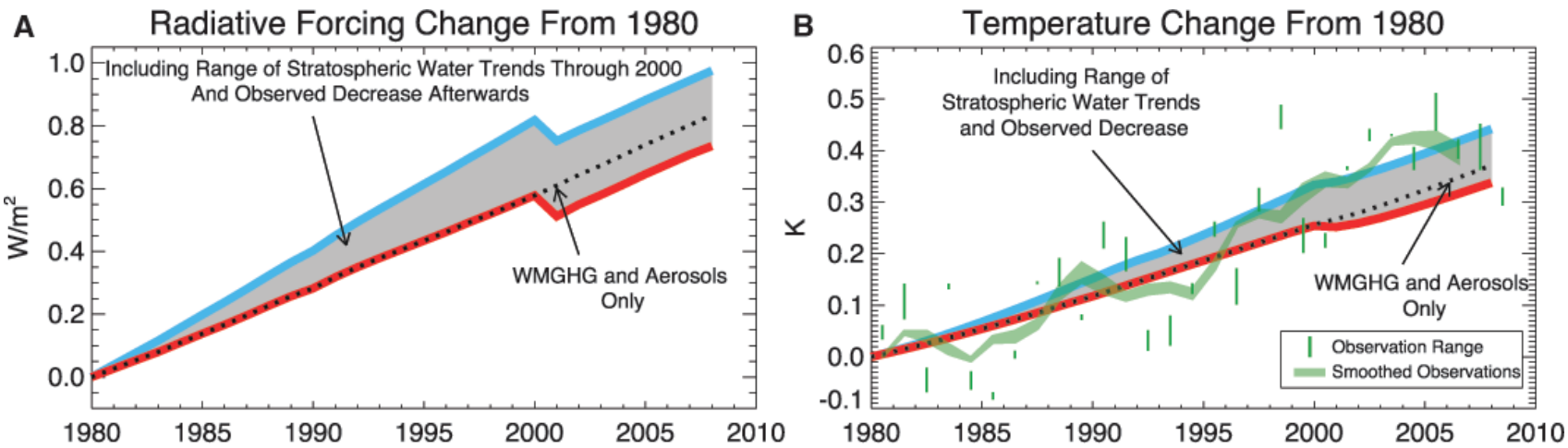
Colder tropopause temperatures should lead to lower water vapor concentrations in the stratosphere.

Stratospheric water vapor increased by $\sim$1% yr^{-1} from the 1950s to 2000. This trend is remarkably consistent across datasets.



From *Rosenlof et al.* 2001

Comparison of climate model output and observations indicates that the trend influenced stratospheric ozone, stratospheric temperature, and surface climate.



From *Solomon et al.* 2010

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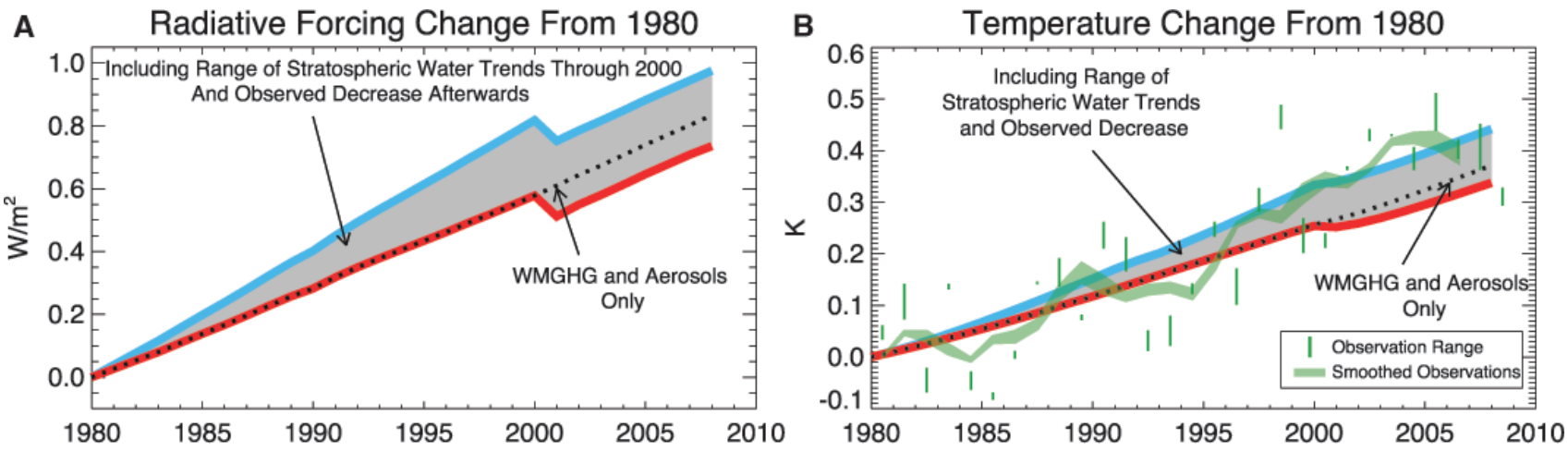

From *Solomon et al.* 2010

It could even be partially responsible for the plateau in global surface temperatures during the early 2000s.

The trend has yet to be fully accounted for:

Increases in methane can account for approximately half of the trend, but...

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2. Increases in aircraft emissions are too small;

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3. Transport pathways do not appear to have changed significantly;

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3. Transport pathways do not appear to have changed significantly;
4. Measurements of stable water isotopes indicate only minor changes in the transport of ice across the tropopause.

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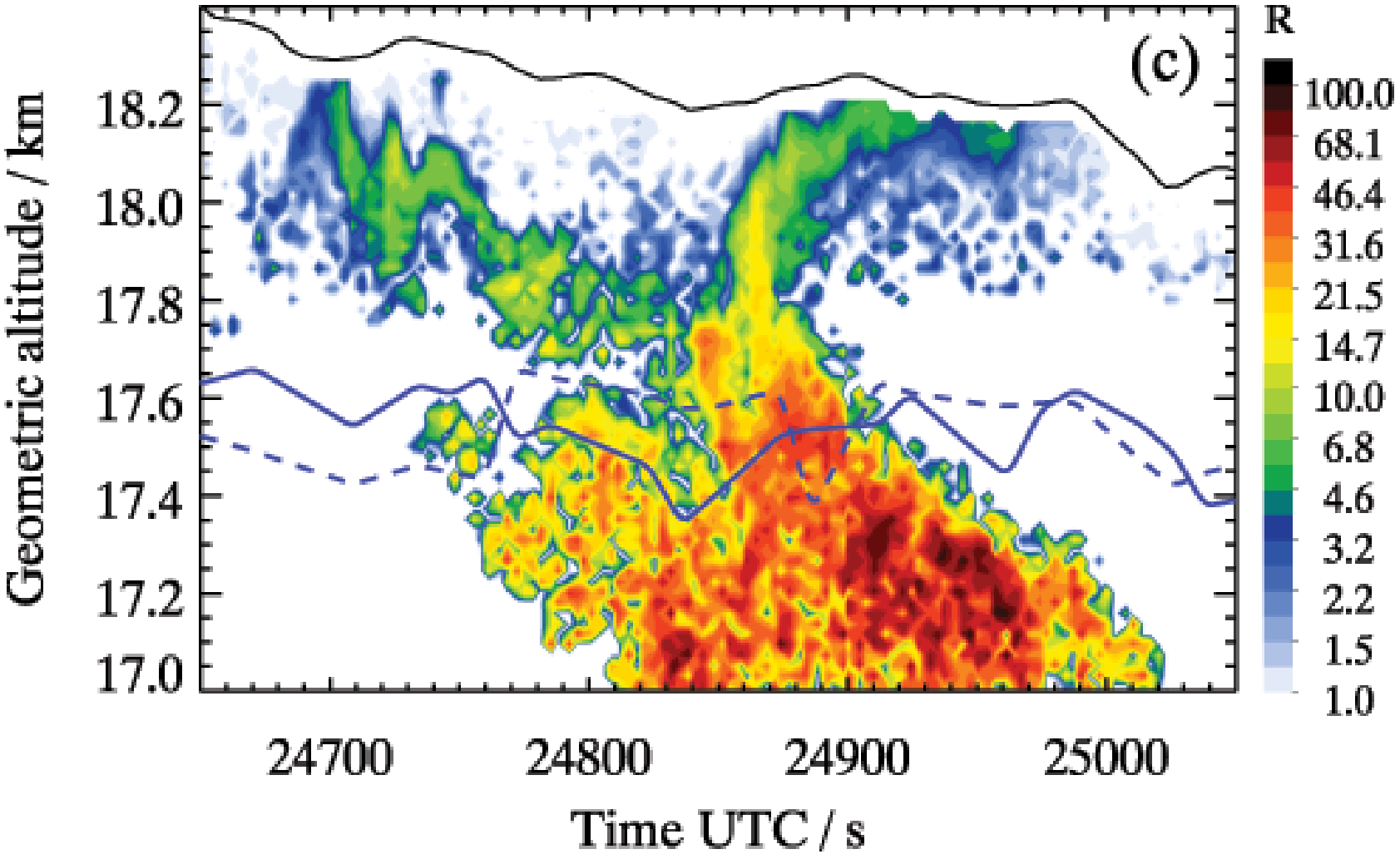
4. Measurements of stable water isotopes indicate only minor changes in the transport of ice across the tropopause.

This remains one of several unanswered questions regarding stratospheric water vapor.

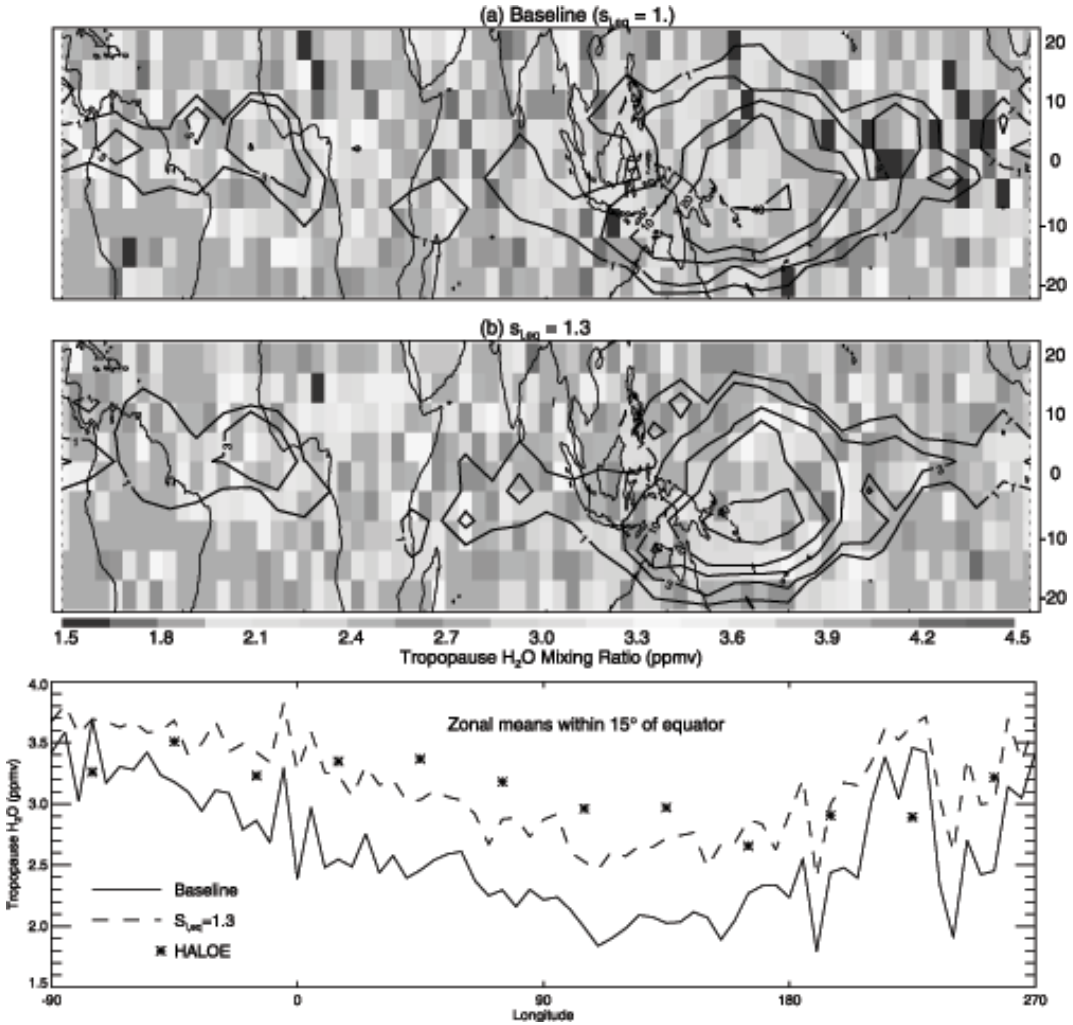
1. Do we really understand the role of convection?
2. What role do cirrus clouds play?
3. How "leaky" is the tropical pipe?
4. How will stratospheric water vapor change in the future?
5. How can we improve observations?

1 Do we really understand the role of convection?



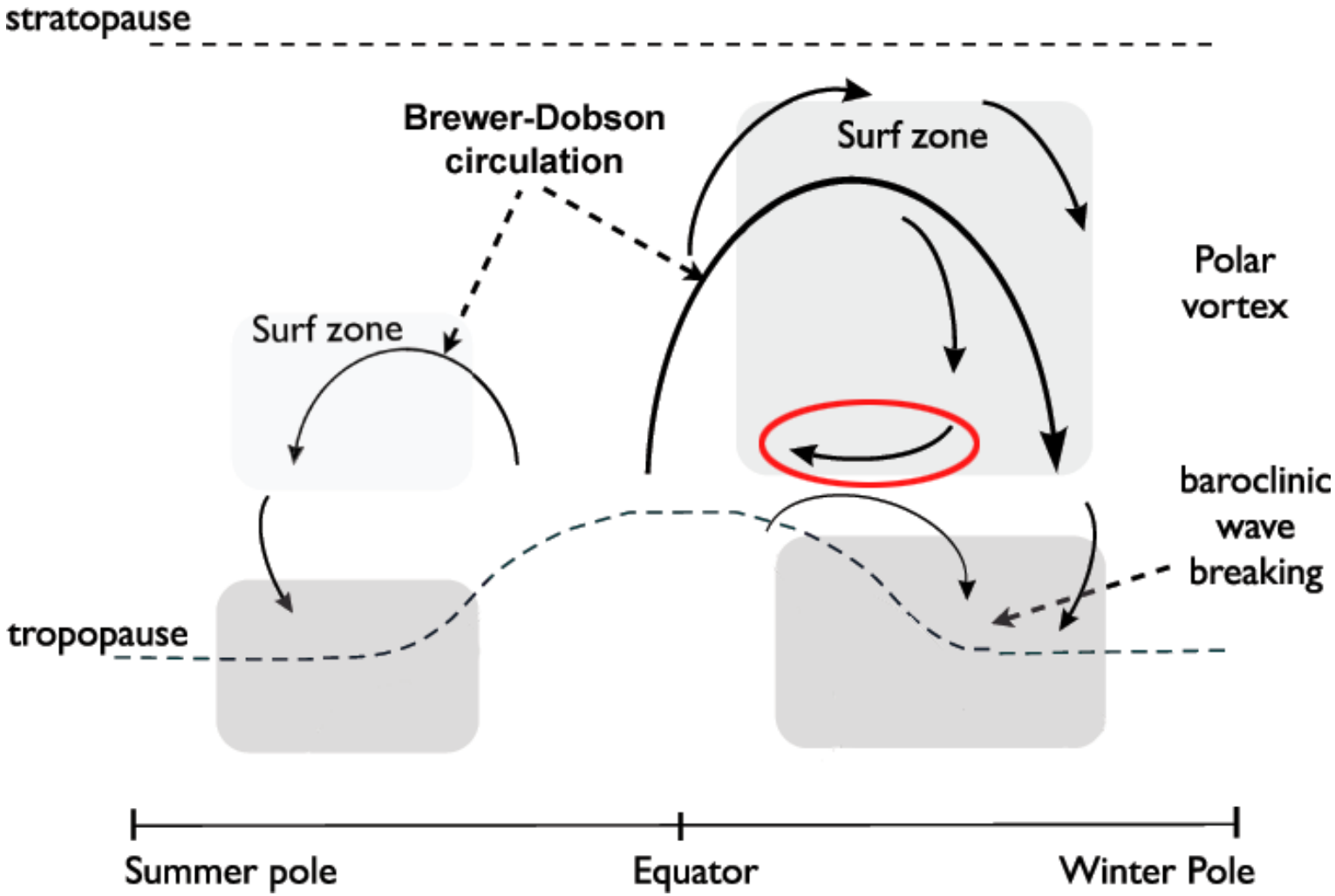
From *Corti et al.* 2008

2 What role do cirrus cloud processes play?



From *Jensen and Pfister* 2005

3 How "leaky" is the tropical pipe?



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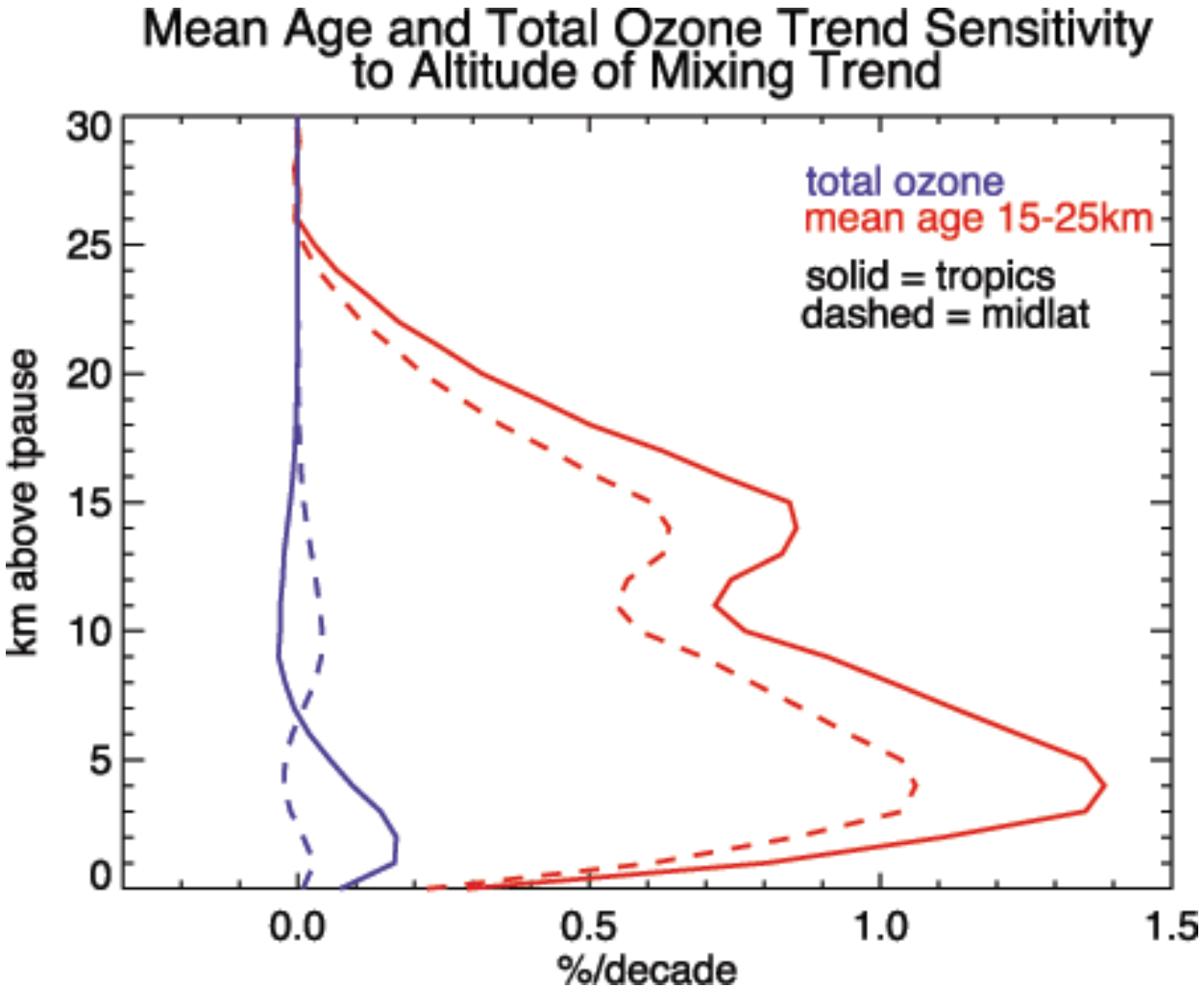
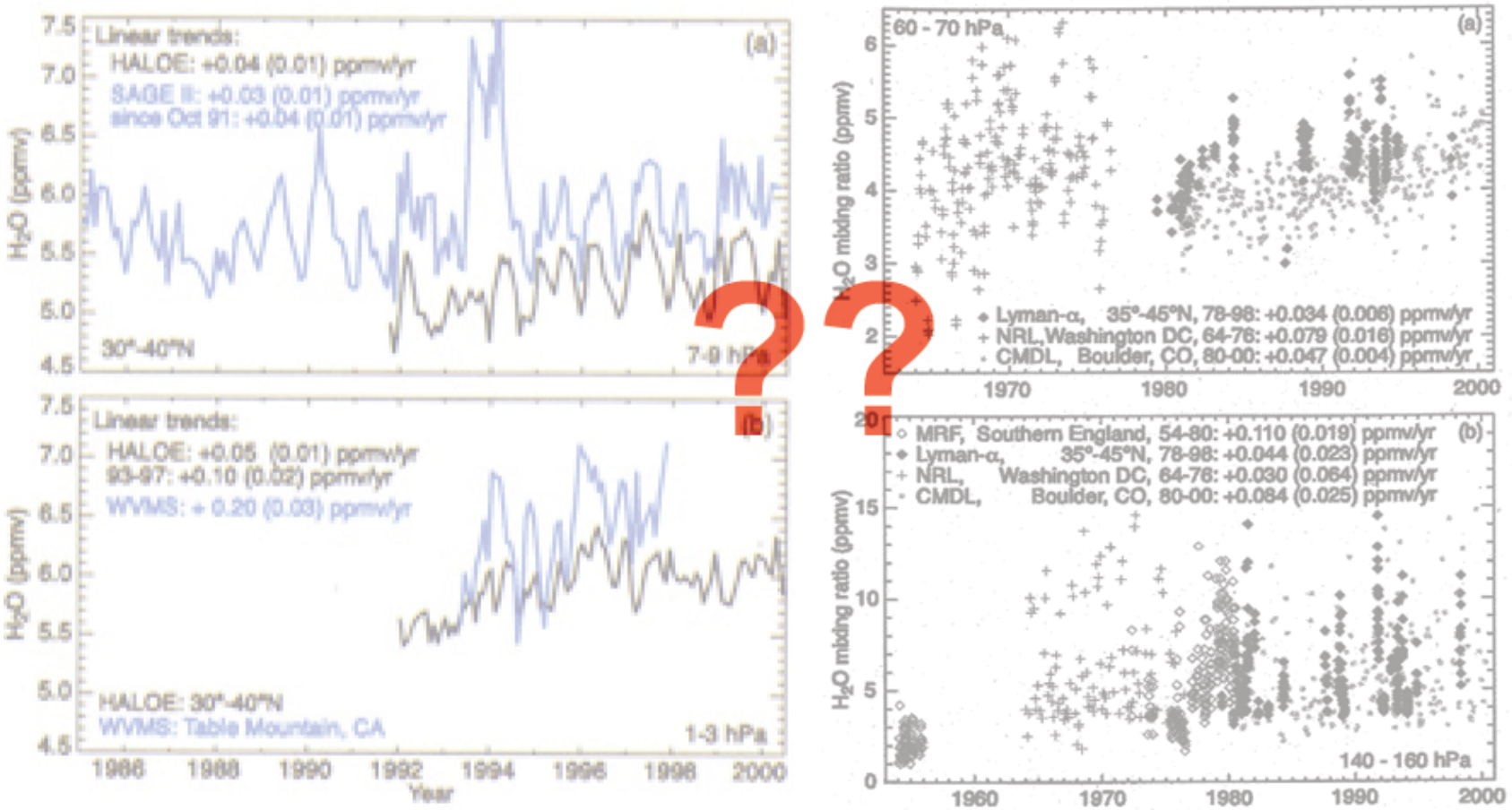


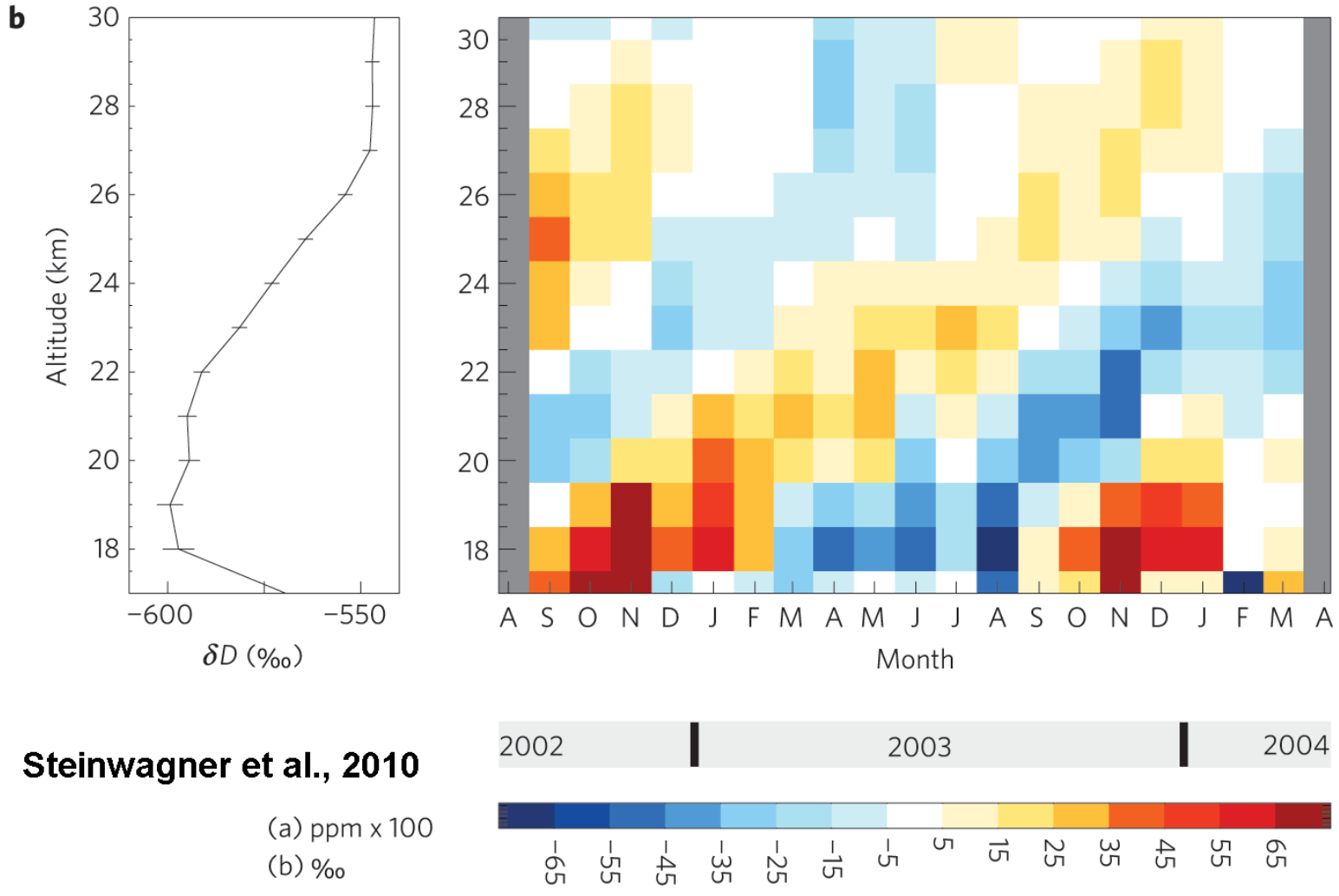
From *Ray et al.* 2010

4 How will stratospheric water vapor change in the future?



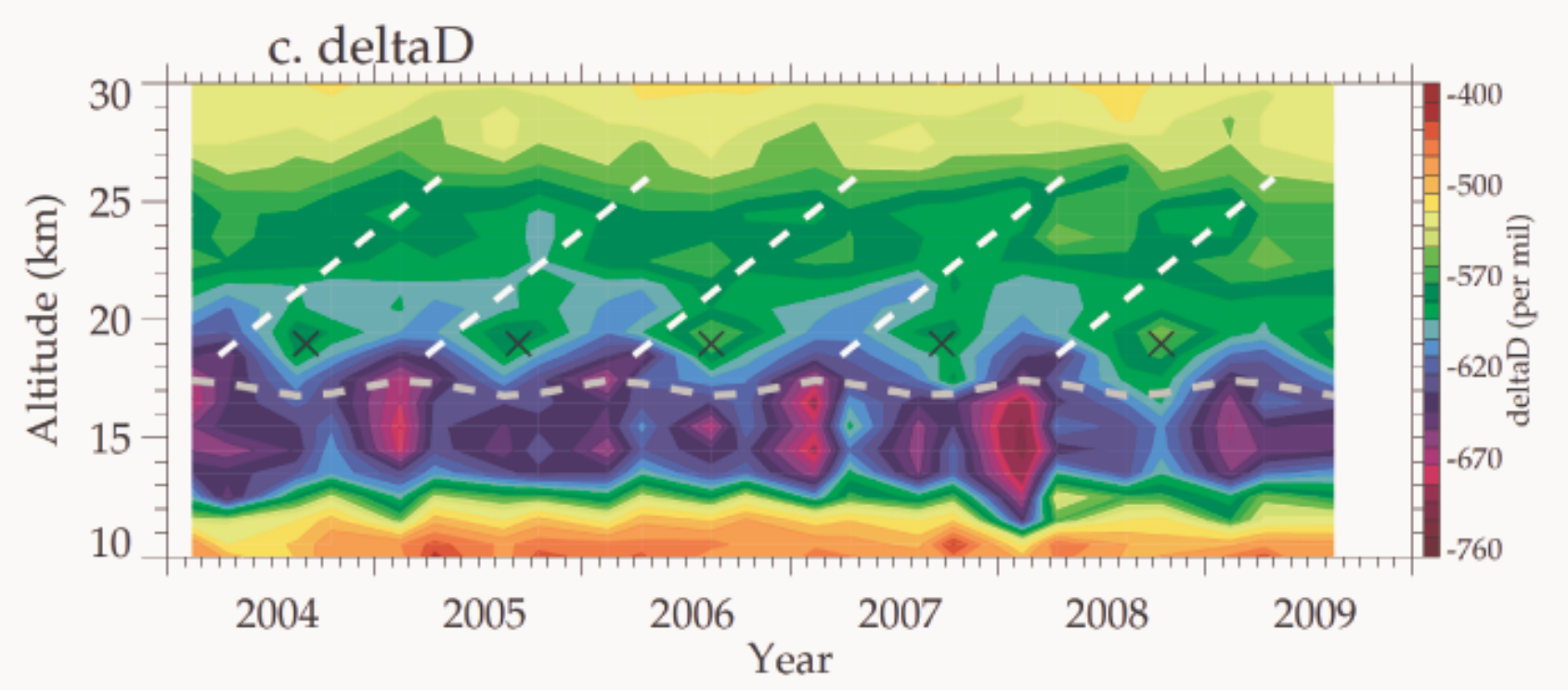
From *Rosenlof et al.* 2001

5 How can we improve observations?



From *Steinwagner et al.* 2010

5 How can we improve observations?



From *Randel et al.* 2012

One satellite (MIPAS) sees a tape recorder in delta-HDO, while another (ACE–FTS) does not.

1. **Do we really understand the role of convection?**
2. **What role do cirrus clouds play?**
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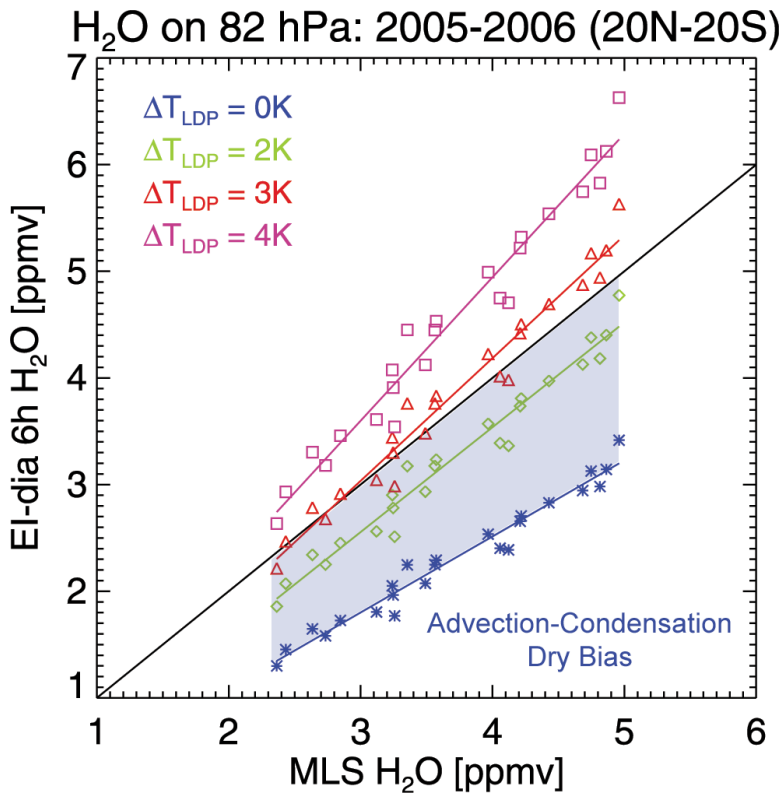
Advection-Condensation is Biased Dry

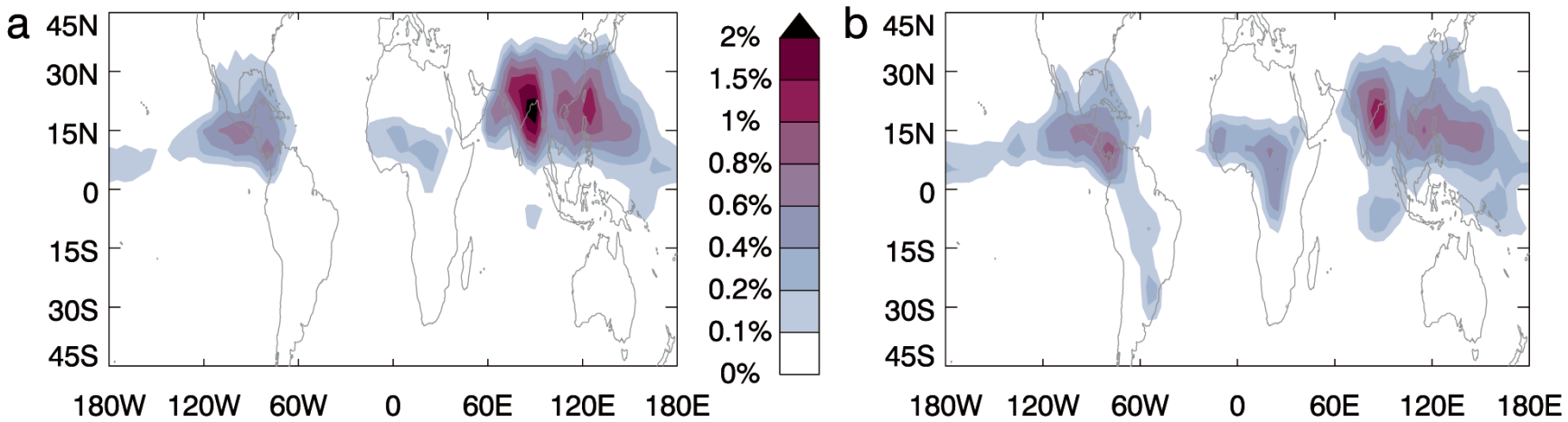
Recent results indicate that advection-condensation simulations of water vapor transport into the tropical lower stratosphere are biased dry, especially during boreal summer.



From *Liu et al.* 2010

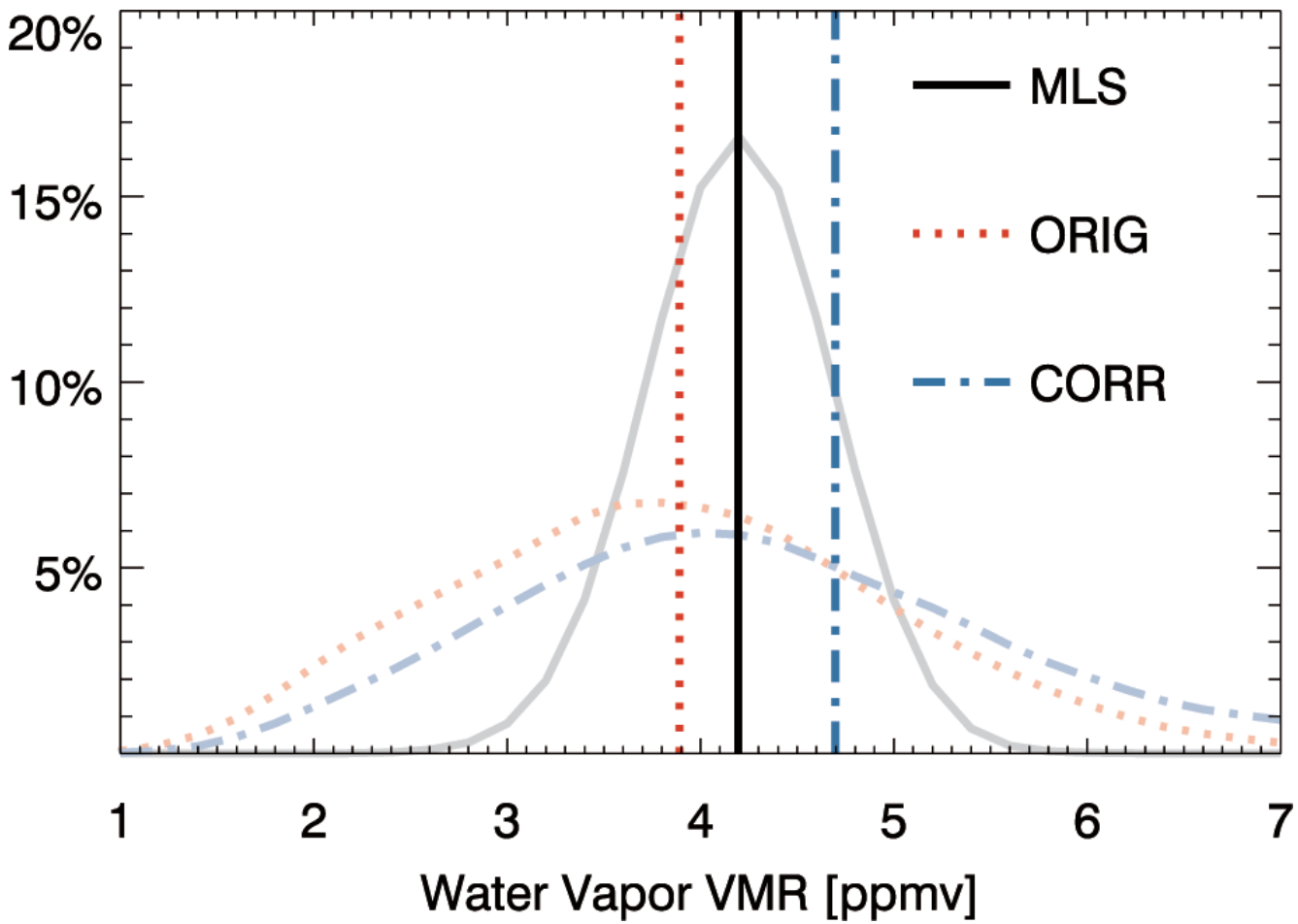
Biases in Cloud Top Height

Estimates of cloud top height using 11µm brightness temperatures tend to be biased low (Sherwood et al., 2004; Minnis et al., 2008). Adjusting cloud tops upwards affects the distribution of convective sources to the LS within the global tropics.



Biases in Cloud Top Height

These biases affect simulated water vapor transport.

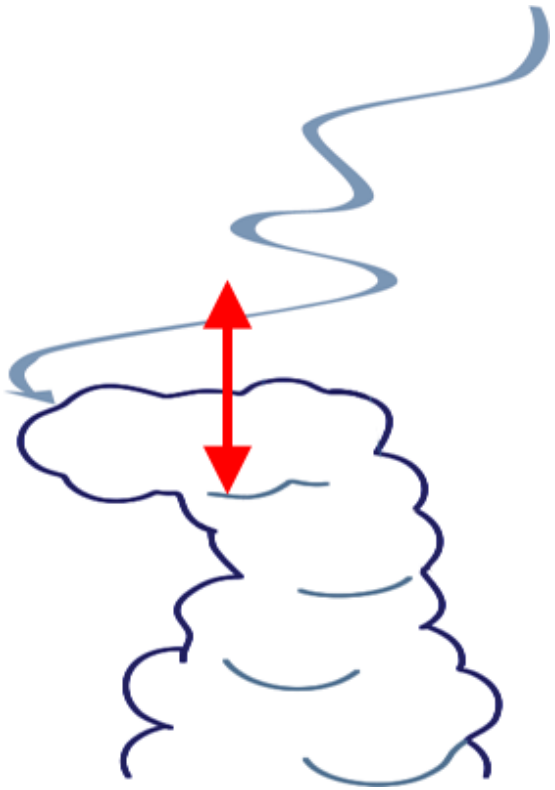


Experimental design

Identify the transport of water vapor into the tropical lower stratosphere according to the advection-condensation paradigm – then add various cloud processes.

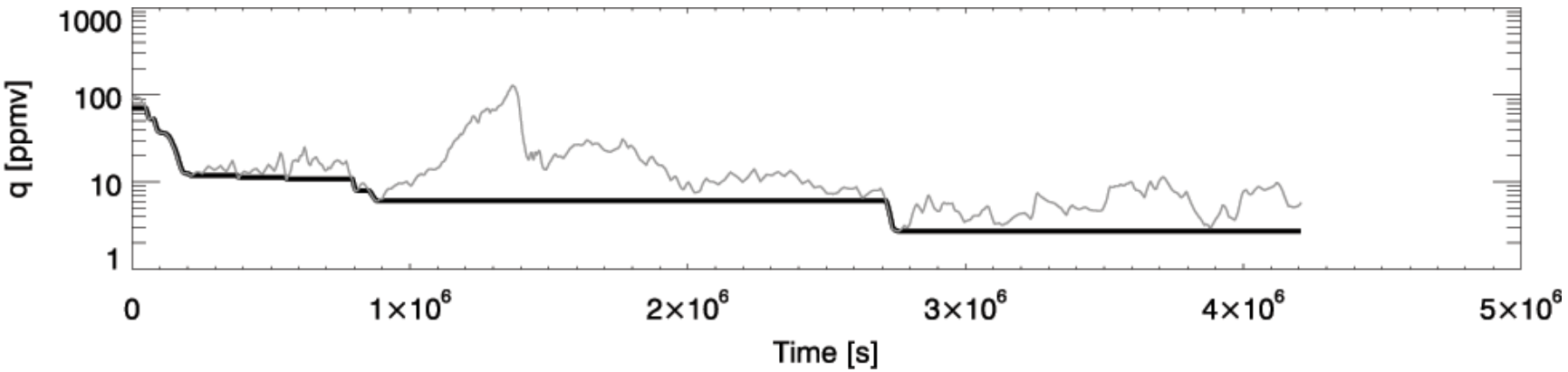
Experimental design

Evaluate whether biases in convective detrainment height may contribute to the dry bias by misidentifying convective source regions or by supplying anvil ice directly to the LS.



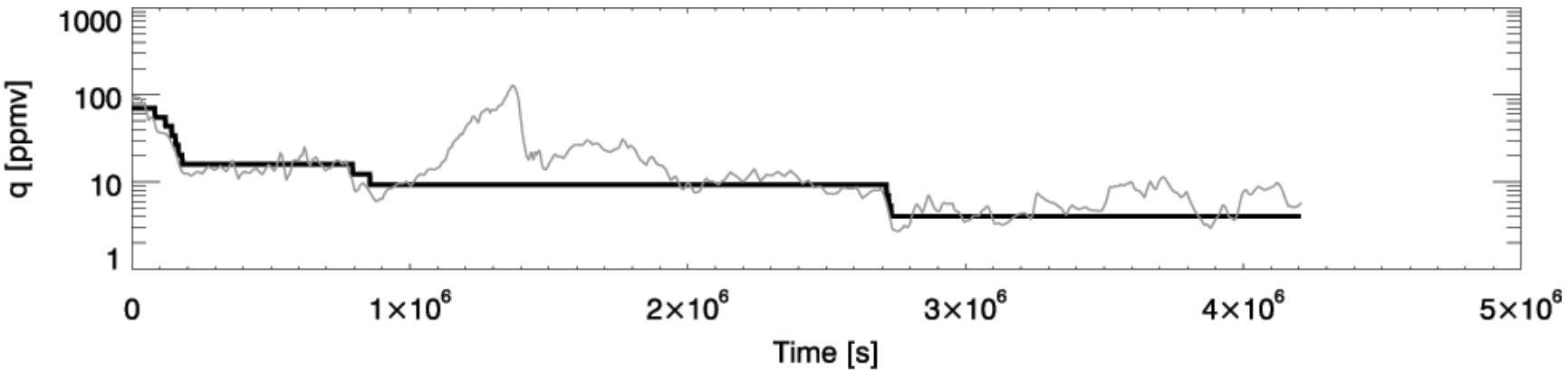
Advection-condensation (ADVCON)

Condensation/deposition occurs at 100%RH with respect to ice, and all condensate falls out immediately.



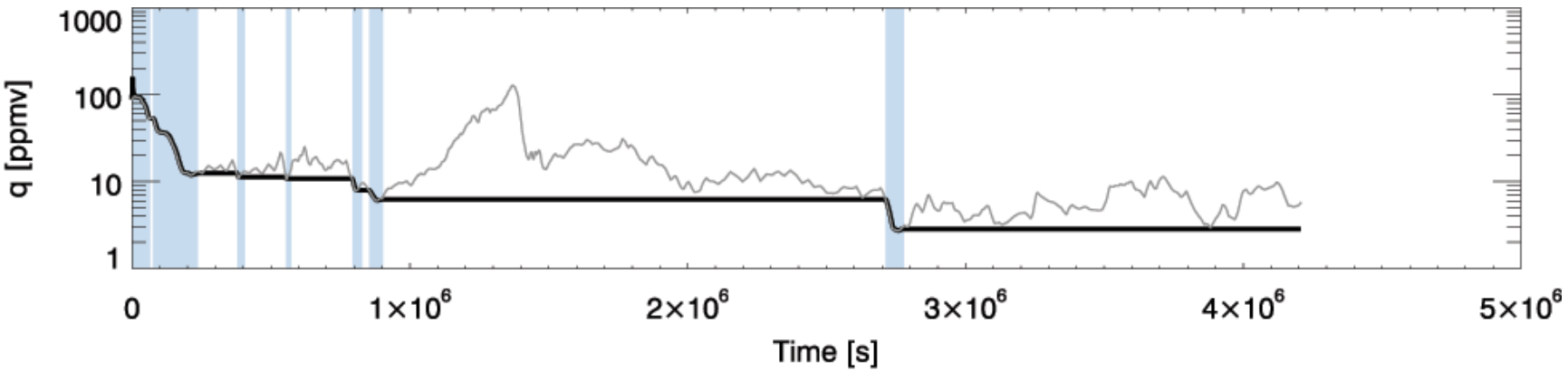
Parameterized supersaturation (SUPSAT)

Condensation occurs at a temperature-dependent threshold supersaturation (Kärcher et al., 2002). All condensate falls out.



Parameterized cirrus clouds (CIRRUS)

Condensation/deposition occurs at 100%RH with respect to ice, but condensate falls out over time and may re-evaporate.



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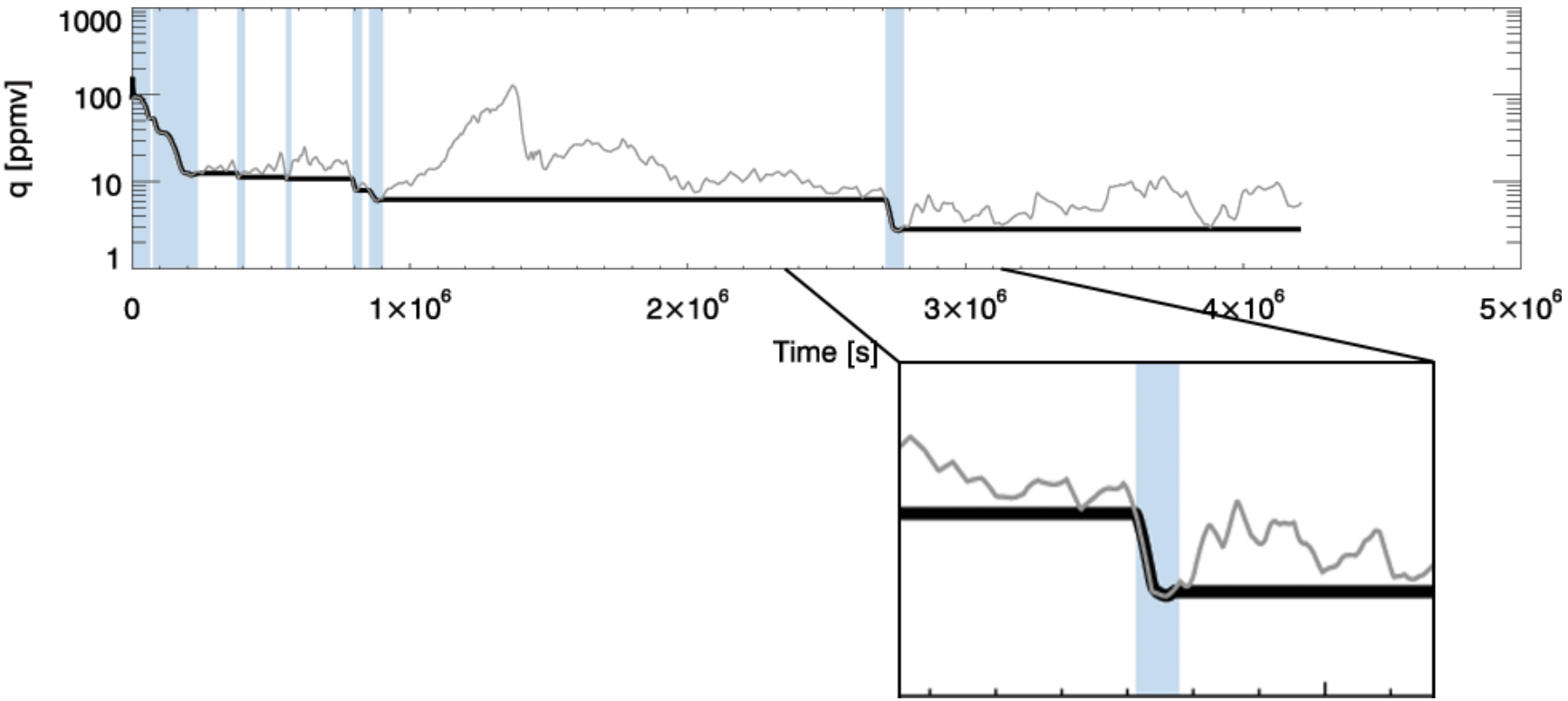
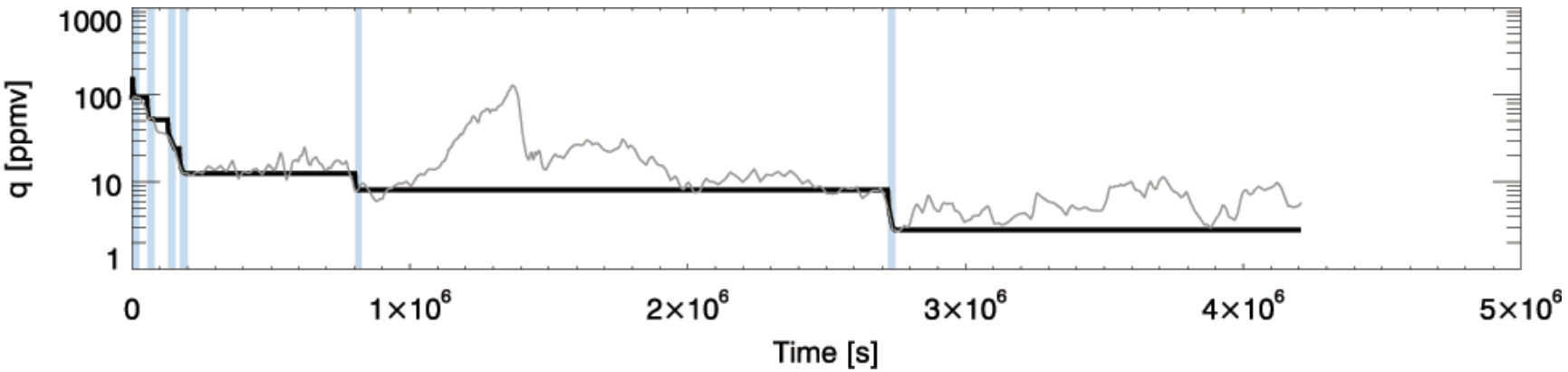
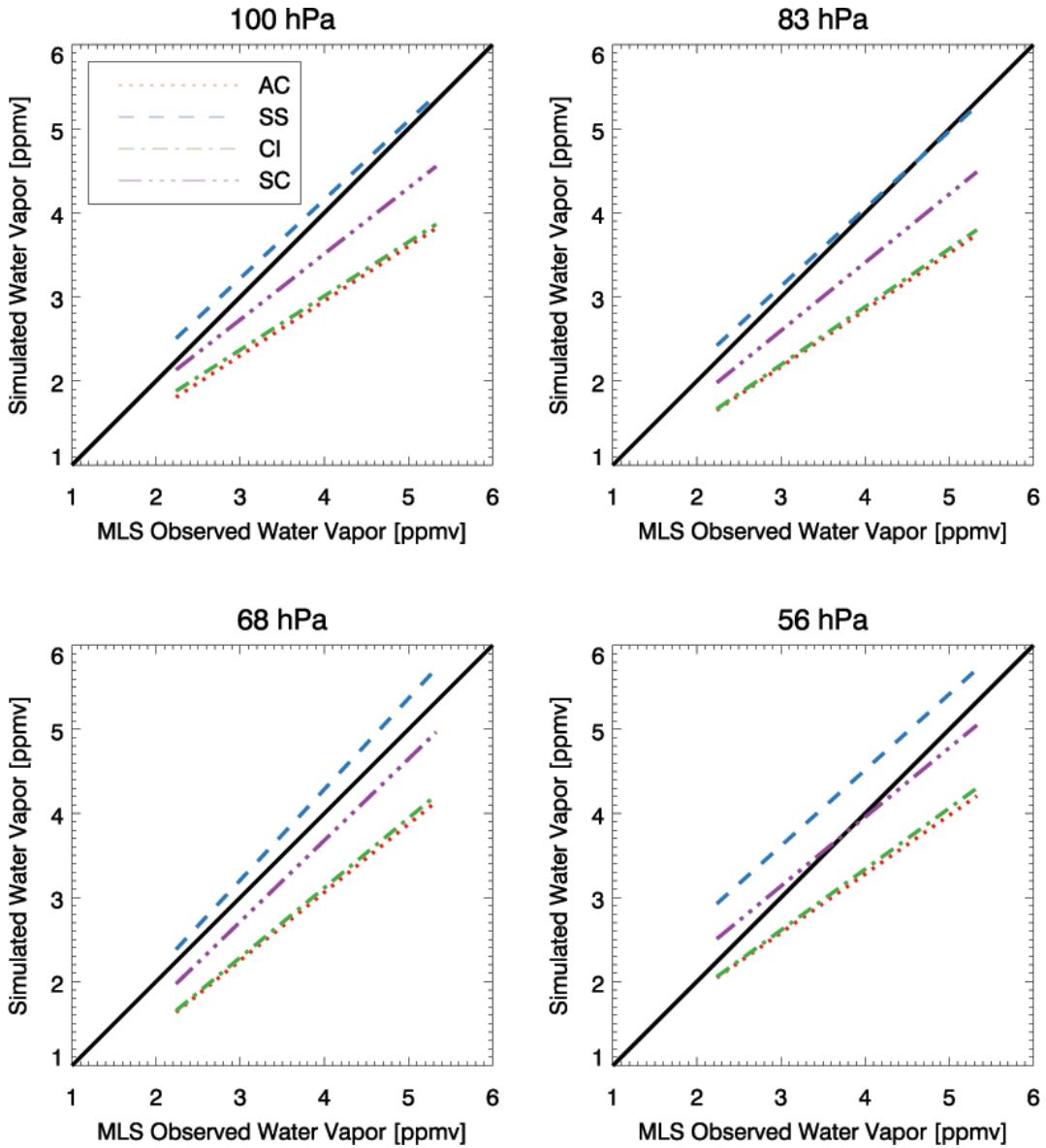
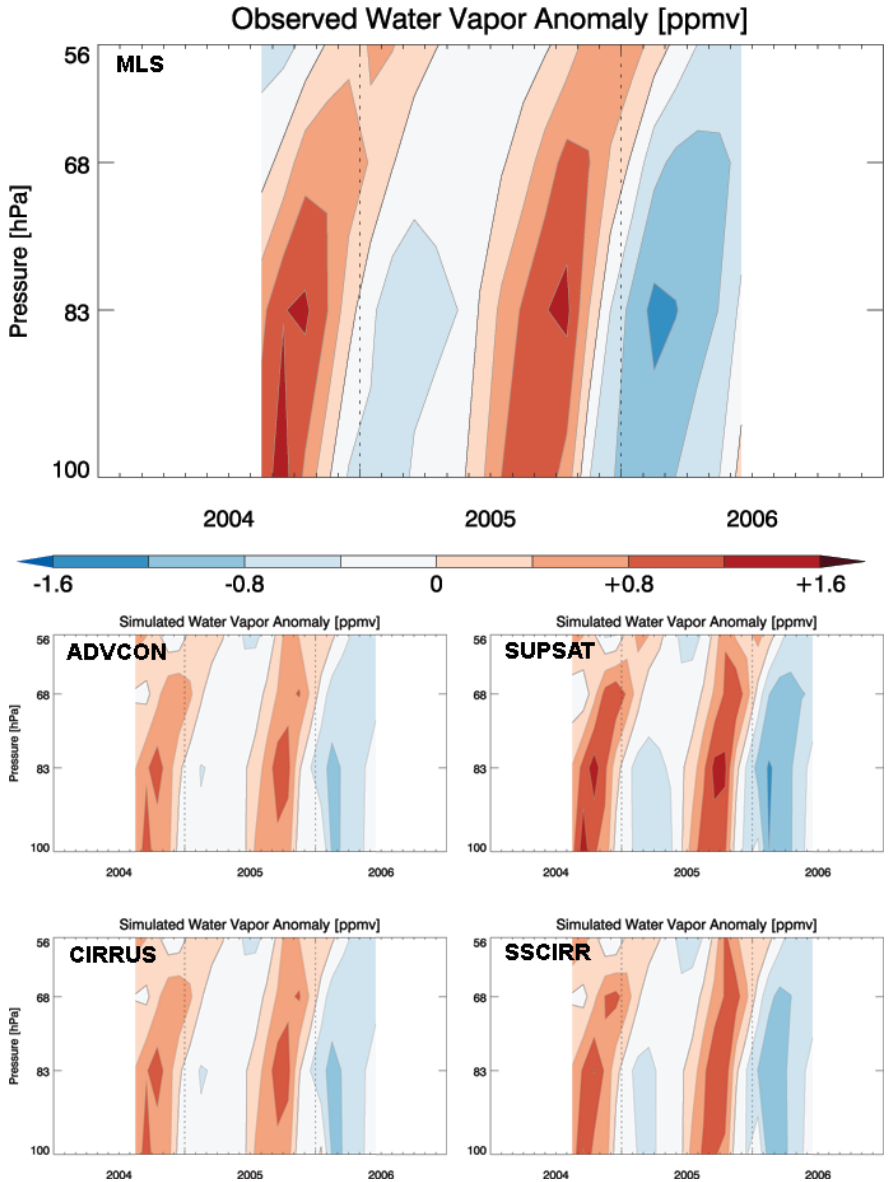


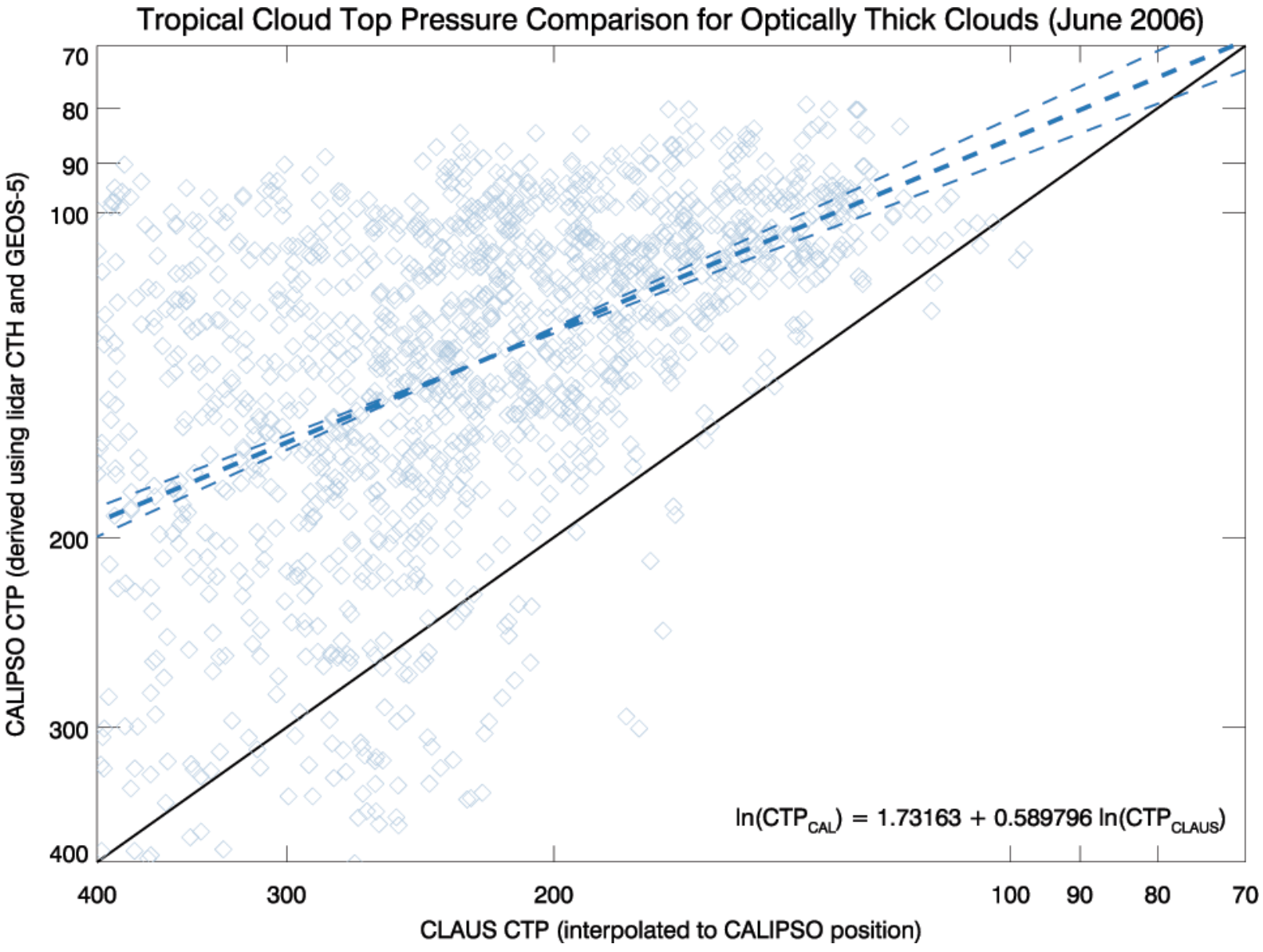
Parameterized supersaturation and cirrus clouds (SSCIRR)

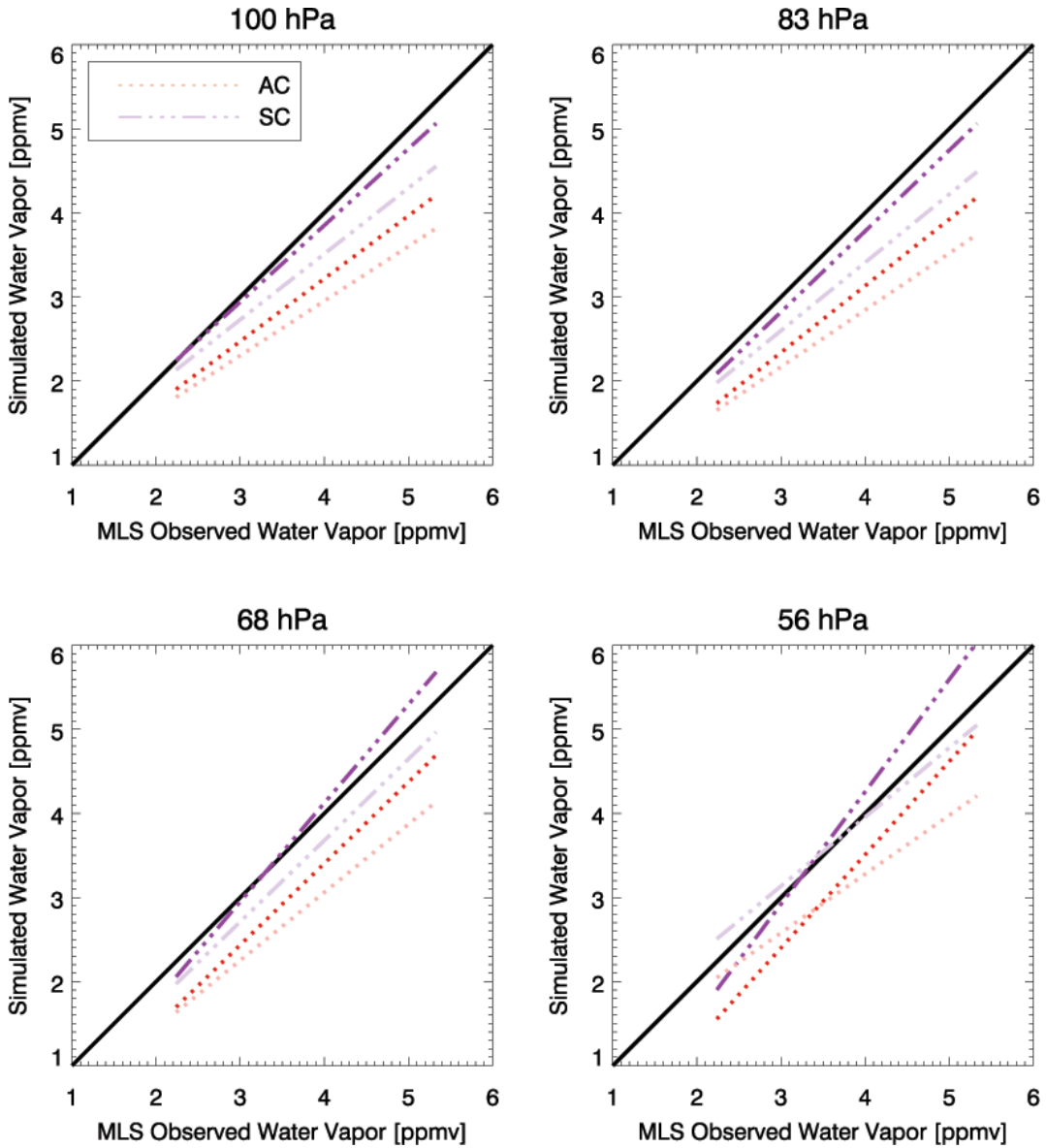
Condensation/deposition occurs at a threshold supersaturation.
Condensate falls out over time and may re-evaporate.




100 hPa
AC
SS
CI
SC
Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]
83 hPa
Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]
68 hPa
Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]
56 hPa
Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]


Observed Water Vapor Anomaly [ppmv]
MLS
Pressure [hPa]
56
68
83
100
2004
2005
2006
-1.6
-0.8
0
+0.8
+1.6
Simulated Water Vapor Anomaly [ppmv]
ADVCON
SUPSAT
CIRRUS
SSCIRR


Tropical Cloud Top Pressure Comparison for Optically Thick Clouds (June 2006)
CALIPSO CTP (derived using lidar CTH and GEOS-5)
70
80
90
100
200
300
400
ln(CTP_CAL) = 1.73163 + 0.589796 ln(CTP_CLAUS)
400
300
200
100
90
80
70
CLAUS CTP (interpolated to CALIPSO position)


100 hPa
AC
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Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]
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Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]
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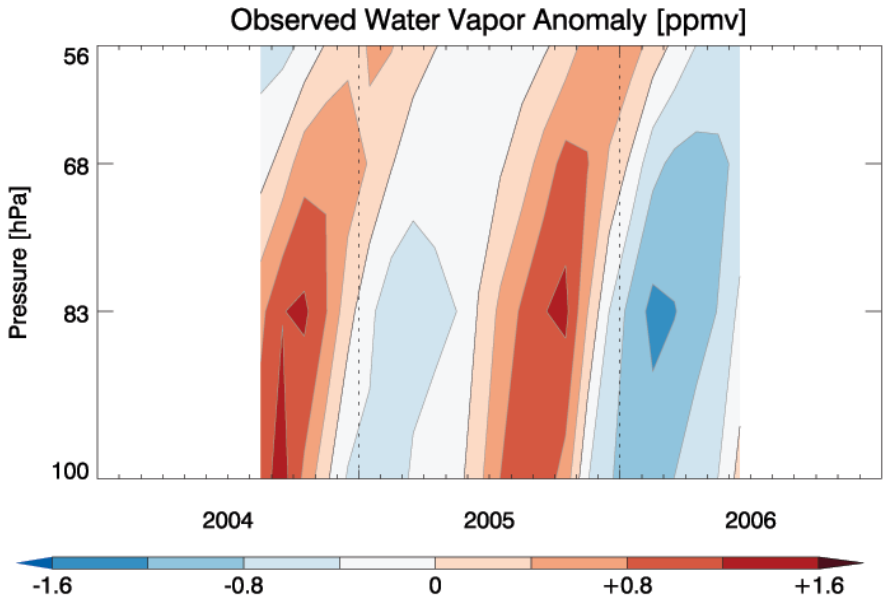
Simulated Water Vapor [ppmv]
MLS Observed Water Vapor [ppmv]


Observed Water Vapor Anomaly [ppmv]
Pressure [hPa]
56
68
83
100
2004
2005
2006
-1.6
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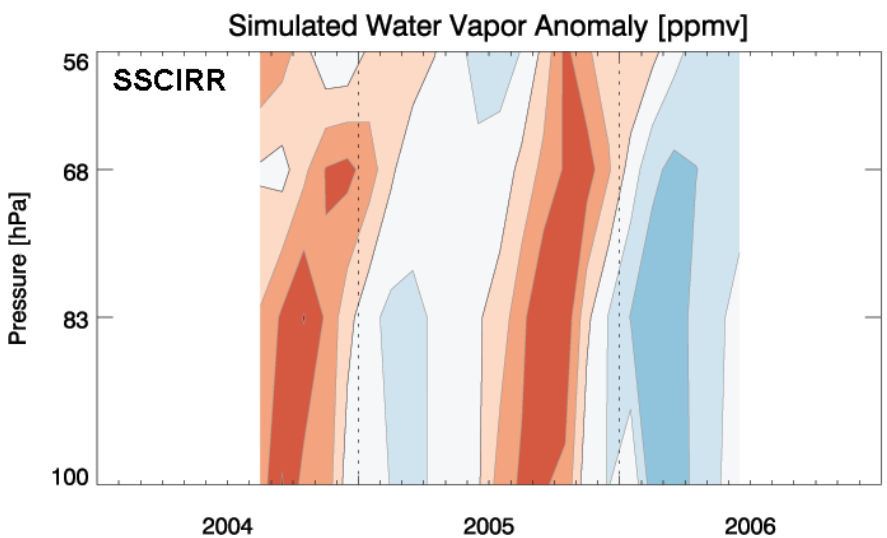
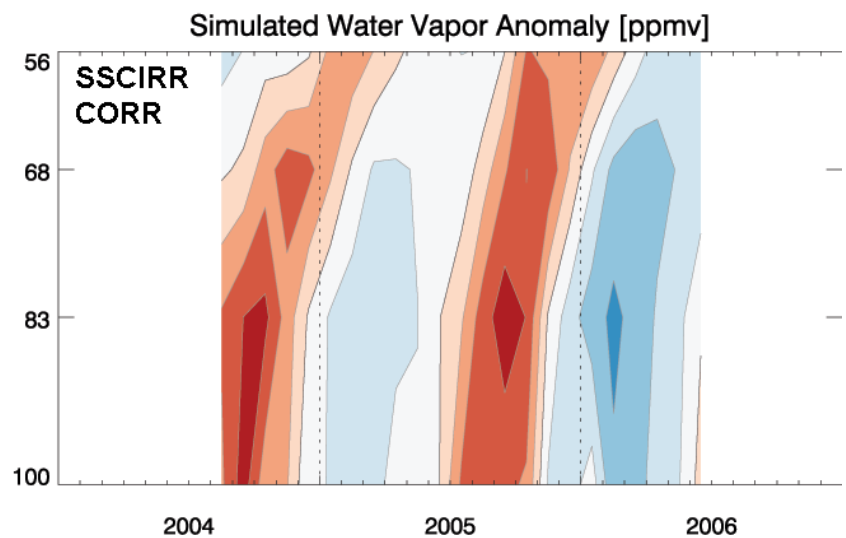
0
+0.8
+1.6


Simulated Water Vapor Anomaly [ppmv]
SSCIRR
Pressure [hPa]
56
68
83
100
2004
2005
2006


Simulated Water Vapor Anomaly [ppmv]
SSCIRR
CORR
56
68
83
100
2004
2005
2006

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