Why does stratospheric water increase in models?

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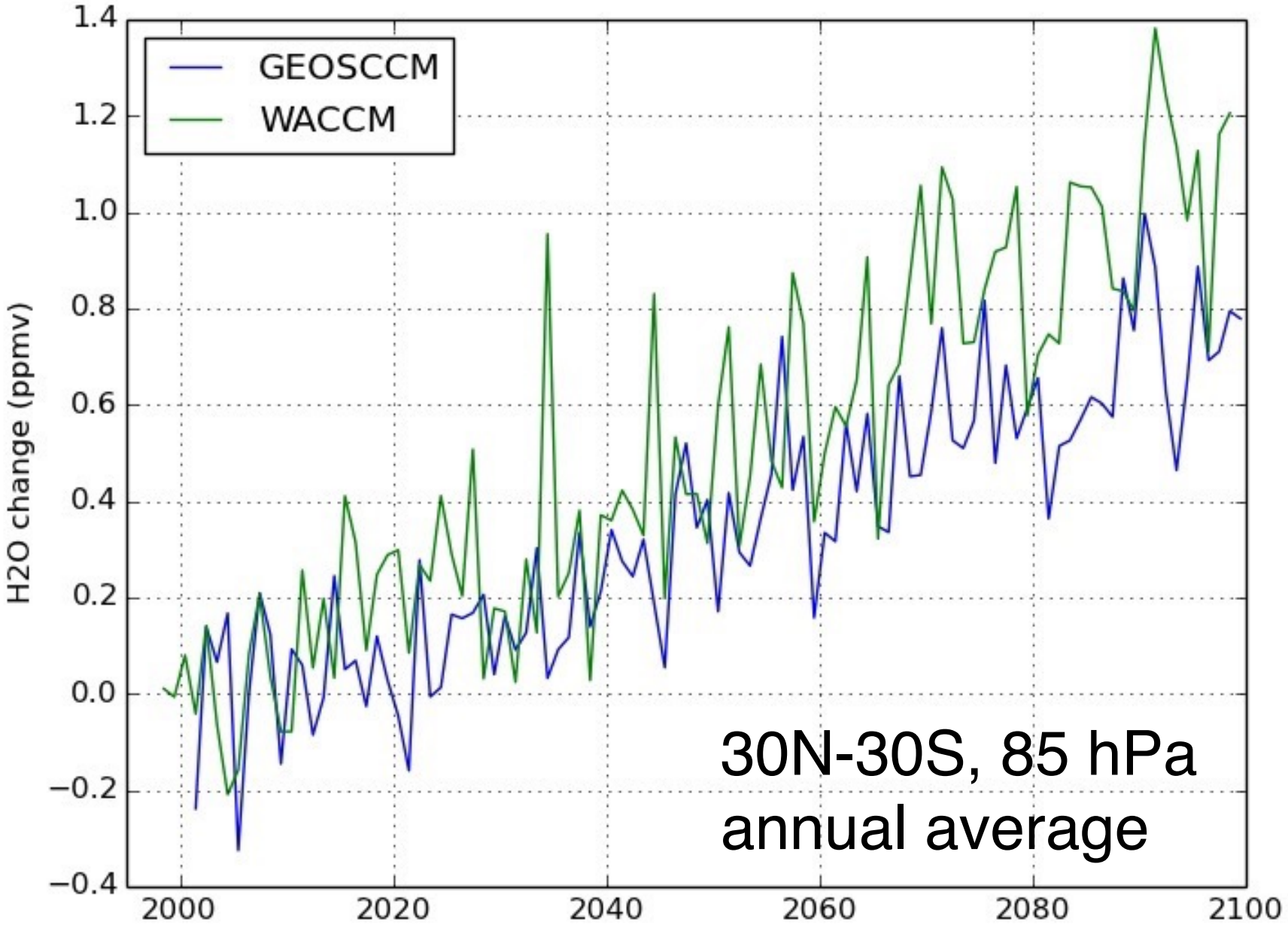
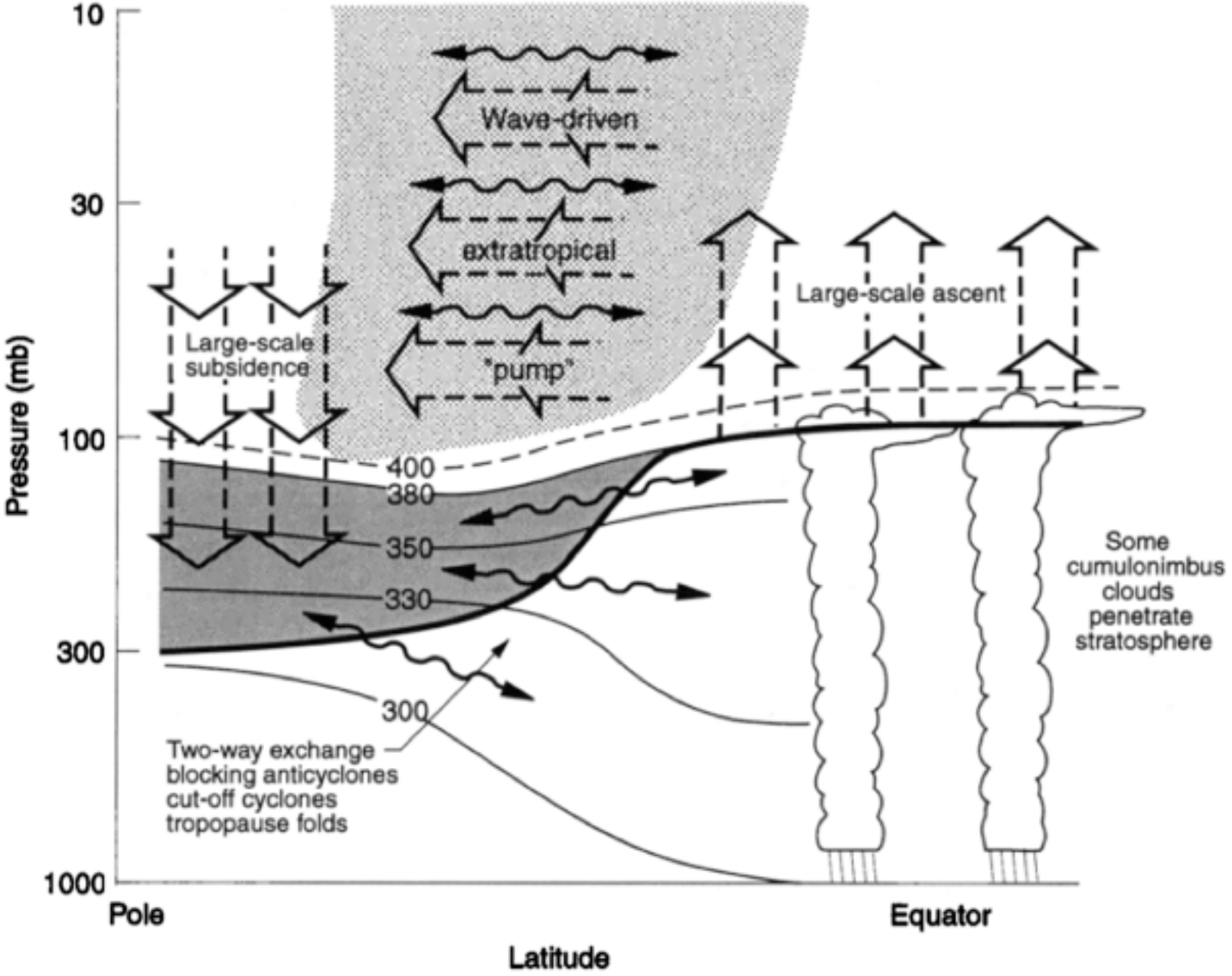
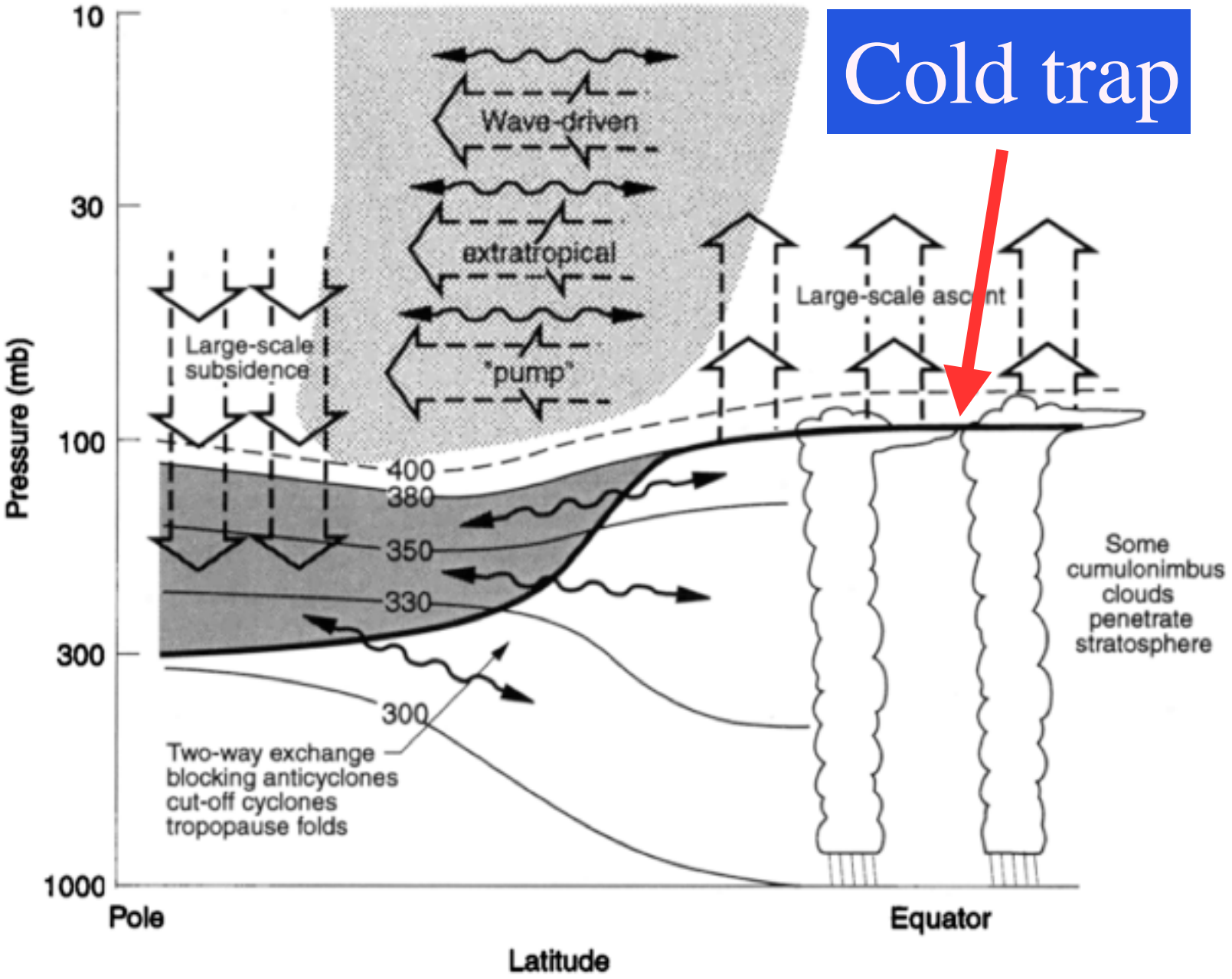
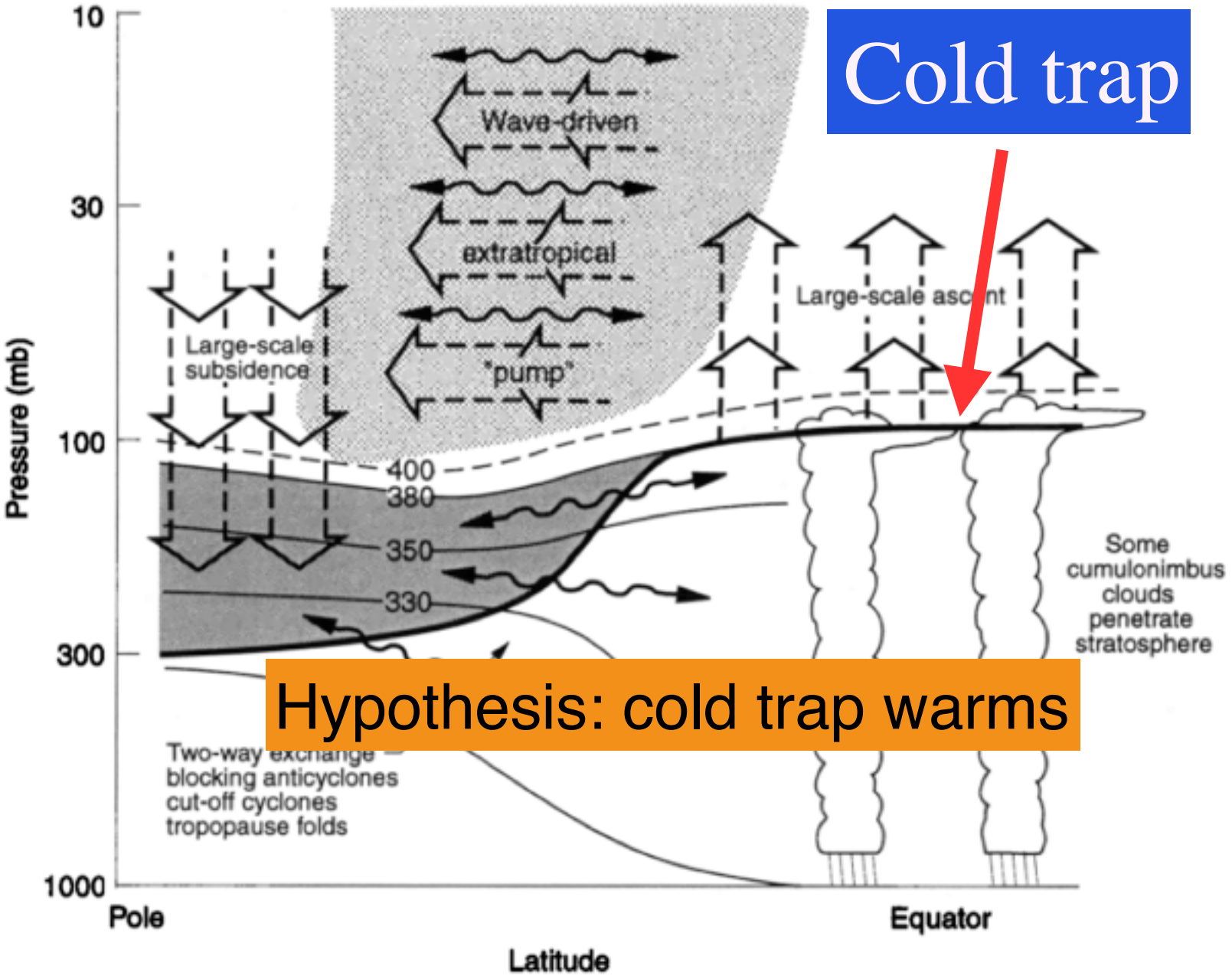
A.H. Butler, K.H. Rosenlof, S.M. Davis,
R.W. Portmann

TEXAS A&M UNIVERSITY

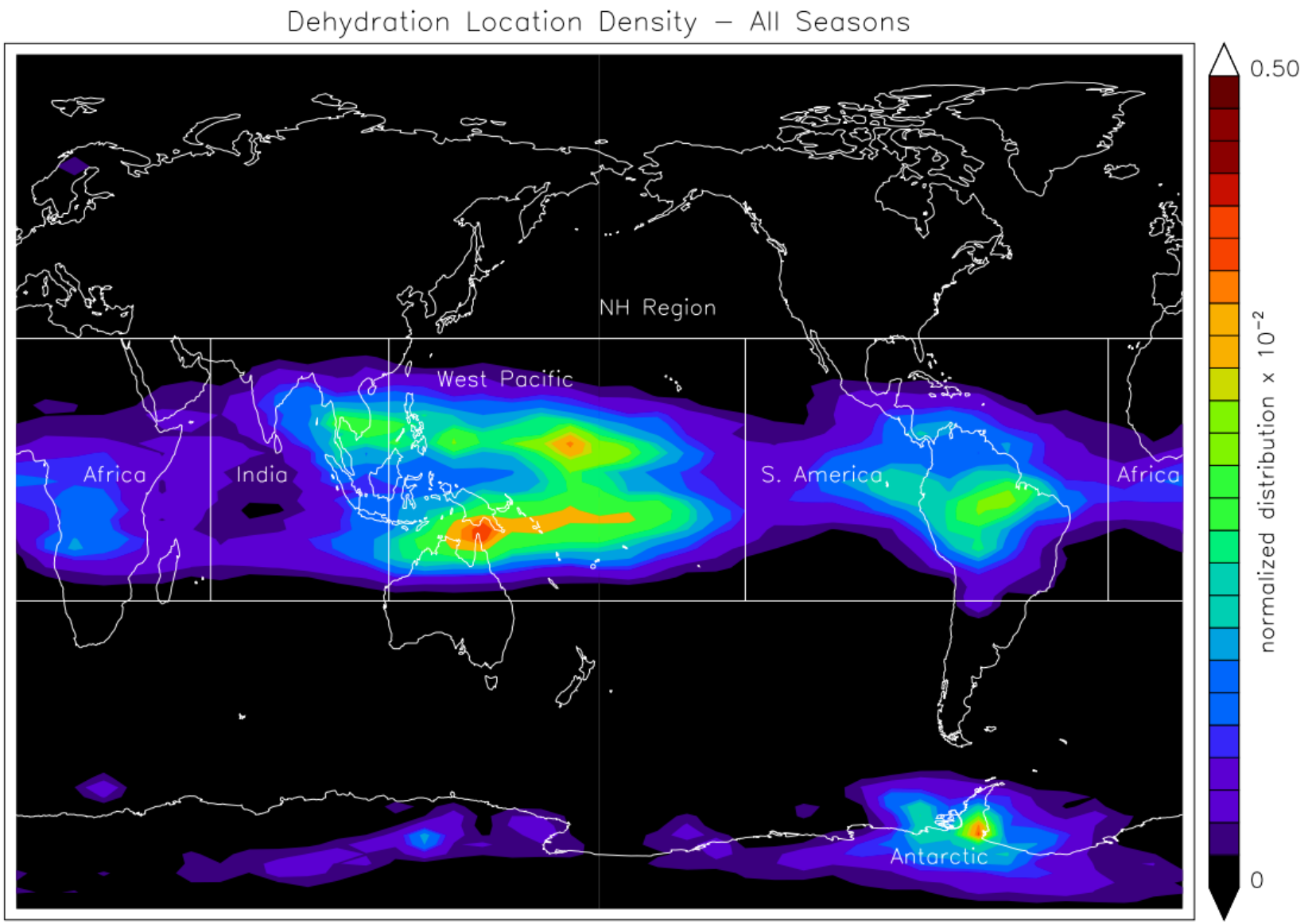

GEOSCCM
WACCM
H2O change (ppmv)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100
30N-30S, 85 hPa
annual average


10
30
100
300
1000
Pressure (mb)
Wave-driven
extratropical
"pump"
Large-scale
subsidence
Large-scale ascent
400
380
350
330
300
Some
cumulonimbus
clouds
penetrate
stratosphere
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
Pole
Equator
Latitude

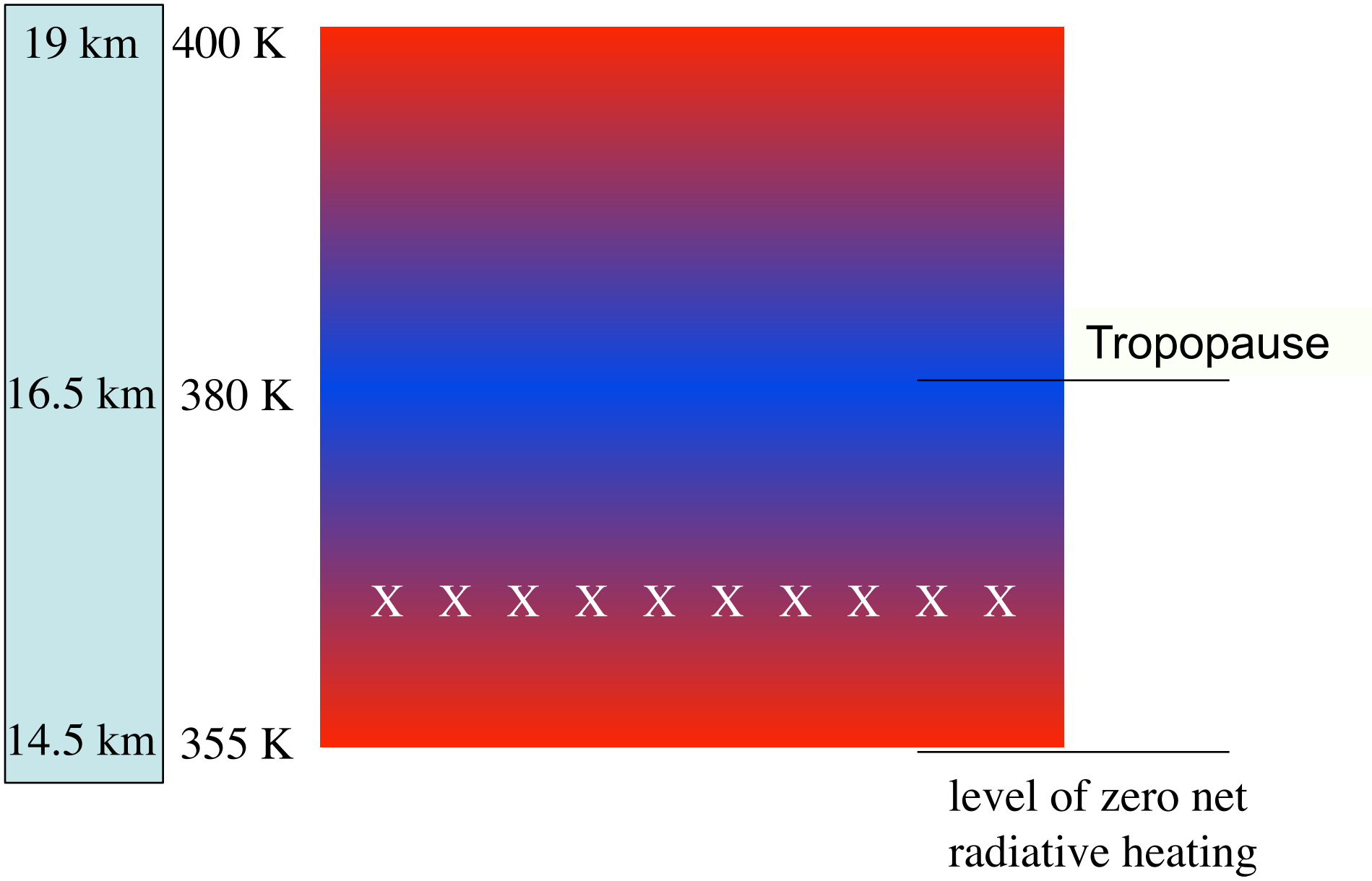

Cold trap
10
30
100
300
1000
Pressure (mb)
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
400
380
350
330
300
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
Some cumulonimbus clouds penetrate stratosphere
Pole
Equator
Latitude

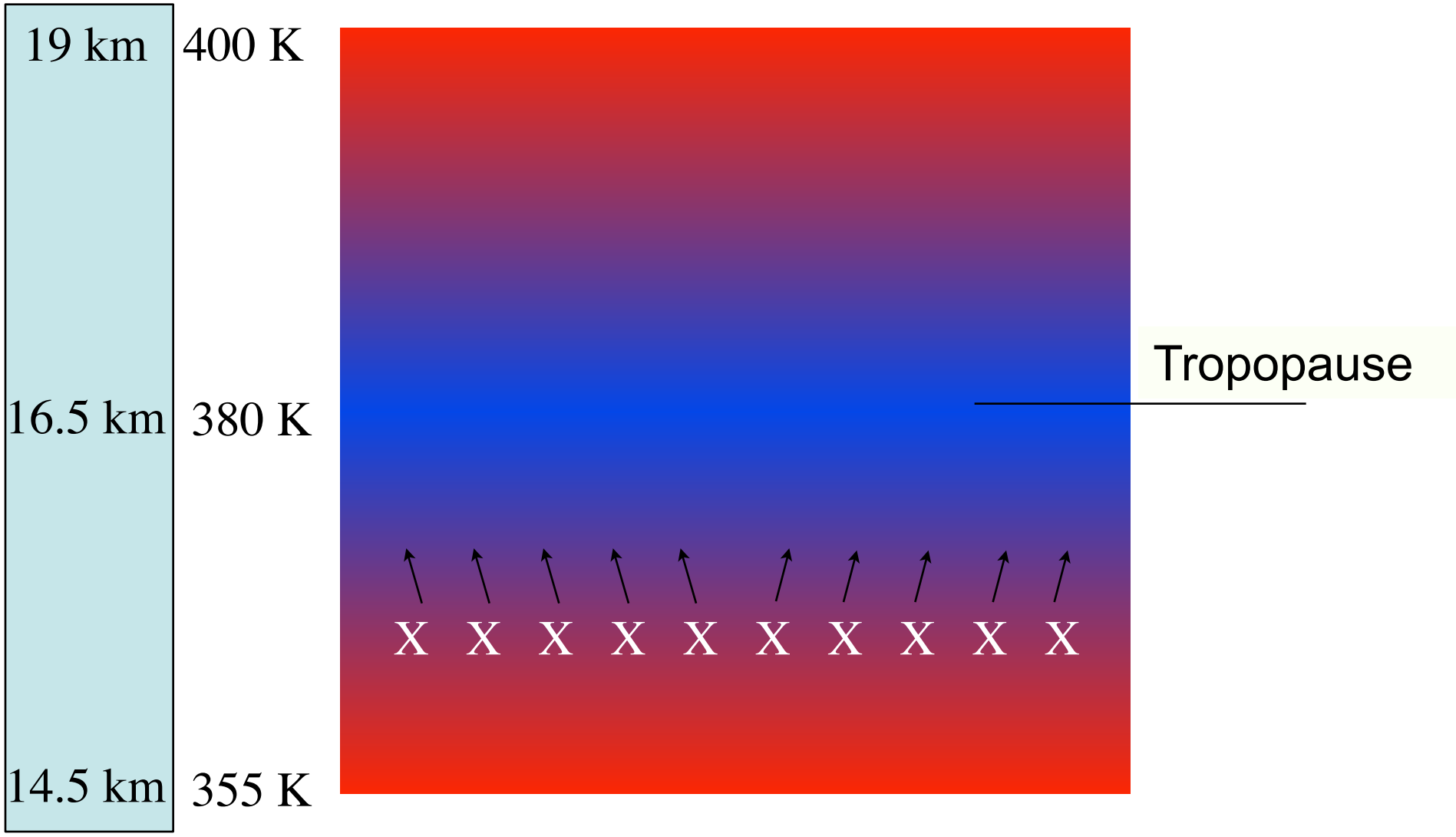

Cold trap
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
400
380
350
330
Some cumulonimbus clouds penetrate stratosphere
Hypothesis: cold trap warms
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
Pressure (mb)
10
30
100
300
1000
Pole
Equator
Latitude

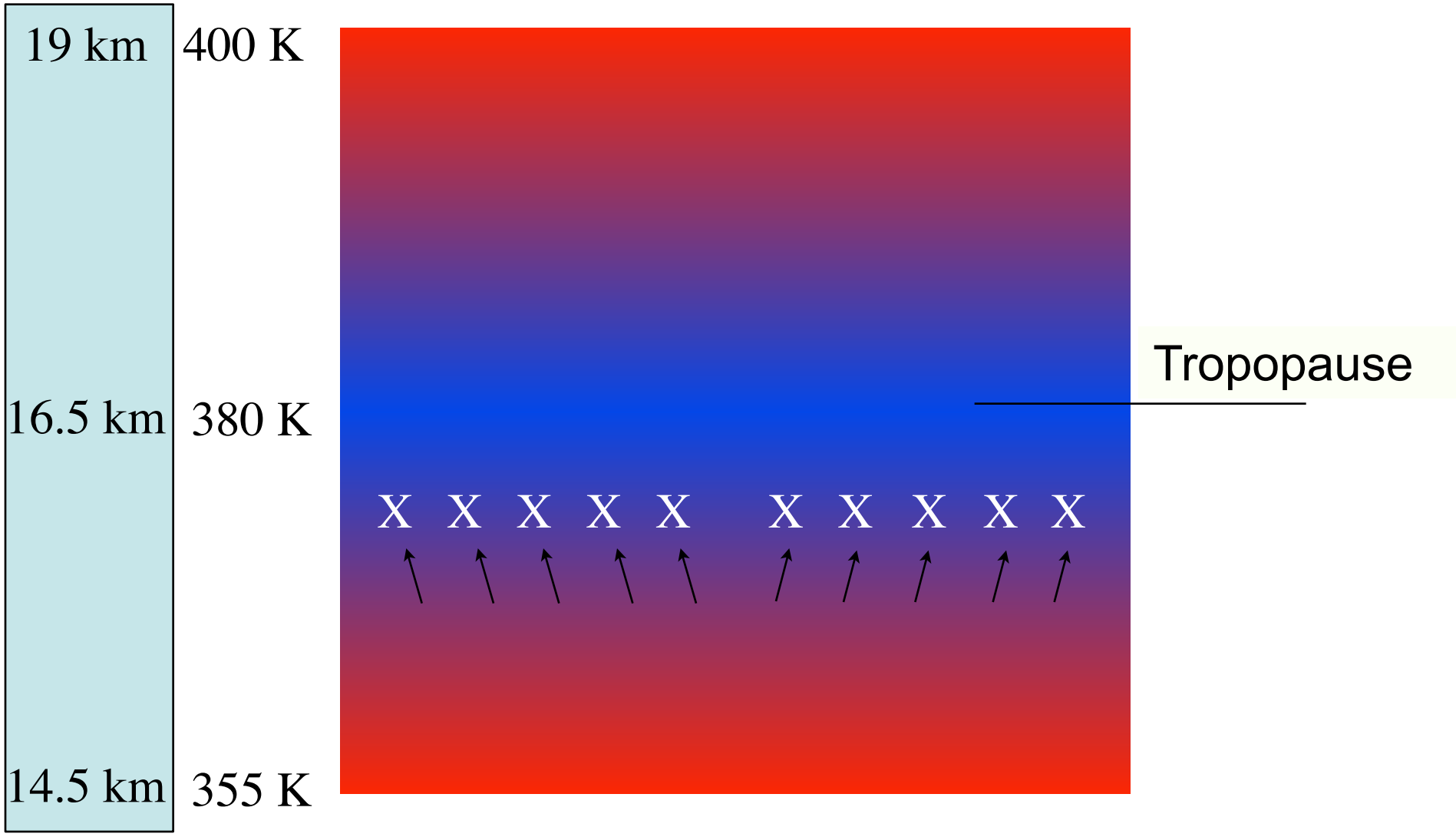
M. R. Schoeberl and A. E. Dessler: Dehydration of the stratosphere

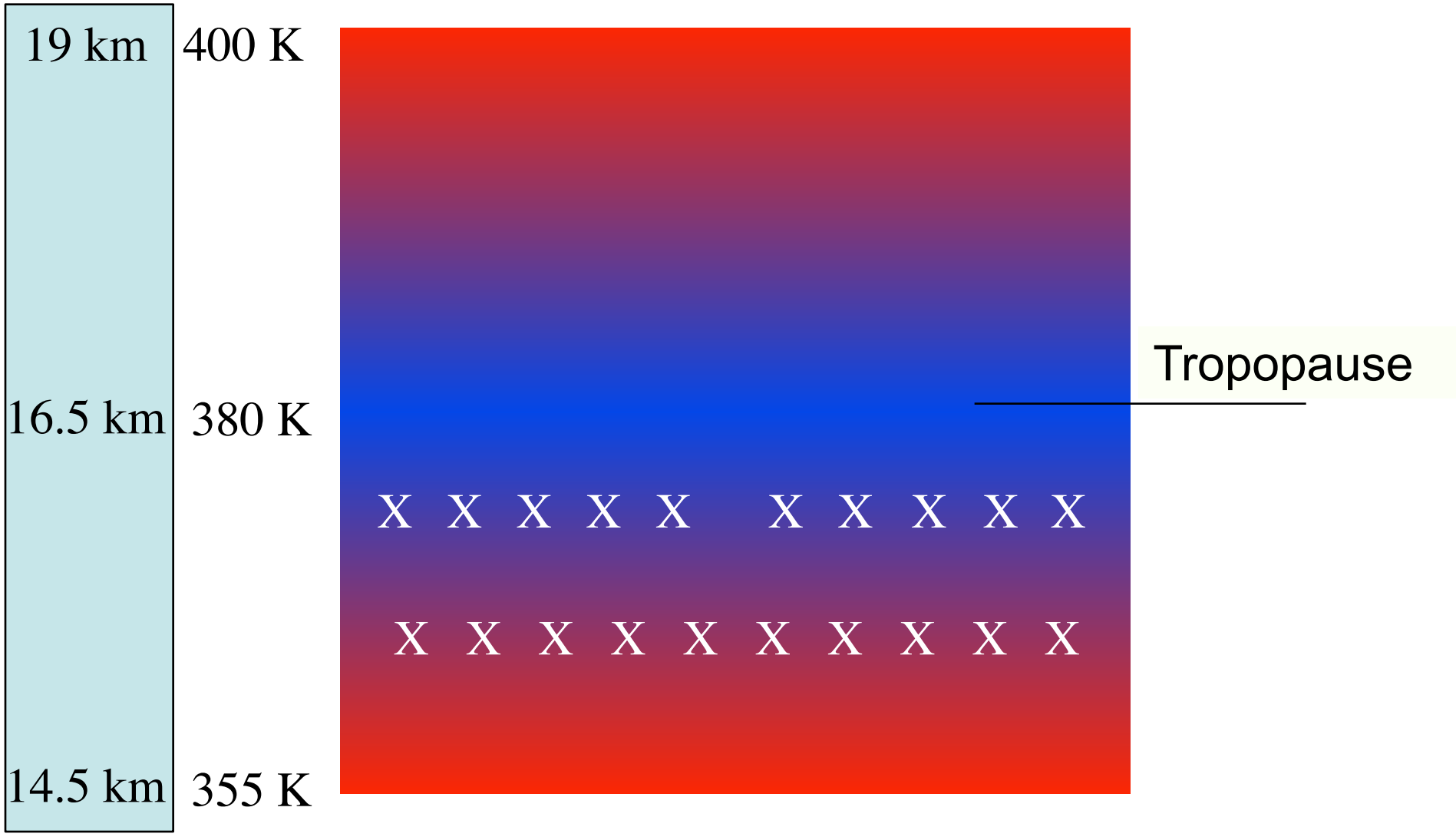


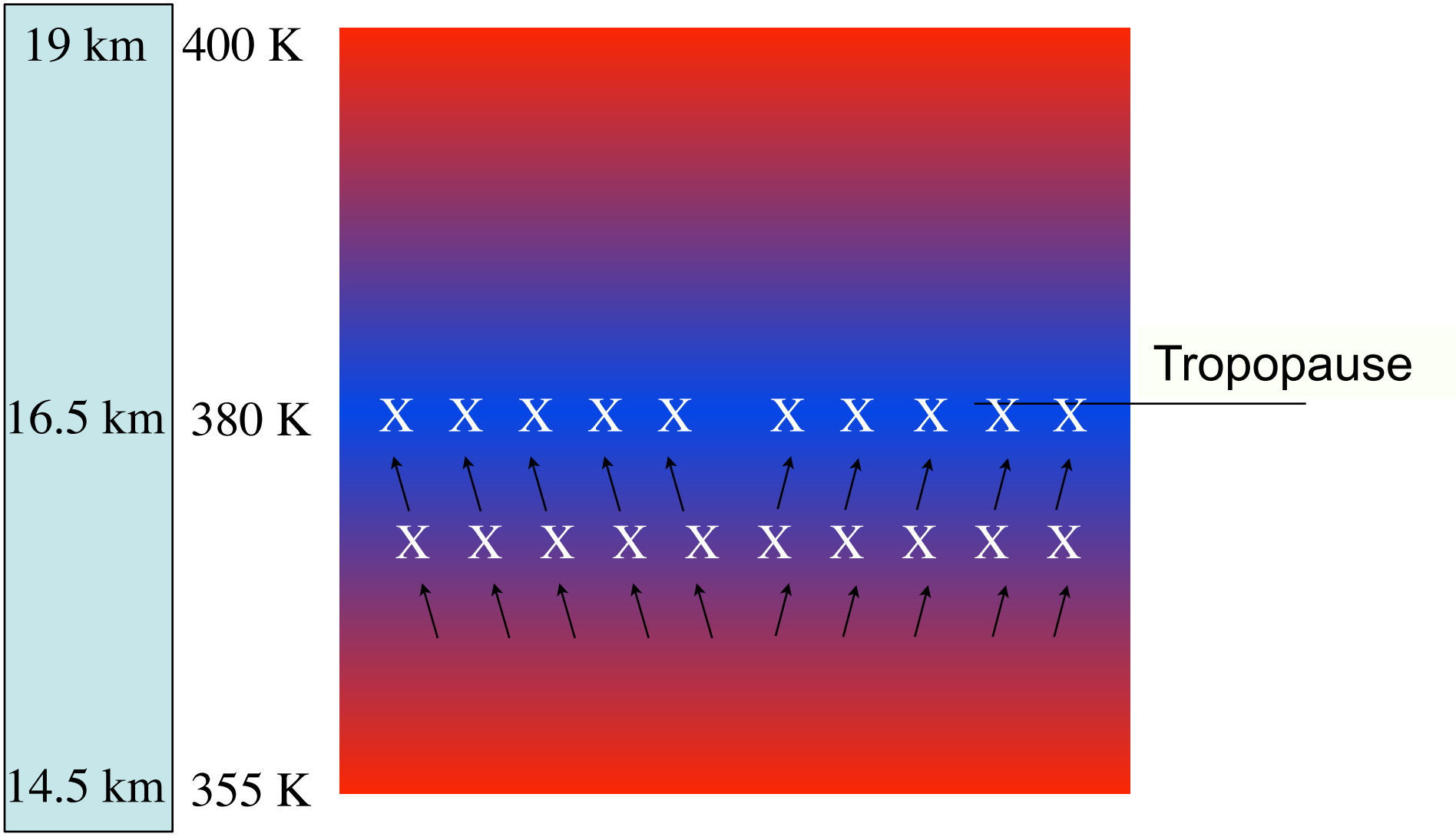
(a)

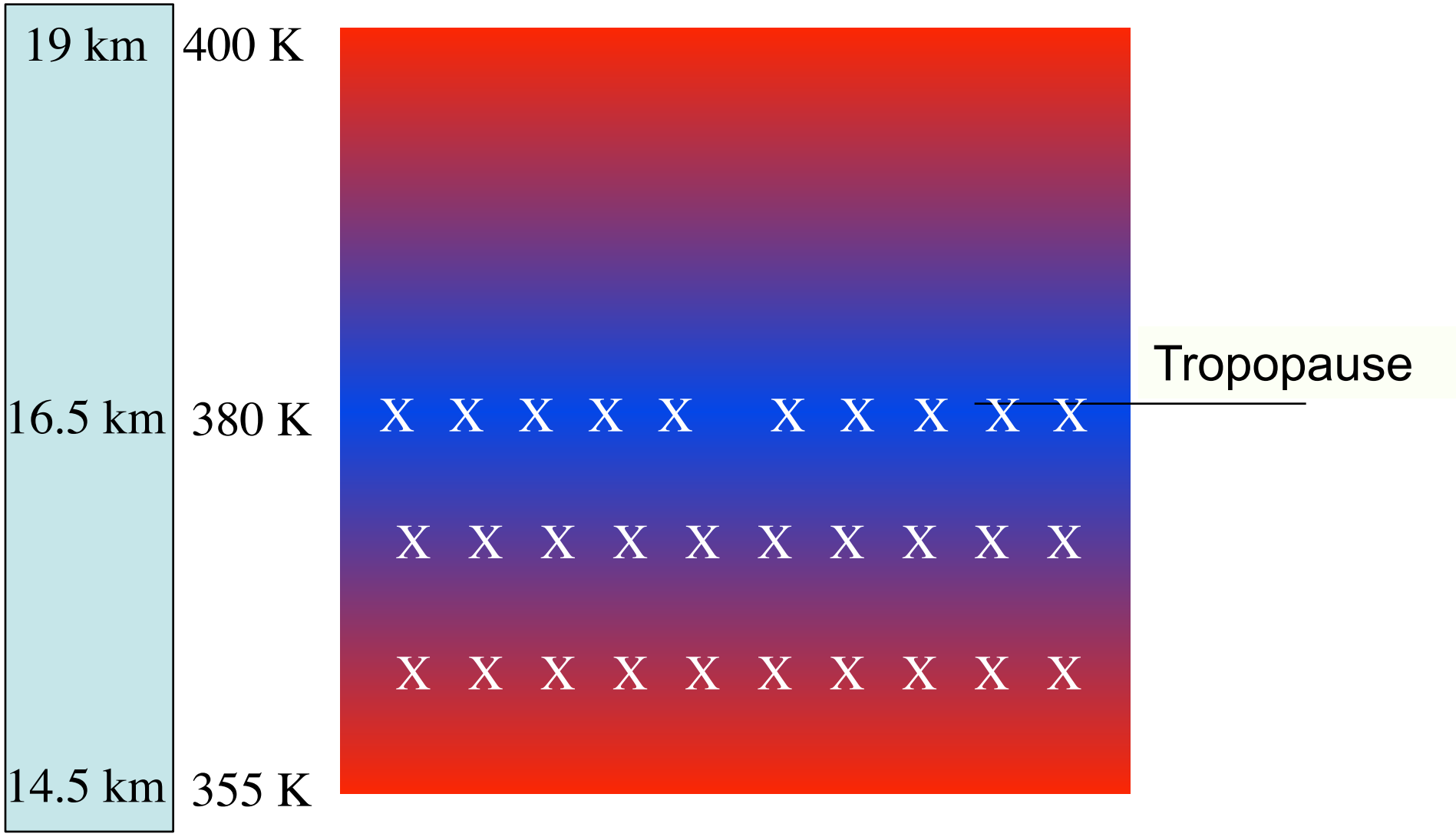

19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause
level of zero net
radiative heating


19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause

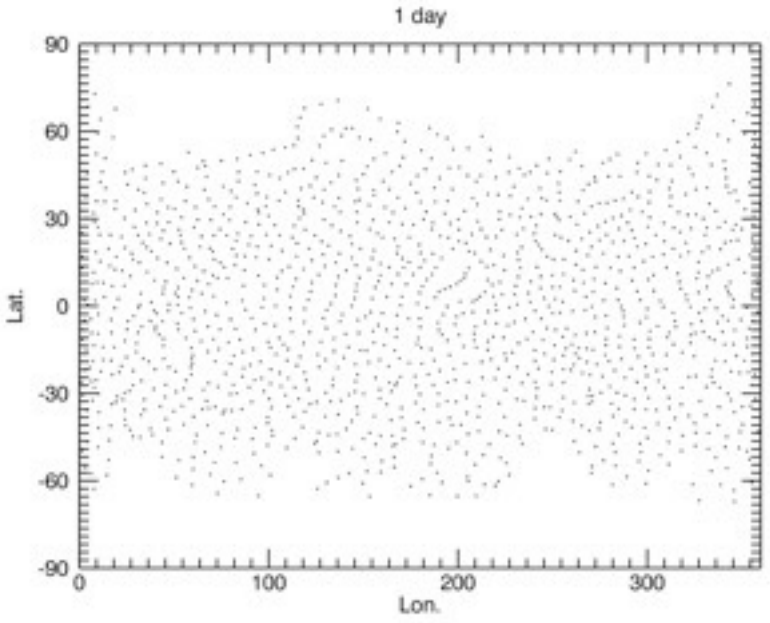

19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause


19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause

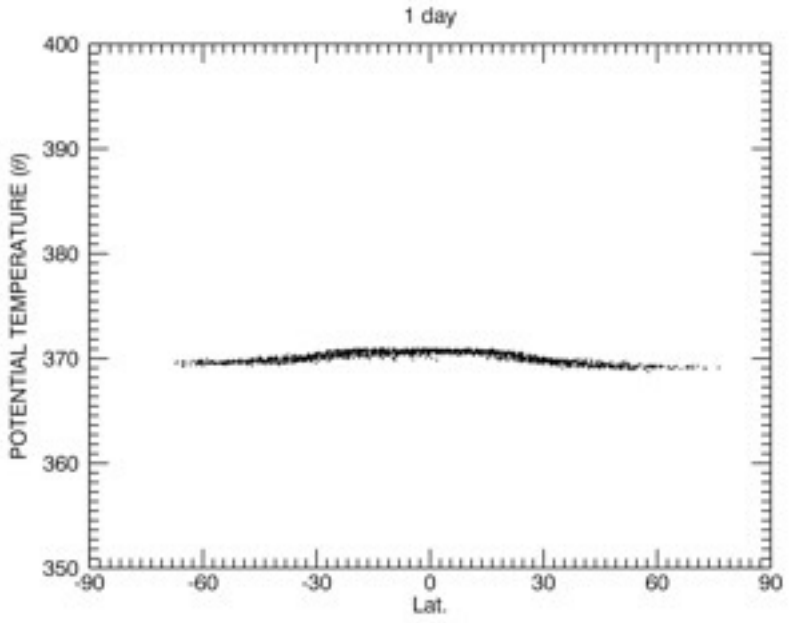

19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause


19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause

1 day

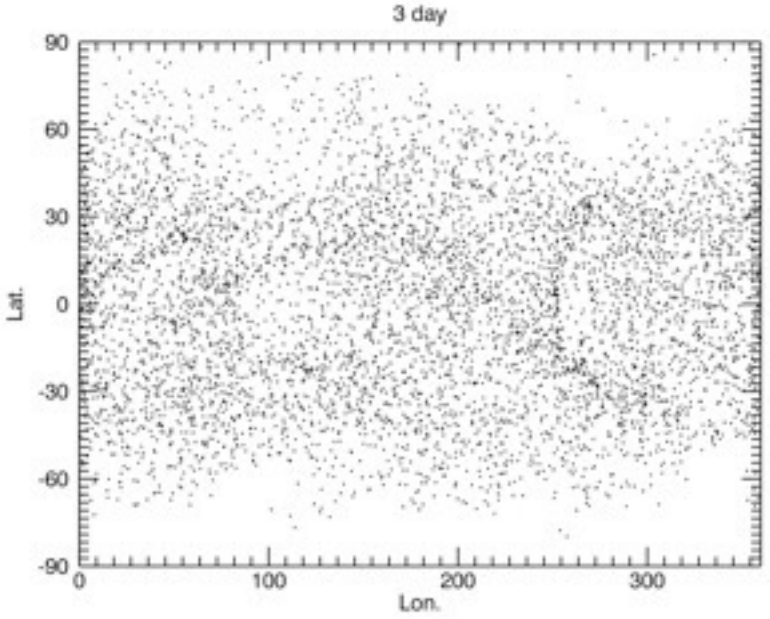


Horizontal view

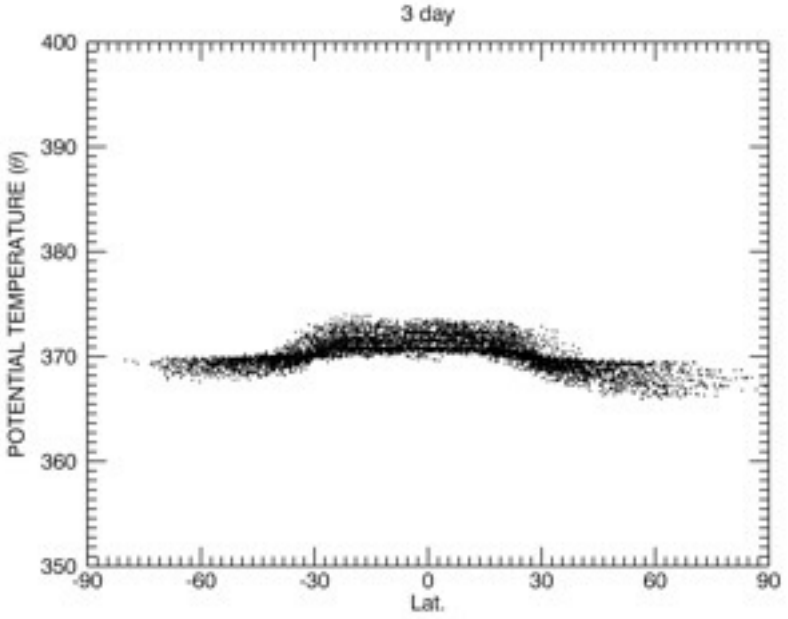


Vertical view

3 days

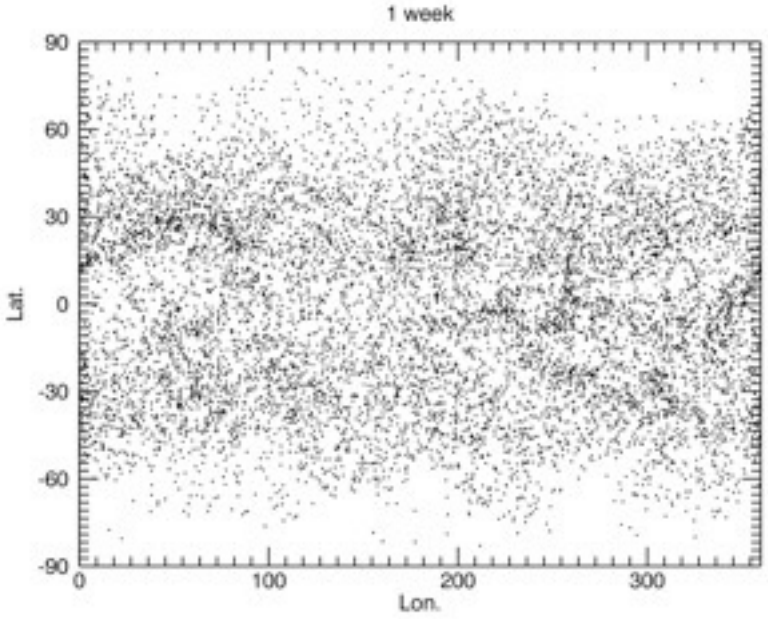


Horizontal view

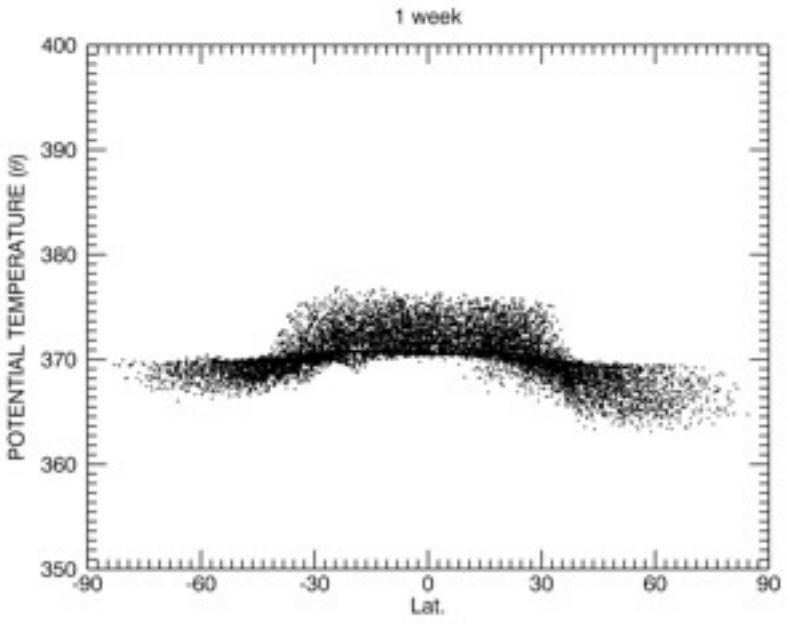


Vertical view

1 week

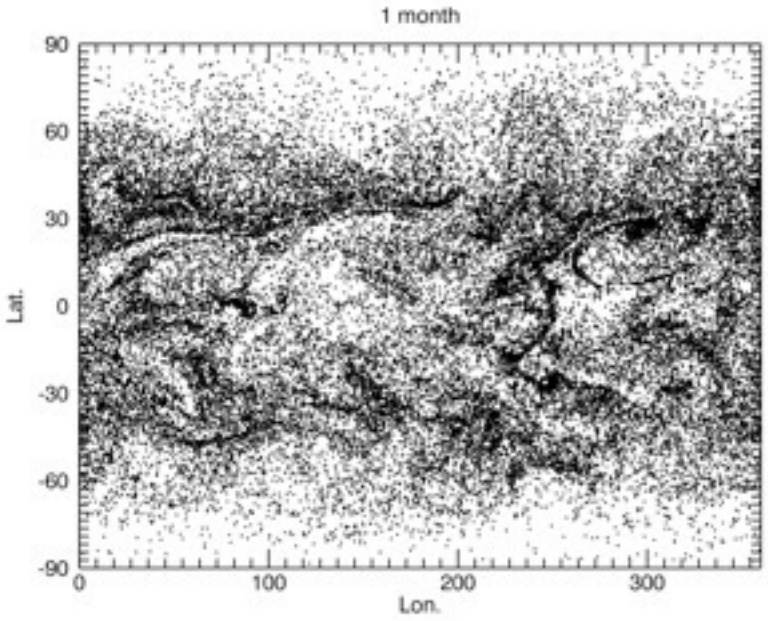


Horizontal view

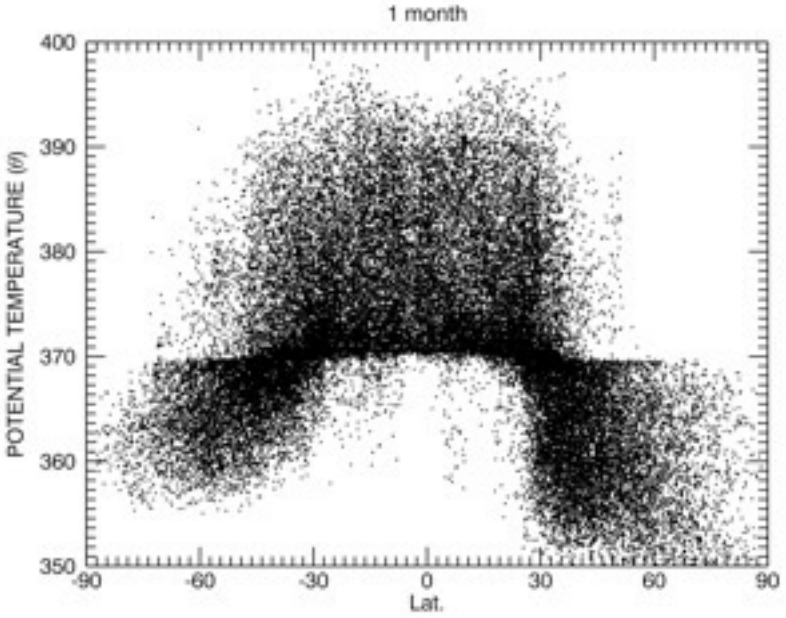


Vertical view

1 month

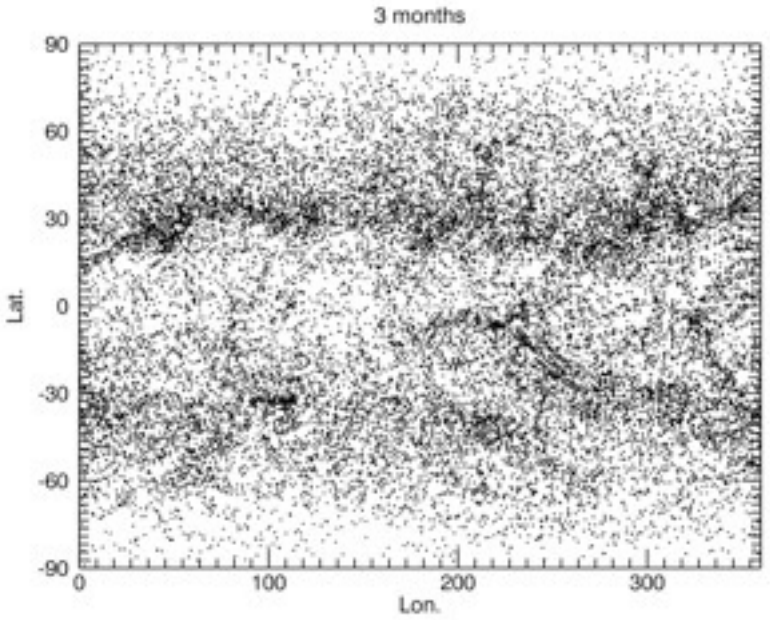


Horizontal view

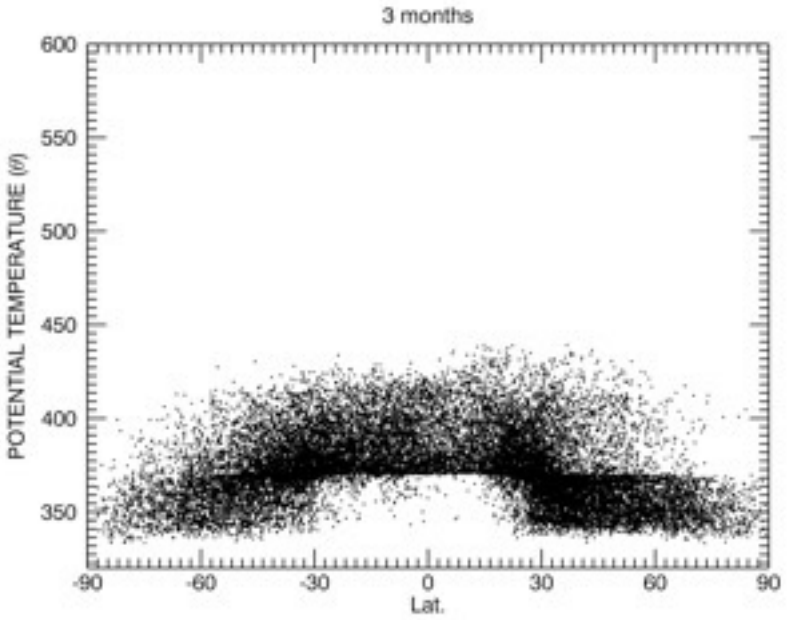


Vertical view

3 months



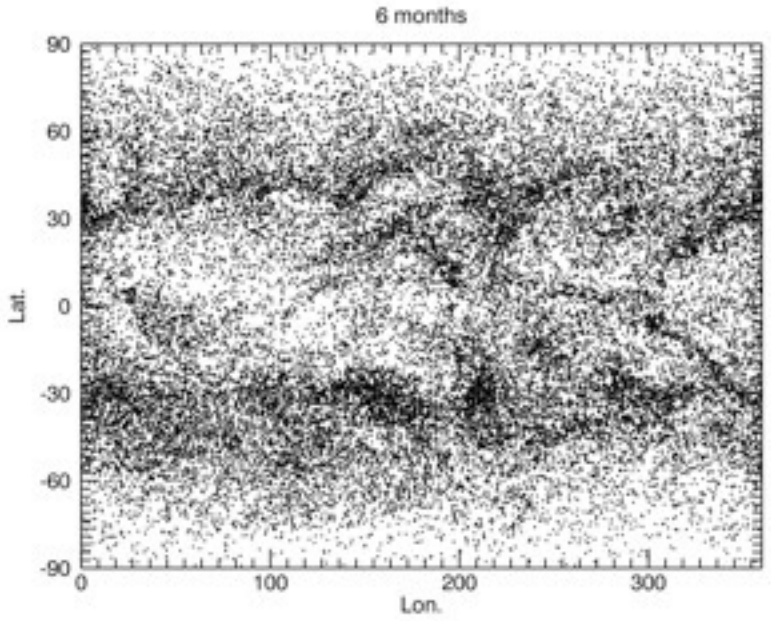
Horizontal view



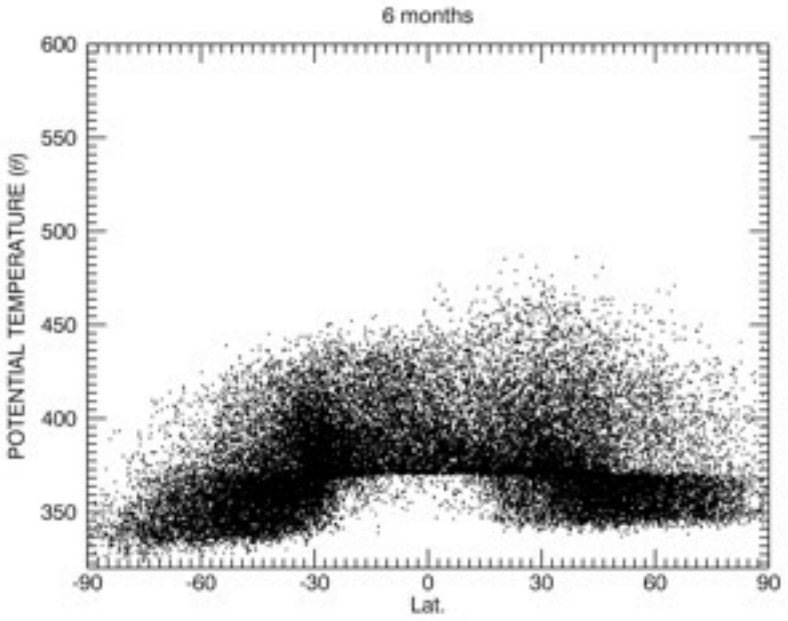
Vertical view

Parcels have been thinned out by a factor of 10
Expanded the altitude scale

6 months



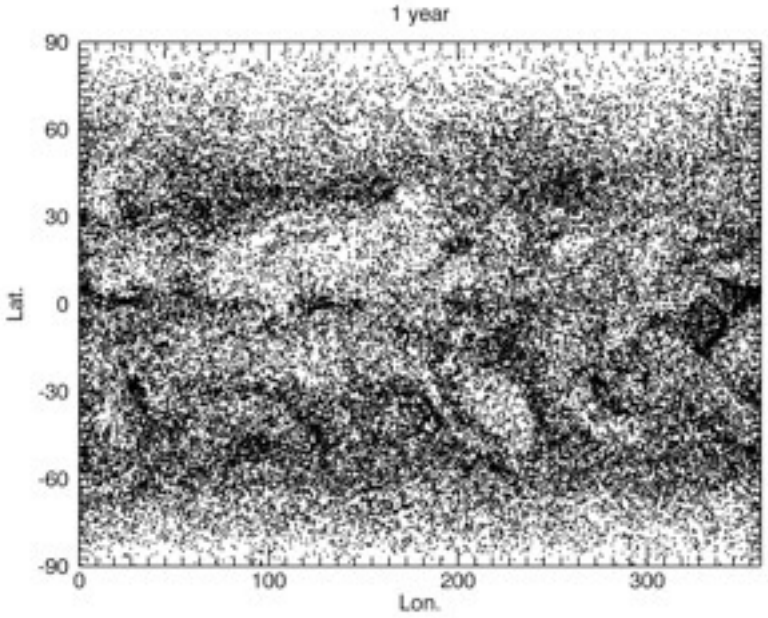
Horizontal view



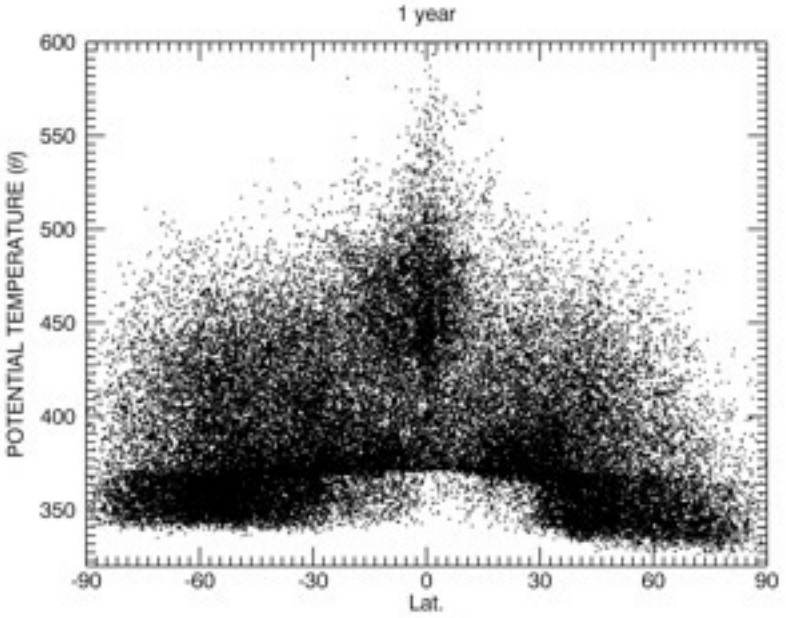
Vertical view

Parcels have been thinned out by a factor of 10

1 year



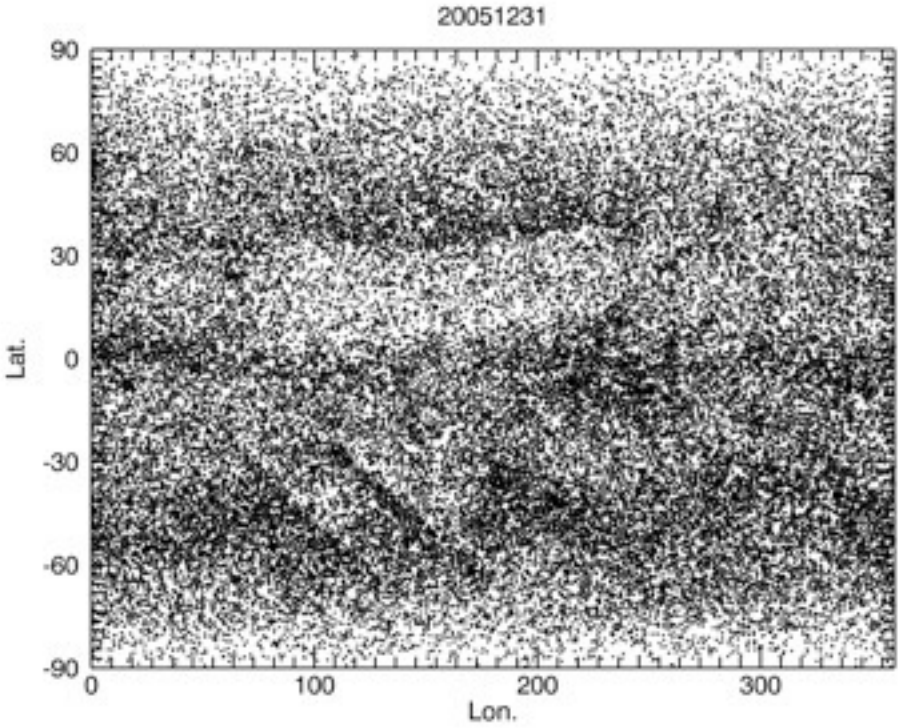
Horizontal view

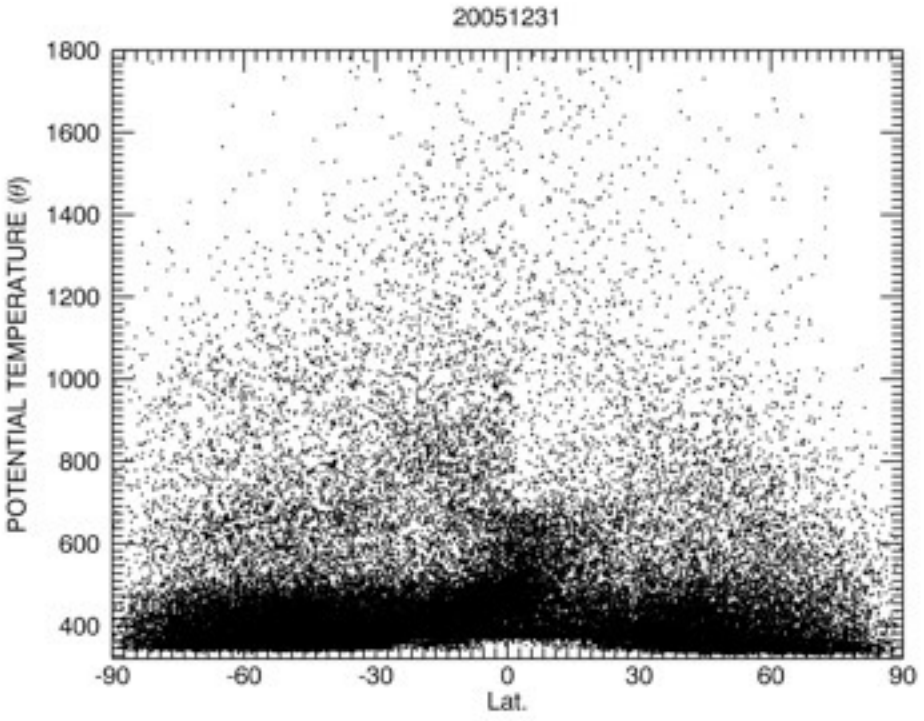


Vertical view

Parcels have been thinned out by a factor of 10

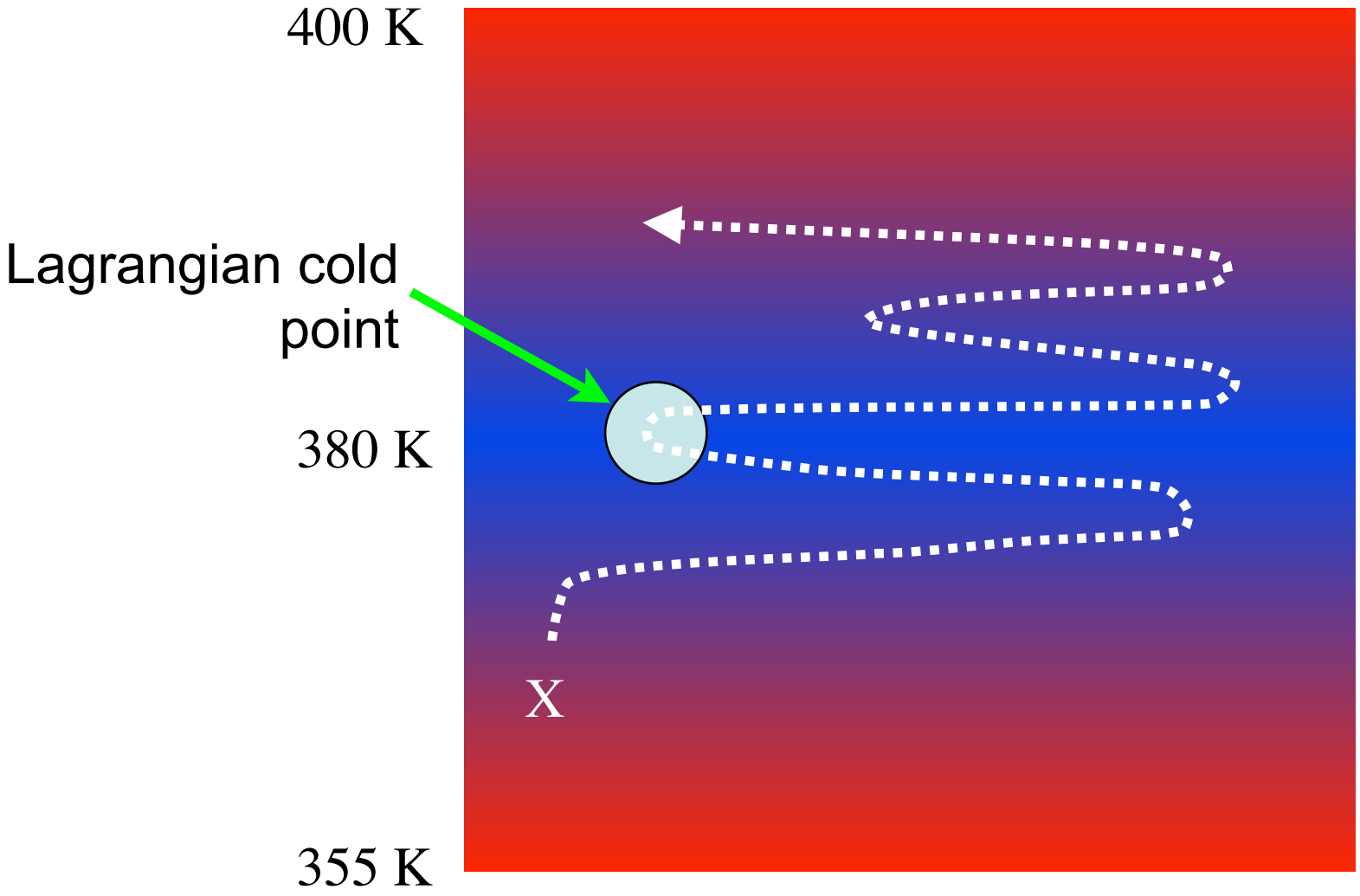
12/31/2005



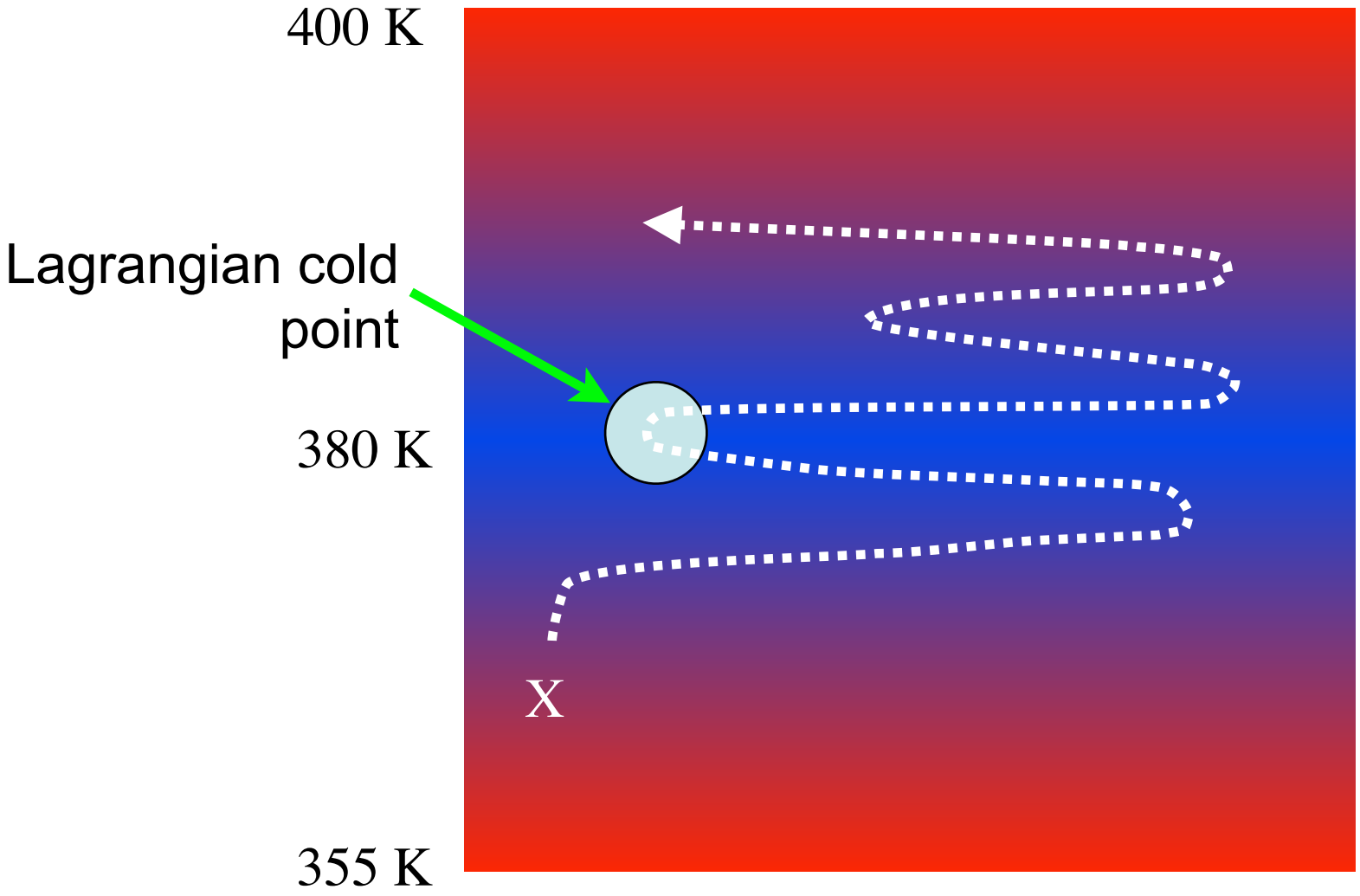


Horizontal view

Parcels have been thinned out by a factor of 10


400 K
Lagrangian cold point
380 K
X
355 K

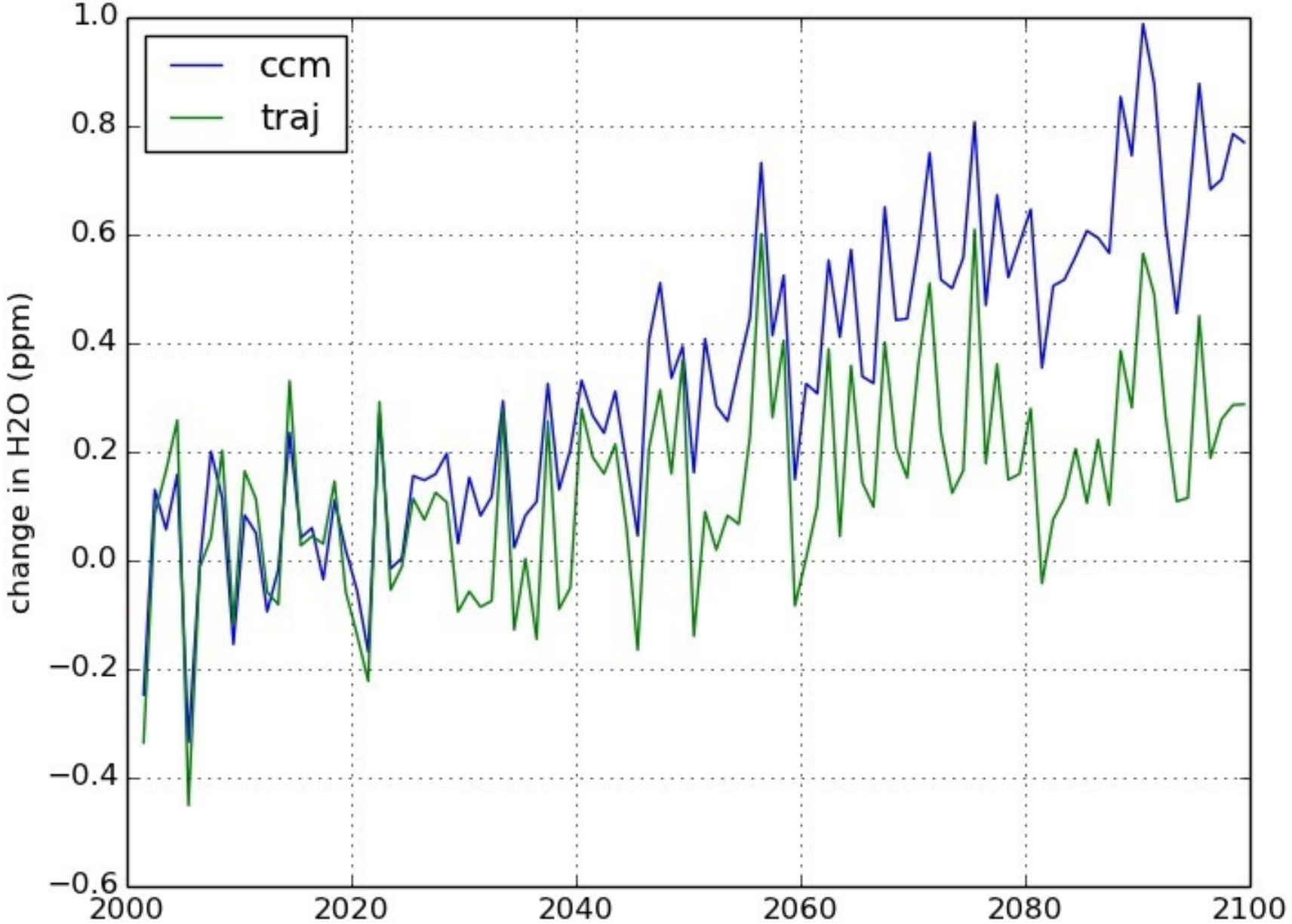
Schoeberl and Dessler, ACP, 2011
Schoeberl et al., ACP, 2012, 2013
Bowman, JGR, 1993; Bowman and Carrie, JAS, 2002



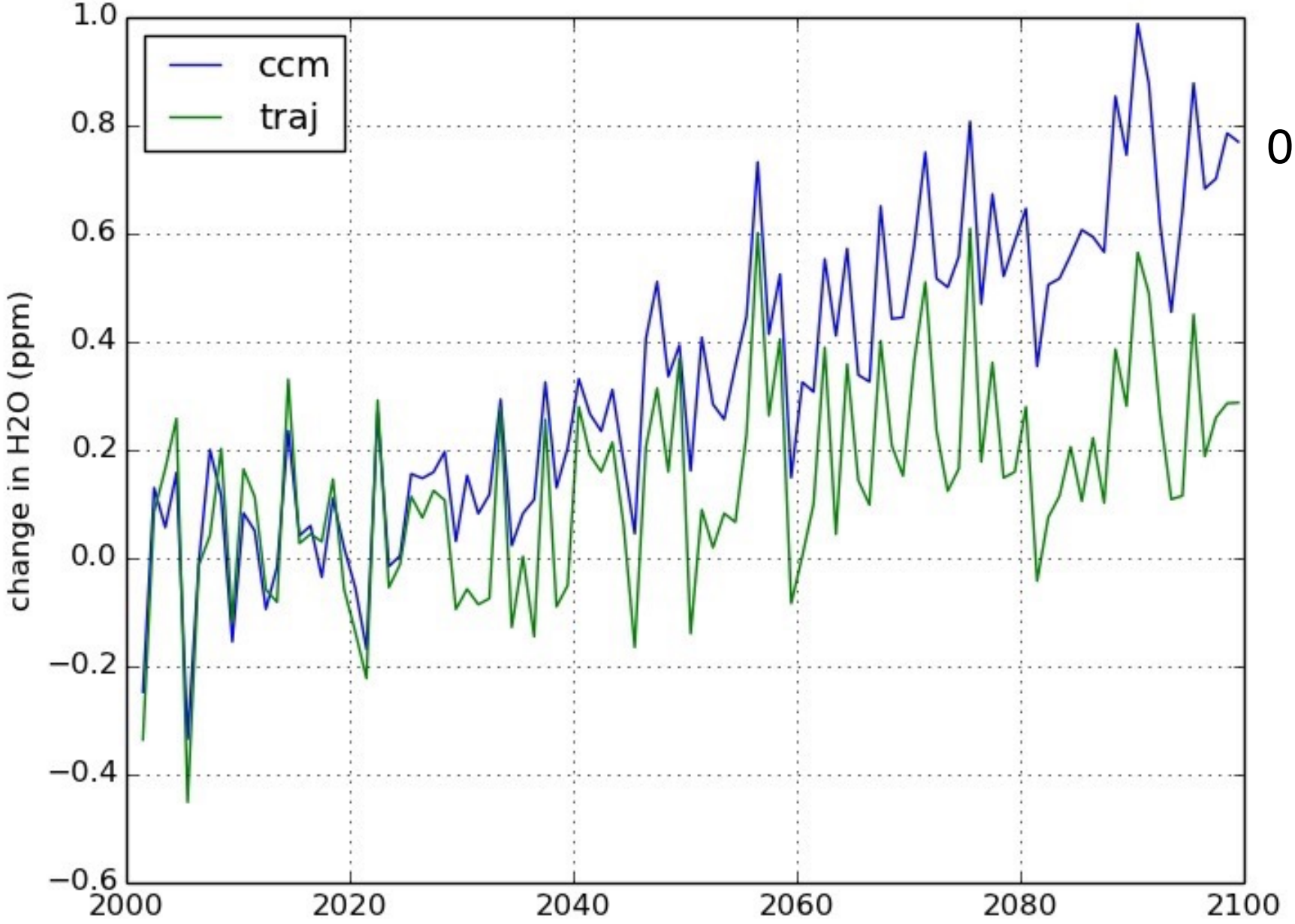
plan

- use 6-hourly met data from GEOSCCM and WACCM to drive our trajectory model
- predict entry-level H2O and compare to full model
- traj. model only contains TTL temperature variations
- compare to CCM prediction; differences caused by other processes

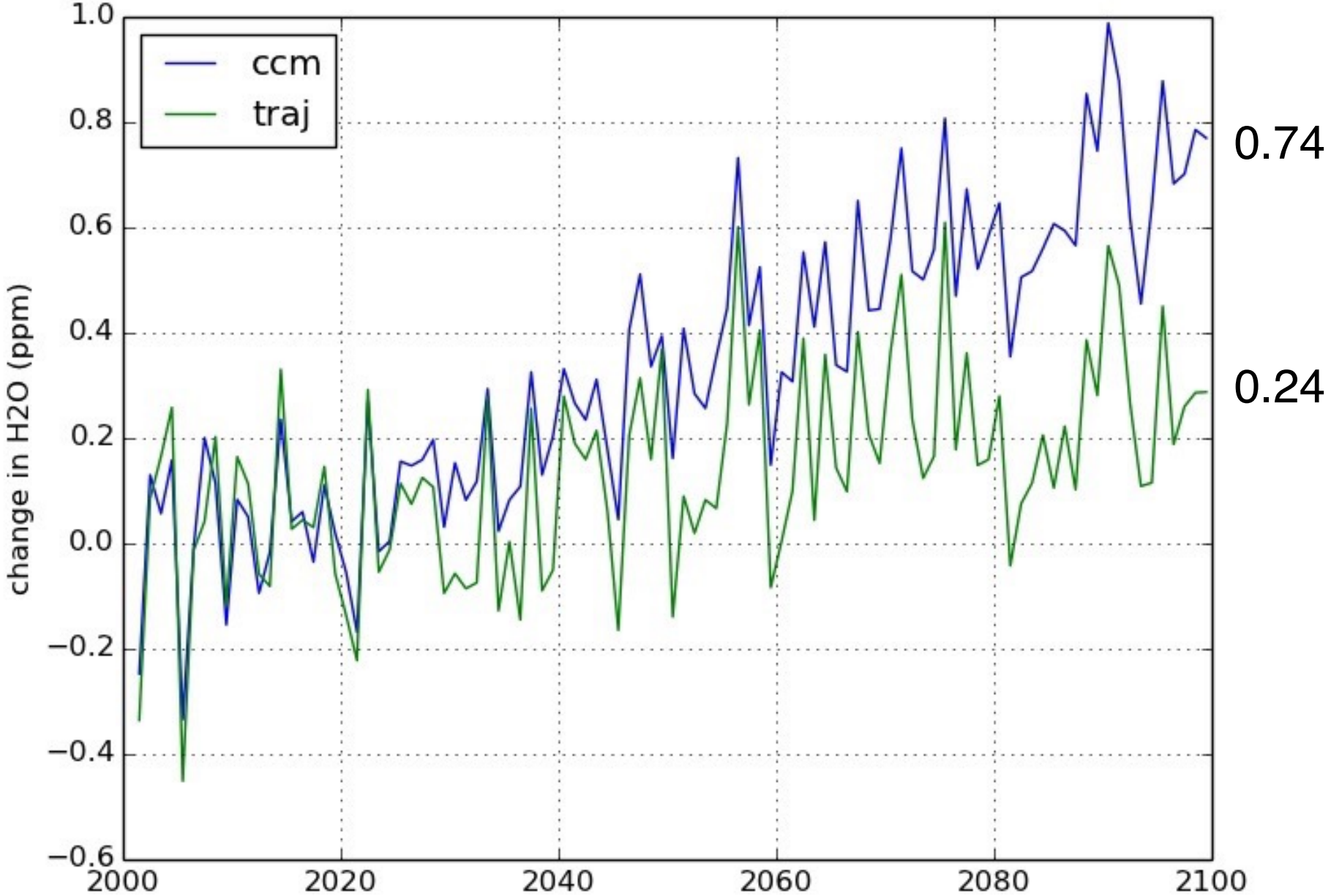
GEOSCCM

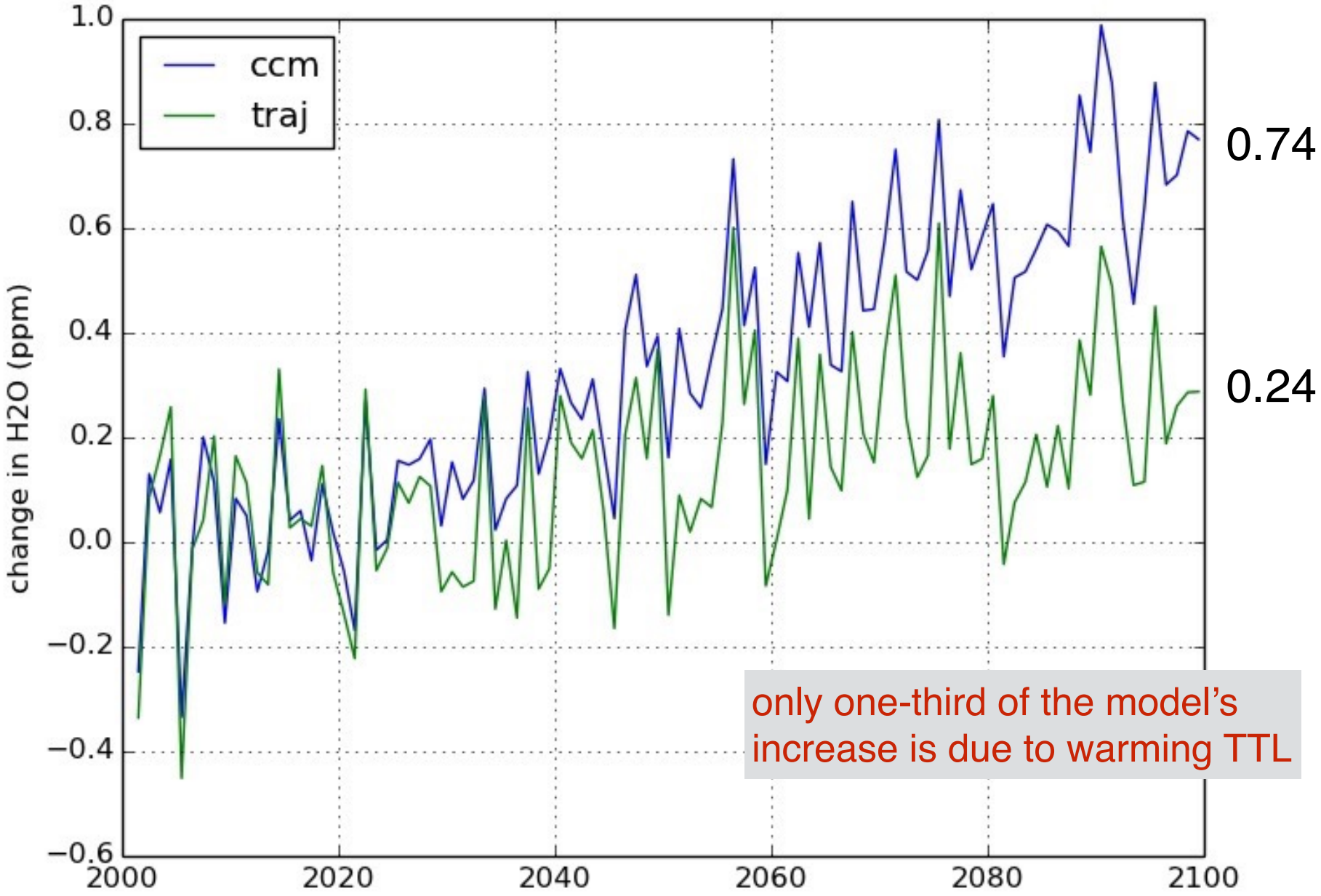

ccm
traj
change in H2O (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
2000
2020
2040
2060
2080
2100

GEOSCCM

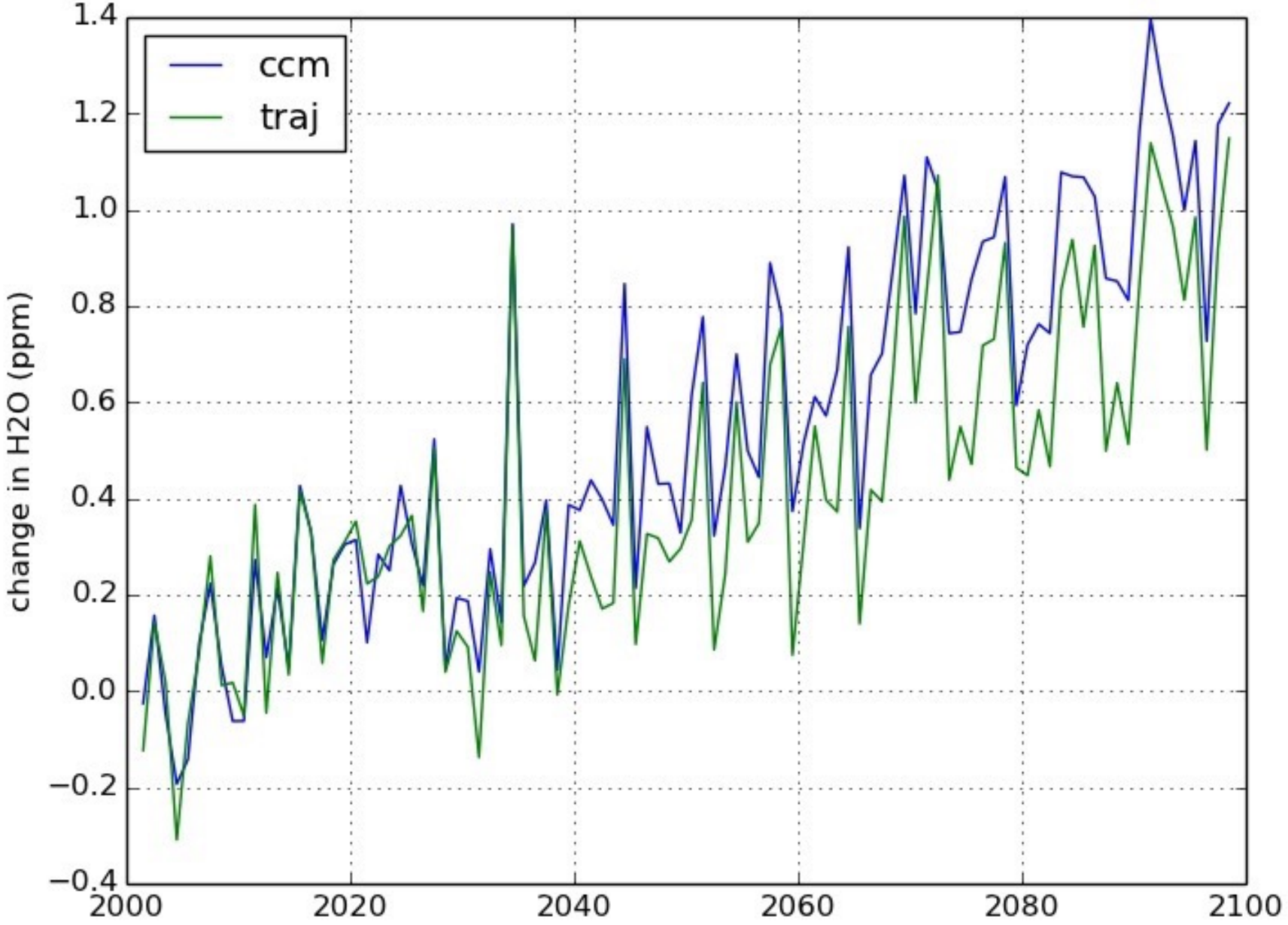

ccm
traj
change in H2O (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
2000
2020
2040
2060
2080
2100

0.74

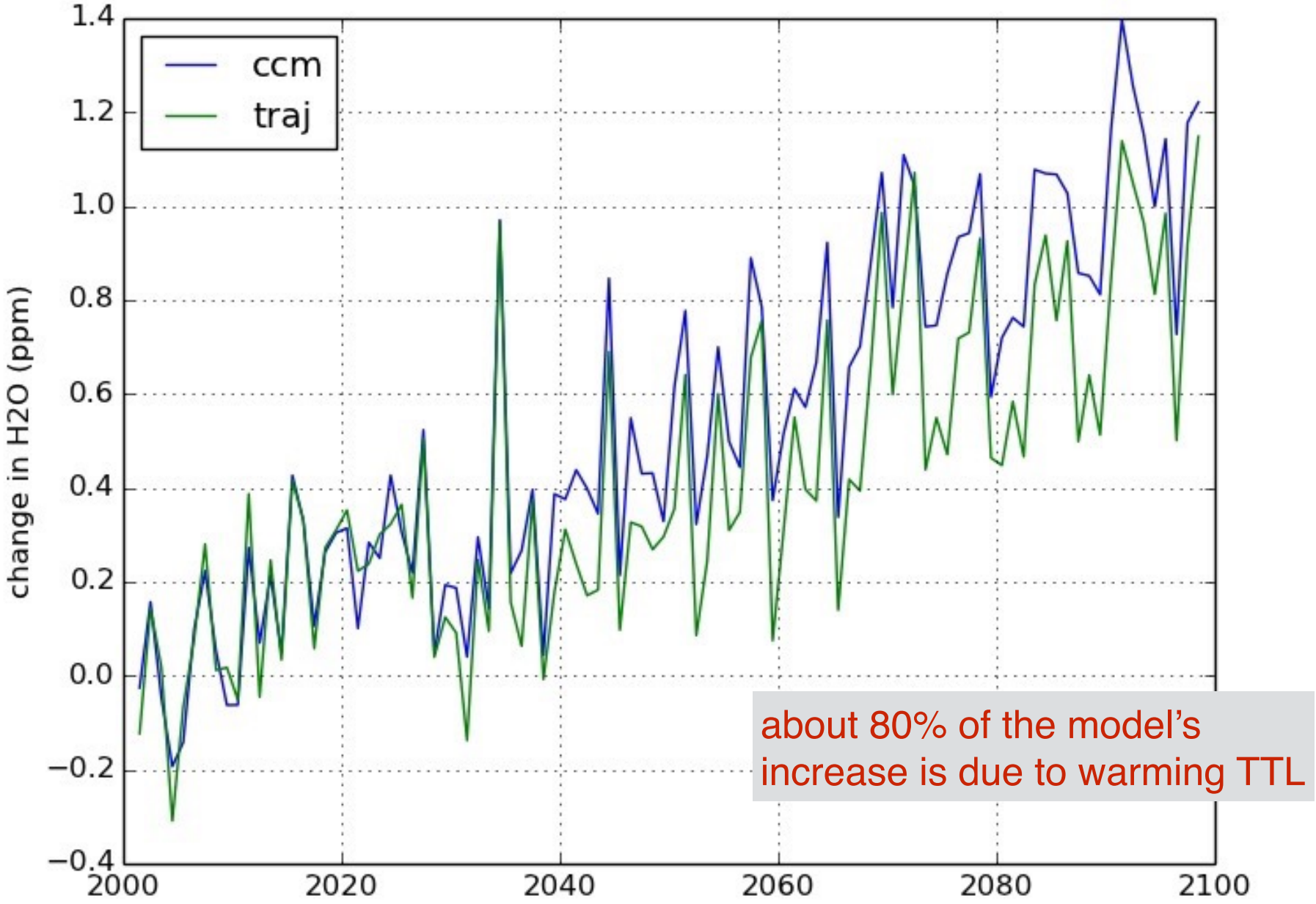

GEOSCCM
ccm
traj
change in H2O (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
2000
2020
2040
2060
2080
2100
0.74
0.24


GEOSCCM
ccm
traj
change in H2O (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
2000
2020
2040
2060
2080
2100
0.74
0.24
only one-third of the model's increase is due to warming TTL

WACCM


ccm
traj
change in H2O (ppm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100

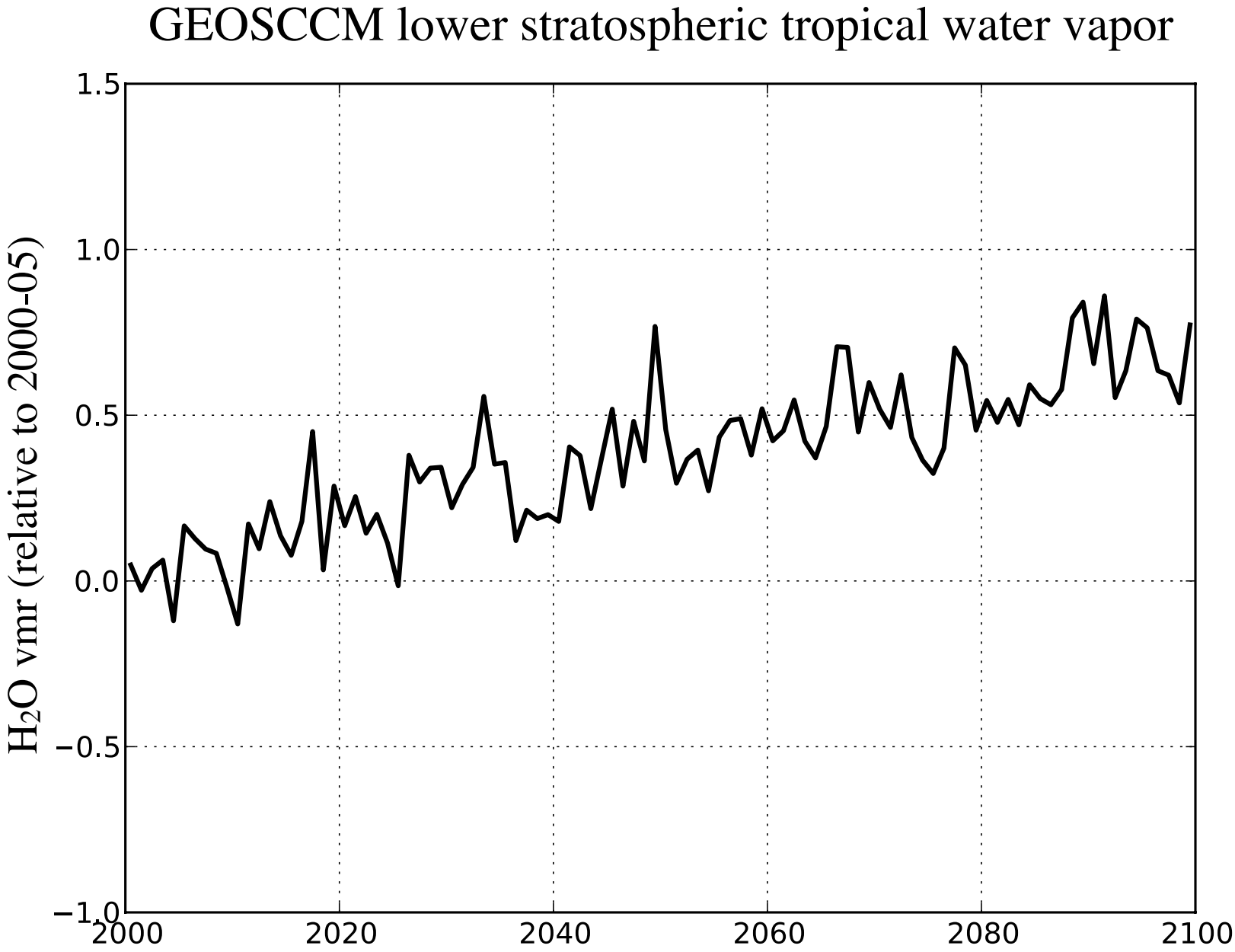
WACCM



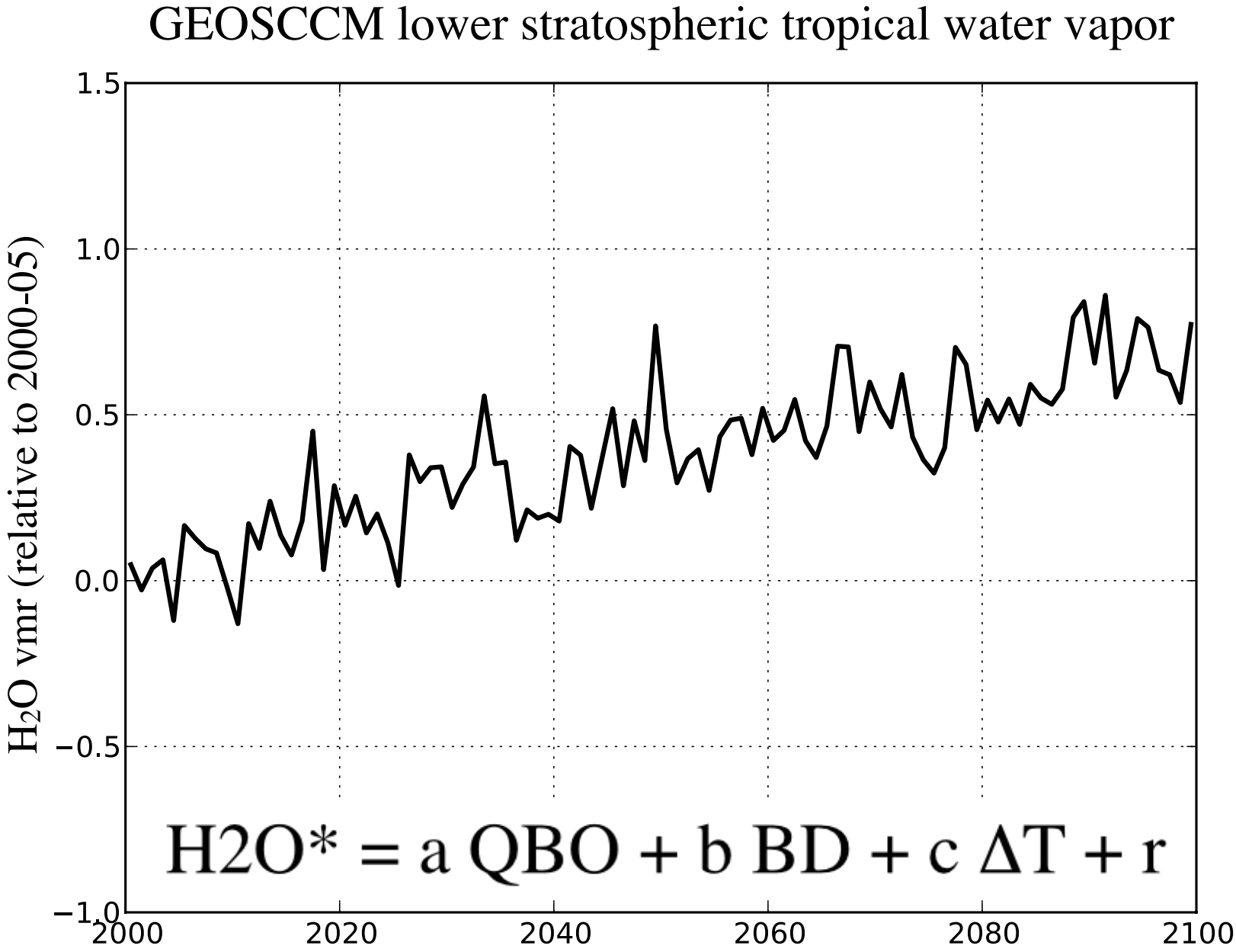
about 80% of the model's increase is due to warming TTL

conclusions, I

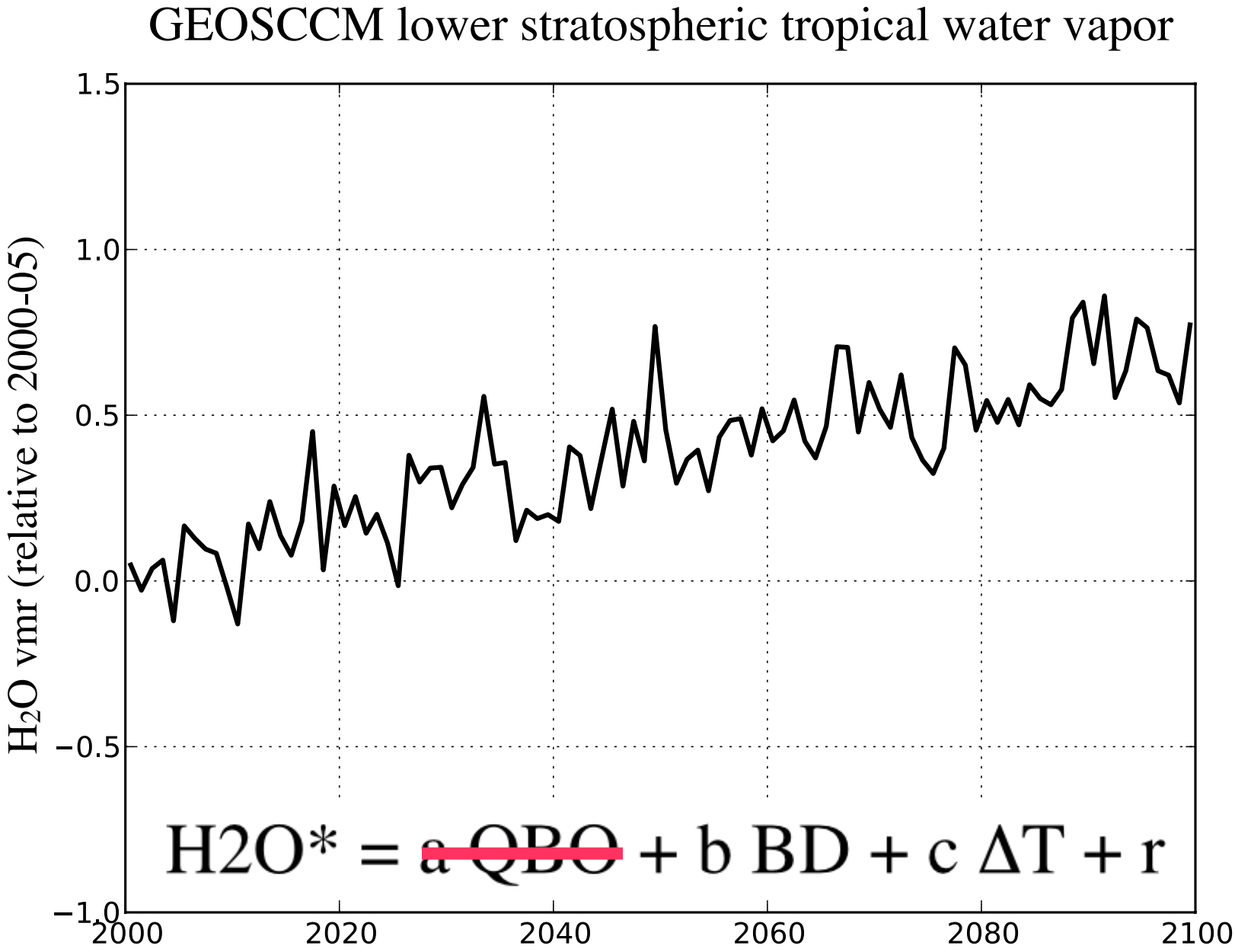
- both models have a bigger change in strat. H_2O than can be explained just by TTL temps
- these other processes explain 66% (GEOSCCM) and 20% (WACCM) of the increase in H_2O



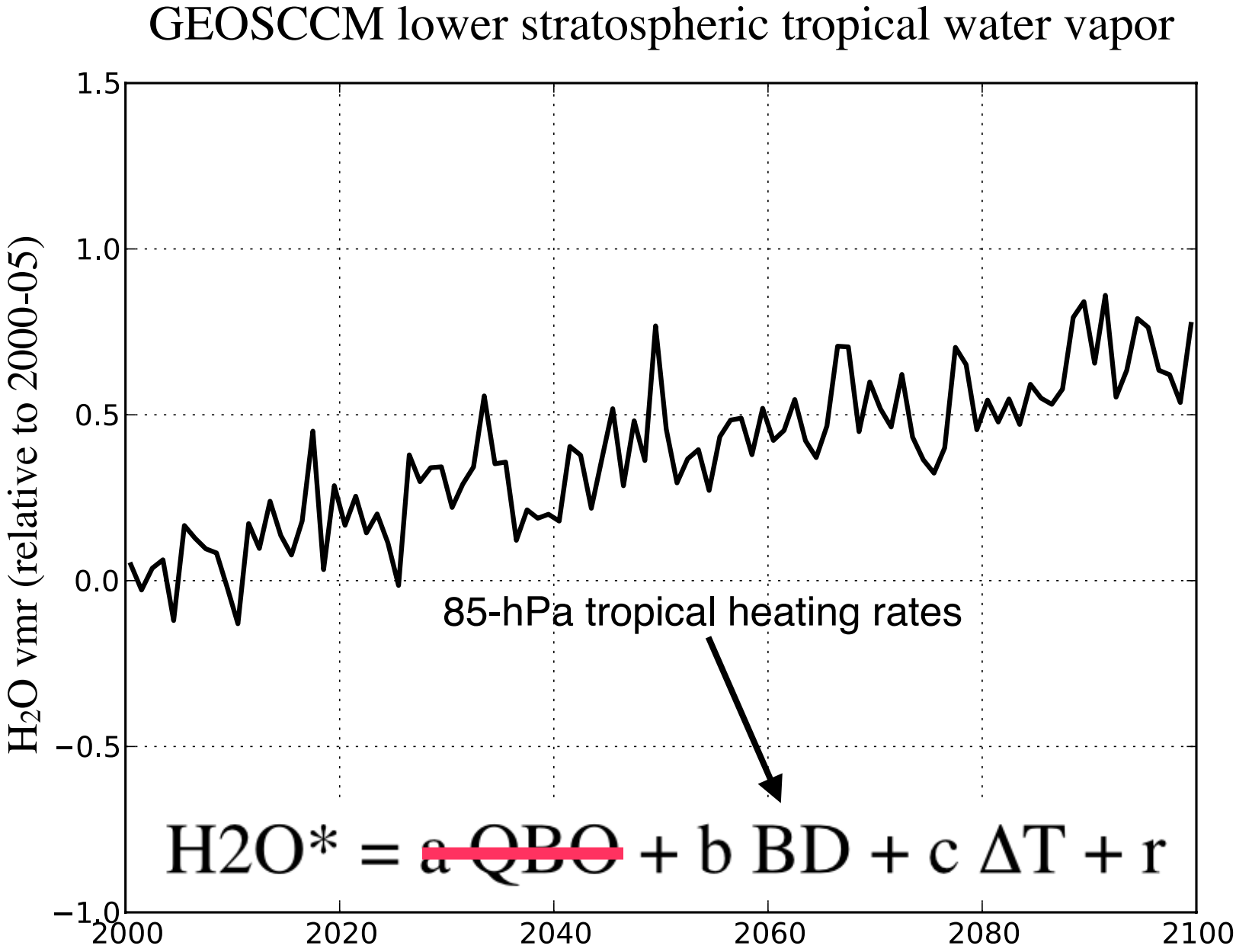
Dessler, PNAS, 2013



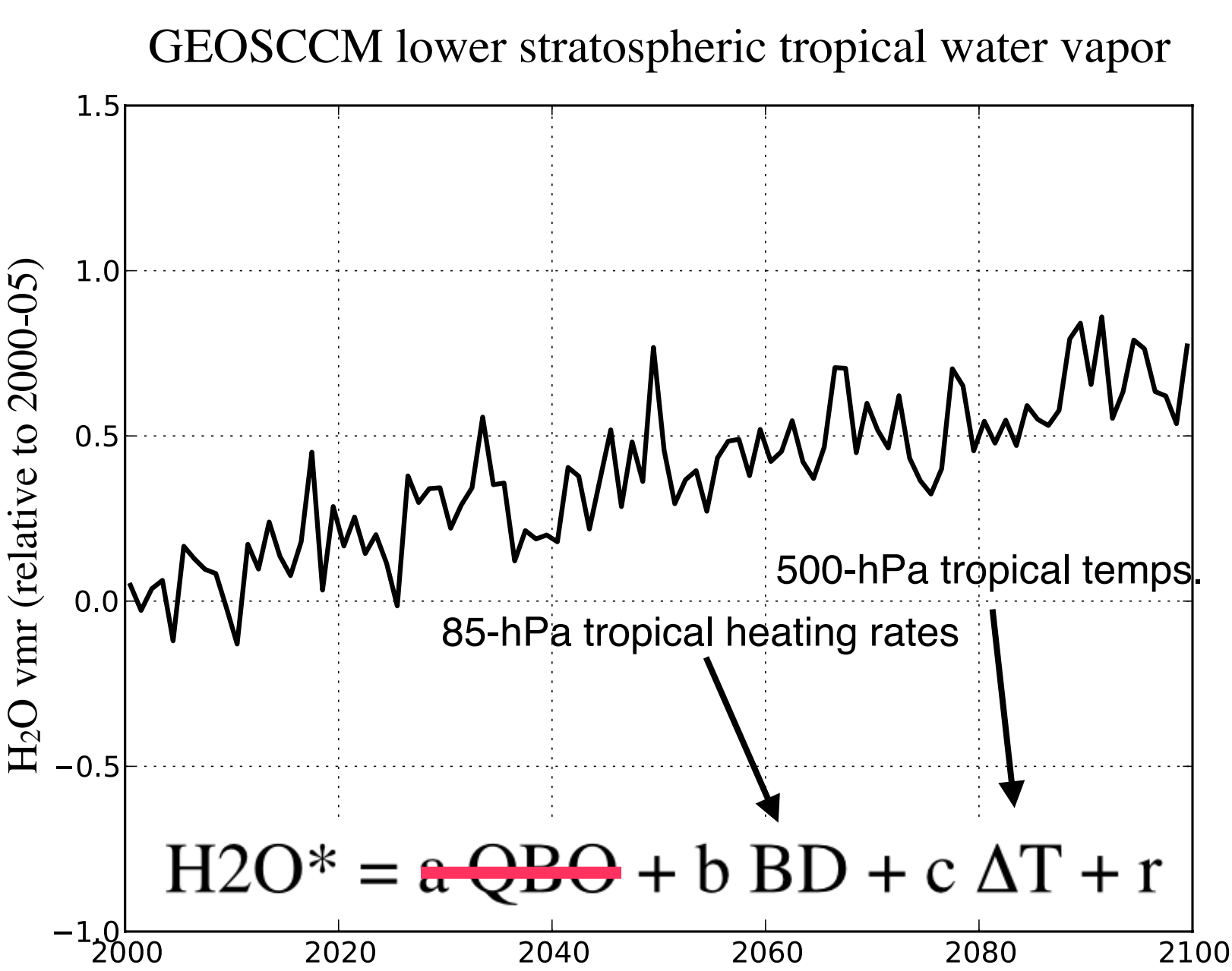
Dessler, PNAS, 2013



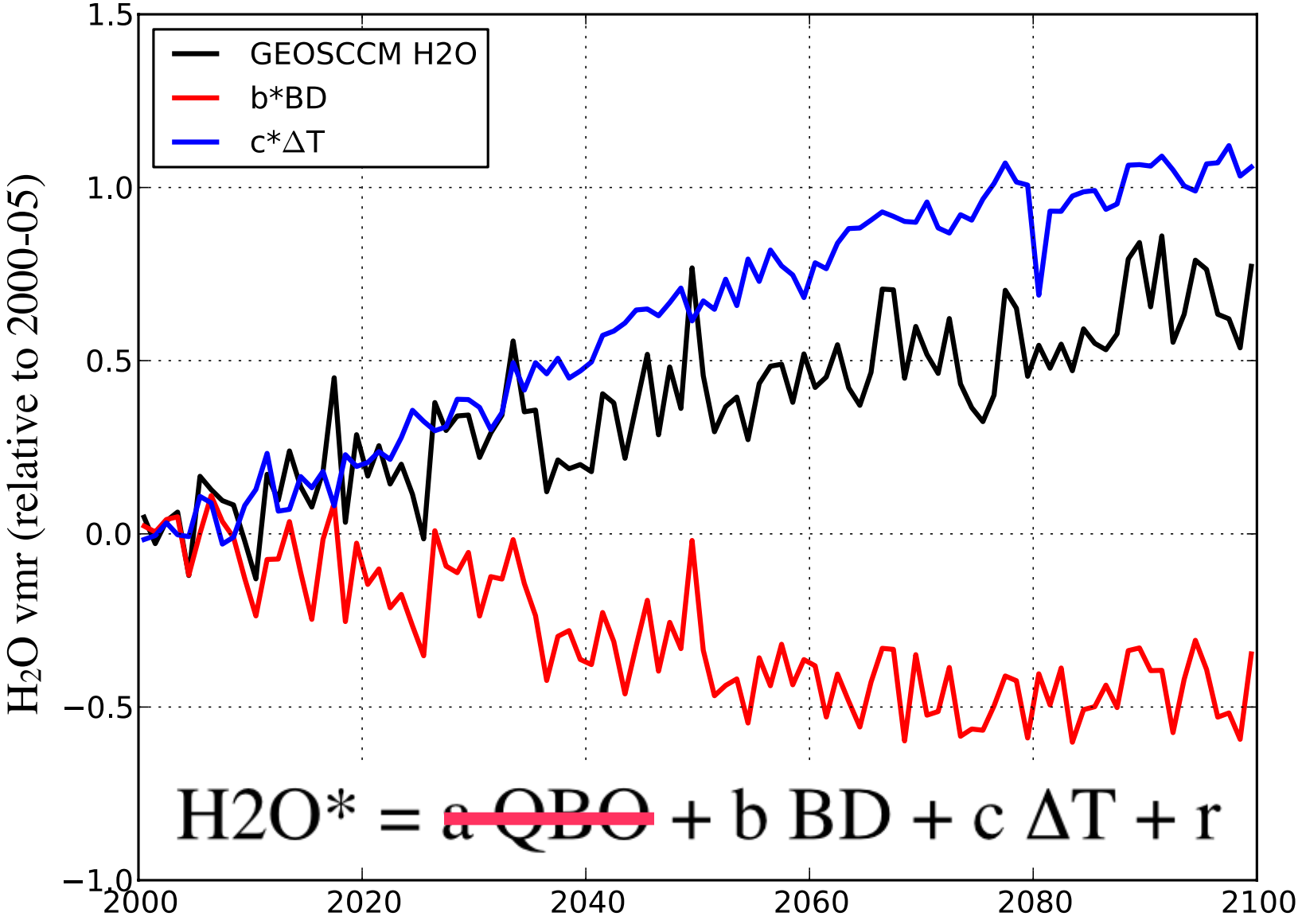
Dessler, PNAS, 2013

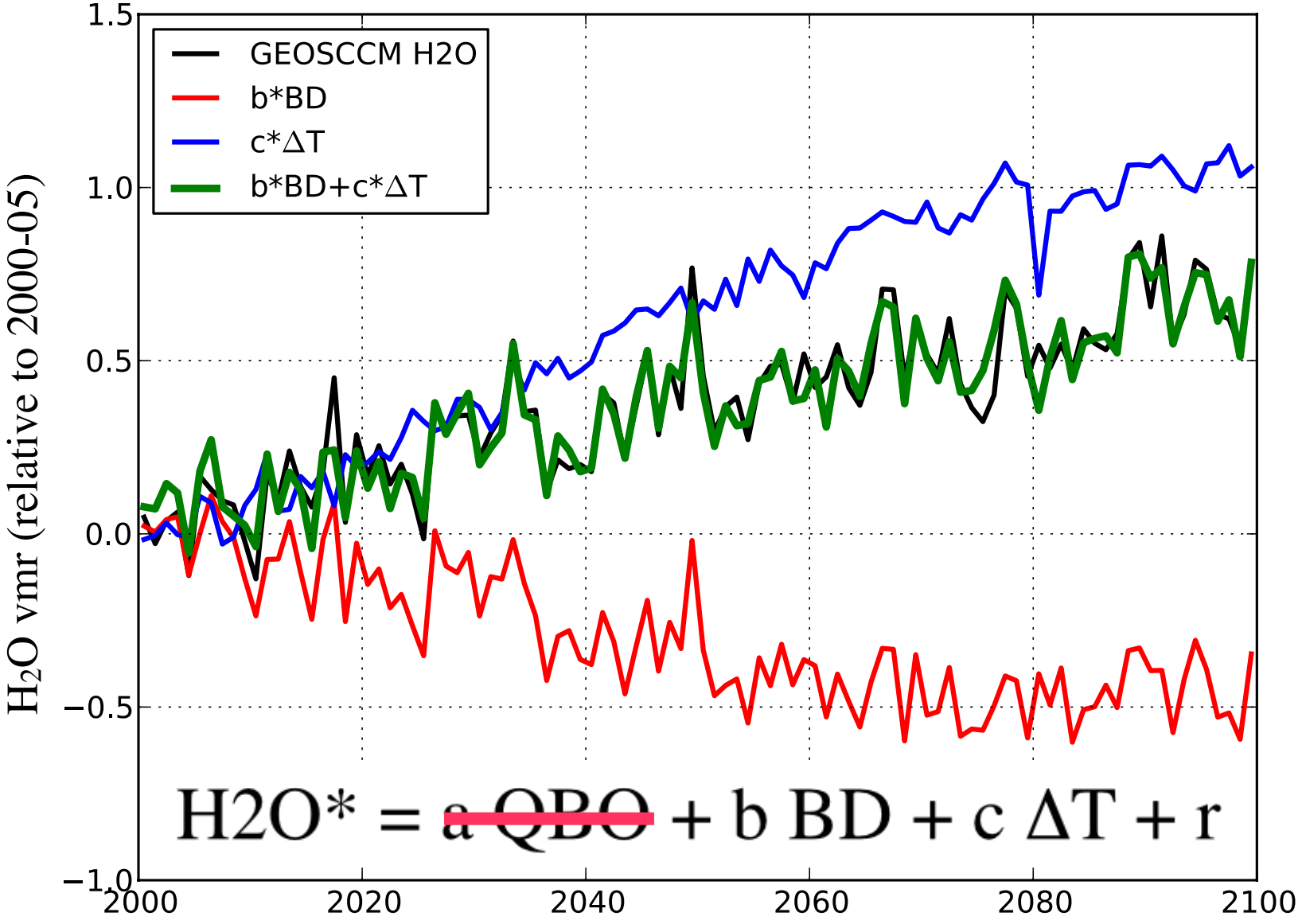


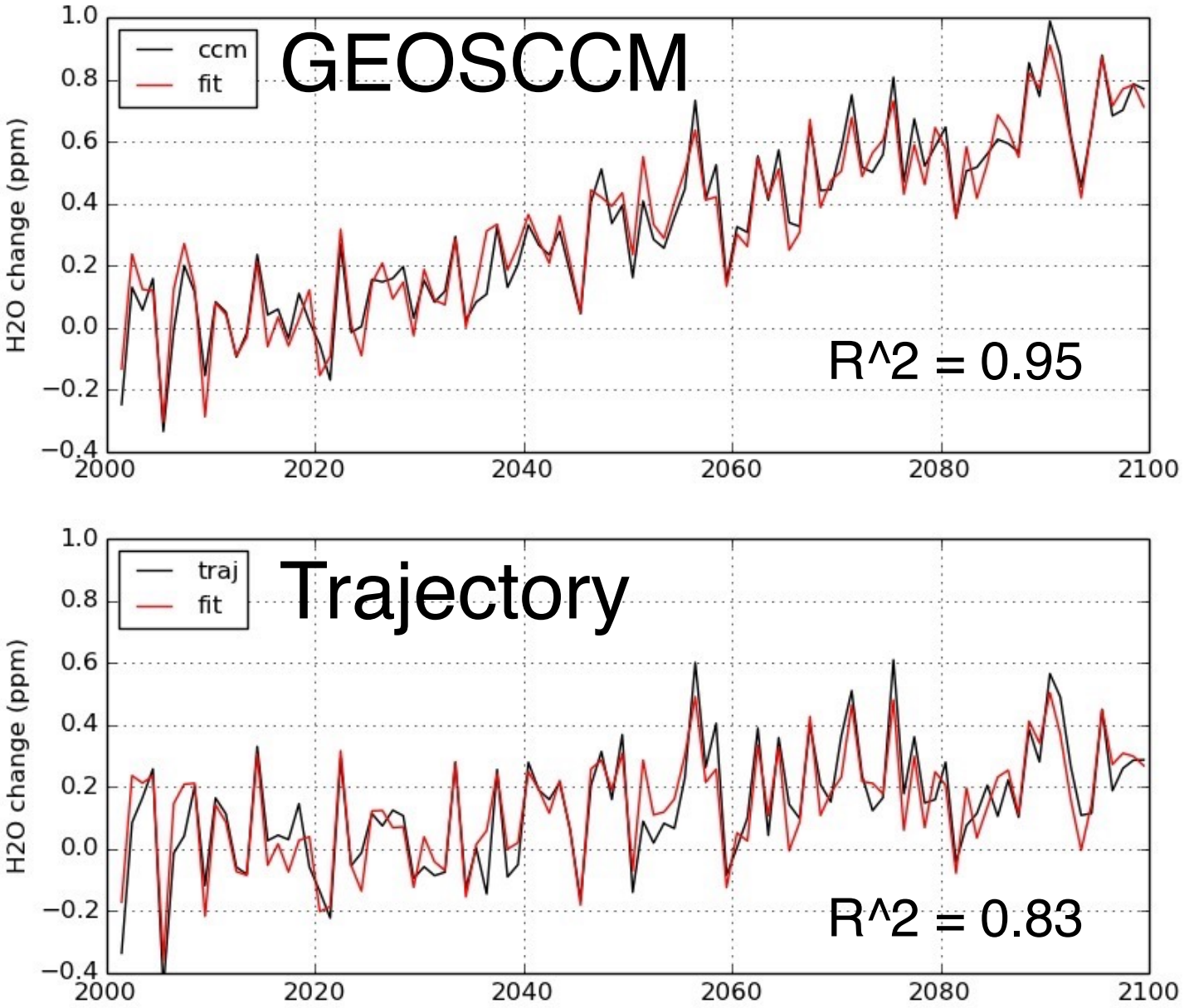
Dessler, PNAS, 2013



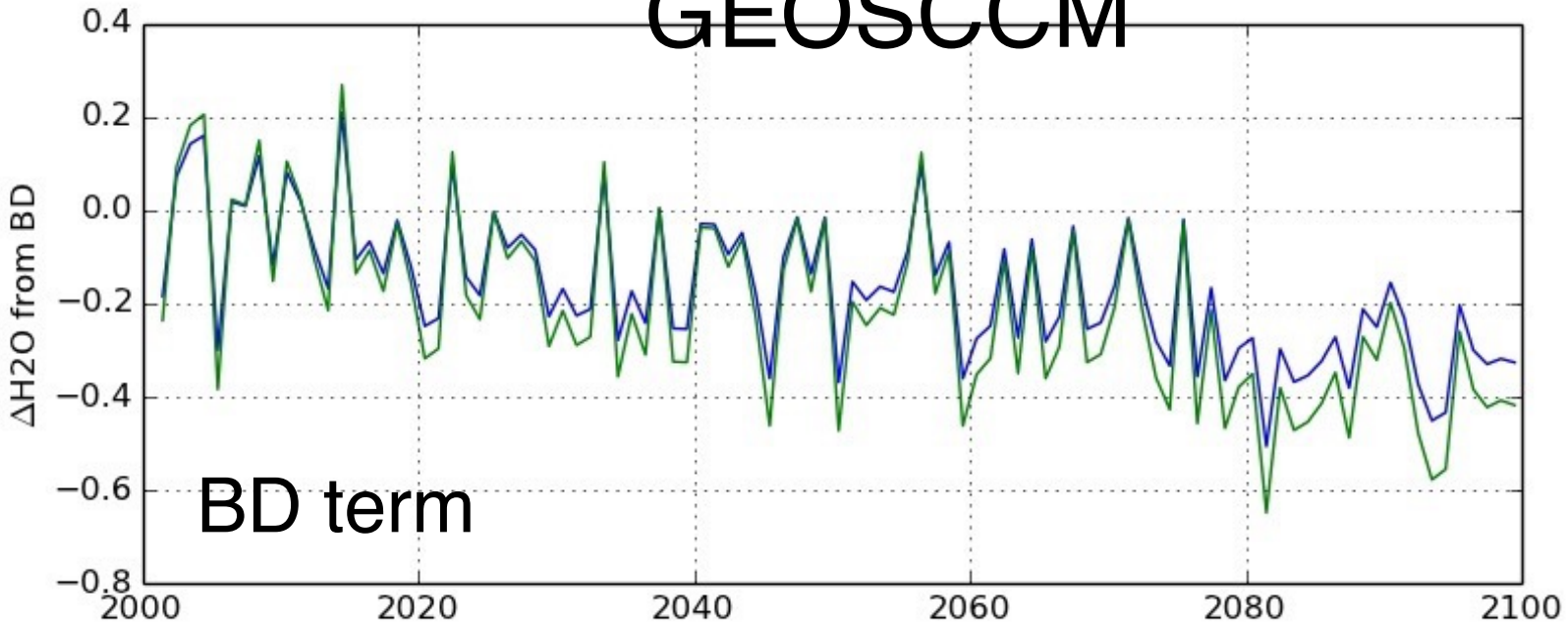
Dessler, PNAS, 2013

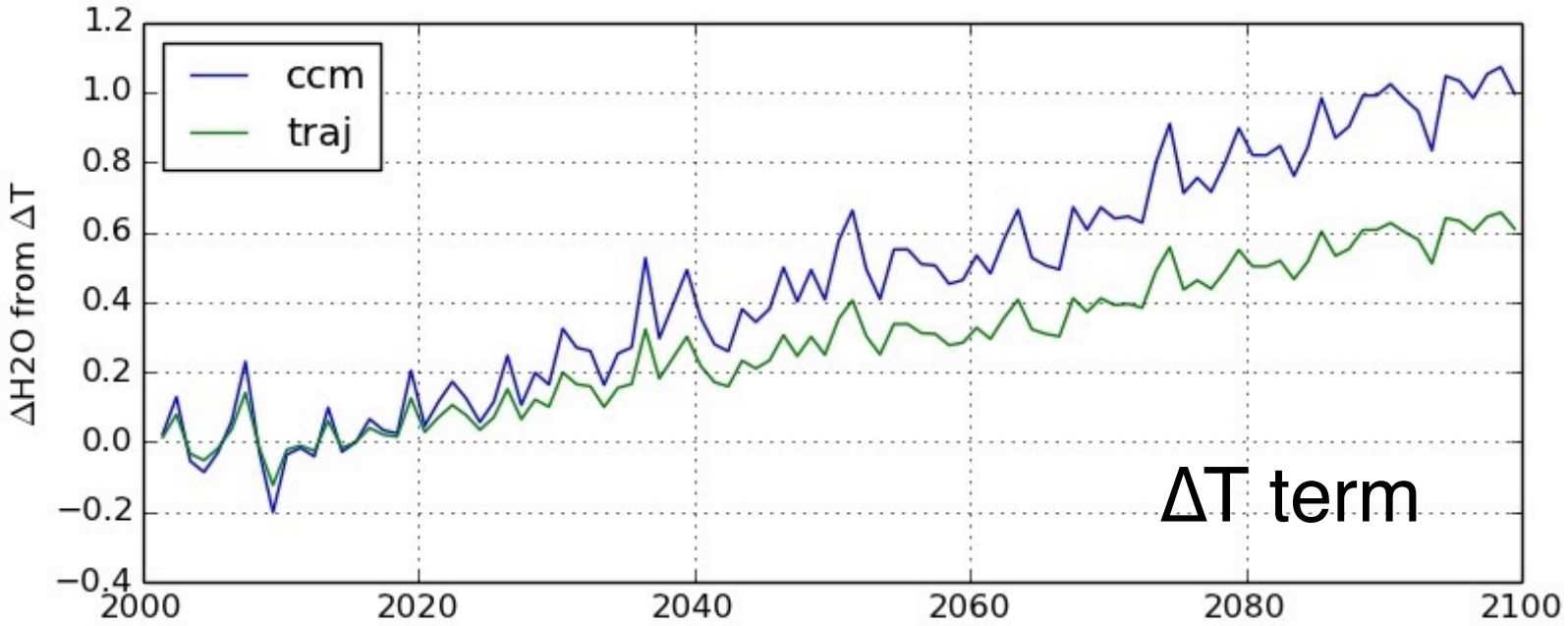

GEOSCCM H2O
b*BD
c*ΔT
H2O vmr (relative to 2000-05)
1.5
1.0
0.5
0.0
−0.5
−1.0
2000
2020
2040
2060
2080
2100
H2O* = a QBO + b BD + c ΔT + r


GEOSCCM H2O
b*BD
c*ΔT
b*BD+c*ΔT
H2O vmr (relative to 2000-05)
1.5
1.0
0.5
0.0
−0.5
−1.0
2000
2020
2040
2060
2080
2100
H2O* = a QBO + b BD + c ΔT + r

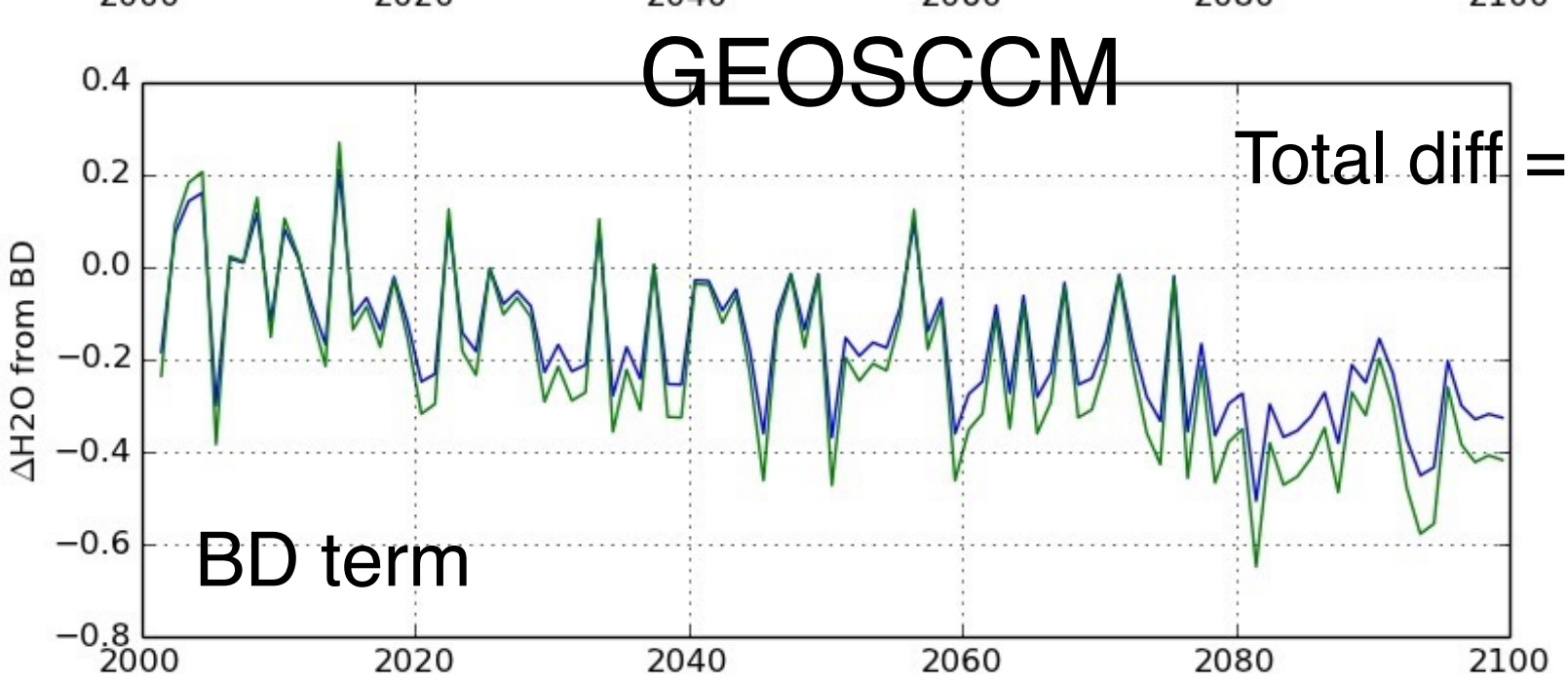

GEOSCCM
ccm
fit
H2O change (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100
R^2 = 0.95
Trajectory
traj
fit
H2O change (ppm)
R^2 = 0.83

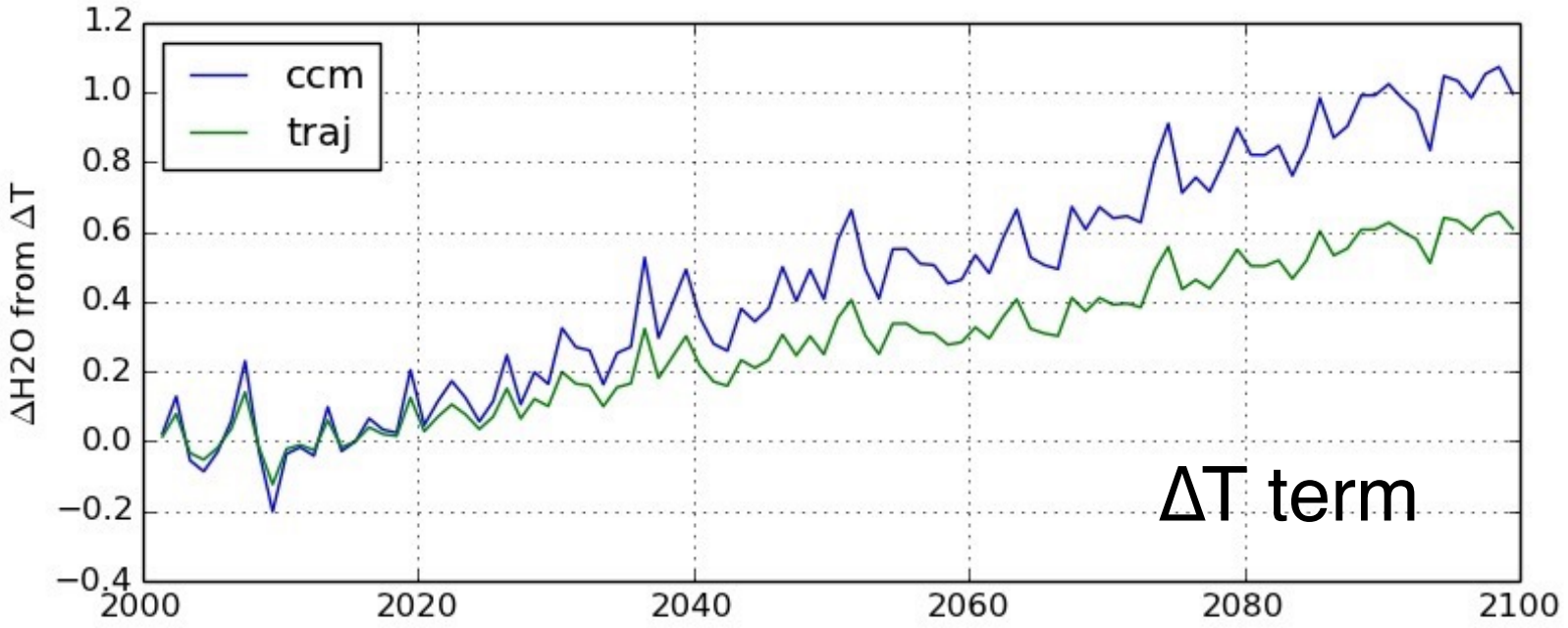
GEOSCCM


ΔH2O from BD
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2000
2020
2040
2060
2080
2100
BD term

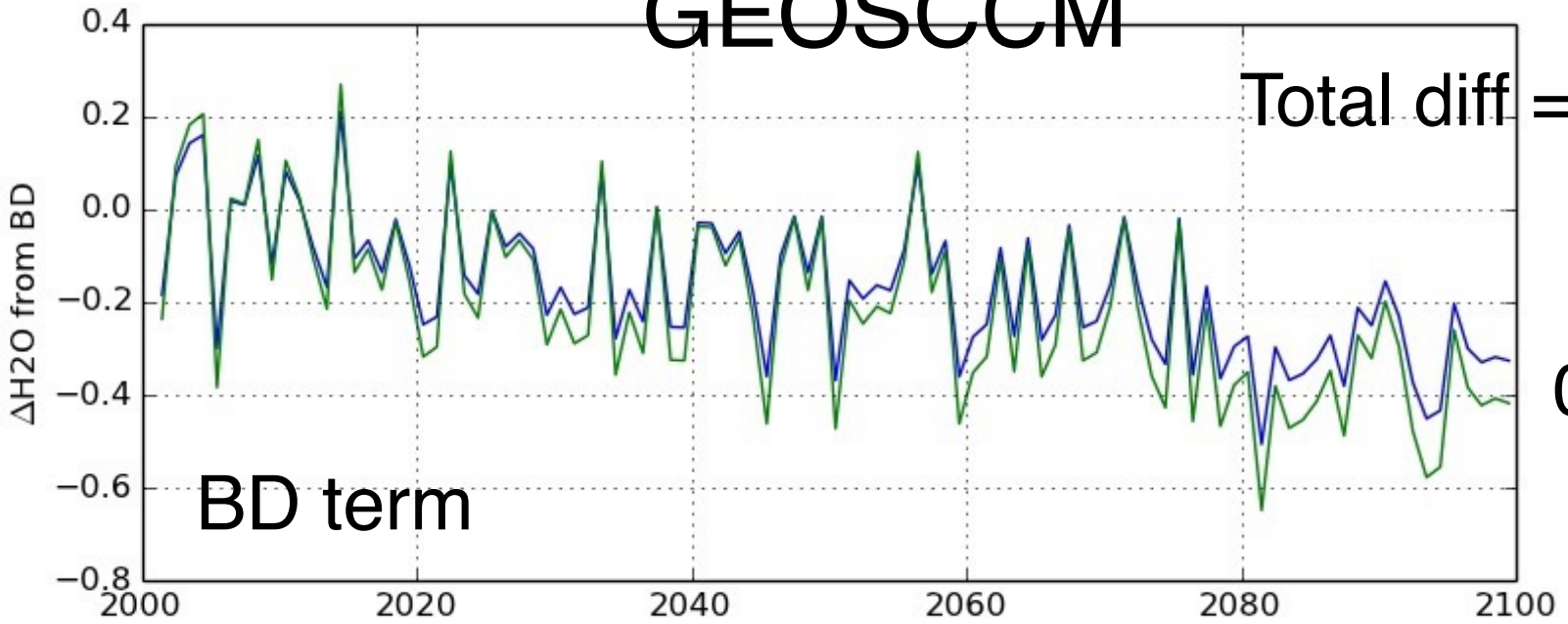

ΔH2O from ΔT
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100
ccm
traj
ΔT term

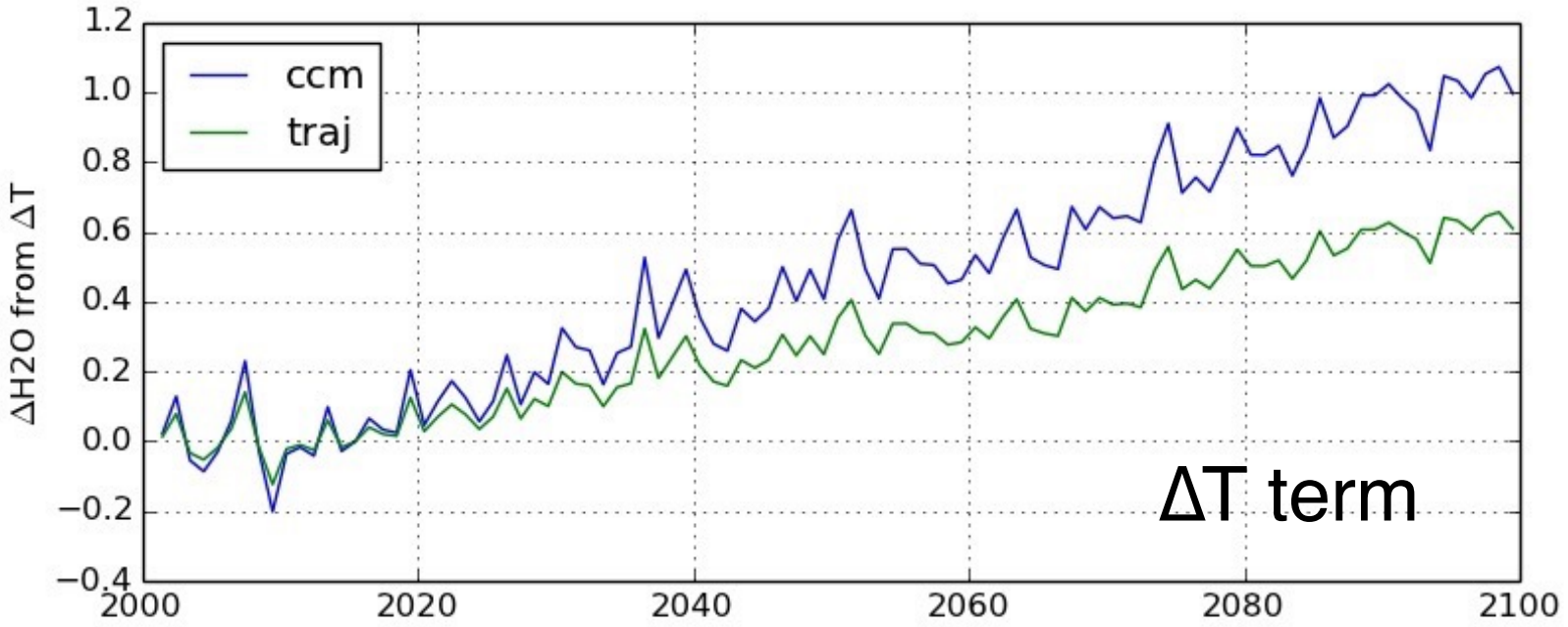
GEOSCCM


Total diff = 0.50
ΔH2O from BD
BD term
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2000
2020
2040
2060
2080
2100

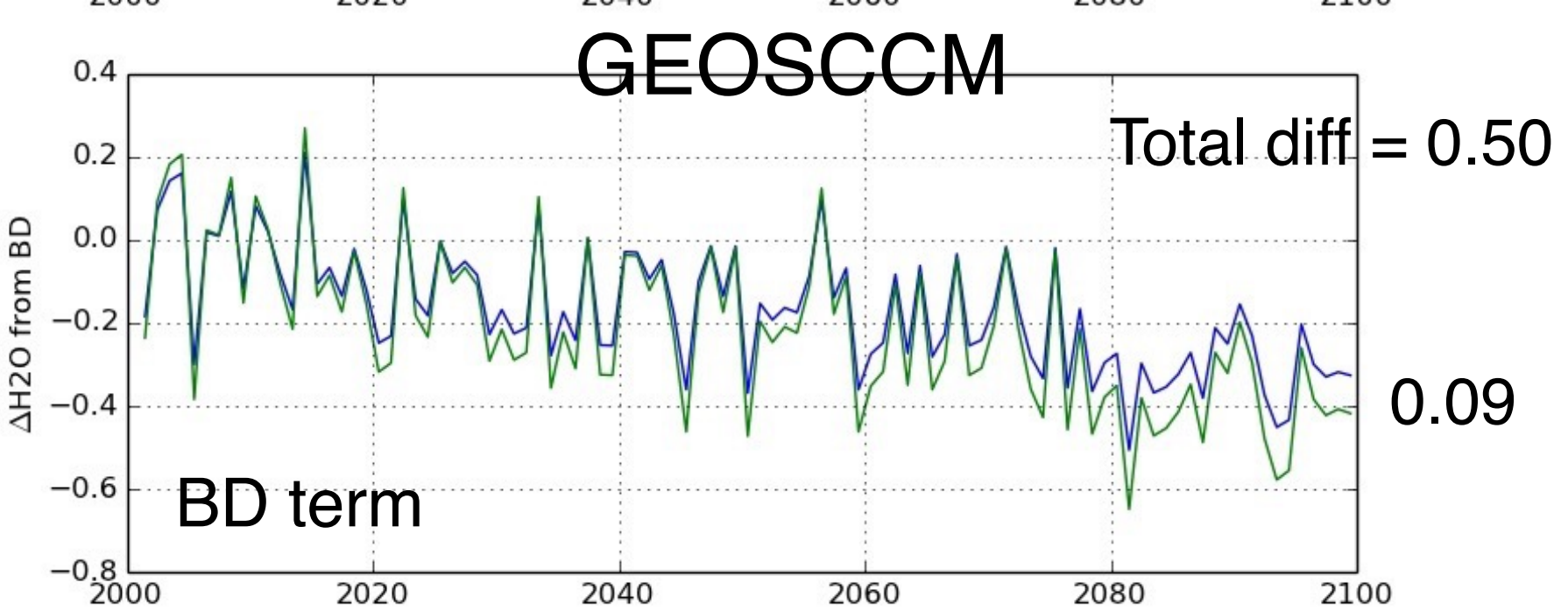

ccm
traj
ΔH2O from ΔT
ΔT term
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100

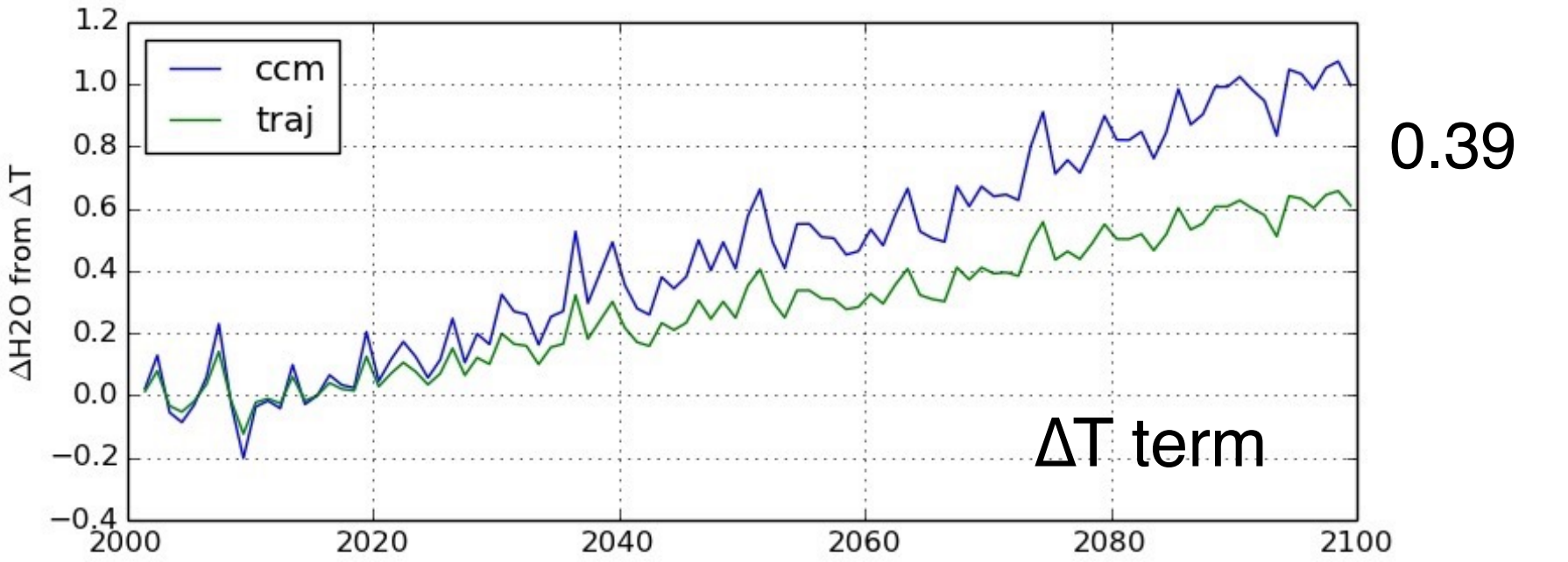
GEOSCCM

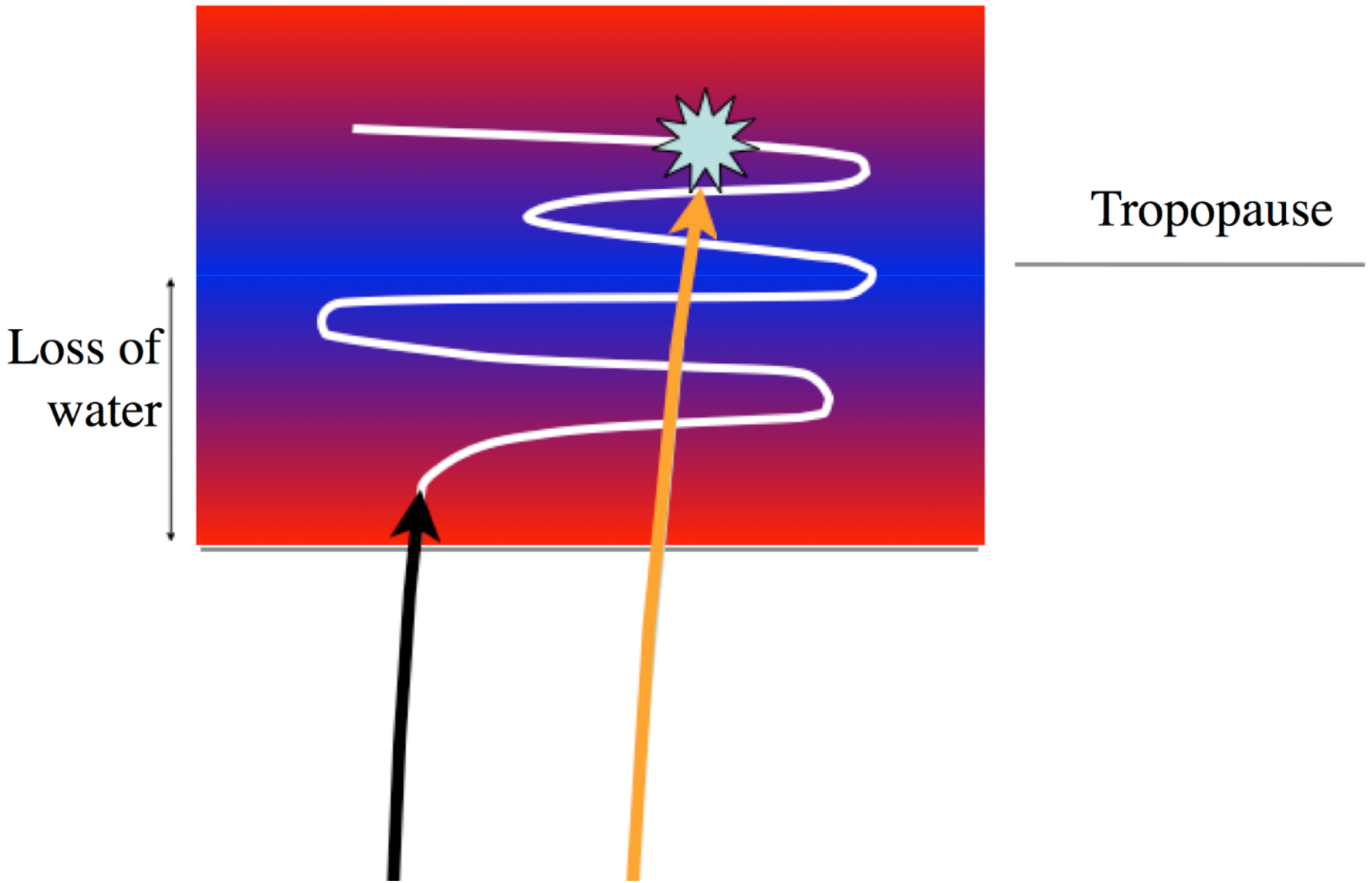

Total diff = 0.50
0.09
BD term
ΔH2O from BD
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2000
2020
2040
2060
2080
2100

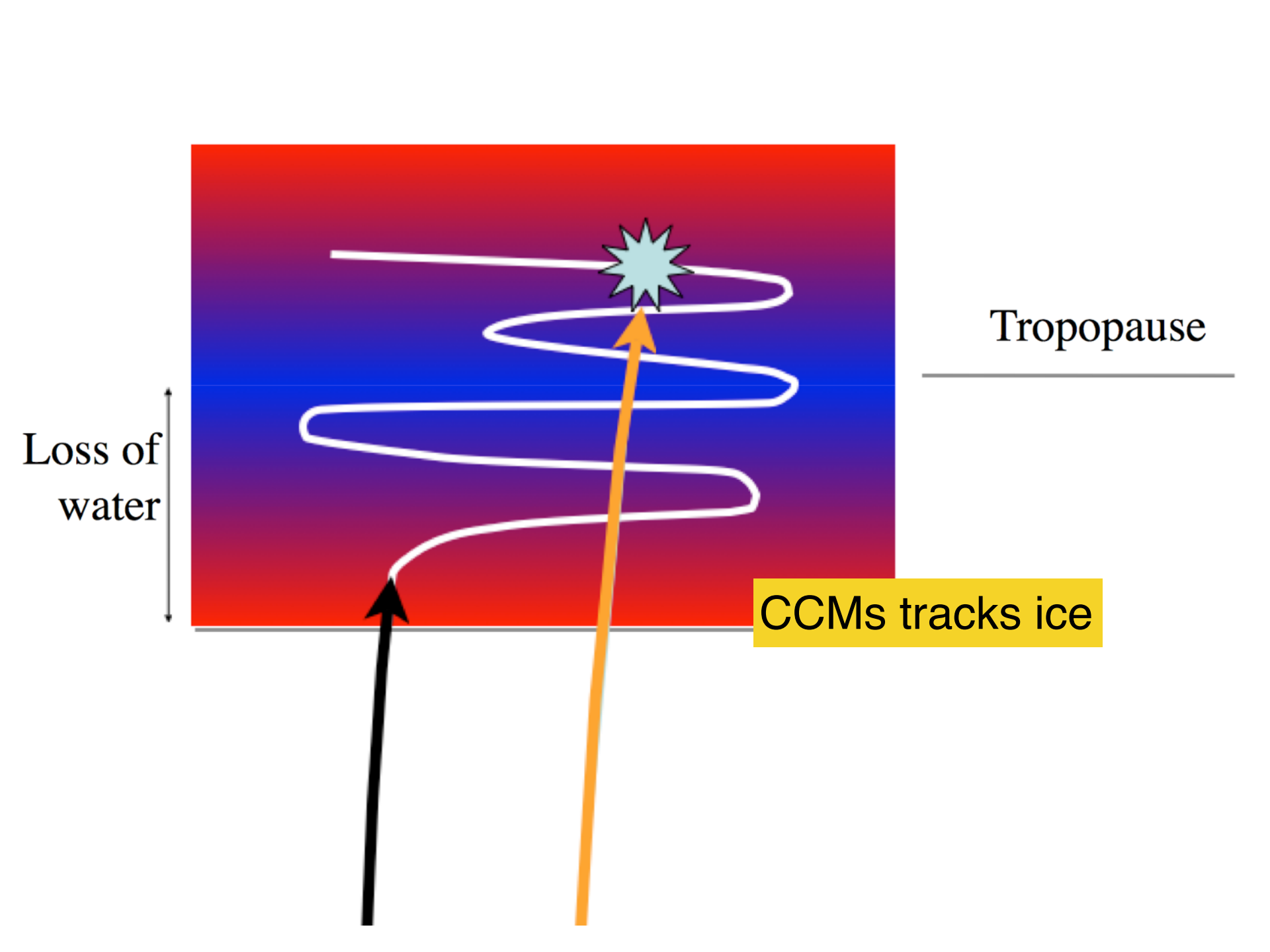

ccm
traj
ΔT term
ΔH2O from ΔT
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100

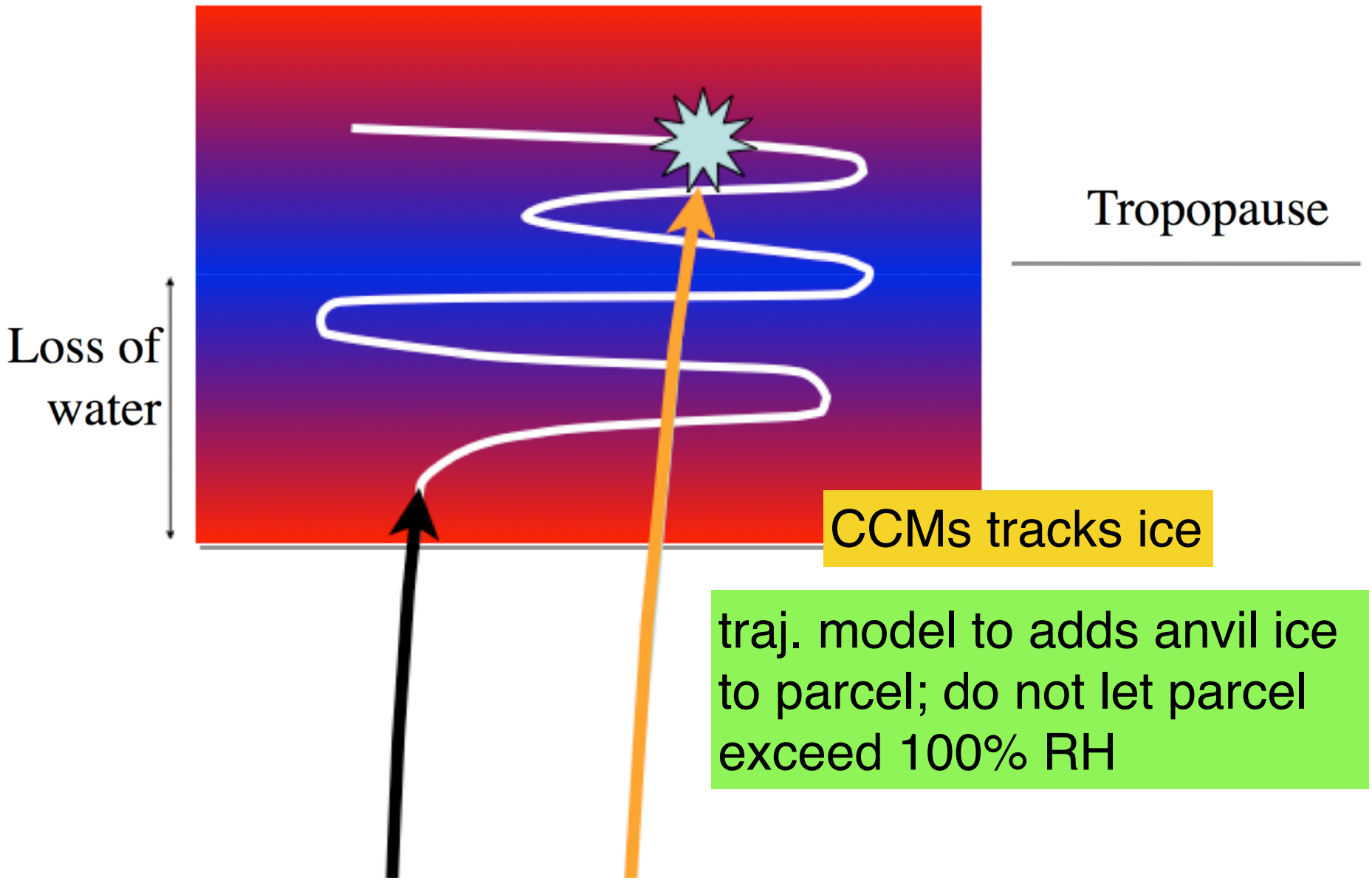
GEOSCCM

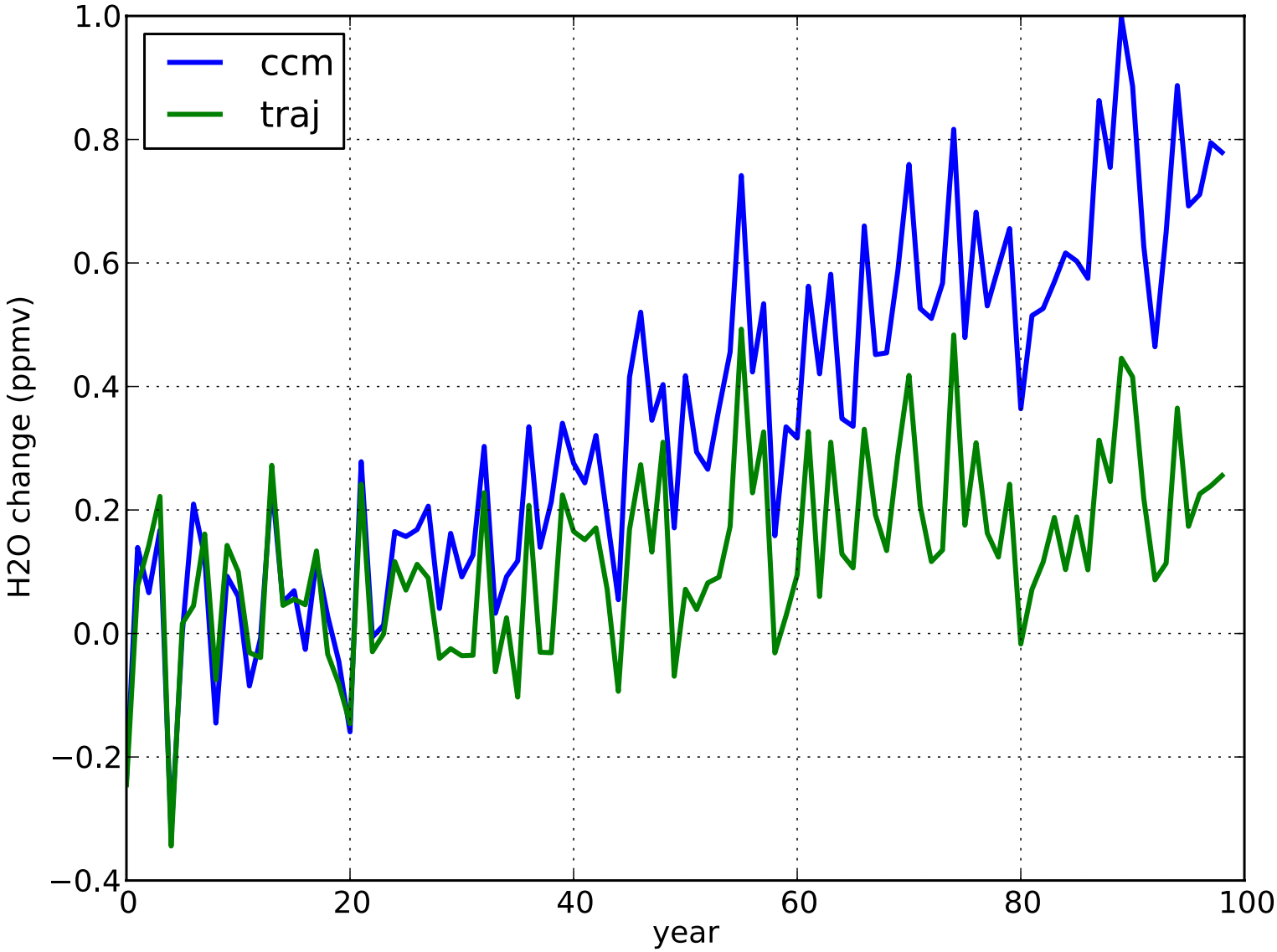

Total diff = 0.50
0.09
BD term
ΔH2O from BD
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2000
2020
2040
2060
2080
2100


ccm
traj
0.39
ΔT term
ΔH2O from ΔT
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2020
2040
2060
2080
2100

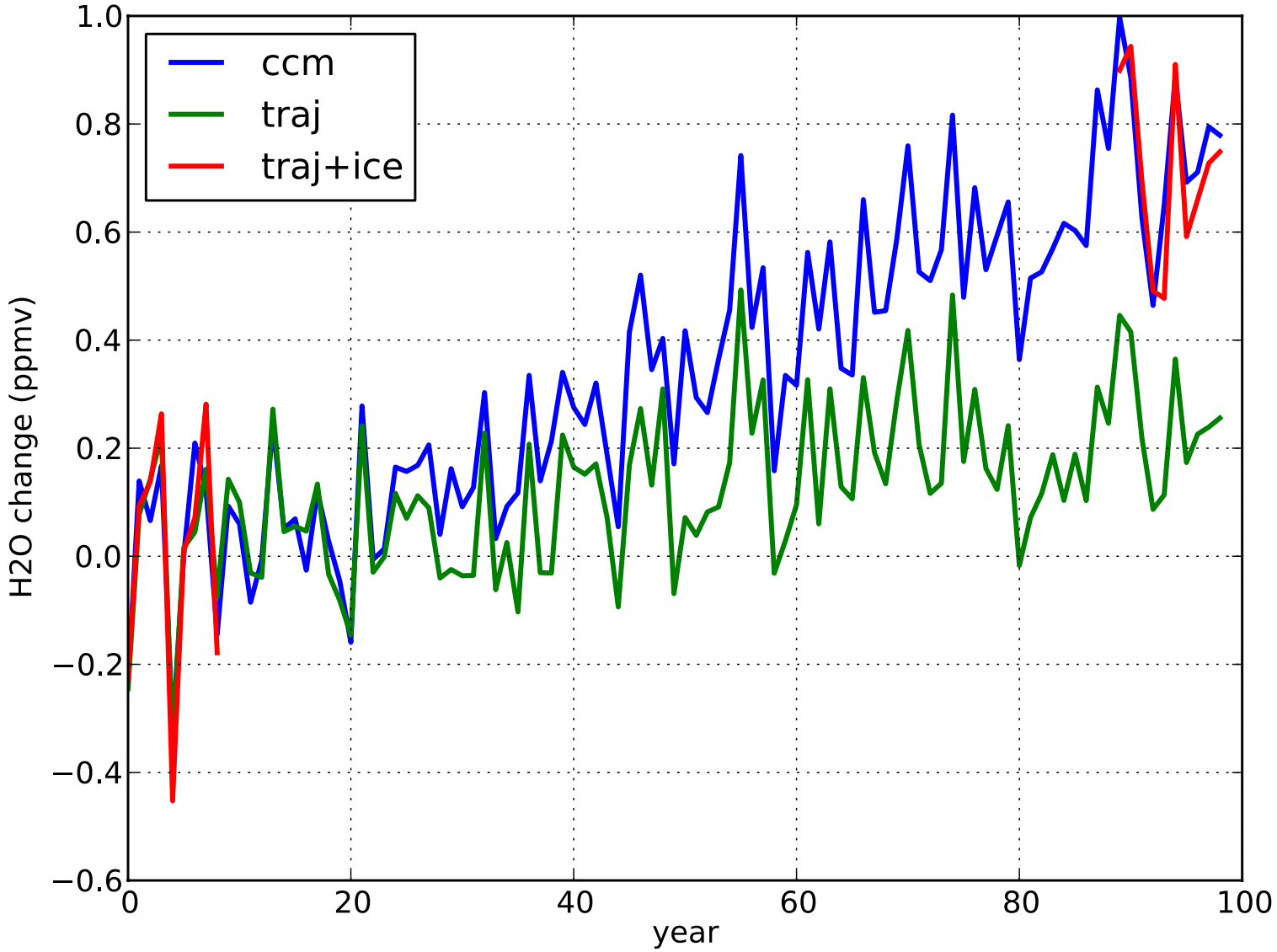

Tropopause
Loss of water


Tropopause
Loss of water
CCMs tracks ice

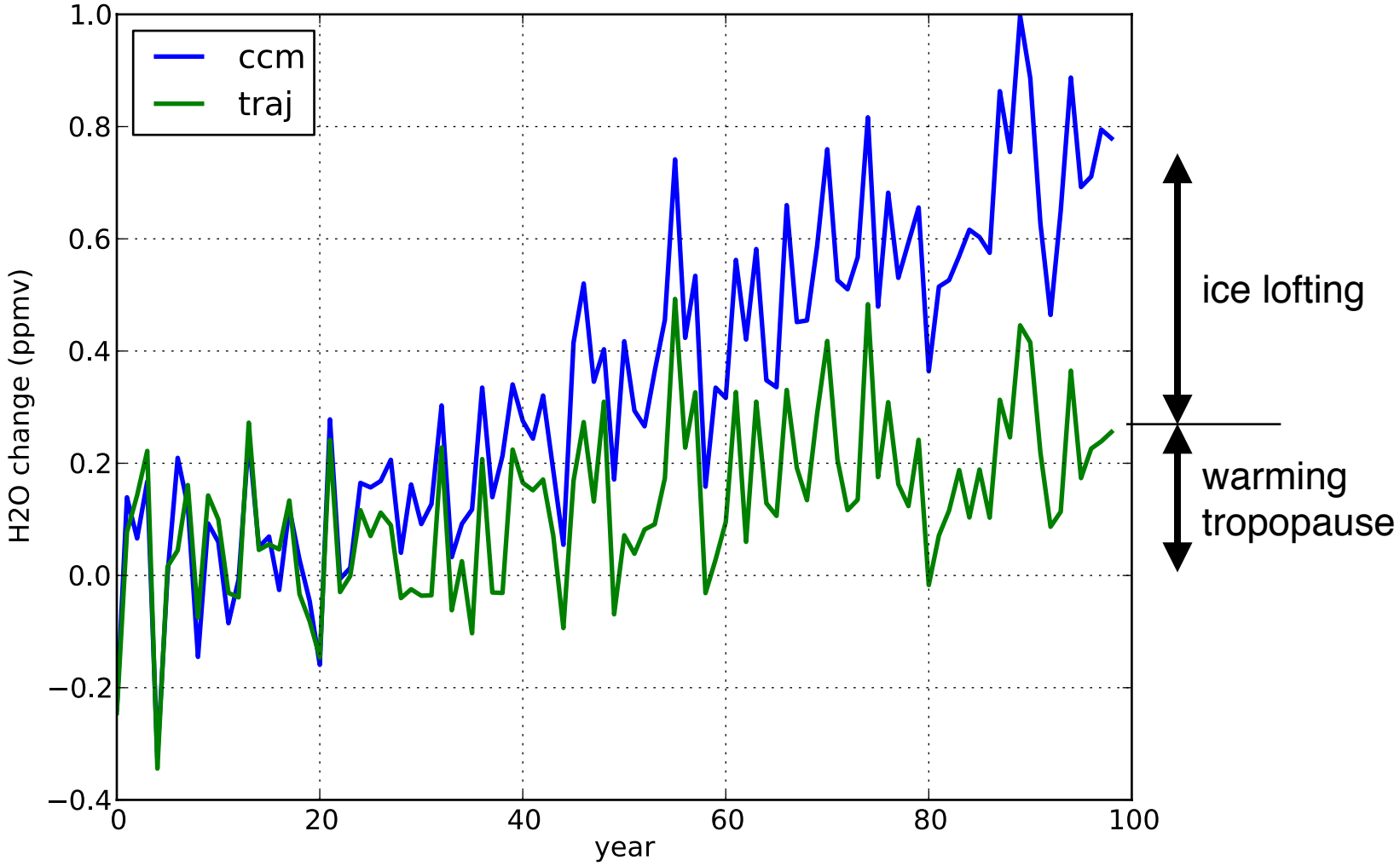

Tropopause
Loss of water
CCMs tracks ice
traj. model to adds anvil ice to parcel; do not let parcel exceed 100% RH



GEOSCCM & trajectory, 85-hPa tropical annual avg.

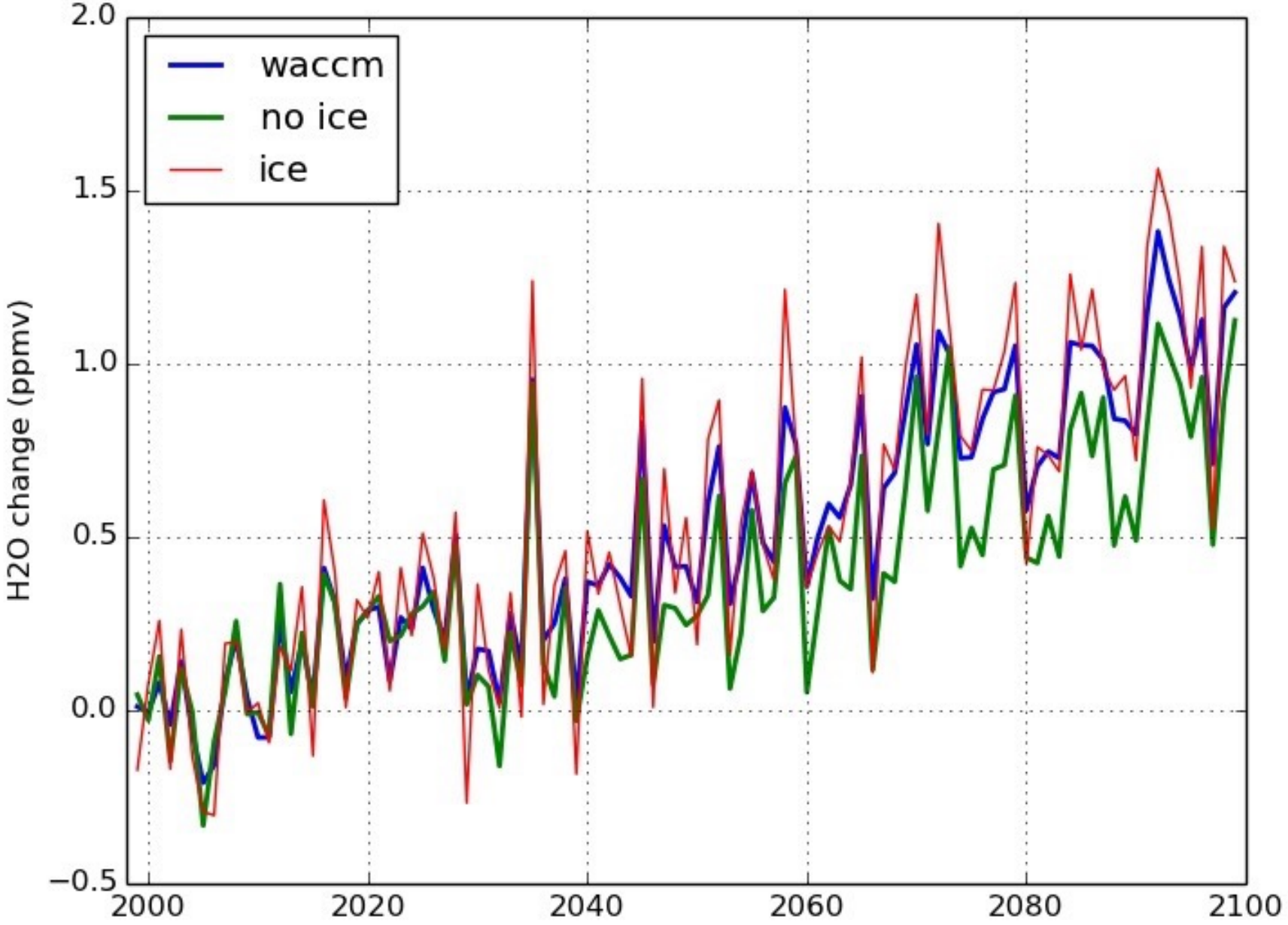


GEOSCCM & trajectory, 85-hPa tropical annual avg.



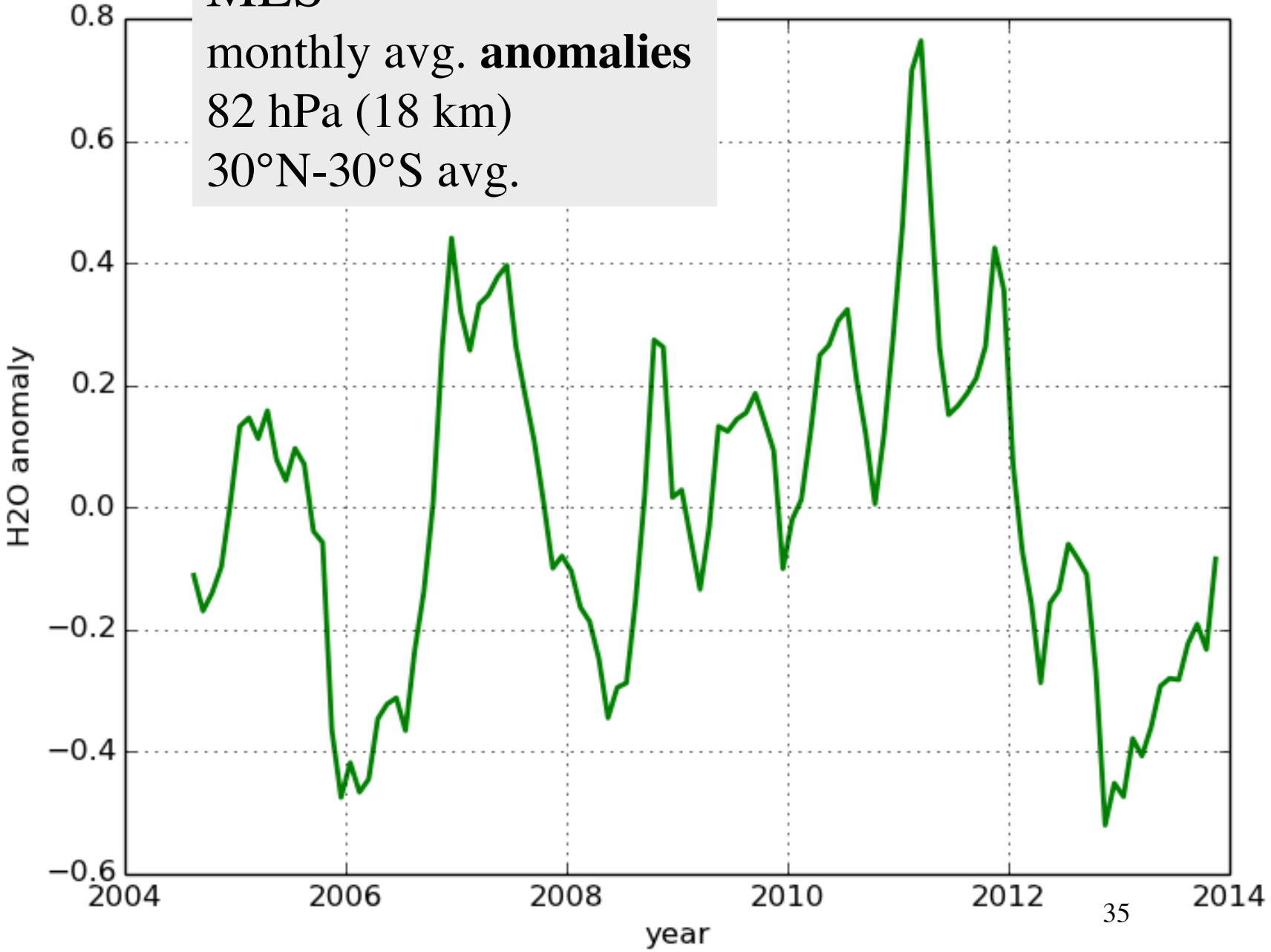
GEOSCCM & trajectory, 85-hPa tropical annual avg.

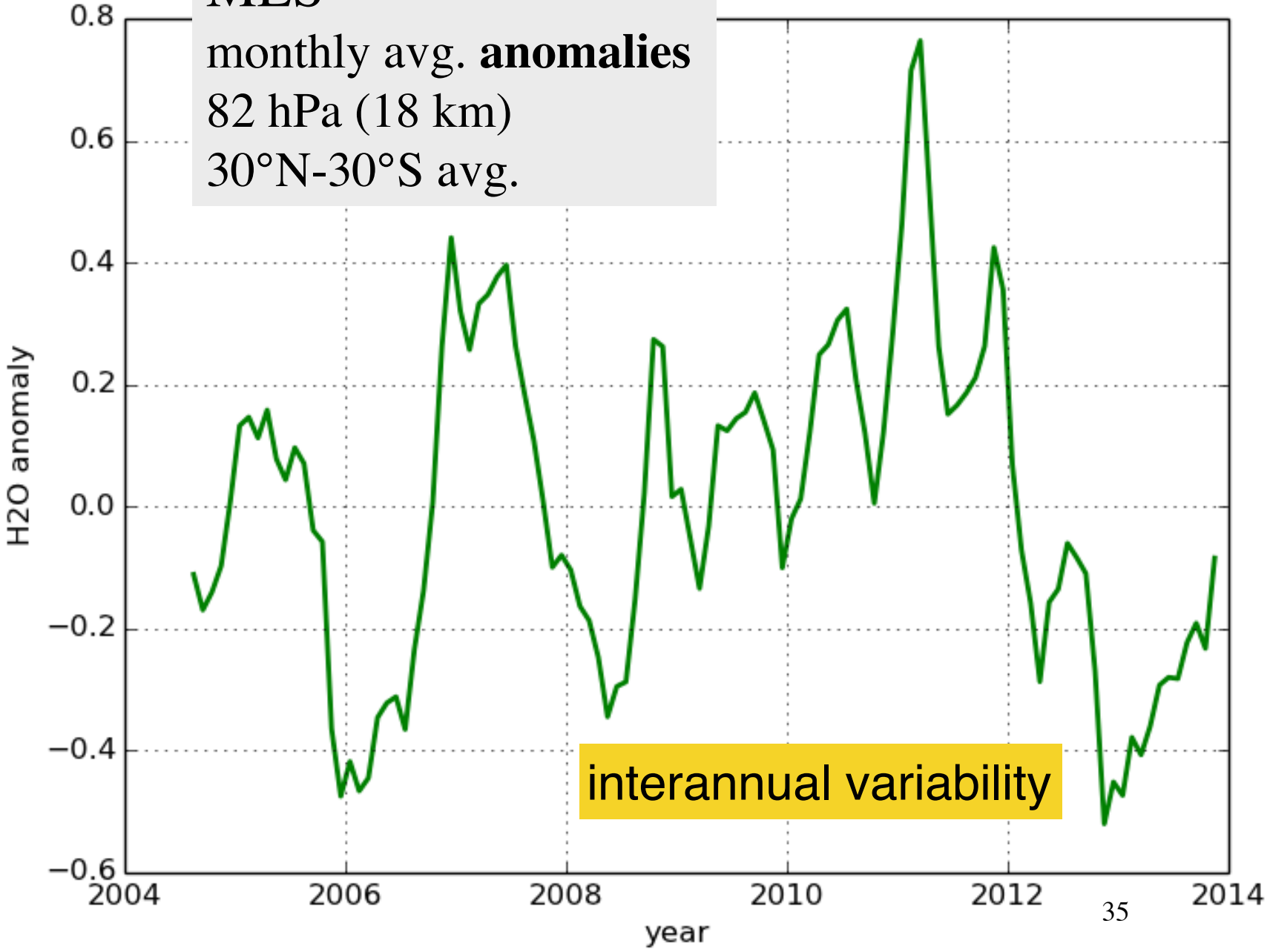
WACCM


waccm
no ice
ice
H2O change (ppmv)
2.0
1.5
1.0
0.5
0.0
−0.5
2000
2020
2040
2060
2080
2100

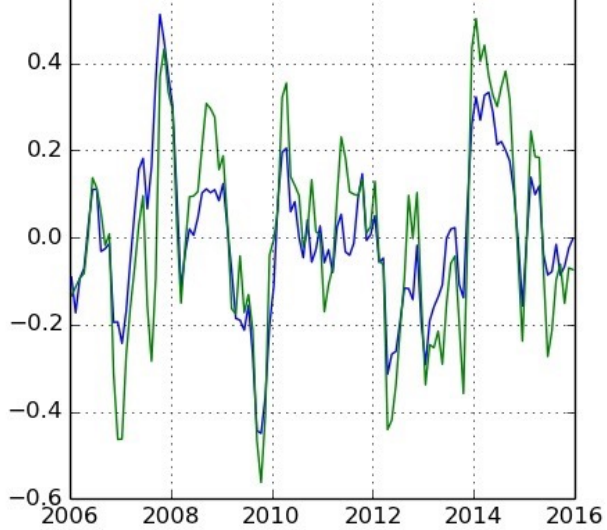
conclusions, II

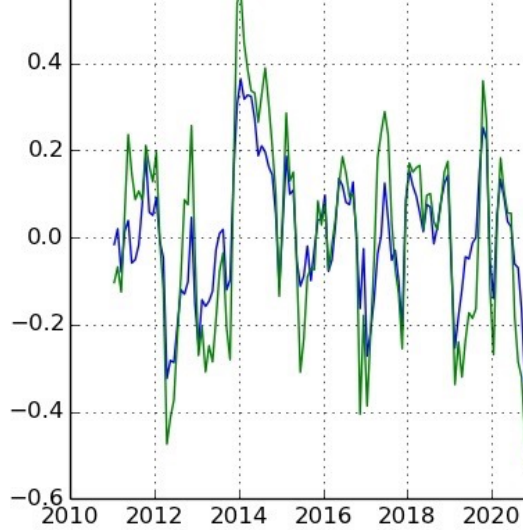
- both models have a bigger change in strat. H_2O than can be explained just by TTL temps
- these other processes explain 15% (WACCM) and 60% (GEOSCCM) of the increase
- missing processes mainly correlate with tropospheric temperature
- ice lofting is a very plausible solution

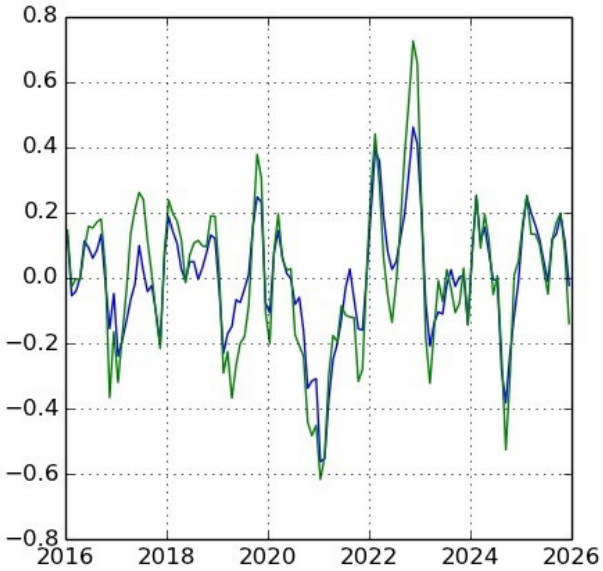

MLS
monthly avg. **anomalies**
82 hPa (18 km)
30°N-30°S avg.
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
H2O anomaly
2004
2006
2008
2010
2012
2014
year

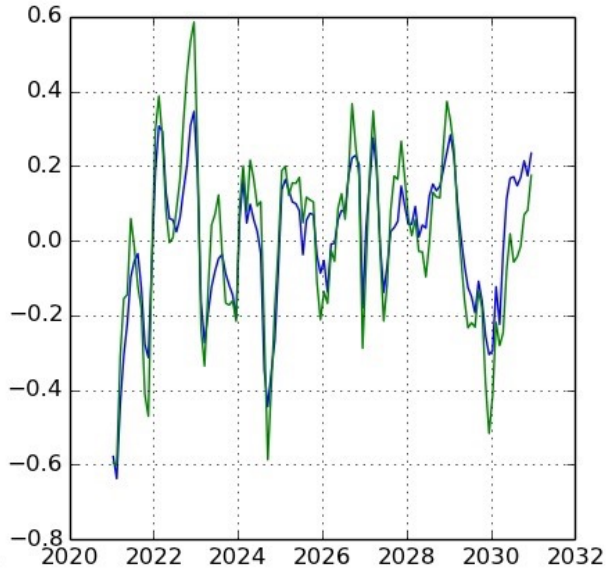

MLS
monthly avg. **anomalies**
82 hPa (18 km)
30°N-30°S avg.
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
H2O anomaly
2004
2006
2008
2010
2012
2014
year
interannual variability

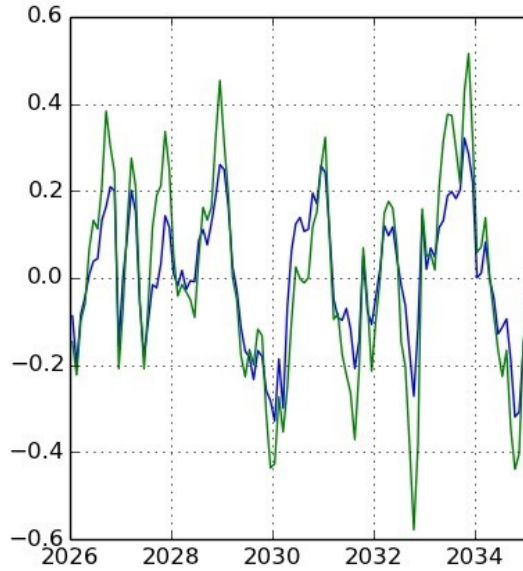

0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2000
2002
2004
2006
2008
2010
2012

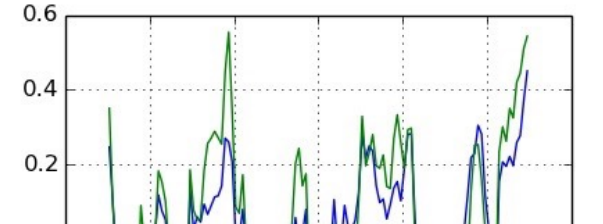

0.4
0.2
0.0
−0.2
−0.4
−0.6
2006
2008
2010
2012
2014
2016

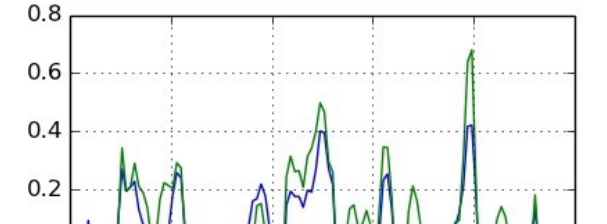

0.4
0.2
0.0
−0.2
−0.4
−0.6
2010
2012
2014
2016
2018
2020

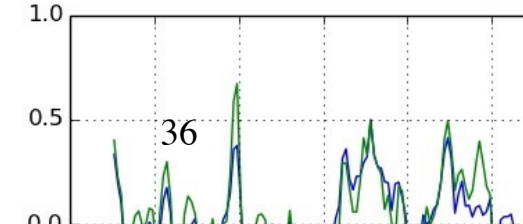

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2020
2022
2024
2026
2028
2030
2032

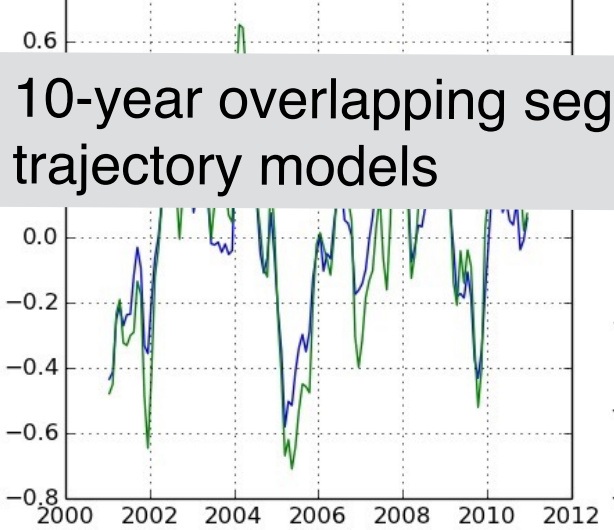

0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
2026
2028
2030
2032
2034

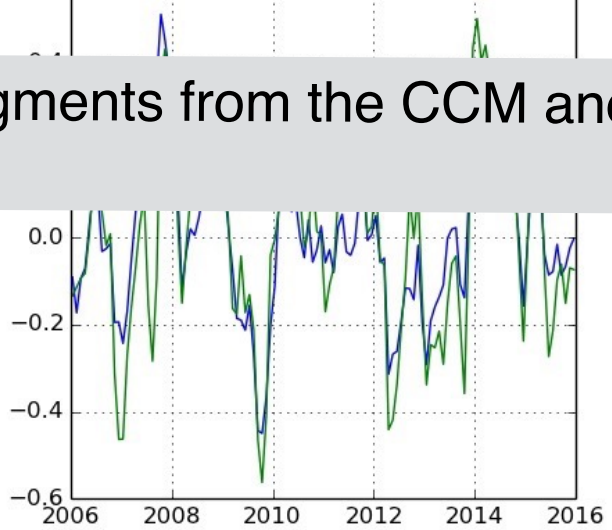

0.6
0.4
0.2

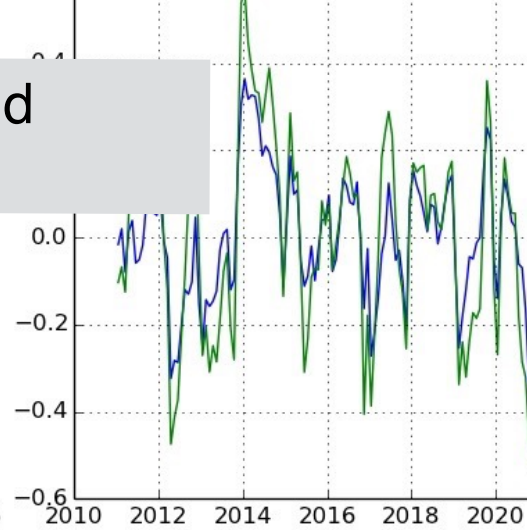

0.8
0.6
0.4
0.2

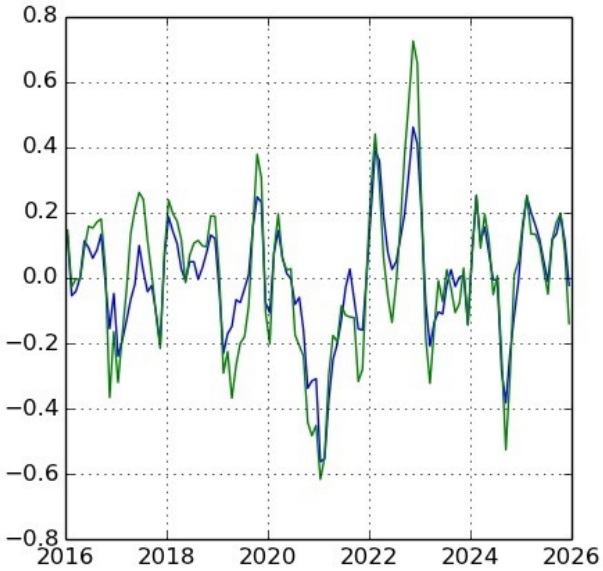

1.0
0.5

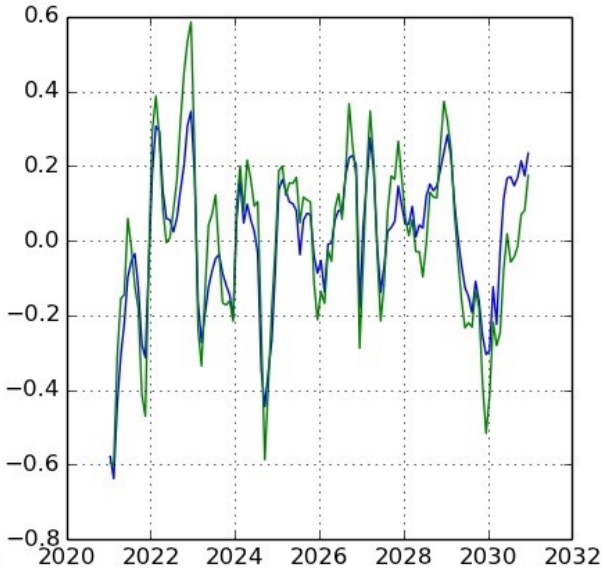
- 10-year overlapping segments from the CCM and trajectory models

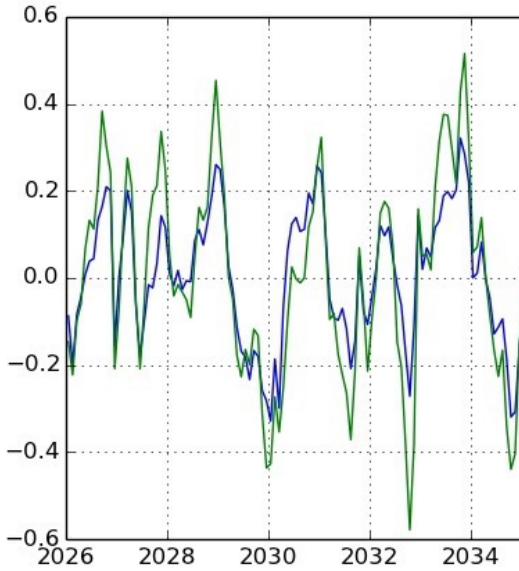


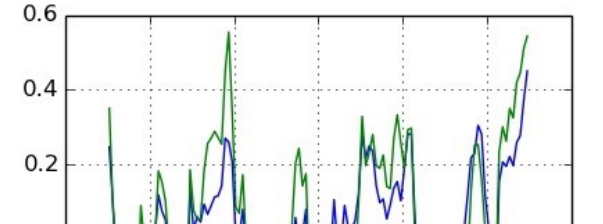


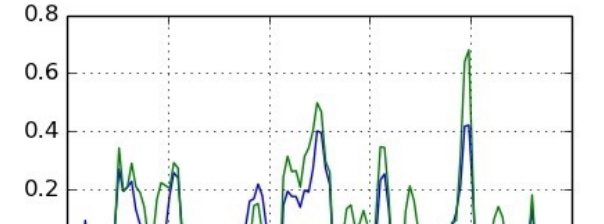


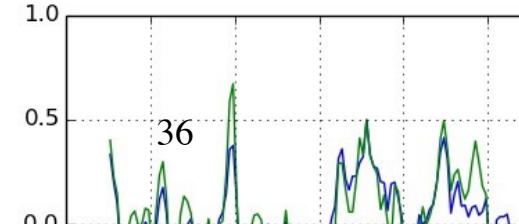




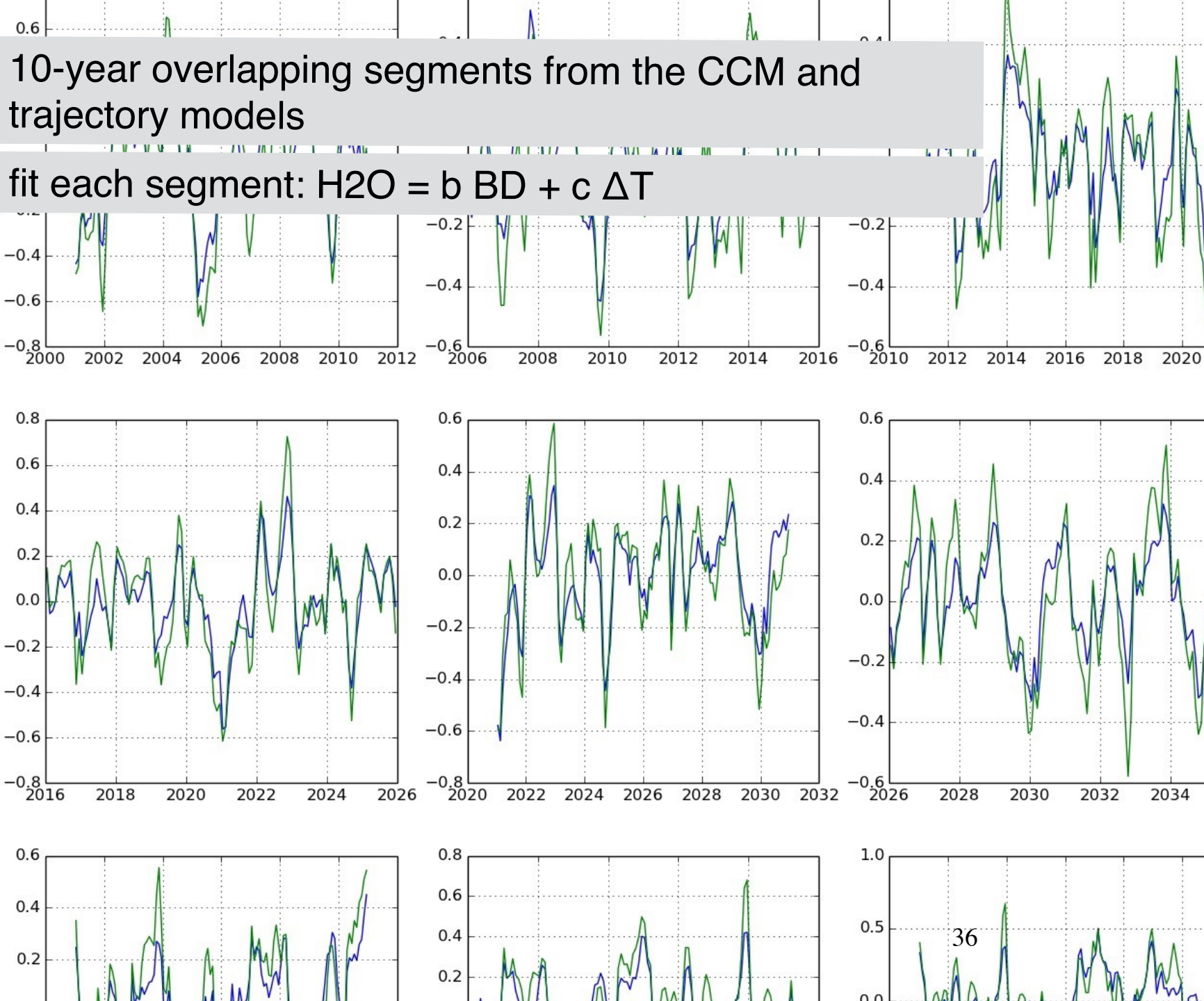




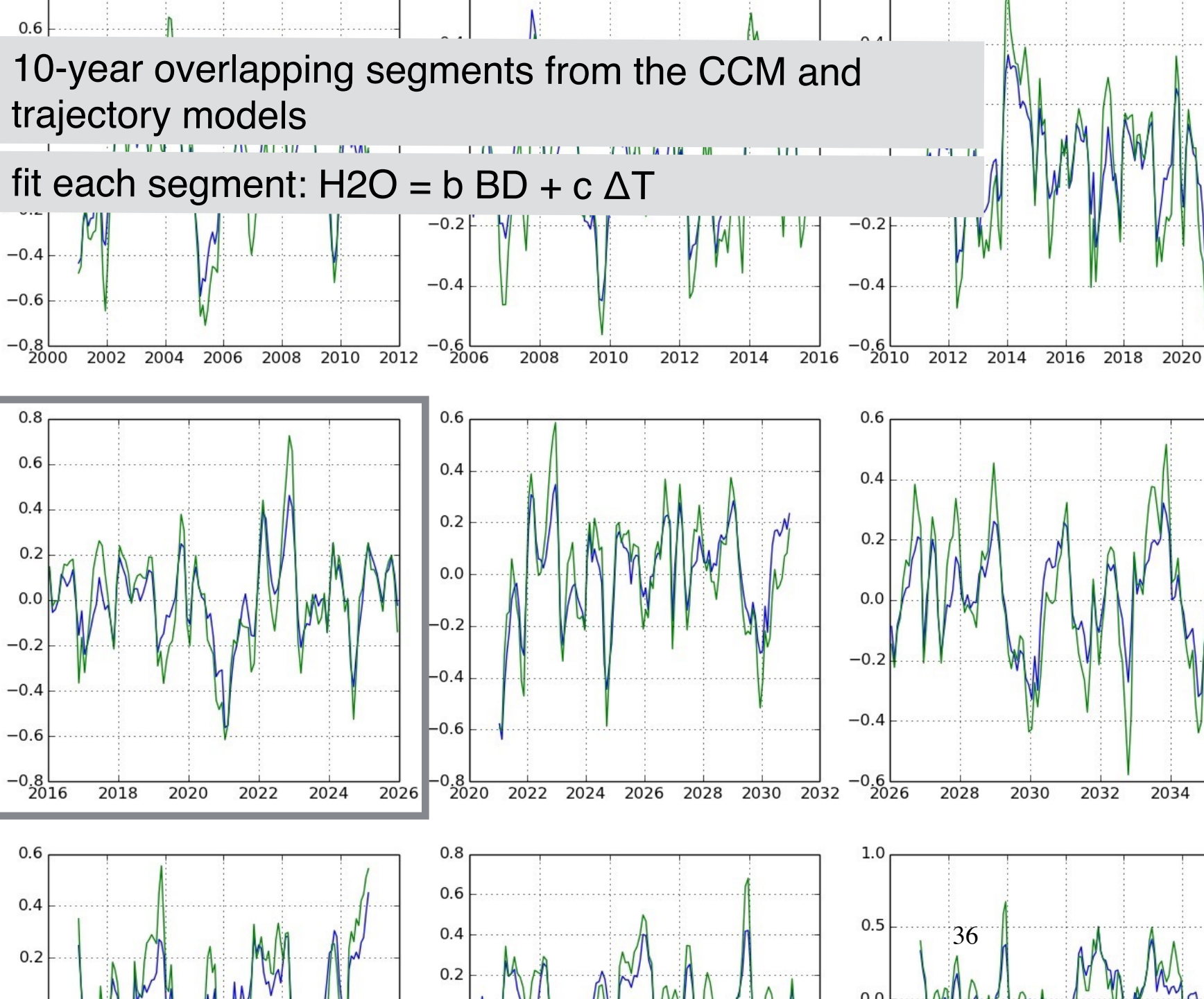


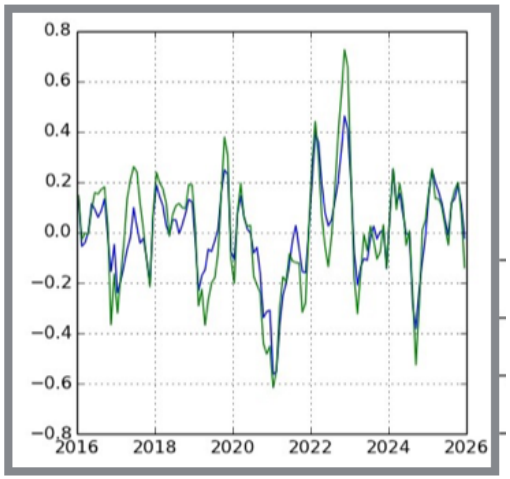


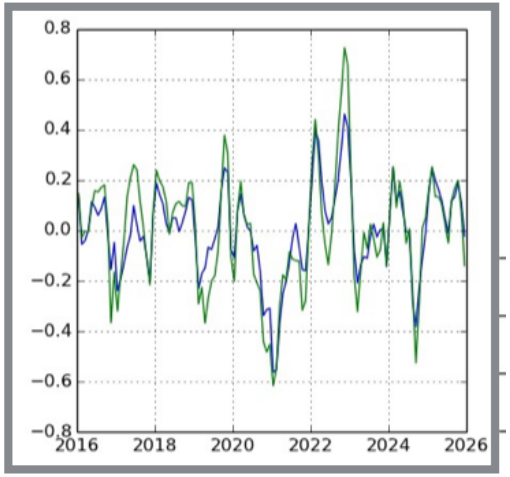
- 10-year overlapping segments from the CCM and trajectory models
- fit each segment: $H_2O = b\,BD + c\,\Delta T$

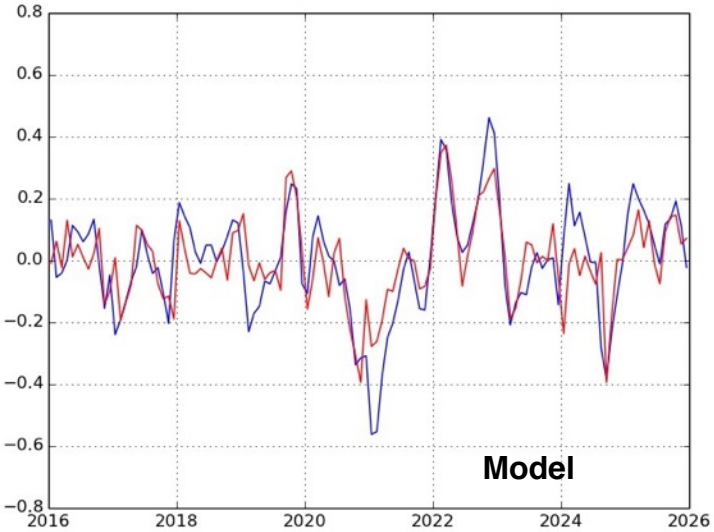


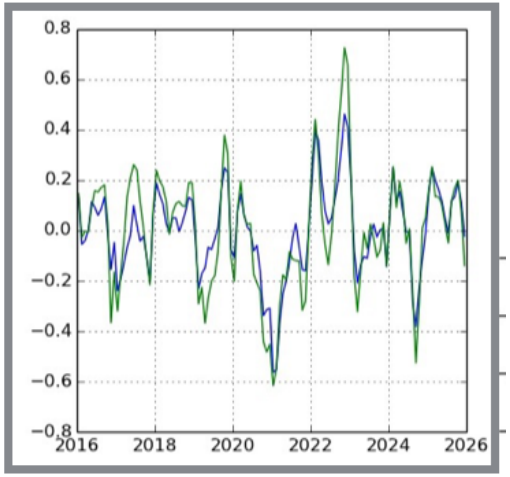
- 10-year overlapping segments from the CCM and trajectory models
- fit each segment: H2O = b BD + c ΔT

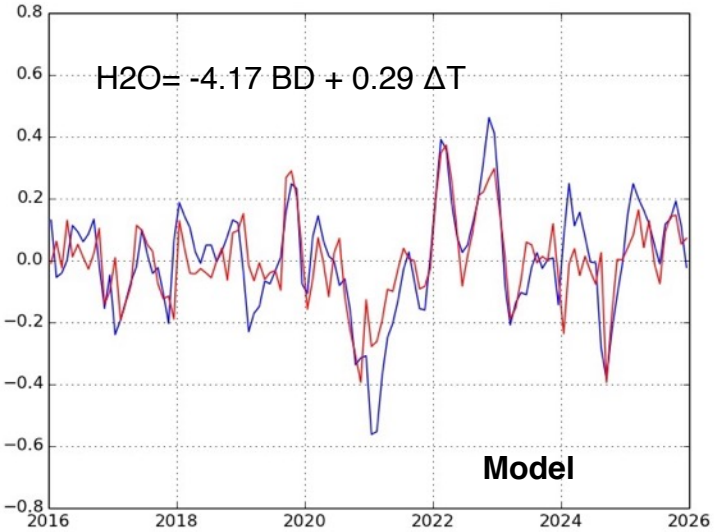


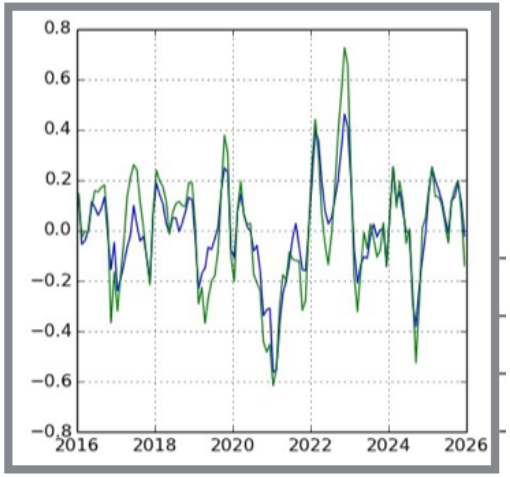

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

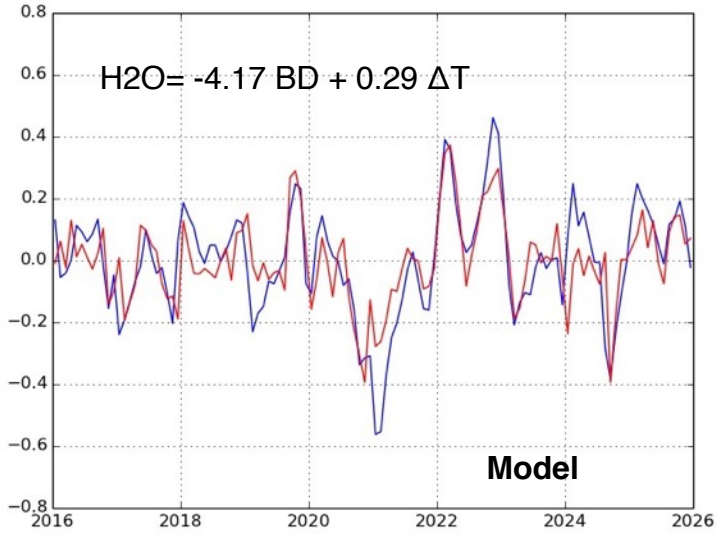

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026


0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026
Model

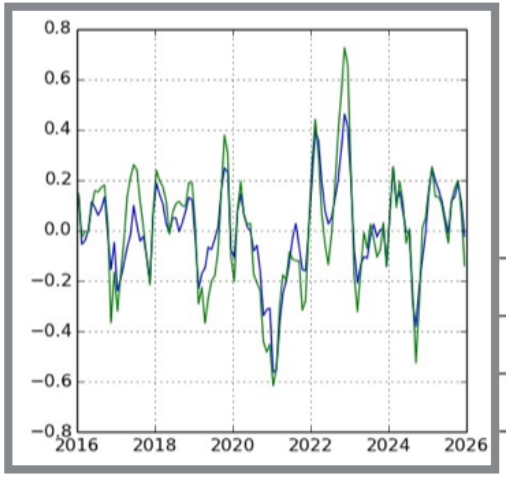

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

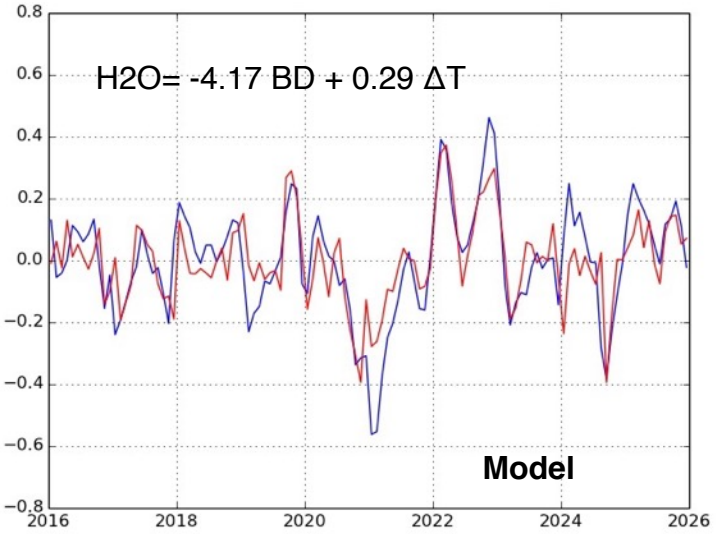

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

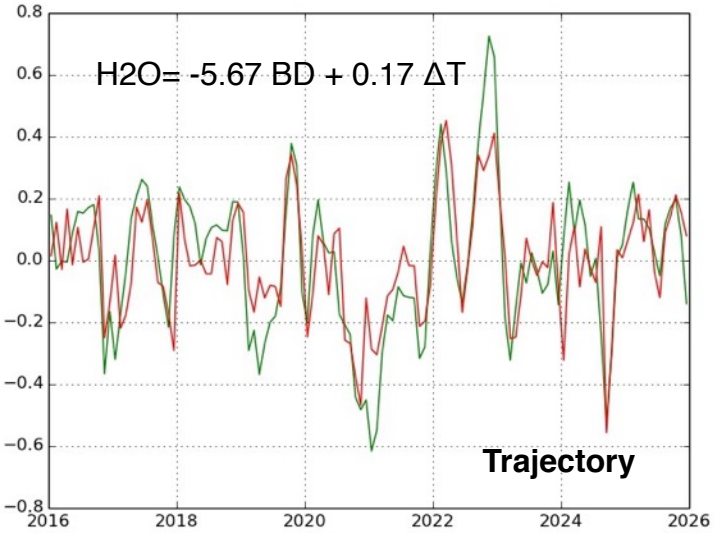

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

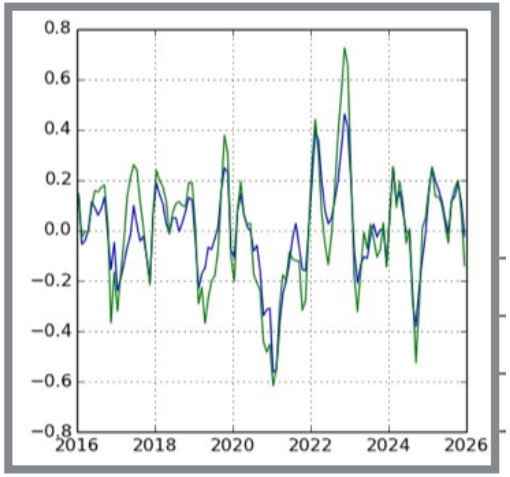

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

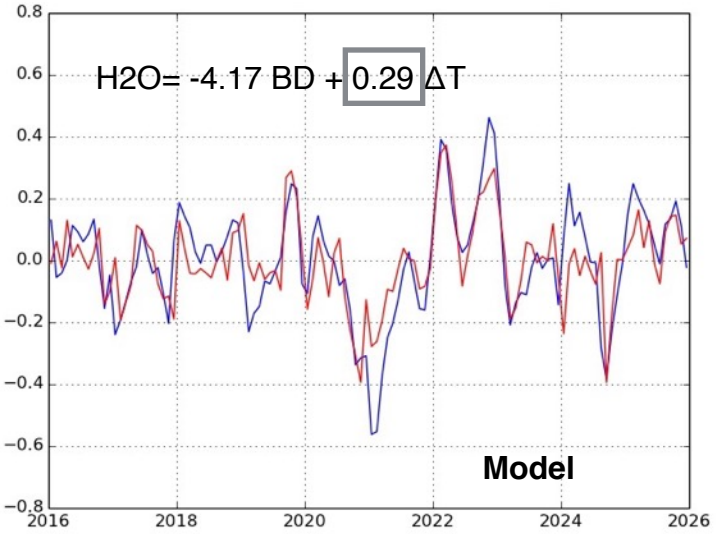

Trajectory
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

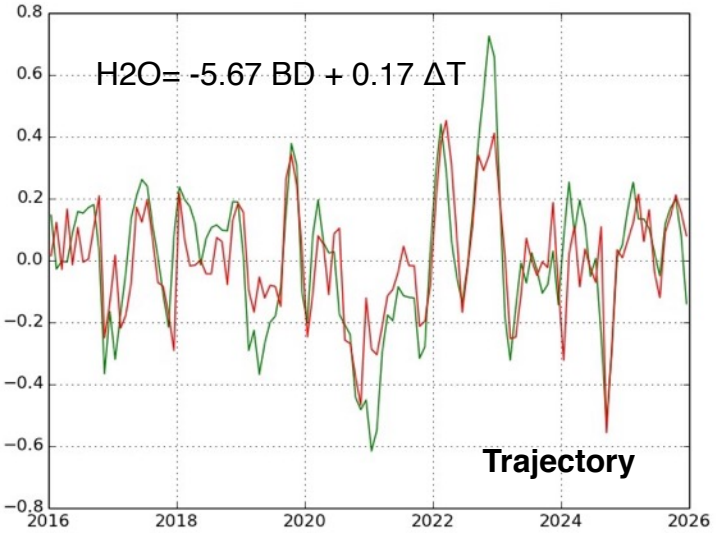

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

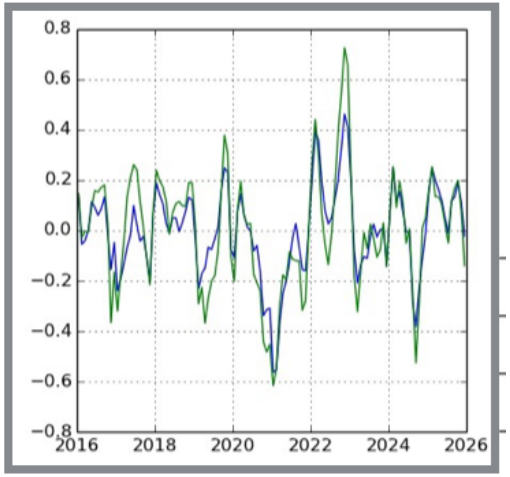

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

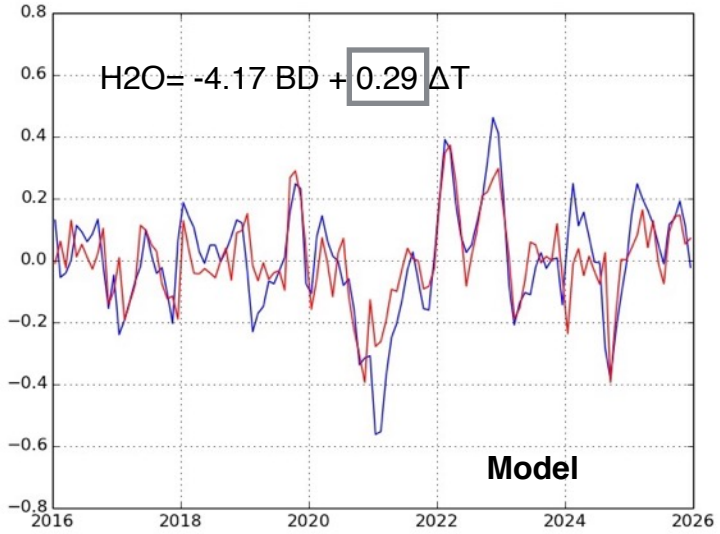

H2O= -5.67 BD + 0.17 ΔT
Trajectory
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

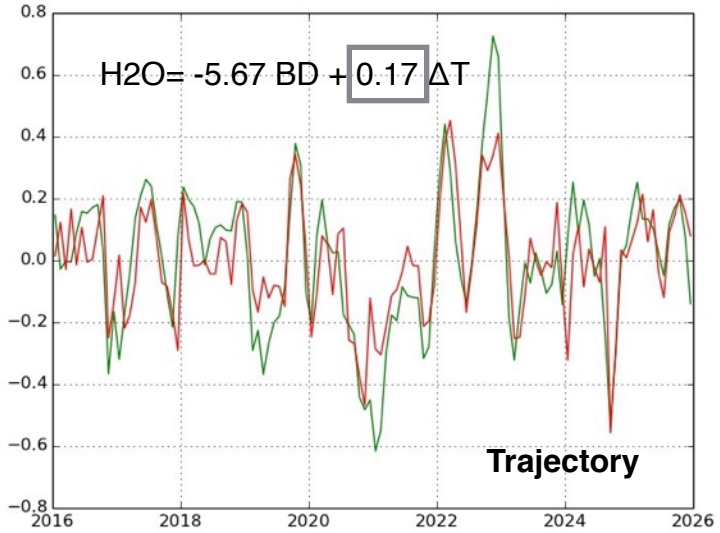

0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

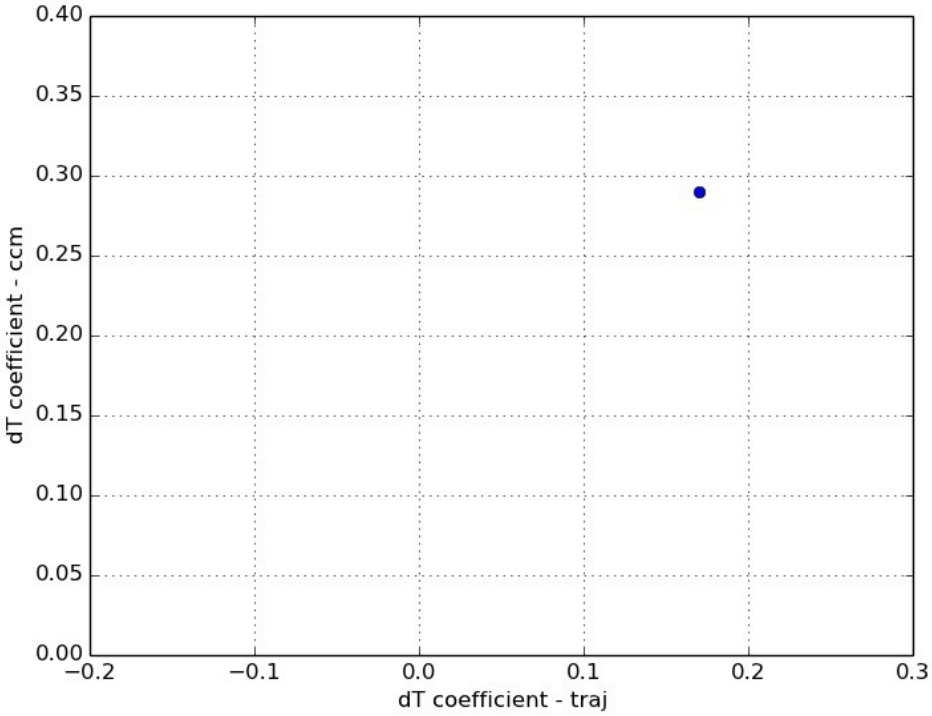

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

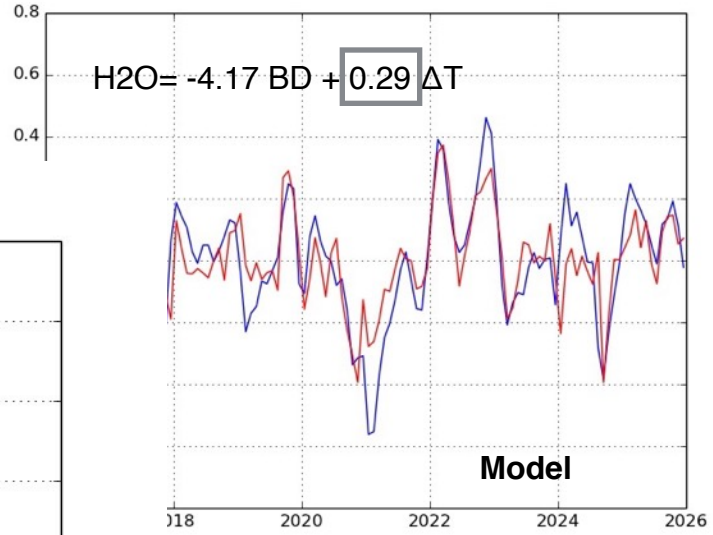

H2O= -5.67 BD + 0.17 ΔT
Trajectory
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026


0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

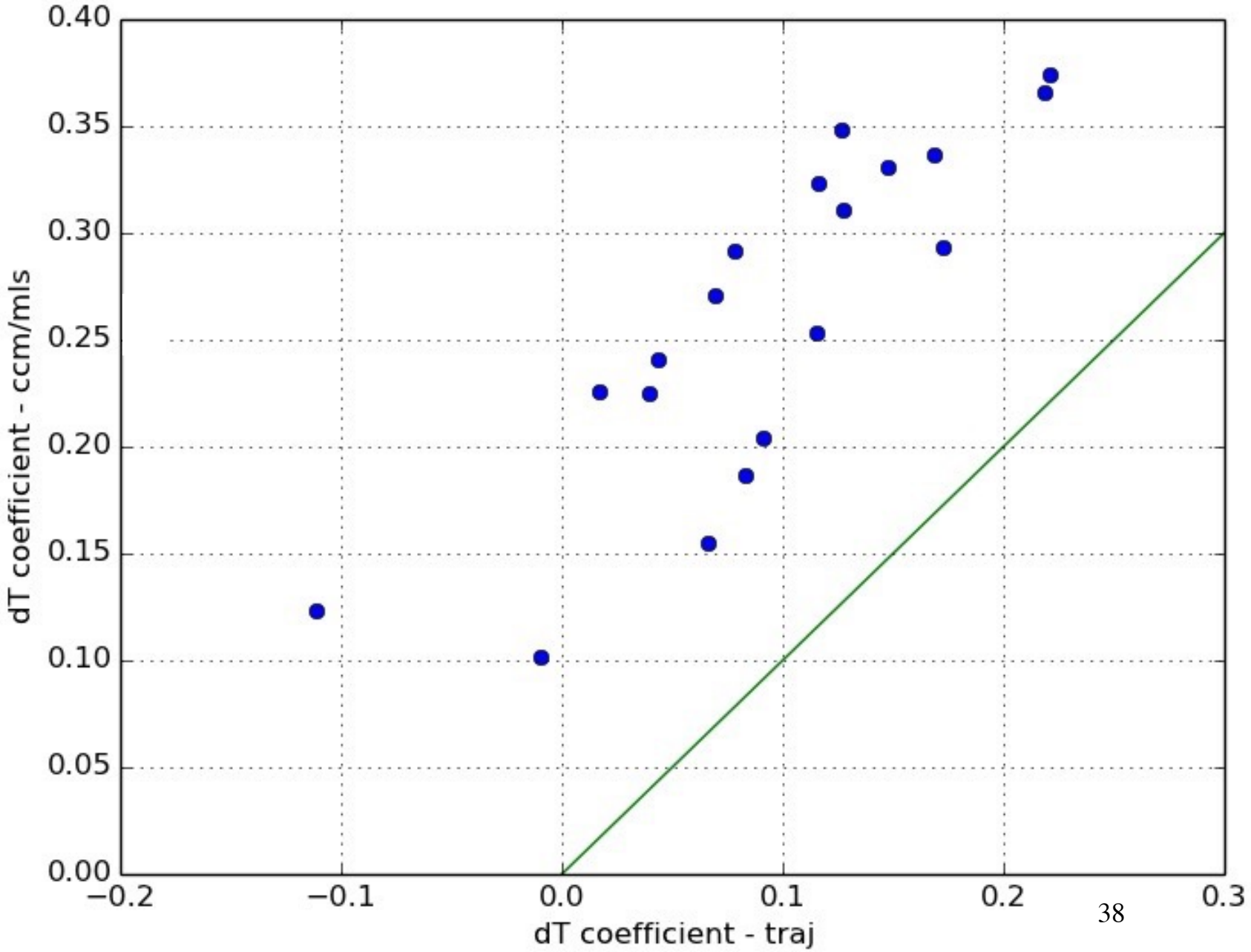

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026


H2O= -5.67 BD + 0.17 ΔT
Trajectory
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

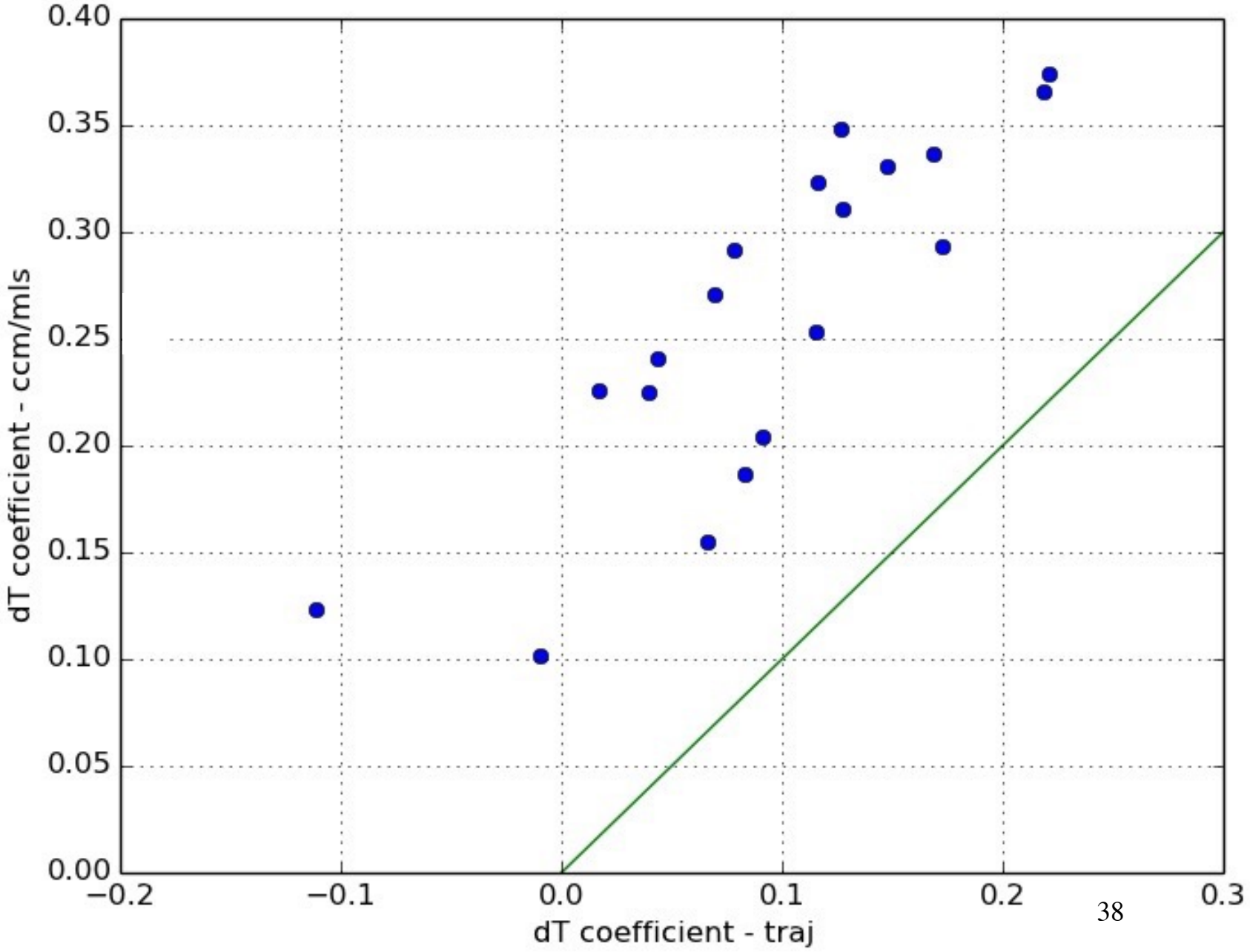

dT coefficient - ccm
dT coefficient - traj
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.2
−0.1
0.0
0.1
0.2
0.3

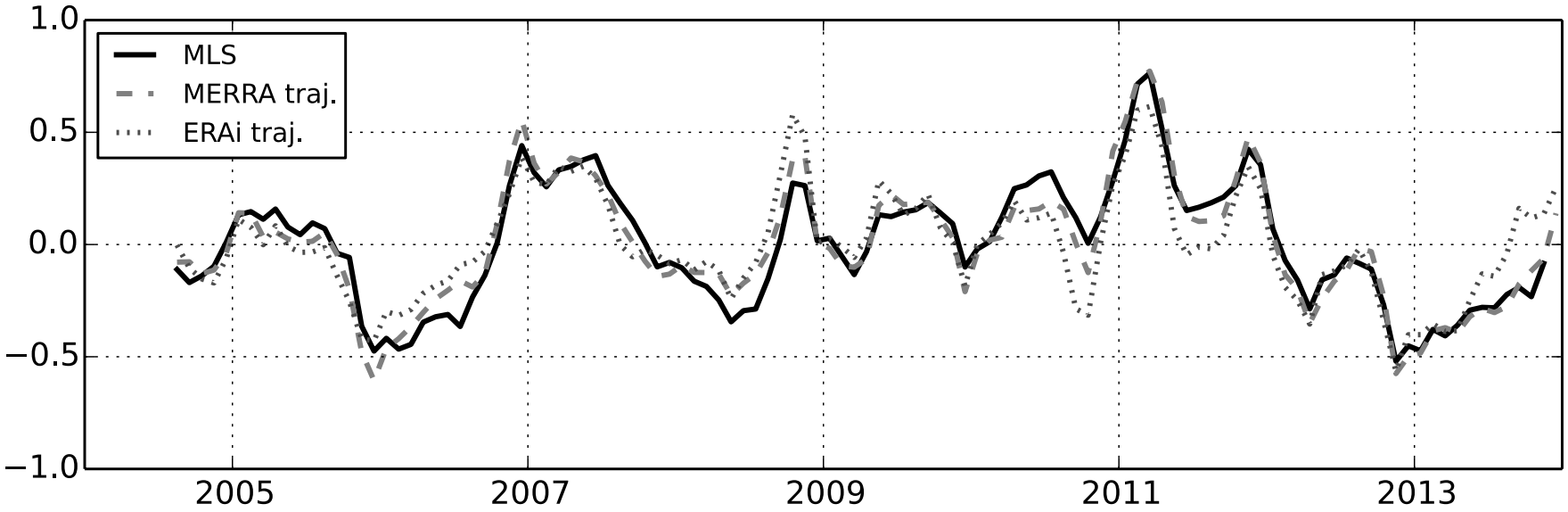

H2O= -4.17 BD + 0.29 ΔT
Model
0.8
0.6
0.4
018
2020
2022
2024
2026


= -5.67 BD + 0.17 ΔT
Trajectory
−0.4
−0.6
−0.8
2016
2018
2020
2022
2024
2026

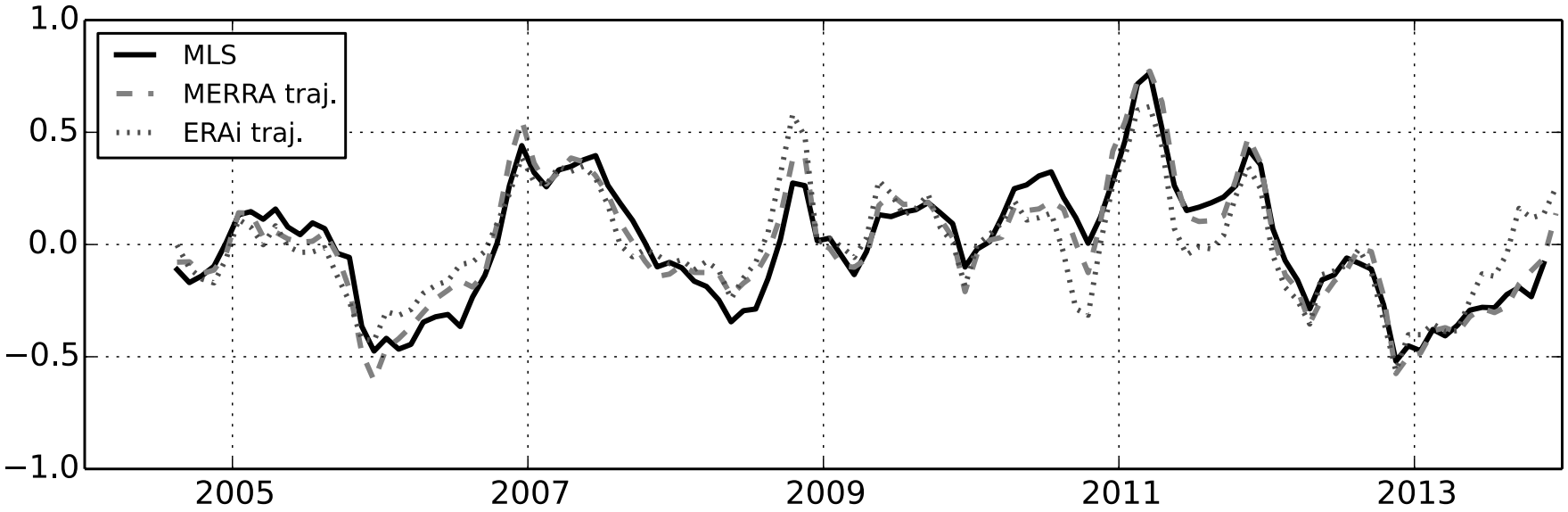

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
dT coefficient - ccm/mls
−0.2
−0.1
0.0
0.1
0.2
0.3
dT coefficient - traj

ΔT coefficient = increase in water vapor per degree warming of the troposphere





monthly avg. **anomalies**
82 hPa (18 km)
30°N-30°S avg.



monthly avg. **anomalies**
82 hPa (18 km)
30°N-30°S avg.

$$H2O^* = a\,QBO + b\,BD + c\,\Delta T + r$$

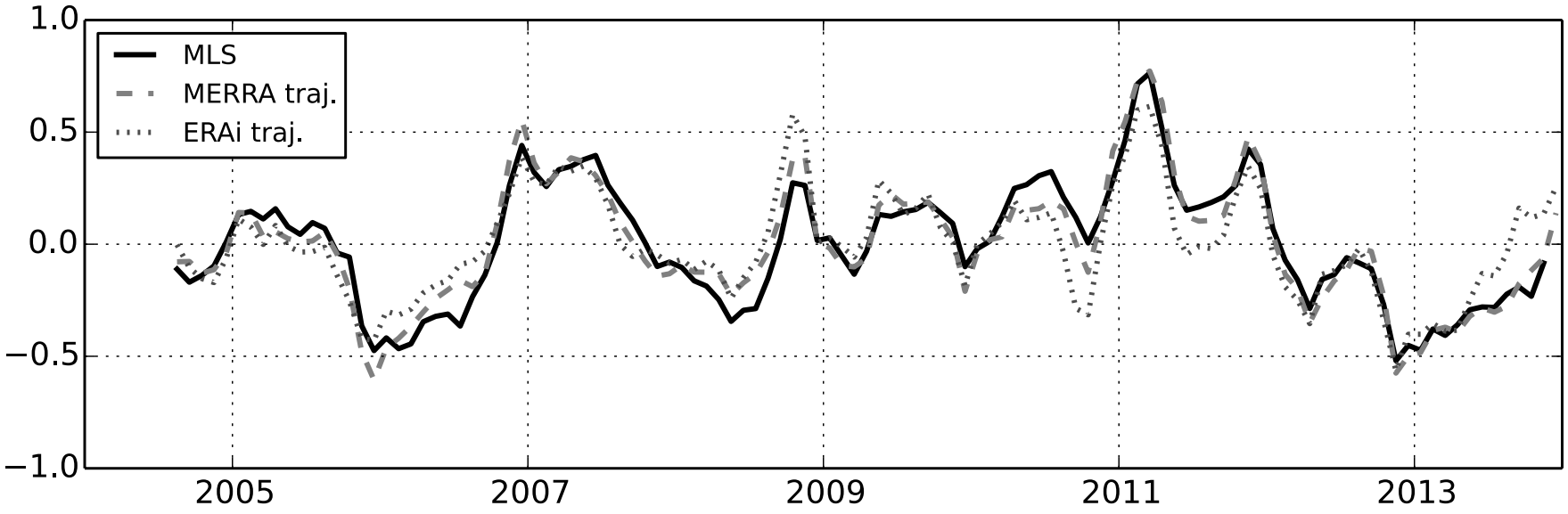
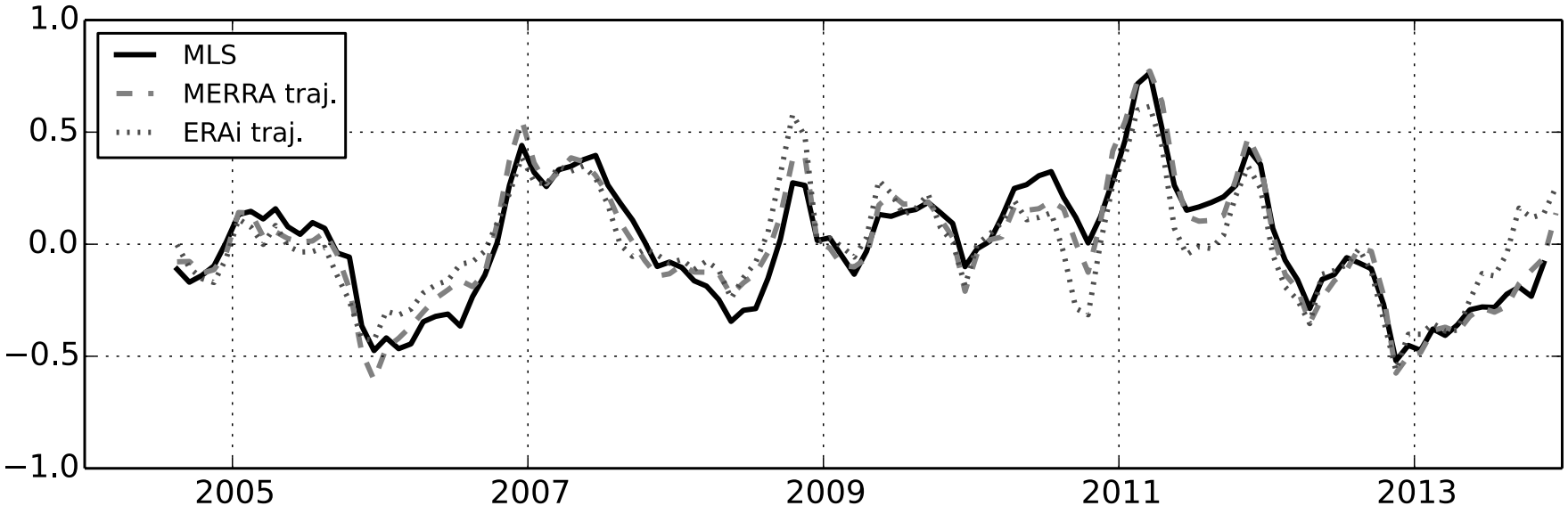


Table 1. Coefficients From Fits to $H_2O_{ov\text{-}entry}$ Time Series[a]

Dessler et al., JGR, 2014

	Modern Era Retrospective-Analysis for Research and Applications (MERRA) traj	European Centre for Medium-Range Weather Forecasts interim reanalysis (ERAi) traj	Microwave Limb Sounder (MLS)/MERRA	MLS/ERAi
Regression period	2004–2014	2004–2014	2004–2014	2004–2014
Quasi-biennial oscillation (QBO)	0.10 +/− 0.05	0.09 +/− 0.03	0.12 +/− 0.05	0.11 +/− 0.04
Brewer-Dobson circulation (BDC)	−4.25 +/− 1.40	−2.48 +/− 0.55	−3.48 +/− 1.62	−2.51 +/− 0.83
Tropospheric temperature (ΔT)	0.18 +/− 0.17	0.17 +/− 0.11	0.30 +/− 0.20	0.34 +/− 0.17
R^2	0.74	0.79	0.72	0.75



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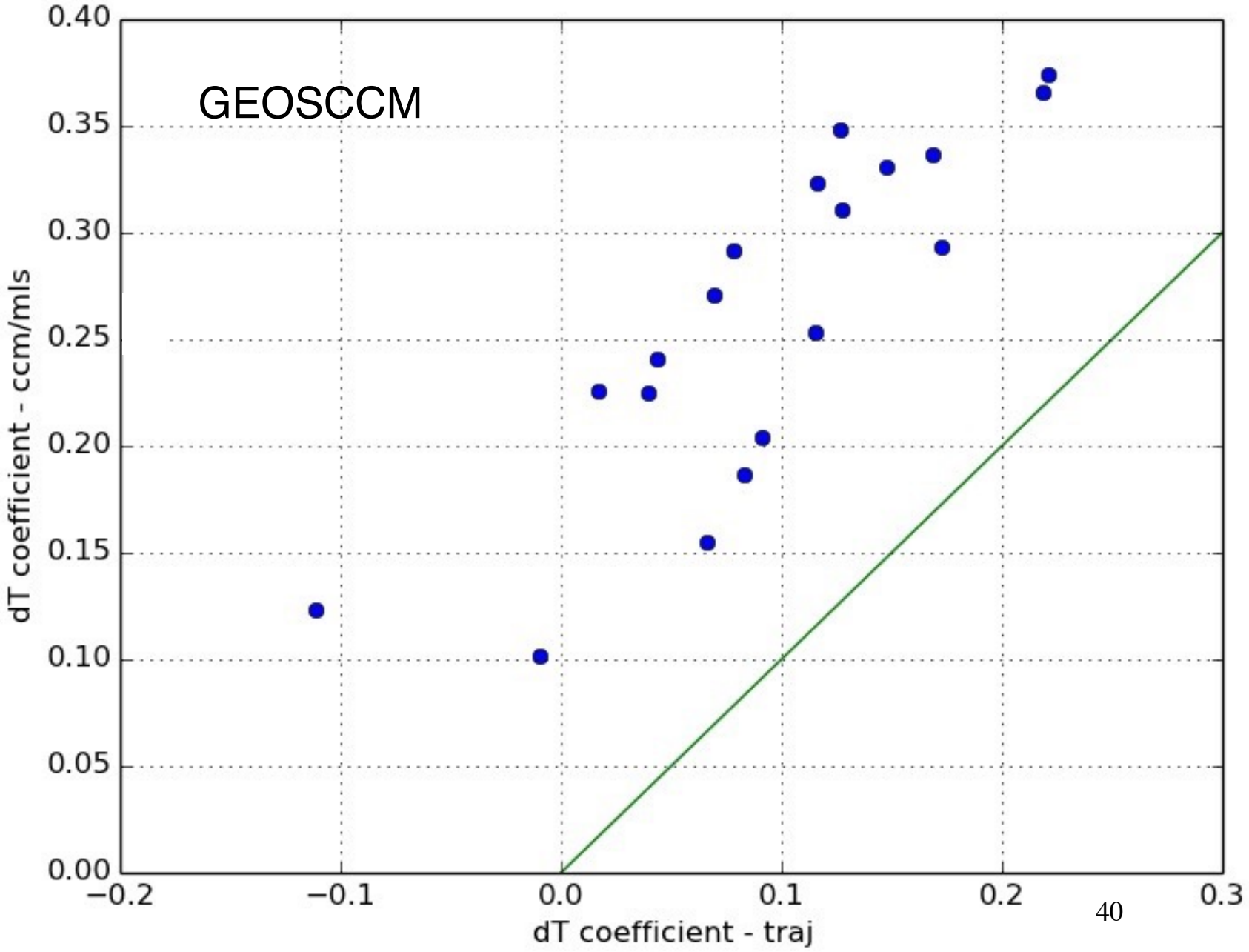
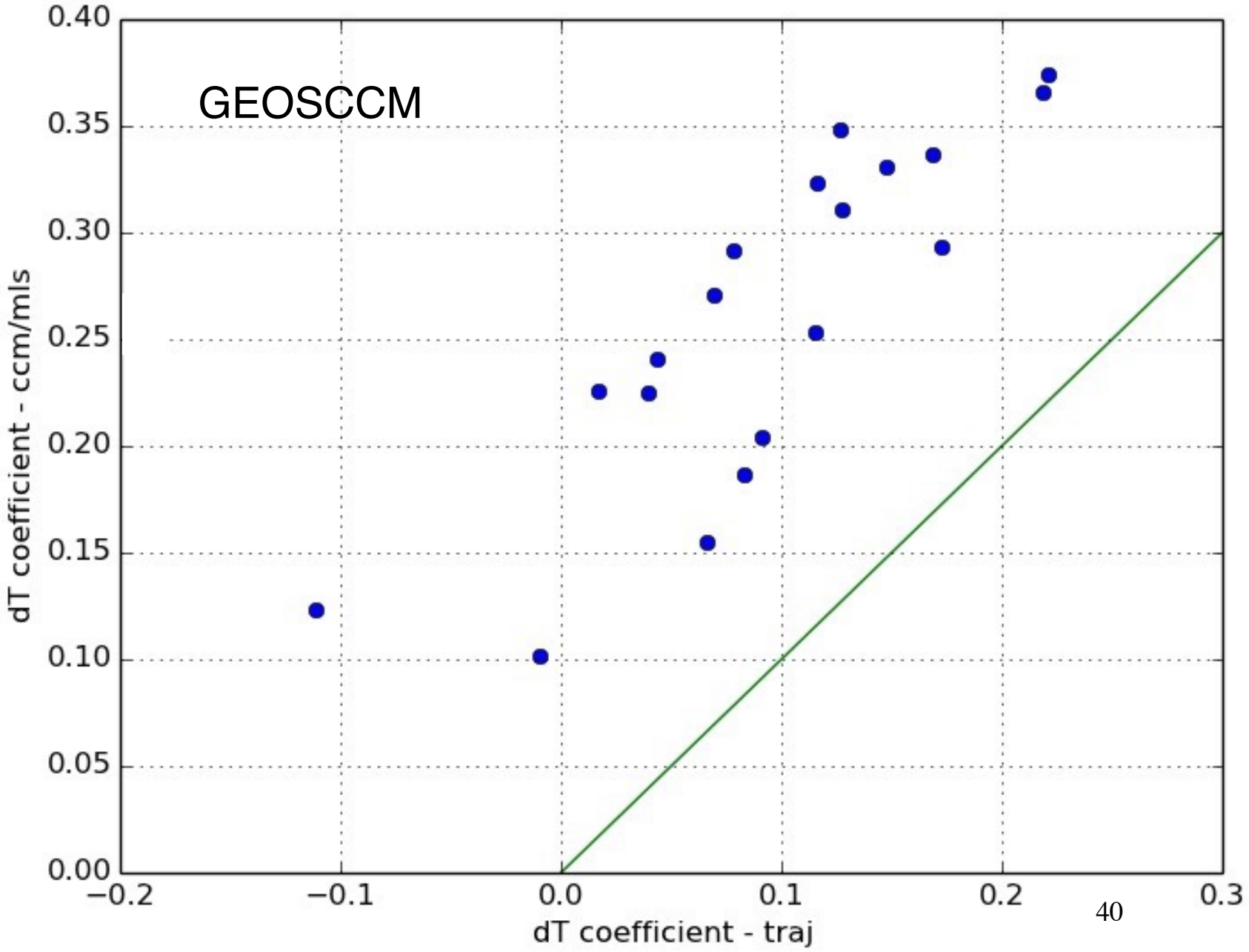
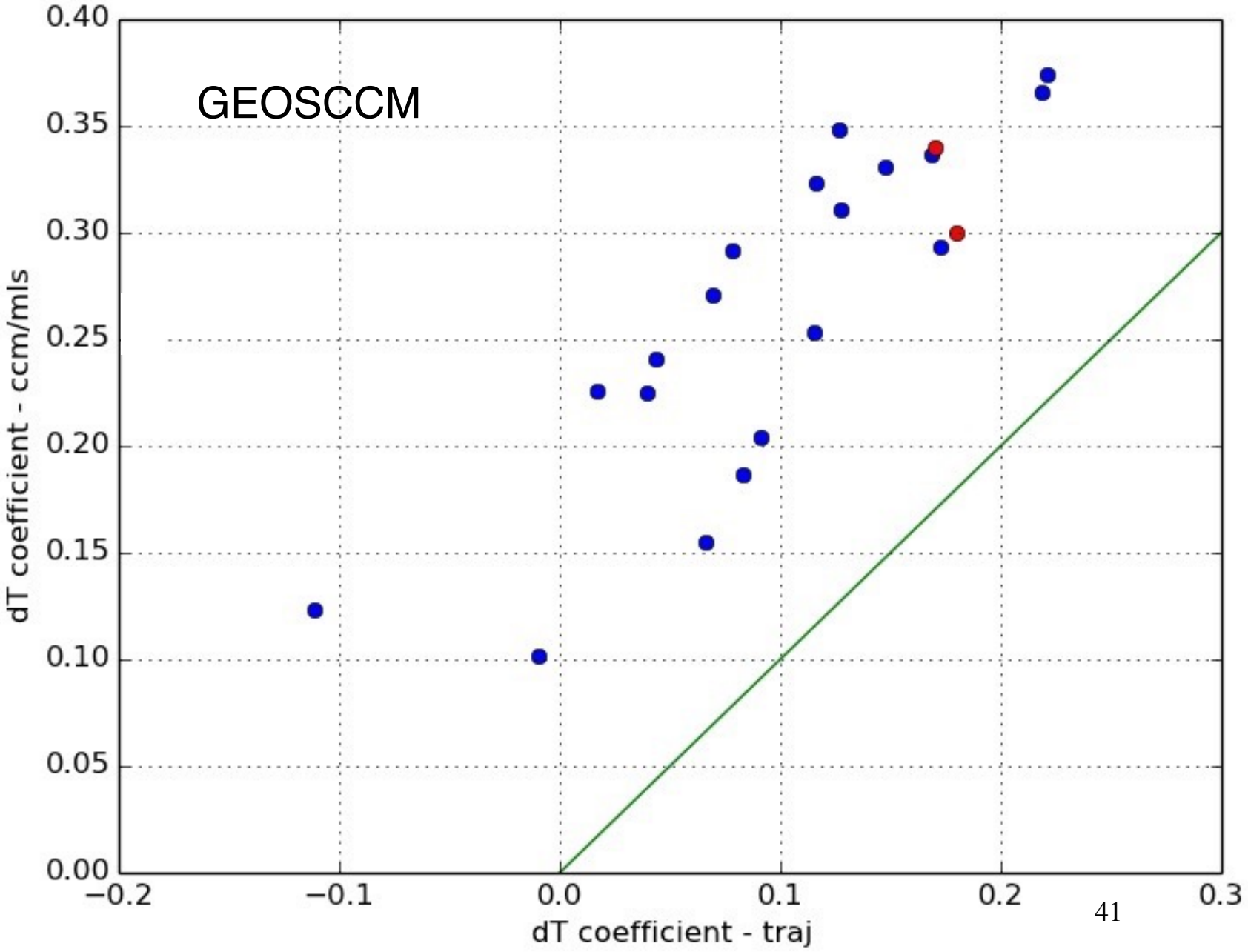

GEOSCCM
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
dT coefficient - ccm/mls
−0.2
−0.1
0.0
0.1
0.2
0.3
dT coefficient - traj

ΔT coefficient = increase in water vapor per degree warming of the troposphere




GEOSCCM
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
dT coefficient - ccm/mls
−0.2
−0.1
0.0
0.1
0.2
0.3
dT coefficient - traj

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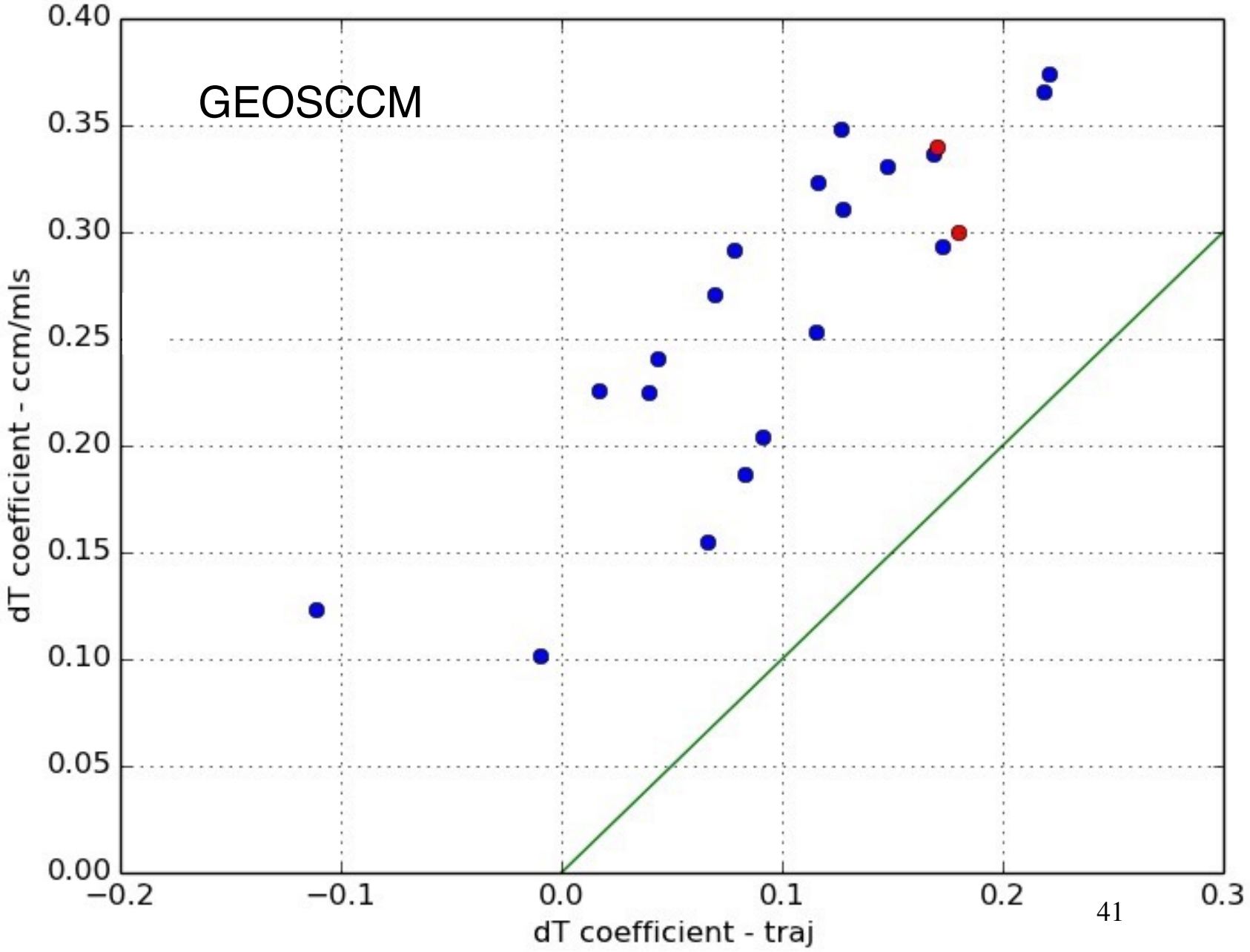
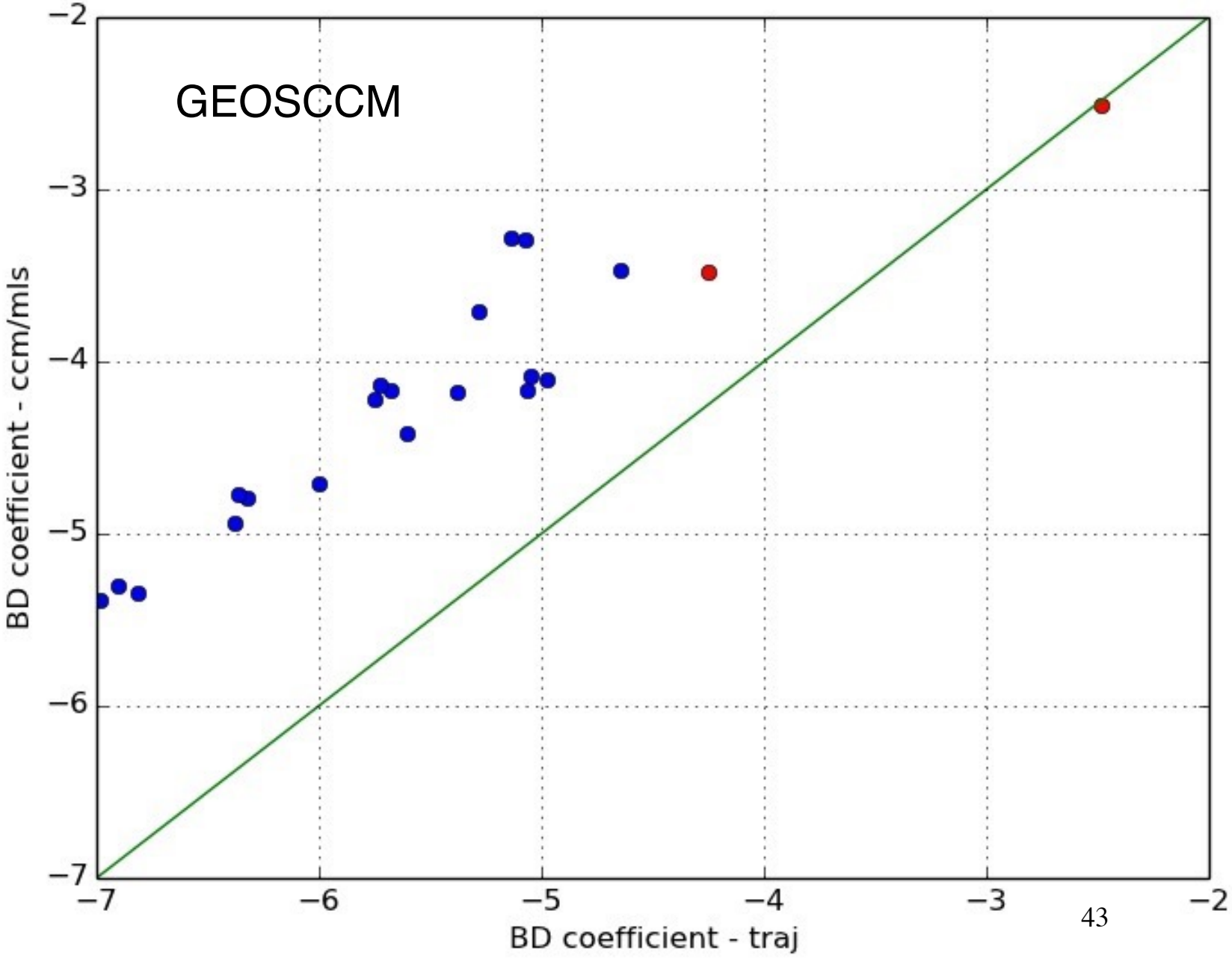
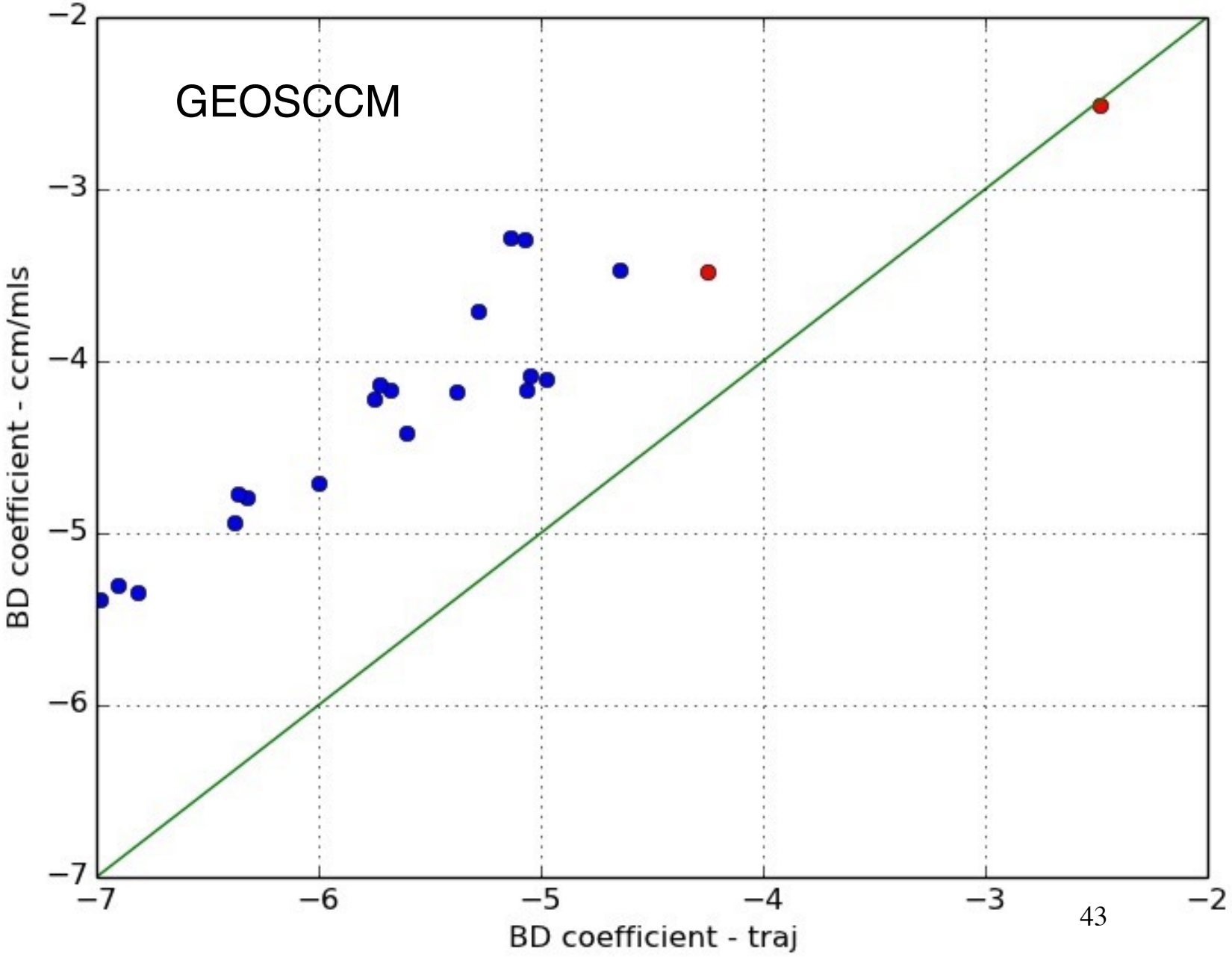


conclusions, III

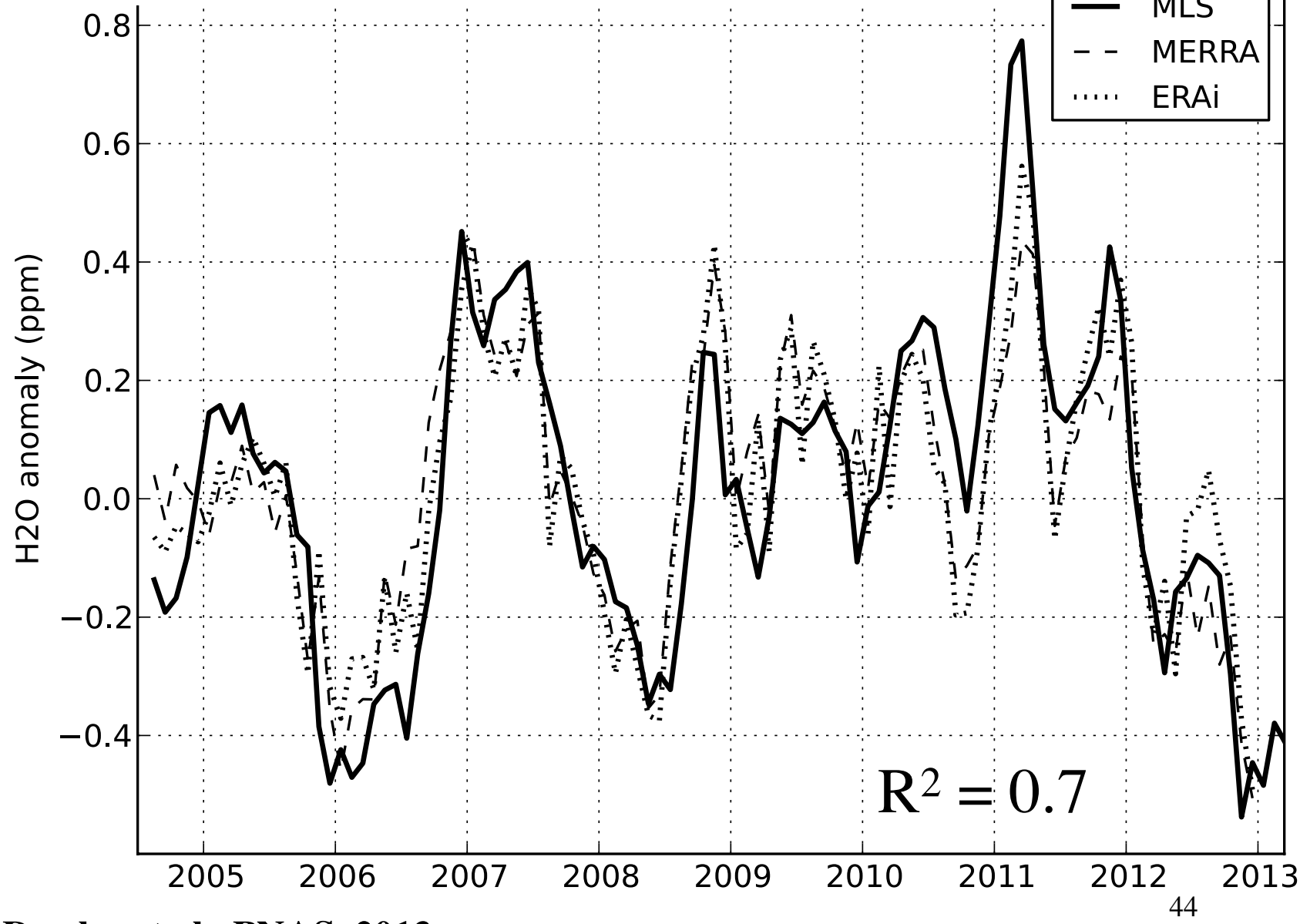
- trend in ice lofting is responsible for a significant part of the trend in strat. H_2O in models over the 21st century
- signature of ice lofting can is (potentially) apparent in short-term climate variability in the model
- a similar signature is apparent in the MLS data


GEOSCCM
BD coefficient - ccm/mls
BD coefficient - traj
−2
−3
−4
−5
−6
−7
−7
−6
−5
−4
−3
−2

BD coefficient = increase in water vapor per unit change in BD circulation strength



$$H2O^* = a\,QBO + b\,BD + c\,\Delta T + r$$



Dessler et al., PNAS, 2013

Table 1. Coefficients from regressions of the $H_2O_{ov\text{-}entry}$ time series

	MLS observations	
Regressor	MERRA	ERAi
QBO	0.09 ± 0.05	0.09 ± 0.04
BD	−3.9 ± 1.6	−2.6 ± 0.8
ΔT	0.27 ± 0.19	0.30 ± 0.16

The units of the QBO, BD, and ΔT coefficients are ppm, ppm/(K/d), ppm/K, respectively. The uncertainty is the 95% confidence interval. The two MLS fits use MERRA and ERAi values of BD and ΔT.

$$H2O^* = a\,QBO + b\,BD + c\,\Delta T + r$$

Dessler et al., PNAS, 2013

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	MLS observations		GEOSCCM simulations
Regressor	MERRA	ERAi	All variability
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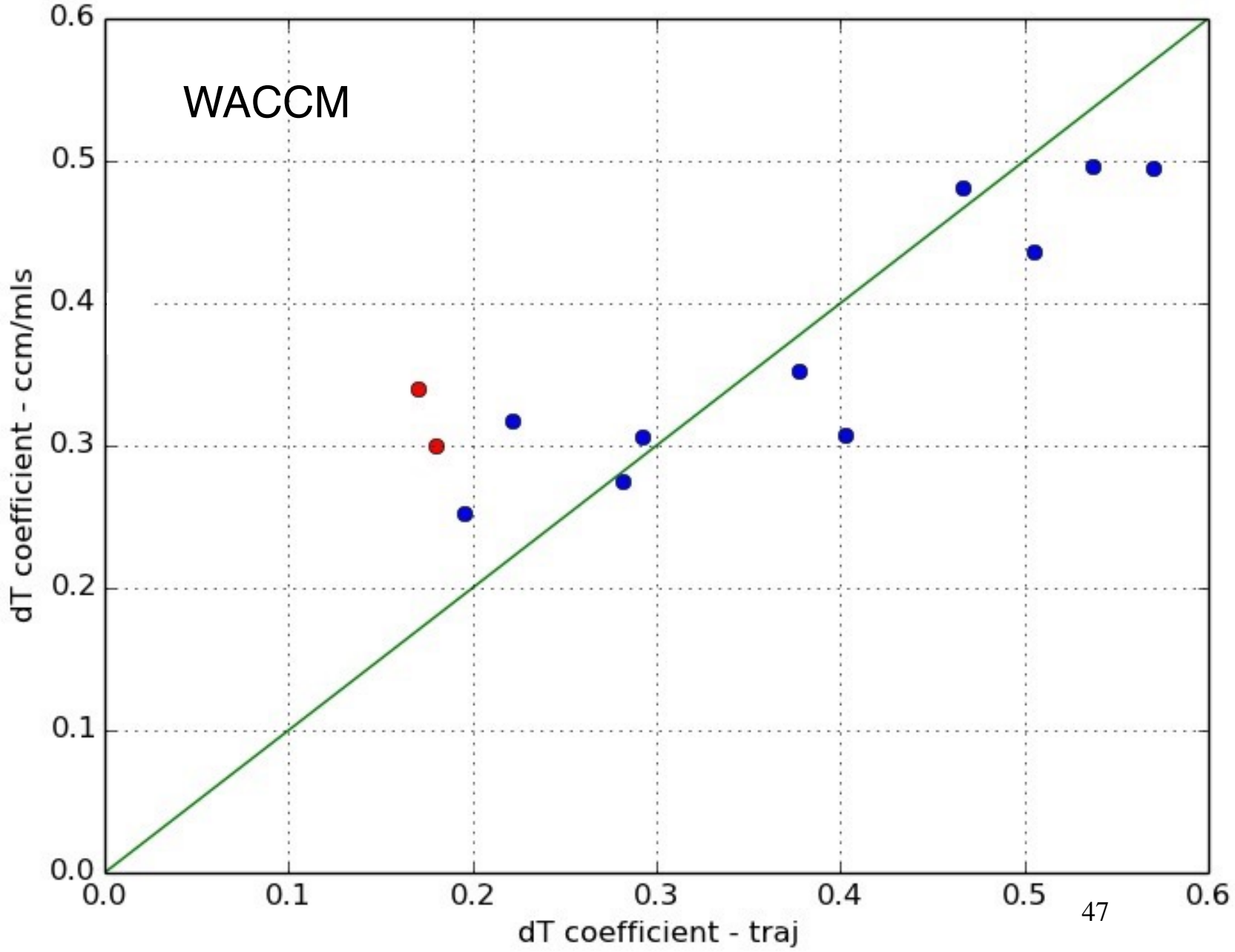
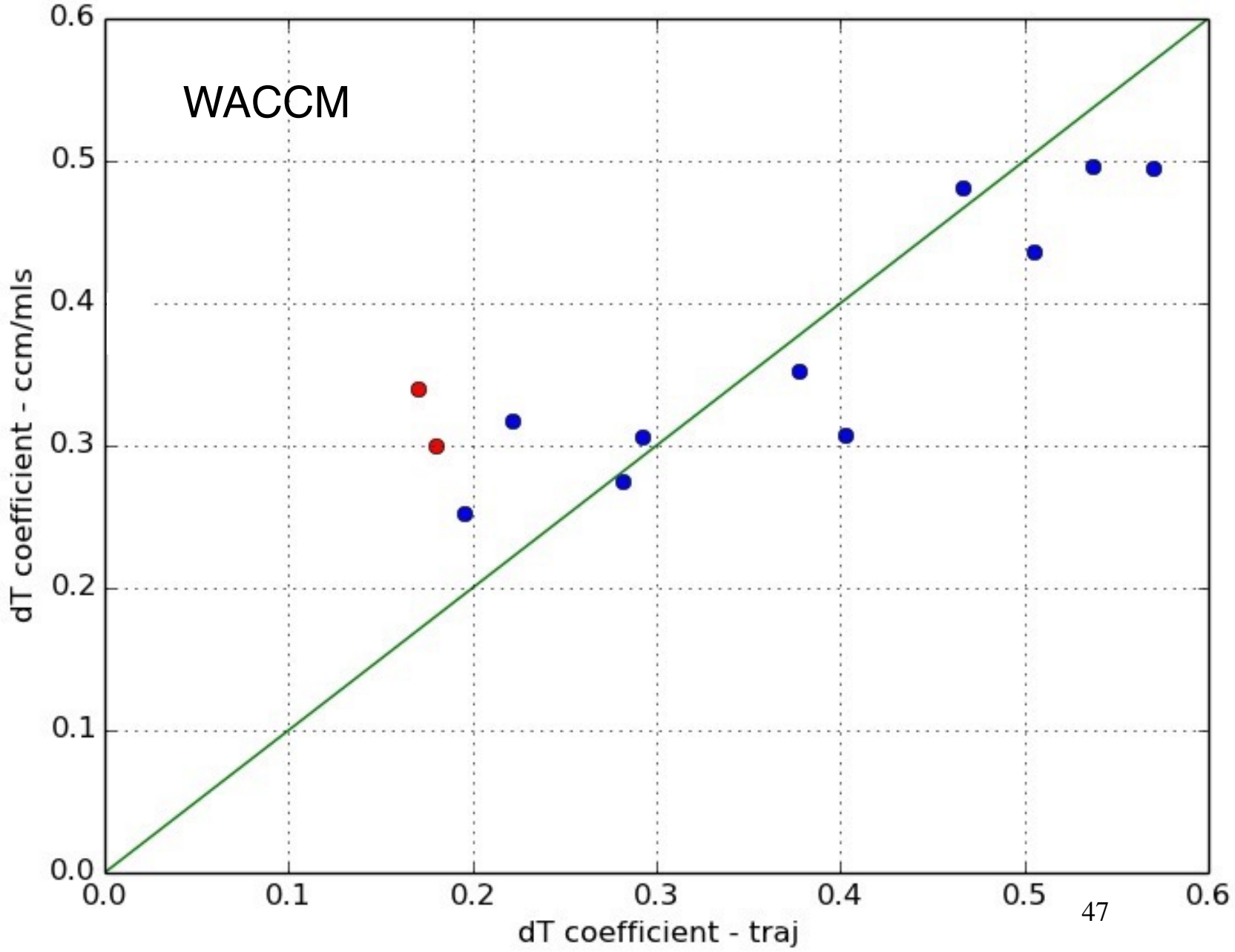
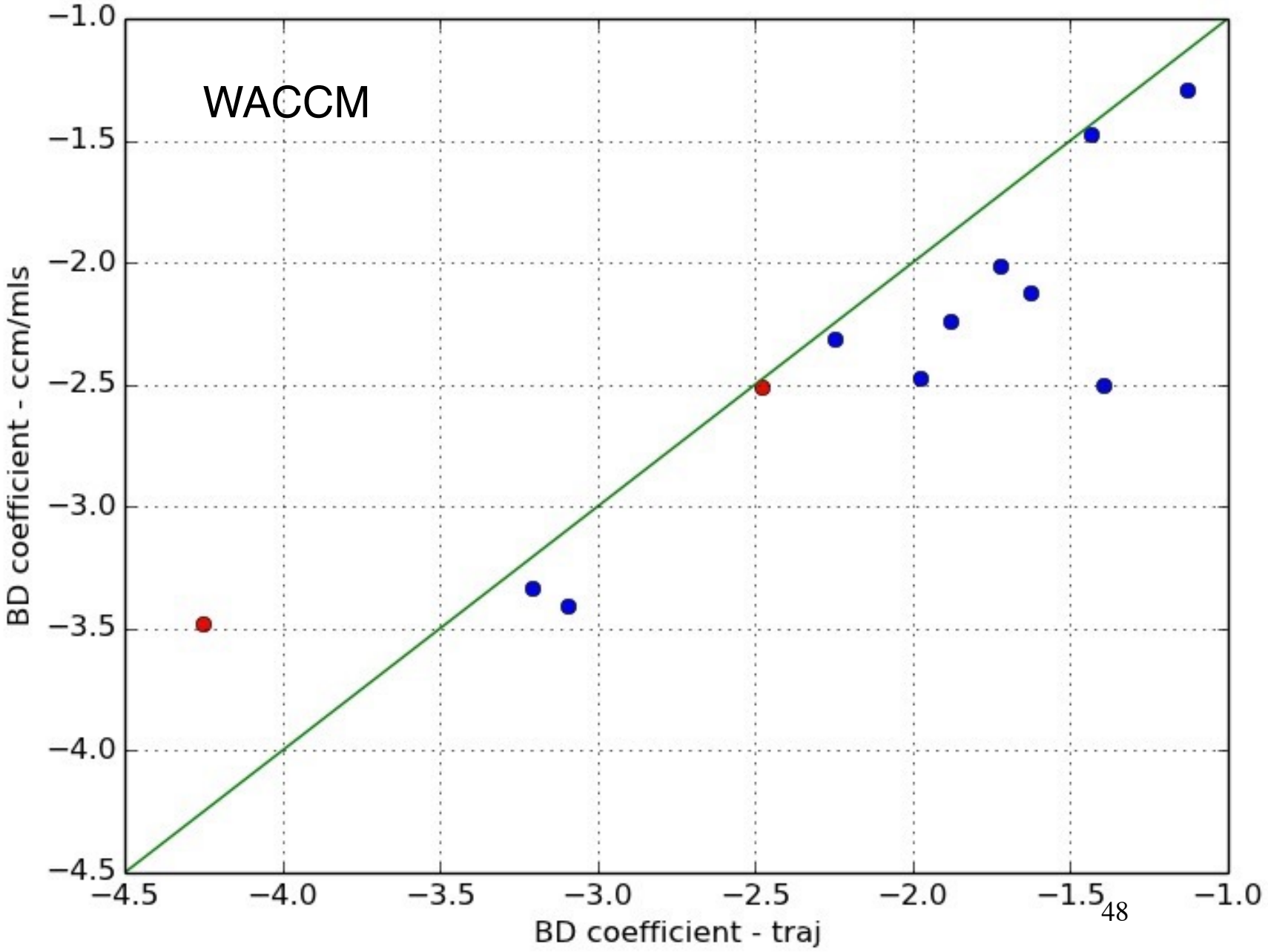
$$H2O^* = a\,QBO + b\,BD + c\,\Delta T + r$$

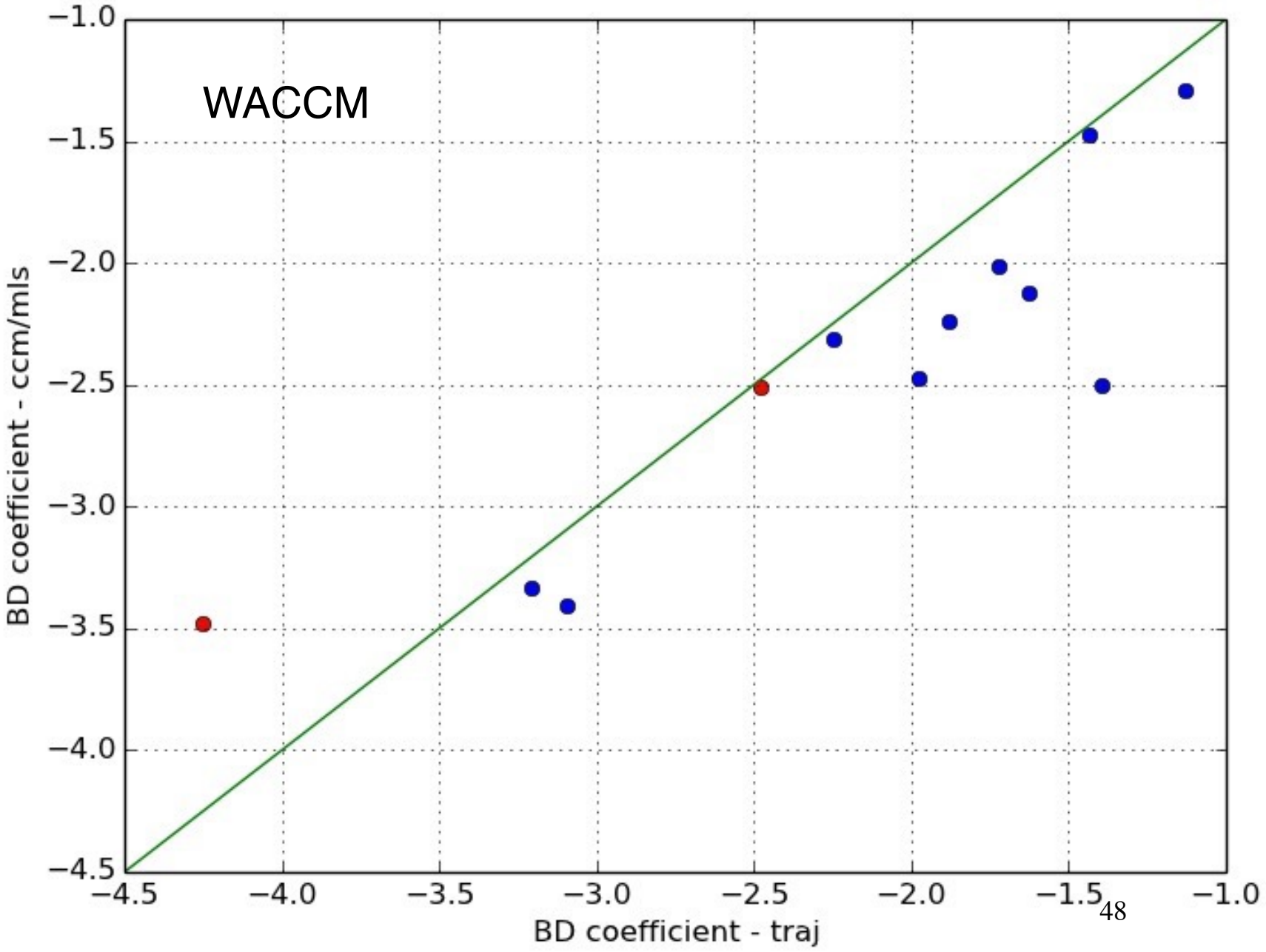

WACCM
dT coefficient - ccm/mls
dT coefficient - traj
0.0
0.1
0.2
0.3
0.4
0.5
0.6

ΔT coefficient = increase in water vapor per degree warming of the troposphere

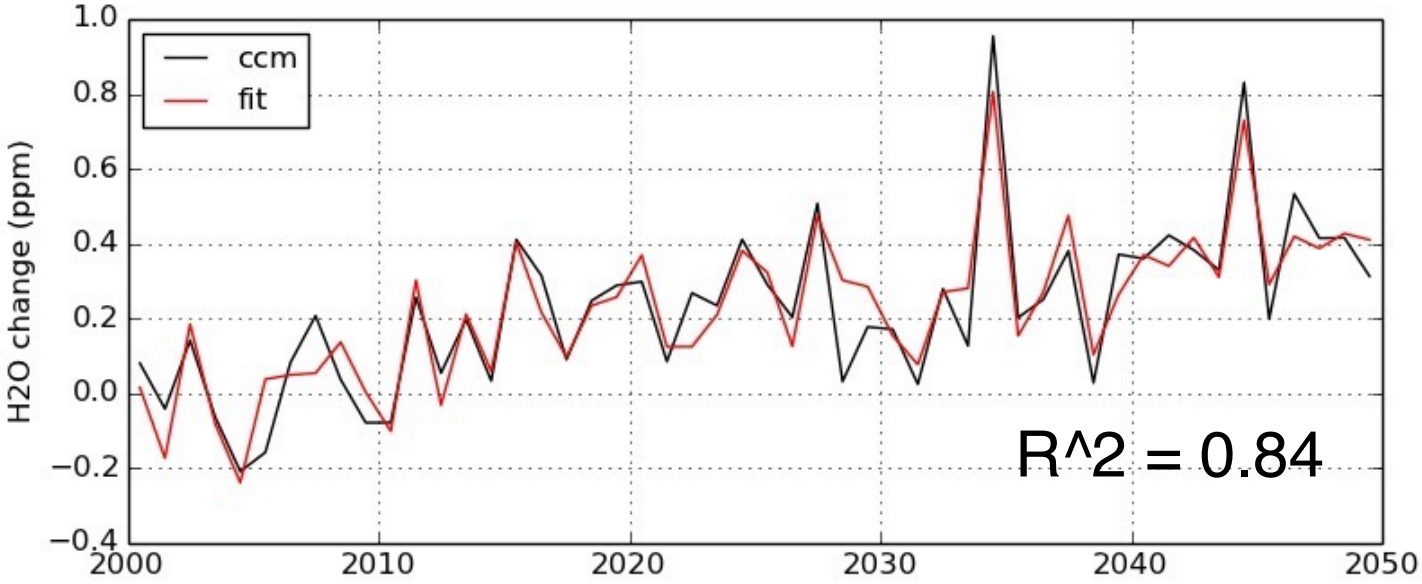


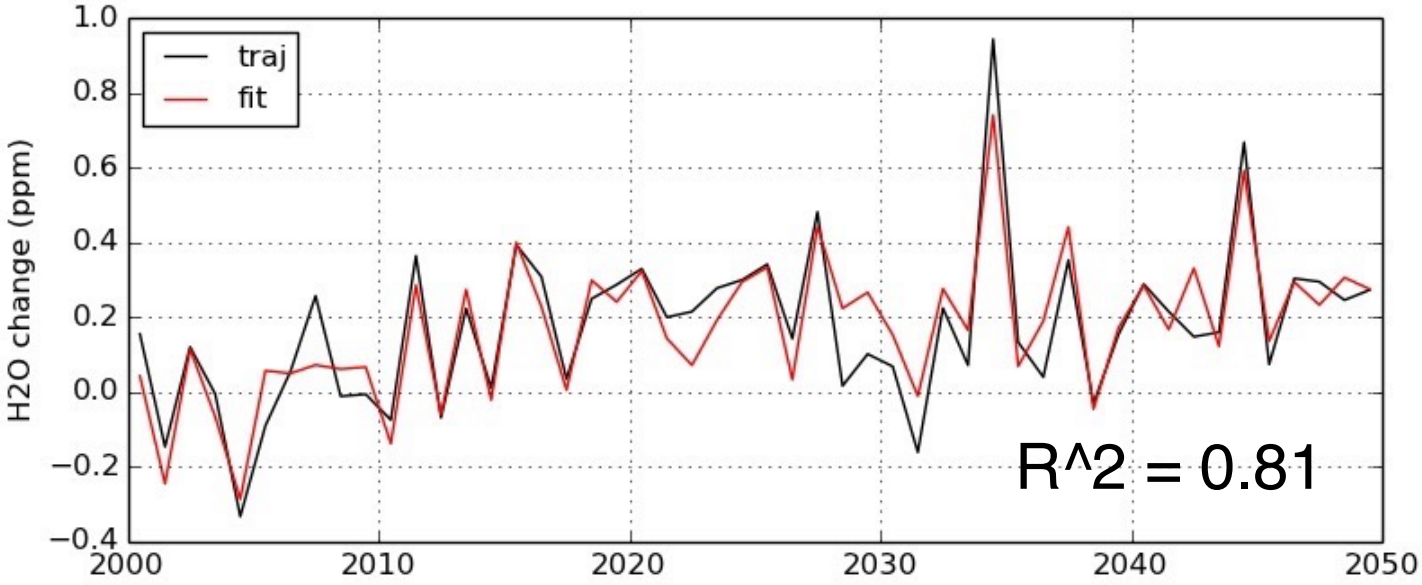

WACCM
BD coefficient - ccm/mls
BD coefficient - traj
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−4.5
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0

BD coefficient = increase in water vapor per unit change in BD circulation strength

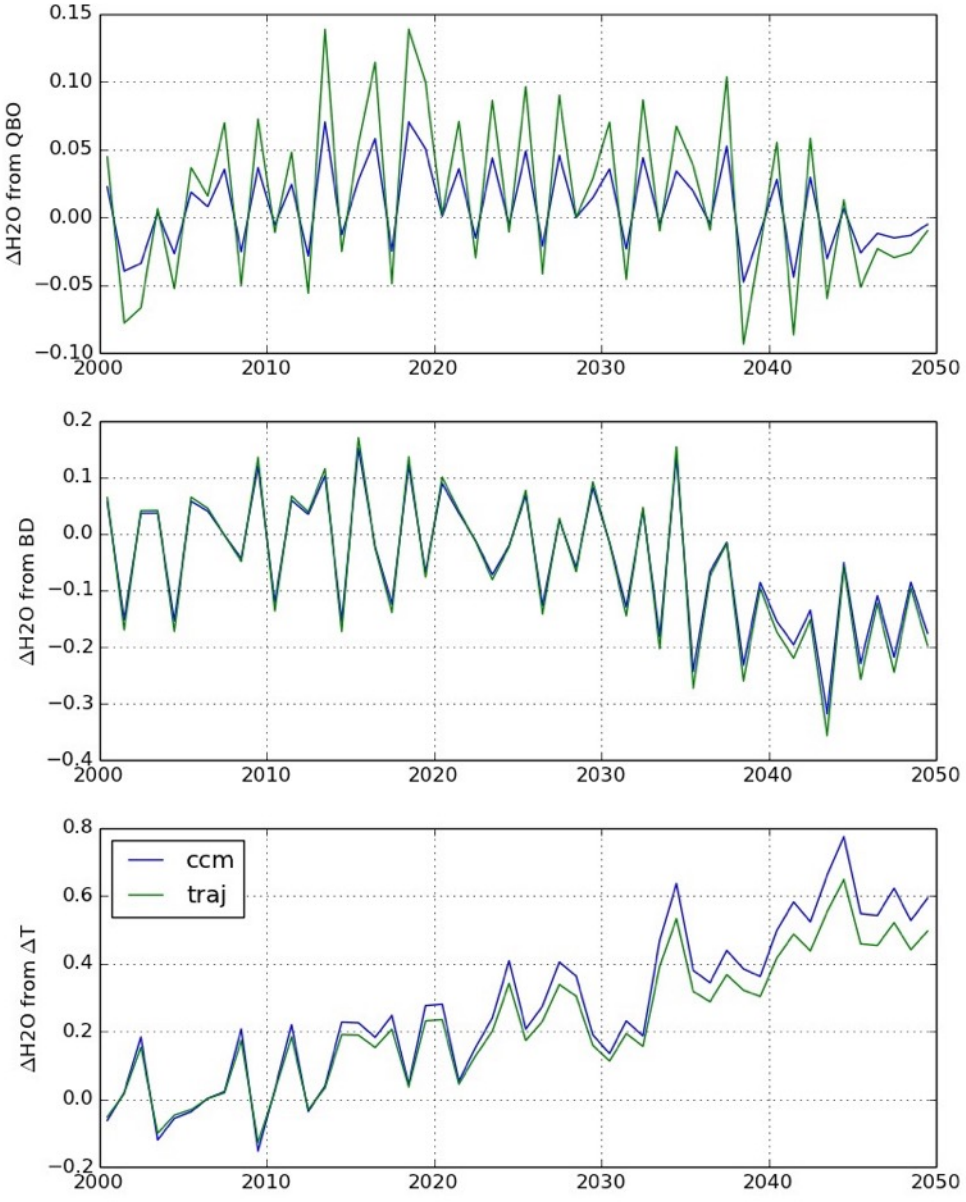


WACCM

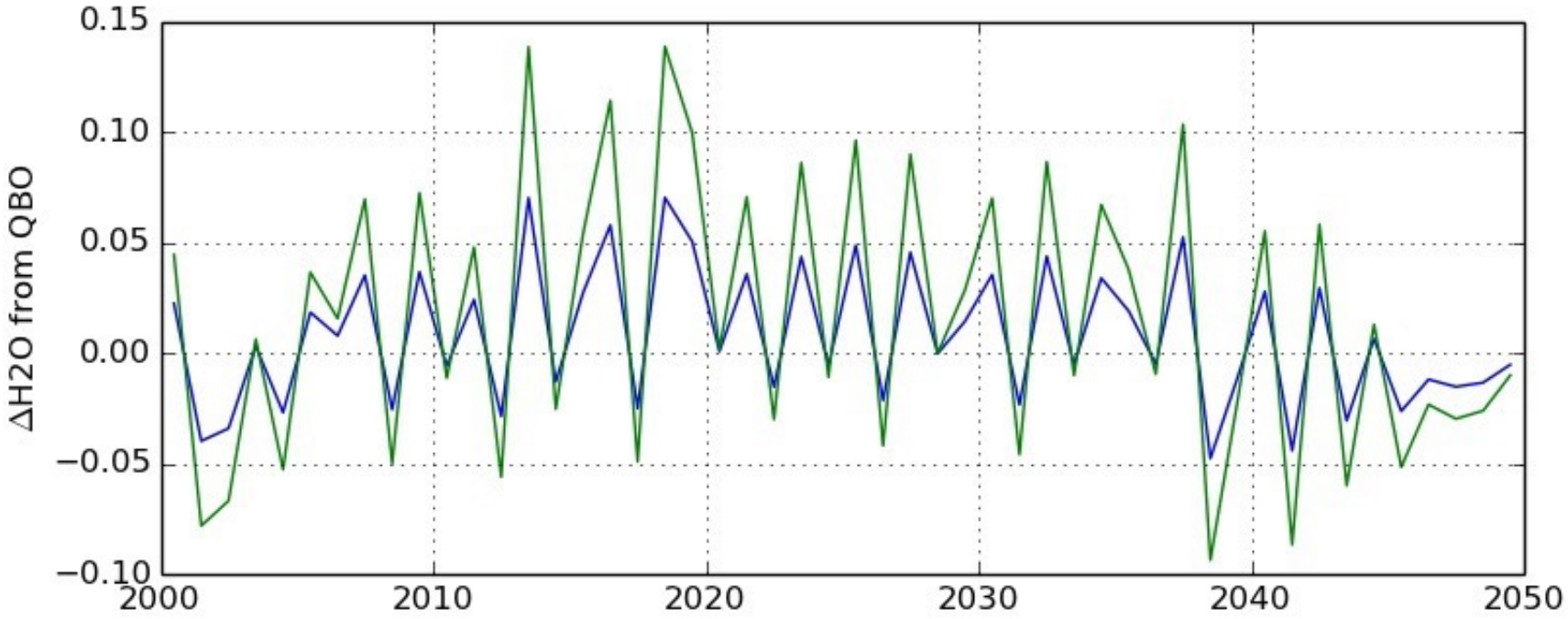

ccm
fit
H2O change (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2010
2020
2030
2040
2050
R^2 = 0.84

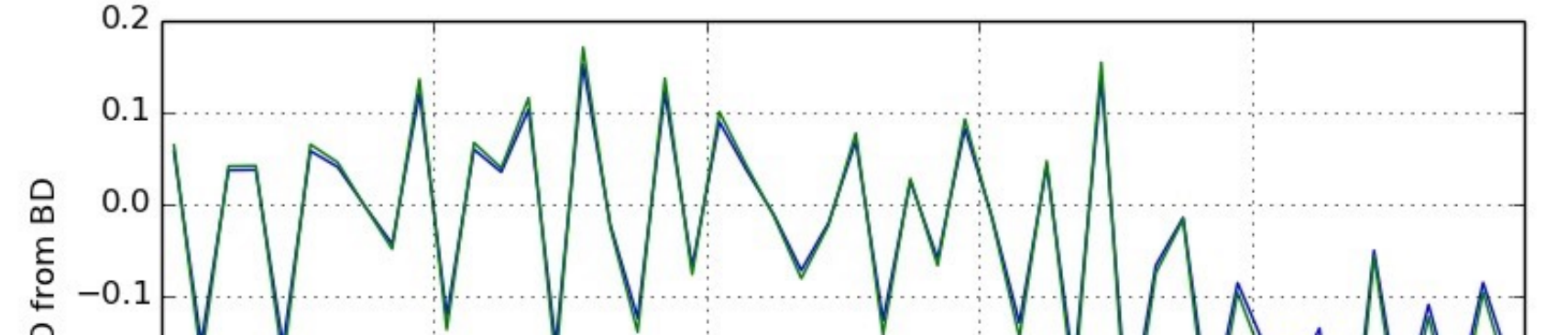

traj
fit
H2O change (ppm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2000
2010
2020
2030
2040
2050
R^2 = 0.81

WACCM

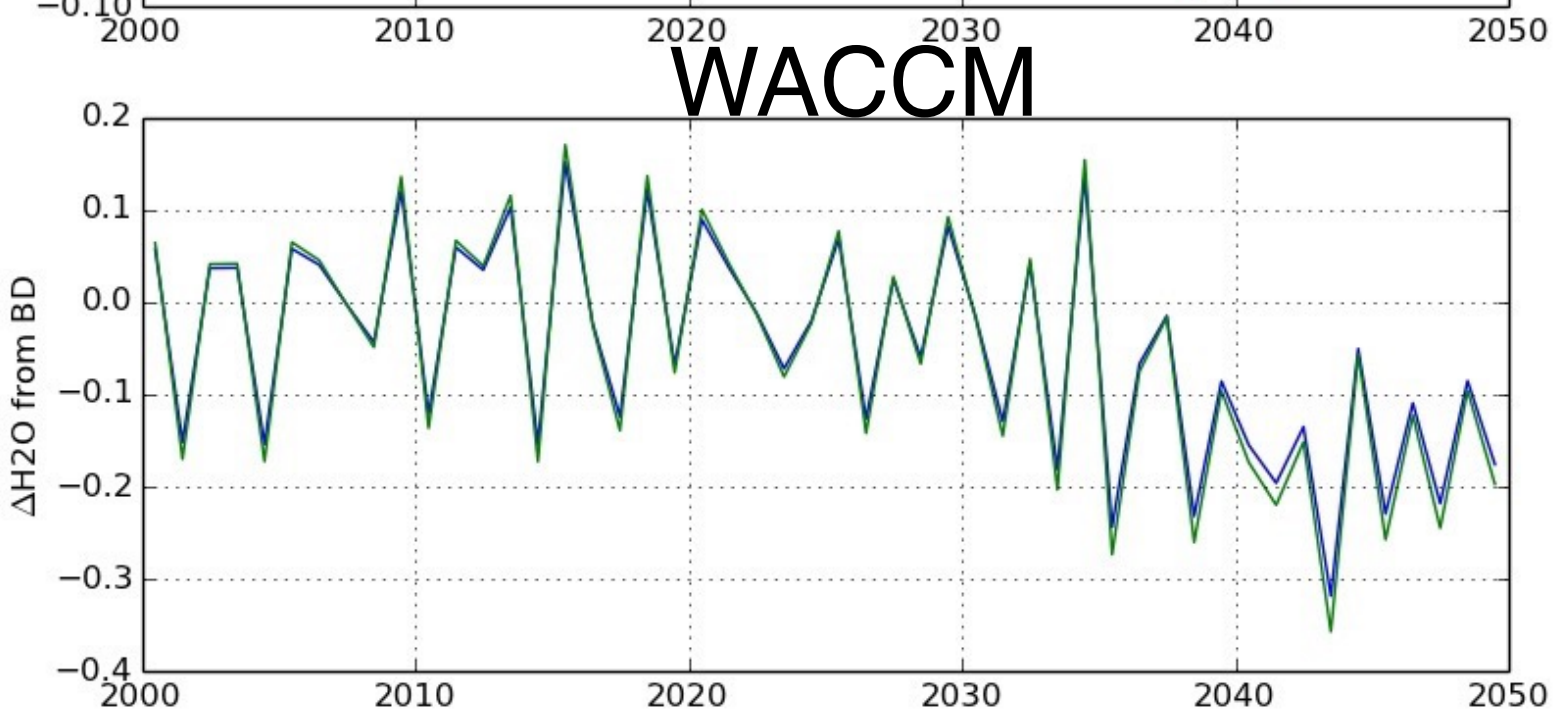

ΔH2O from QBO
0.15
0.10
0.05
0.00
−0.05
−0.10
2000
2010
2020
2030
2040
2050
ΔH2O from BD
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
ΔH2O from ΔT
0.8
0.6
0.4
0.2
0.0
−0.2
ccm
traj

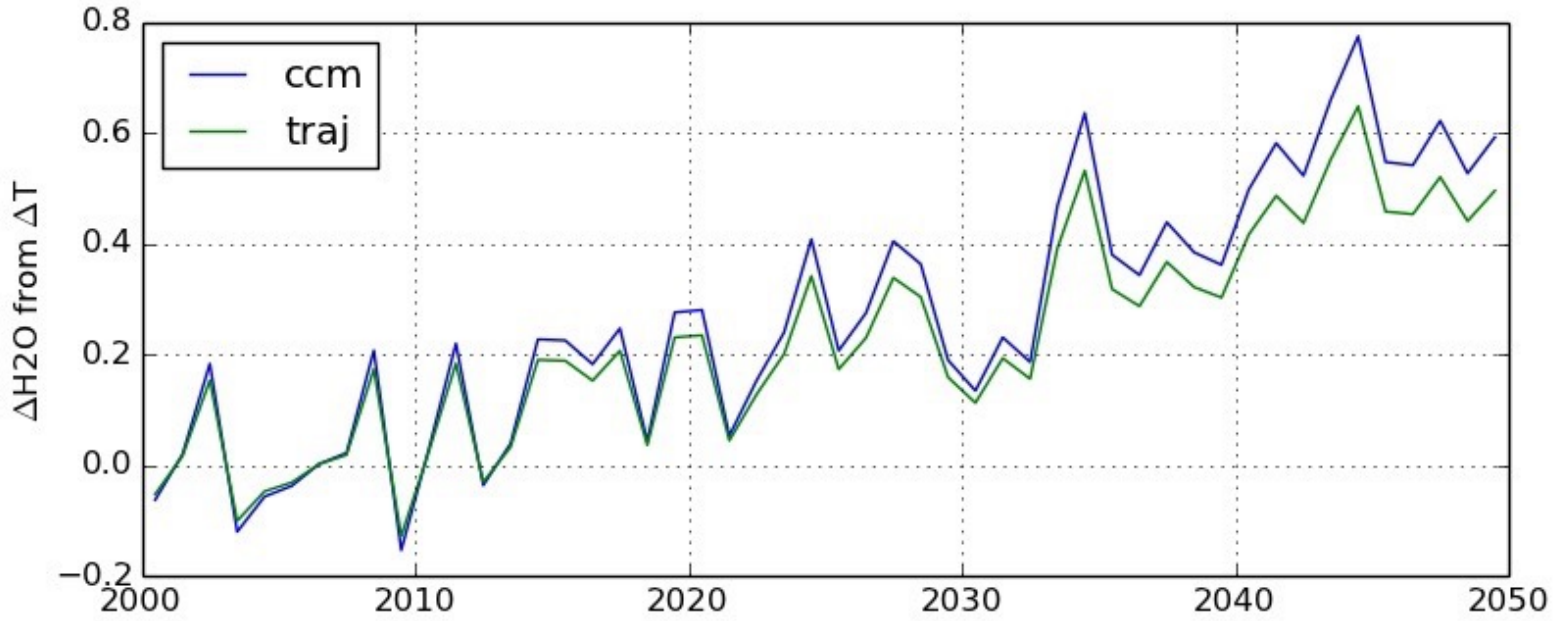
WACCM


0.15
0.10
0.05
0.00
−0.05
−0.10
ΔH2O from QBO
2000
2010
2020
2030
2040
2050

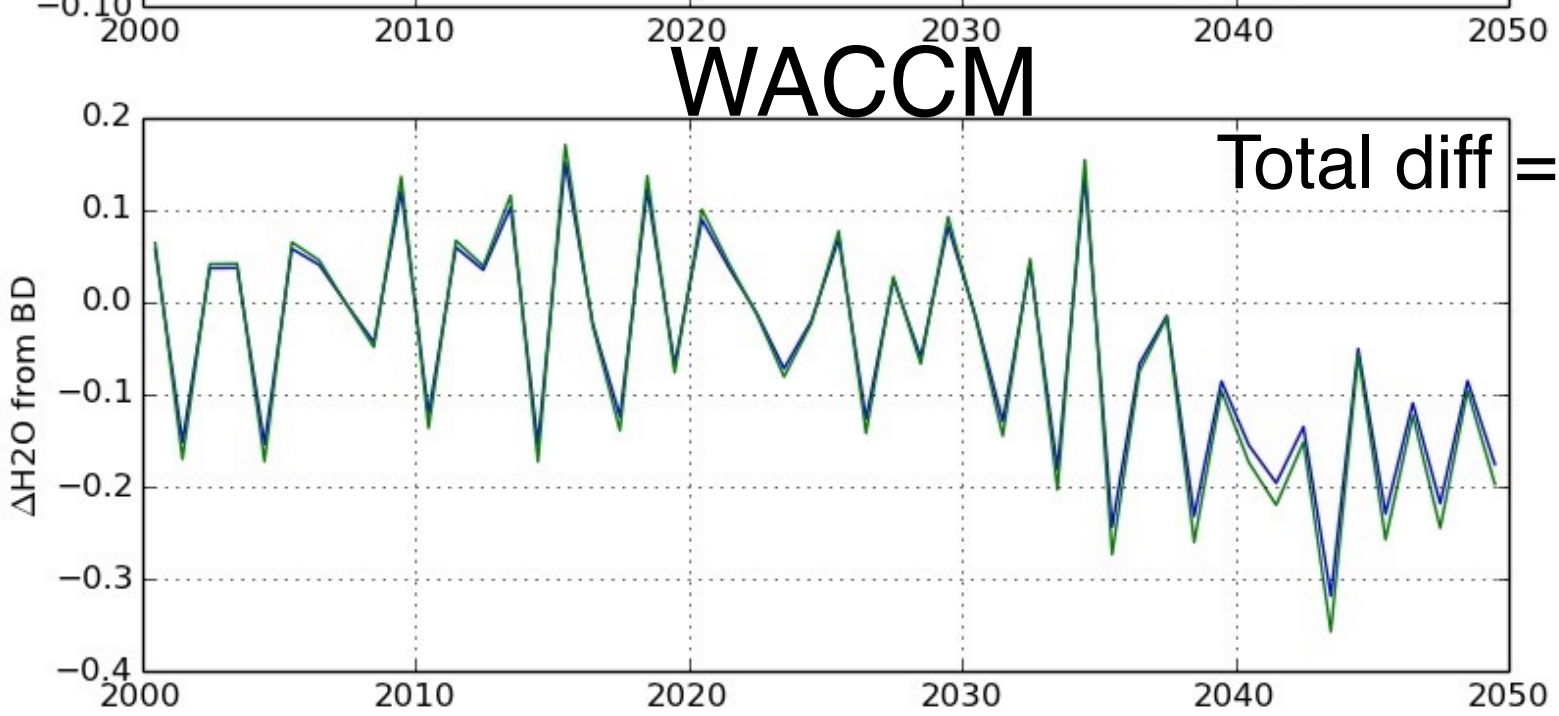

0.2
0.1
0.0
−0.1
from BD

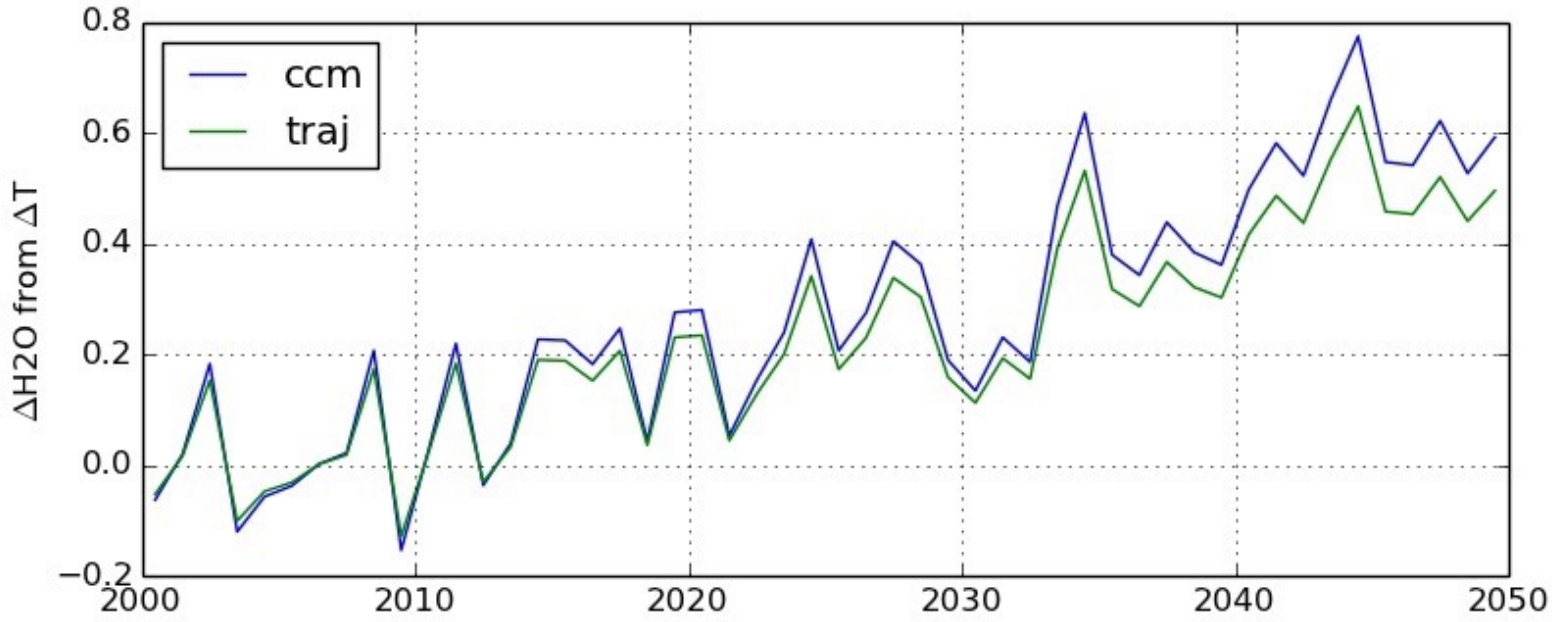
WACCM

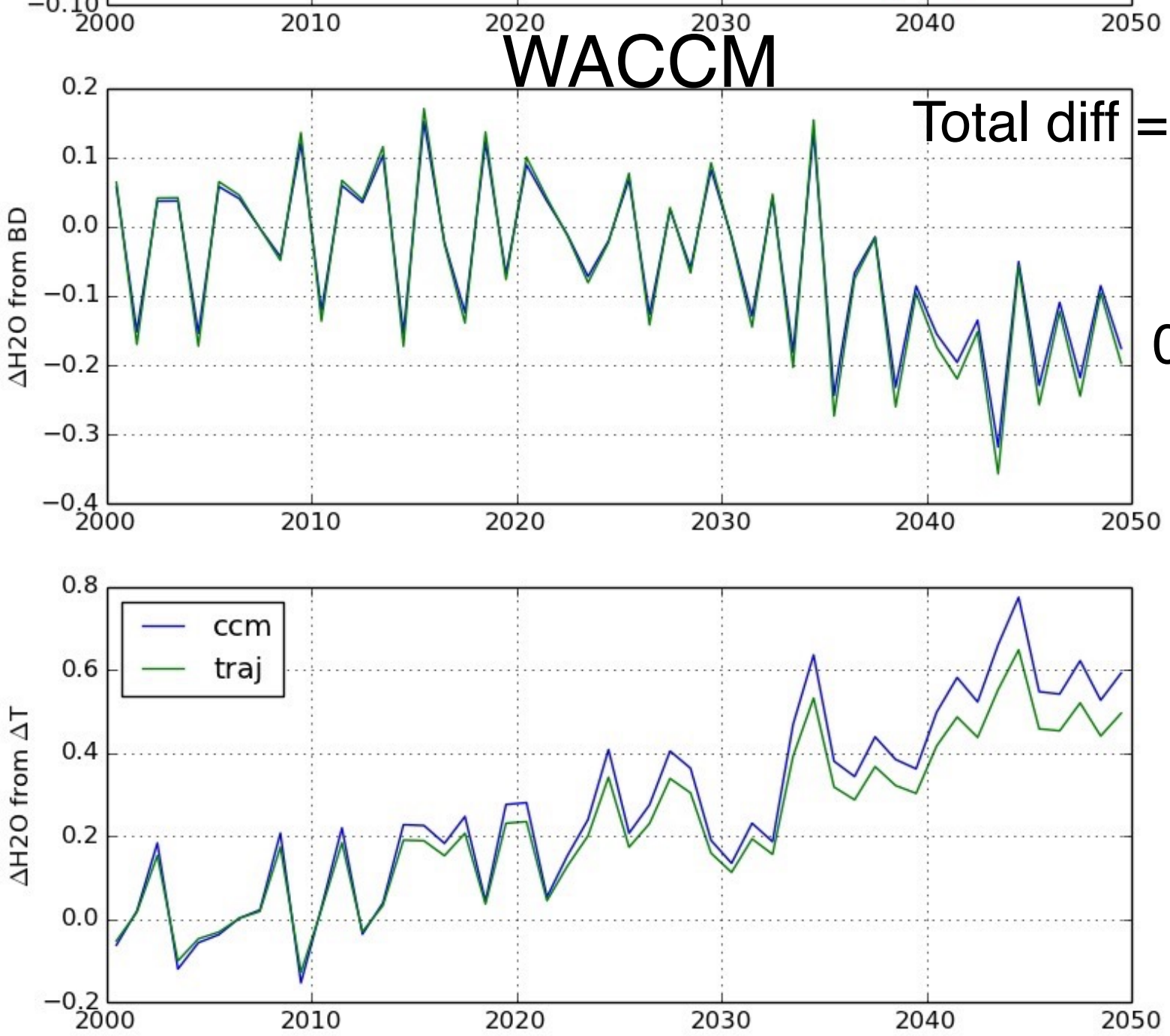

ΔH2O from BD
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
2000
2010
2020
2030
2040
2050

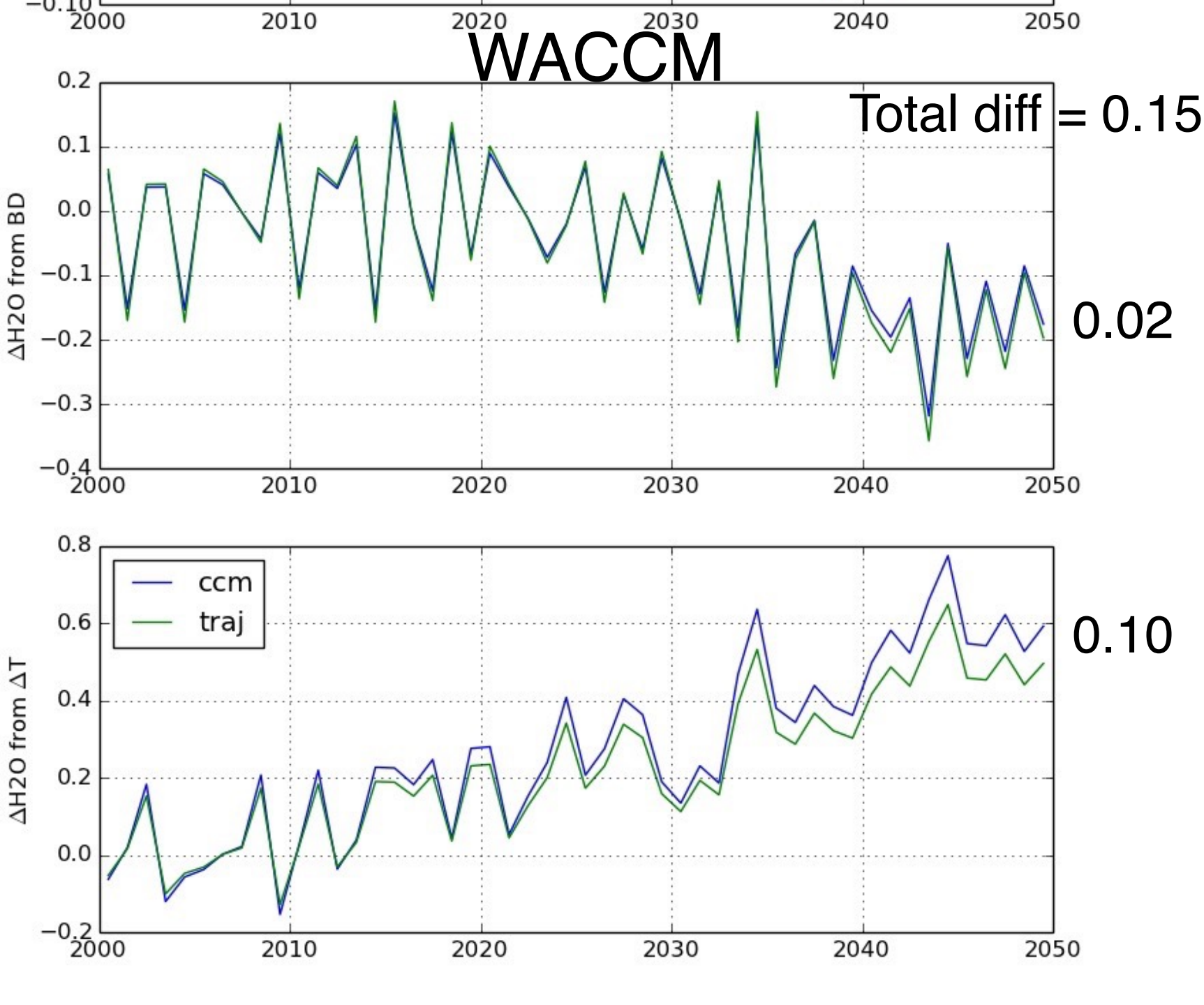

ΔH2O from ΔT
ccm
traj
0.8
0.6
0.4
0.2
0.0
−0.2
2000
2010
2020
2030
2040
2050

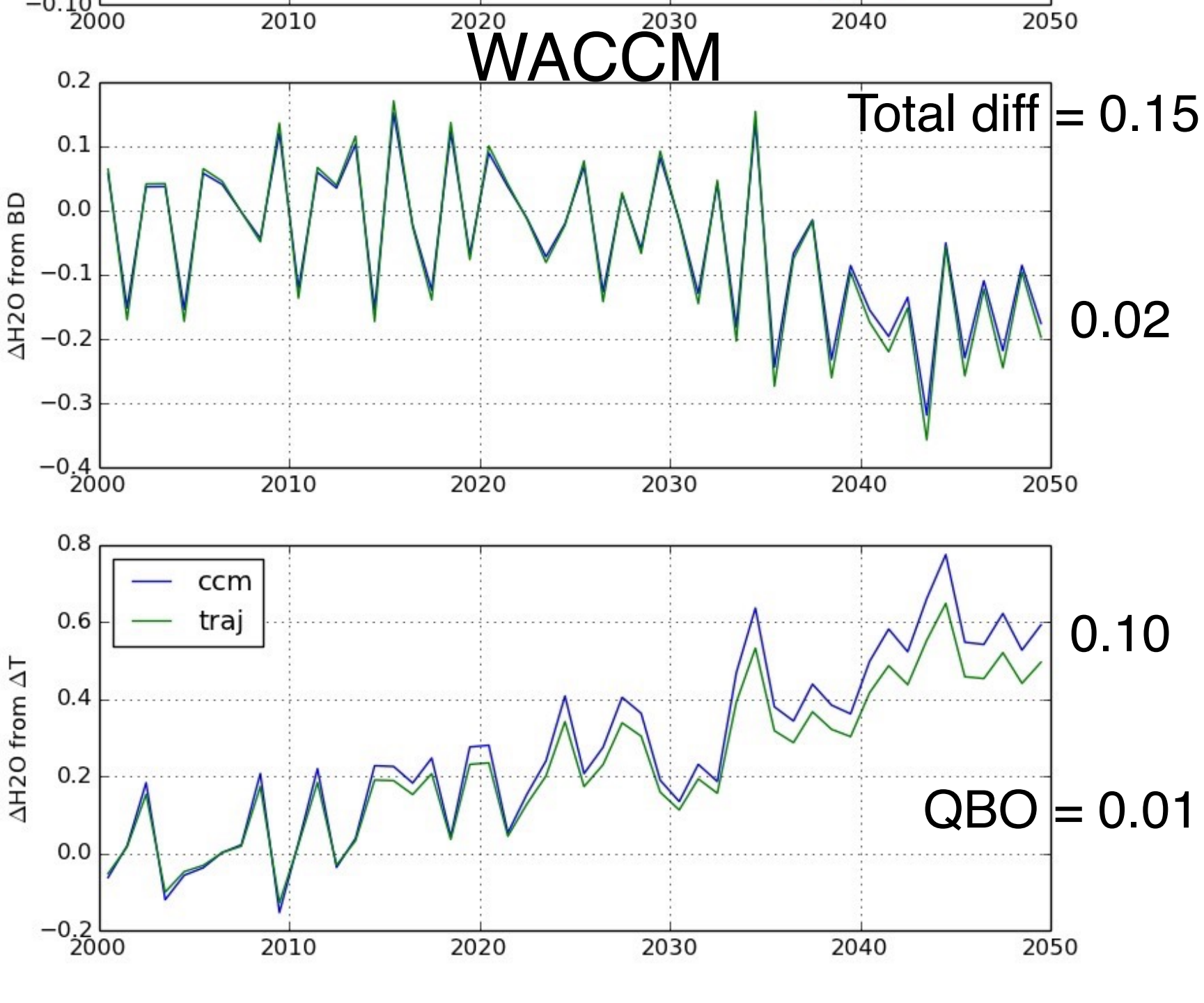
WACCM

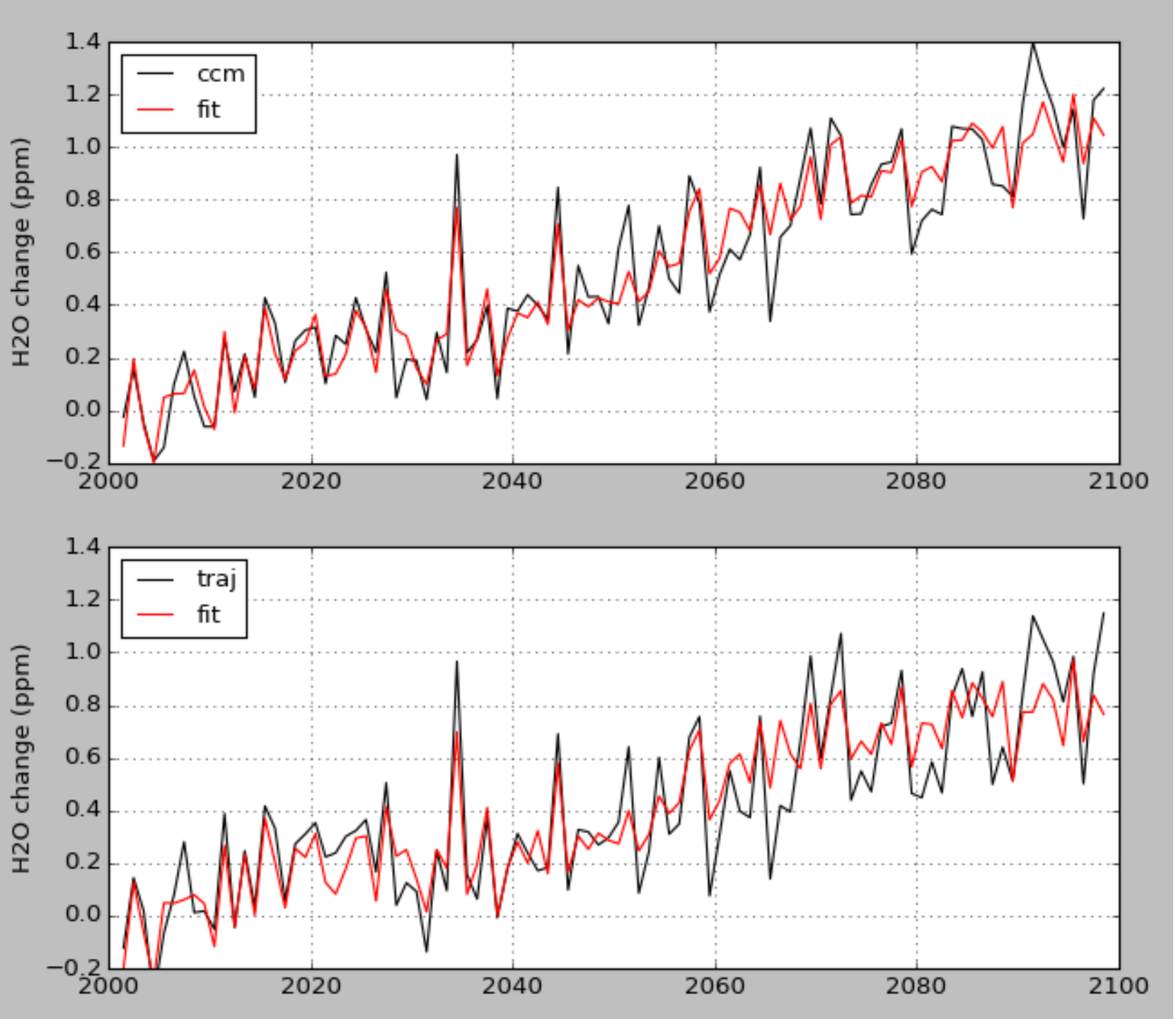

Total diff = 0.15
ΔH2O from BD
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
2000
2010
2020
2030
2040
2050


ccm
traj
ΔH2O from ΔT
0.8
0.6
0.4
0.2
0.0
−0.2
2000
2010
2020
2030
2040
2050


WACCM
Total diff = 0.15
0.02
ΔH2O from BD
ΔH2O from ΔT
ccm
traj
2000
2010
2020
2030
2040
2050


WACCM
Total diff = 0.15
0.02
0.10
ΔH2O from BD
ΔH2O from ΔT
ccm
traj
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0.8
0.6
0.4
0.2
0.0
−0.2
2000
2010
2020
2030
2040
2050


WACCM
Total diff = 0.15
0.02
0.10
QBO = 0.01
ΔH2O from BD
ΔH2O from ΔT
ccm
traj
2000
2010
2020
2030
2040
2050


ccm
fit
H2O change (ppm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
2000
2020
2040
2060
2080
2100
traj
fit
H2O change (ppm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
2000
2020
2040
2060
2080
2100