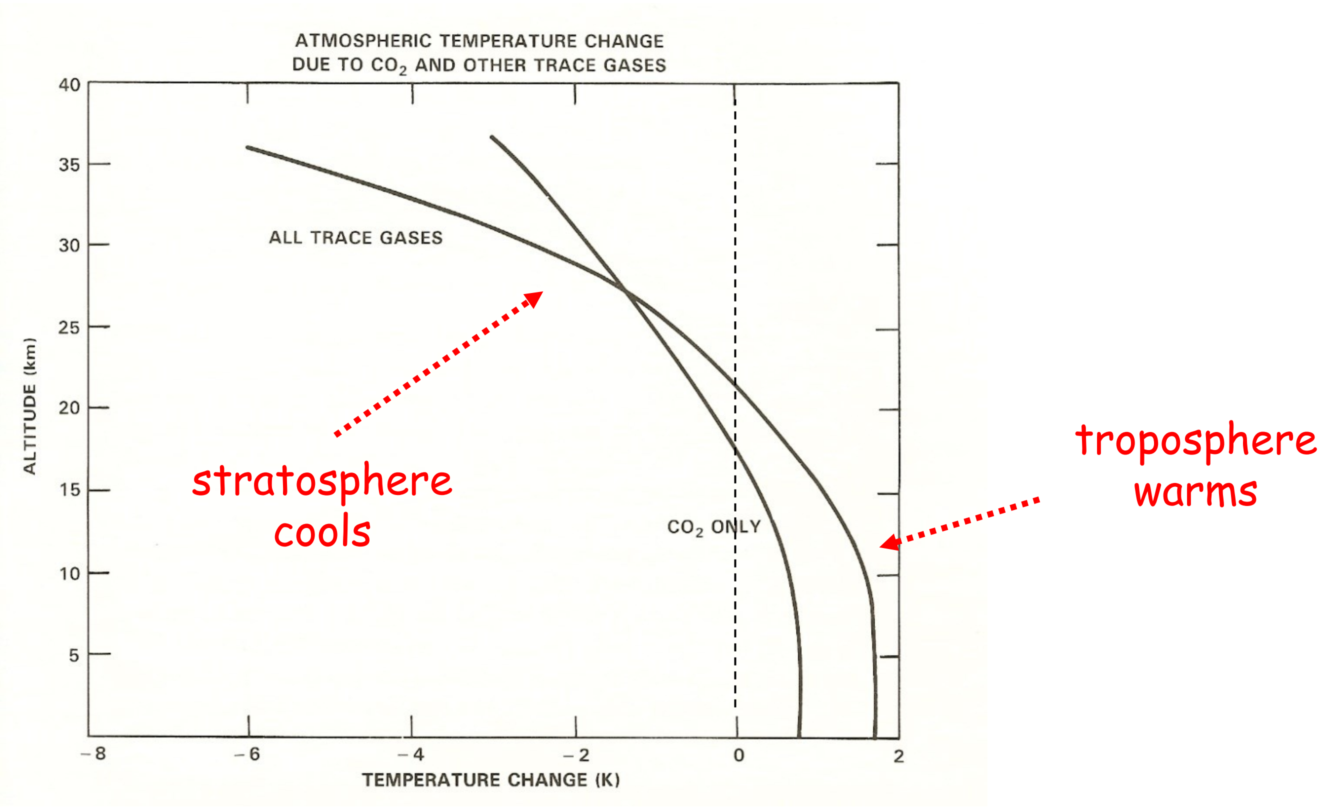
Lecture 2: Variability and trends in stratospheric temperature and water vapor

- Stratospheric temperature
  - Climate change and the stratosphere
  - Stratospheric temperature trends:
    observations (balloons and satellites) and model simulations
  - Recent results from the upper stratosphere
- Stratospheric water vapor
  - Seasonal cycle and the ‘tape recorder’
  - Interannual changes
  - Links to tropical tropopause temperatures

Simple view: climate change in the stratosphere



WMO Ozone Assessment, 1985

United States CCSP 2006 Assessment: Temperature Trends in the Lower Atmosphere

temp trends for 1958-1999

model results

ozone

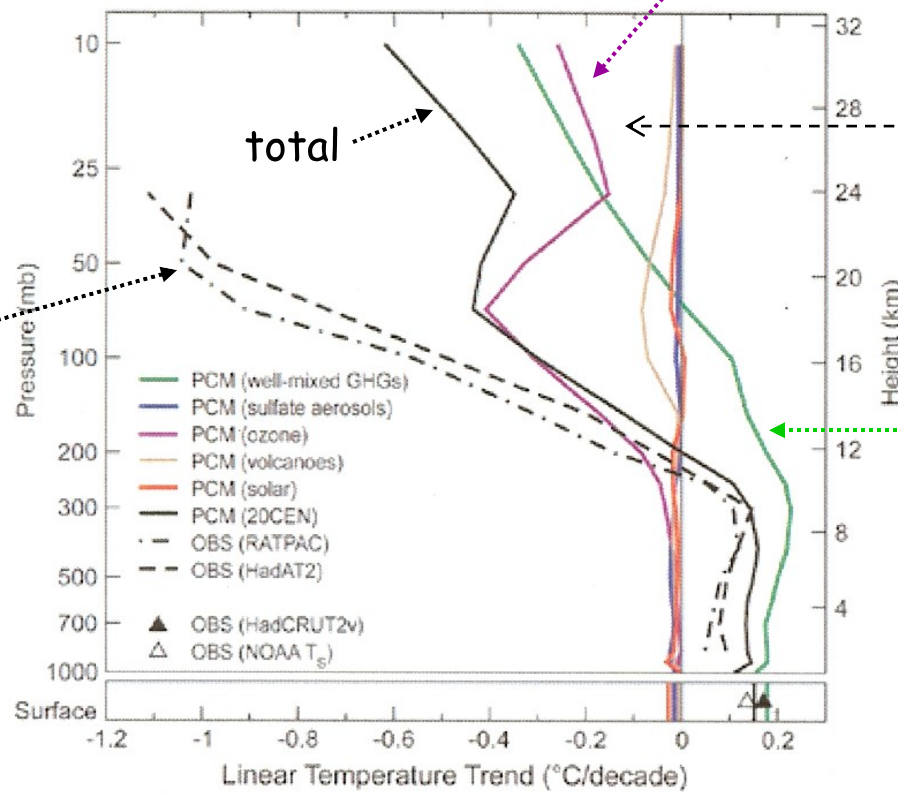
CO_2 increases and O_3 decreases act to cool the stratosphere

total

radiosonde data sets

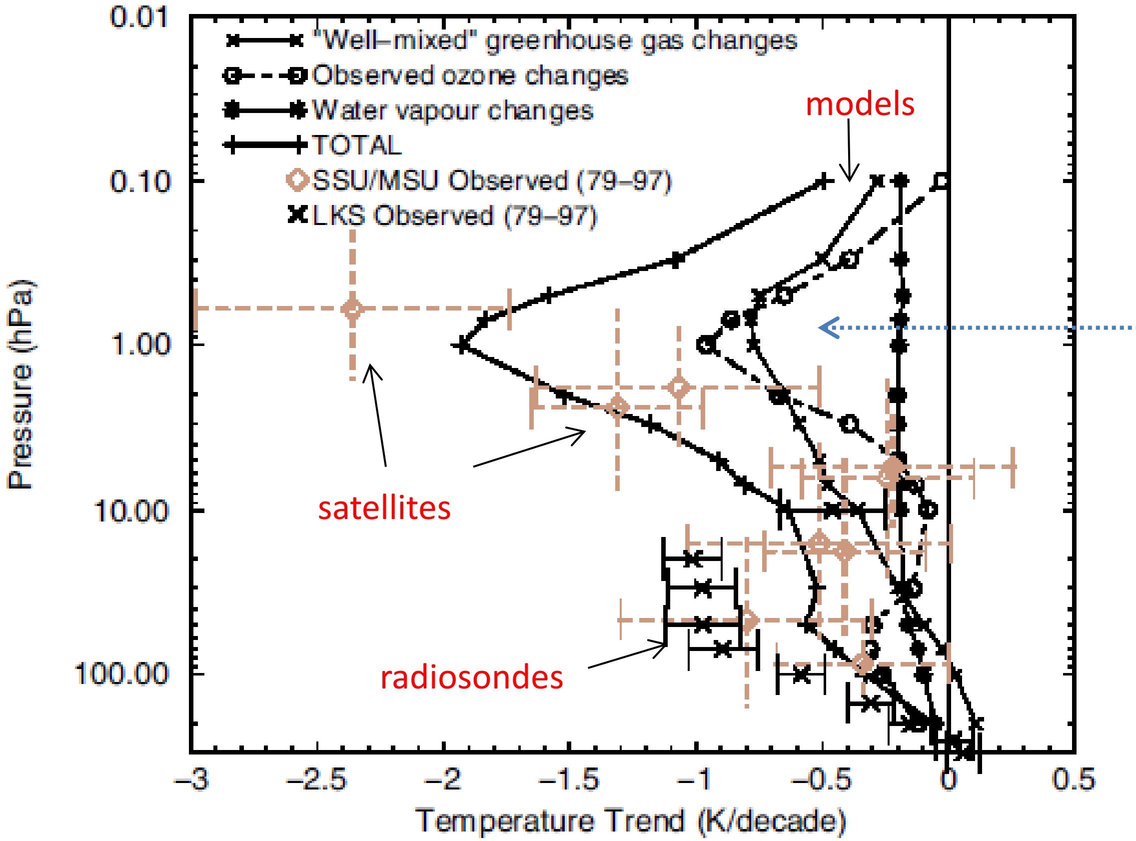
CO_2

note that radiosonde data give stronger cooling than models



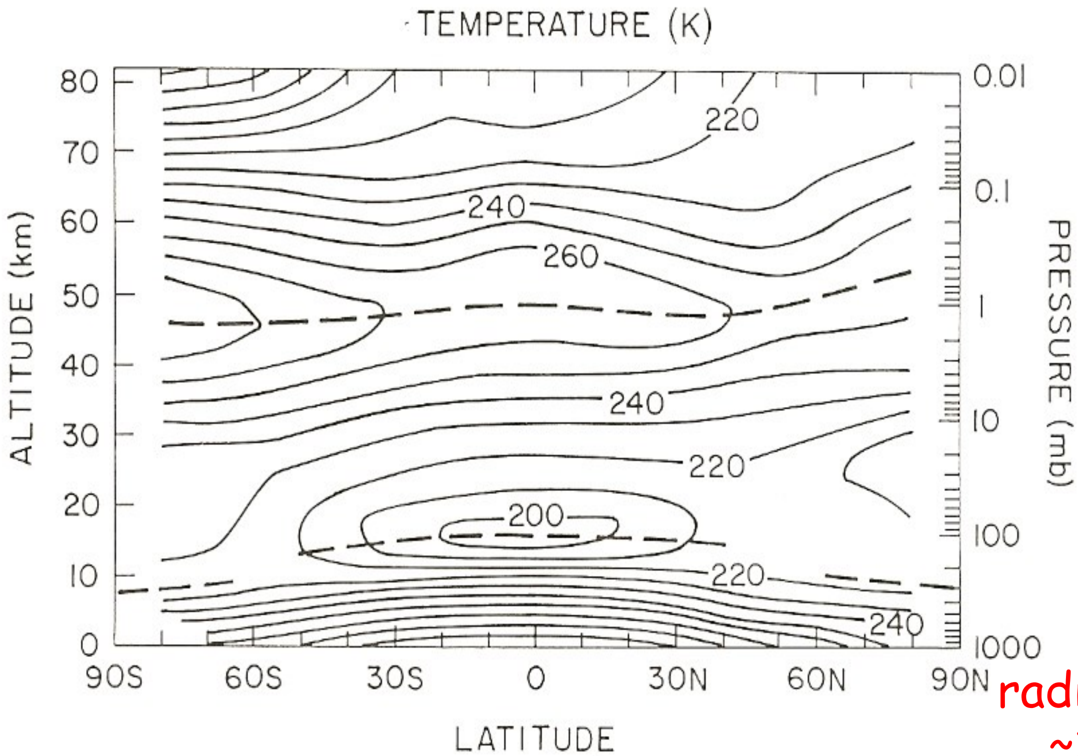
Model calculated stratospheric temperature trends

Shine et al 2003



stratosphere cooling:
about ½ from CO_2 increase
and ½ from O_3 decrease

Data sources for stratospheric temperature trends:



mainly for research

lidars >1980

rockets ~1960-1990

satellites > 1979

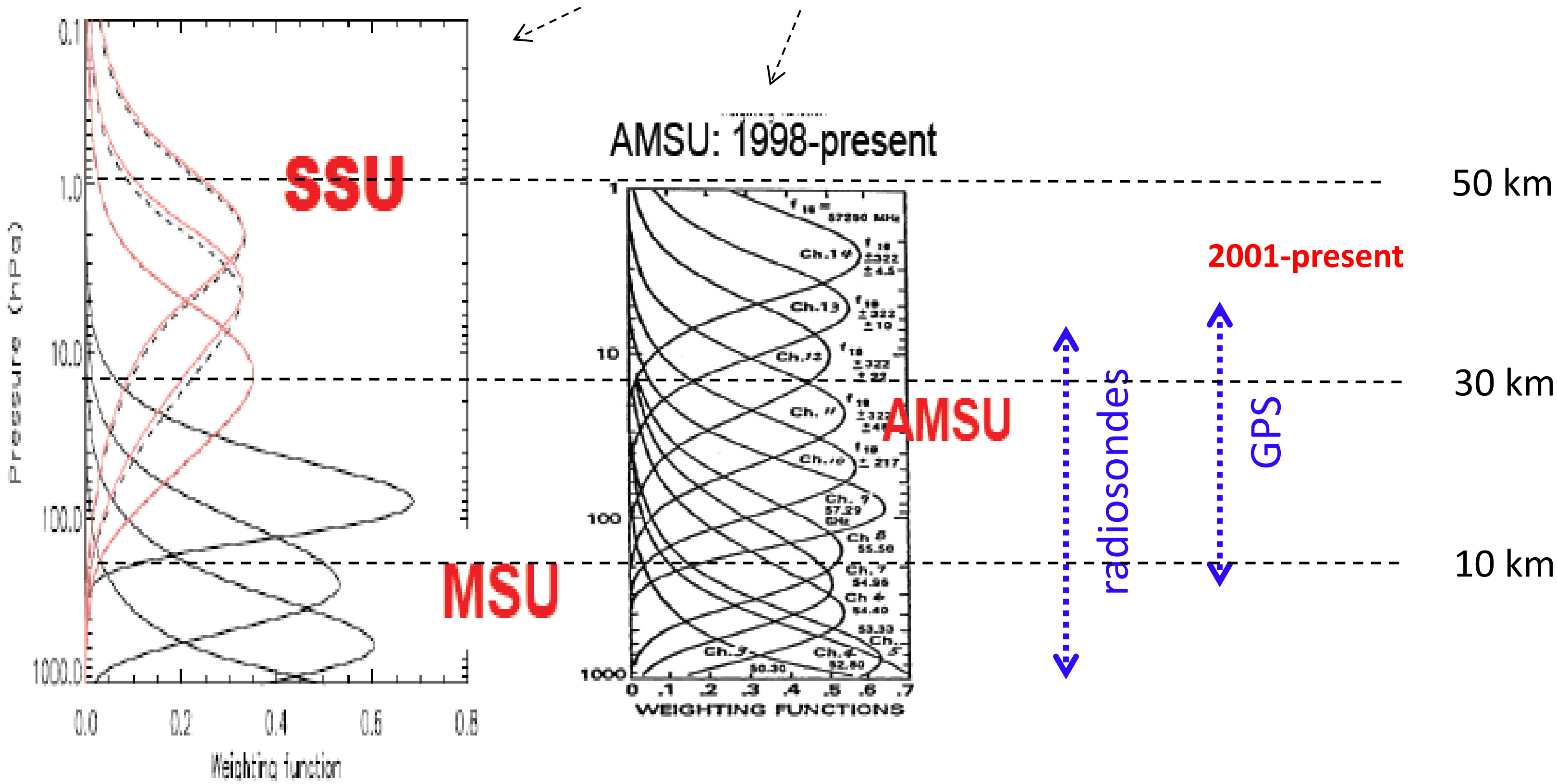
radiosondes ~1960

<u>Fundamental problem</u>: data are intended for weather forecasting, not climate variability and trends

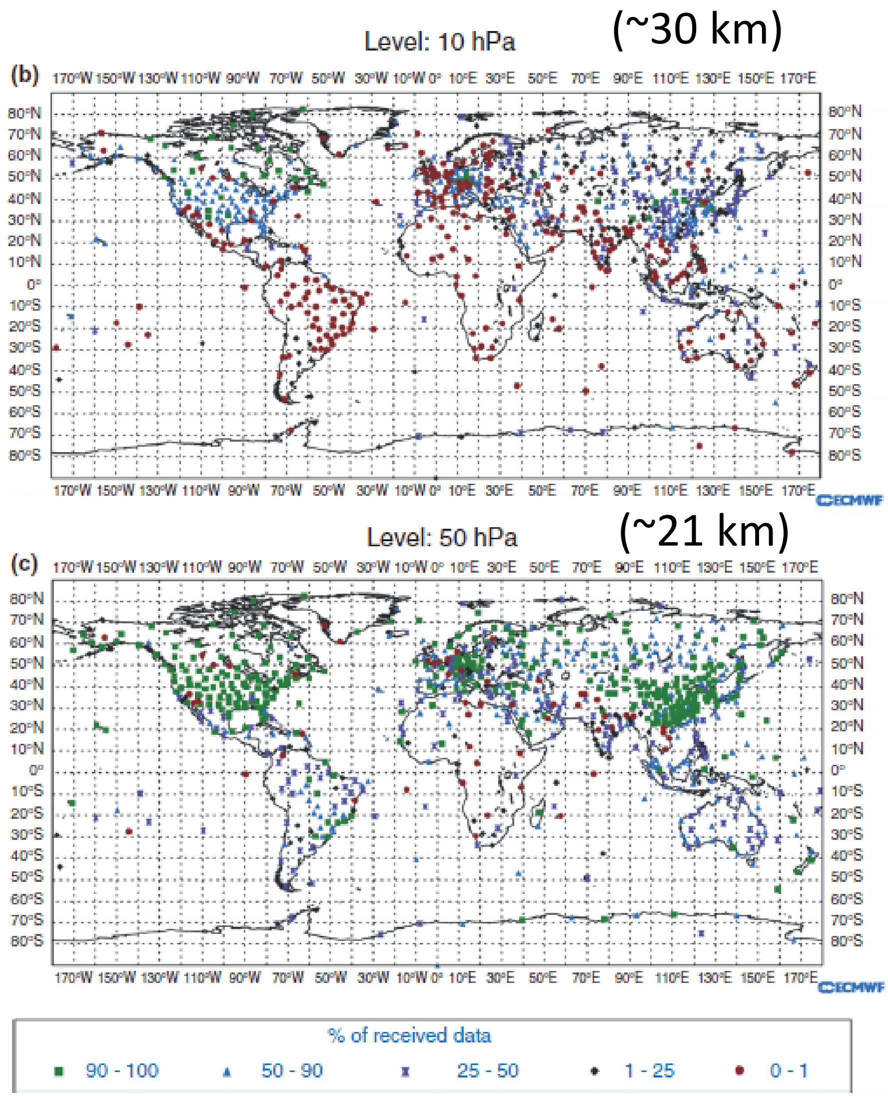
Operational satellites (nadir sounders)

nadir sounders are sensitive to
temperatures over deep layers (~10-15 km)

MSU+SSU: 1979-2007



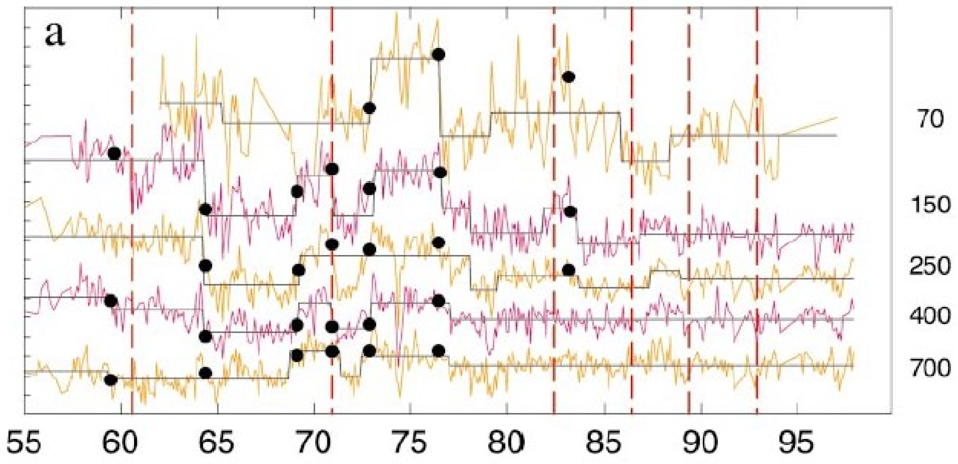
Global radiosonde network



Characteristics:

- Majority of measurements over continents
- Poorer coverage at upper levels
- Radiosonde sensors change over time

<u>Problem</u>: inhomogeneities in historical radiosonde data due to instrumentation changes, radiation corrections, etc.



radiosonde record from Naimey

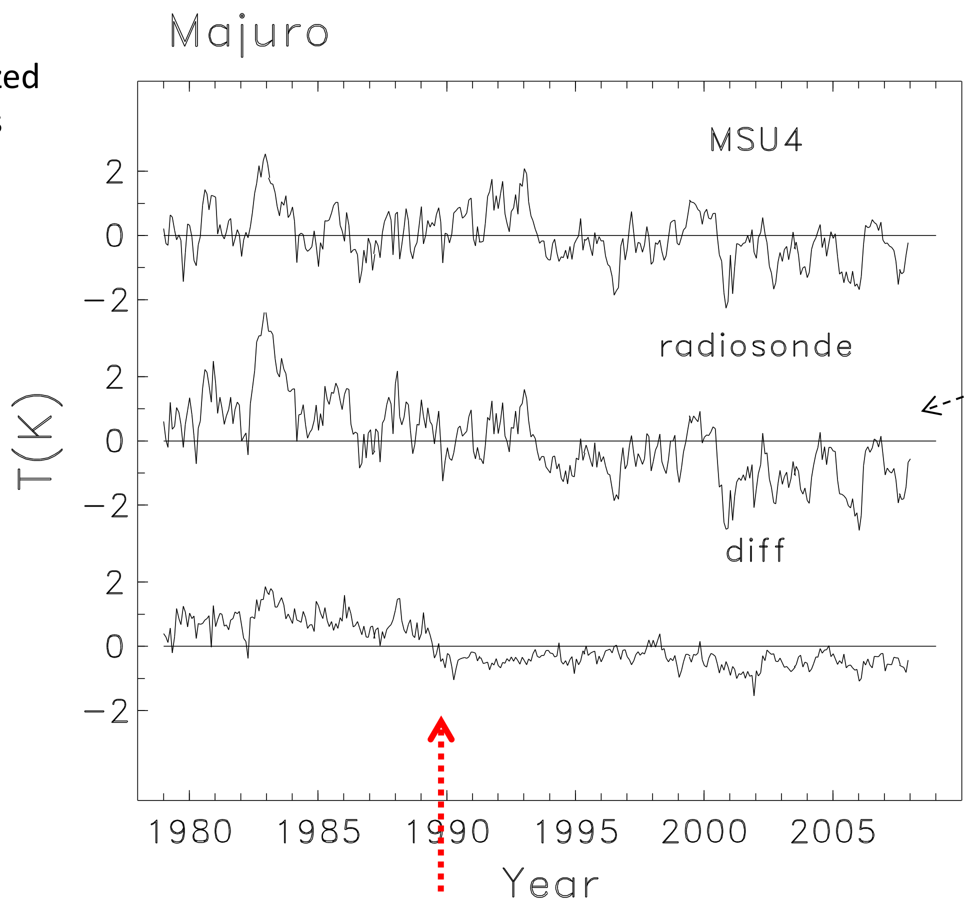
Lanzante et al 2003

Corrections can be made using different techniques:

- Manual adjustments for ~80 key stations (RATPAC, Free et al , 2005)
- Statistical adjustments (HADAT2; Thorne et al, 2005)
- Statistical identification of 'break points' (IUK, Sherwood et al, 2008)
- Using meteorological data assimilation increments to identify break points (Raobcore, RICH; Haimberger et al, 2008)

Example of radiosonde station with artificial change

deseasonalized anomalies



satellite

radiosonde

difference

note that jumps are not evident in anomaly time series

jump due to change in radiosonde

Common problem; many historical radiosonde data have similar jumps

Historical radiosonde results now available from
6 separate homogenized data sets:

RATPAC (Free et al, 2005) (expert judgement for 85 stations)

RATPAC-lite (Randel and Wu, 2006) (subset of RATPAC stations)

HadAT2 (Thorne et al, 2005) (use near neighbors to identify breaks)

IUK (Sherwood, 2007) (statistical fits to identify break points)

RAOBCORE 1.4 (Haimberger, 2007)

RICH (Haimberger et al., 2008)

(use ERA40 assimilation increments to identify breaks) [applies to RAOBCORE 1.4 and RICH]

differences provide a measure of 'structural uncertainty'

An update of observed stratospheric temperature trends

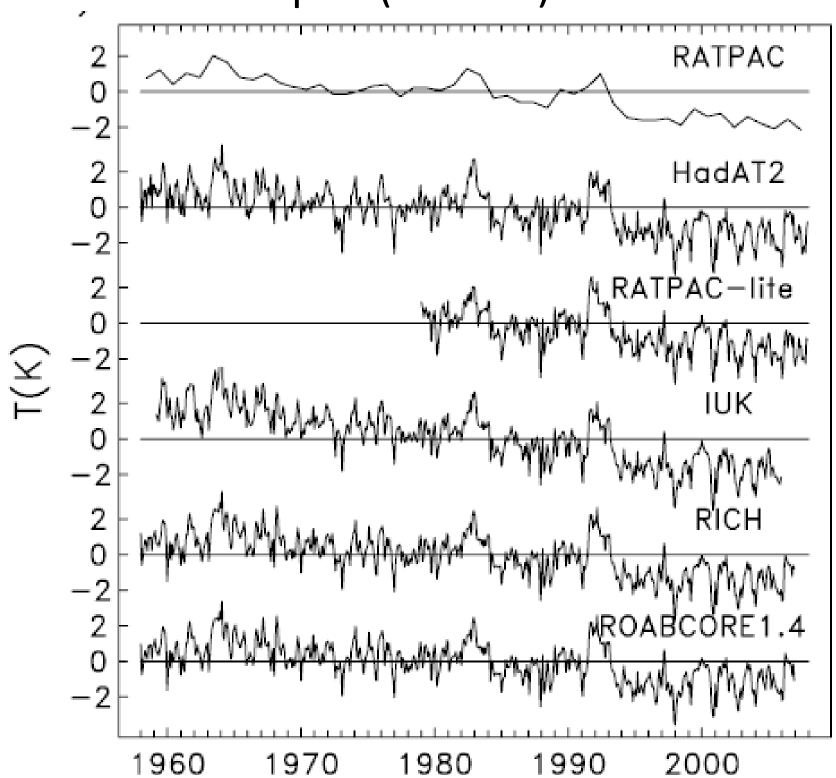
JGR, 2009

William J. Randel,[1] Keith P. Shine,[2] John Austin,[3] John Barnett,[4] Chantal Claud,[5] Nathan P. Gillett,[6] Philippe Keckhut,[7] Ulrike Langematz,[8] Roger Lin,[9] Craig Long,[9] Carl Mears,[10] Alvin Miller,[9] John Nash,[11] Dian J. Seidel,[12] David W. J. Thompson,[13] Fei Wu,[1] and Shigeo Yoden[14]

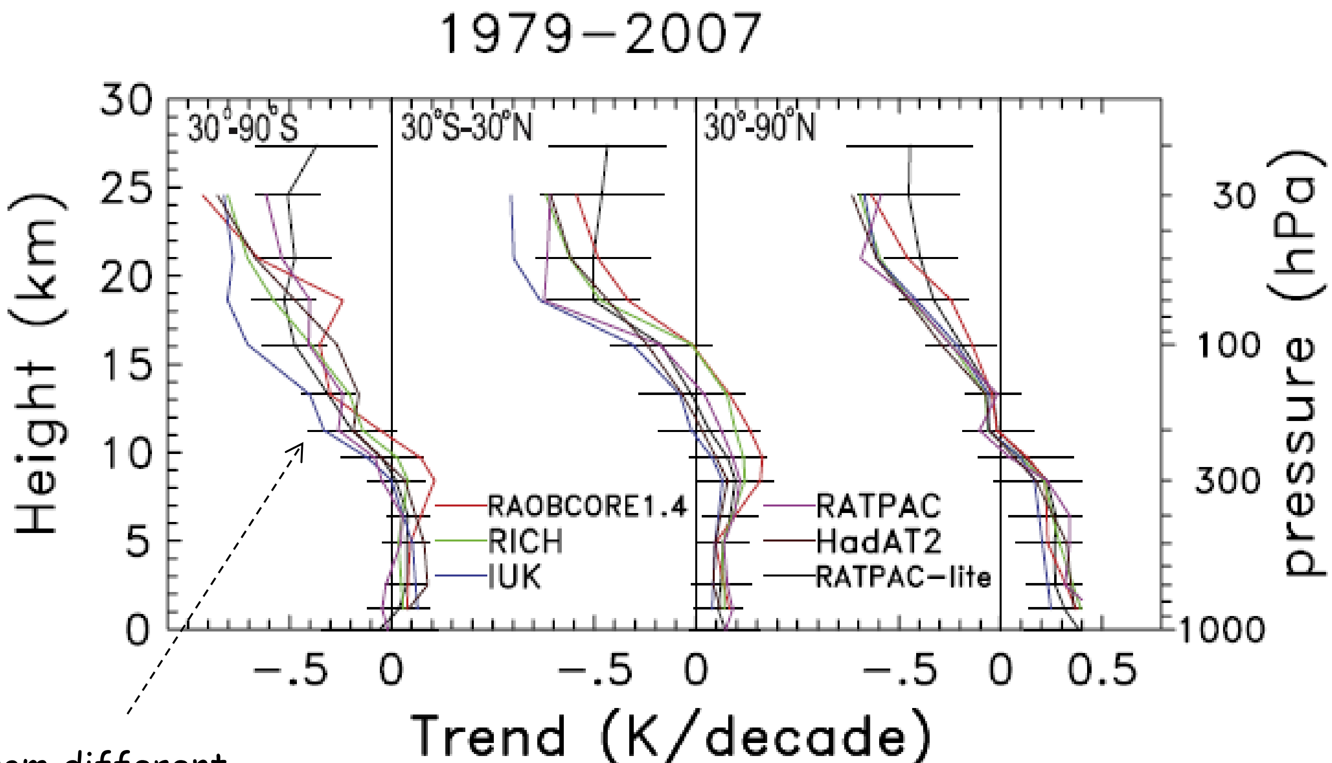
Comparison of time series from different homogenized radiosonde data sets

Tropics (30° N-S) 50 hPa

deseasonalized anomalies



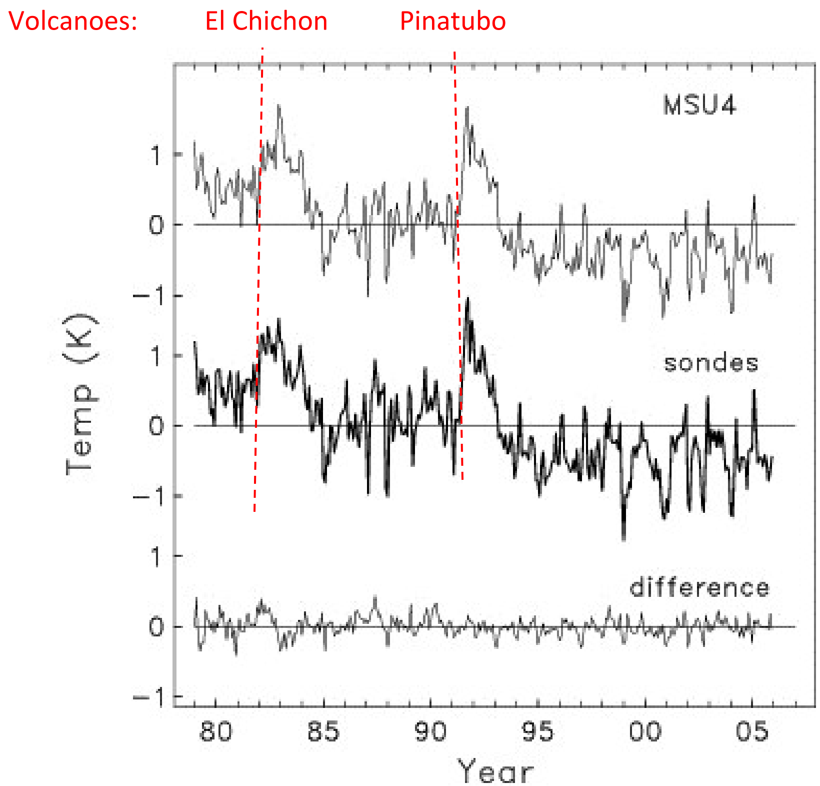
Temperature trends from radiosonde data



results from different
homogenized data sets

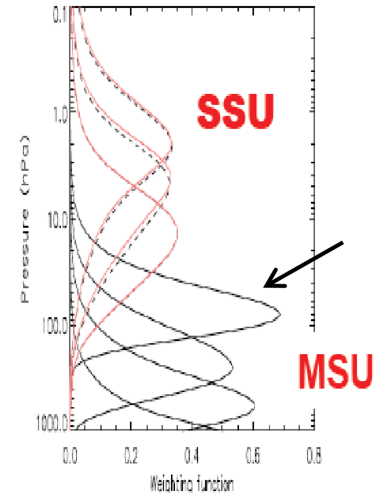
Randel et al., 2009, J. Geophys. Res.

Lower stratosphere temps: MSU4 satellite and radiosondes, 60 N-S



MSU4 satellite

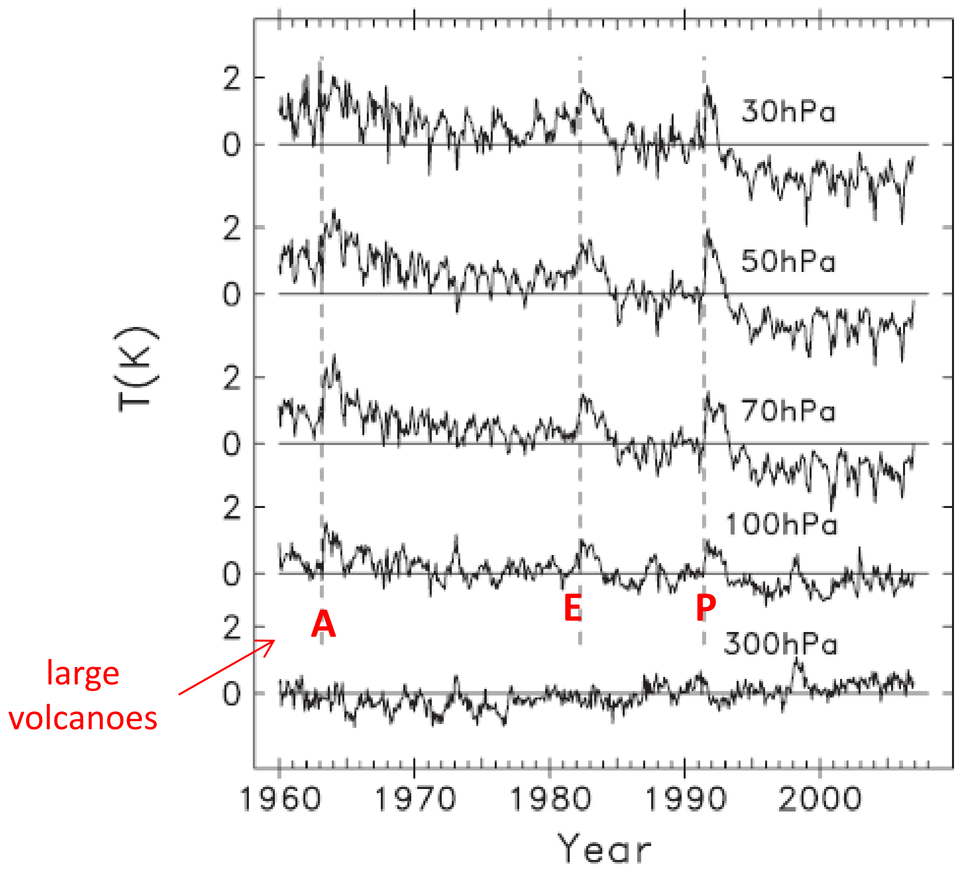
Radiosondes, using
RATPAC-lite stations



note relatively constant
temps after ~1995

Randel, 2010, American Geophysical Union

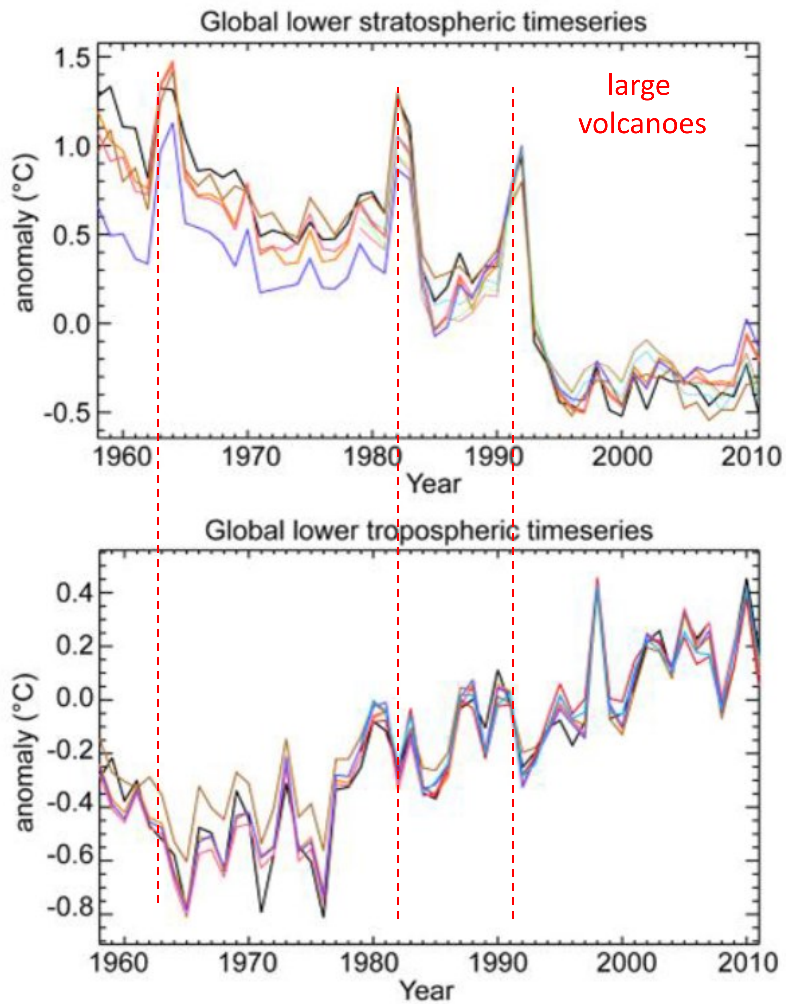
Global average time series from RICH radiosonde data



Randel, 2010, American Geophysical Union

Reasonable overall agreement among radiosonde and satellite data sets

lower stratosphere



lower troposphere

black: satellite
colors: radiosondes

IPCC AR5 2014

Quantifying temperature variability using multiple linear regression

From experience, stratospheric temperature is known to be influenced by the QBO, the 11-year solar cycle, volcanoes, ENSO, plus changes in CO_2 and O_3 and H_2O

$$O3\ (t) = A1 * QBO1(t) + A2 * QBO2(t) + A3 * solar(t) + A4 * t$$

Use two orthogonal proxies for QBO

Long-term change or linear tend

Could also include other proxies, such as for ENSO, volcanoes or EP fluxes

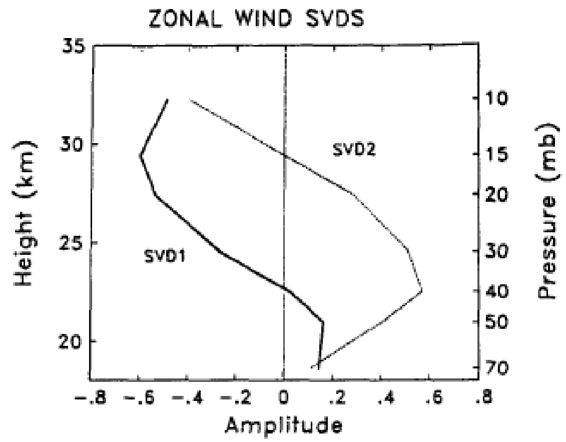
Representation of the Equatorial Stratospheric Quasi-Biennial Oscillation in EOF Phase Space

JOHN M. WALLACE

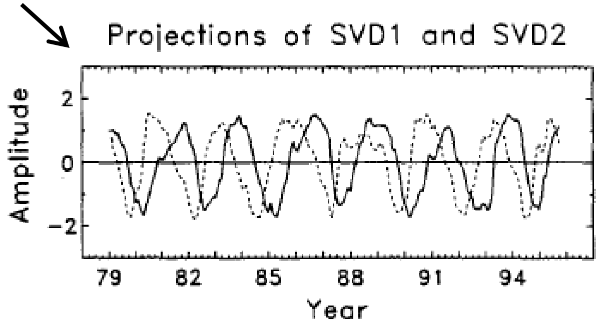
Department of Atmospheric Sciences, University of Washington, Seattle, Washington

JAS 1993

Key point: two orthogonal EOF's explain almost all of the variance tied to the QBO

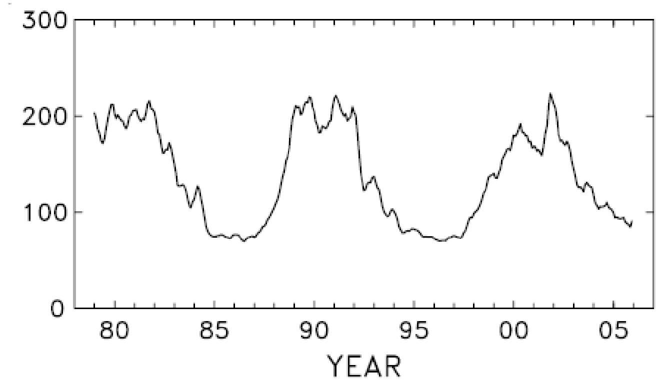


QBO1 and QBO2: orthogonal proxies

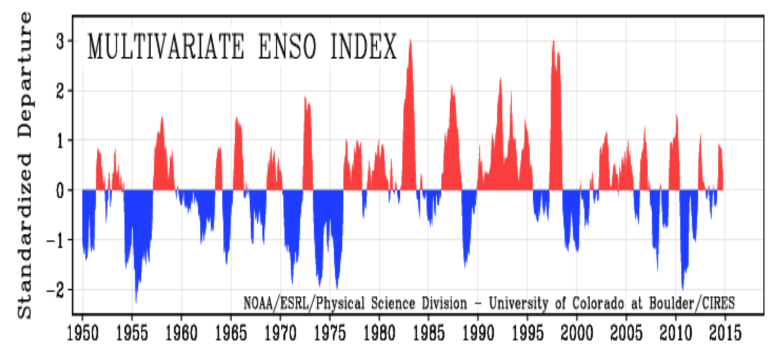


Other proxies:

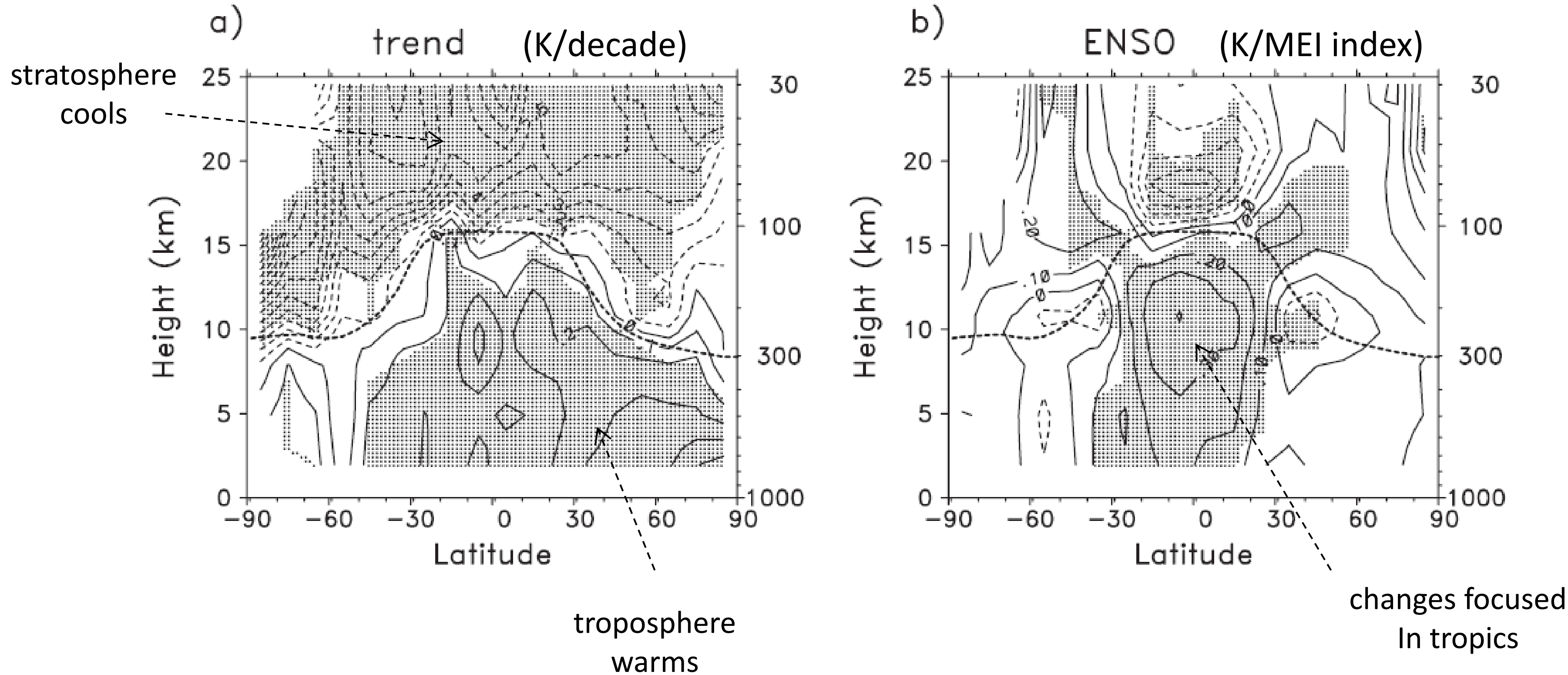
Solar cycle (F10.7 flux)



ENSO



Temperature trends and ENSO signal derived from RICH radiosonde data 1970-2010

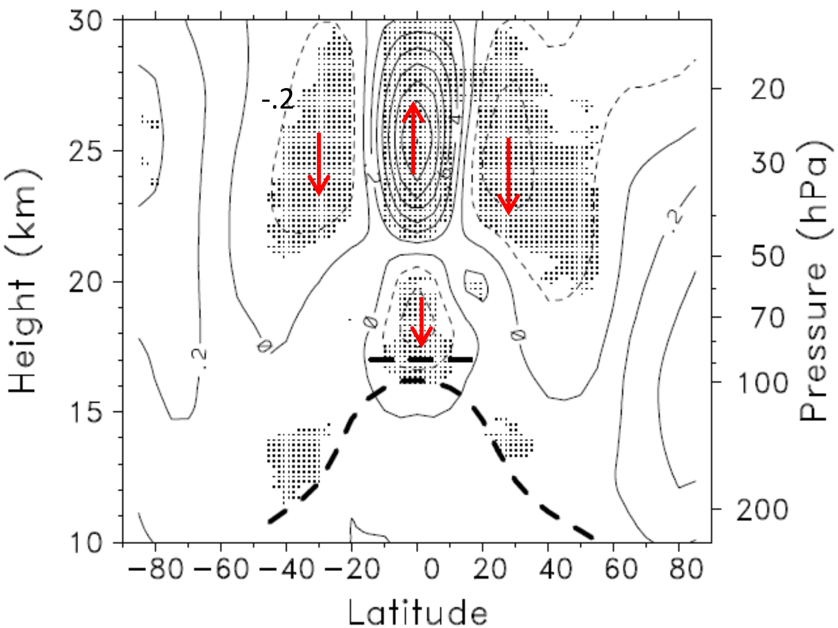


Randel, 2010, American Geophysical Union

Regression fits of QBO using GPS temperatures

there is a corresponding QBO2 pattern (orthogonal to QBO1)

QBO1

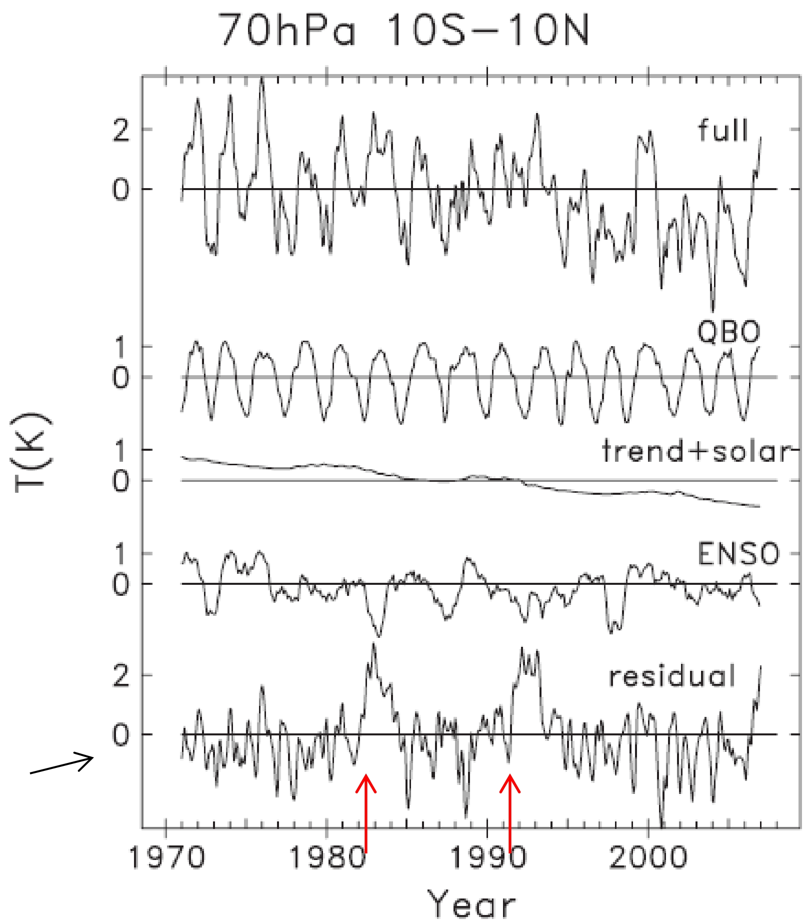


- Signals confined to stratosphere
- Out-of-phase patterns in subtropics reflect meridional circulation

Randel and Wu, 2014, J. Atmos. Sci.

Variability in the tropical lower stratosphere:

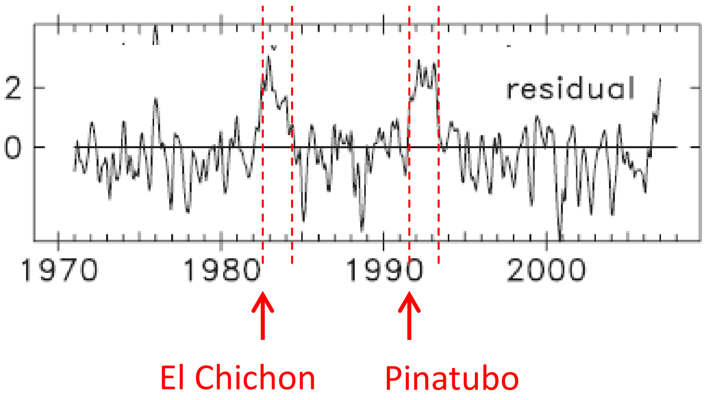
time series and regression fits
at 70 hPa, 10° N-S



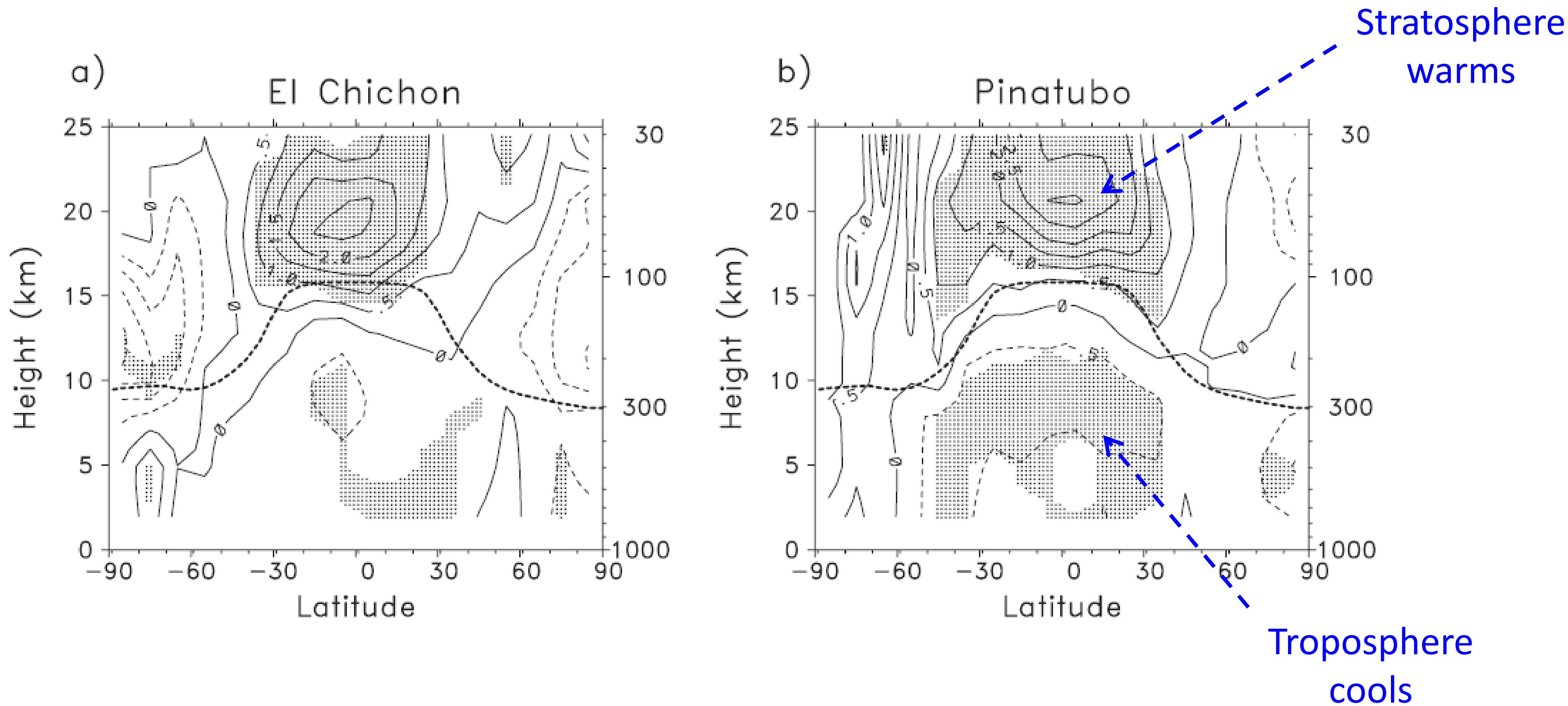
note that the volcanic signal
is clear if you first remove
'other' variability

Randel, 2010, American Geophysical Union

Volcanic signals derived as ‘residuals’ to regression fits

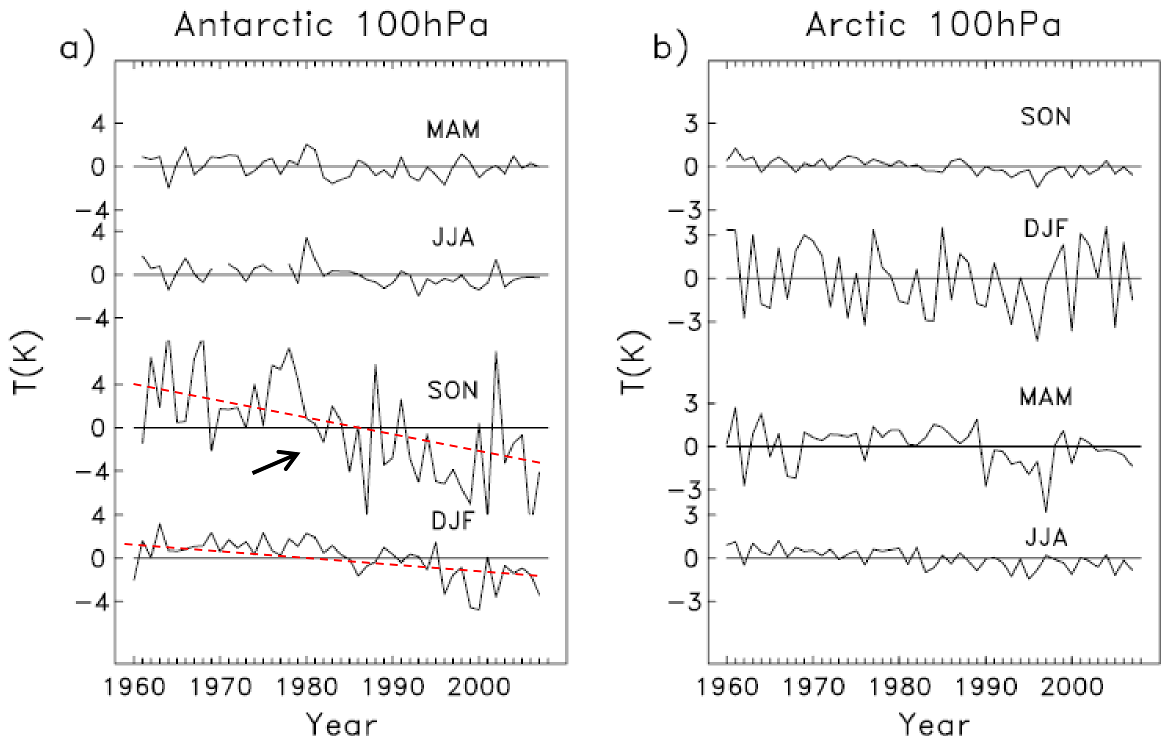


Temperature anomalies for 2 years after volcanic eruptions



Randel, 2010, American Geophysical Union

Polar stratosphere temperatures

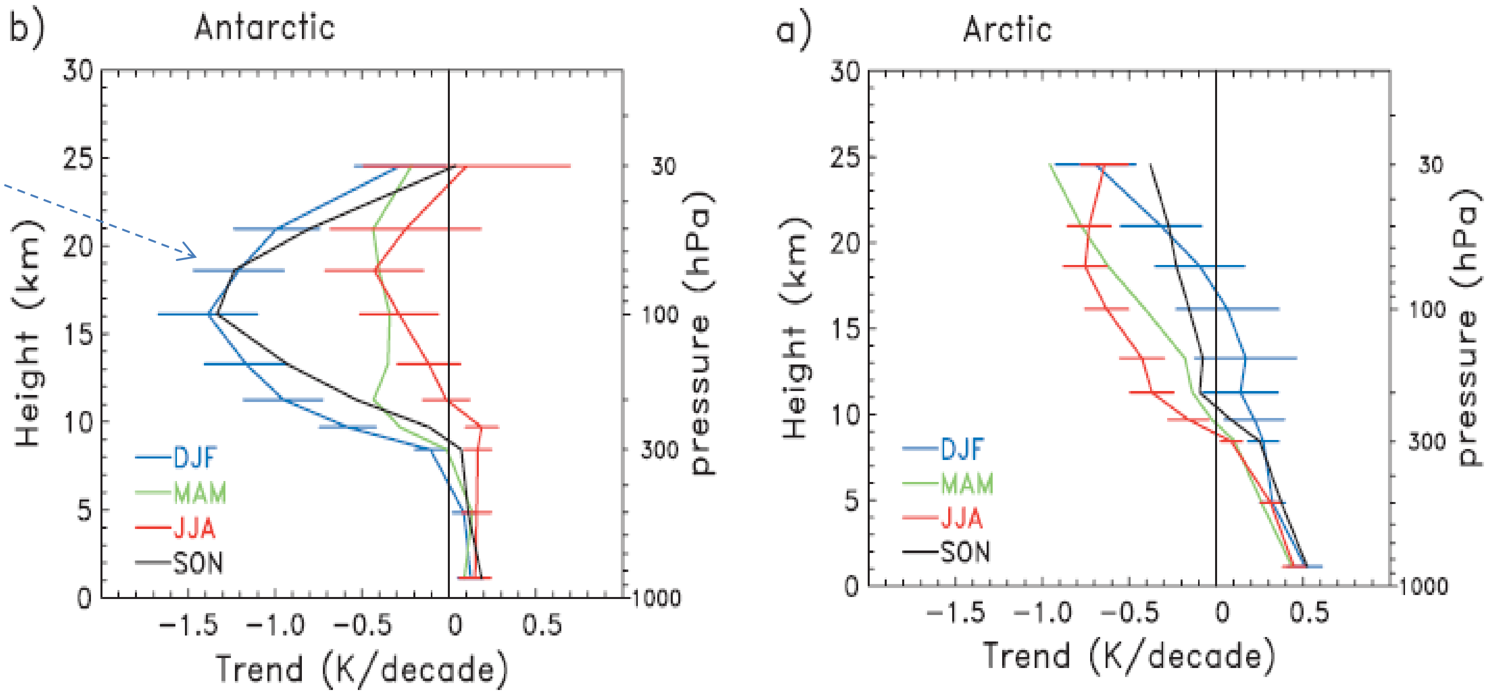


Large 'natural' year-to-year variability during winter

Randel et al., 2009, J. Geophys. Res.

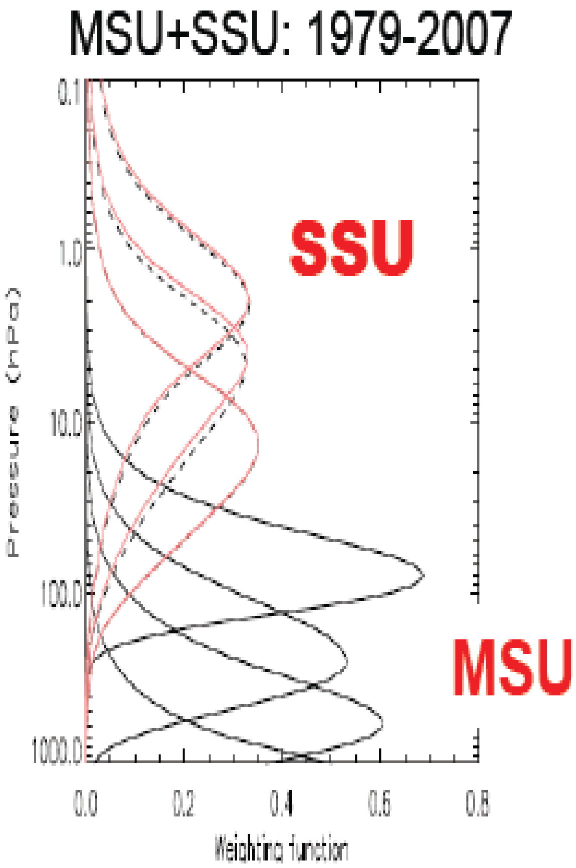
Polar temperature trends

Cooling due to Antarctic ozone hole



Randel, 2010, American Geophysical Union

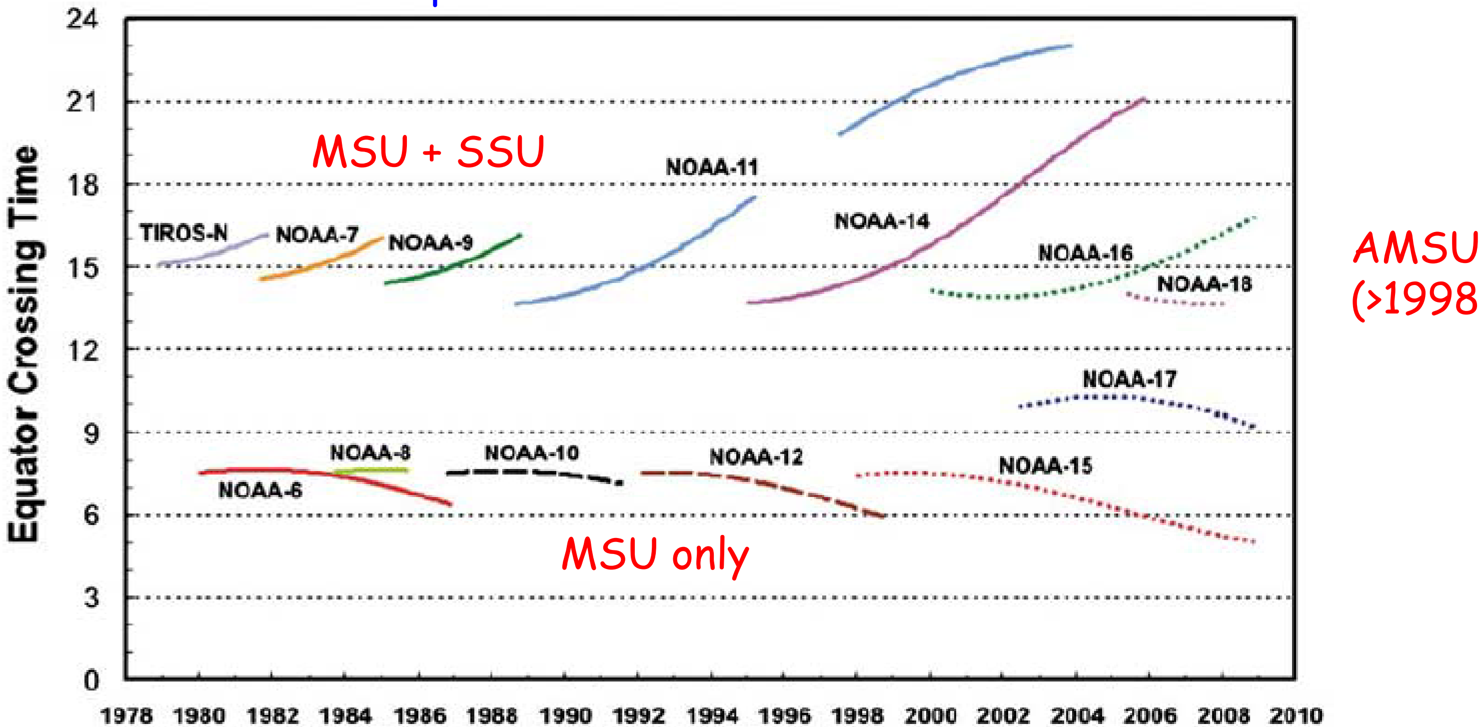
In the middle and upper stratosphere, satellite measurements are the primary data set for variability and trends



- Broad layer temperatures
- Derived from many separate operational instruments
- Long-term records need to be constructed for trend studies

Satellite records are constructed from many separate instruments

Operational NOAA satellites

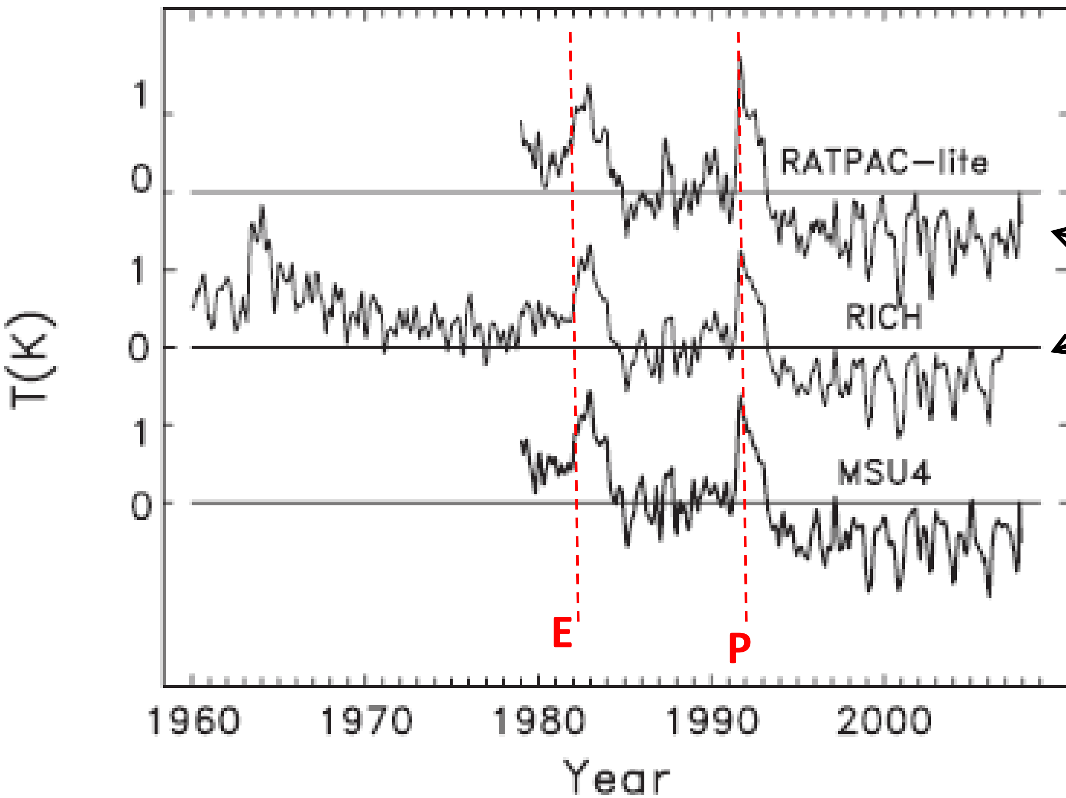


HALOE (>45 km)

Research satellites: MIPAS, GOMOS, SABER, MLS

Randel, 2010, American Geophysical Union

Lower stratosphere temperatures (MSU4) are well characterized



radiosondes

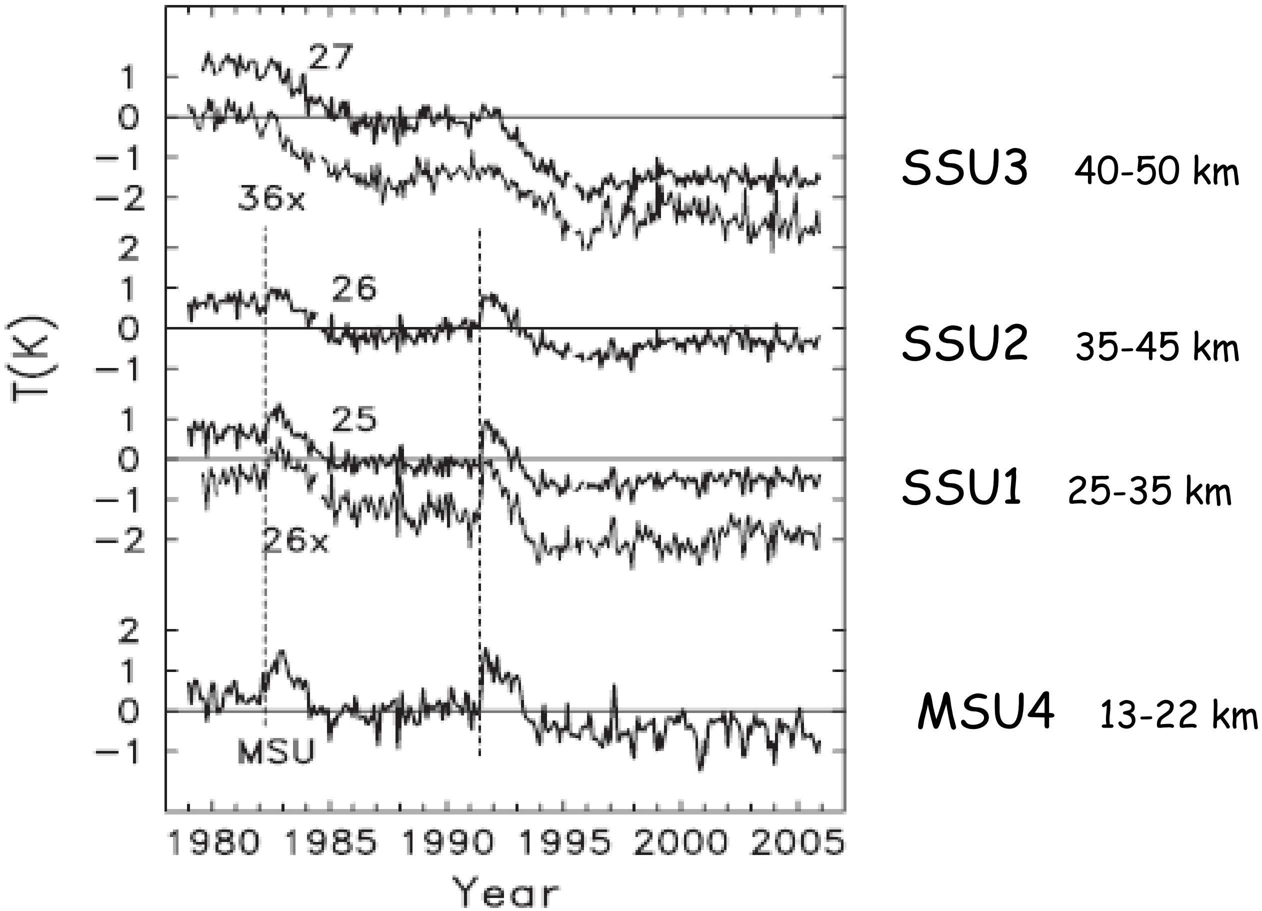
MSU4 satellite

Several groups have constructed climate records from MSU

Randel, 2010, American Geophysical Union

Middle-upper stratosphere temperatures from SSU

Constructed by
John Nash
from UK Met Office



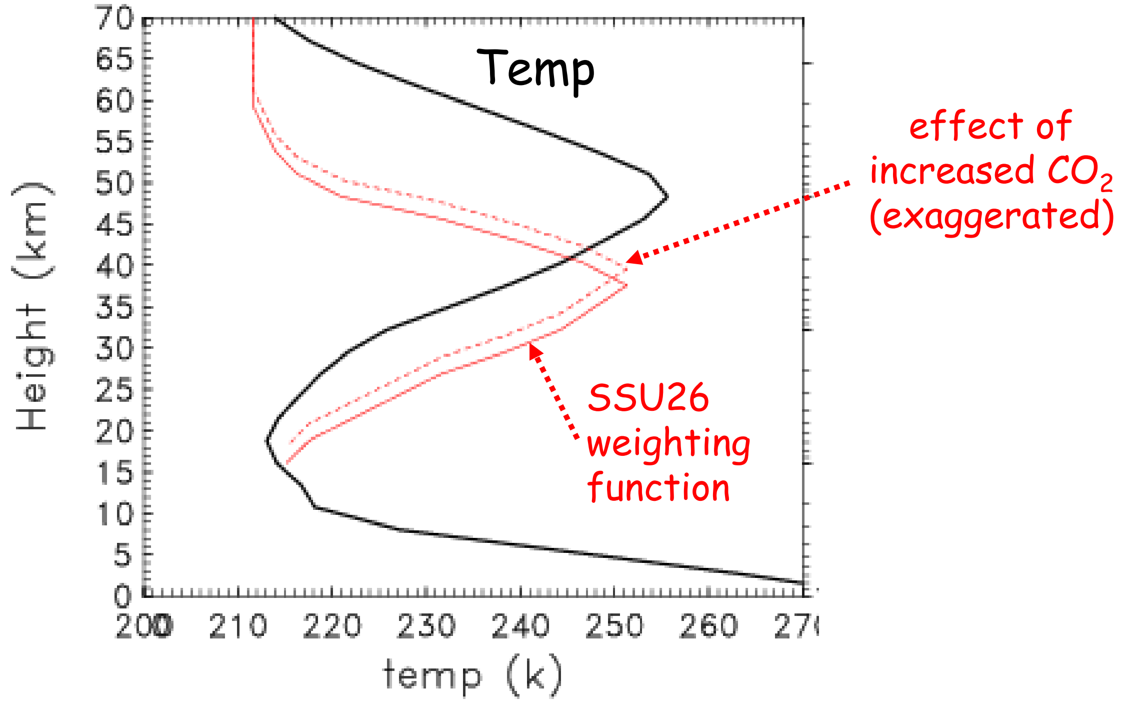
But:

- Details not well understood
- No independent analyses of SSU data

SSU Data Issues

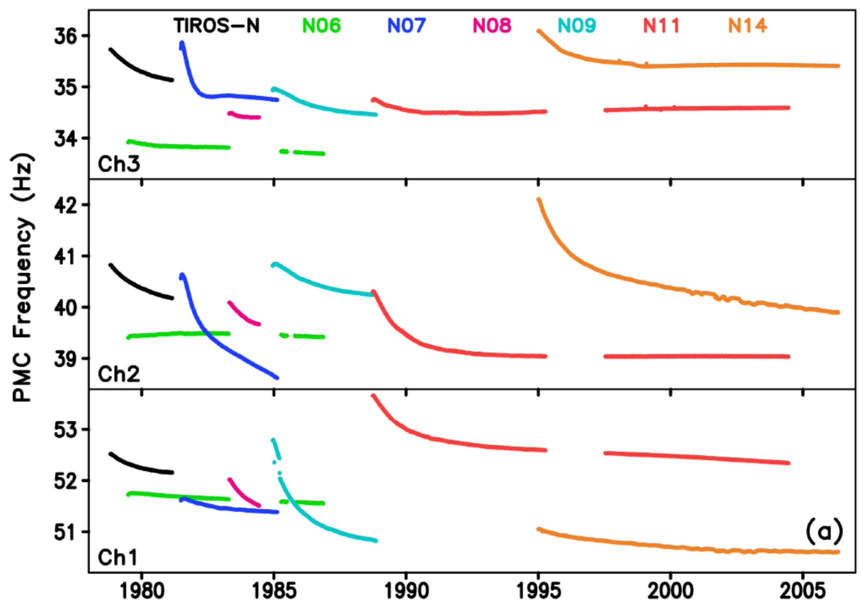
- instrument CO_2 leaking problem
- atmospheric CO_2 variations
- limb-effect
- diurnal drift effect
- inter-satellite biases
- No instruments on NOAA-10 and NOAA-12
- No overlap between NOAA-9 and NOAA-11

CO_2 increases and the SSU weighting function

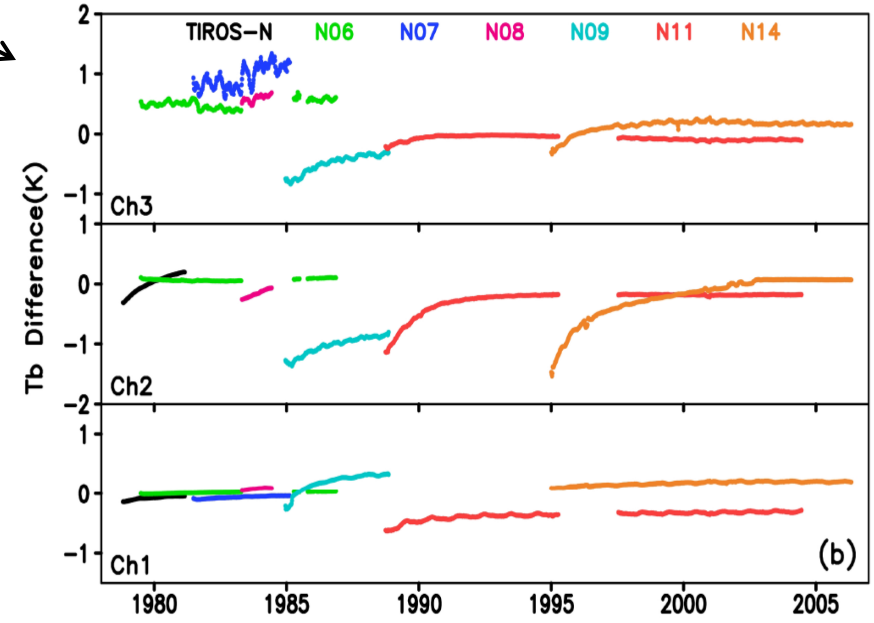


Higher CO_2 raises SSU weighting function, with resulting (apparent) positive temperature trend

SSU pressure modulator cells leak over time. These leaks cause a change in the modulator frequency over time, which can be used to monitor the gas leakage.



these effects on measured temperatures can be estimated using SSU radiative transfer model



Zou et al, 2014

Recent independent analysis of SSU data

Construction of Stratospheric Temperature Data Records from Stratospheric Sounding Units

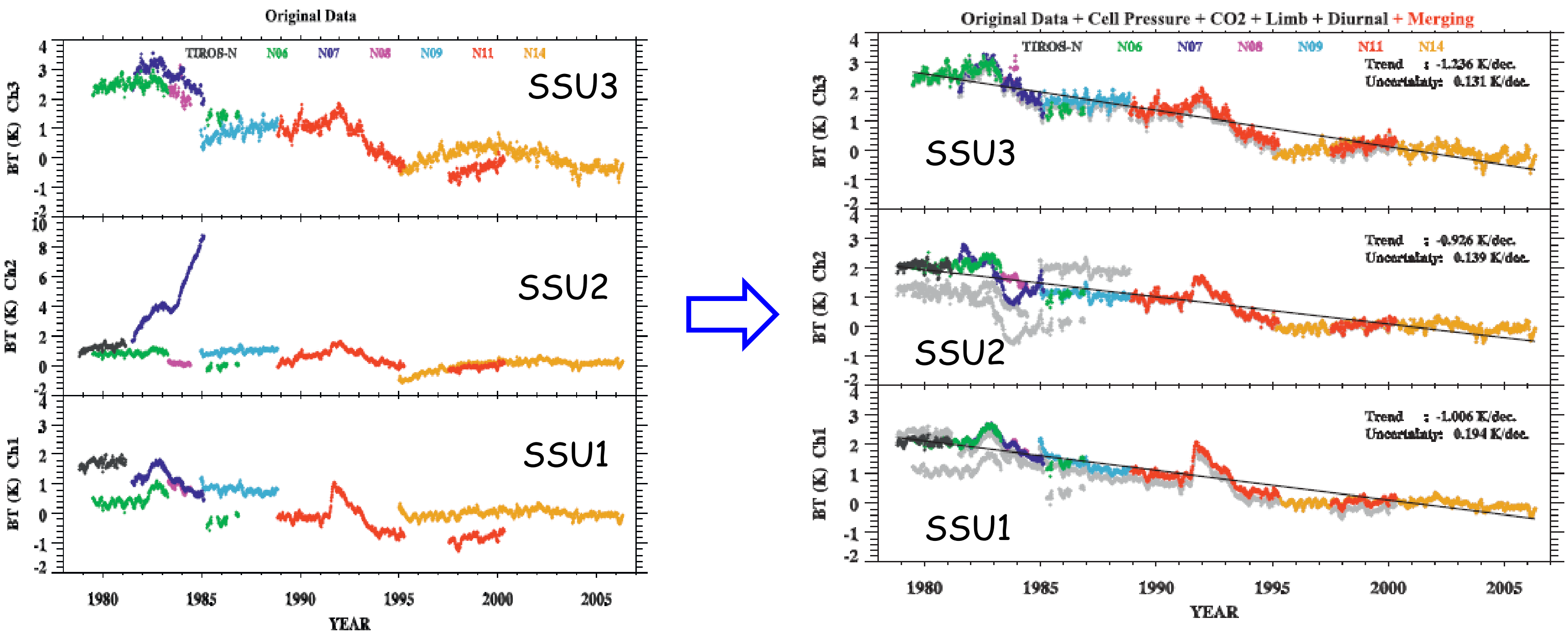
LIKUN WANG

Dell Services Federal Government, Fairfax, Virginia

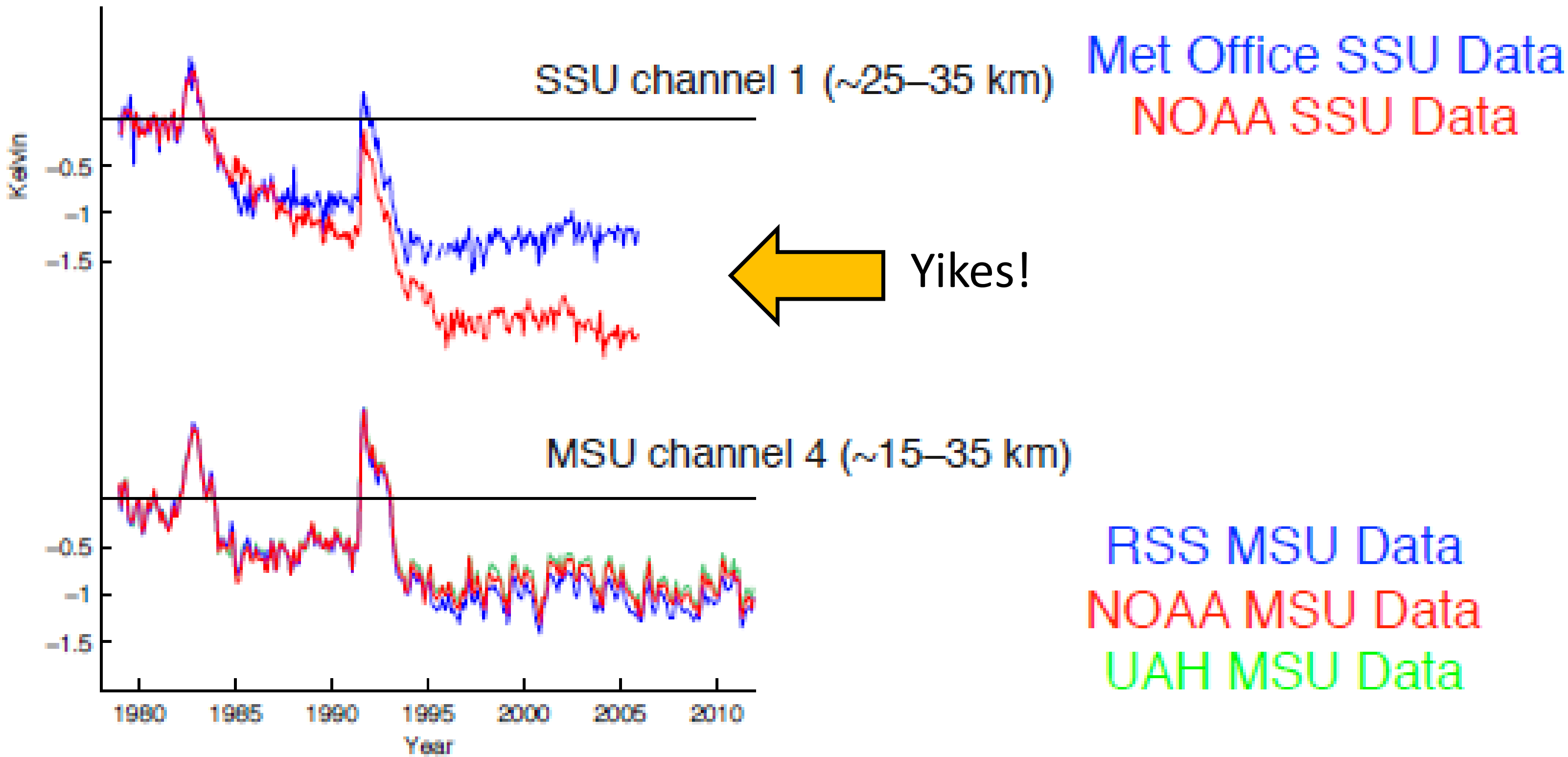
CHENG-ZHI ZOU

NOAA/NESDIS/STAR, Camp Springs, Maryland

J. Climate 2012



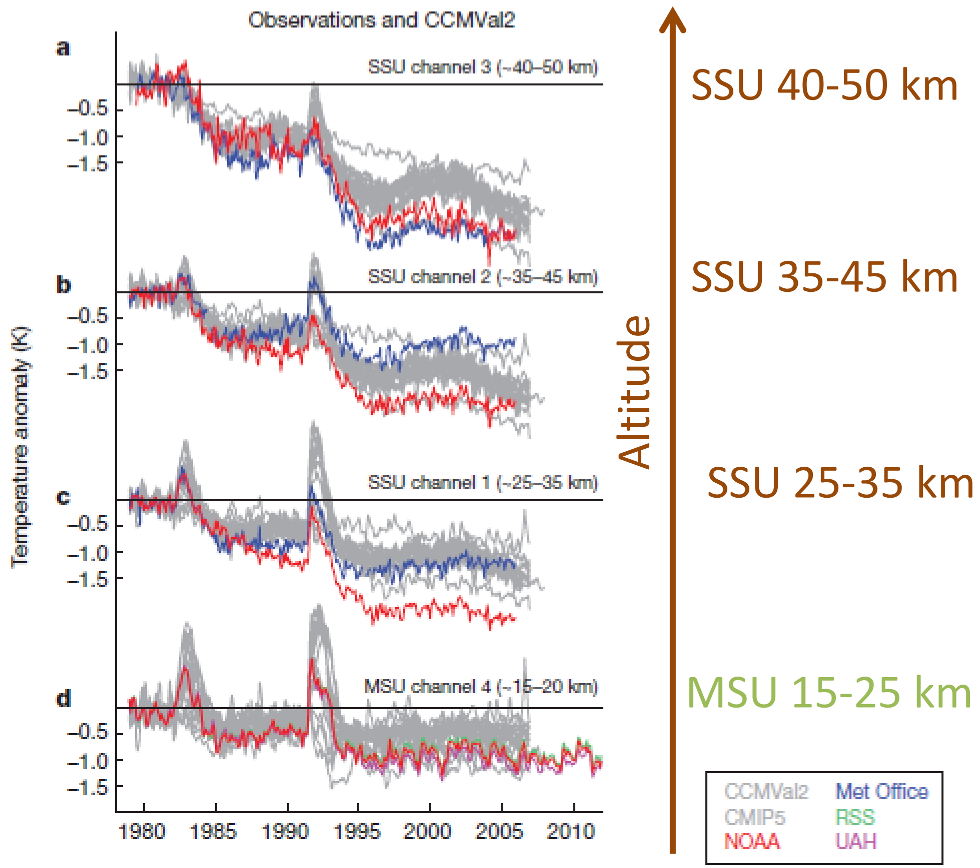
Global-average Stratospheric Temperature



Thompson et al 2012

Comparisons with Models

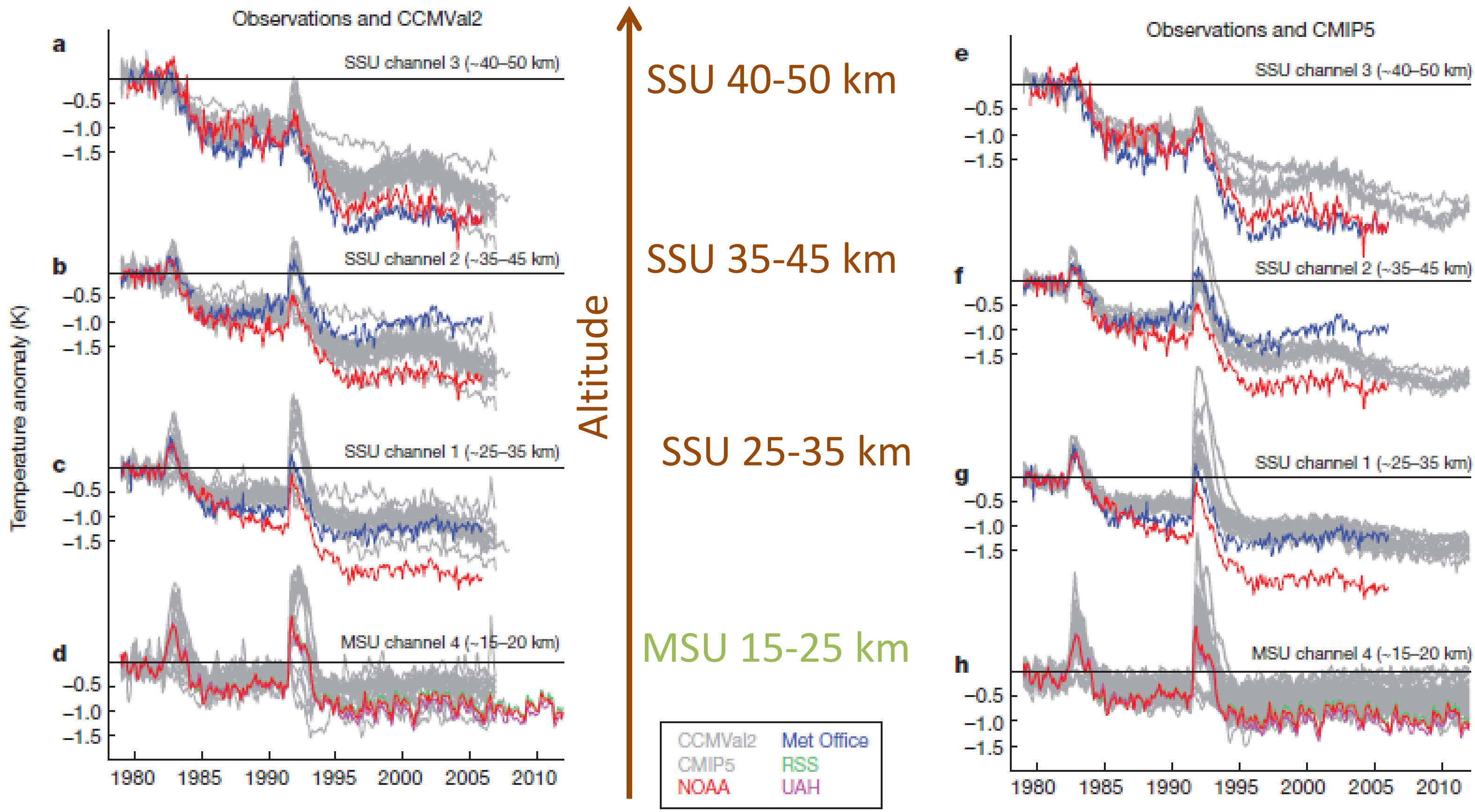
Chemistry-Climate Models



Thompson et al., 2012, Nature

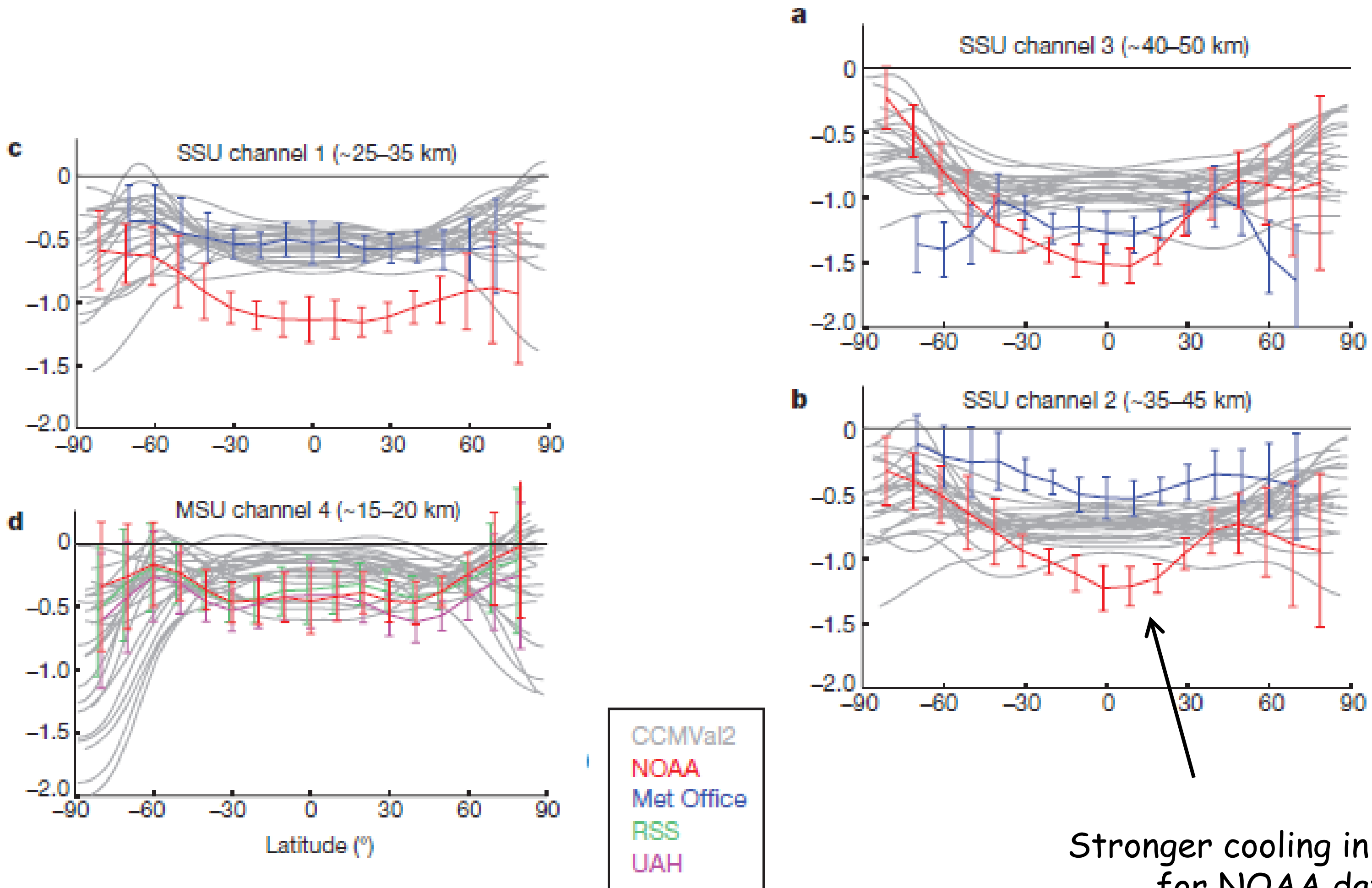
Comparisons with Models

Chemistry-Climate Models　　Atmosphere-Ocean Global Climate Models



Thompson et al, Nature, 2012

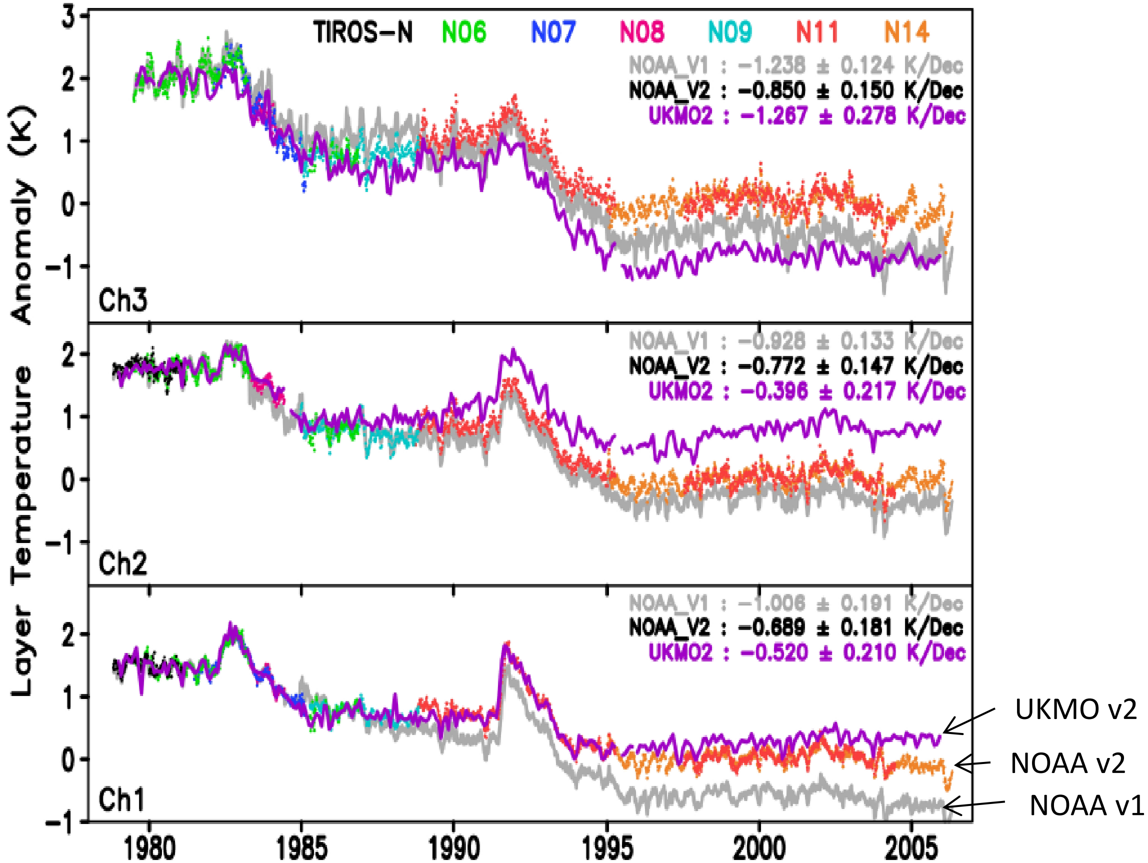
Latitudinal profile of trends



Stronger cooling in tropics for NOAA data

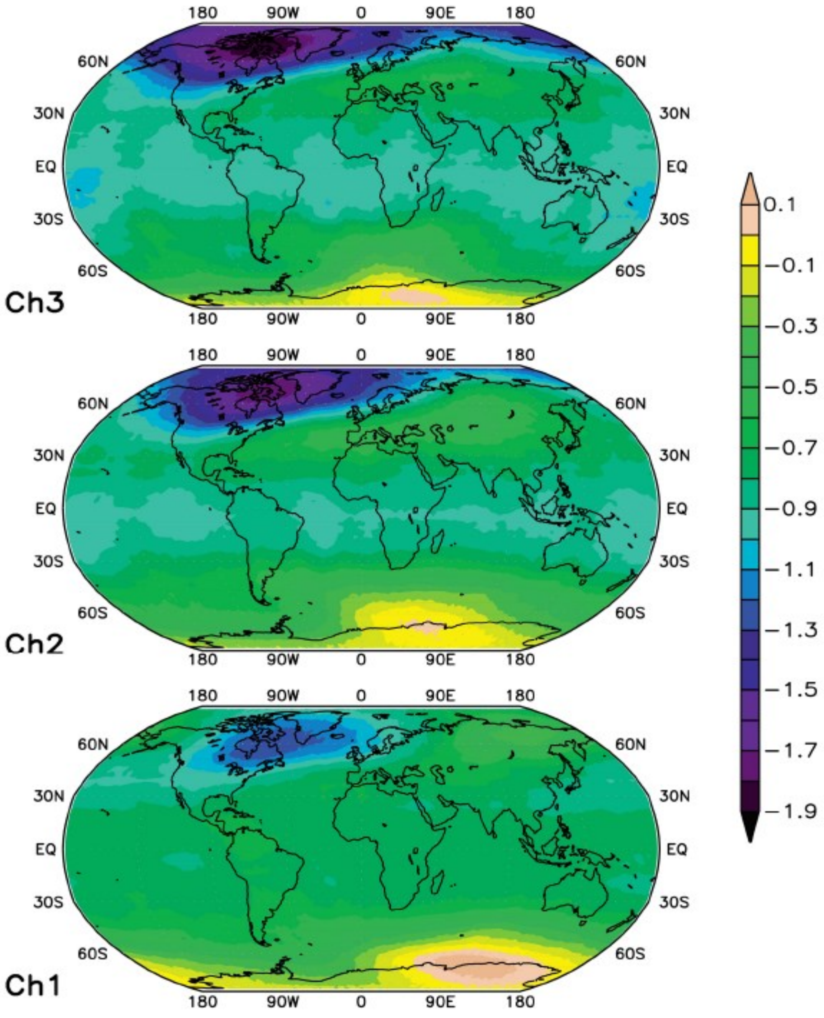
Thompson et al., 2012, Nature

Not the last word: new, updated versions of NOAA and UKMO SSU data



Zou et al, JGR 2014, in press

Upper stratosphere temperature trends 1979-2006

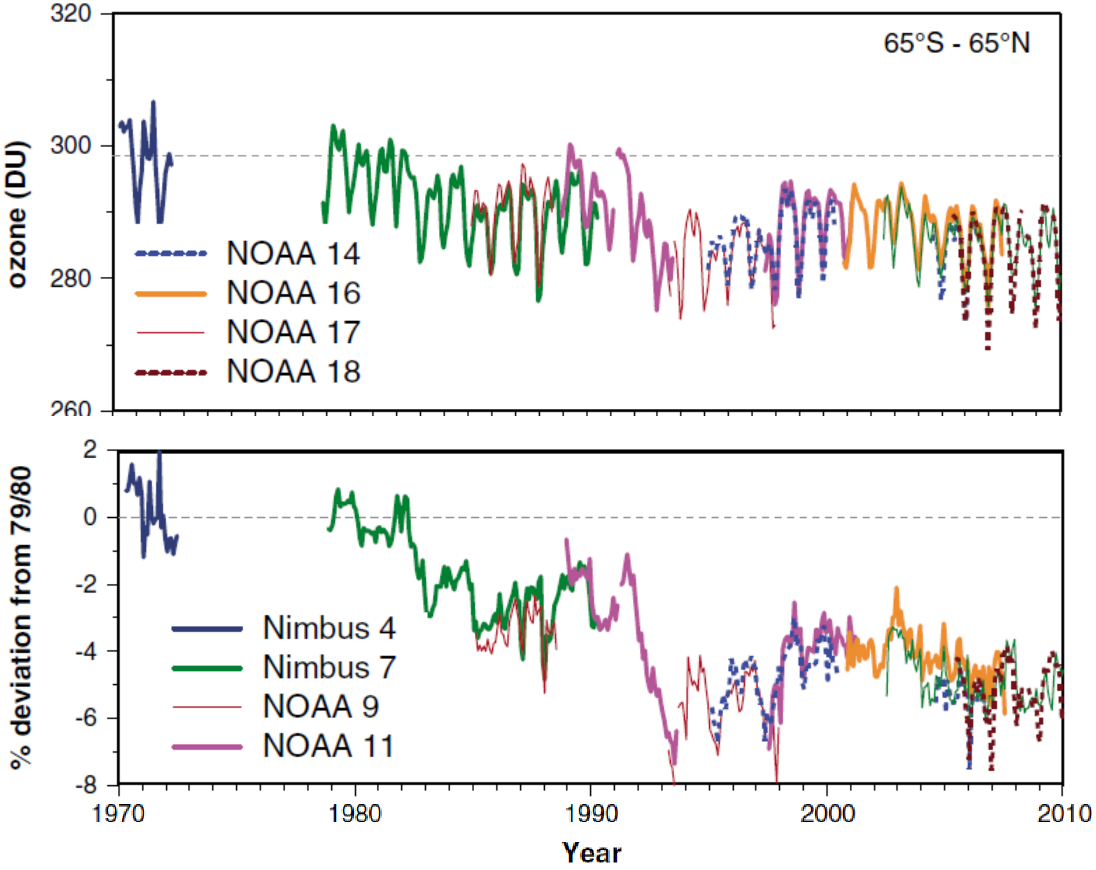


relatively 'flat' latitudinal structure

Zou et al, JGR 2014, in press

A similar situation exists for measurements of stratospheric ozone:

Global ozone anomalies derived from combined SBUV measurements



Global column ozone

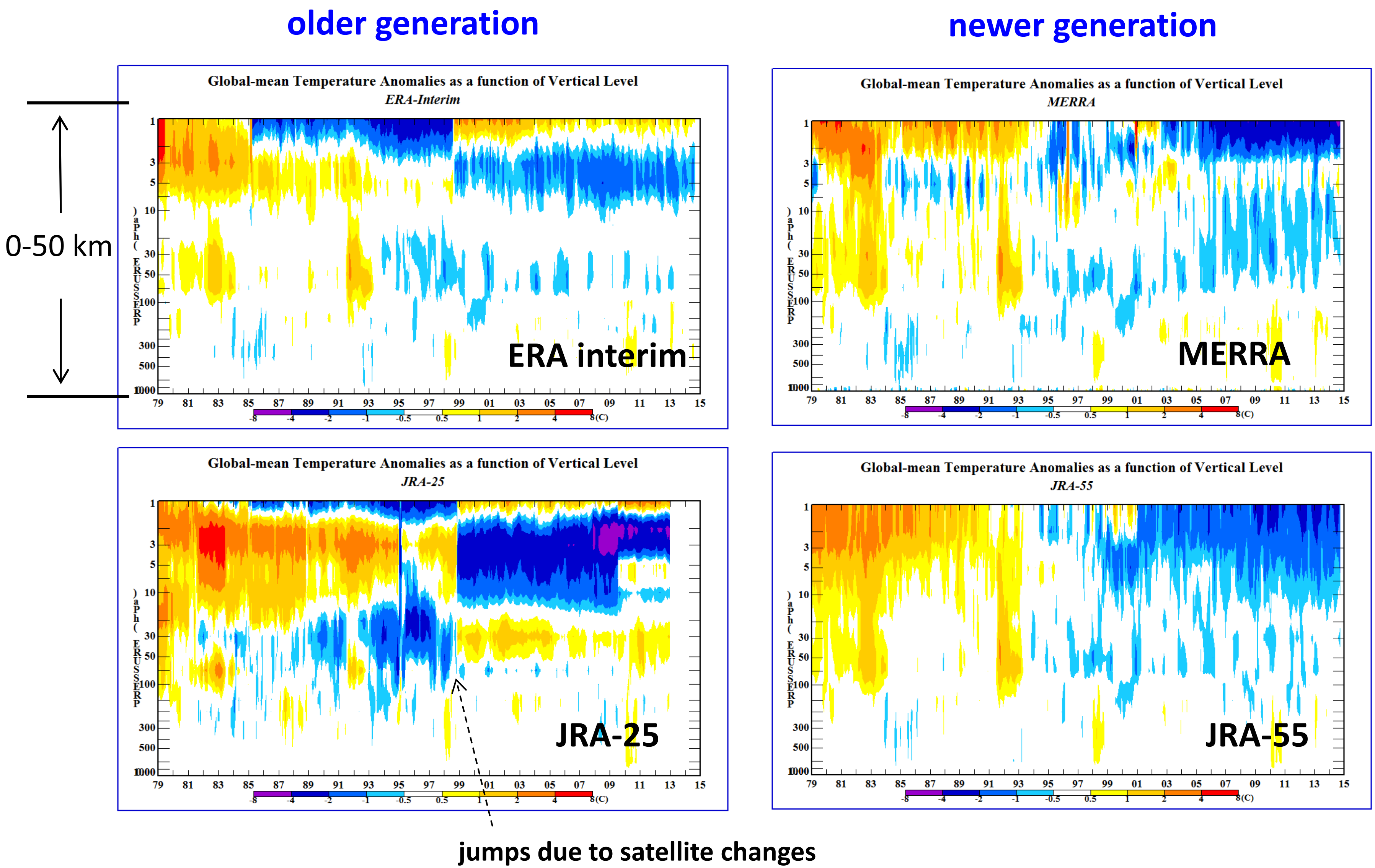
anomalies

McPeters et al 2014

Some important points:

- Radiosondes and satellites primarily intended for weather forecasting, not climate monitoring
- Historical radiosonde data have artificial cooling biases, but these have been corrected using different techniques
- Long-term temperature changes are small, and correcting/merging data sets is difficult
- Valuable to have different groups evaluate and homogenize data sets (examples: radiosondes and MSU satellite data, and now SSU)
- Upper stratosphere satellite data (SSU) still a work in progress
- Meteorological reanalyses rely on satellite data, and can be affected by the same problems

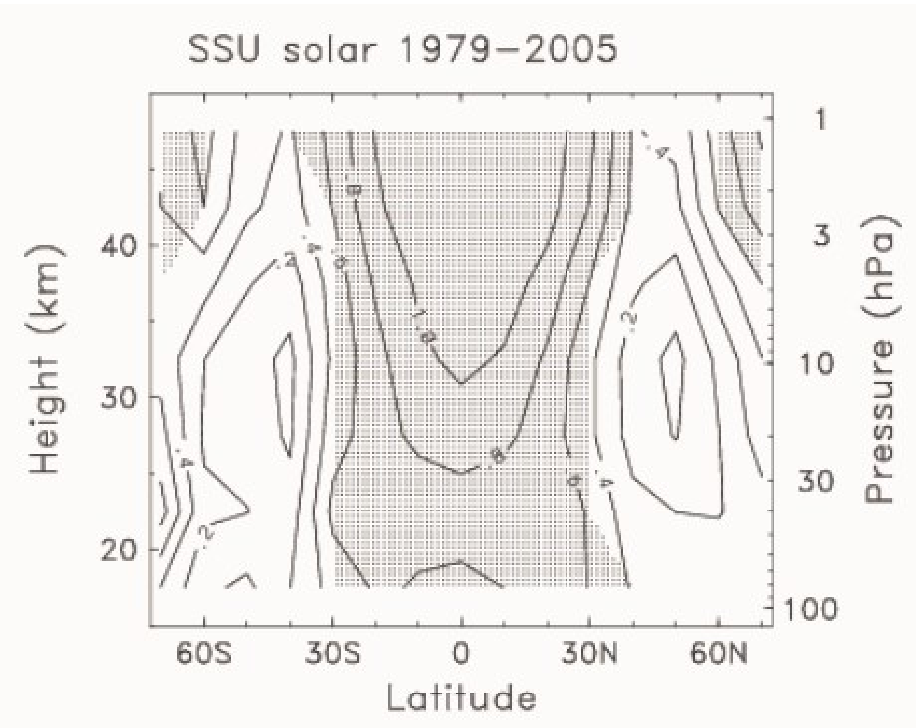
Global temperature anomalies from reanalyses



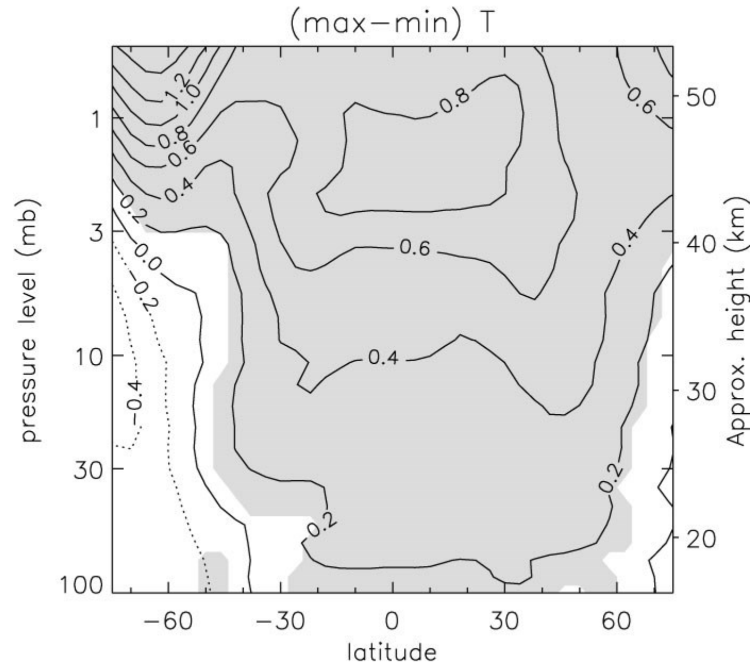
Extra slides

11-year solar cycle in temperature derived from SSU data

Observed

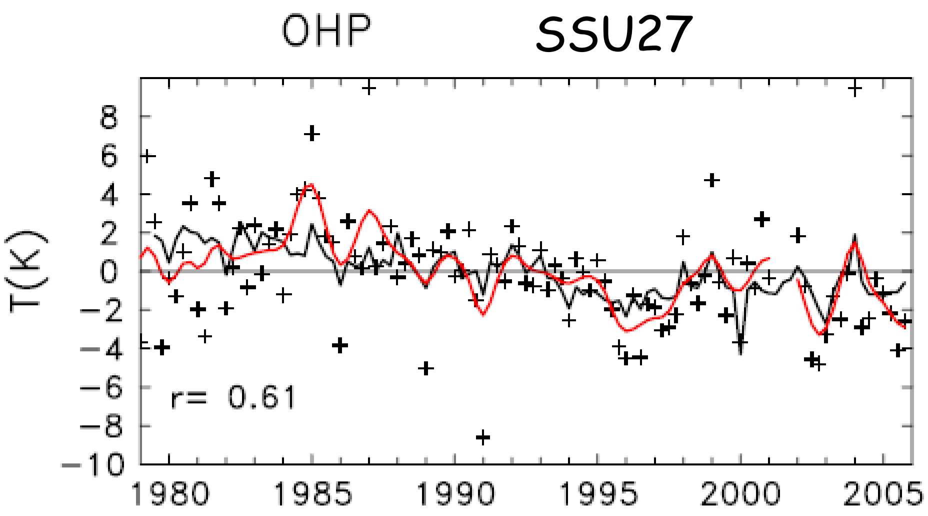


WACCM model



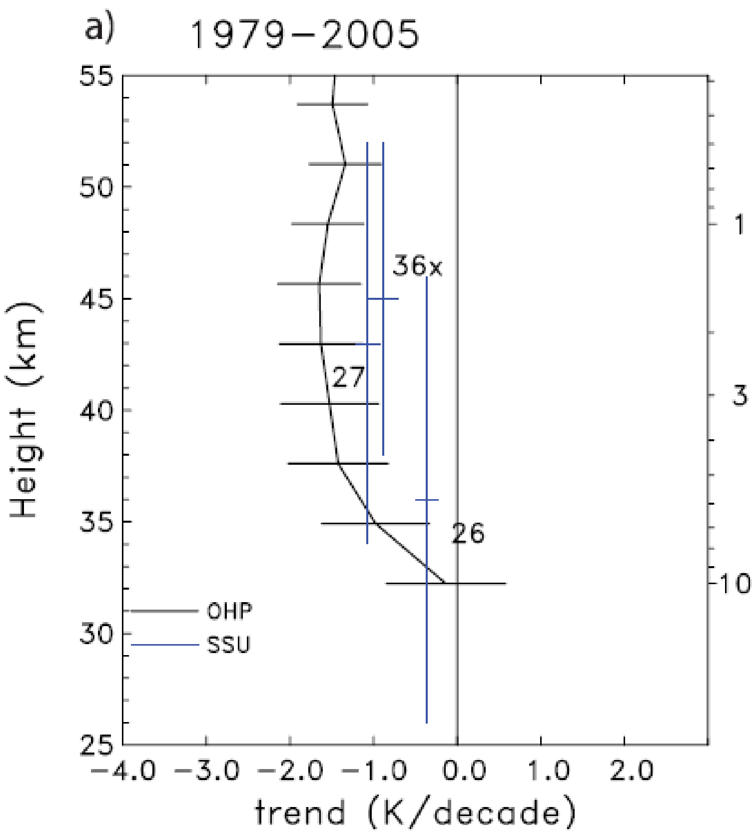
Marsh et al, 2007

Comparison of SSU data with lidar measurements at OHP



Seasonal (3-month avg.) anomalies

trends



Randel et al 2009

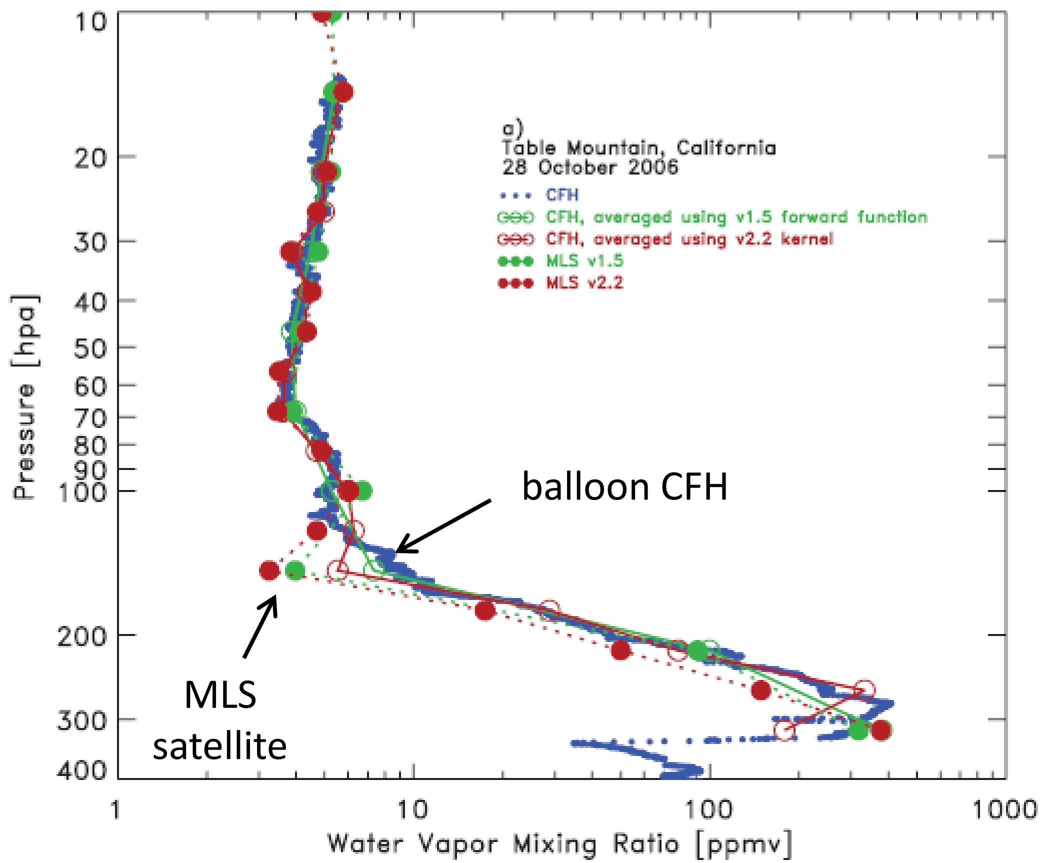
Stratospheric water vapor

- Measurements of stratospheric H_2O
- Global variability and seasonal cycle
- Simulations of H_2O: trajectory models and global models
- Long-term variability, trends and links to tropical tropopause temperatures

Measurements of stratosphere water vapor

JGR, 2009

VÖMEL ET AL.: MLS WATER VAPOR VALIDATION BY CFH



cryogenic frostpoint hygrometer

JGR, 2011

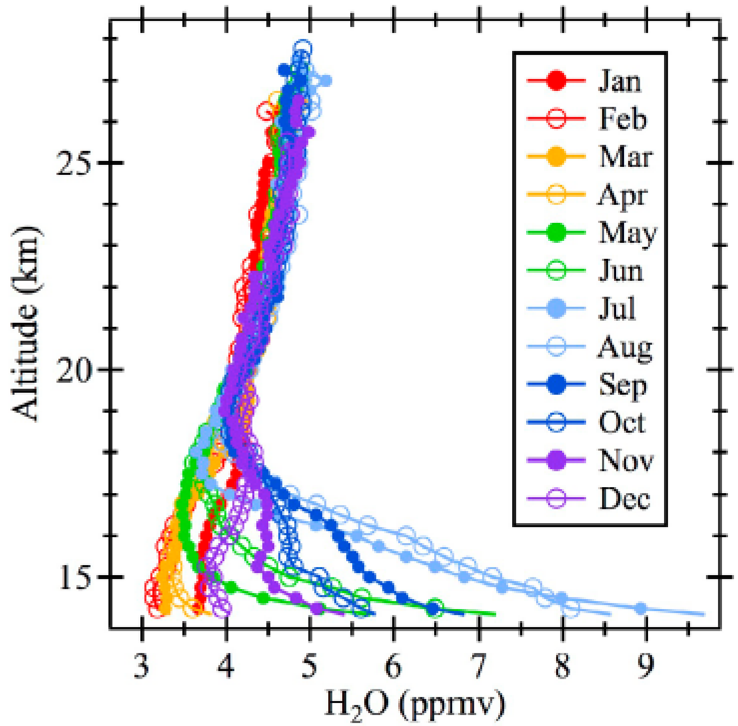


Figure 3. Monthly averaged vertical profiles of stratospheric water vapor over Boulder, Colorado. Each average profile is based on 22–37 individual soundings in the specified month during 1980–2010. The seasonal cycle is evident for altitudes <19 km.

balloon frostpoint hygrometer measurements at Boulder (40° N) 1980 – present

(~ 1 per month)

aircraft measurements ACP, 2009

9650 C. Schiller et al.: Hydration and dehydration at the tropical tropopause

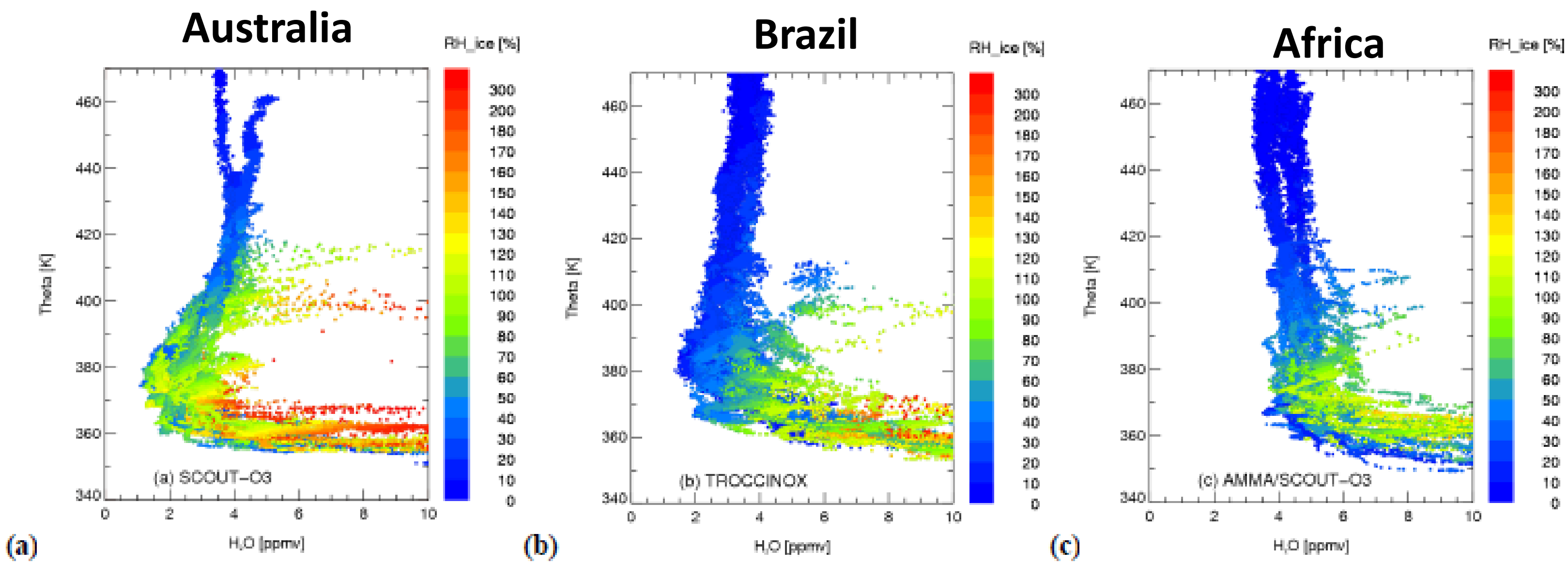
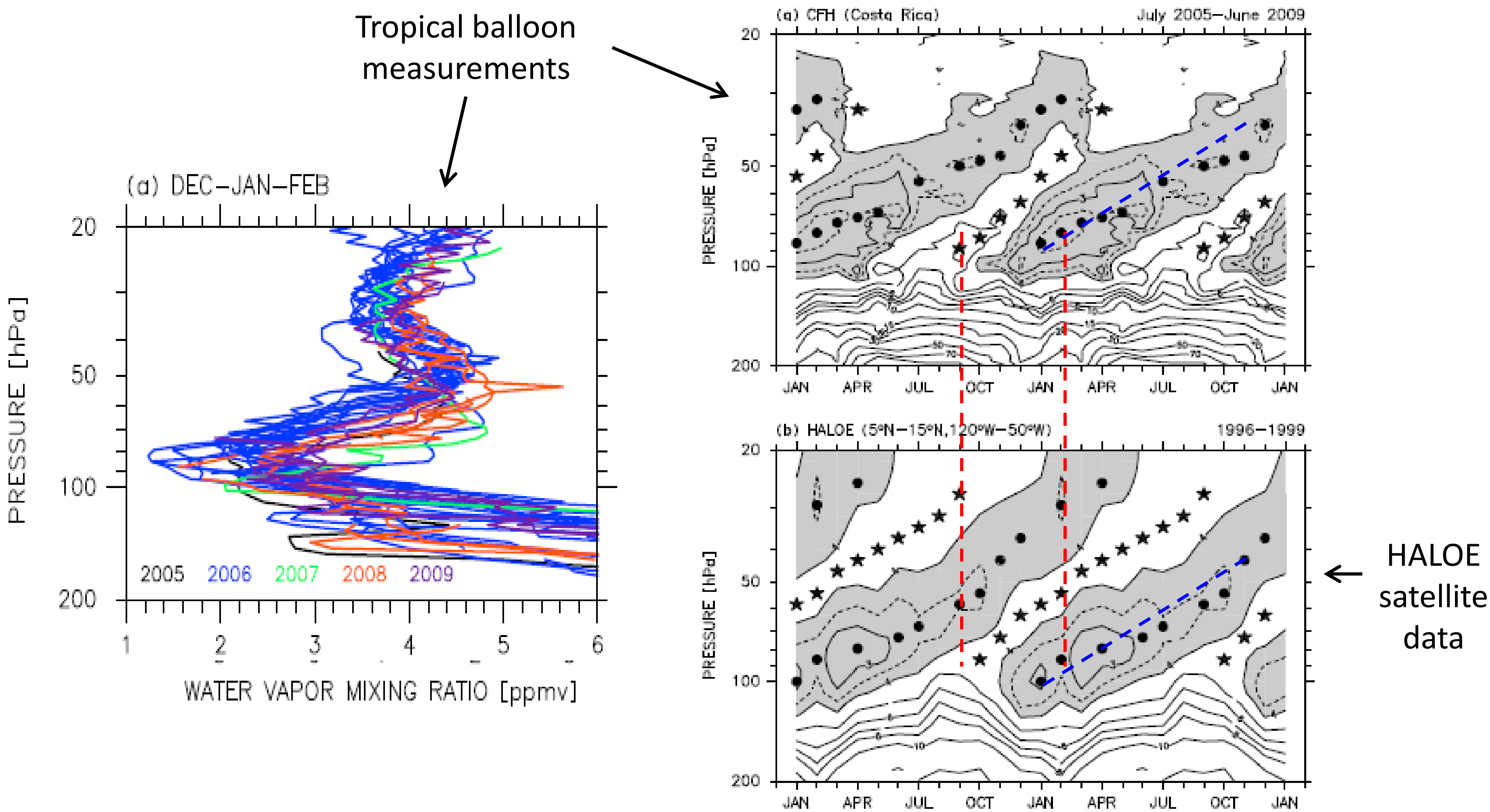


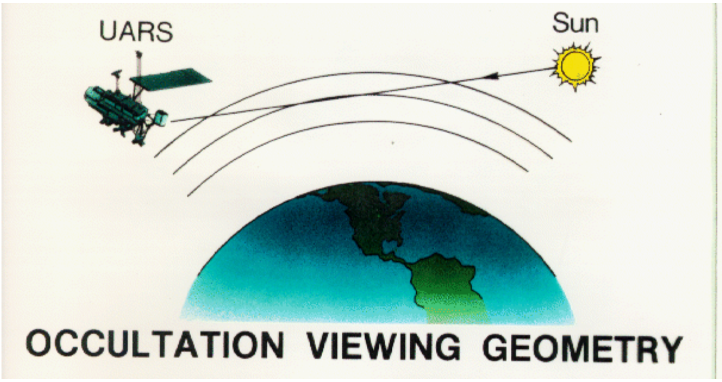
Fig. 2. Vertical profiles of total water during the tropical aircraft campaigns **(a)** SCOUT-O3 in Northern Australia (November 2005), **(b)** TroCCiNOx in Brazil (February 2005), and **(c)** AMMA/SCOUT-O3 in West Africa (August 2008). Colour code denotes the relative humidity with respect to ice.

FUJIWARA ET AL.: TROPICAL LOWER STRATOSPHERIC WATER VAPOR

JGR 2010

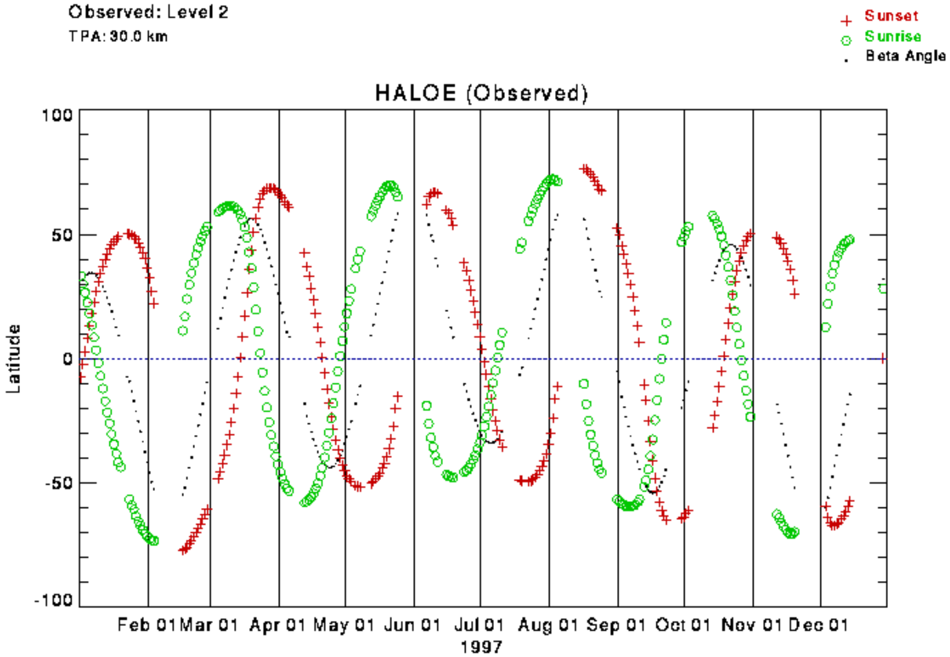


HALOE solar occultation Measurements



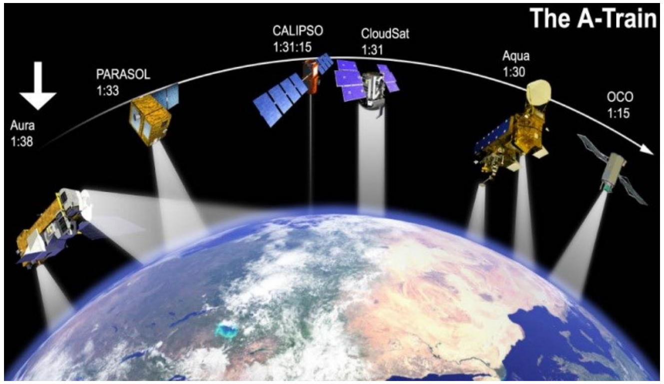
- Good vertical resolution ~2 km
- Limited space-time sampling
- Observations 1992-2005

HALOE sampling for one year

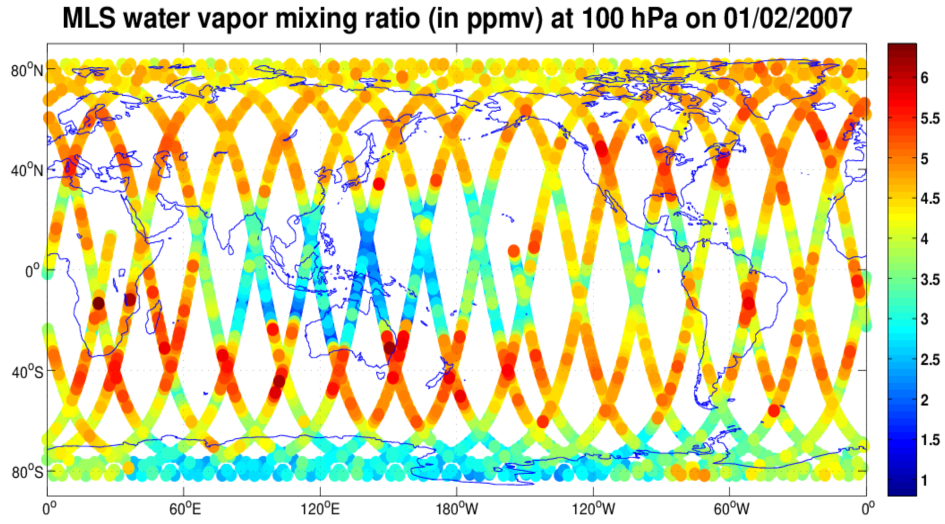


Latitude Progression

Aura Microwave Limb Sounder (MLS)



- Vertical resolution ~3 km
- Daily global sampling
- Observations 2004-present

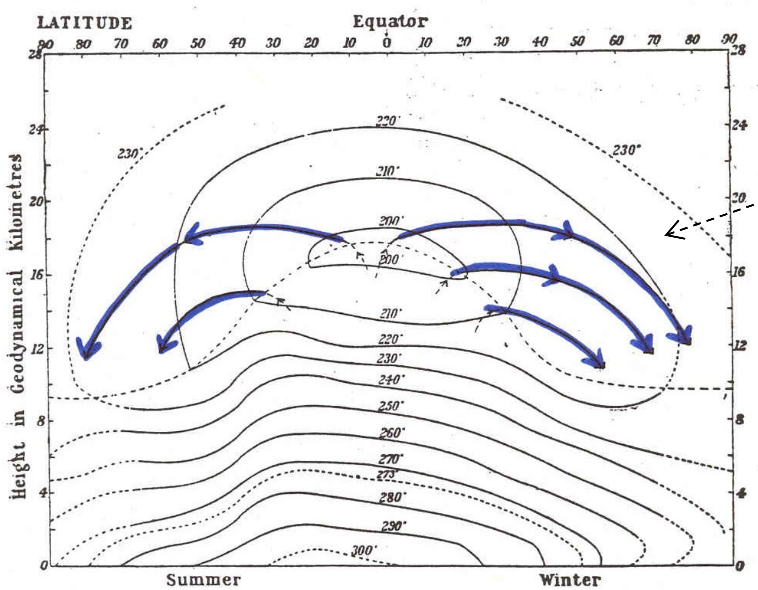


MLS daily orbital data

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

QJRMS, 1949



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

The stratosphere is extremely dry because air is dehydrated passing the cold tropical tropopause

Workshop on Brewer-Dobson circulation, Oxford University, December 1999

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

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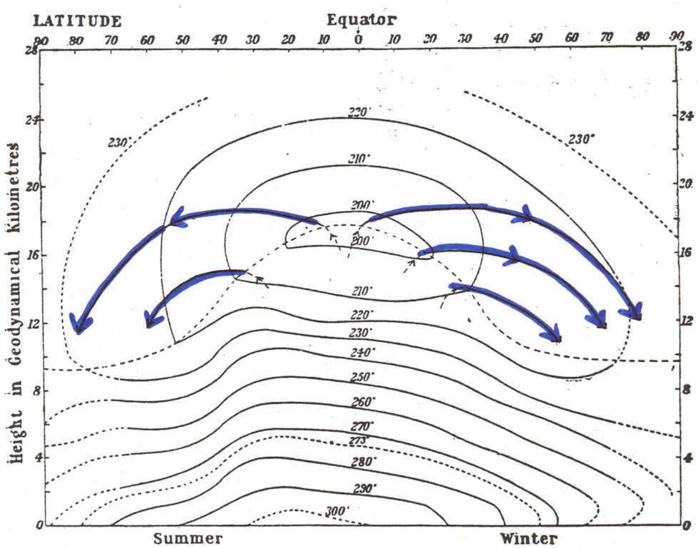
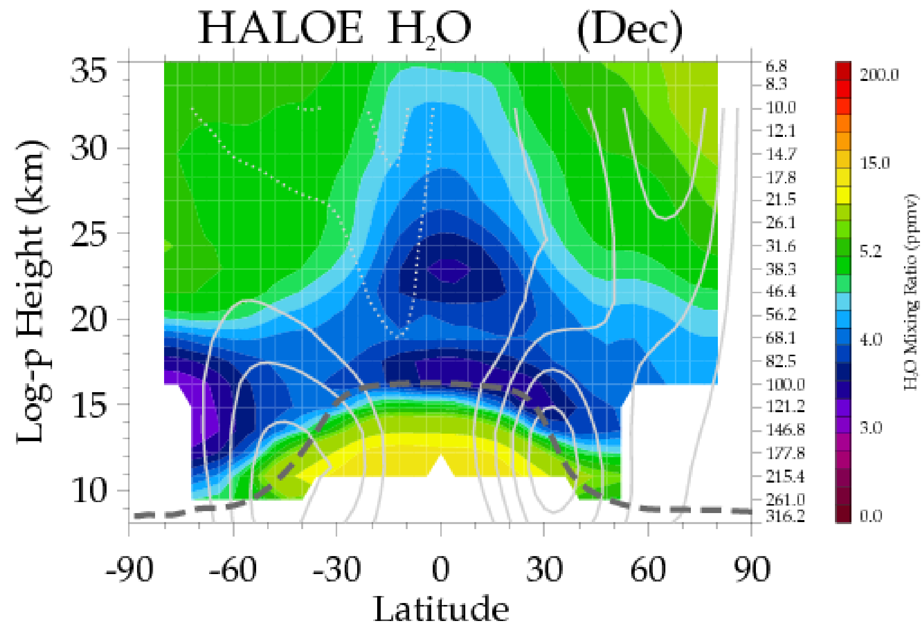


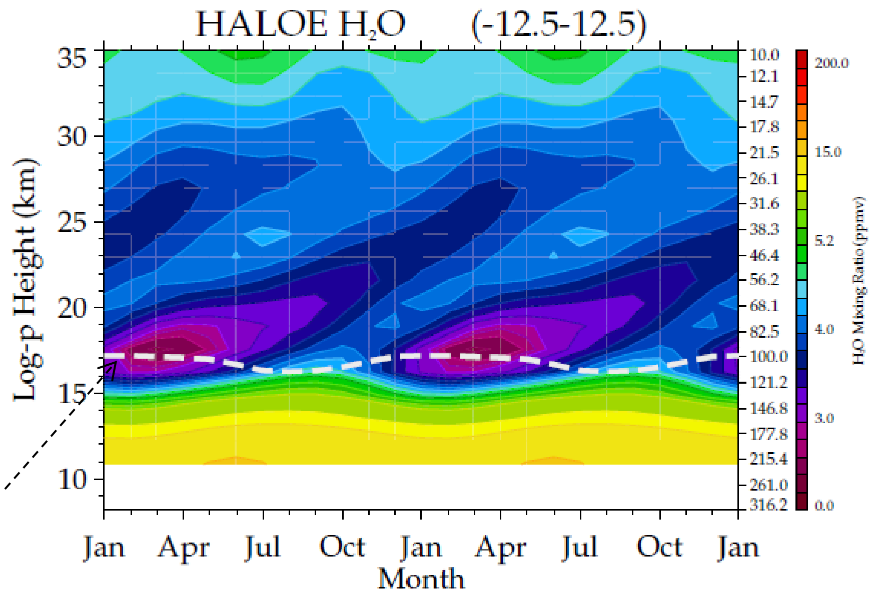
Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

HALOE global climatology

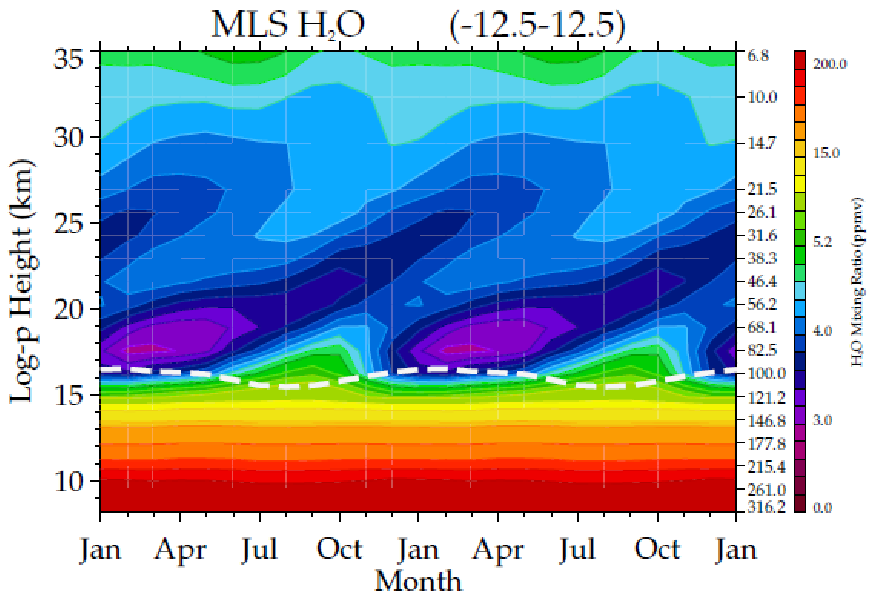


Climatological 'tape recorder'



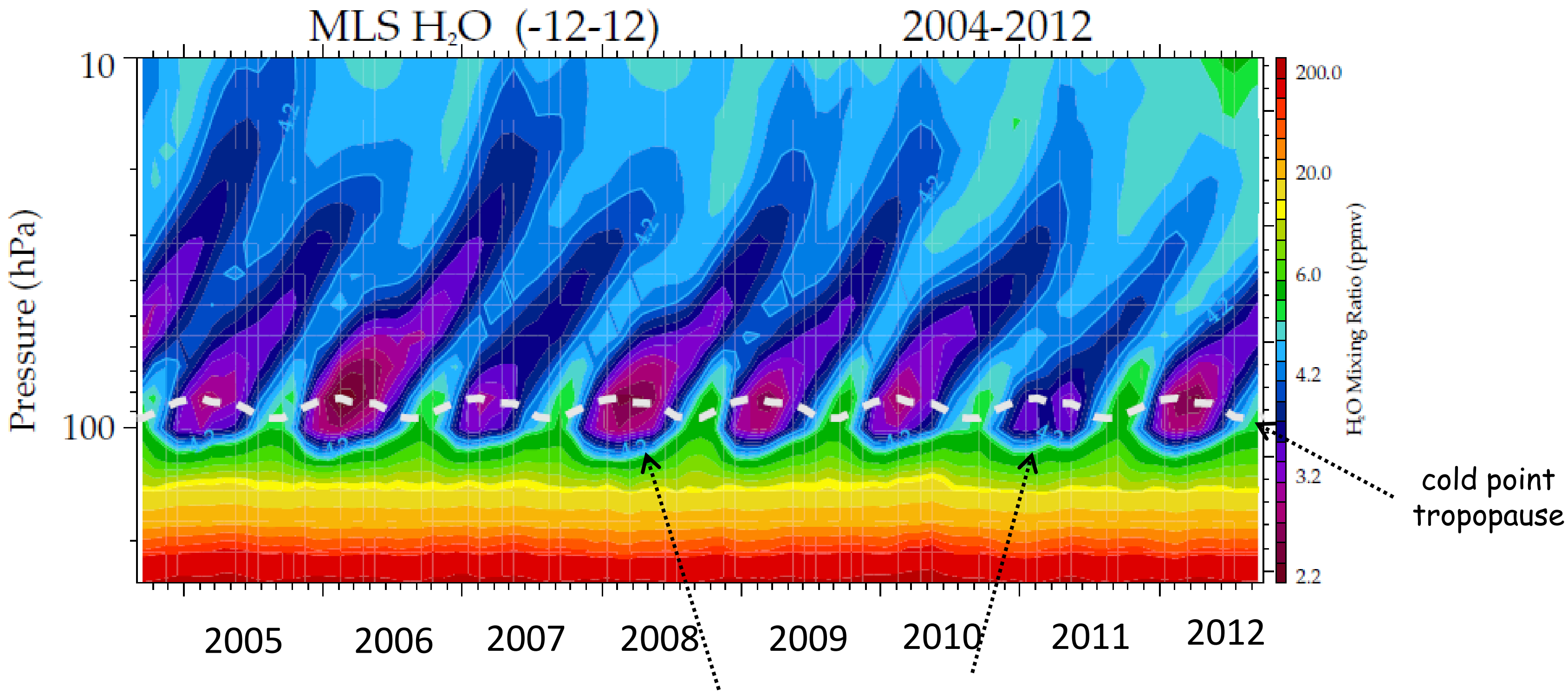
cold point tropopause

HALOE



MLS

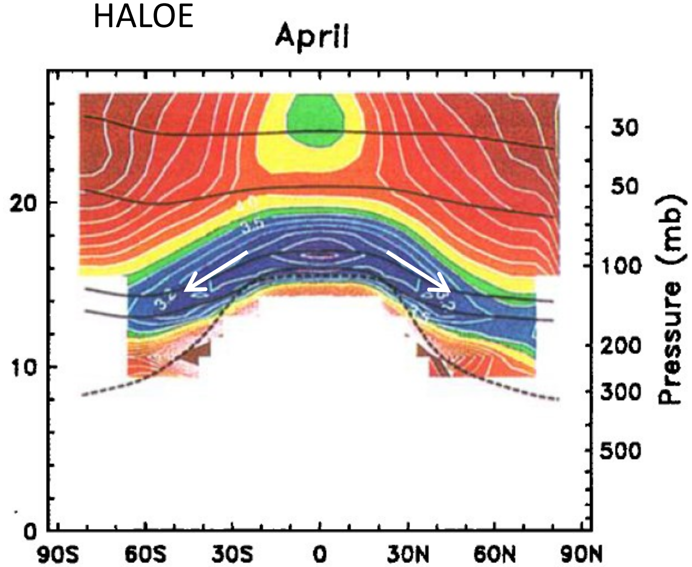
Tropical tape recorder observed by MLS 2004-2012



Interannual variations in tropopause temperature reflected in H_2O

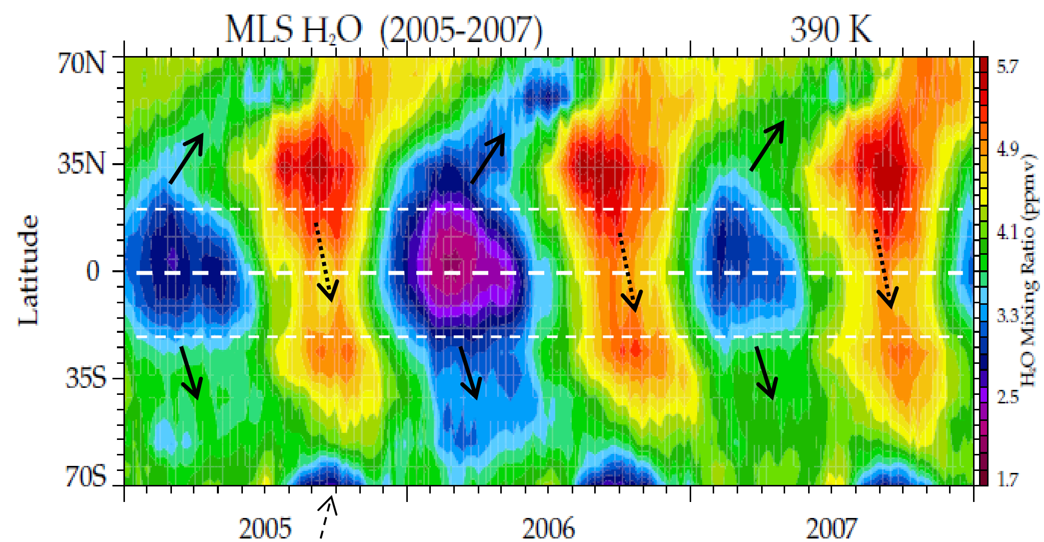
Lower stratosphere horizontal tape recorder   390 K

HALOE



quasi-horizontal transport
in lower stratosphere, approximately
following 400 K isentrope

3 years from MLS observations

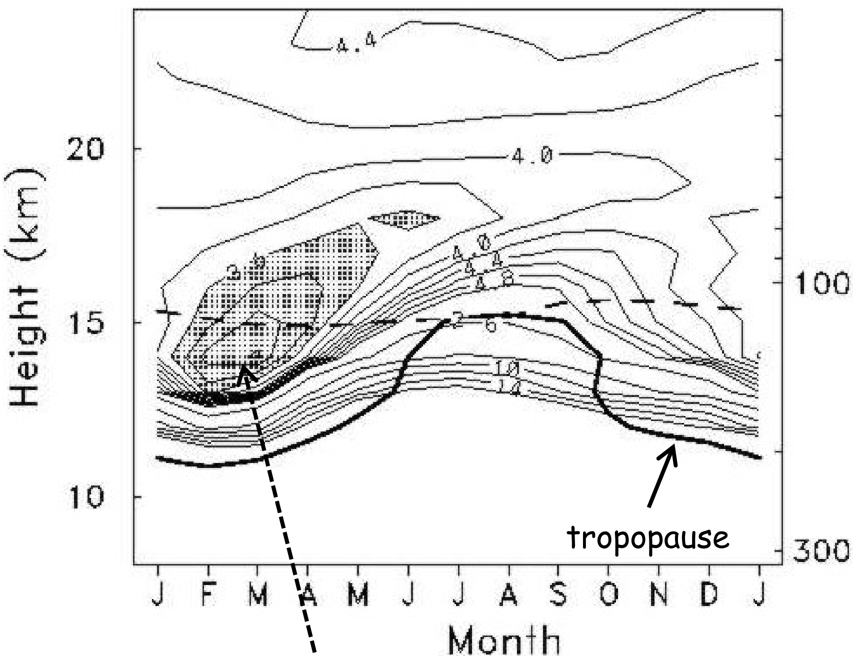


dehydration in
Antarctic polar vortex

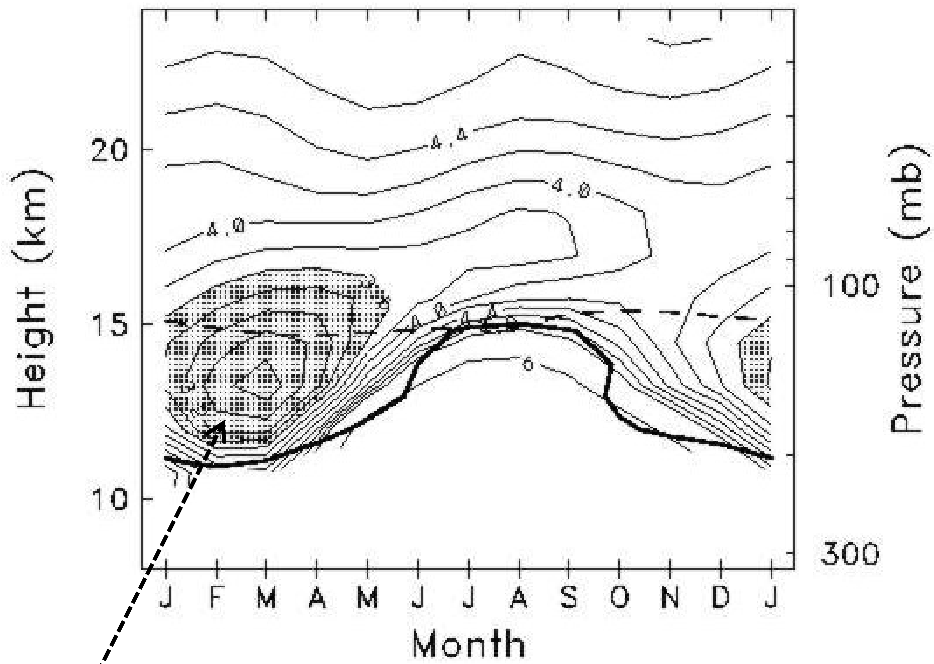
Tropical dehydration
zone is ~20 N-S

Climatology at Boulder (40° N)

Balloon



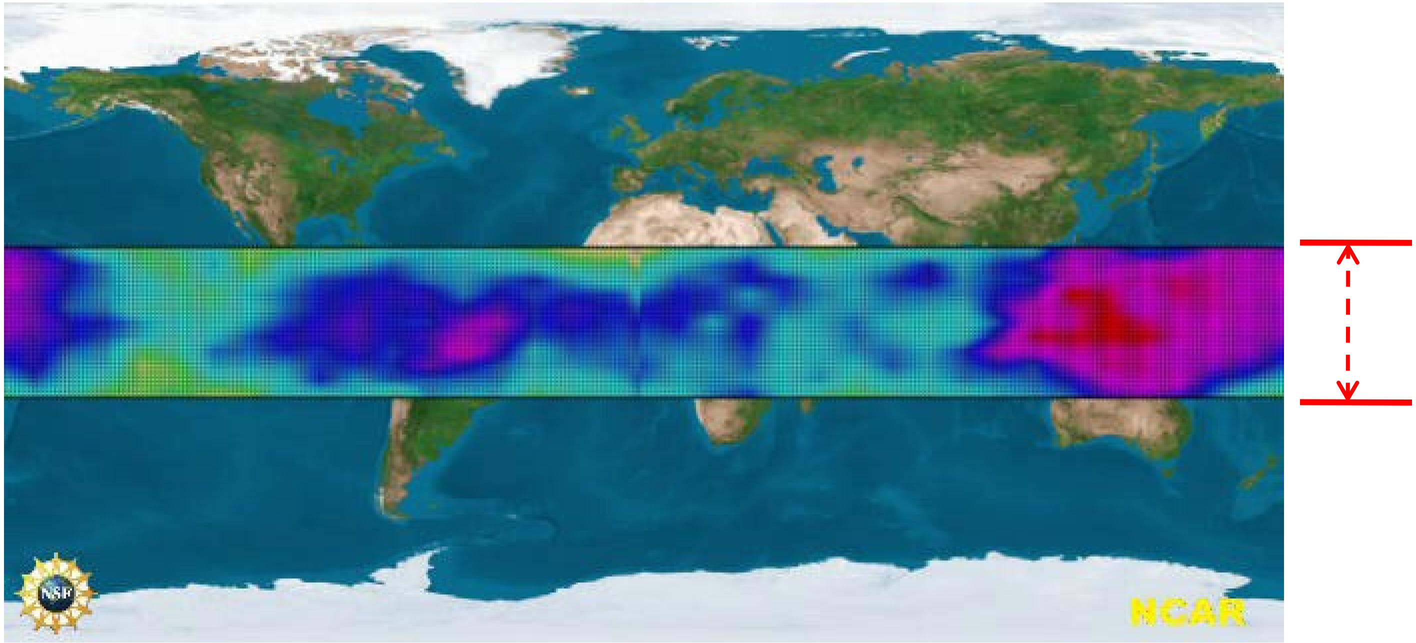
HALOE



seasonal minimum due to transport from tropics

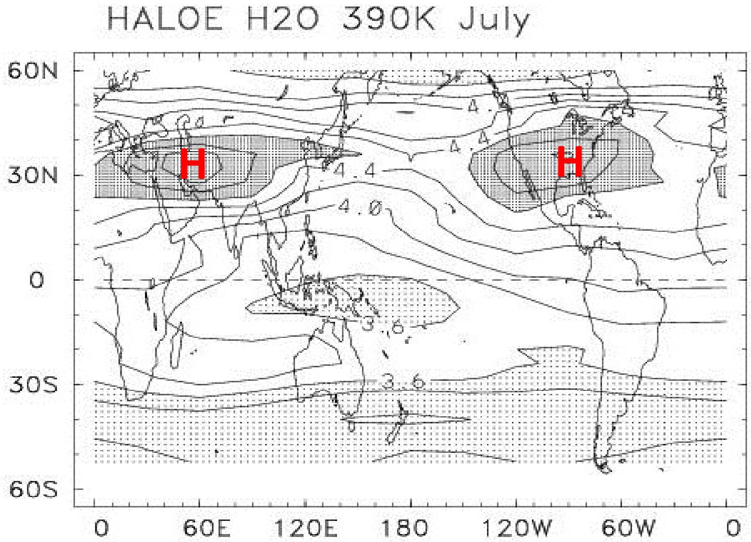
Trajectory simulation of transport on 400 K isentrope

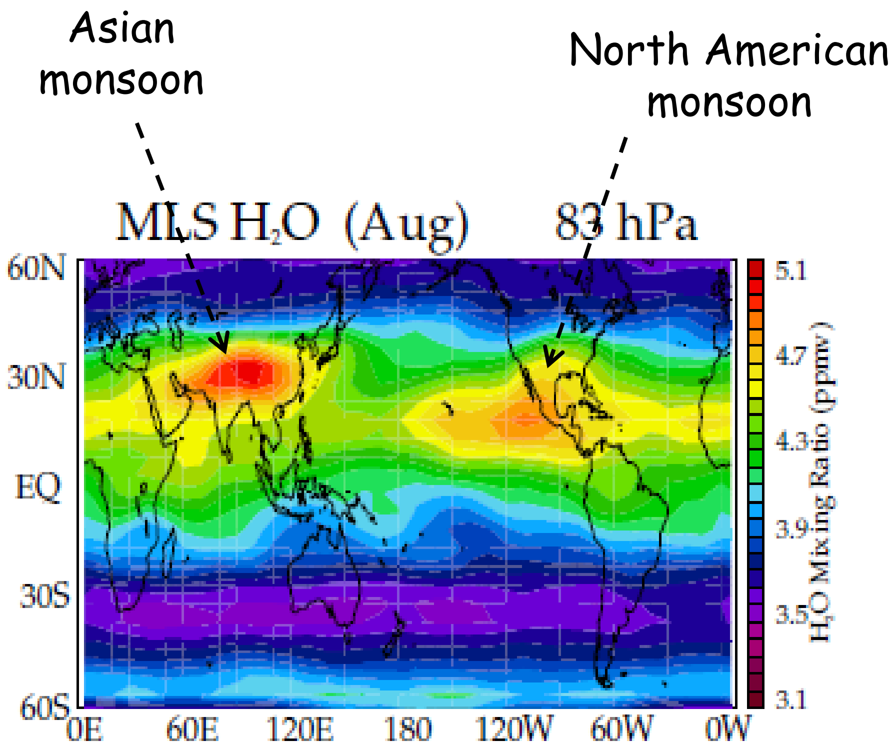
calculations for June-August 2001



Summertime lower stratosphere maxima linked to monsoon circulations

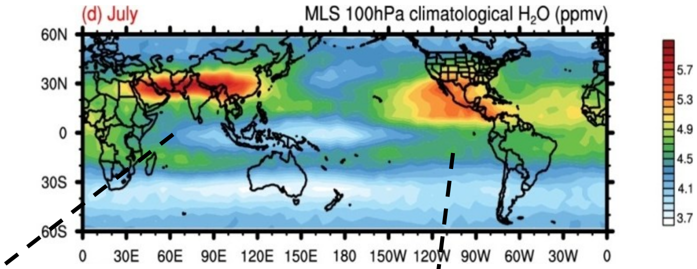
HALOE climatology

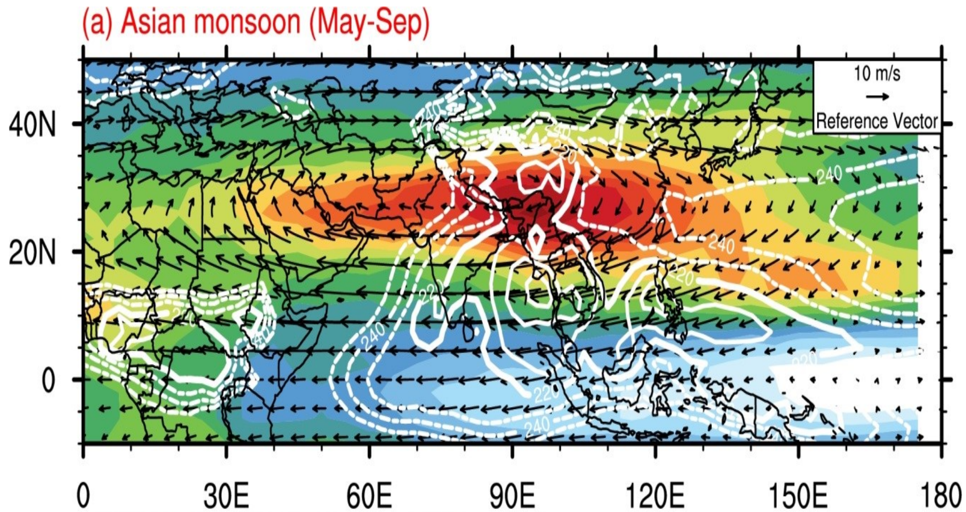




Climatological circulation and OLR

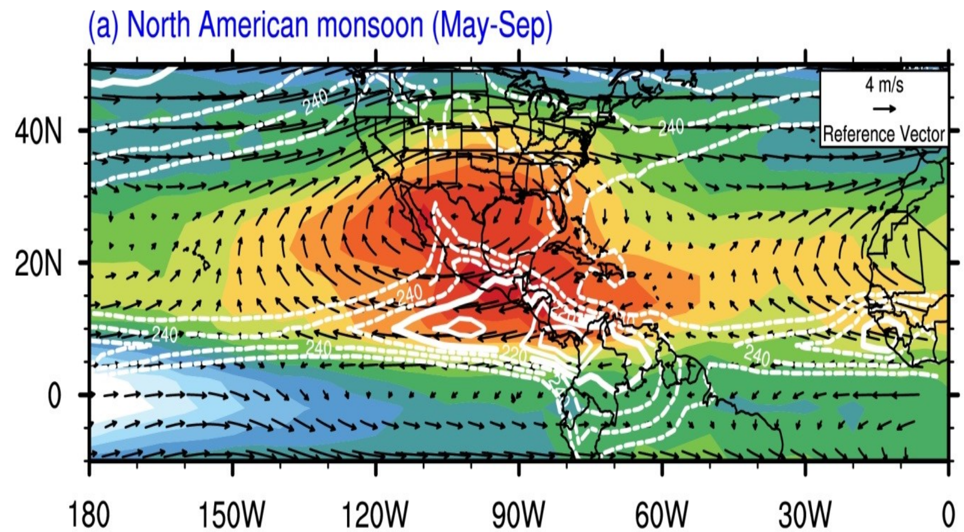
MLS climatology





monsoon anticyclones, much stronger over Asia

white lines: OLR (deep convection)

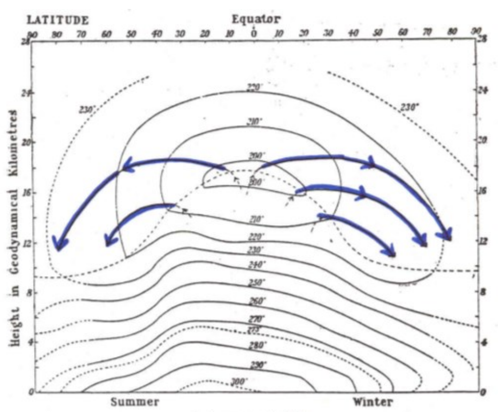


100 hPa H_2O aligned
more with circulation
than with deep convection

Trajectory simulations of seasonal cycle

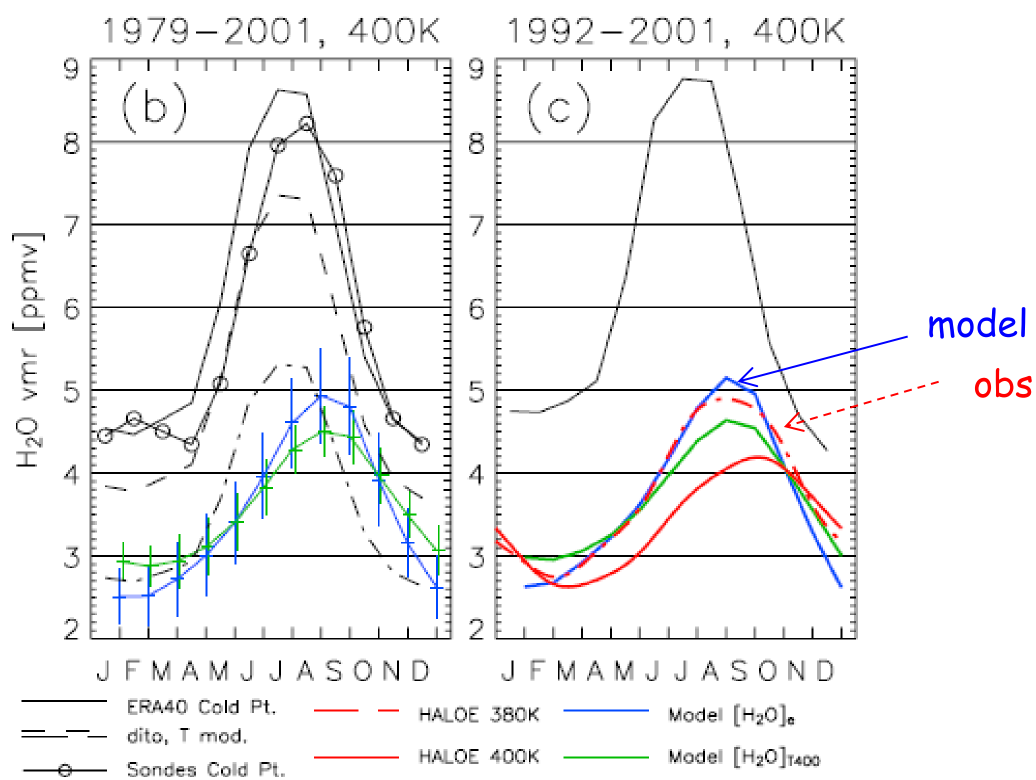
so-called advection-condensation paradigm

* dehydration at Lagrangian cold point *



Brewer, 1949

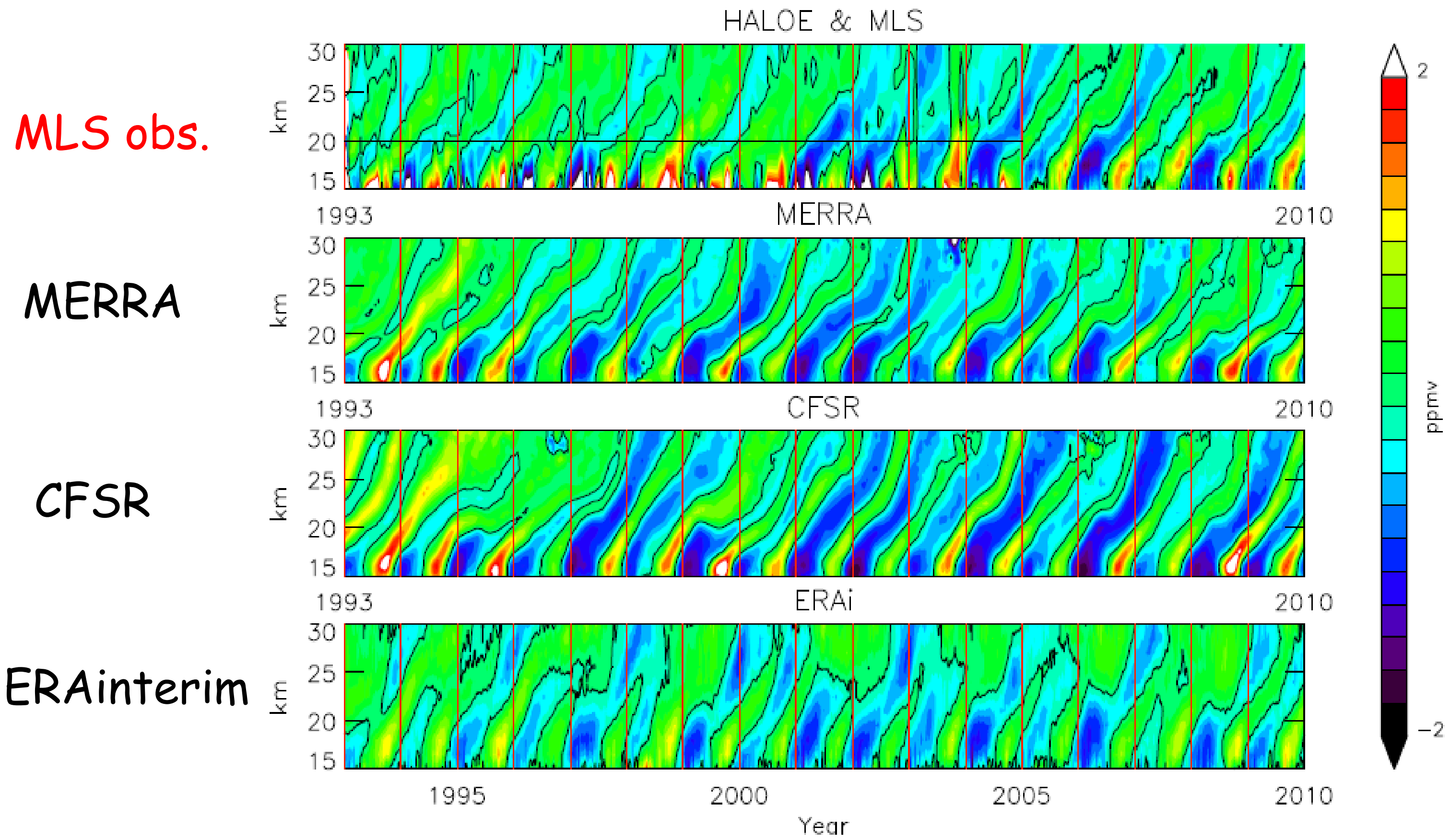
Note that results are sensitive
to many details of the calculations:
kinematic vs. diabatic trajectories,
temperature data, supersaturation,….



Fueglistaler et al 2005 JGR
also Liu, Fueglistaler, Haynes, JGR 2010

Trajectory calculations based on different data sets

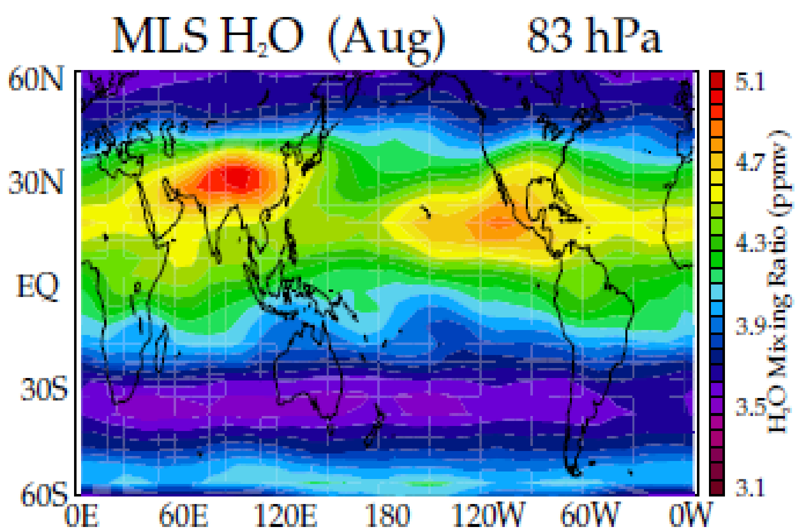
Schoeberl et al 2012 ACP



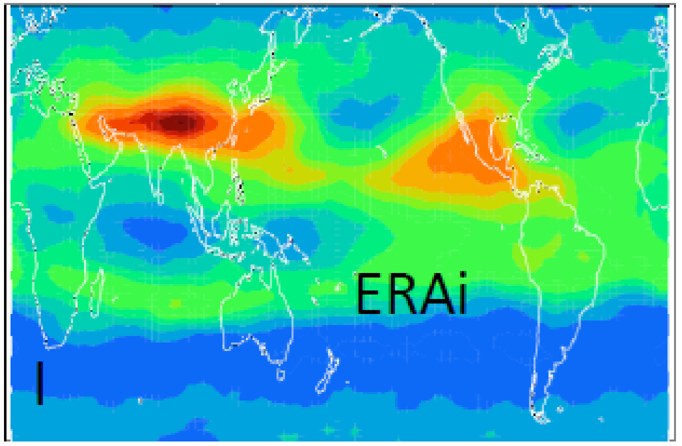
Details are sensitive to the meteorological data

Water vapor in summer monsoons simulated in trajectory models

observations



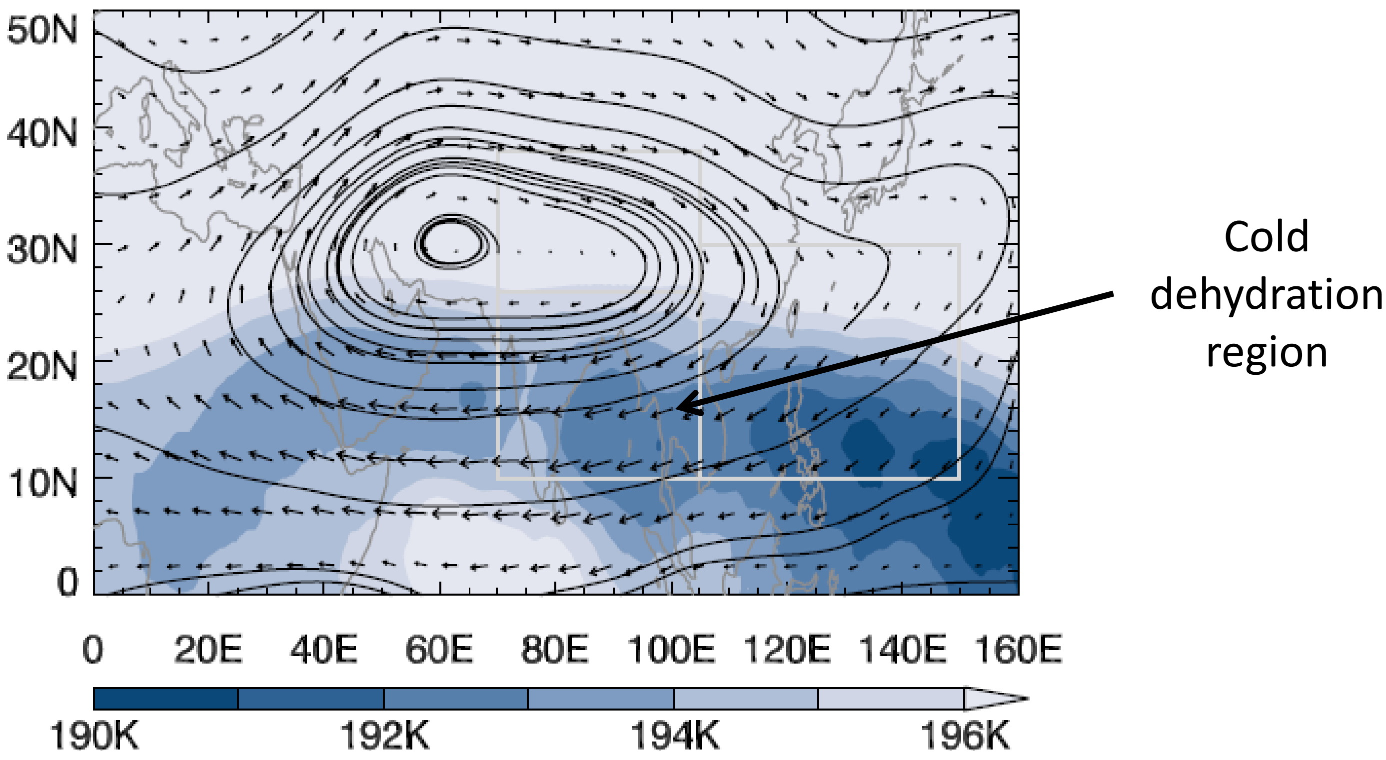
trajectory model



Schoeberl et al 2013

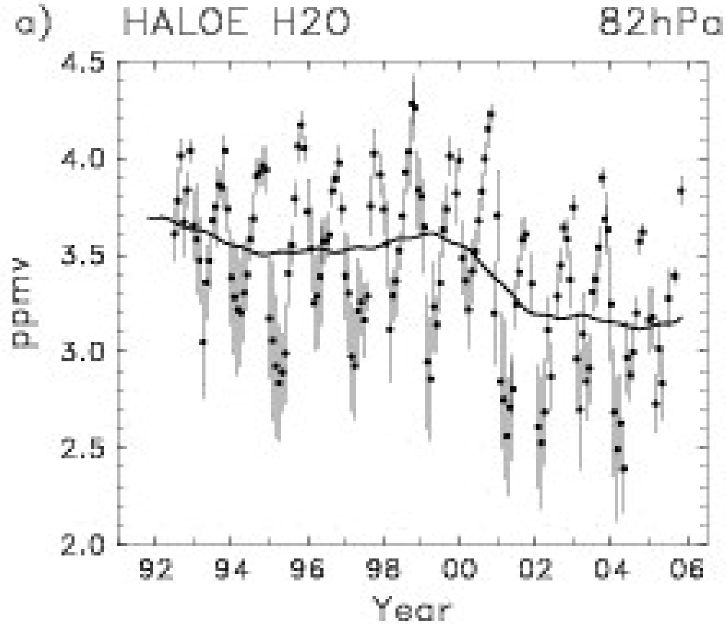
Trajectory simulation of dehydration in Asian monsoon

Wright et al 2011 JGR

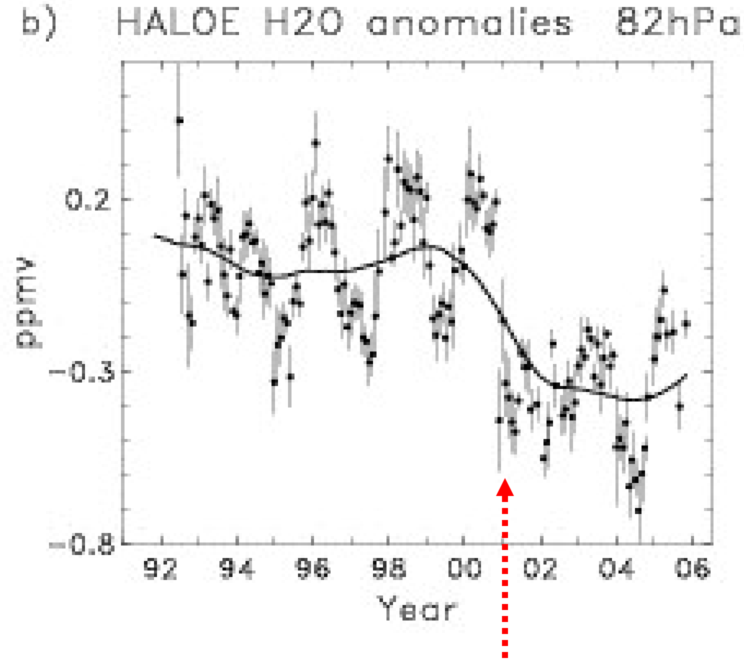


Interannual changes in stratospheric water vapor

HALOE global mean, 82 hPa



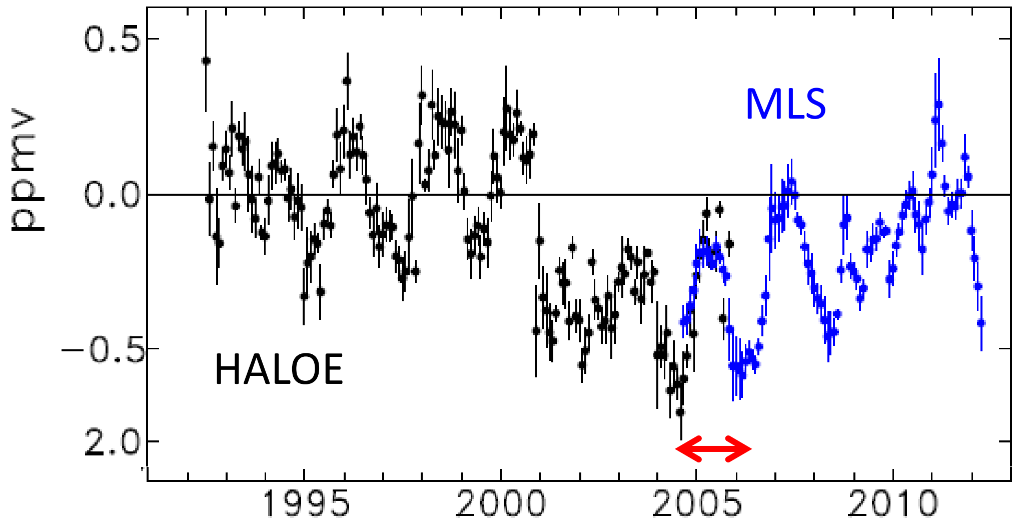
deseasonalized



decrease after 2001

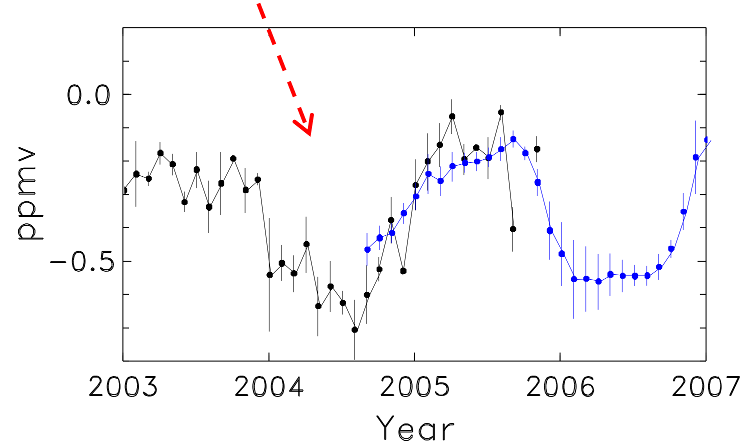
Randel et al., 2004, J. Atmos. Sci.

Extending the satellite record: HALOE + Aura MLS data



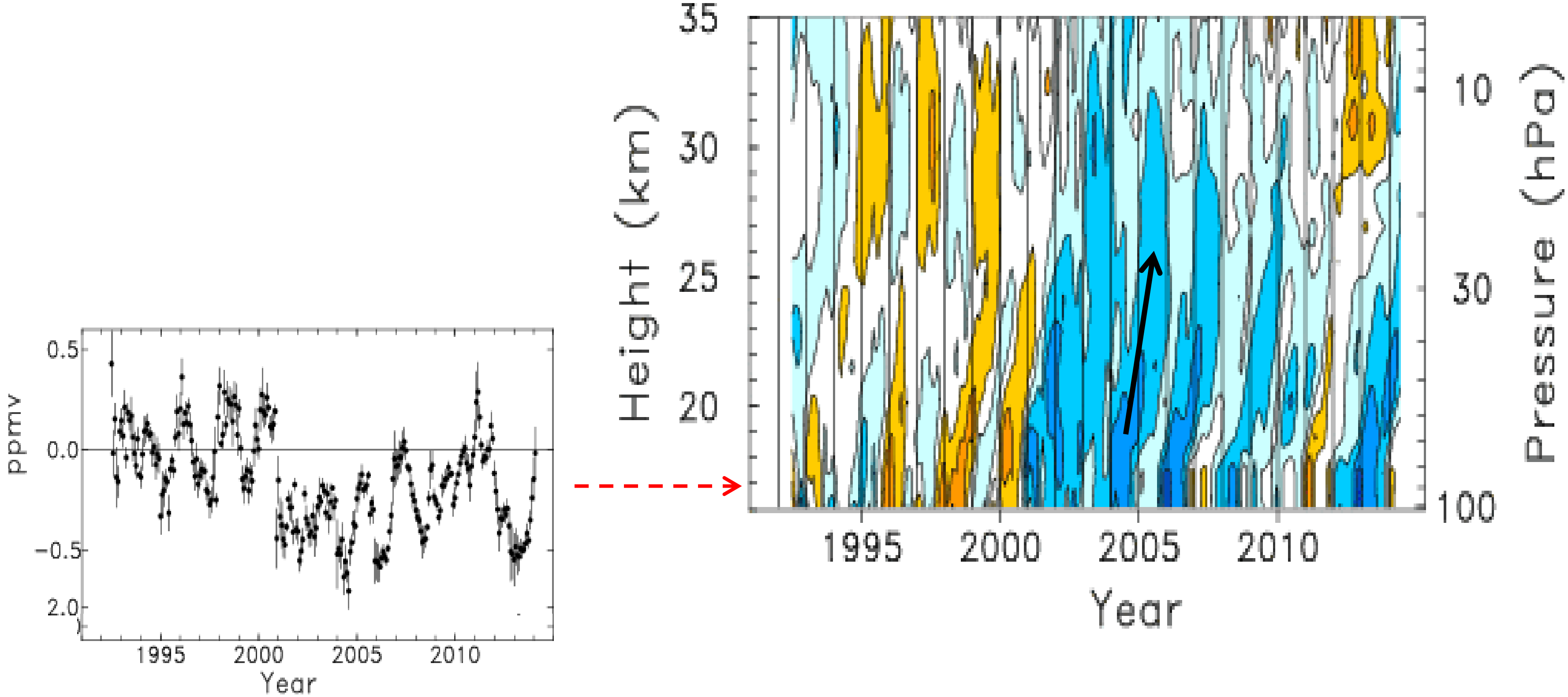
Variability tied to the QBO. What else?

overlap during 2004-2005

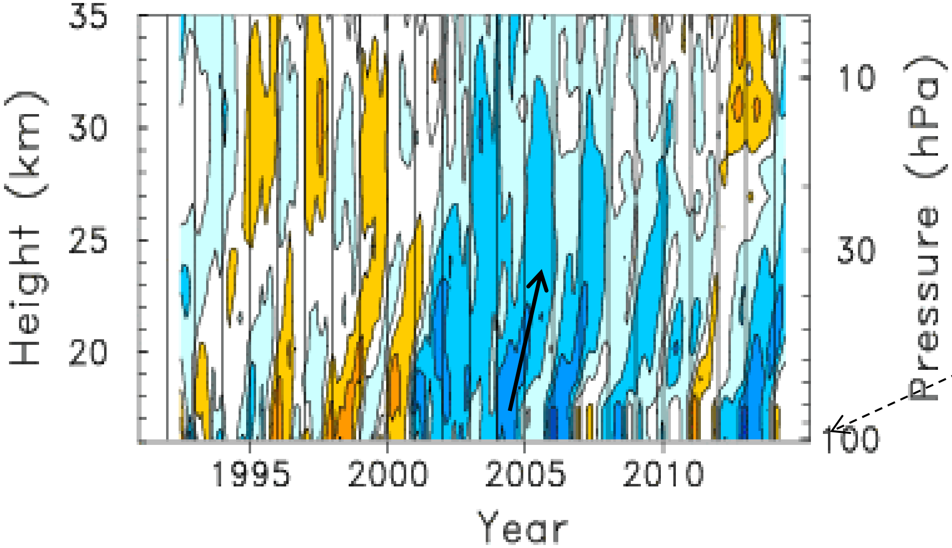


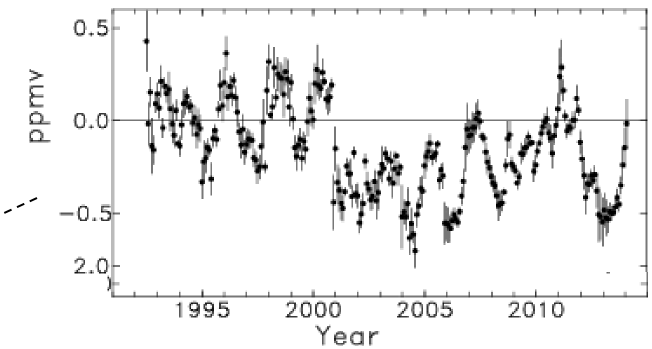
H_2O anomalies originate near the tropical tropopause, and propagate coherently with time

vertical propagation

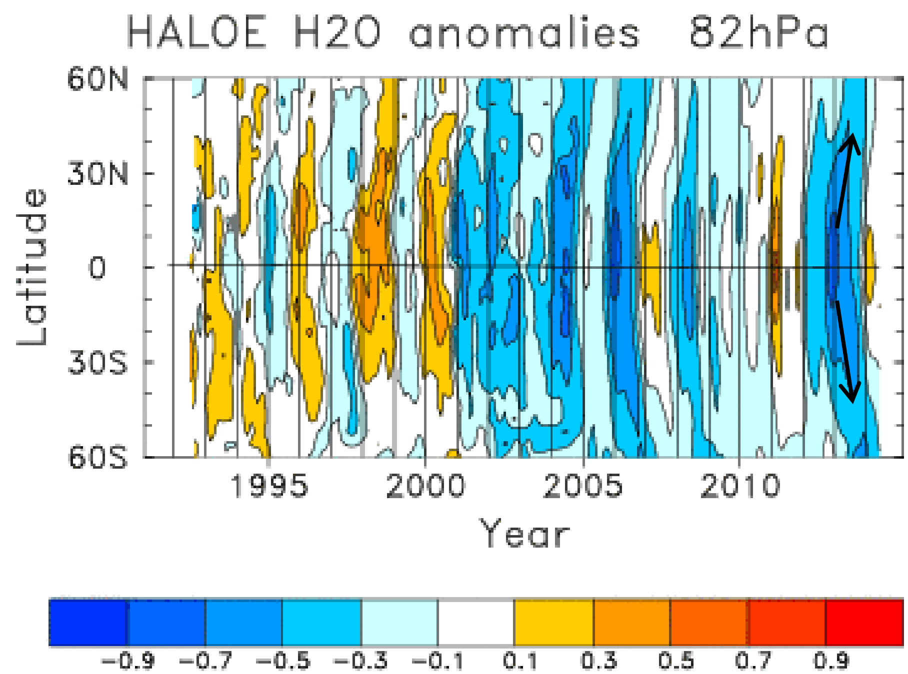


vertical propagation

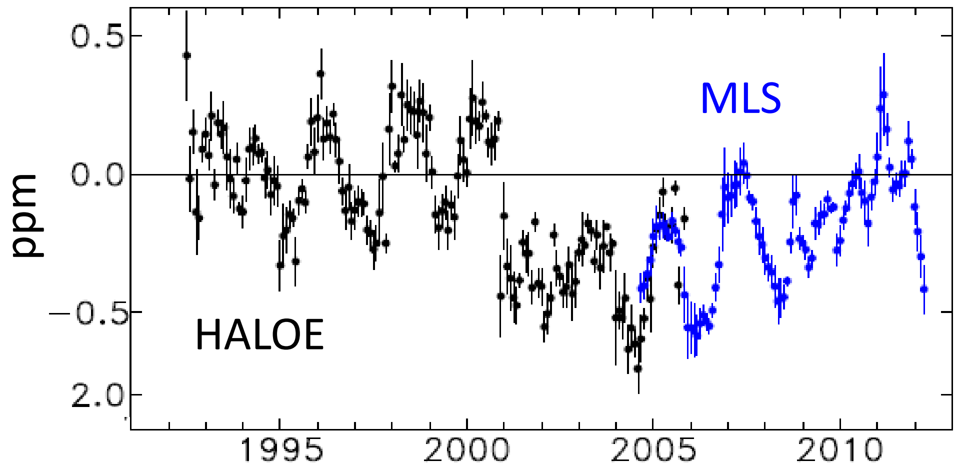




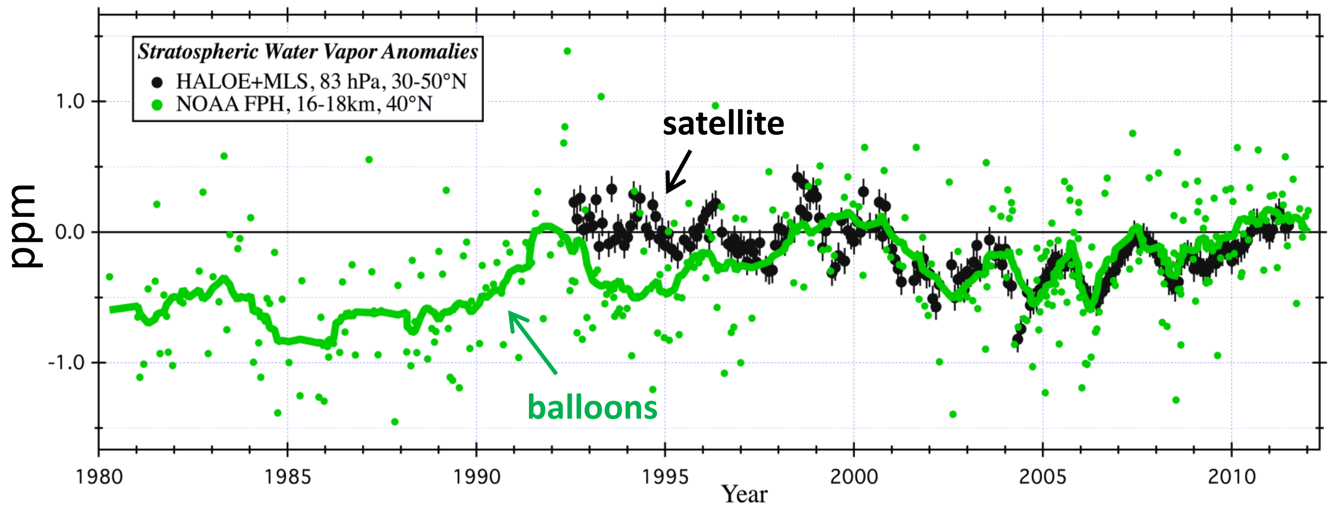
latitudinal propagation from tropics



Comparisons with the Boulder balloon record

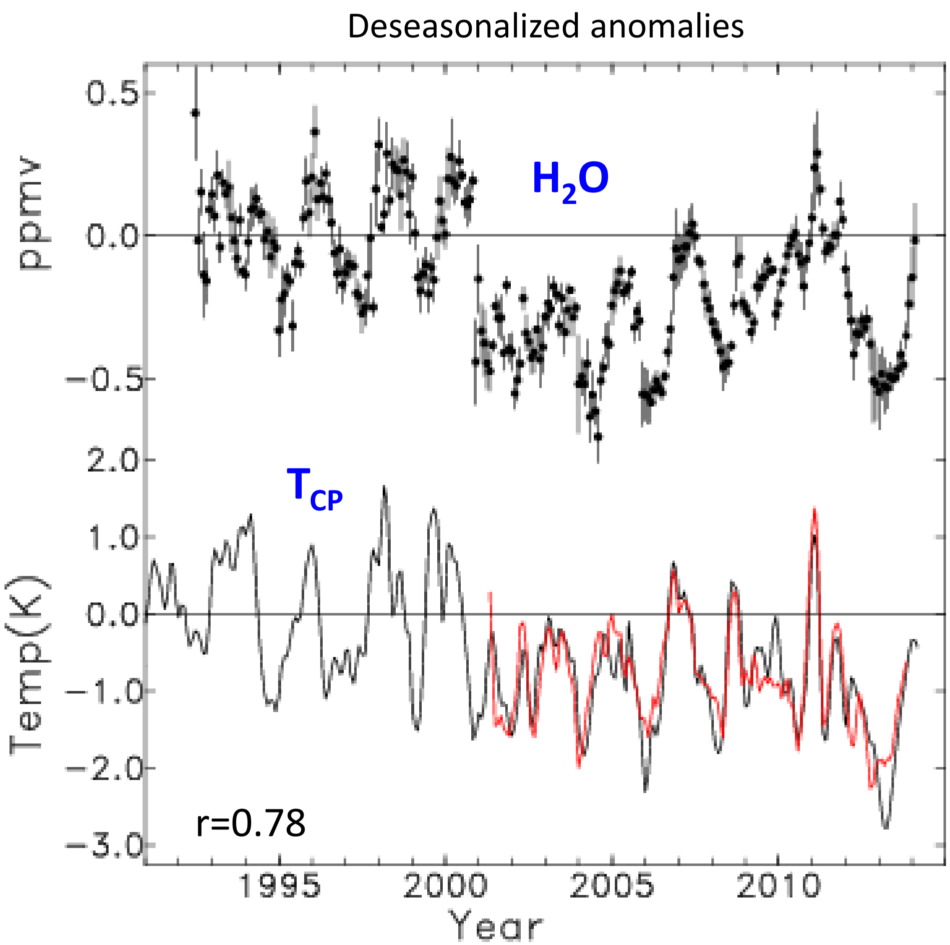


near-global



measurements near Boulder (40° N)

Correlated variations in stratospheric H_2O and cold point temperatures



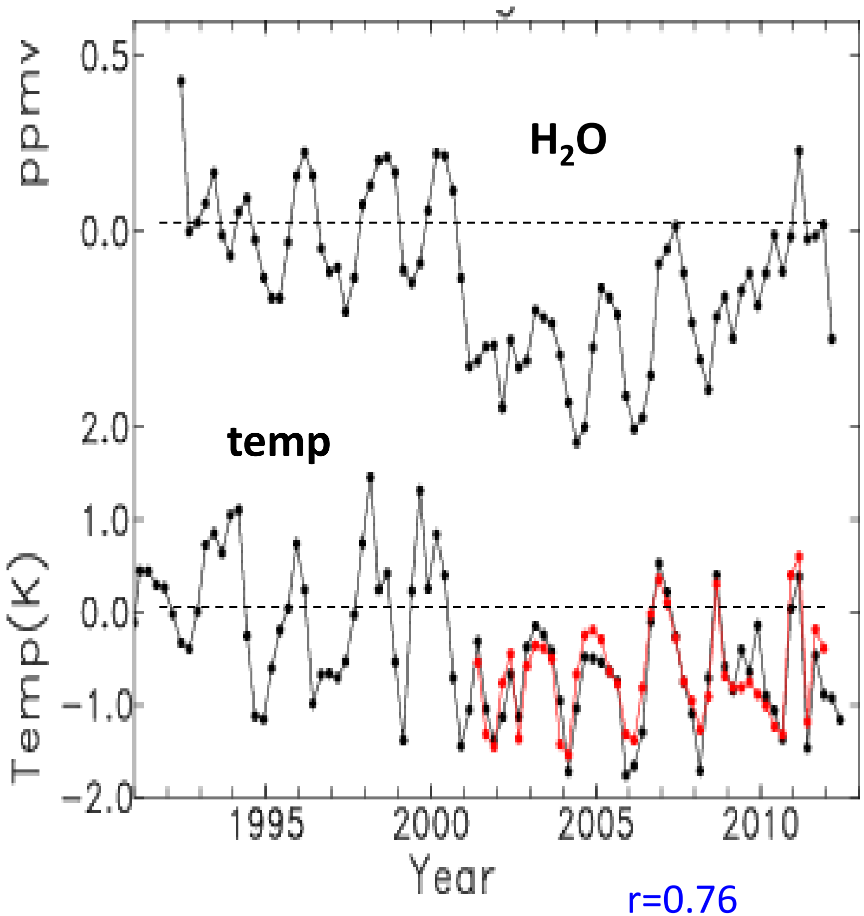
most recent plot, updated through 2013

near-global mean (60° N-S)
water vapor at 82 hPa
from combined HALOE-MLS data

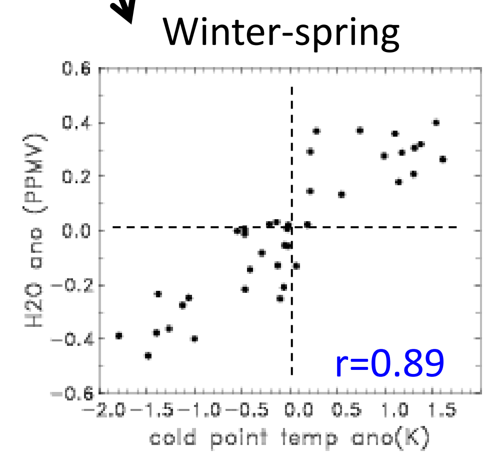
cold-point tropical
tropopause temperatures

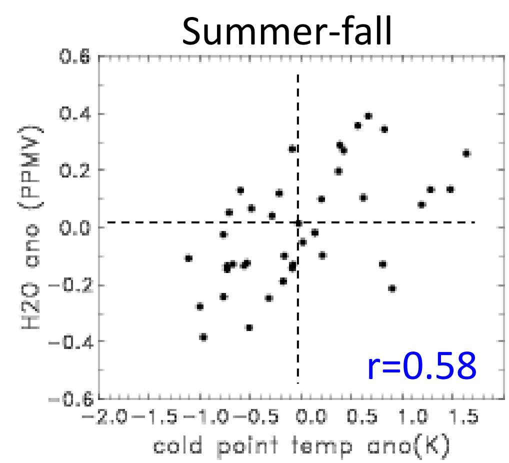
black: radiosondes
red: GPS (after 2001)

Same data, 3-month averages



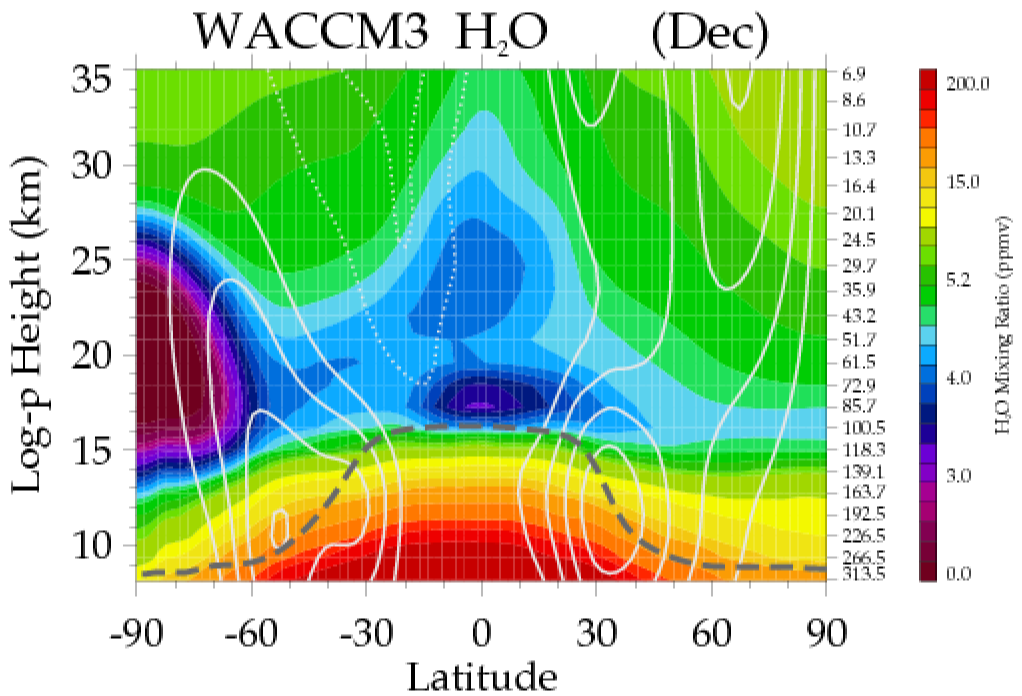
Very strong correlation during cold season



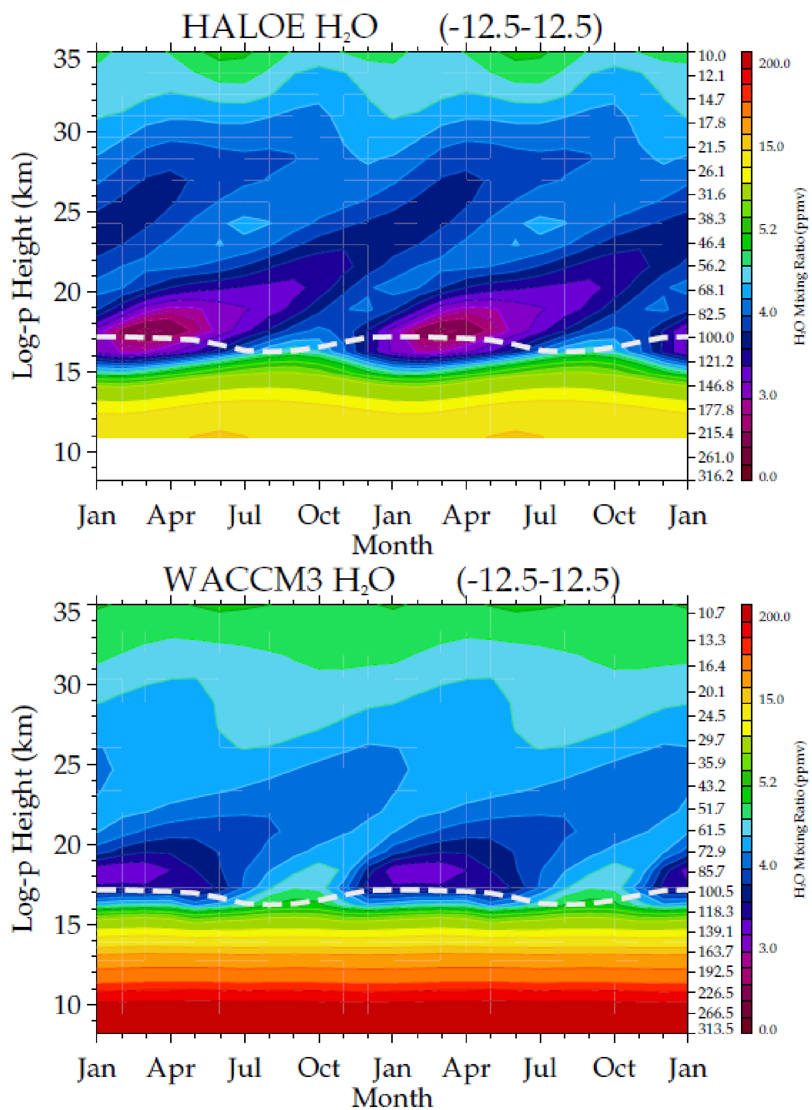


Seasonal correlations

Chemistry-climate model simulations from WACCM

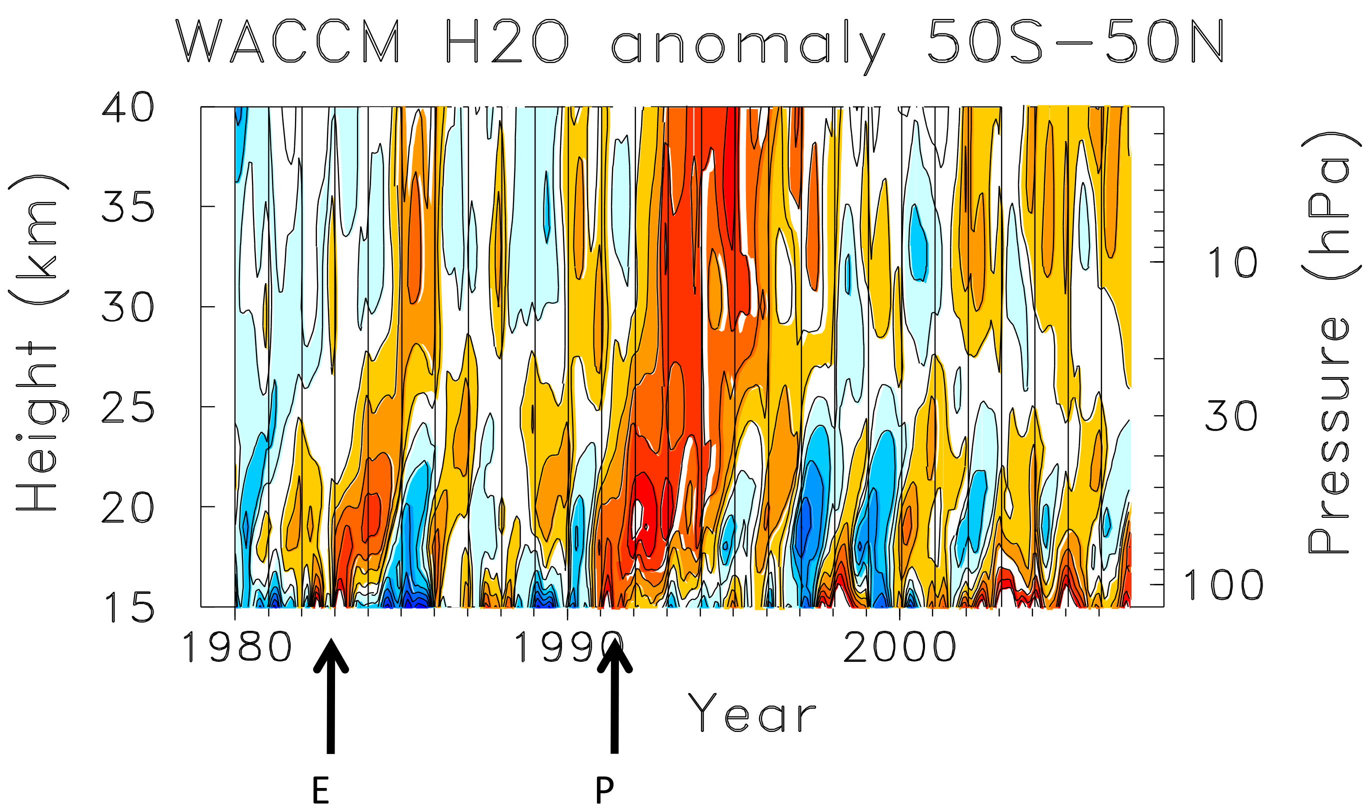


'tape recorder'
HALOE vs. WACCM

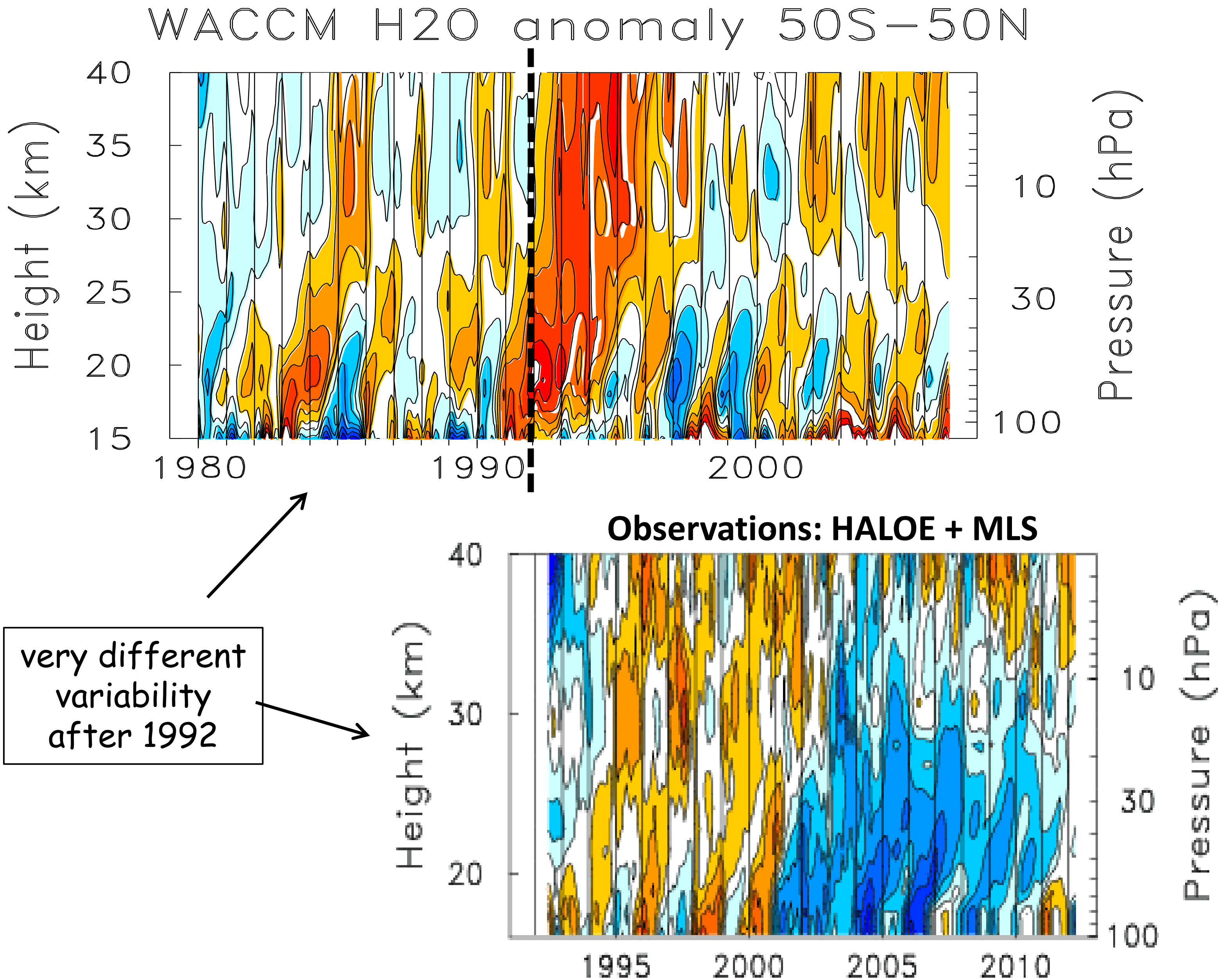


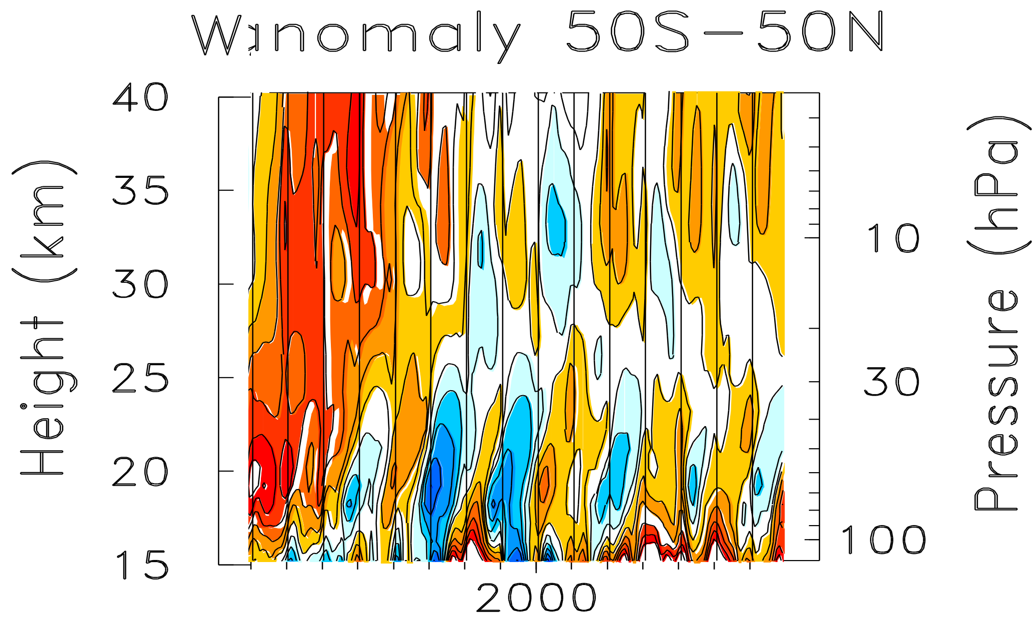
HALOE

WACCM

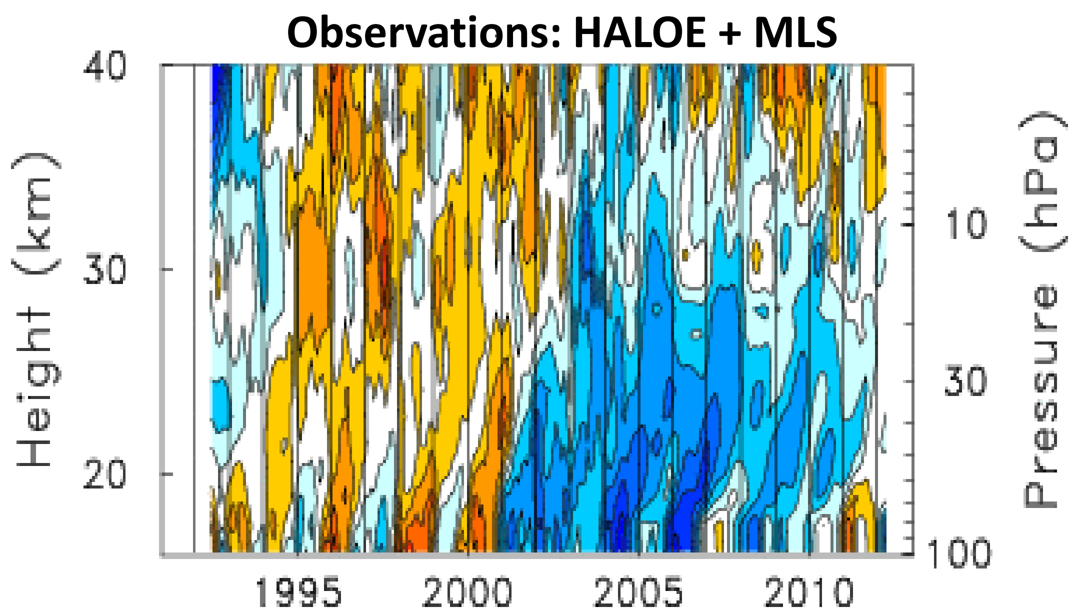


In the model, volcanoes dominate interannual variability


WACCM H2O anomaly 50S–50N
Height (km)
40
35
30
25
20
15
1980
1990
2000
10
30
100
Pressure (hPa)
Observations: HALOE + MLS
Height (km)
40
30
20
1995
2000
2005
2010
10
30
100
Pressure (hPa)
very different variability after 1992



very different variability after 1992



Key points:

- Stratospheric H_2O seasonal cycle is well understood. Tropical dehydration mainly during boreal winter (cold season). Tape recorder, rapid global transport in lower stratosphere, monsoons in UTLS during NH summer. Also Antarctic dehydration.

- Interannual changes for satellite record (1992-2013) in good (quantitative) agreement with tropical cold point. Cold point controls stratospheric water vapor; what controls the cold point?

- What controls water vapor in summer monsoon regions? Is deep overshooting convection important?

- Simulation of seasonal cycle in trajectory calculations and chemistry-climate models is reasonable. Interannual variability in models is different from observations.

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