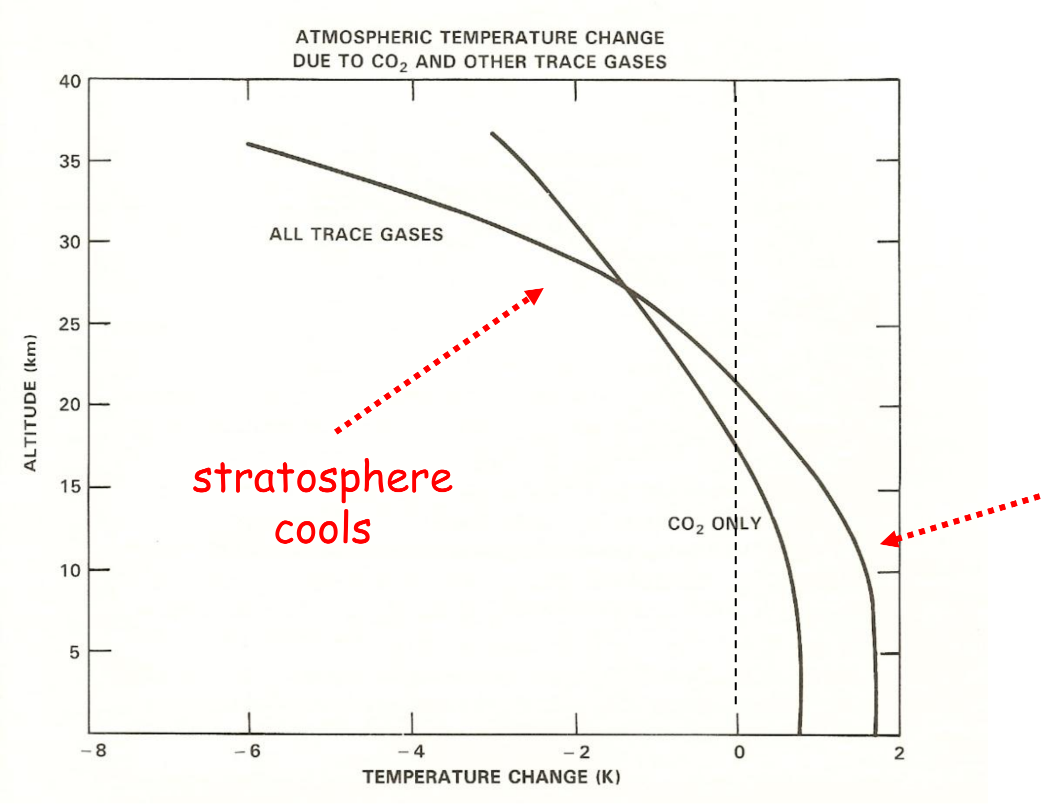
Stratospheric temperature trends

- Climate change and the stratosphere
- Stratospheric temperature trends:

  observations (balloons and satellites) and model simulations
- Recent results from the upper stratosphere

Simple view: climate change in the stratosphere



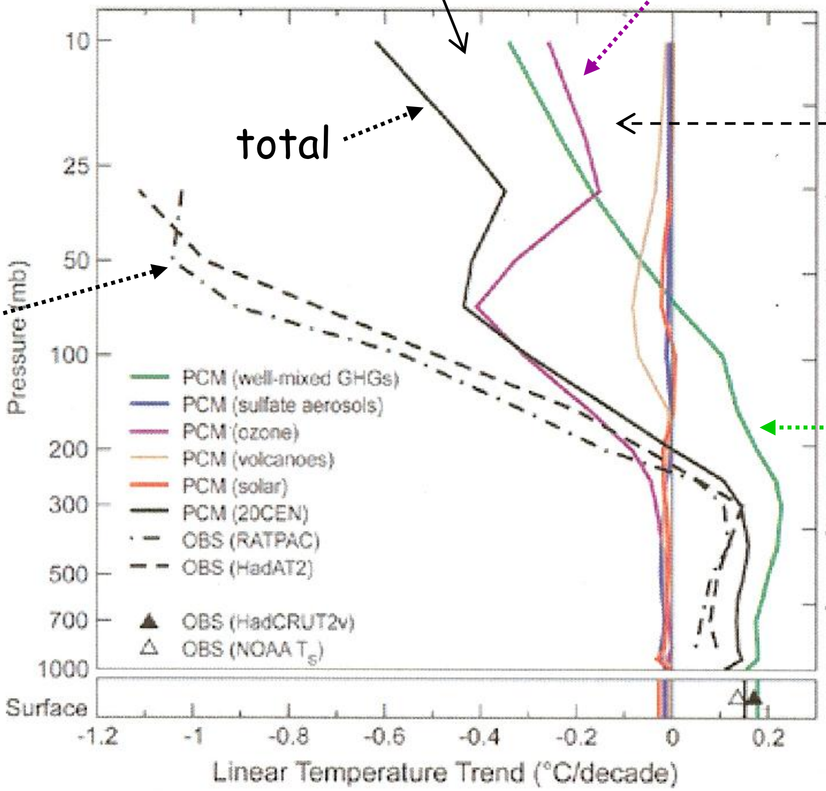
stratosphere cools

troposphere warms

WMO Ozone Assessment, 1985

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

temp trends
for 1958-1999



model
results

ozone

total

CO$_2$ increases and
O$_3$ decreases act to
cool the stratosphere

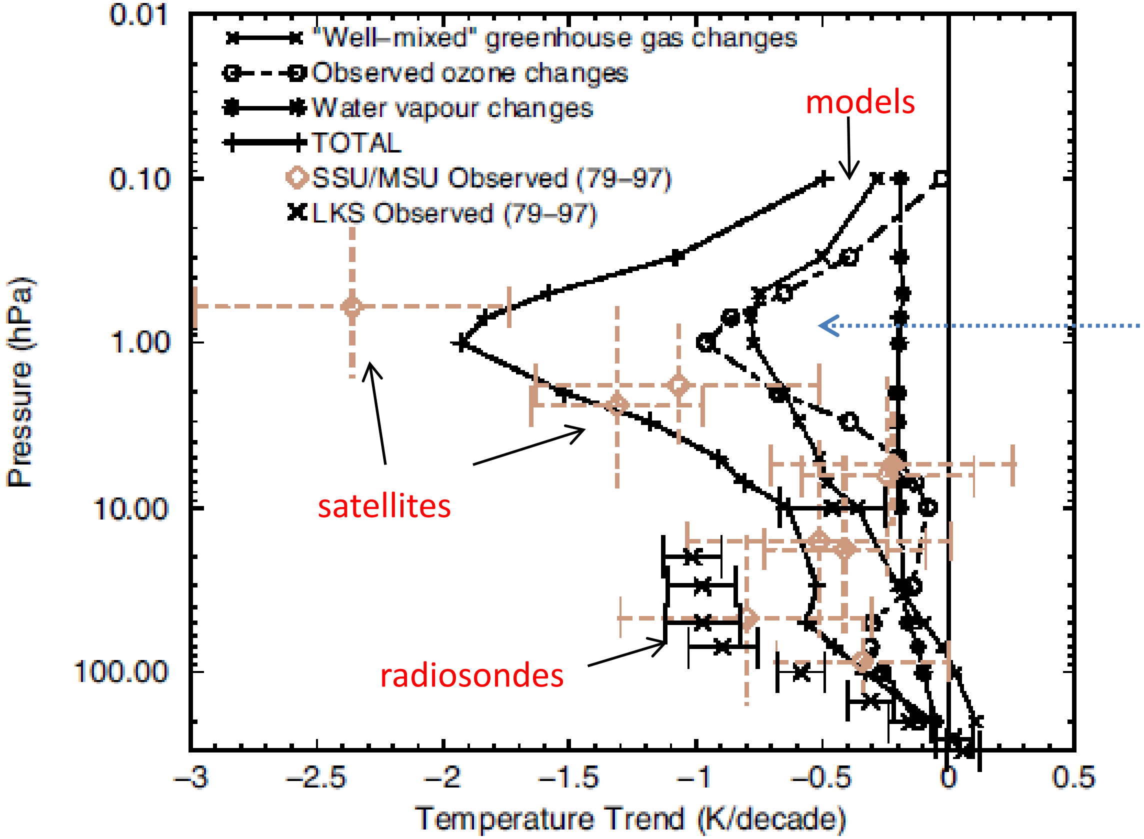
radiosonde
data sets

CO$_2$

note that radiosonde
data give stronger
cooling than models

Model calculated stratospheric temperature trends

Shine et al 2003

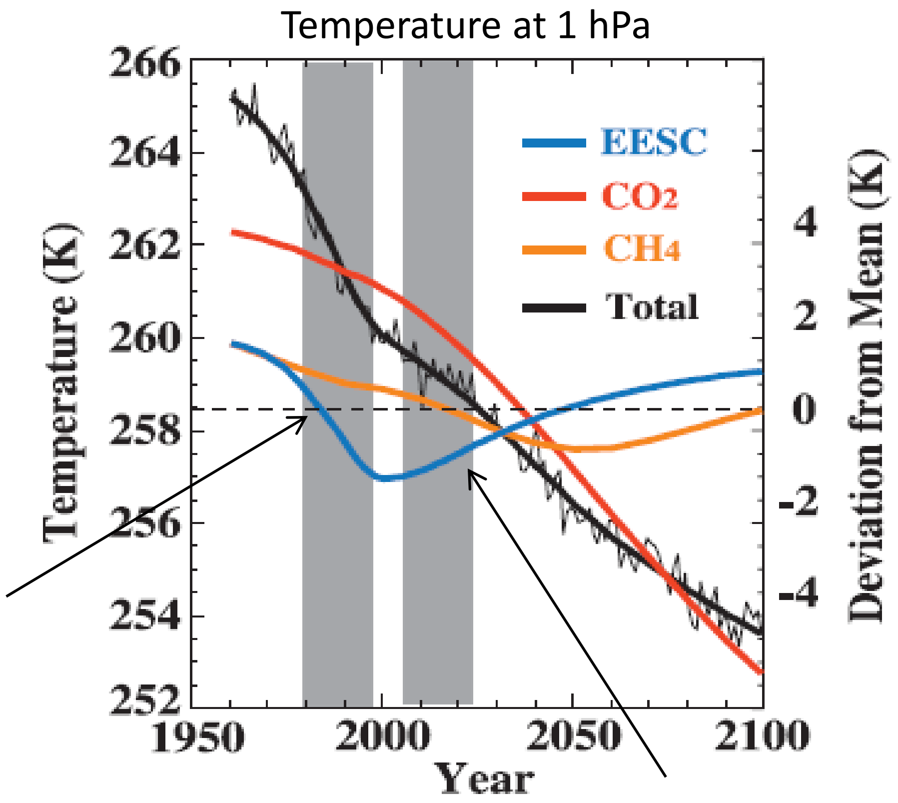


stratosphere cooling:
about ½ from CO_2 increase
and ½ from O_3 decrease

Chemistry-climate model simulation of Stolarski et al 2009

Upper stratosphere: stronger cooling pre-2000 due to ozone depletion

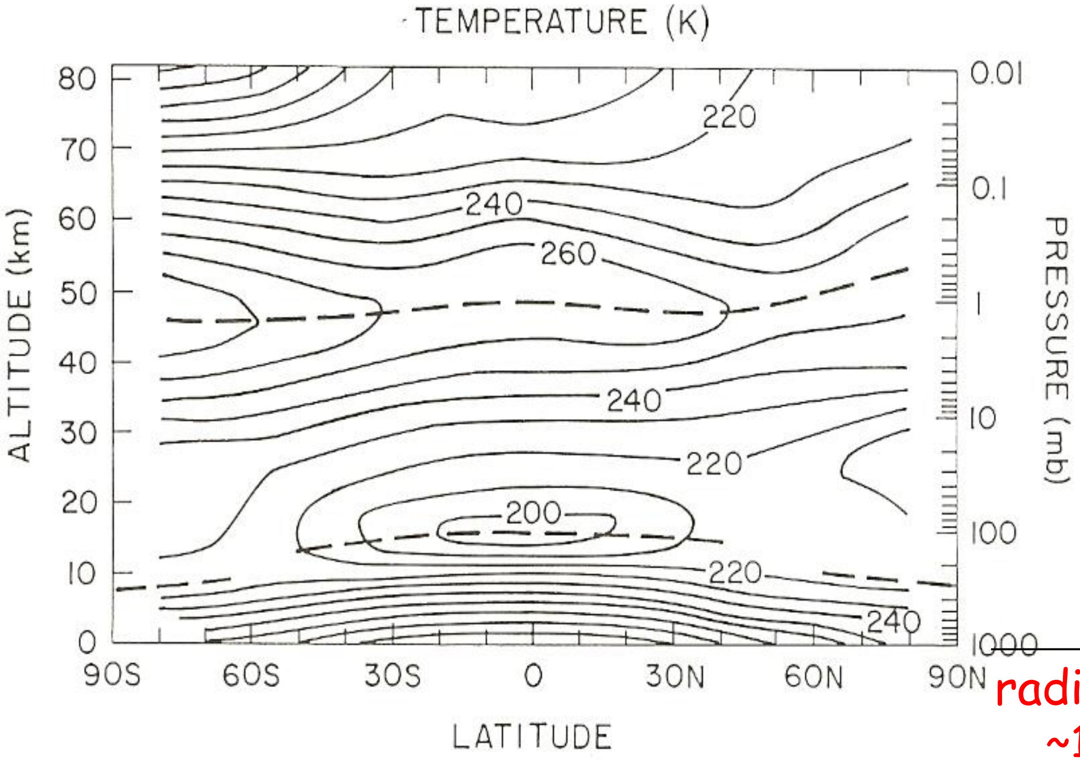
Temperature at 1 hPa



decreasing ozone

increasing ozone

Data sources for stratospheric temperature trends:



sparse sampling

lidars
>1980

rockets
~1960-1990

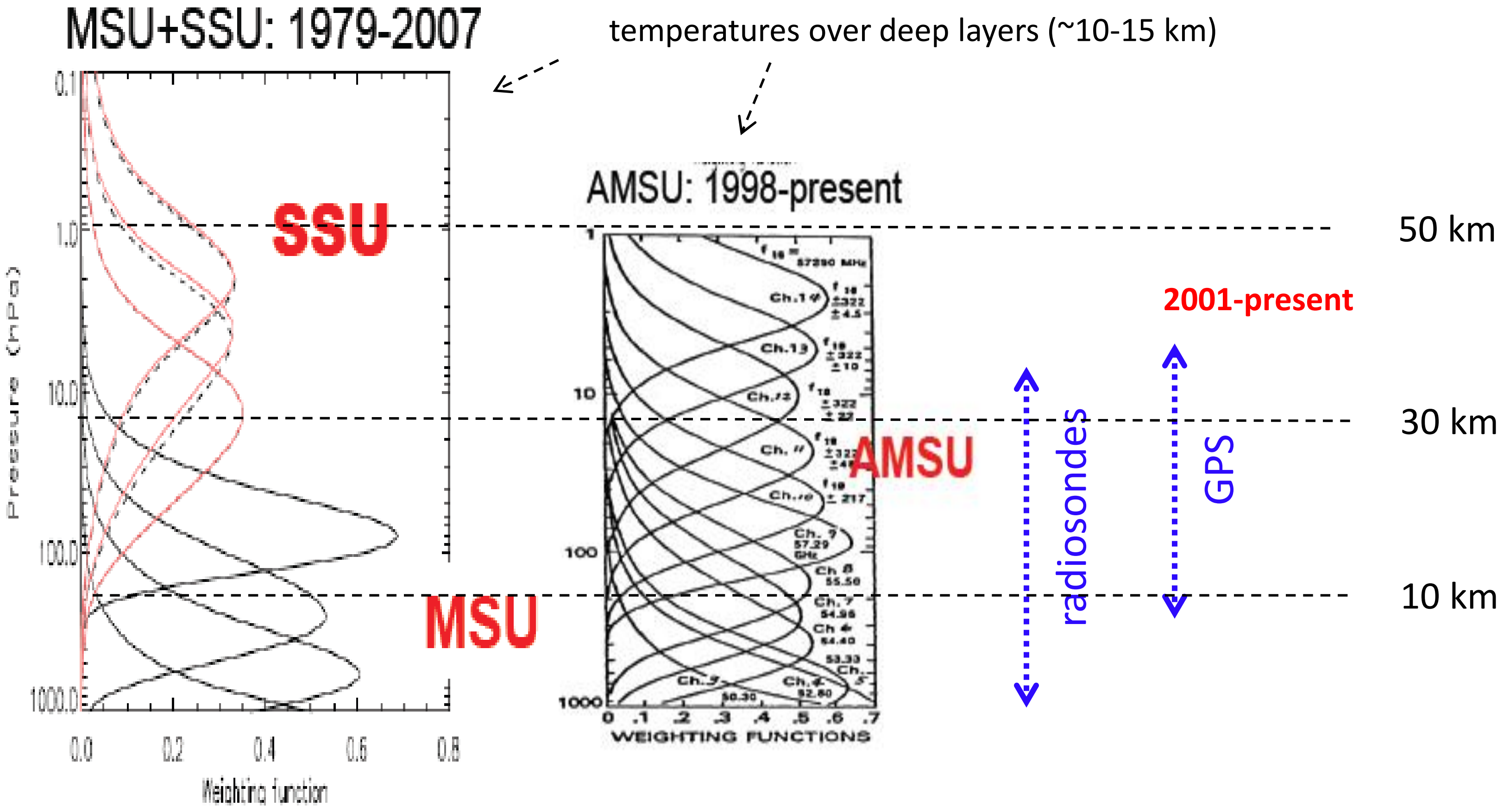
satellites
> 1979

radiosondes
~1960

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

Operational satellites (nadir sounders)

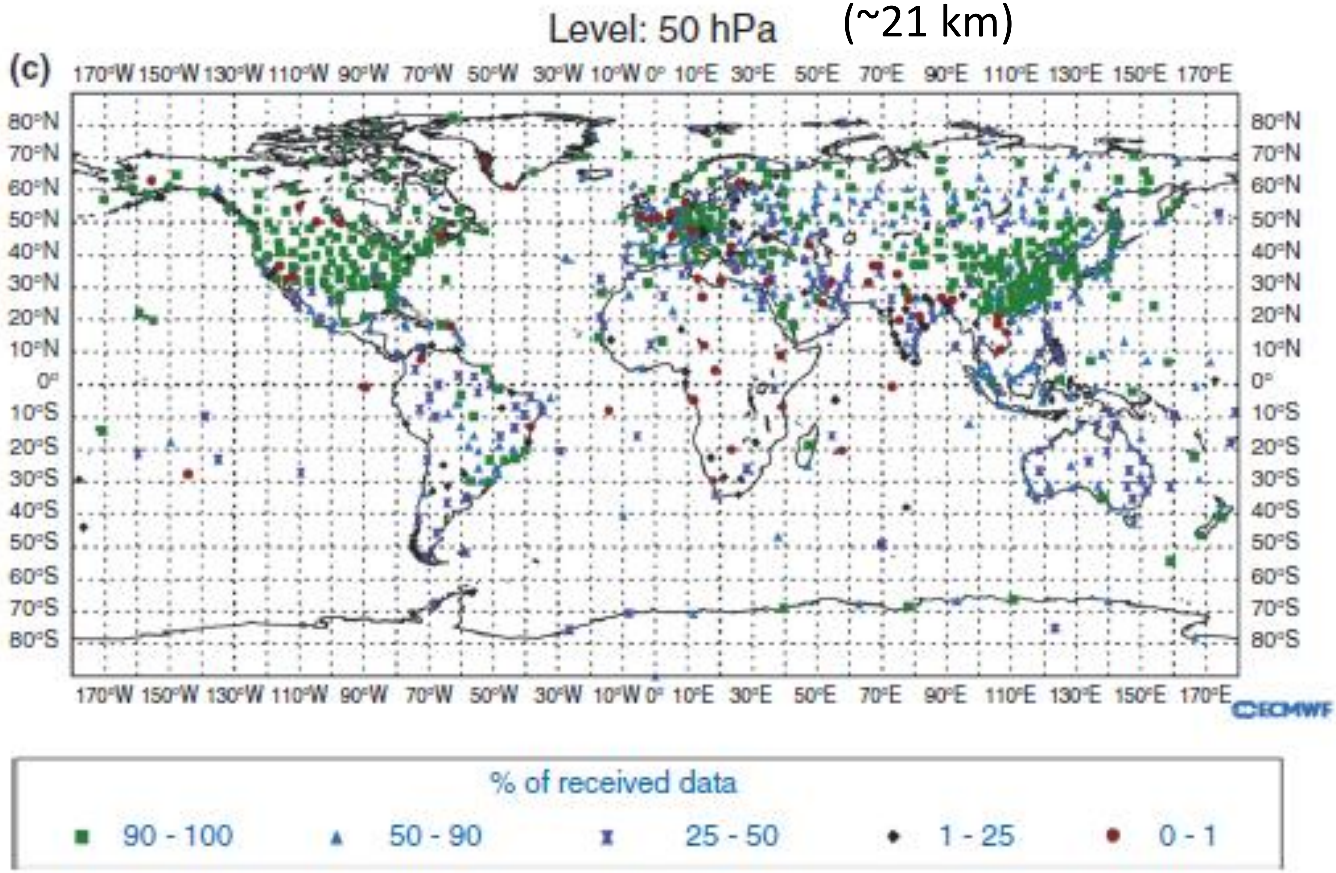
nadir sounders are sensitive to
temperatures over deep layers (~10-15 km)



Global radiosonde network

Characteristics:

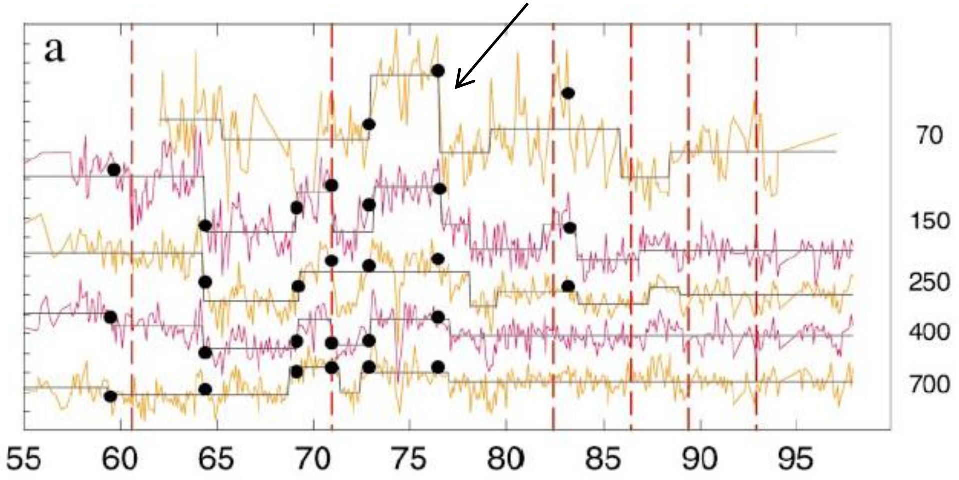
- Majority of measurements over continents
- Poorer coverage at upper levels
- Radiosonde sensors change over time



(~21 km)

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

subjectively determined break points



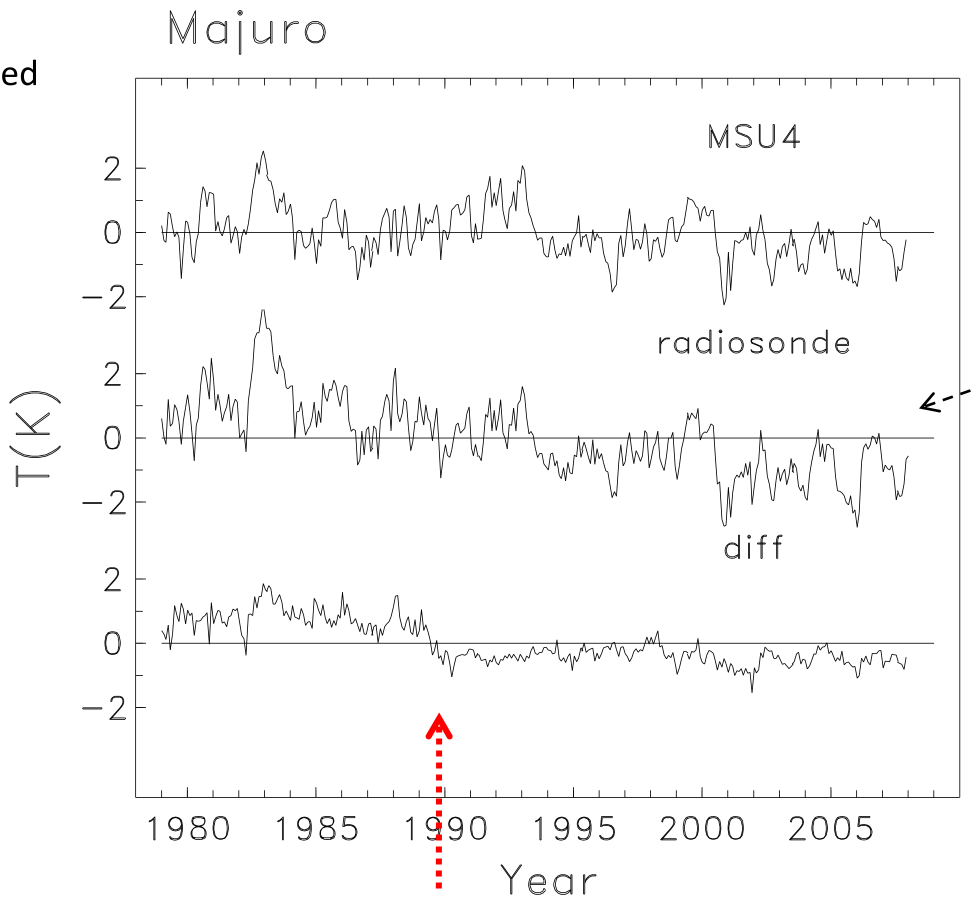
radiosonde record
from Niamey

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

An update of observed stratospheric temperature trends

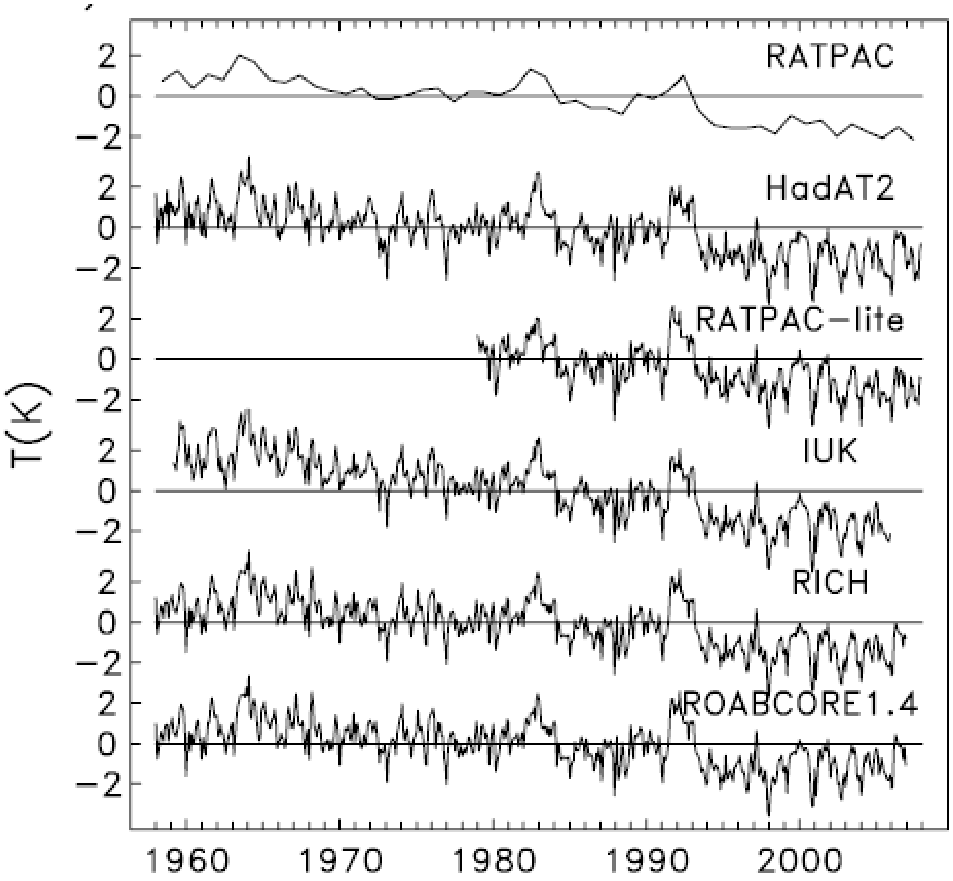
William J. Randel,[1] Keith P. Shine,[2] John Austin,[3] John Barnett,[4] Chantal Claud,[5]
Nathan P. Gillett,[6] Philippe Keckhut,[7] Ulrike Langematz,[8] Roger Lin,[9] Craig Long,[9]
Carl Mears,[10] Alvin Miller,[9] John Nash,[11] Dian J. Seidel,[12] David W. J. Thompson,[13]
Fei Wu,[1] and Shigeo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

JGR, 2009

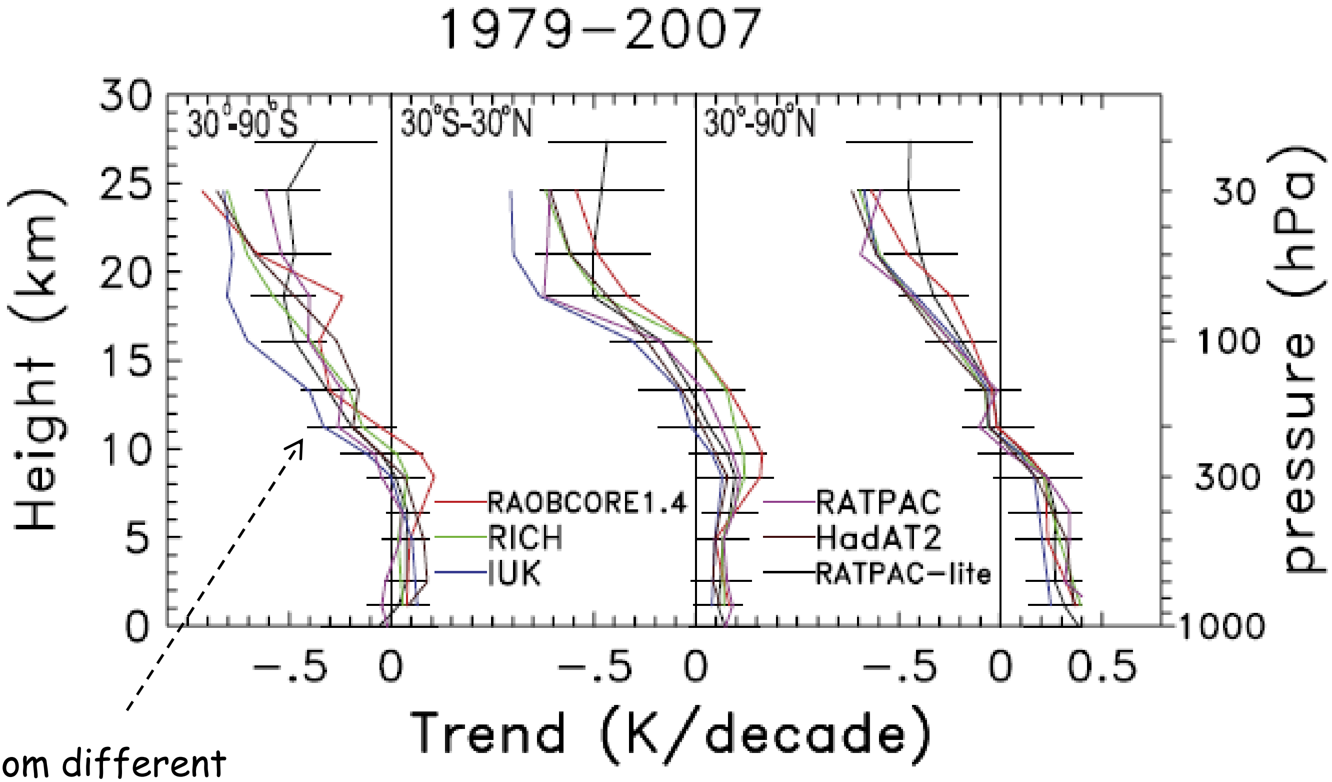
Comparison of time series
from different homogenized
radiosonde data sets

deseasonalized
anomalies

Tropics (30° N-S) 50 hPa

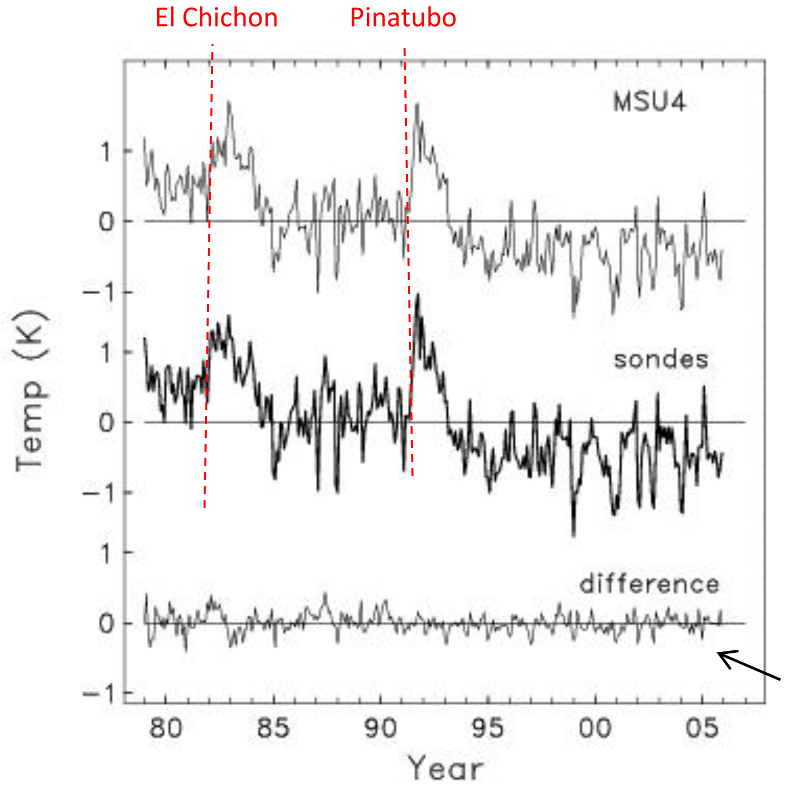


Temperature trends from homogenized radiosonde data



results from different
homogenized data sets

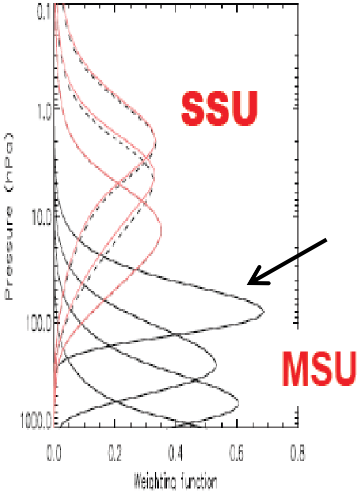
Lower stratosphere temps: MSU4 satellite and radiosondes, 60 N-S



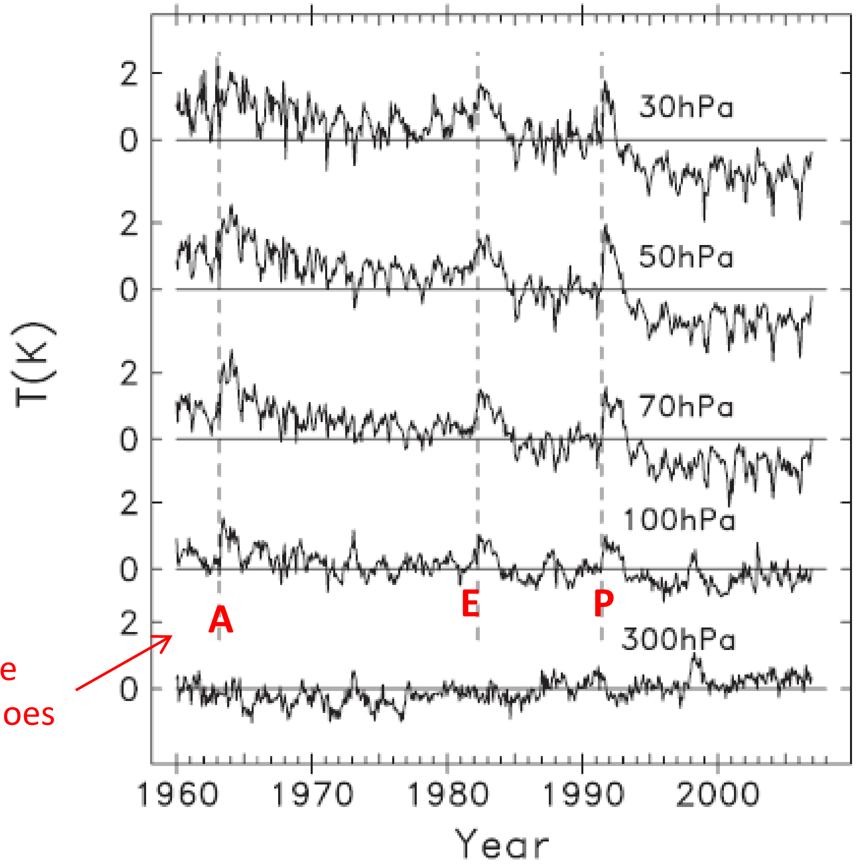
MSU4 satellite

Radiosondes, using
RATPAC-lite stations

excellent
agreement



Global average time series from RICH radiosonde data

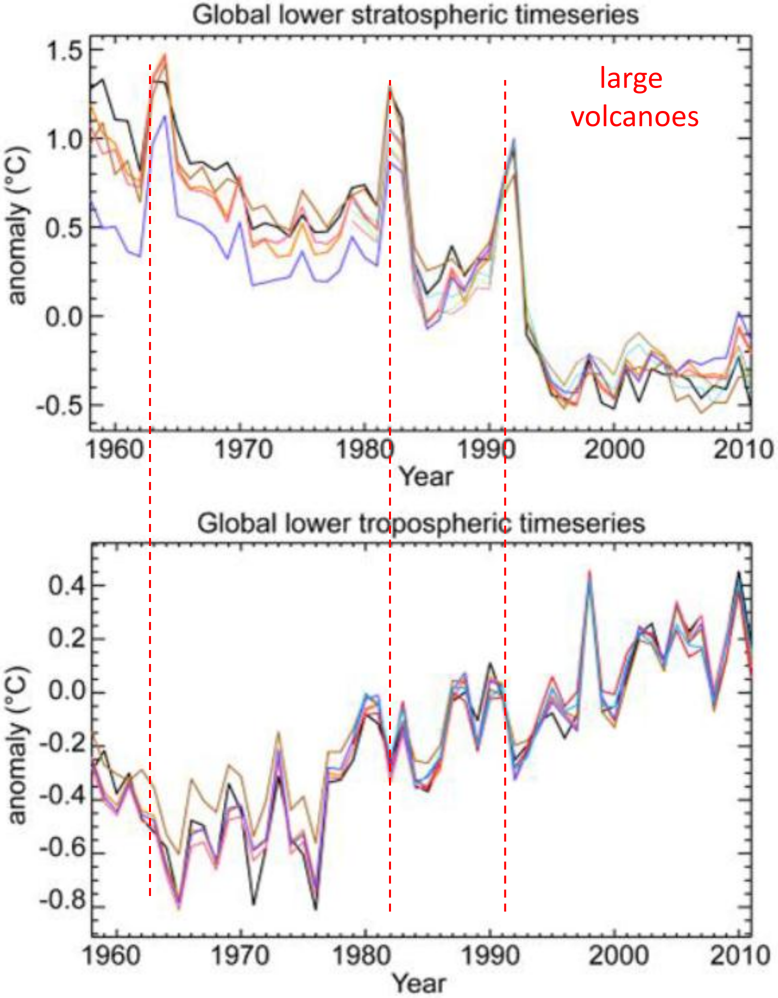


large
volcanoes

stratosphere cools

troposphere warms

Reasonable overall agreement among radiosonde and satellite data sets



large
volcanoes

lower
stratosphere

lower
troposphere

black: satellite
colors: radiosondes

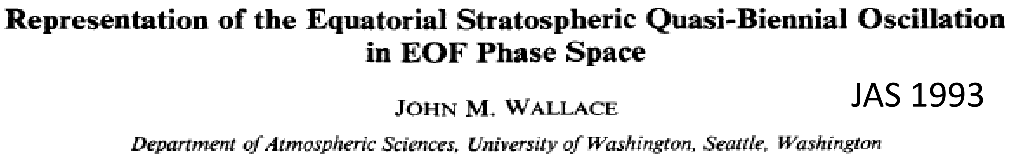
IPCC AR5 2014

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

$$O3\ (t) = \underbrace{A1 * QBO1(t) + A2 * QBO2(t)}_{\substack{\text{Use two orthogonal proxies}\\ \text{for QBO}}} + A3 * solar(t) + A4 * \underset{\substack{\uparrow\\ \text{Long-term change}\\ \text{or linear tend}}}{t}$$

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



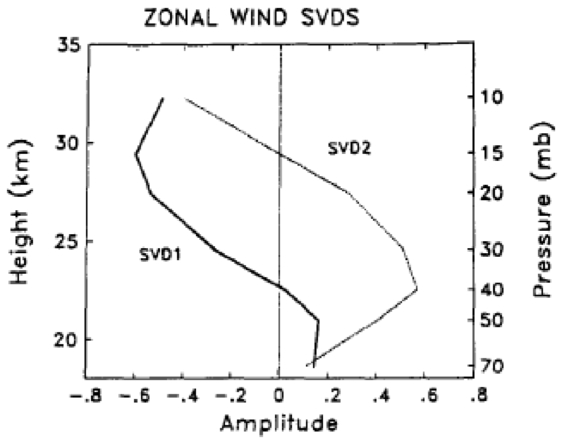
Representation of the Equatorial Stratospheric Quasi-Biennial Oscillation in EOF Phase Space

JOHN M. WALLACE

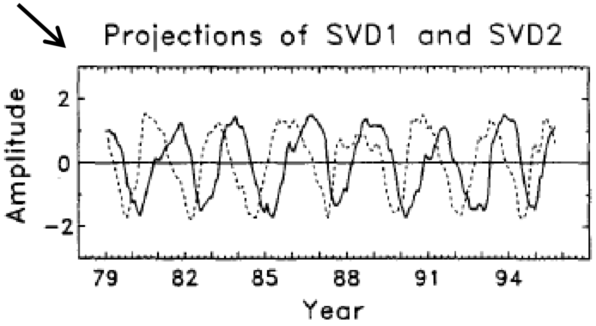
Department of Atmospheric Sciences, University of Washington, Seattle, Washington

JAS 1993

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

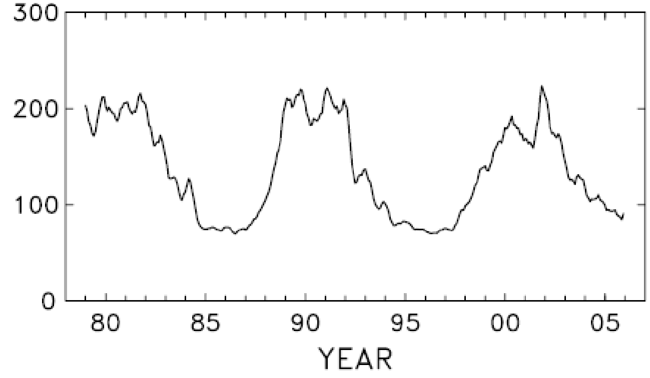


QBO1 and QBO2: orthogonal proxies

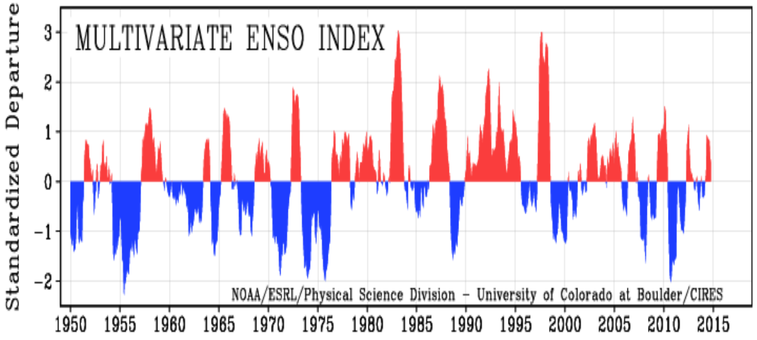


Other proxies:

Solar cycle (F10.7 flux)

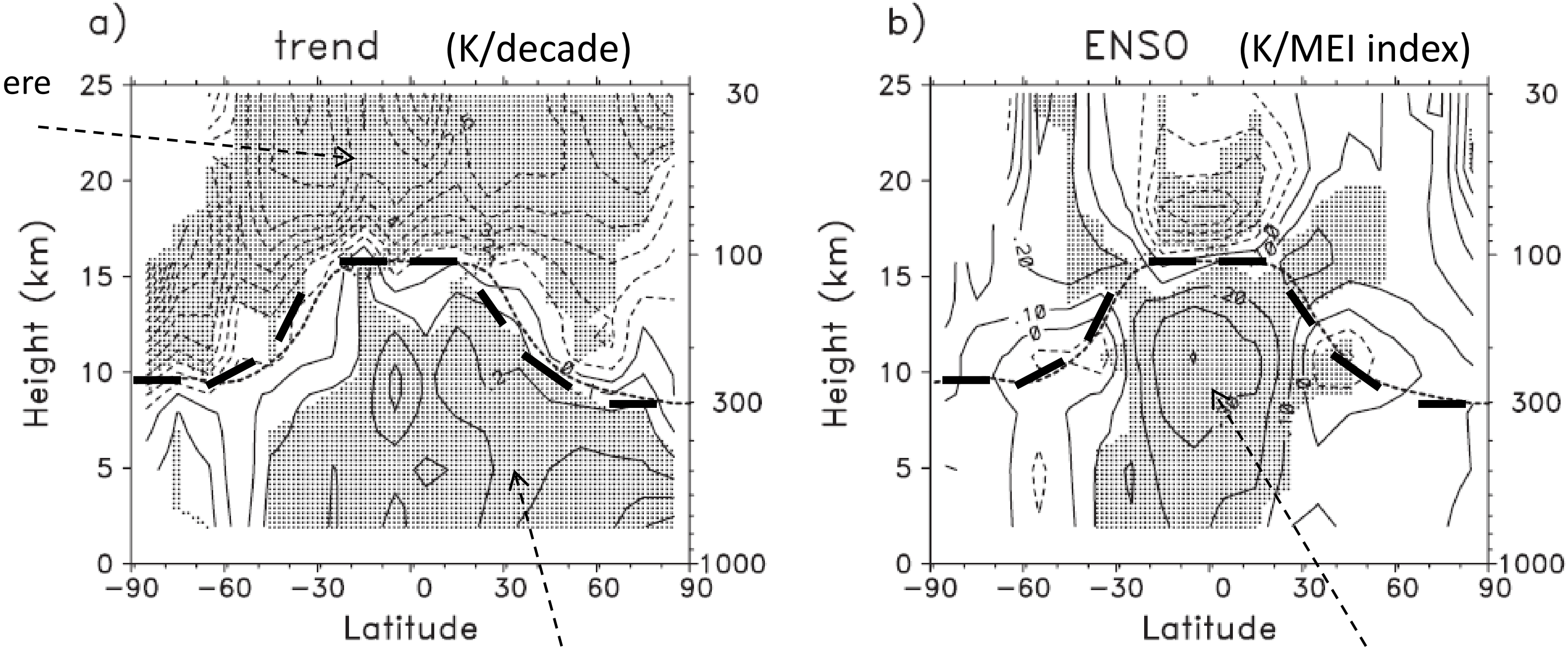


ENSO



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

stratosphere cools



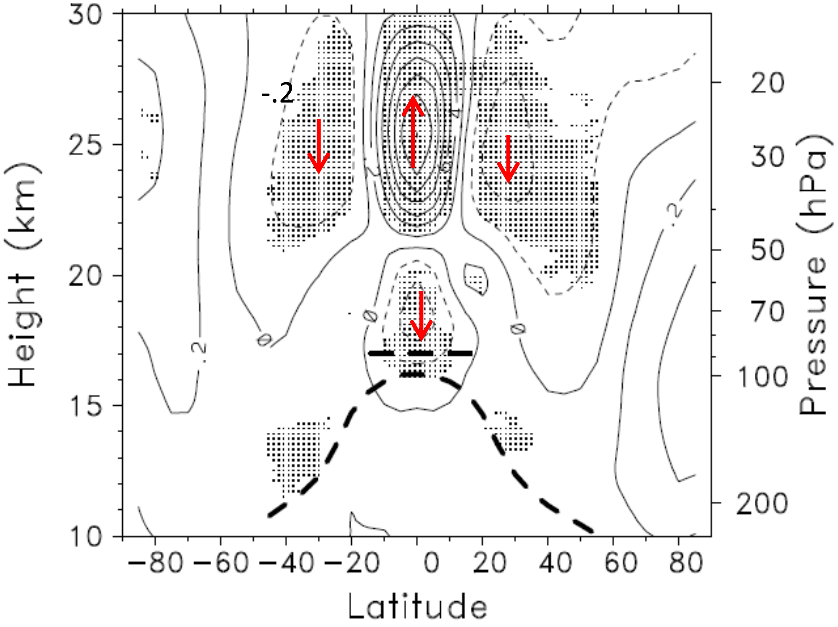
troposphere warms

changes focused
In tropics

Regression fits of QBO using GPS temperatures

there is a corresponding QBO2 pattern (orthogonal to QBO1)

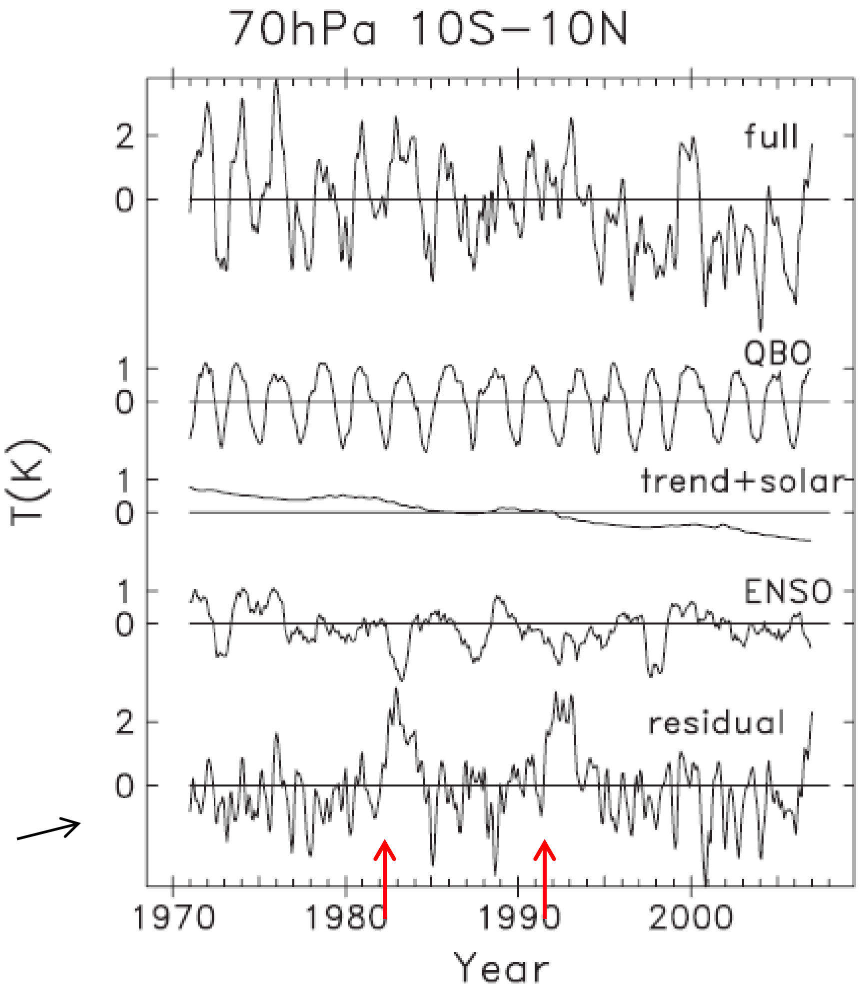
QBO1



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

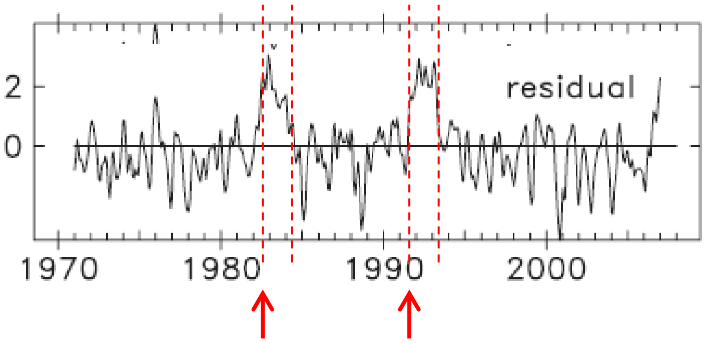
Variability in the tropical lower stratosphere:

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



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

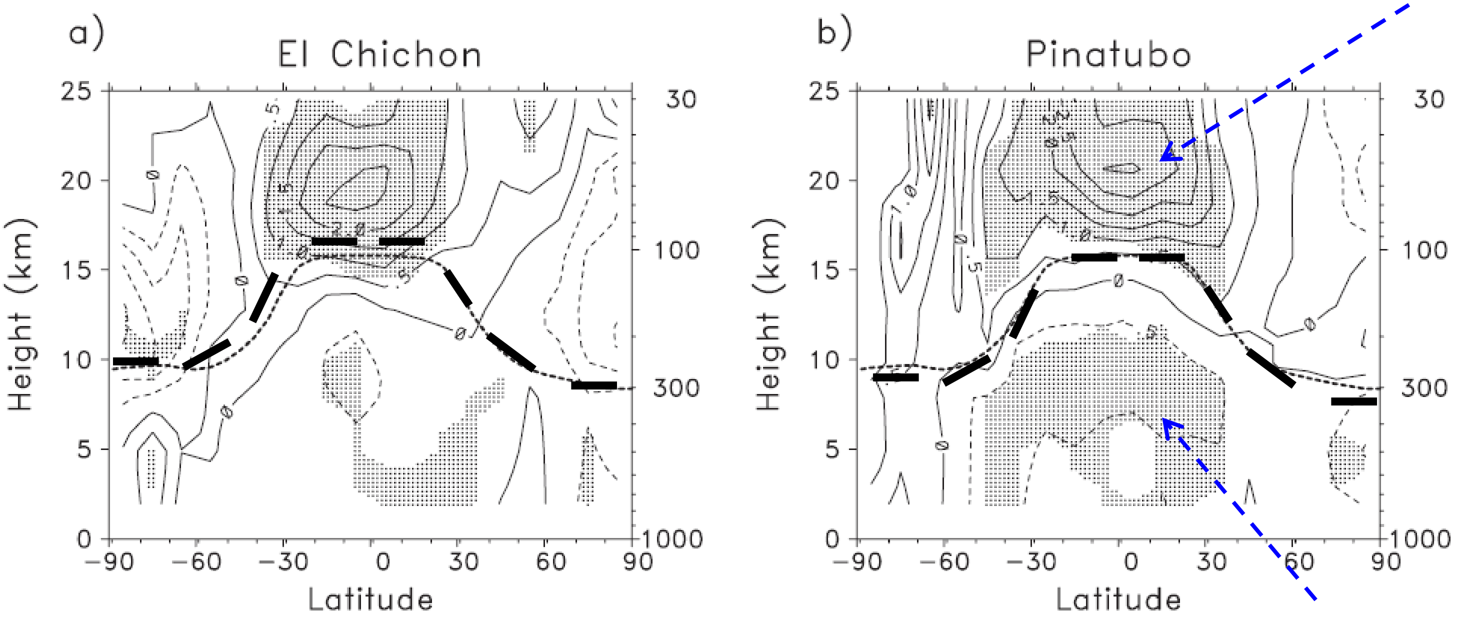
Volcanic signals derived as ‘residuals’ to regression fits



El Chichon

Pinatubo

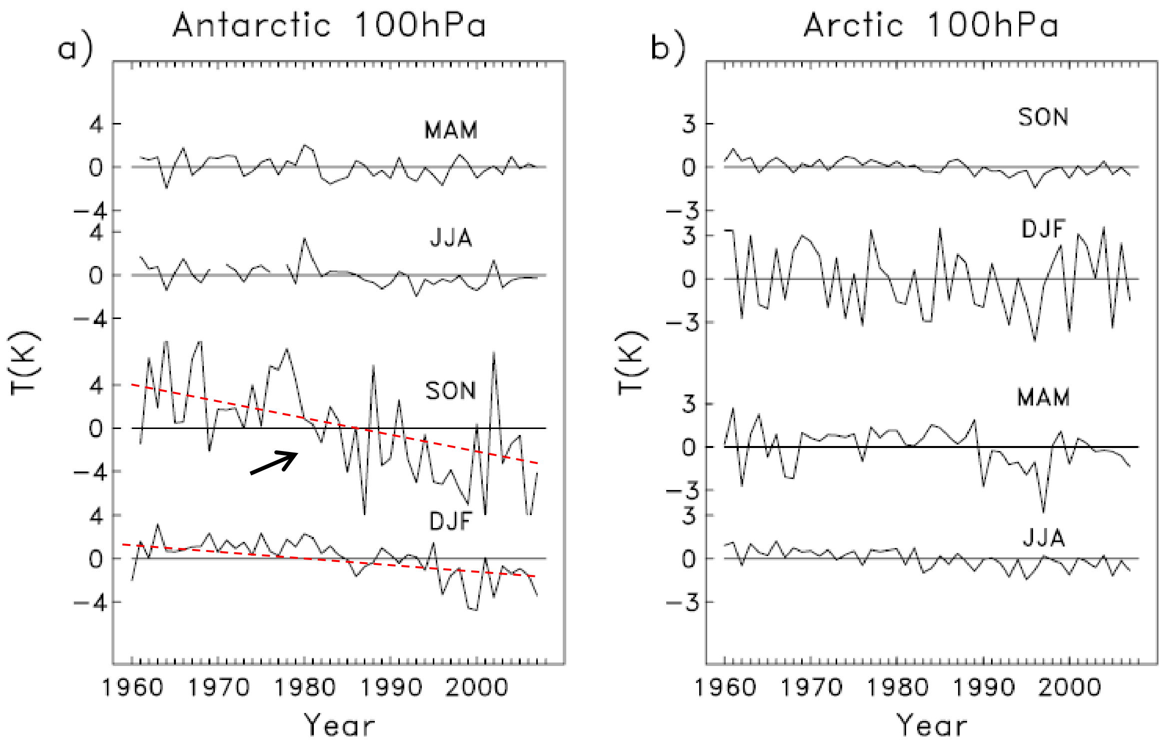
Temperature anomalies for 2 years after volcanic eruptions



Stratosphere warms

Troposphere cools

Polar stratosphere temperatures

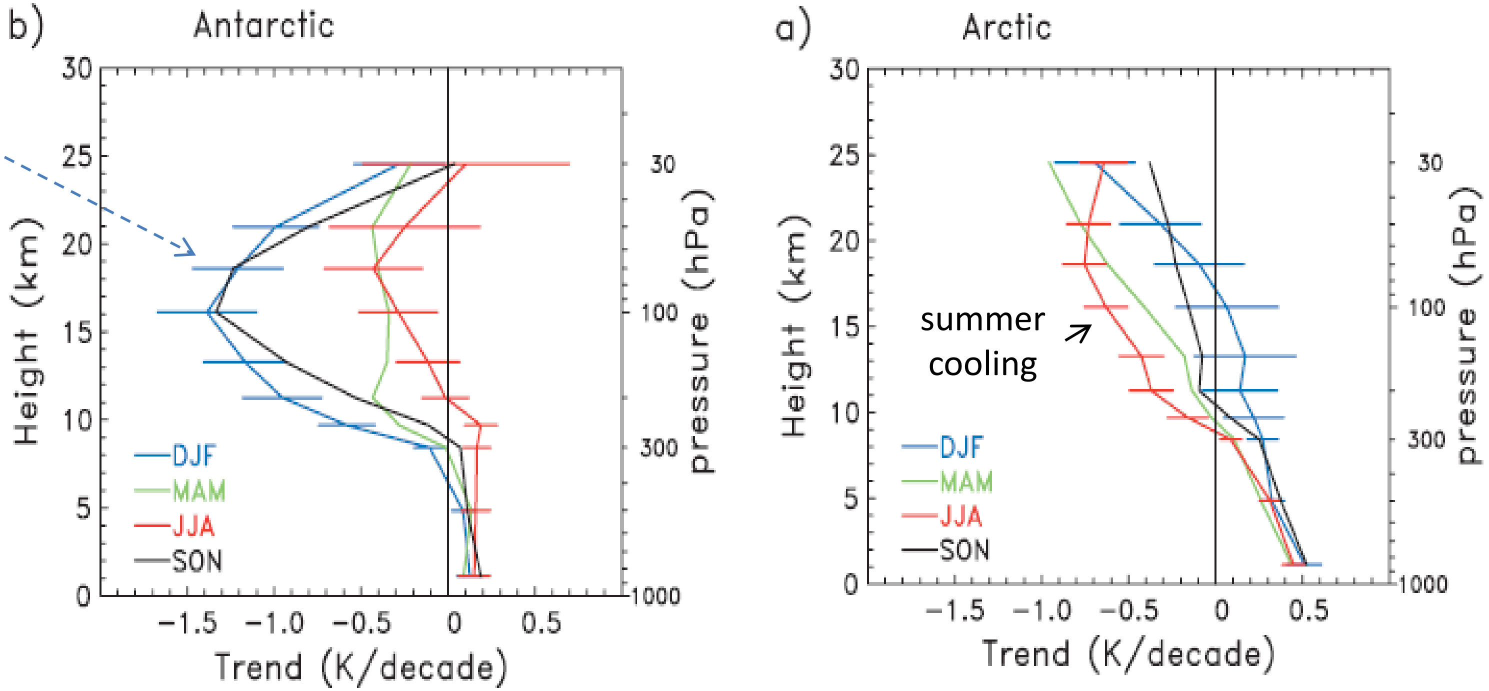


Large 'natural' year-to-year variability during winter

Polar temperature trends: 1970-2010

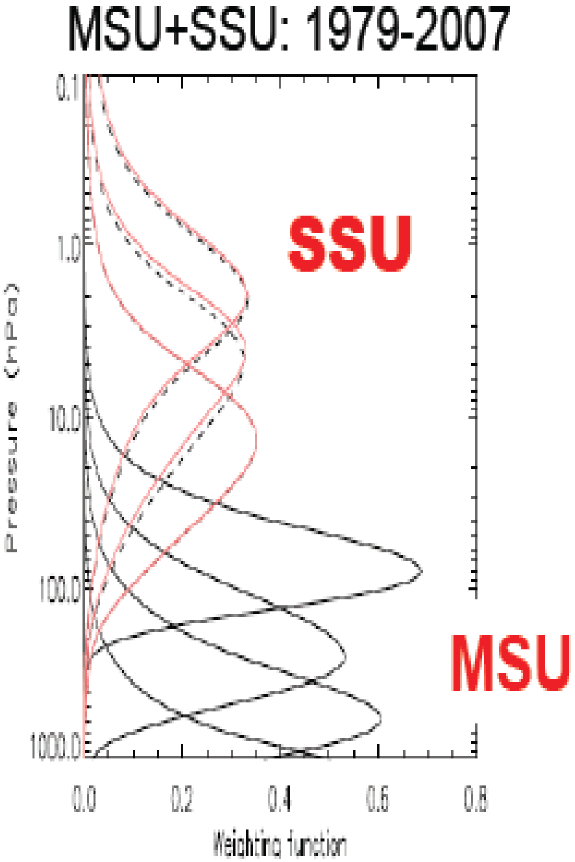
Cooling due to Antarctic ozone hole

spring and summer



summer cooling

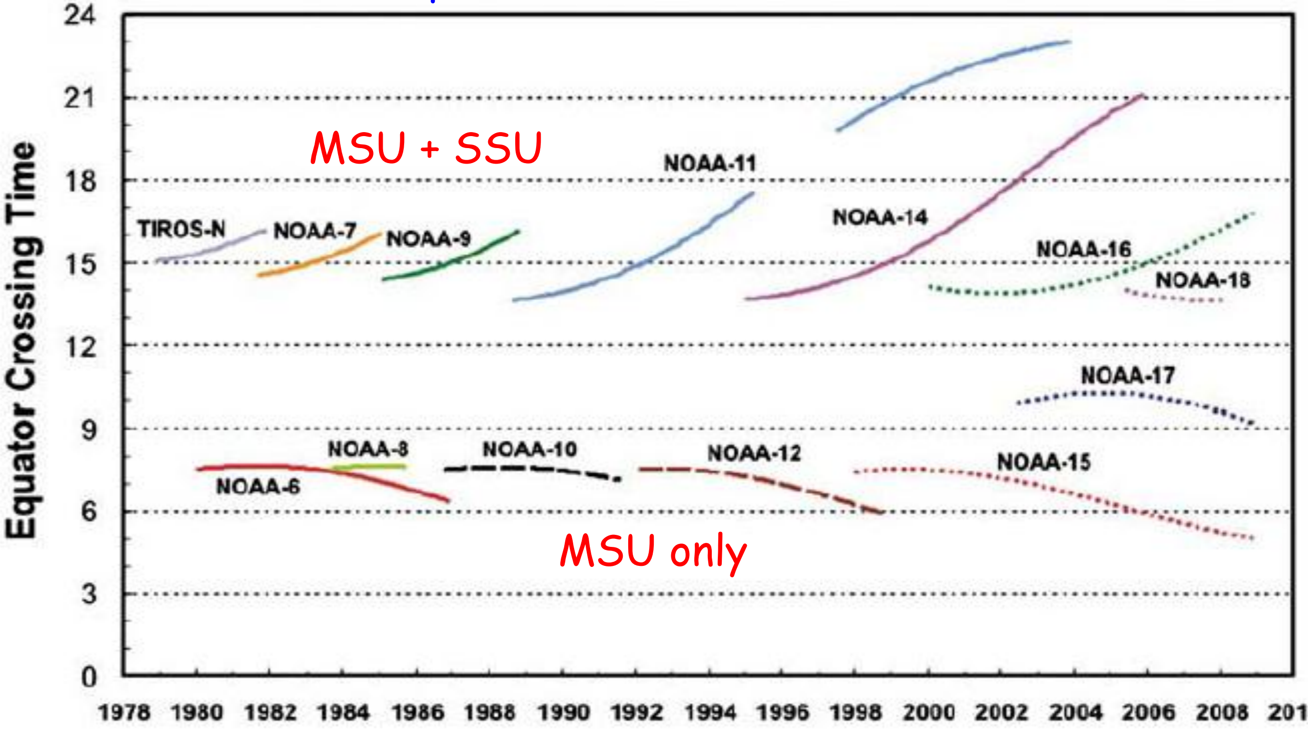
In the middle and upper stratosphere, satellite measurements are the primary data set for variability and trends



- 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



MSU + SSU

MSU only

AMSU
(>1998)

HALOE (>45 km)

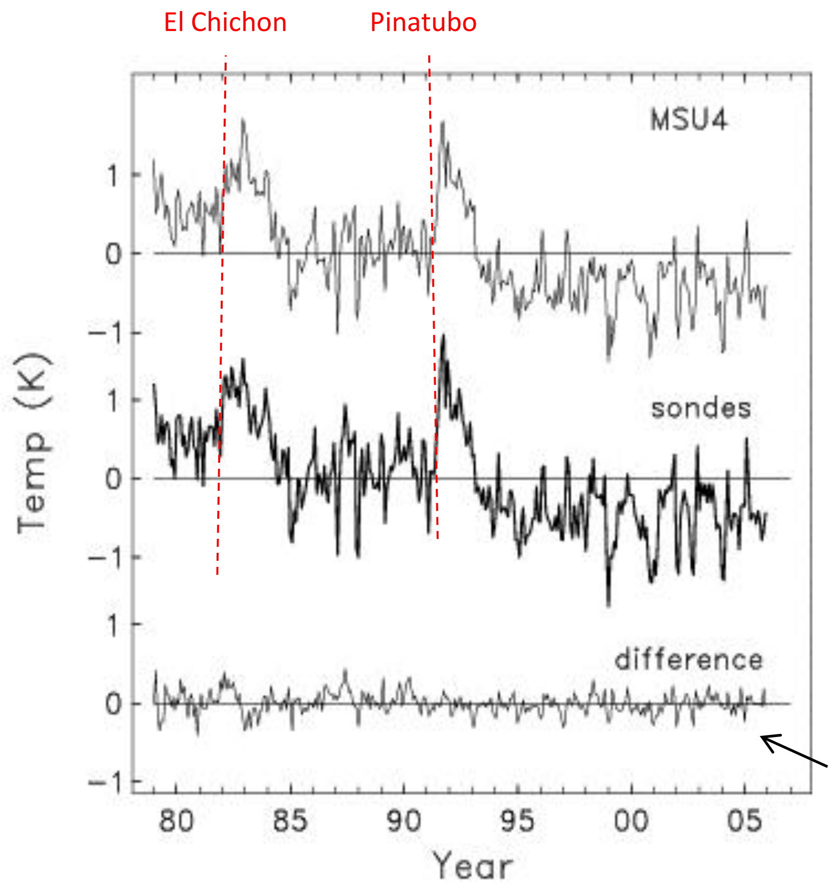
↔

Research satellites:

MIPAS, GOMOS, SABER, MLS

↔

Lower stratosphere temperatures (MSU4) are well characterized



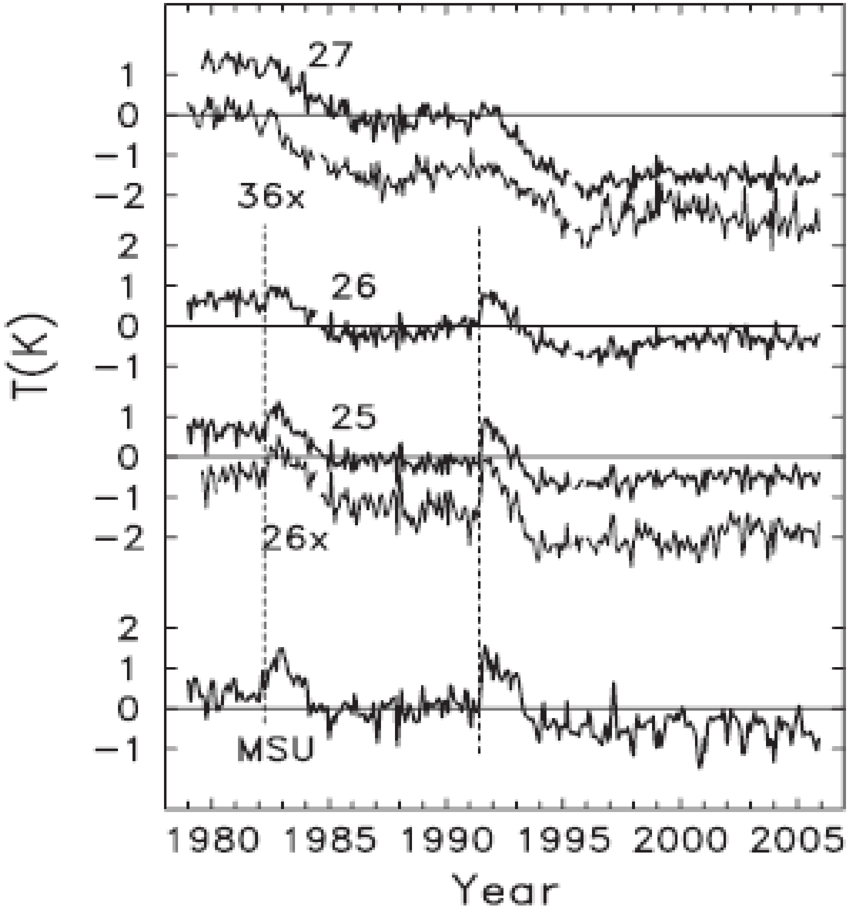
MSU4 satellite

Radiosondes, using
RATPAC-lite stations

excellent
agreement

Middle-upper stratosphere temperatures from SSU

Constructed by
John Nash
from UK Met Office



SSU3 40-50 km

SSU2 35-45 km

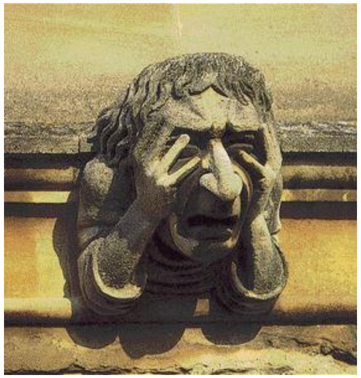
SSU1 25-35 km

MSU4 13-22 km

But:

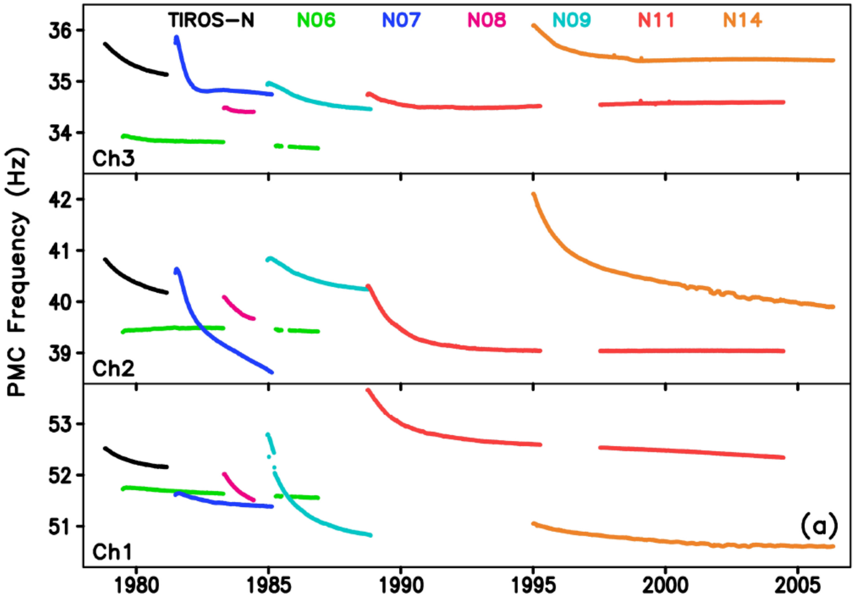
- Construction details not well understood
- No independent analyses of SSU data

SSU Data Issues

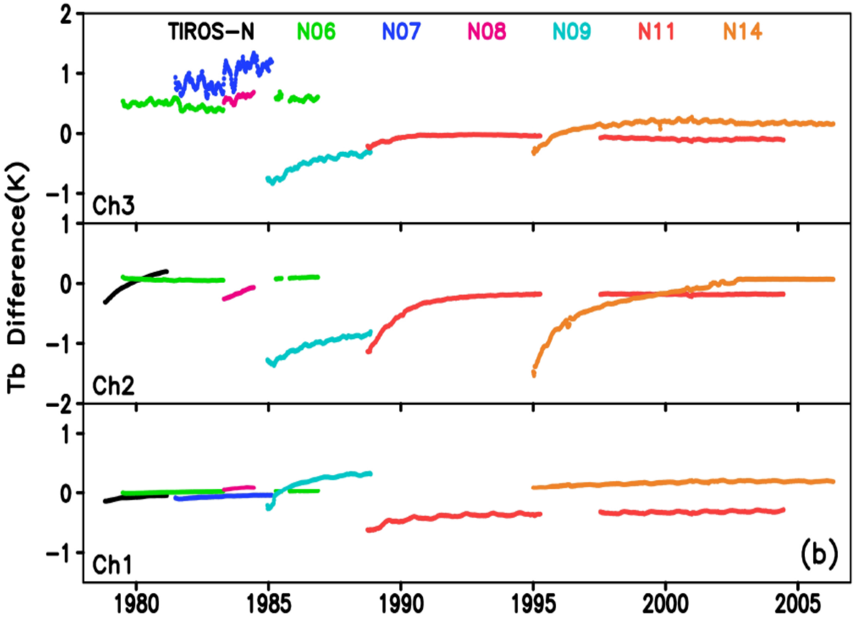


- instrument CO_2 leaking problem
- atmospheric CO_2 variations
- limb-effect
- diurnal drift effect (drifting satellite orbits)
- inter-satellite biases
- No instruments on NOAA-10 and NOAA-12

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

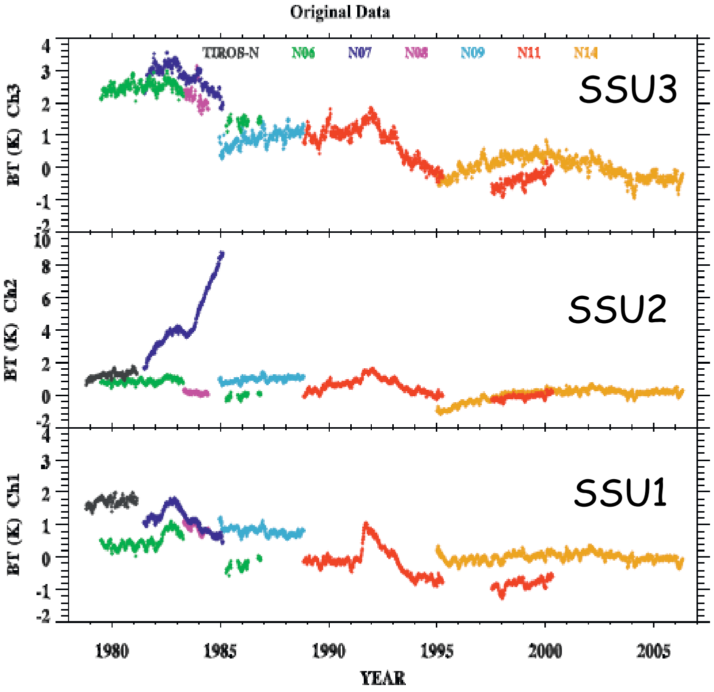
LIKUN WANG
Dell Services Federal Government, Fairfax, Virginia

CHENG-ZHI ZOU
NOAA/NESDIS/STAR, Camp Springs, Maryland

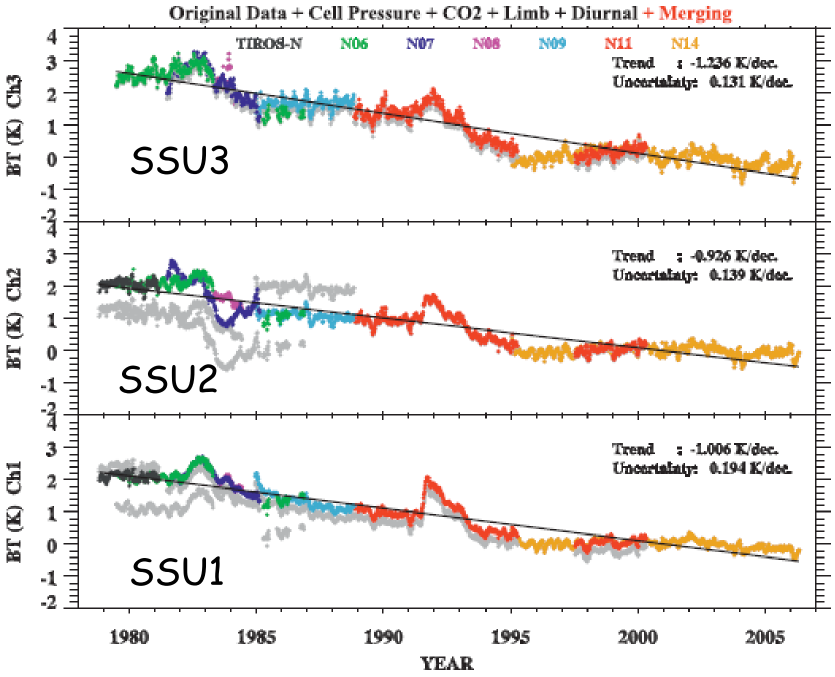
J. Climate 2012

NOAA version 1

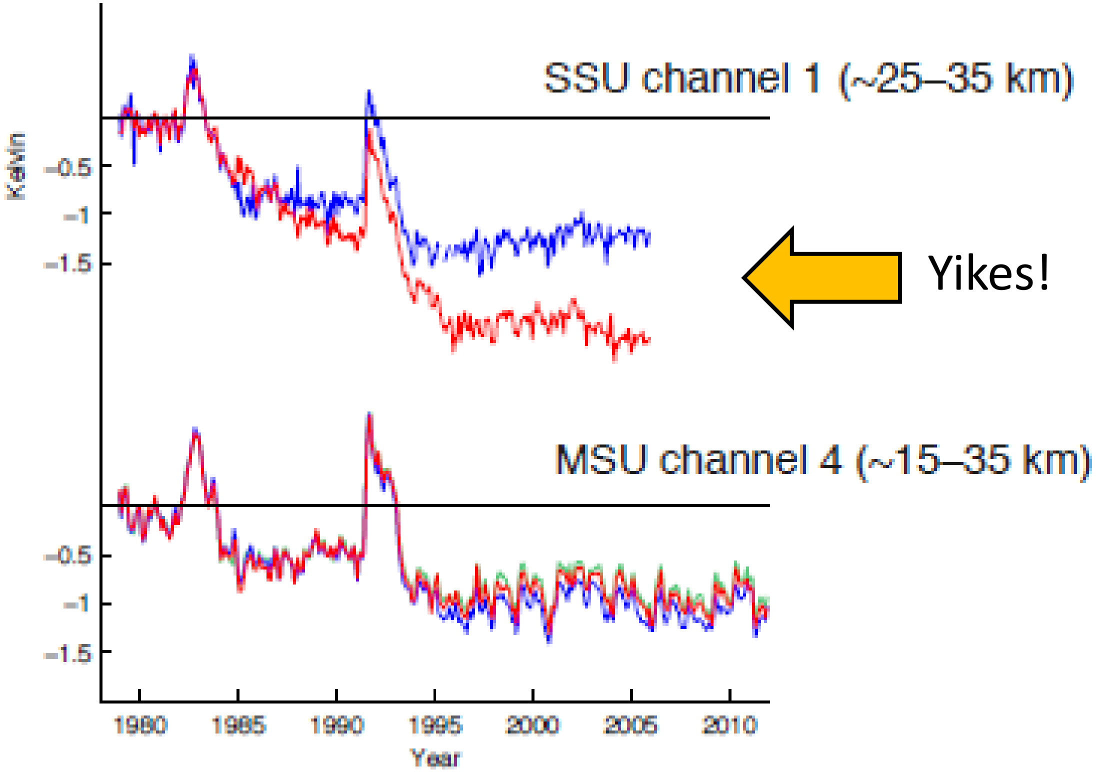
original data



adjusted and merged data



Global-average Stratospheric Temperature



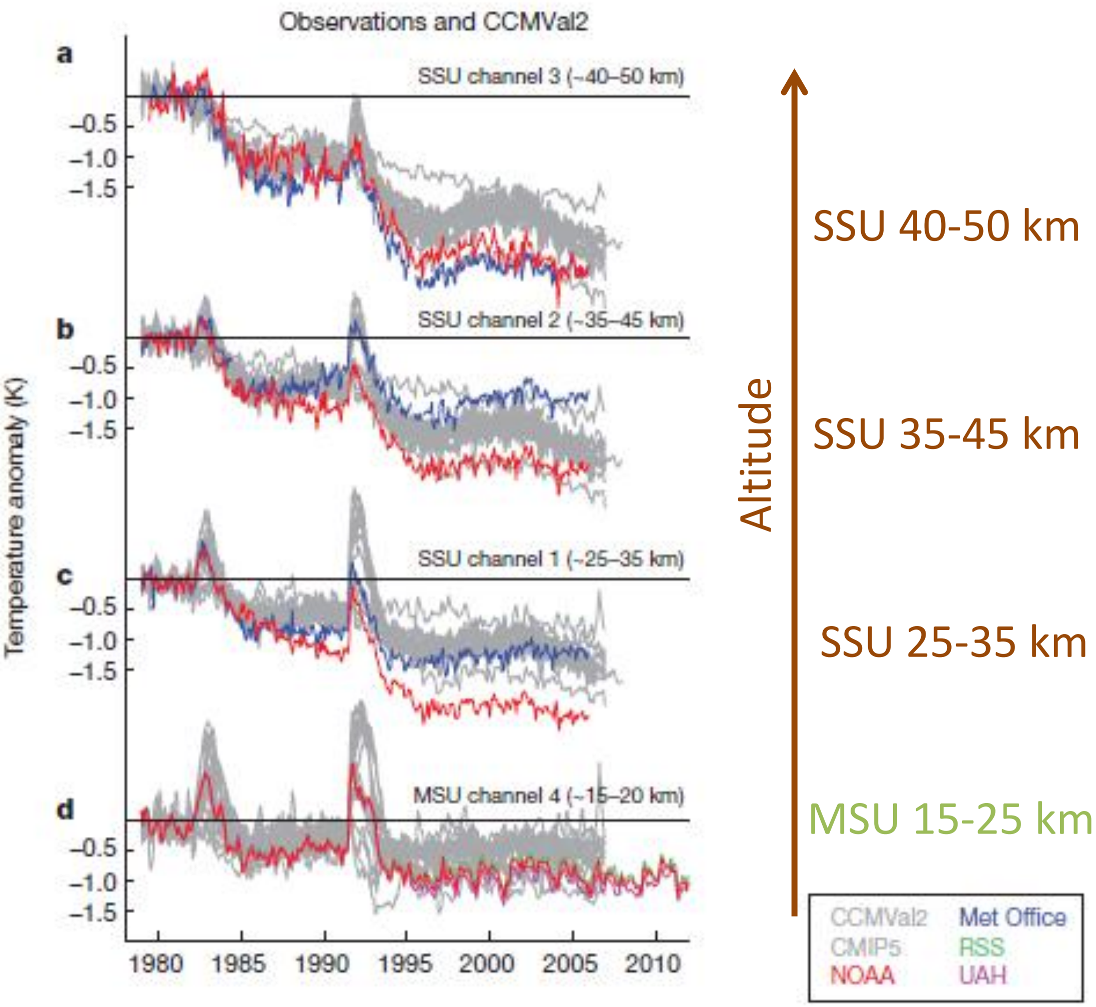
Met Office SSU Data
NOAA SSU Data

Yikes!

RSS MSU Data
NOAA MSU Data
UAH MSU Data

Thompson et al 2012

Comparisons with chemistry-climate models



Altitude

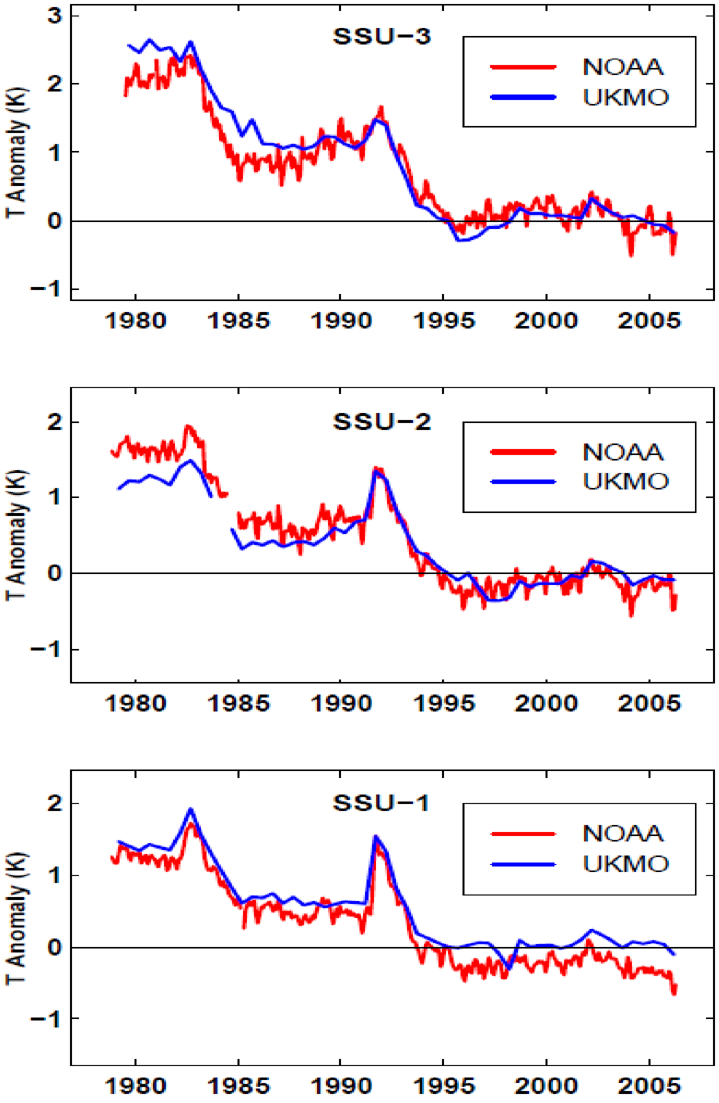
SSU 40-50 km

SSU 35-45 km

SSU 25-35 km

MSU 15-25 km

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



NOAA version 2

UKMO version 2

Zou et al 2014

Nash and Saunders 2015

Some important points:

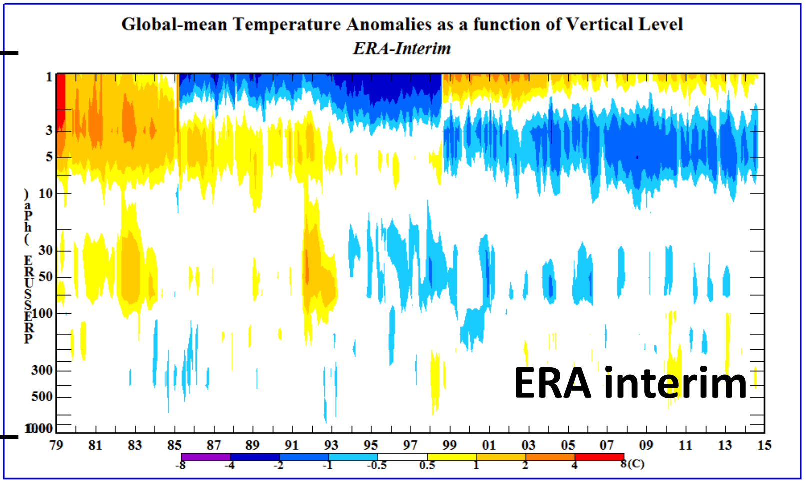
- Radiosondes and satellites primarily intended for weather forecasting, not climate monitoring. This is changing with GRUAN.
- Historical radiosonde data have artificial cooling biases, but these have been corrected using different techniques
- Long-term temperature changes are small, and correcting/merging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

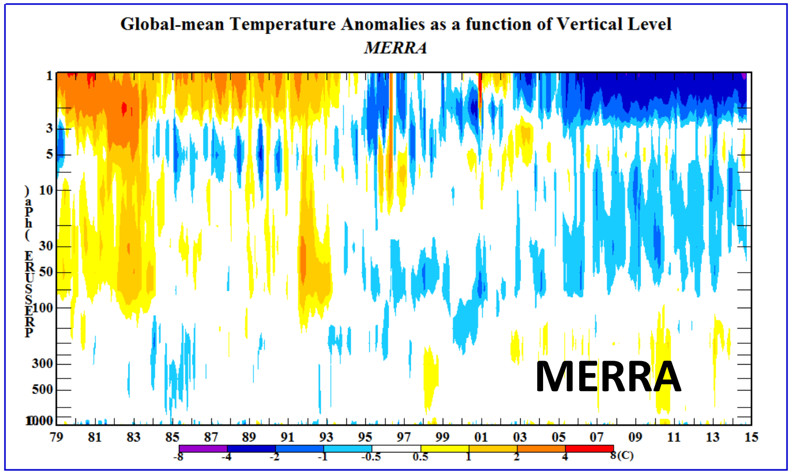
Global temperature anomalies from reanalyses

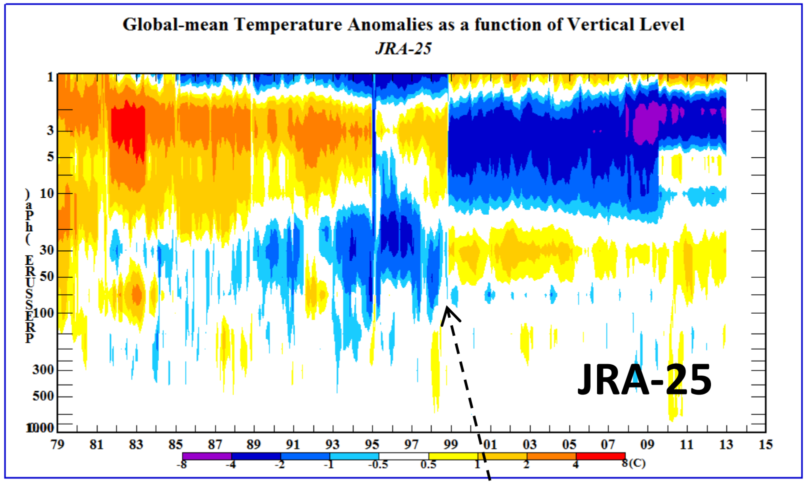
older generation

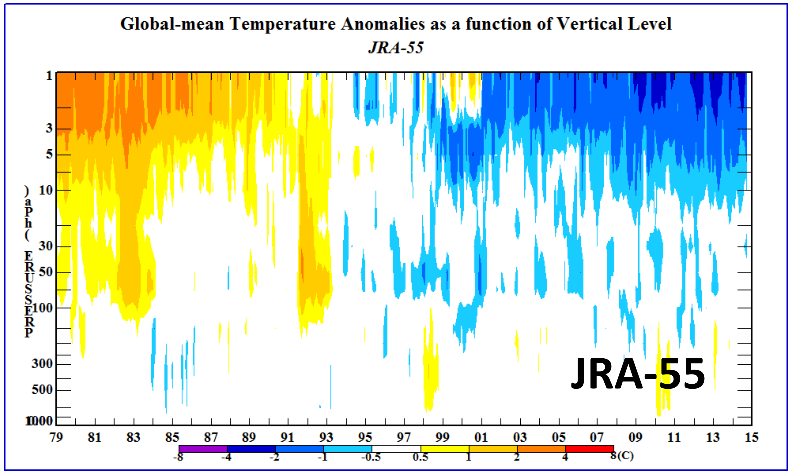
newer generation

0-50 km



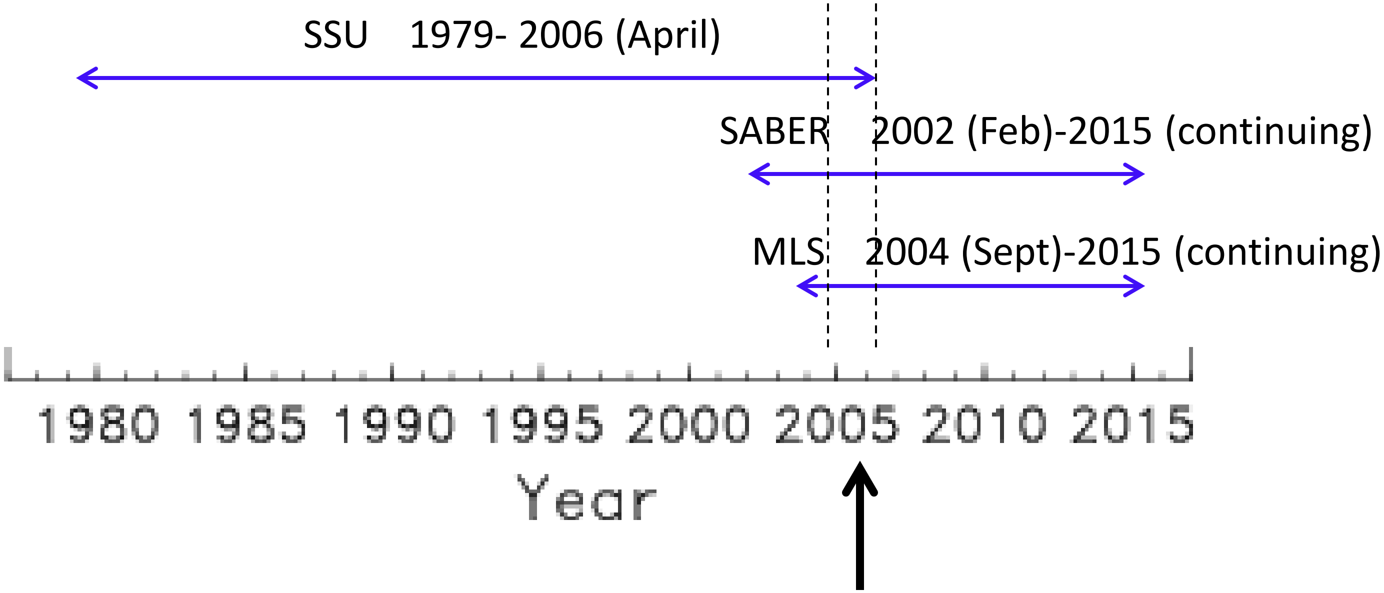






jumps due to satellite changes

Newest results: extend NOAA v2 SSU data record with SABER and MLS observations



SSU 1979- 2006 (April)

SABER 2002 (Feb)-2015 (continuing)

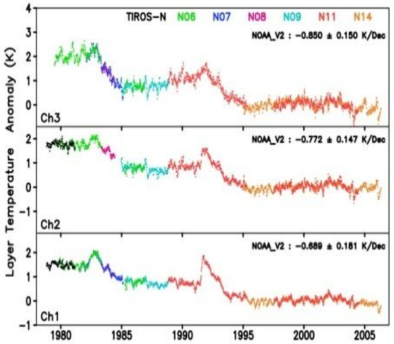
MLS 2004 (Sept)-2015 (continuing)

direct overlap for
Sept 2004 – April 2006

Data details:

SSU: NOAA v2 (Zhou et al, 2014, JGR)

Nadir viewing CO_2 emission radiometers
Recalibrated and merged NOAA operational data



SABER

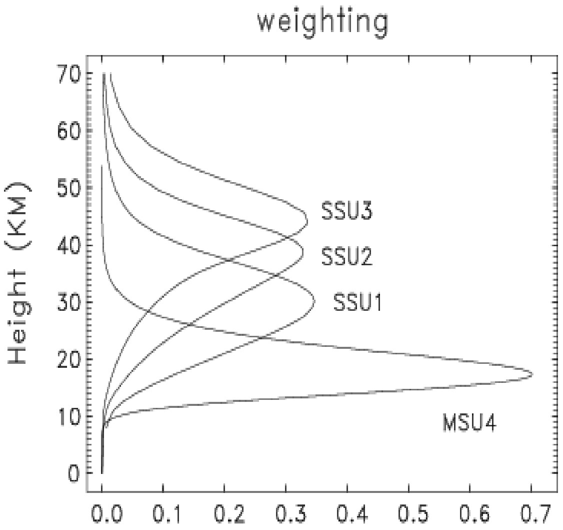
- Limb emission viewing geometry
- Broadband radiometry, T(p) derived from CO_2 emissions
- Coverage: 50° S – 80° N / 80° S – 50° N (60-day yaw cycles)
- Altitudes ~20-100 km; Vertical resolution ~2 km

Aura MLS

- Limb emission viewing geometry
- T(p) derived from O_2 microwave emissions
- Near-global coverage (82° N-S) on a daily basis
- Altitudes ~10-90 km; Vertical resolution ~3-4 km

Data analysis details:

1) Construct SSU-equivalent layer temperatures
from SABER and MLS



2) Deseasonalize each data set using:

2002-2006 for SSU
2004-2008 for SABER
2004-2008 for MLS

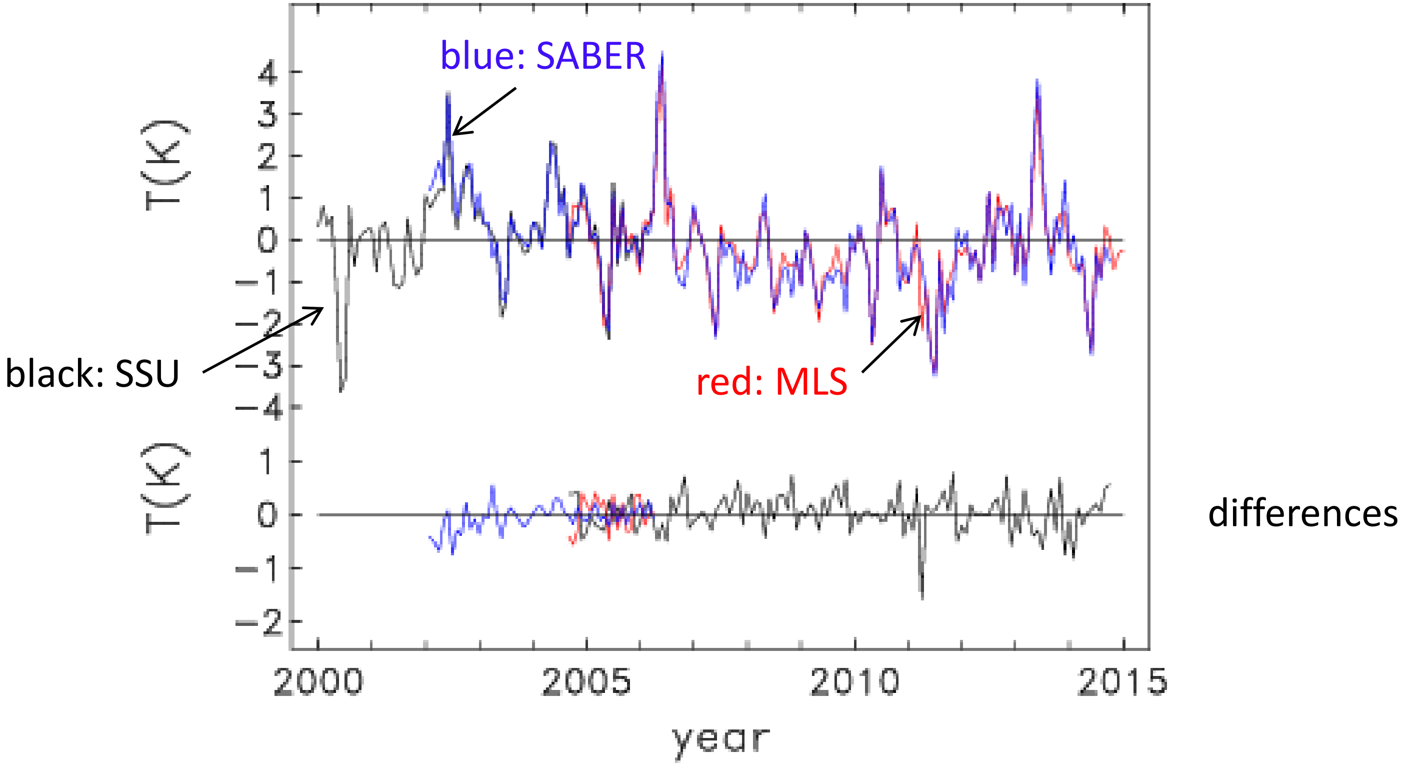
3) Normalize all anomalies to zero for the overlap
period: Sept. 2004 – April 2006

4) Regression fits using standard multivariate model: (Jan 1979 – Oct. 2014)

linear trend, solar cycle, ENSO, QBO (2 orthogonal terms)
+ volcanic periods omitted from fits (volcanic effects as residuals)

comparison of deseasonalized anomalies:

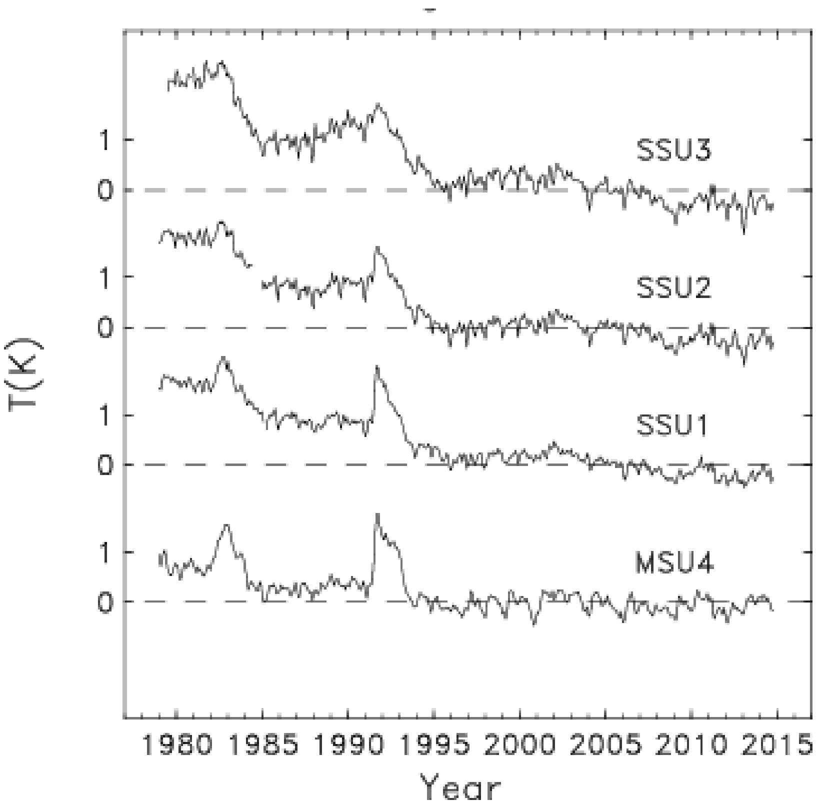
SSU channel 3 40° S


blue: SABER

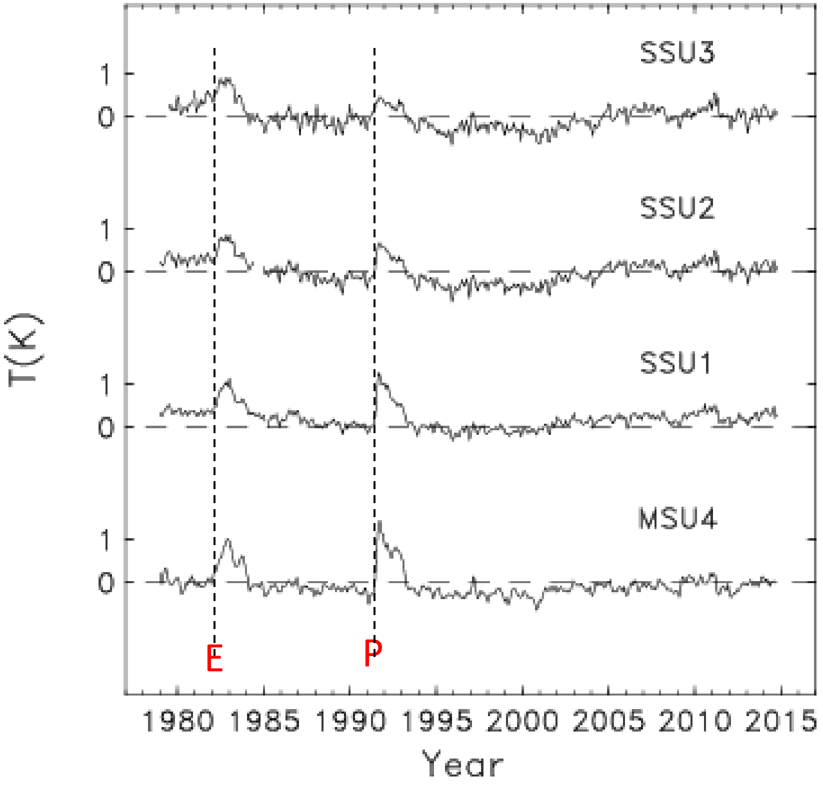
black: SSU

red: MLS

differences

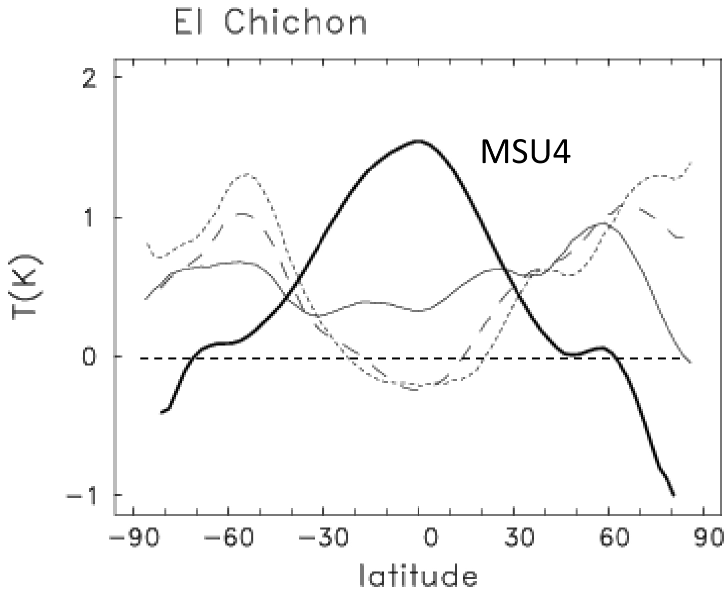


global average anomalies

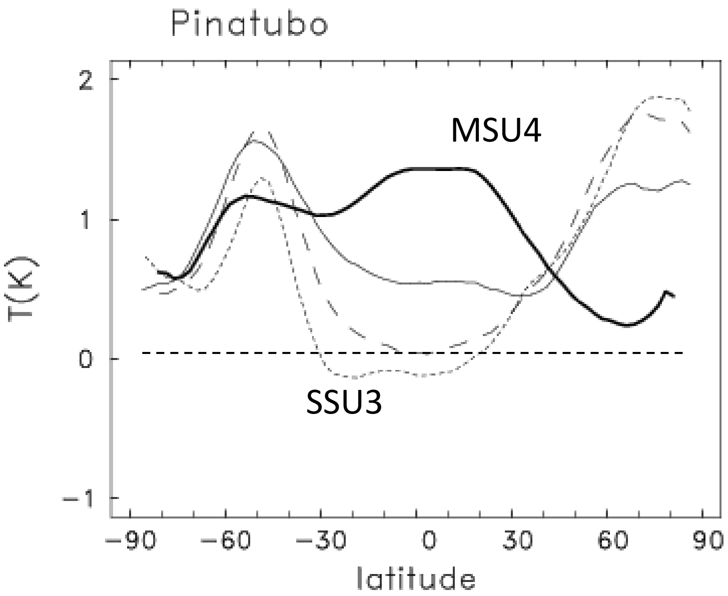


residuals from regression

Volcanic signals derived from residuals (avg. of first year after eruption)

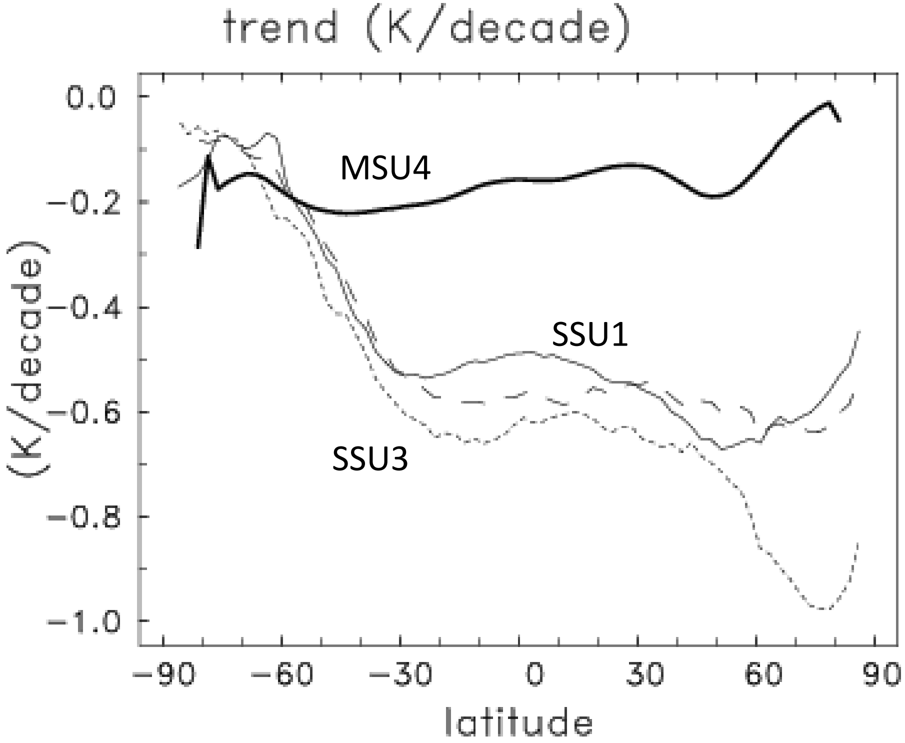


El Chichon



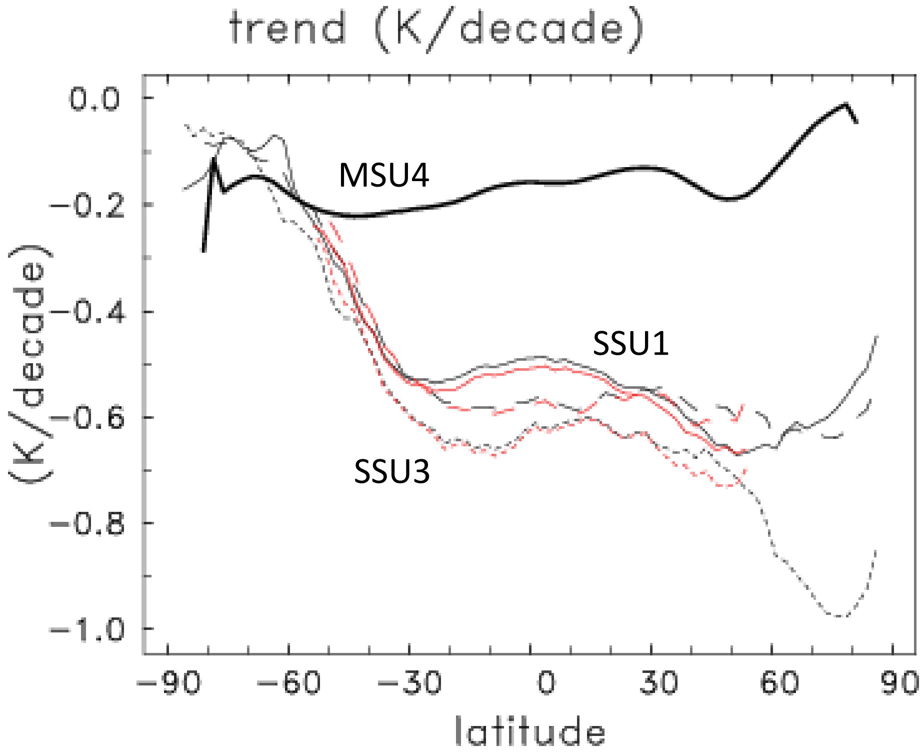
Pinatubo

trends vs. latitude (linear trends for 1979-2015):



nearly identical results using MLS and SABER:

1979-2015



black: SSU + MLS

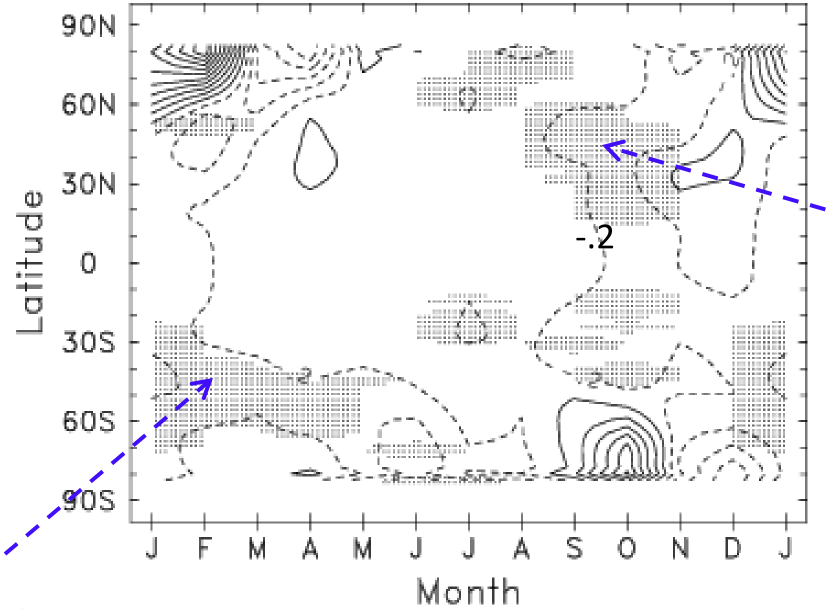
red: SSU + SABER

monthly-varying trends

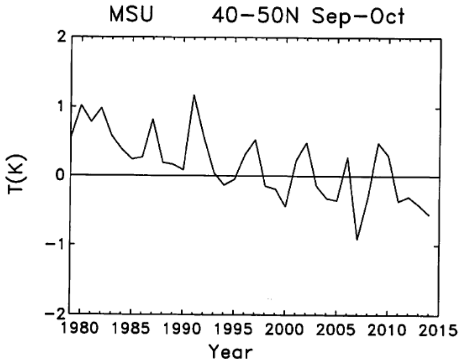
shading = statistically significant

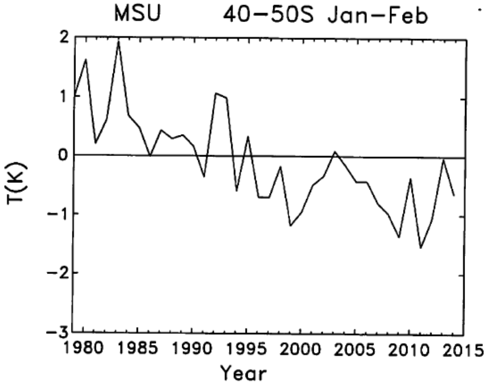
(K/decade)

MSU4

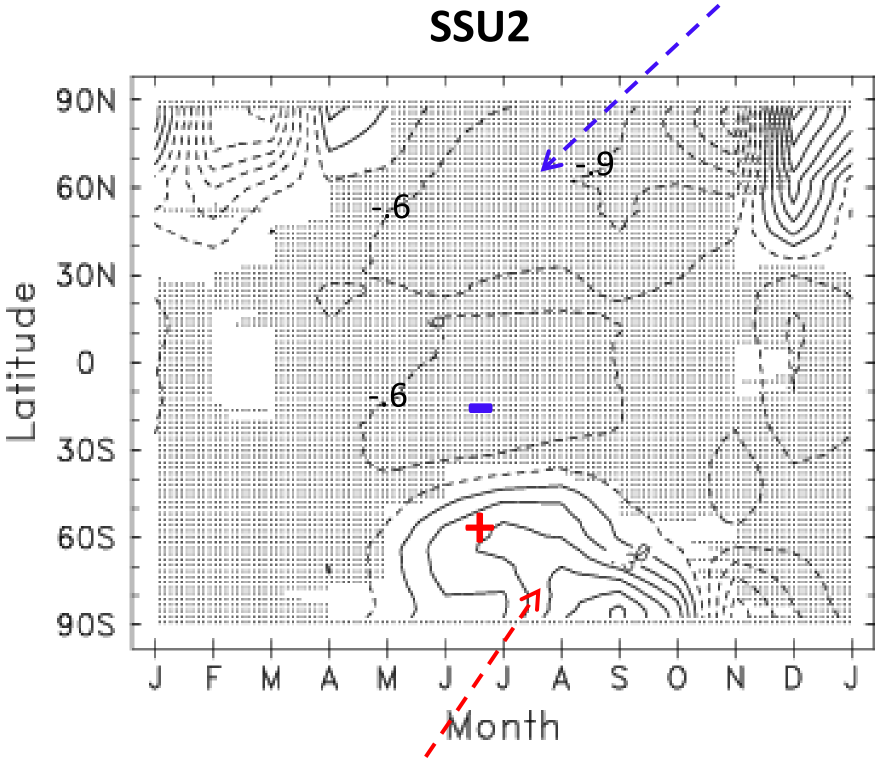


cooling in summer
middle-high
latitudes





upper stratosphere:

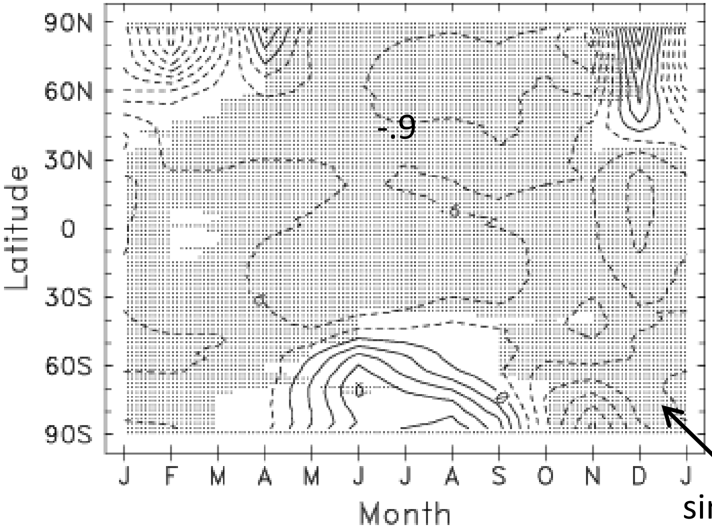


strong cooling in NH summer

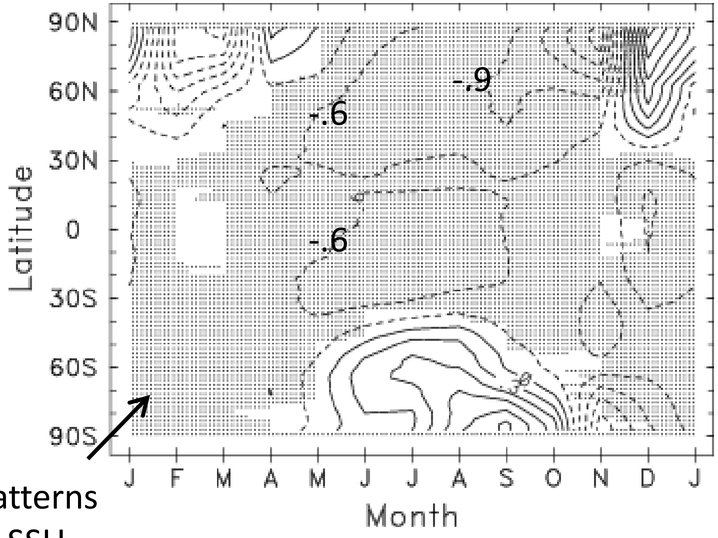
warming in Austral winter

trends in K/decade

SSU3

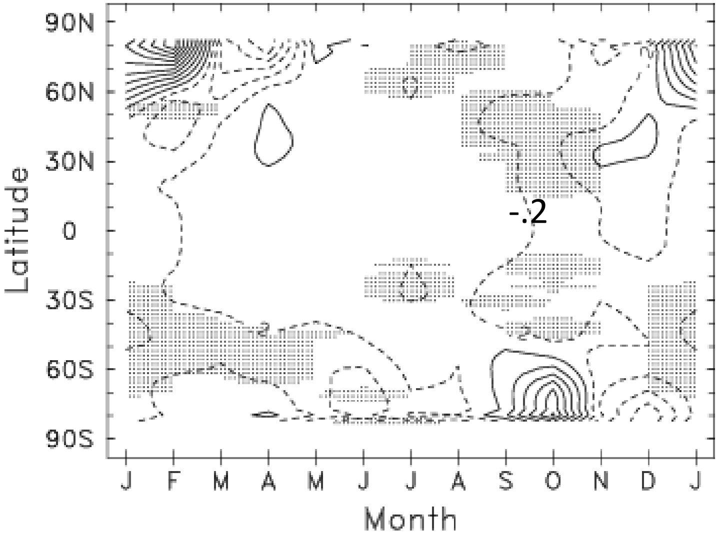


SSU2

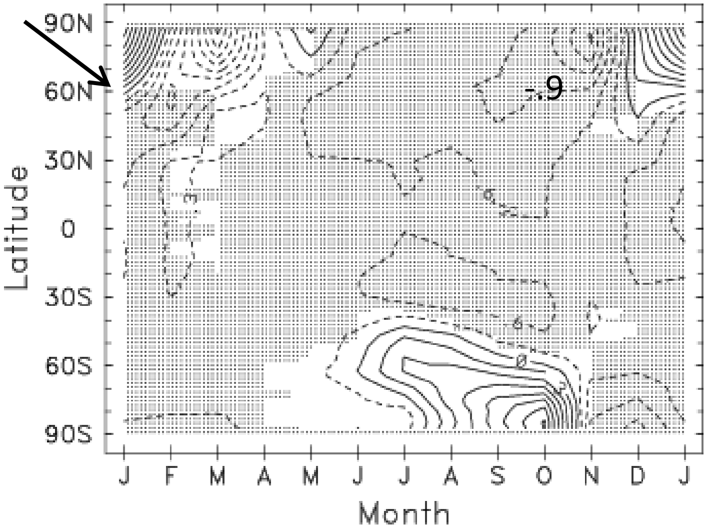


similar patterns
for al 3 SSU
channels

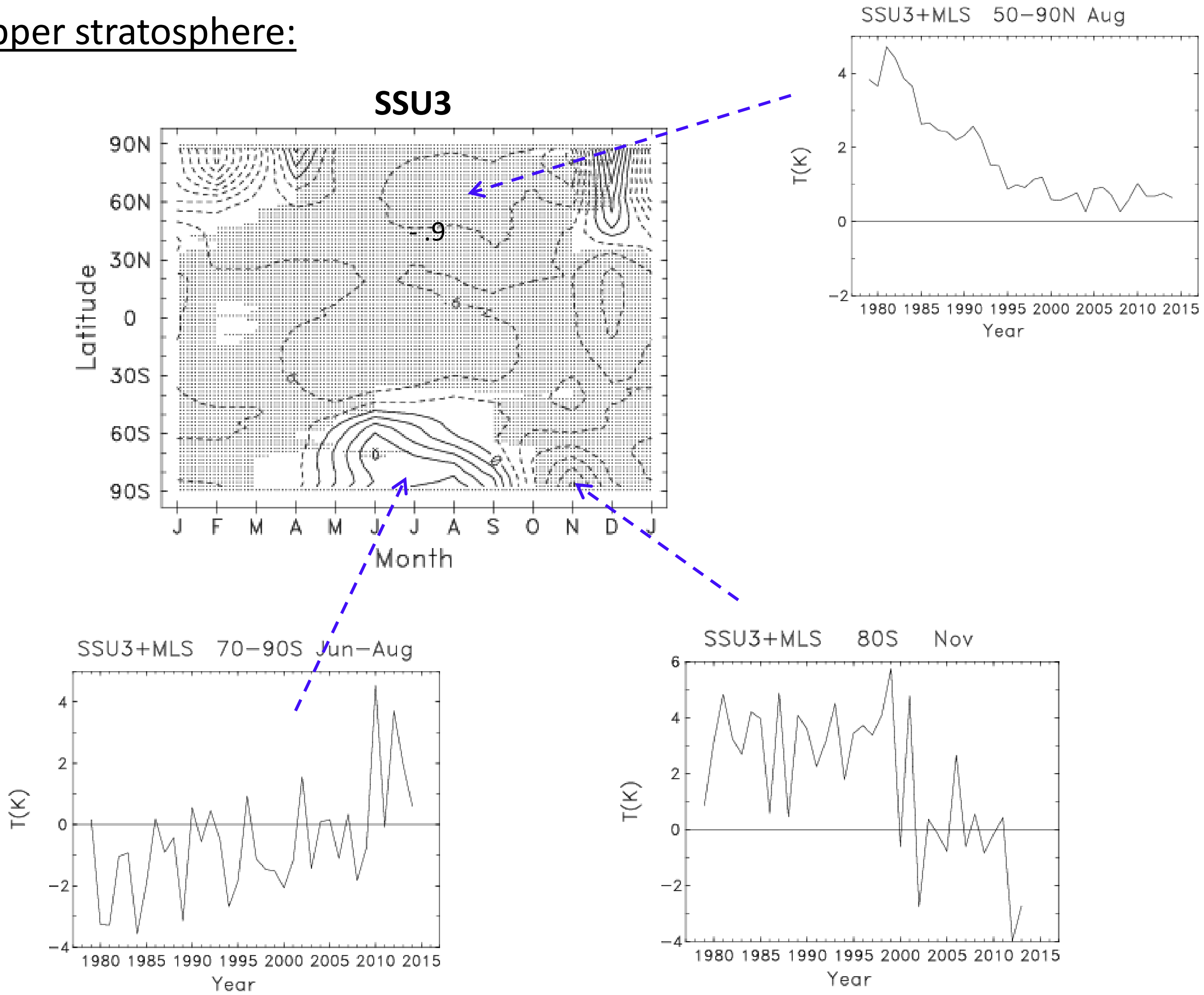
MSU4



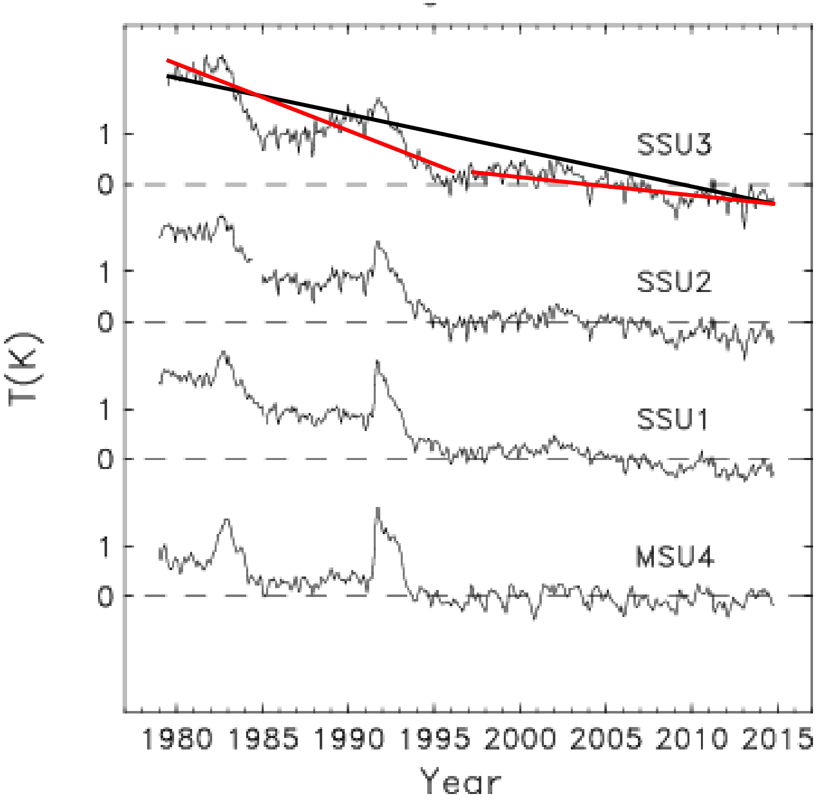
SSU1



upper stratosphere:

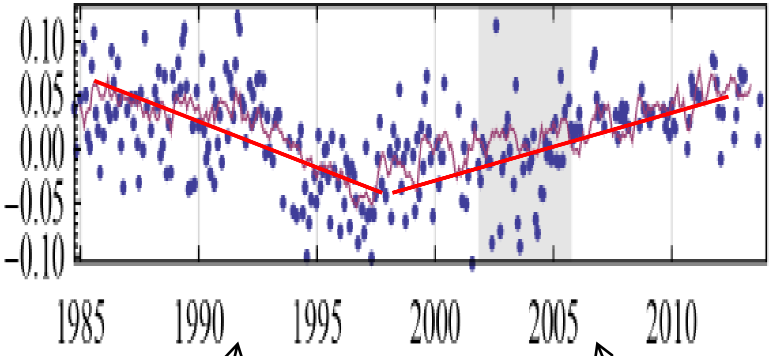


changing temperature trends in the upper stratosphere in response to ozone



observed ozone in upper stratosphere

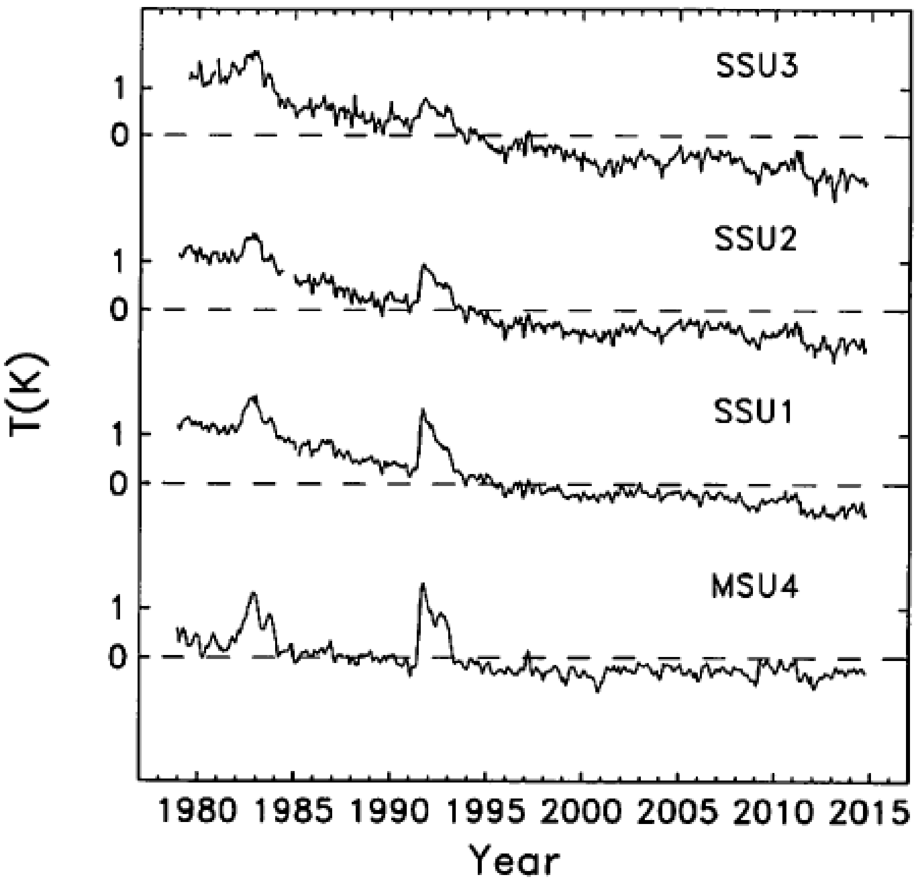
Bourassa et al 2014



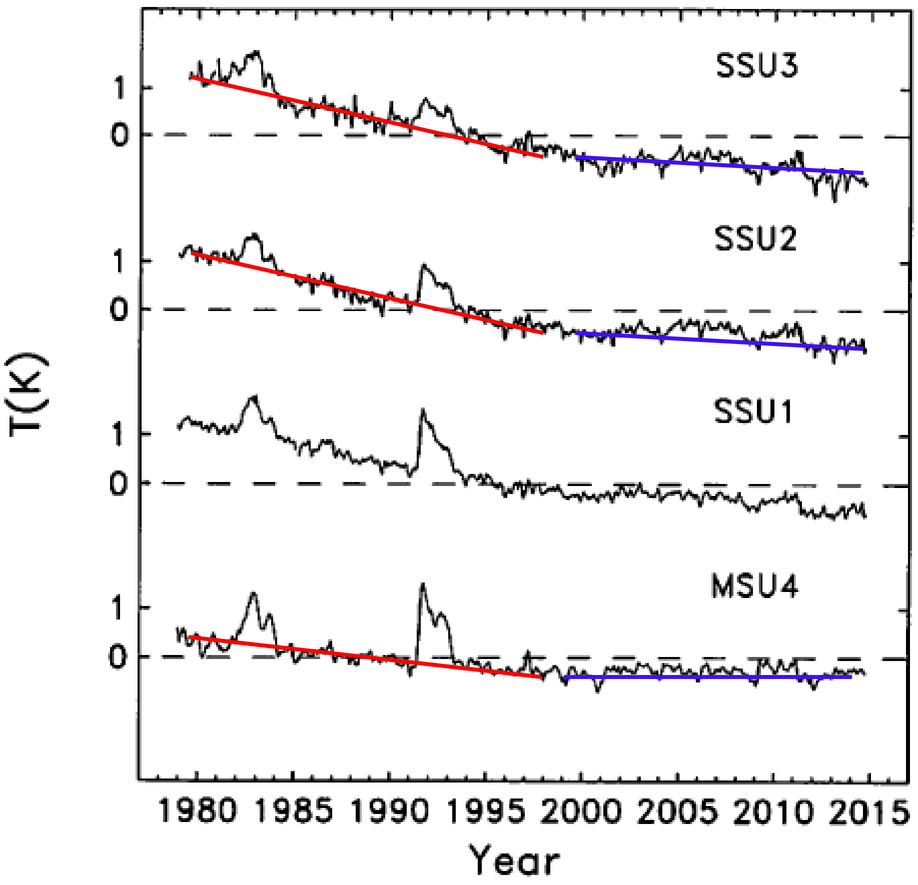
decrease
pre-1995

increase
post-1995

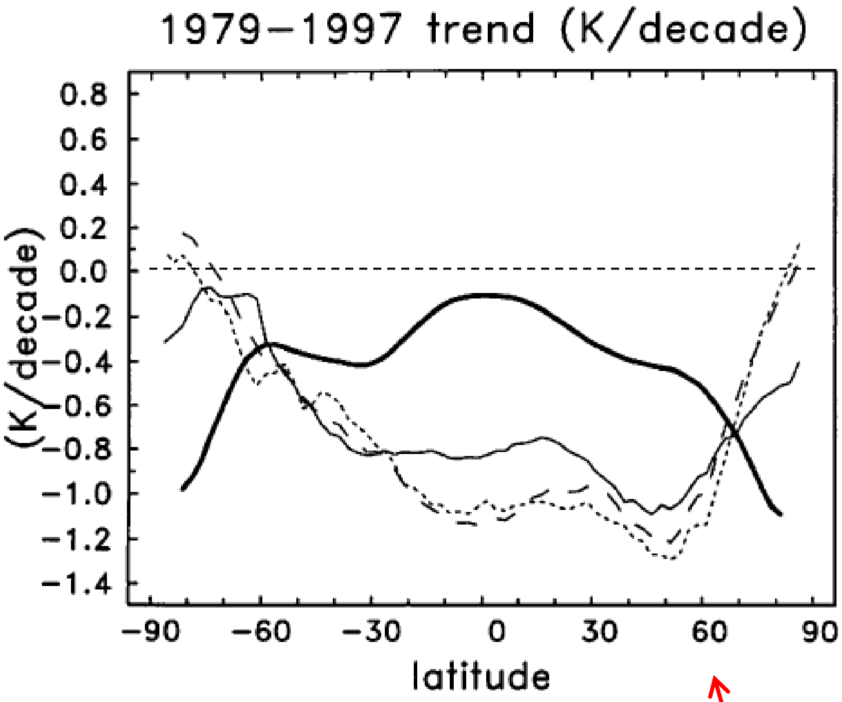
Global anomalies after removing solar, QBO and ENSO

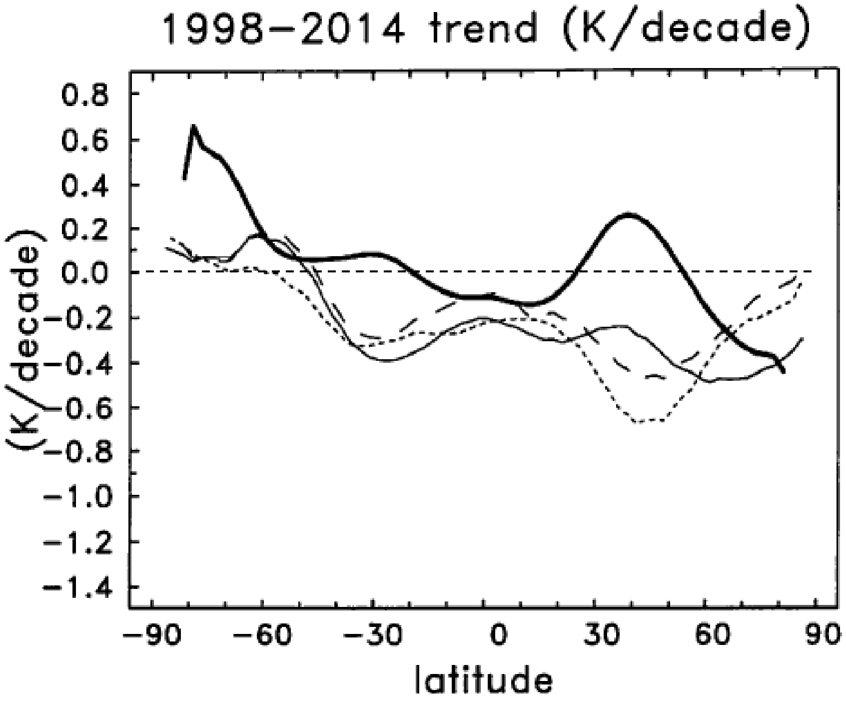


Global anomalies after removing solar, QBO and ENSO



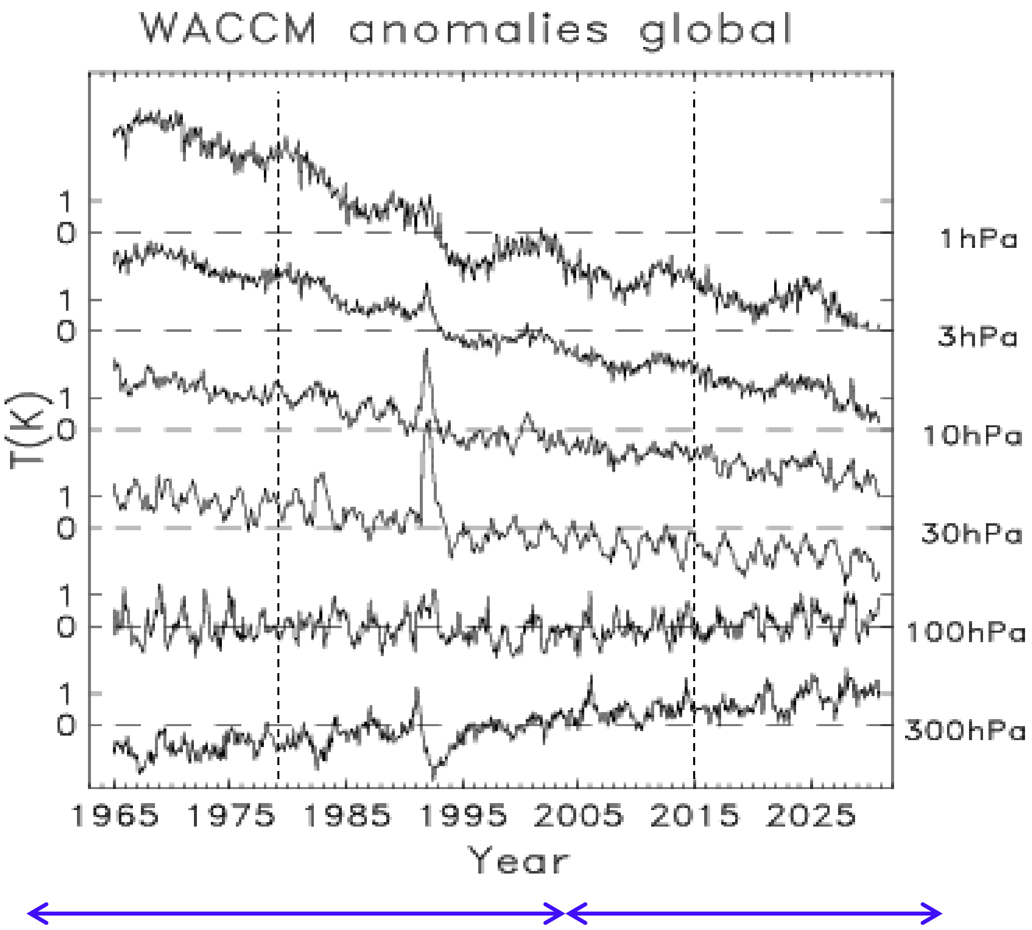
trends before and after 1997





much stronger cooling trends for 1979-1997

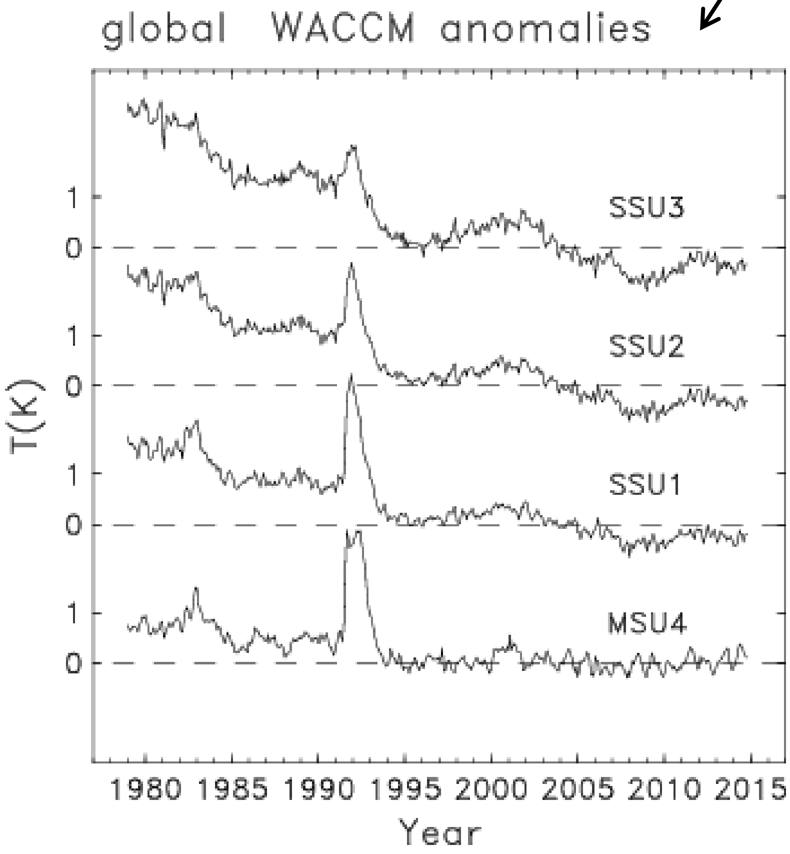
Comparisons with WACCM simulation



CMIP5

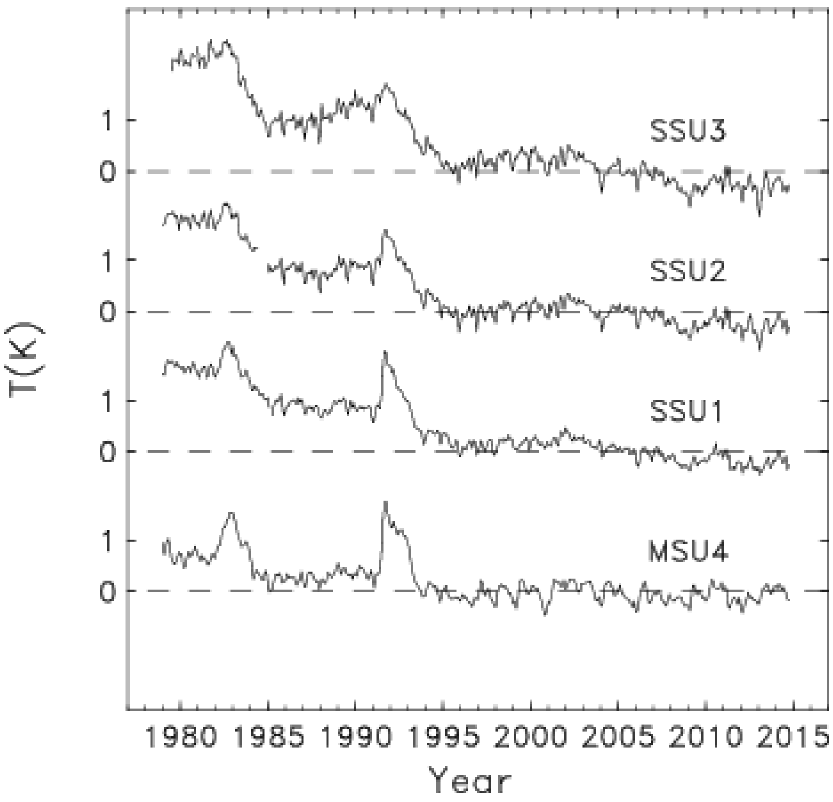
RCP6.0

WACCM



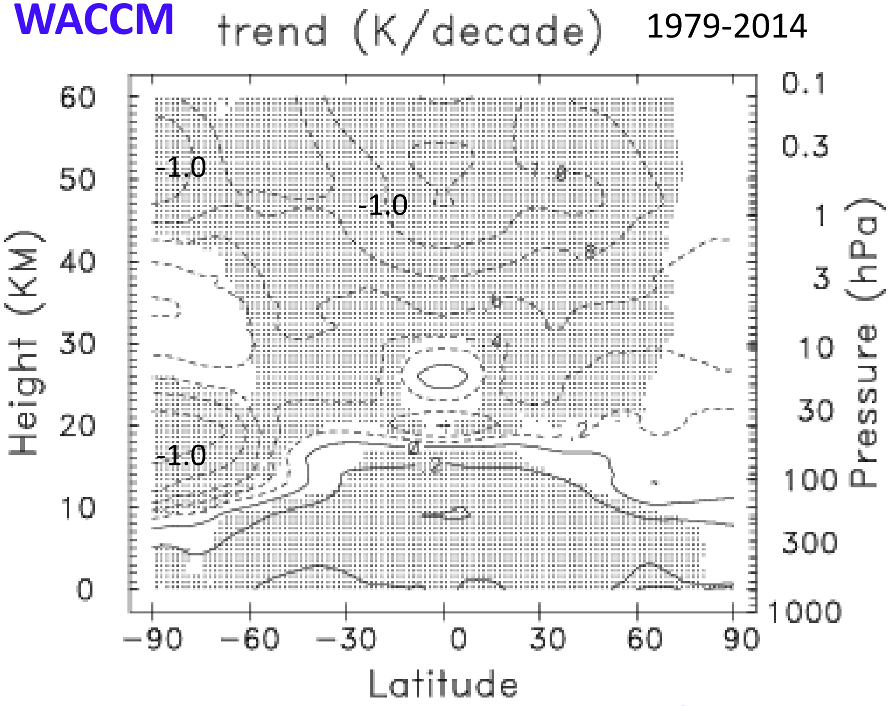
WACCM sampled like SSU, MSU4

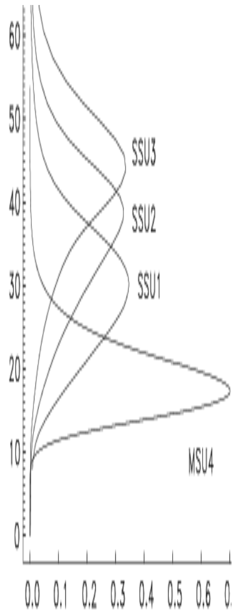
observations



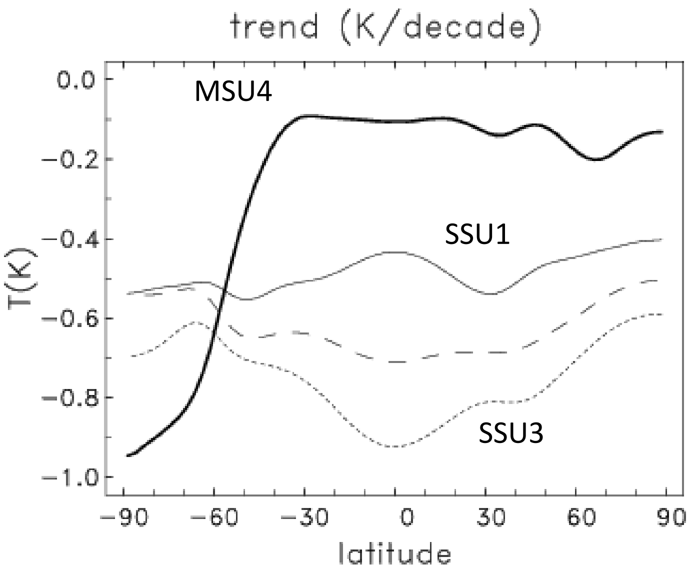
WACCM trends
1979-2014
(K/decade)

WACCM 1979-2014



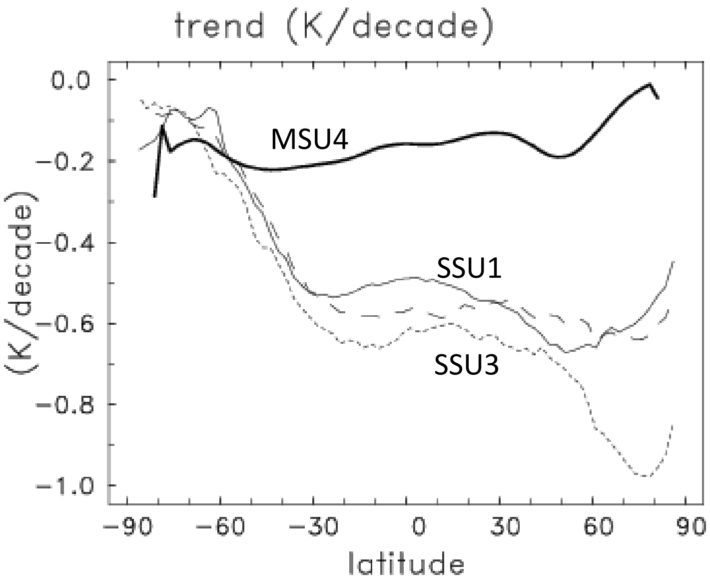


WACCM



↔

observations



Key points:

- SABER and MLS show nearly identical variability (and trends when combined with SSU)

- Observed trends for 1979-2014:

    - Small trends in lower stratosphere
    - Upper stratosphere: global cooling, except for high latitude SH
    - *Warming* in Antarctic winter upper stratosphere (!)

- Comparisons with WACCM:

    - Overall consistent with observations, but:
    - Much stronger ozone hole cooling in LS
    - Global cooling in upper stratosphere (no Antarctic winter warming)

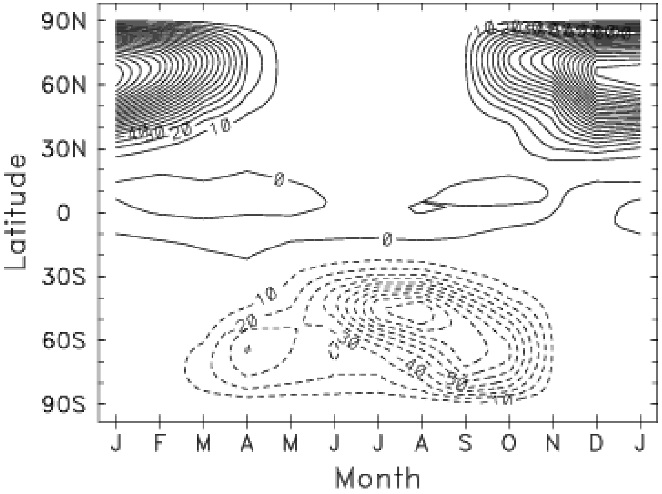
Thank you

stratosphere from
balloon over
Boulder, Colorado

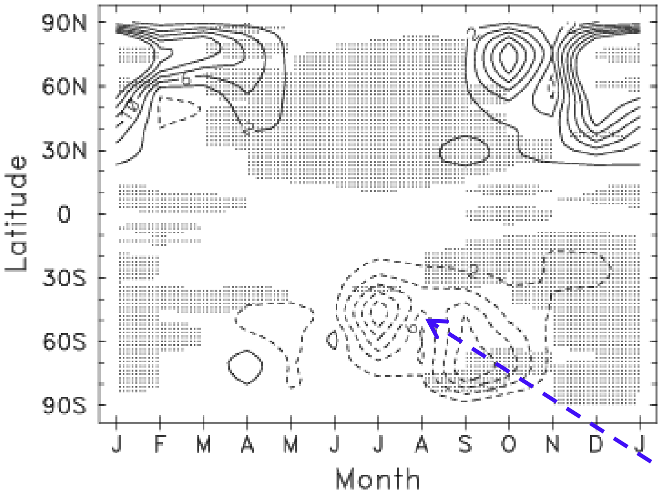
What is causing the wintertime warming over Antartica?

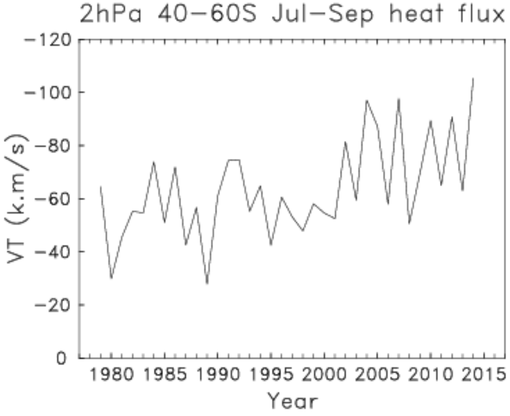
increases in wave forcing
from ERAinterim reanalysis

2 hPa wave forcing climatology



2 hPa wave forcing trends





increasing
wave forcing
??