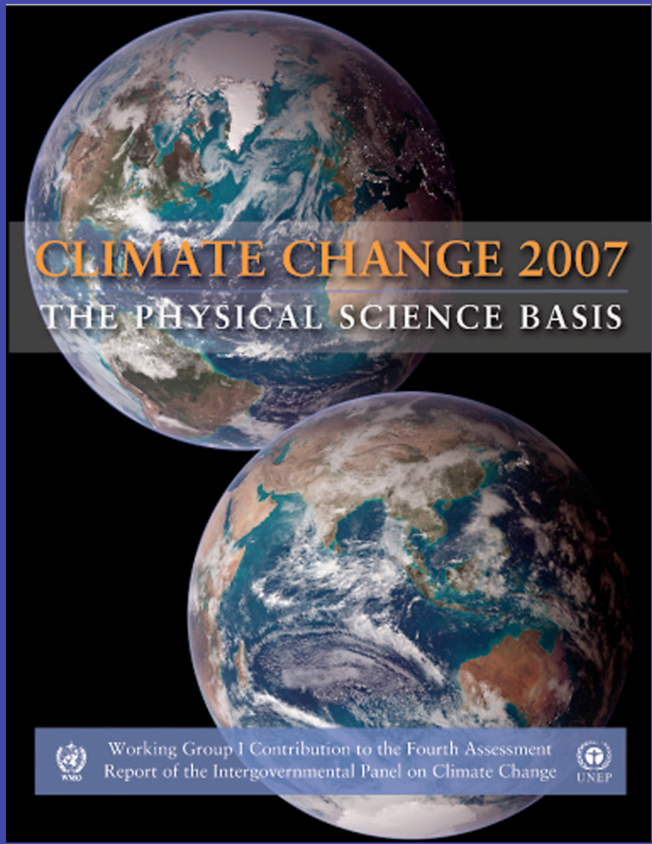
From the IPCC Assessment to Current Research and Back: An Overview of Key Findings and Issues in the Stratosphere and UTLS

Susan Solomon Co-Chair IPCC WG1
and Senior Scientist, NOAA Boulder, CO

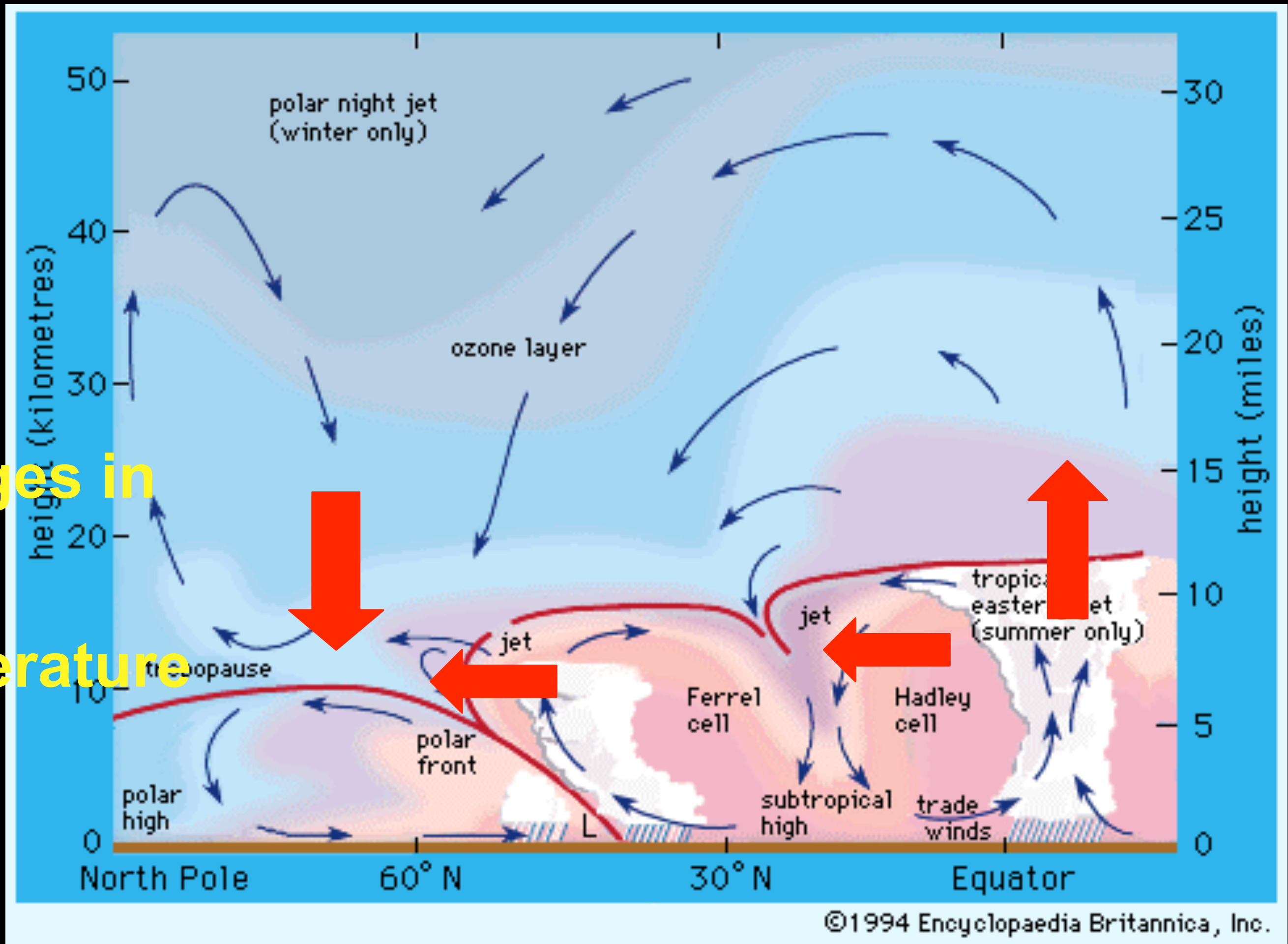
1. The stratosphere and the profile of warming
2. Brewer-Dobson circulation changes: Mechanism(s)? Implications? Expansion of tropics/link to drought? H2O? Ozone?
3. Polar stratospheric change and surface climate: SAM and NAM
4. Summary



My Key Conclusion:

There has never been a better time to invest yourself In stratospheric processes and their role in climate.

Cartoon Of Some Key Stratospheric And Climate Changes



- changes in ozone
- temperature trends

- Cooling
- less strat H_2O

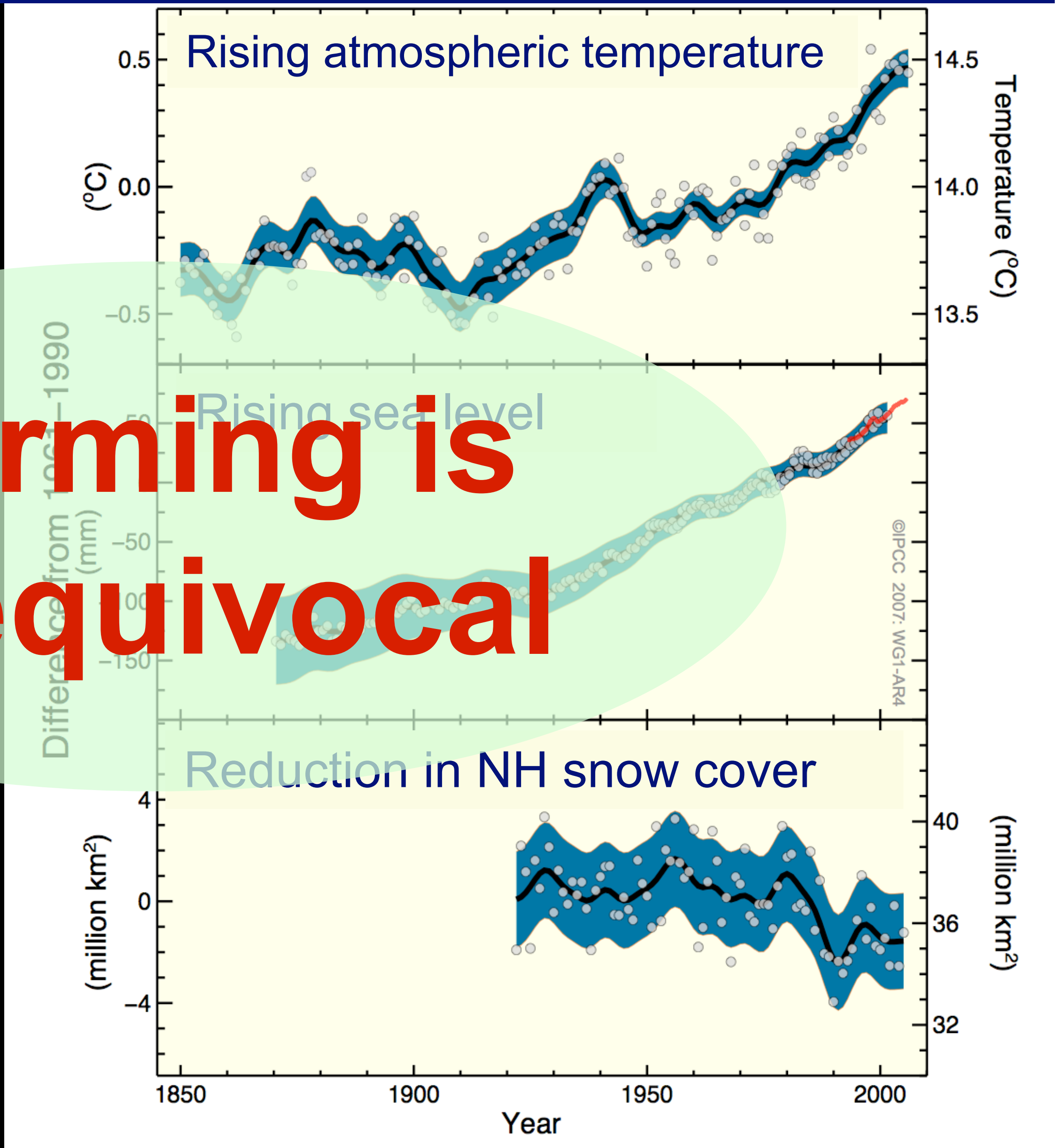
- Shift of storm tracks, regional climates, SAM, NAM

- Drought in subtropics?
- Mechanism? SST forcing? Wave forcing? other?

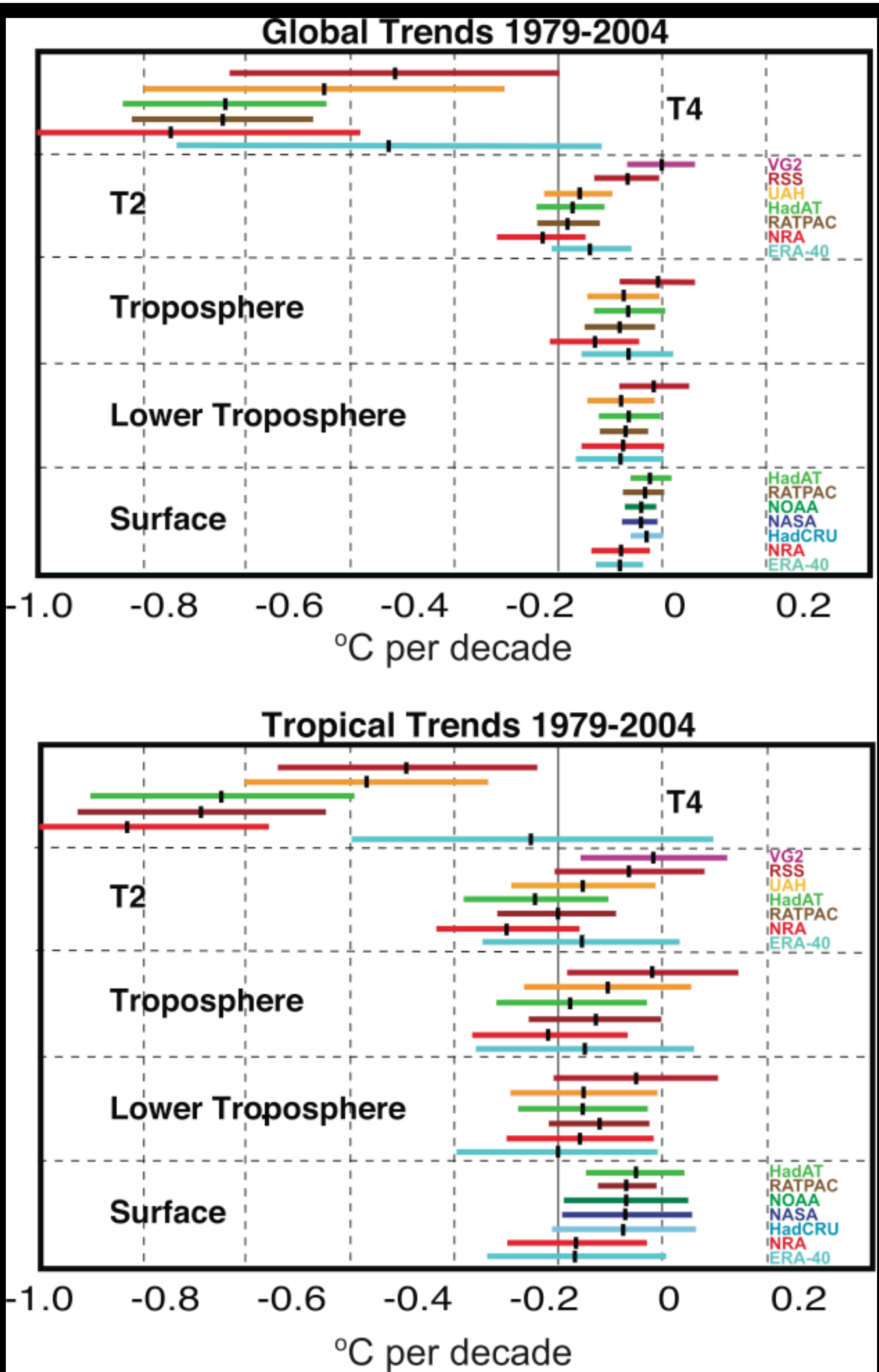
Many Changes Signal A Warming World

And……

- Atmospheric water vapor increasing
- Glaciers retreating
- Arctic sea ice extent decreasing
- **<u>Warming consistency with height</u>**



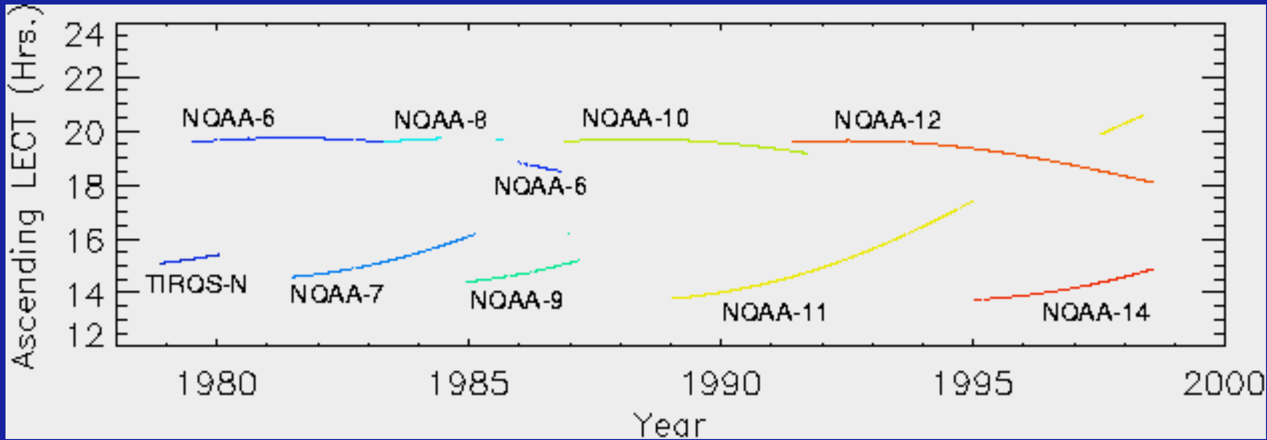
IPCC (2007) Summary for Policymakers



A Milestone of Many Contributions:

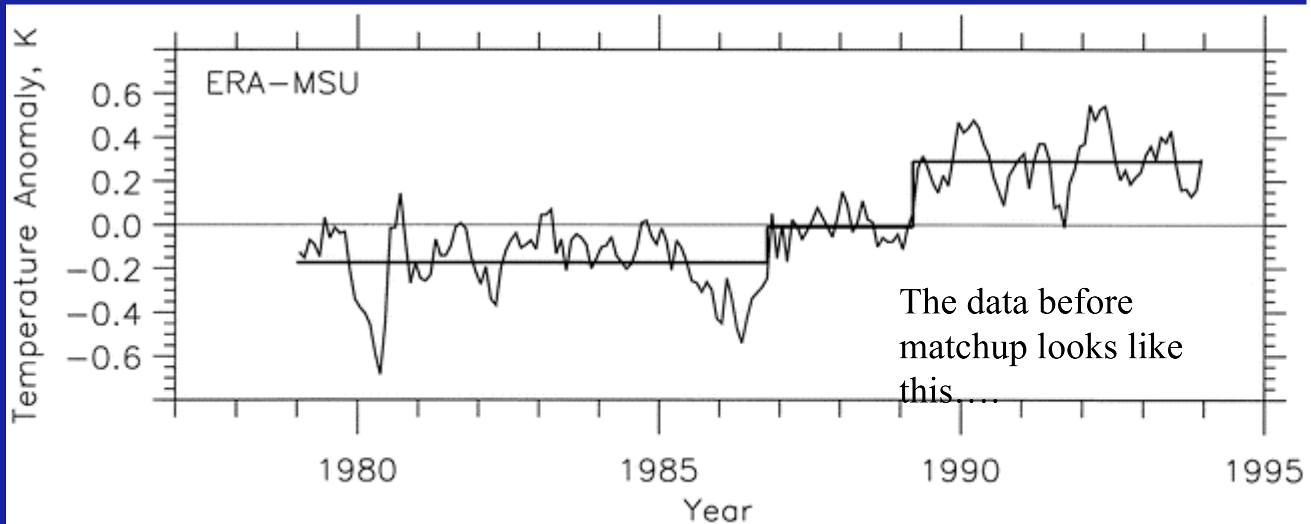
Improved global and tropical temperature trends from the surface to the lower stratosphere in IPCC (2007) chapter 3

Understanding Observations: Uncertainties



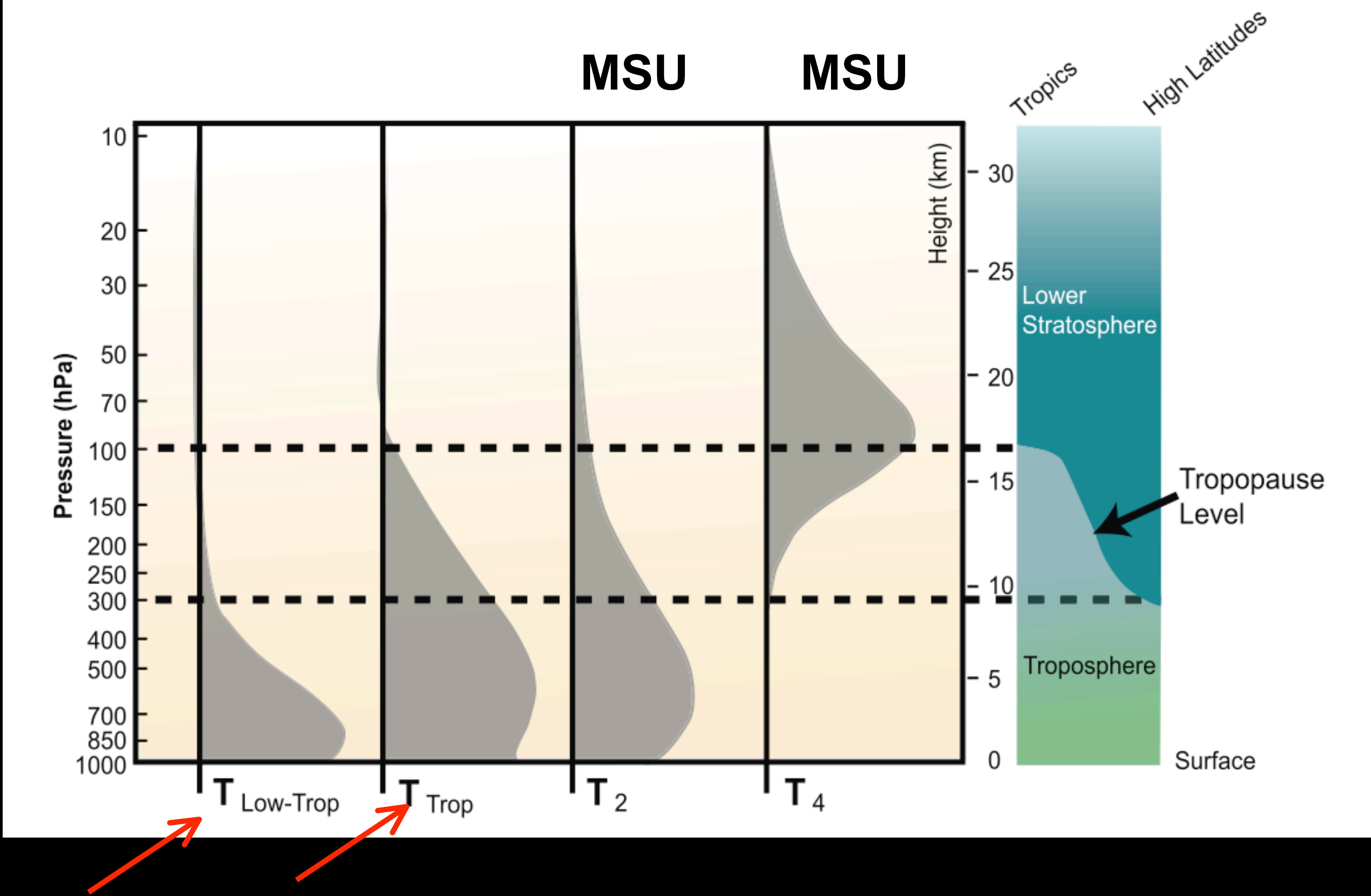
The satellite record is a patchwork quilt of many different instruments.

What are uncertainties in 'matchups' between different instruments?



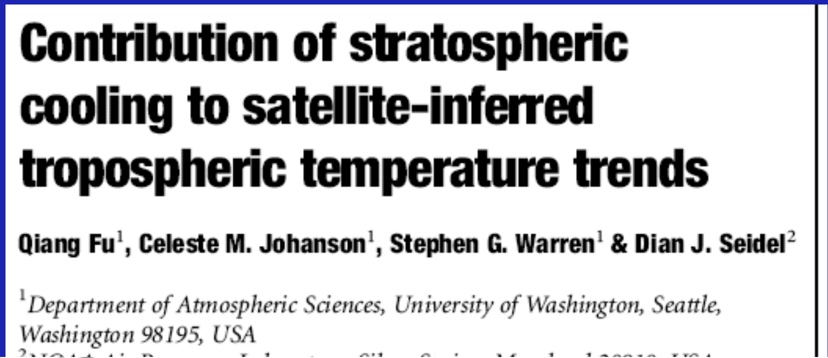
Different 'matchups' give dramatically different answers, from about 0.04°C warming to about 0.2°C warming.

Understanding Observations: Role of Stratosphere



T_{trop} = Use T4 to correct T2 (Fu et al. 2004)

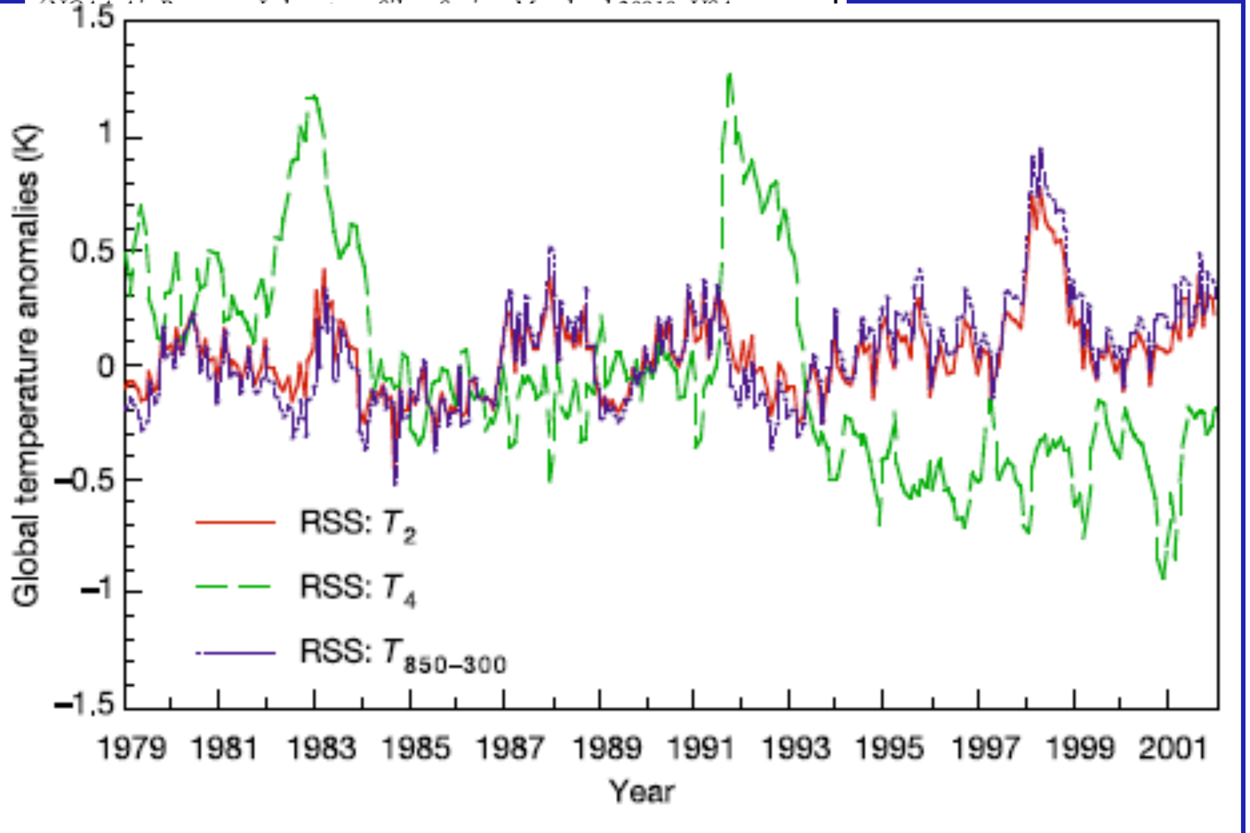
Fu et al.: Importance of the Stratosphere to Fingerprinting Climate Change

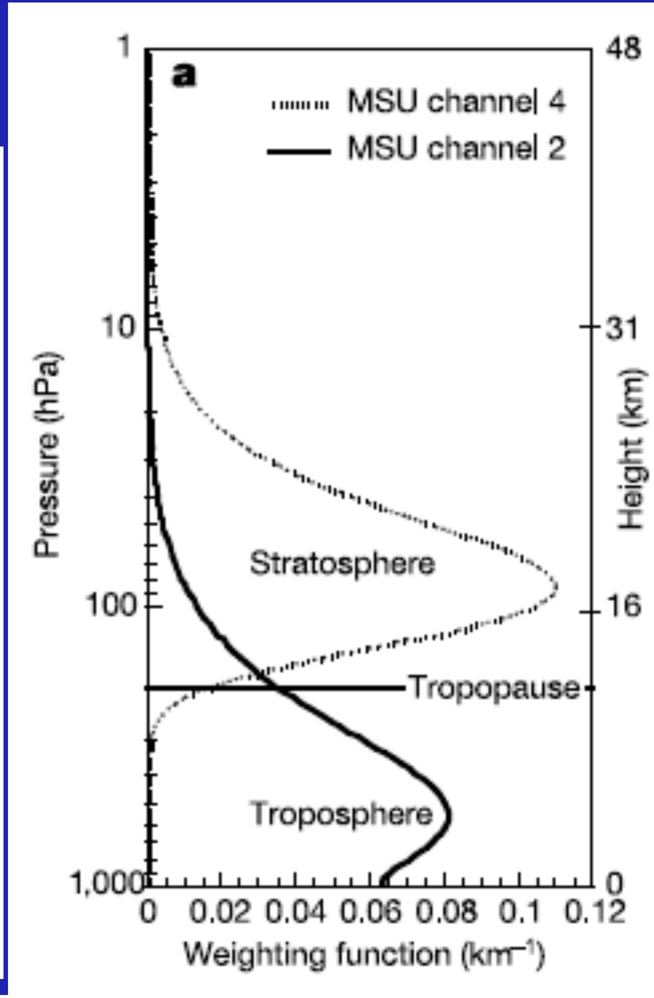


Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends

Qiang Fu[1], Celeste M. Johanson[1], Stephen G. Warren[1] & Dian J. Seidel[2]

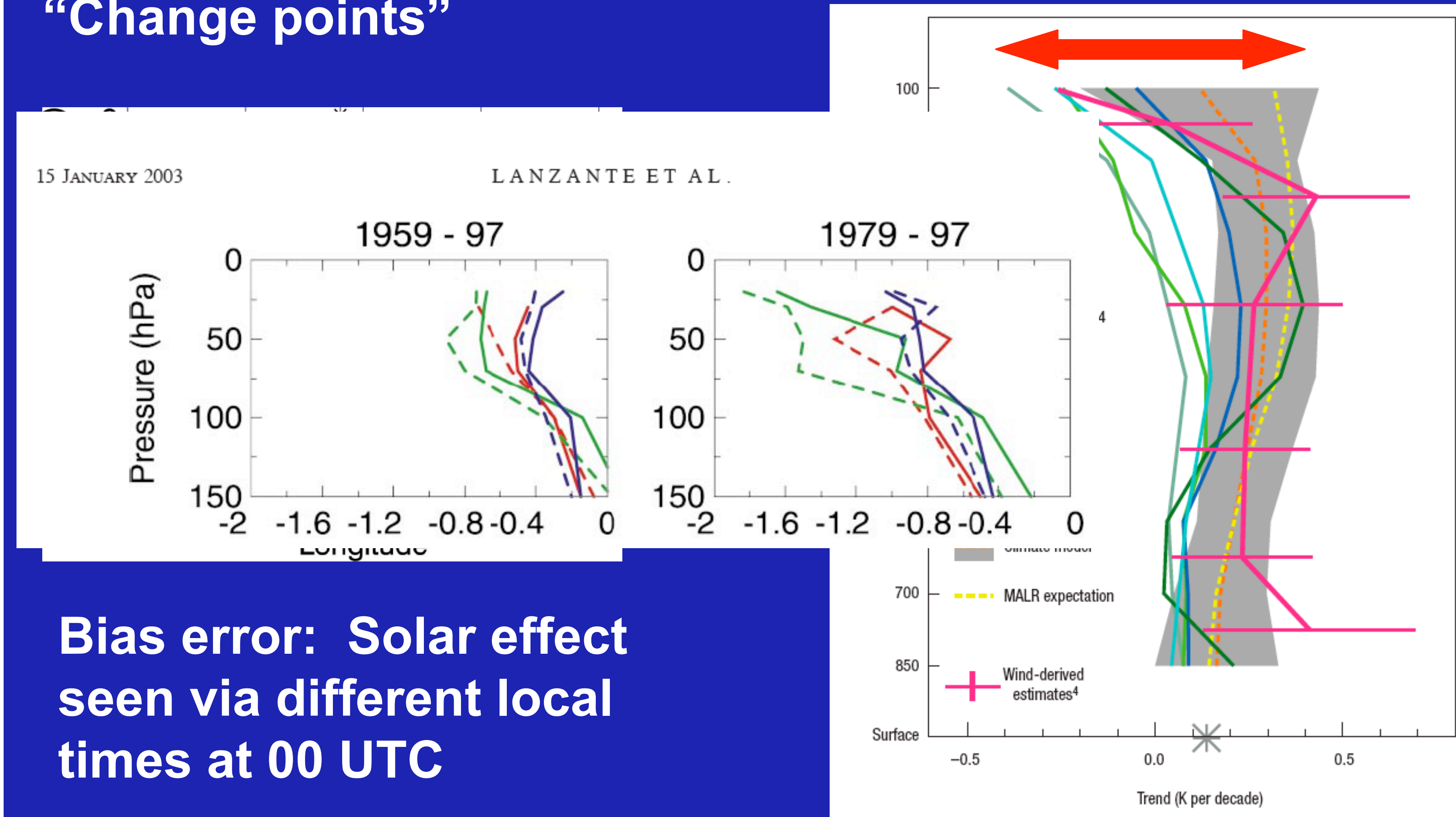
[1]*Department of Atmospheric Sciences, University of Washington, Seattle, Washington 98195, USA*





Sherwood, Seidel, Lanzante, Thorne, and others: Correcting the Radiosondes Too

"Change points"

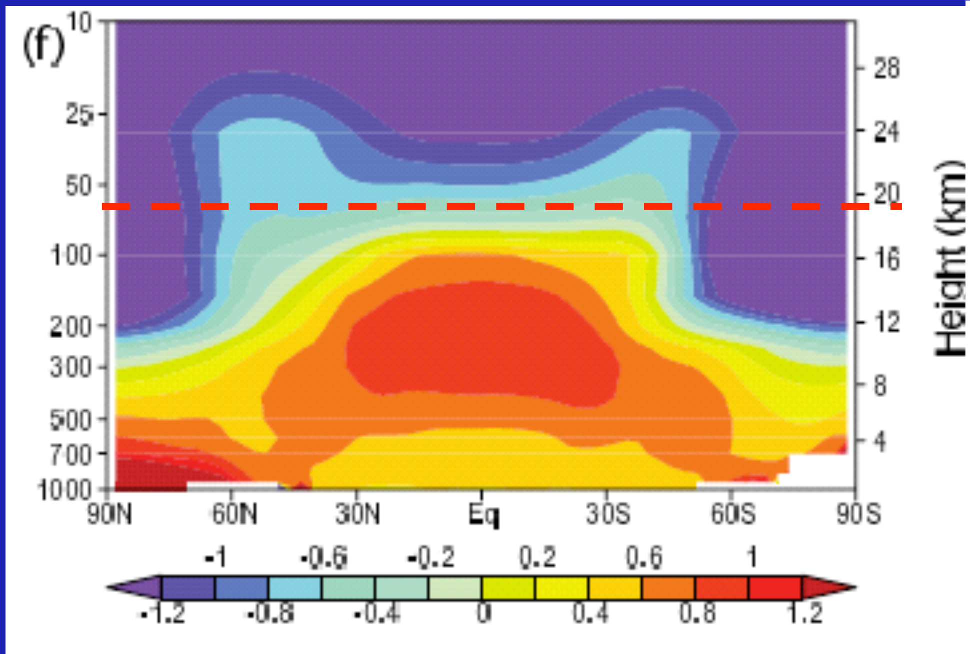


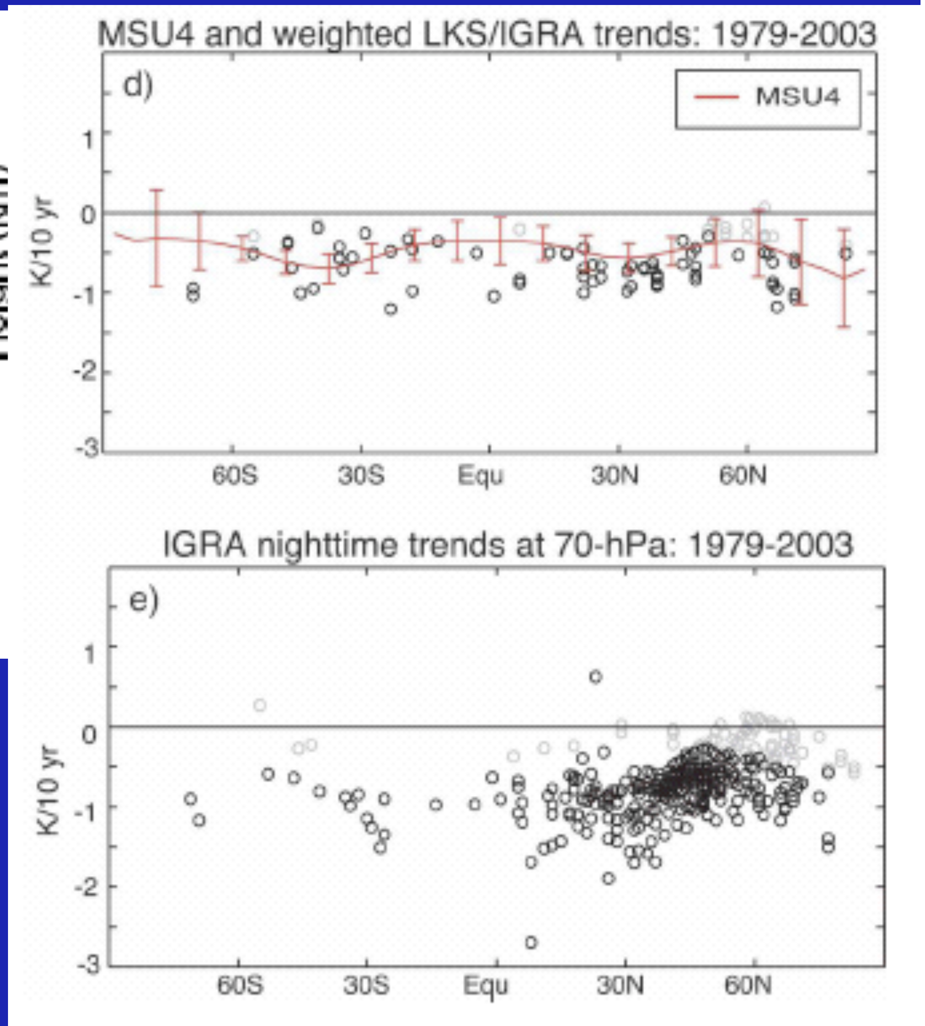
Bias error: Solar effect seen via different local times at 00 UTC

The Meaning Behind the Consistency

Typical GCM [IPCC (2007) ch 9]:
Very little cooling in the tropical lower strat; big gradients in ΔT

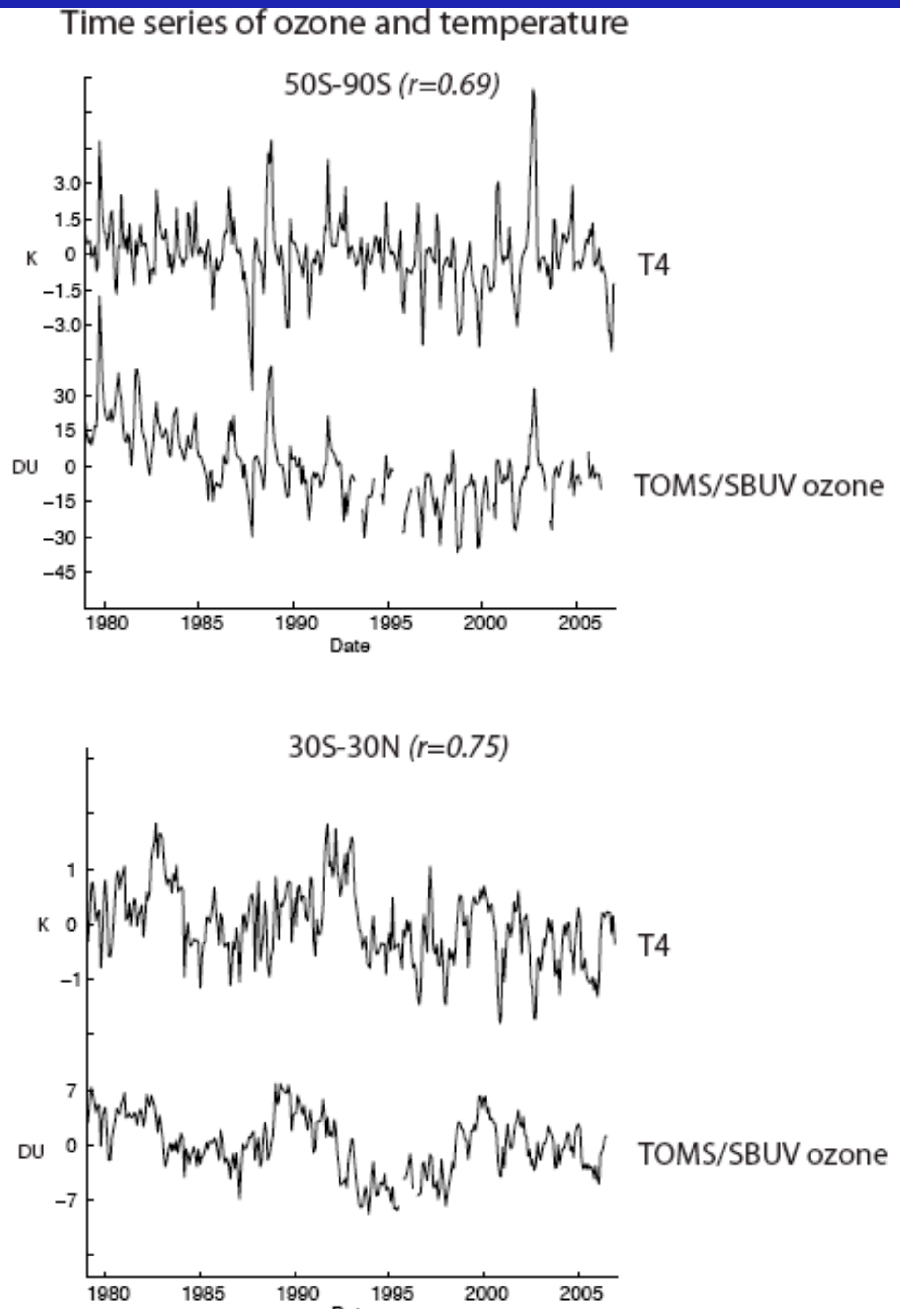
[Thompson and Solomon, 2005]:
Tropical cooling is large; comparable to poles -> dynamical changes





• What does tropical cooling tell us?

More Meaning Behind the Consistency



T4 *(trend = -0.31 K/dec)*

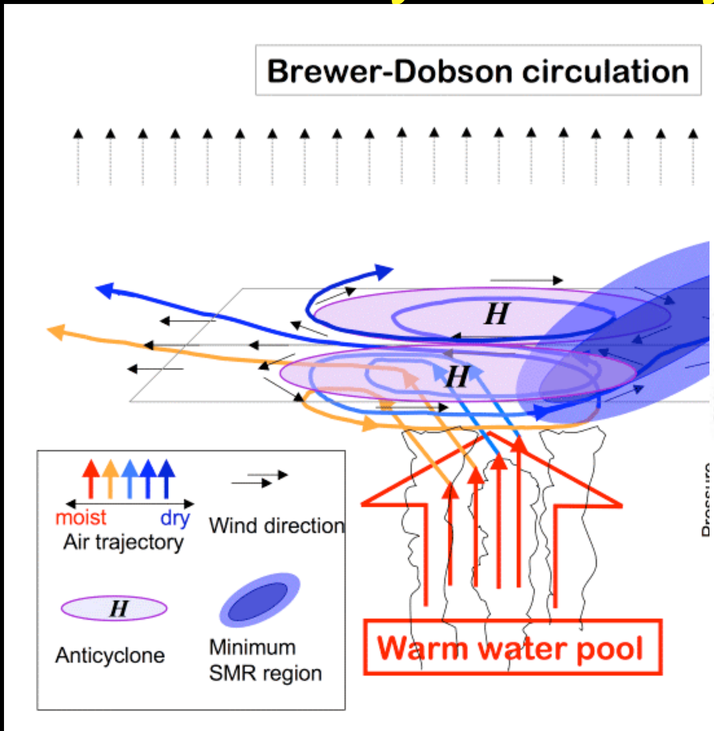
congruent with ozone

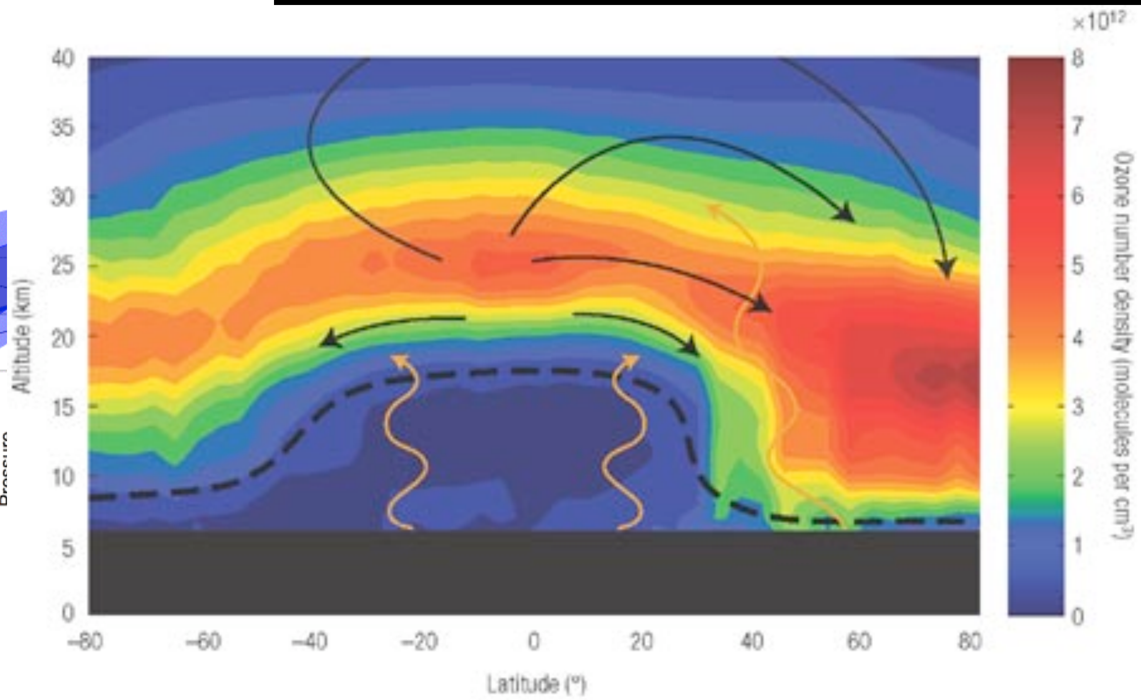
ozone-residual T4
(trend = -0.12 K/dec)

- **volcanoes, ozone and ‘steps’ in temperature**
- **Coupled ozone, circulation change, and T-trends in tropics and polar regions**

Thompson and Solomon, in press, J. Clim., 2008.

A Dynamically Changing Stratosphere





What does it imply?

• Coupling between temperature changes, ozone changes and BD changes? (tropics and higher lats)?

• Influence on polar ozone trends? Should act to warm, increase ozone…working against Cly-induced depletion and cooling….

• Influence on tropical tropopause z, T? Expansion of tropics? TTL? Stratospheric water vapor? Drought? Polar circulation patterns?

Higher tropical SSTs strengthen the tropical upwelling via deep convection

R. Deckert[1] and M. Dameris[1]

Received 21 February 2008; accepted 2 April 2008; published 28 May 2008.

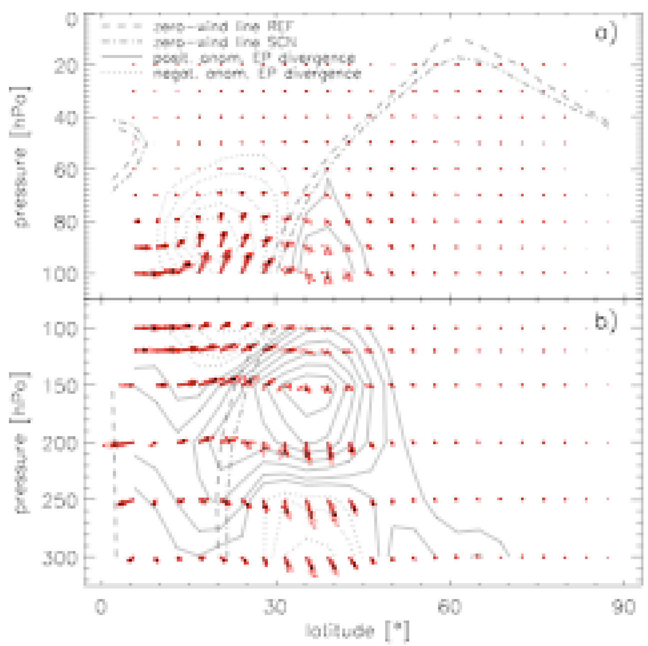
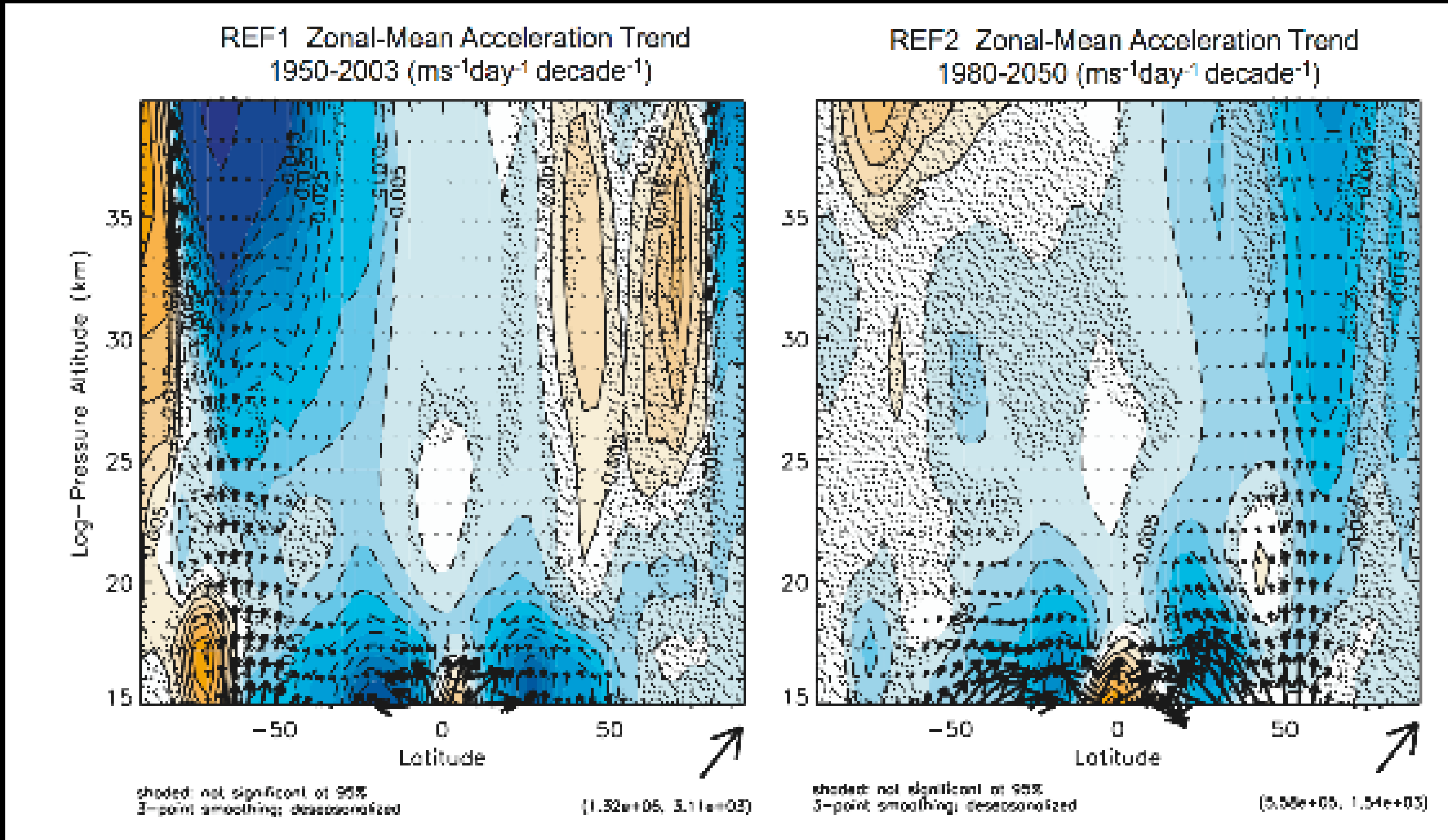


Figure 2. JA anomalous (REF minus SCN) quasi-stationary EP diagnostics in the northern hemisphere. A horizontal EP flux arrow of the same length as 10° latitude corresponds to 1.82×10^{14} m^3 (Figure 2a) and 1.02×10^{14} m^3 (Figure 2b), a vertical EP flux arrow of the same length corresponds to 4.68×10^{18} m^3kPa (Figure 2a) and 1.35×10^{19} m^3kPa (Figure 2b). Black arrows: ensemble mean anomalous EP flux. Red arrows: anomalous EP flux for each of the six individual anomalies. EP divergence is given in values of $\pm 1.0 \pm 2.0 \pm 3.5 \pm 5.0 \pm 6.5 \pm 8.0 \pm 9.5$ (in 10^{14} m^3). Zonal winds at low latitudes are mostly easterly.

Deckert and Dameris: Effect of ocean warming on deep convection and upwelling in some seasons?



Garcia and Randel: emphasize the changes in meridional temperature gradient tropics/extratropics, and effects on wave propagation/dissipation: a basic feature of GHG increases; not necessarily linked to e.g. SST, increased tropospheric wave activity.

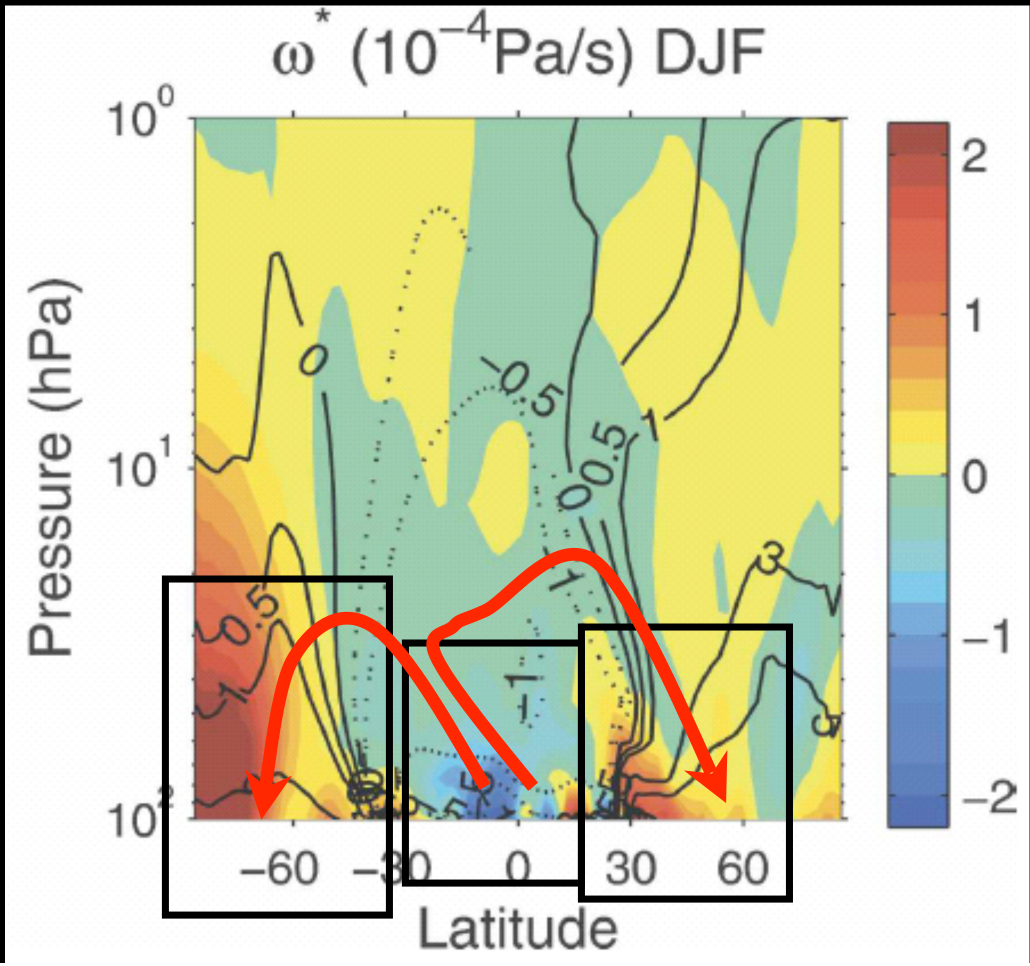
The Strength of the Brewer–Dobson Circulation in a Changing Climate: Coupled Chemistry–Climate Model Simulations

FENG LI

Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, New Jersey

JOHN AUSTIN AND JOHN WILSON

NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey



Understanding HOW, WHY, WHERE Circulation is Changing: Butchart, Sigmond, Li, Garcia, Fomichev, Rind, Eyring, Dameris, Chen, Norton…

-SST/convection?

-Or g-waves? Or p-waves?

-Is wave generation changing, or the propagation/dissipation, or both? Tropics? mid-lats?

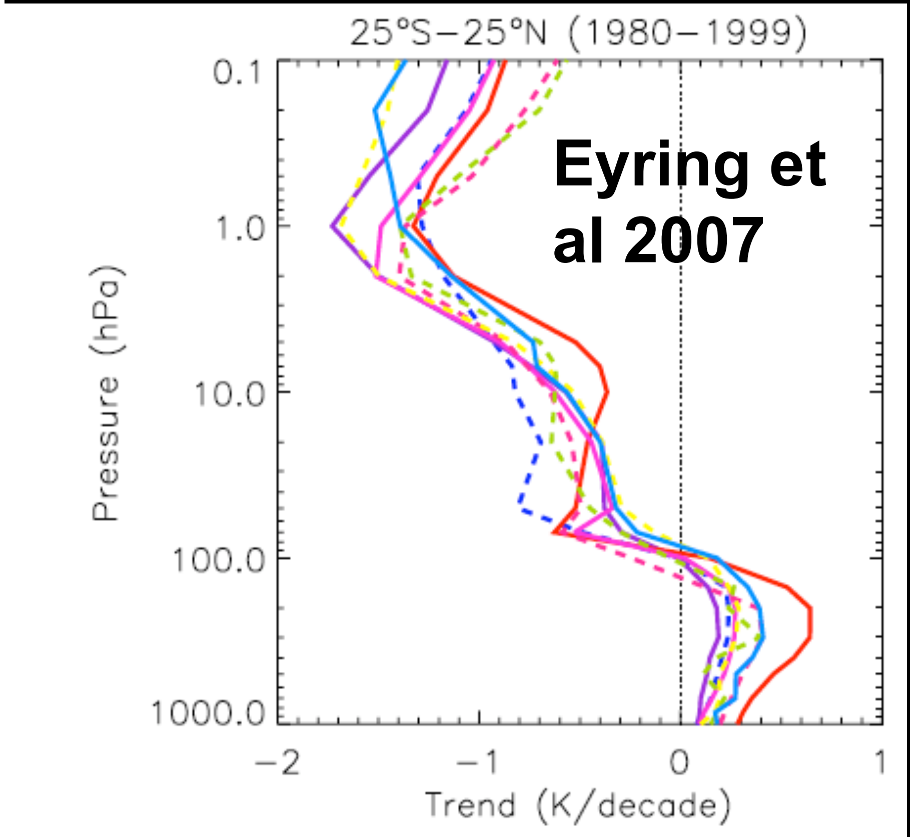
-Link to ozone changes?

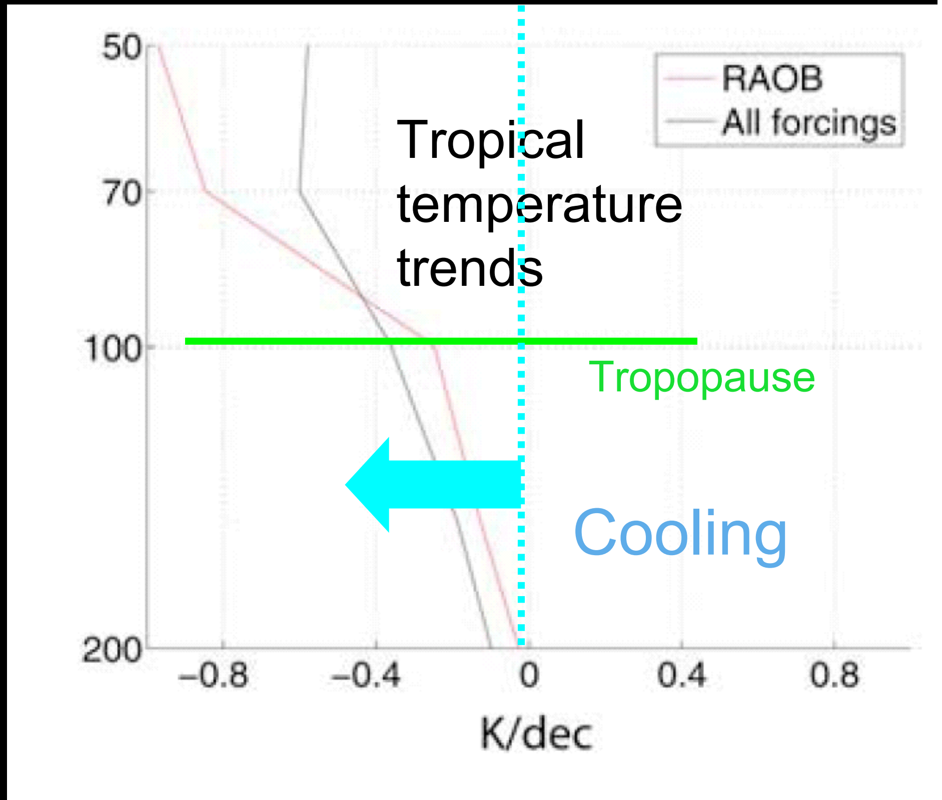
-Or….? Many views….

-AR5 models?

Ozone and Temperature: Stratosphere and Substratosphere

• Stratosphere: Cooling at 50-70 mbar due in part to local ozone losses there.





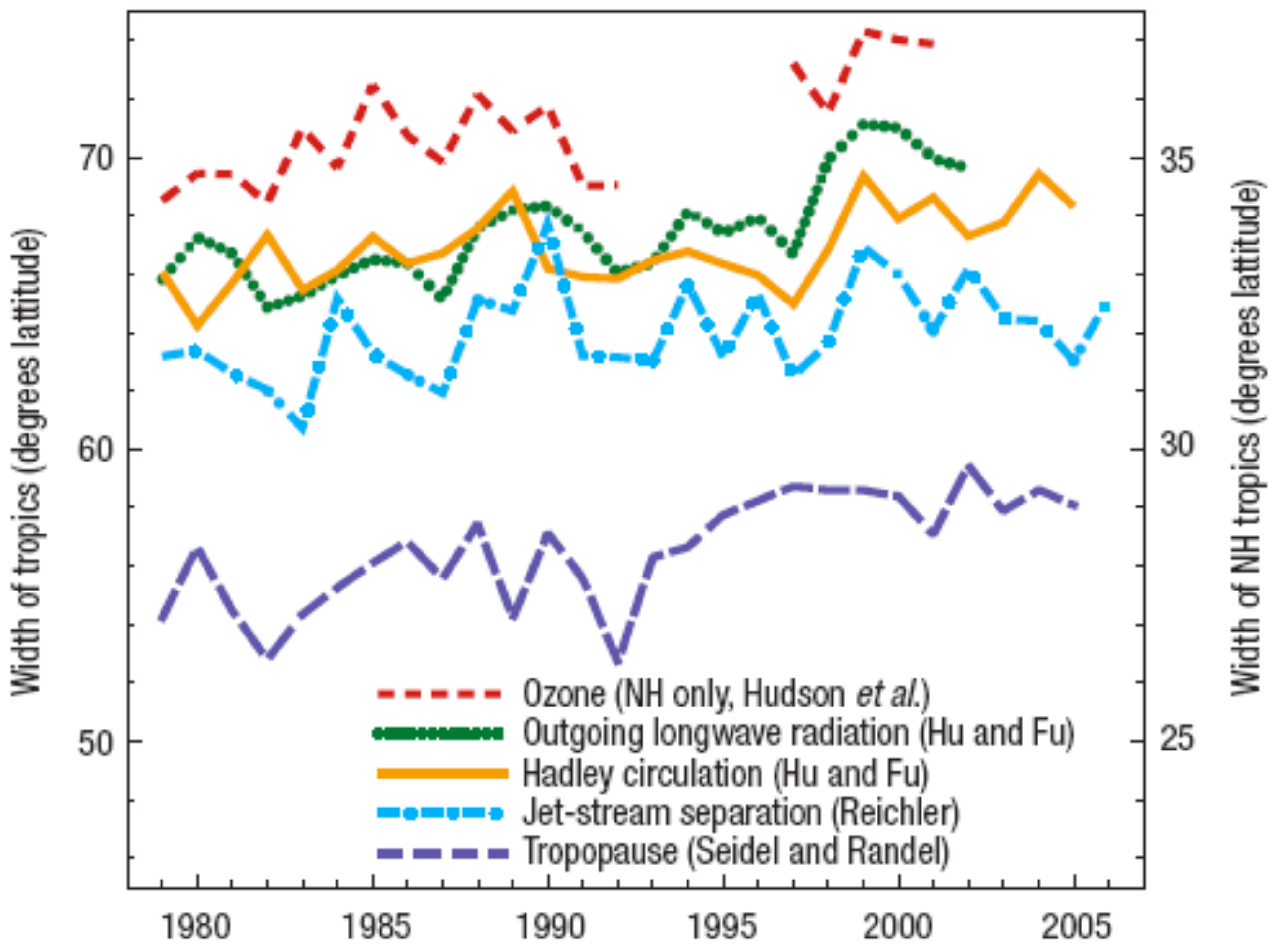
Forster et al., GRL, 2007.

• Effect on model/data comparisons?

• Coupling to dynamics?

• Captured in AOGCMs? AR5?

The Meaning In The Stratosphere



atmospheric structure, circulation, and hydrological features shown in this schematic diagram of the Earth have moved poleward in recent decades, indicating a widening of the tropical belt and the Hadley circulation.

Widening of the tropics seen robustly in various datasets [Seidel et al. Nature, 2007]. Strat/trop linkages?

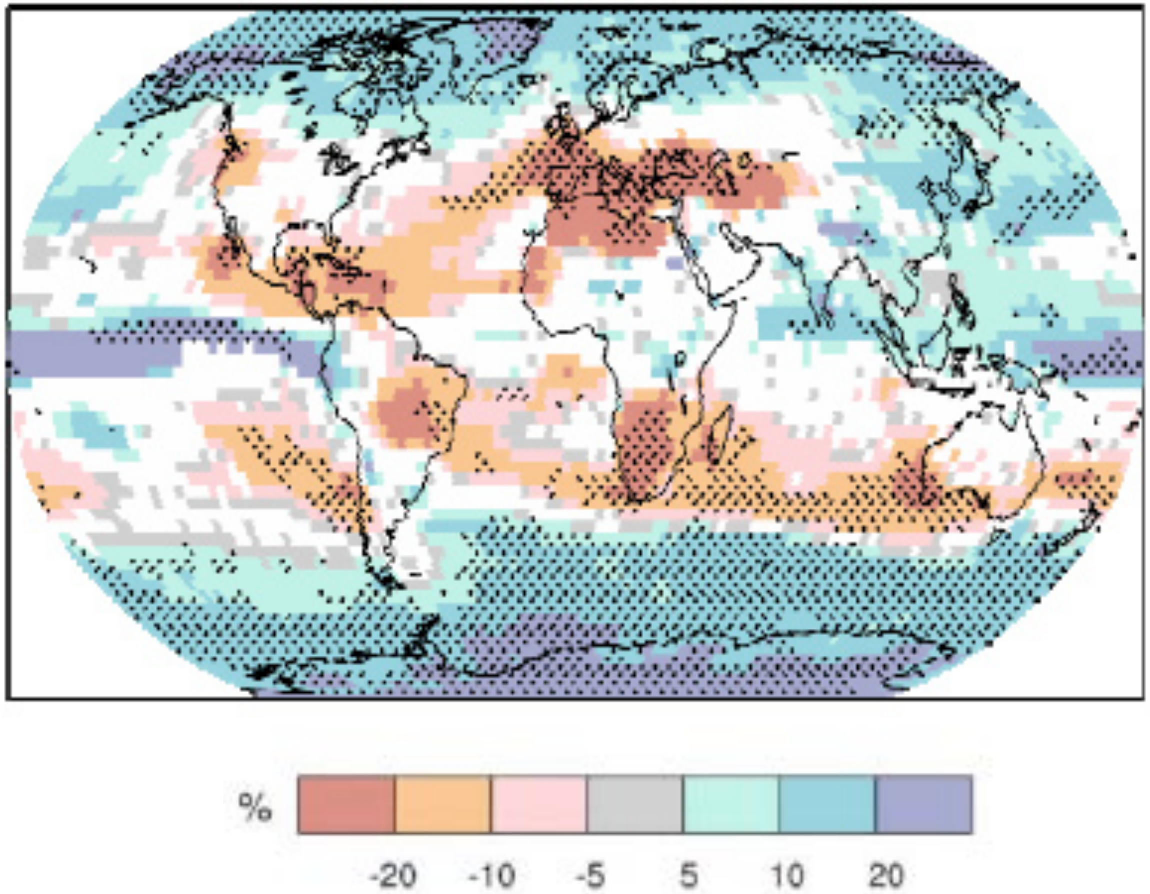
A World of Change: More Rain for Some, Less for Others

Regional changes (+/-) of up to 20% in average rainfall

• Drying in the subtropics in both hemispheres

• More precip in high latitudes

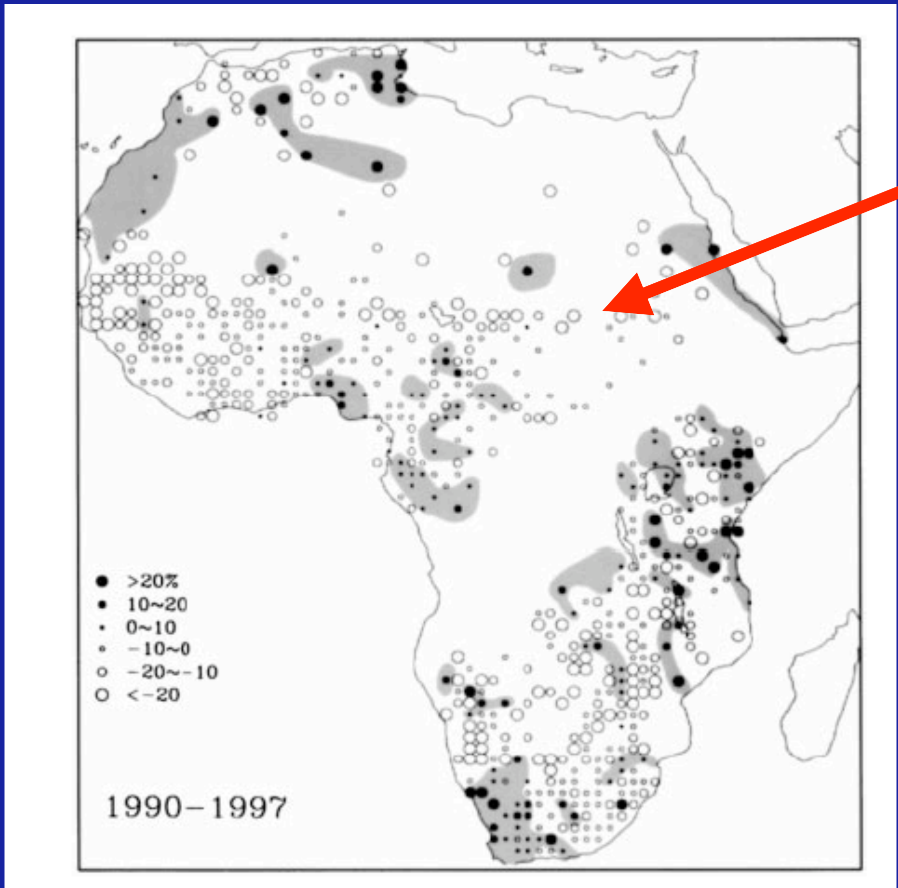
(2090s: medium emissions scenario; high confidence in stippled areas)



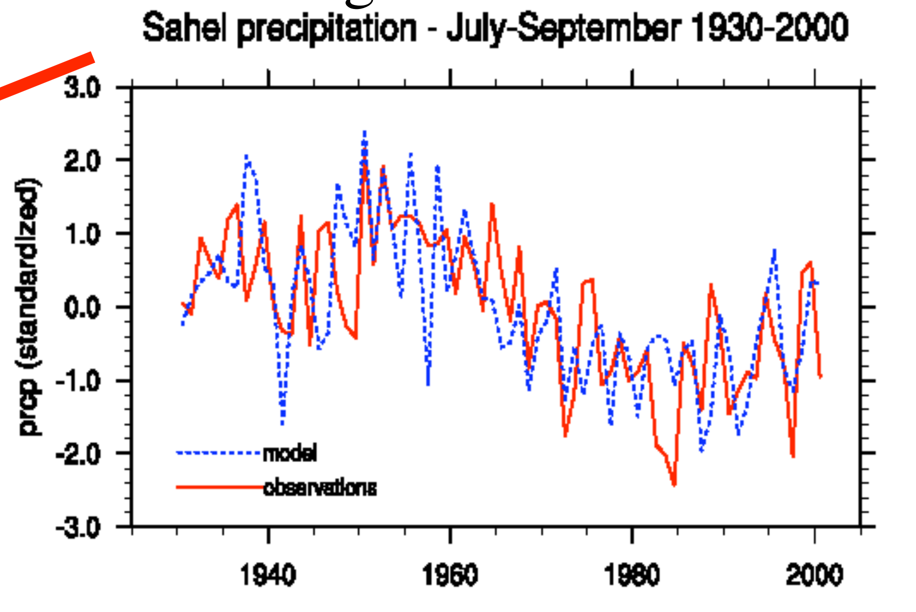
JJA seasonal precipitation

IPCC (2007) Summary for Policymakers

African climate change….clues to an origin in the ocean?



Models using obsvd SST…….



Giannini et al., Science, 2003.

Underscores the link to SST. But why are the SSTs changing? Is there a role for anthropogenic perturbations/chemistry?

Similar conclusion for North American drought is given in Schubert et al., 2004.

Aerosols (Lohmann and colleagues)?

And what about the stratosphere?

Natural variability, land use, or an effect linked to non-local human influences?

Robust Responses of the Hydrological Cycle to Global Warming

ISAAC M. HELD

National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

BRIAN J. SODEN

Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 13 September 2005, in final form 17 March 2006)

(C)

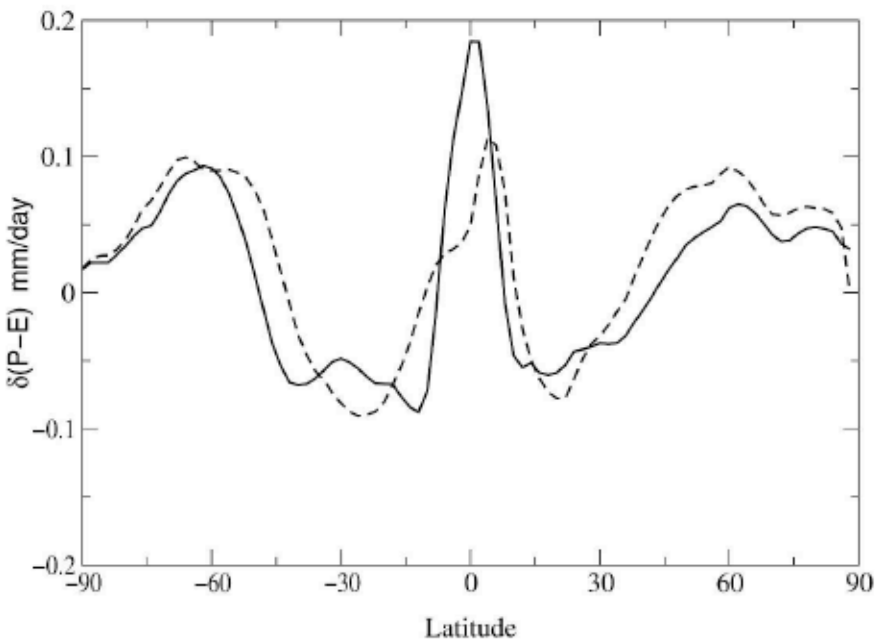


FIG. 6. The zonal-mean $\delta(P - E)$ from the ensemble mean of PCMDI AR4 models (solid) and the thermodynamic component (dashed) predicted from (6). Results are shown from simulations using the (a) 20C3M, (b) SRES A1B, and (c) 2×CO2 slab equilibrium forcing scenarios.

P-E

Drying in subtropics, moistening in extra-tropics

The Meaning In The Stratosphere

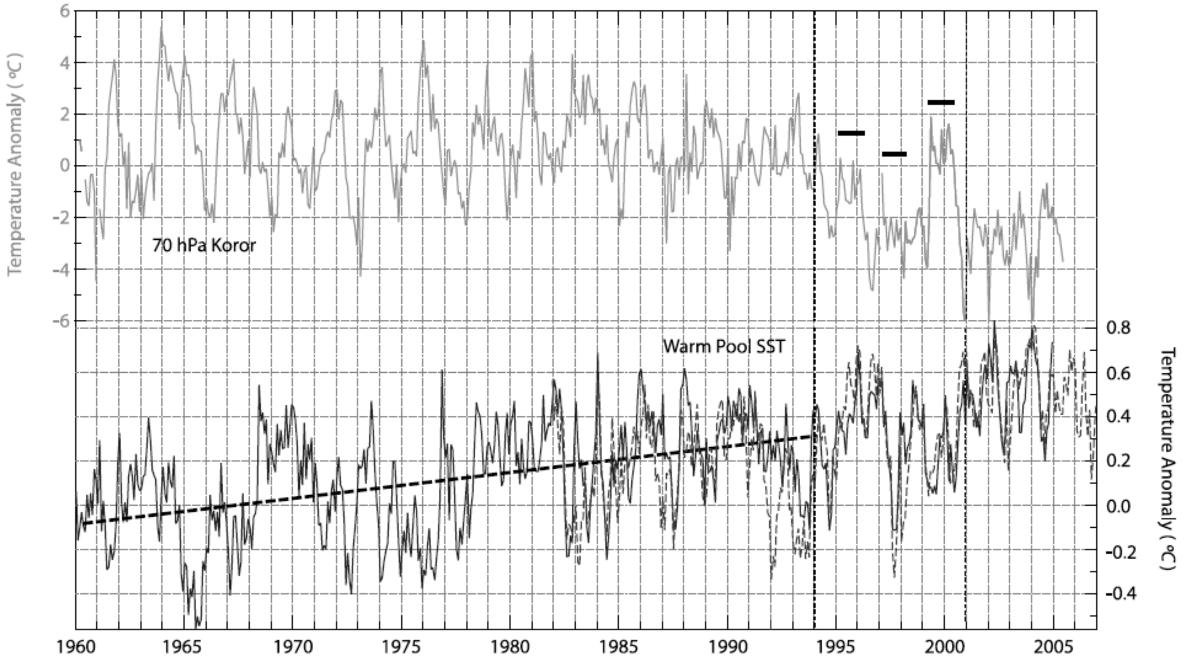


Figure 5. Monthly mean temperature anomalies at the 70-hPa pressure level over Koror (top curve), and SST anomalies averaged over the area of the western tropical Pacific between 7.5°S and 4.5°N latitude and between 120°E and 180° longitude (bottom curves; solid curve is the Kaplan SST anomalies, and dashed curve is the Optimal Interpolation Version 2; data were obtained from the NOAA/CIRES Climate Diagnostics Center). The dashed straight line is a least squares linear fit to the Kaplan data from 1960 to 1994. The short horizontal bars denote the positive phases of the QBO signal in 1995–1996, 1997–1998, and 1999–2000. The vertical bars denote start of features discussed in the text.

- Stratospheric cooling and SST linkage

Stratospheric Water Vapor

Randel: "Abrupt change" around 2000 (not a change point, it's real….)

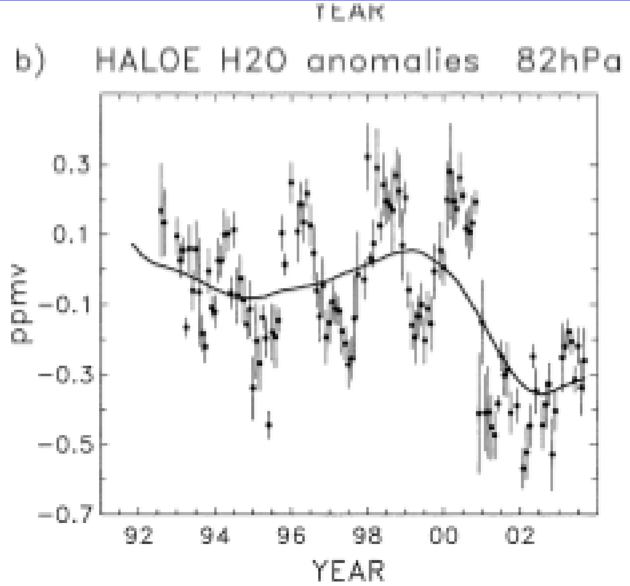


FIG. 1. (a) Time series of near-global mean (~60°N–60°S) water vapor at 82 hPa derived from HALOE data. The circles show monthly mean values, and error bars denote the monthly standard deviation. (b) Deseasonalized near-global mean H_2O anomalies at 82 hPa. The solid lines are running Gaussian-weighted means of the individual points (using a Gaussian half-width of 12 months).

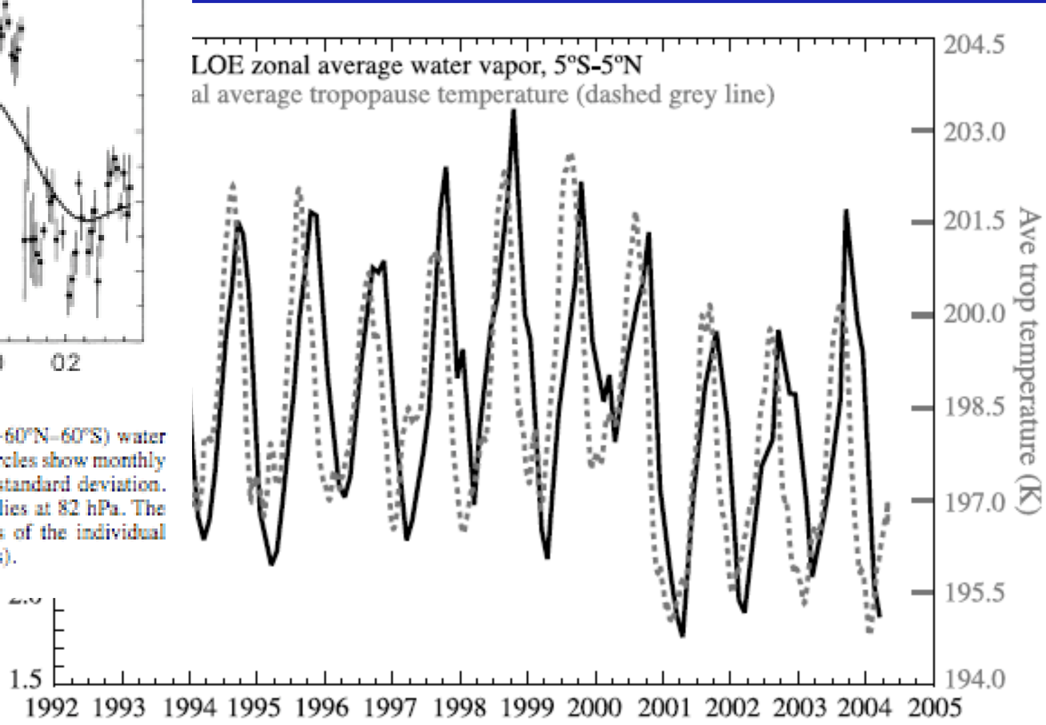
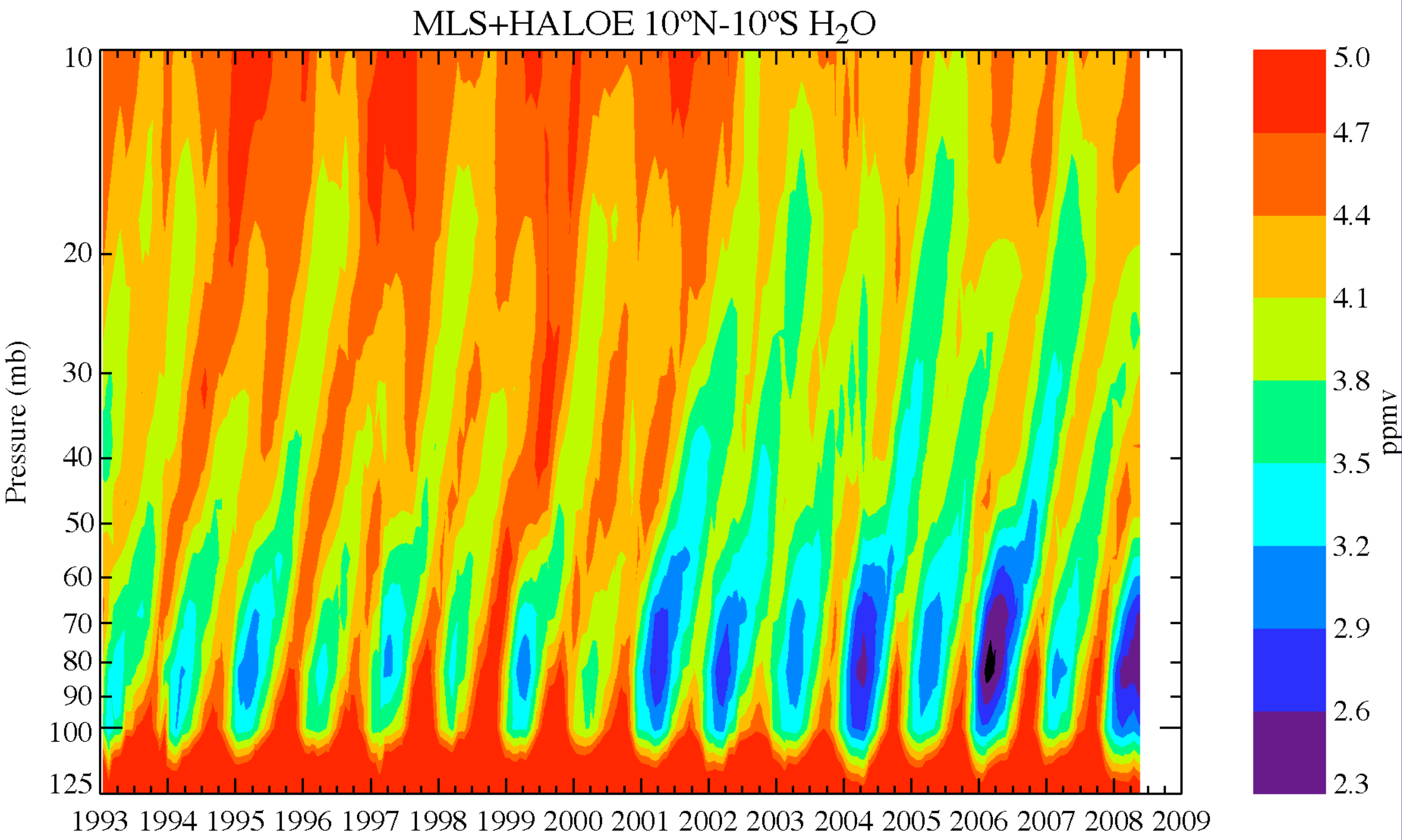


Figure 11. The 10°N–10°S water vapor mixing ratio from HALOE at the altitude of the average profile minimum in the tropics (black solid, scale on left) and NCEP/NCAR reanalysis zonal average tropopause temperatures (grey dashed, scale on right). The correlation maximizes with a 2-month shift, with water vapor lagging.

Link To Water Vapor



Rosenlof, Reid, Dameris, others: SST/convection…

Dhomse et al.: Water Vapor and Eddy Heat Flux

-> Roles of tropical SST vs extratropical waves…?

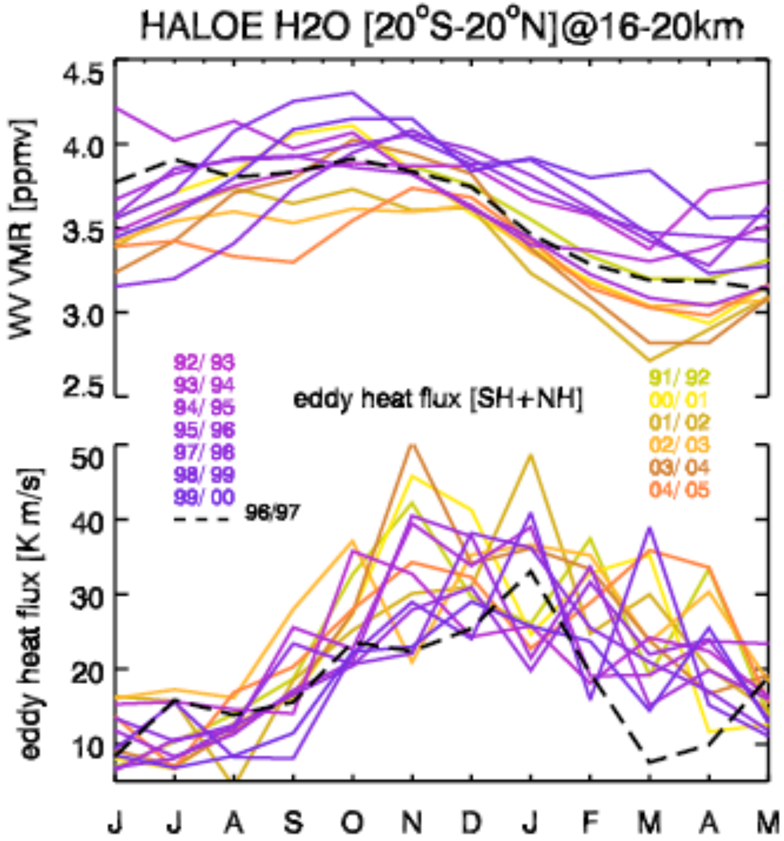


Fig. 1. Annual cycle of monthly mean tropical water vapor VMRs from HALOE V19 data averaged between 16 km and 20 km and between 20° S and 20° N (top) and monthly mean mid-latitude eddy heat flux at 50 hPa averaged from 45° to 75° with area weights and added from both hemispheres (bottom). Years with higher and lower wave activity are shown in yellow-red and blue-violet lines, respectively.

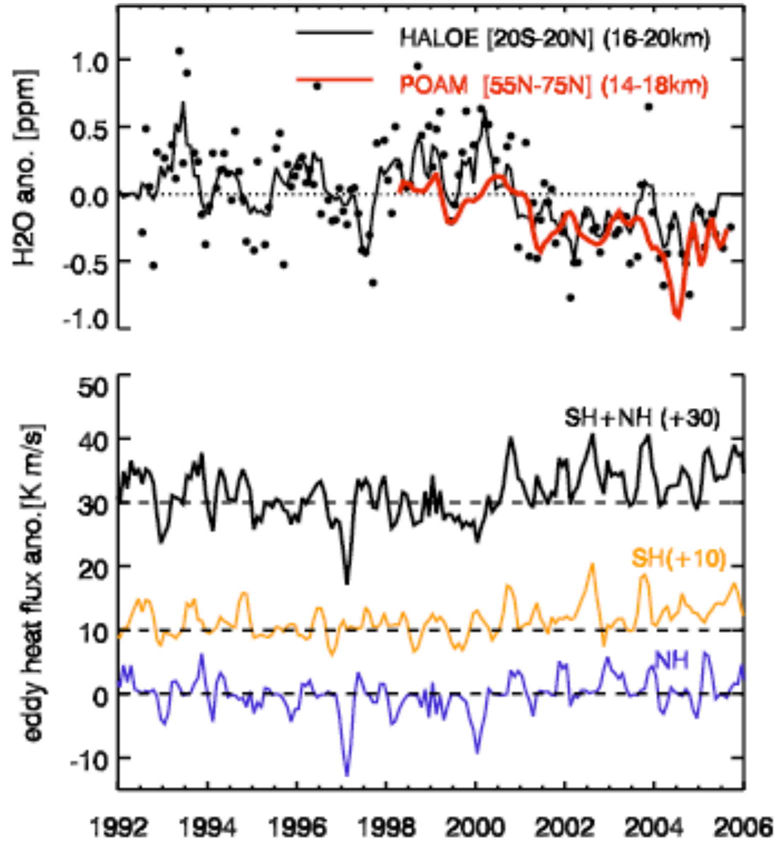
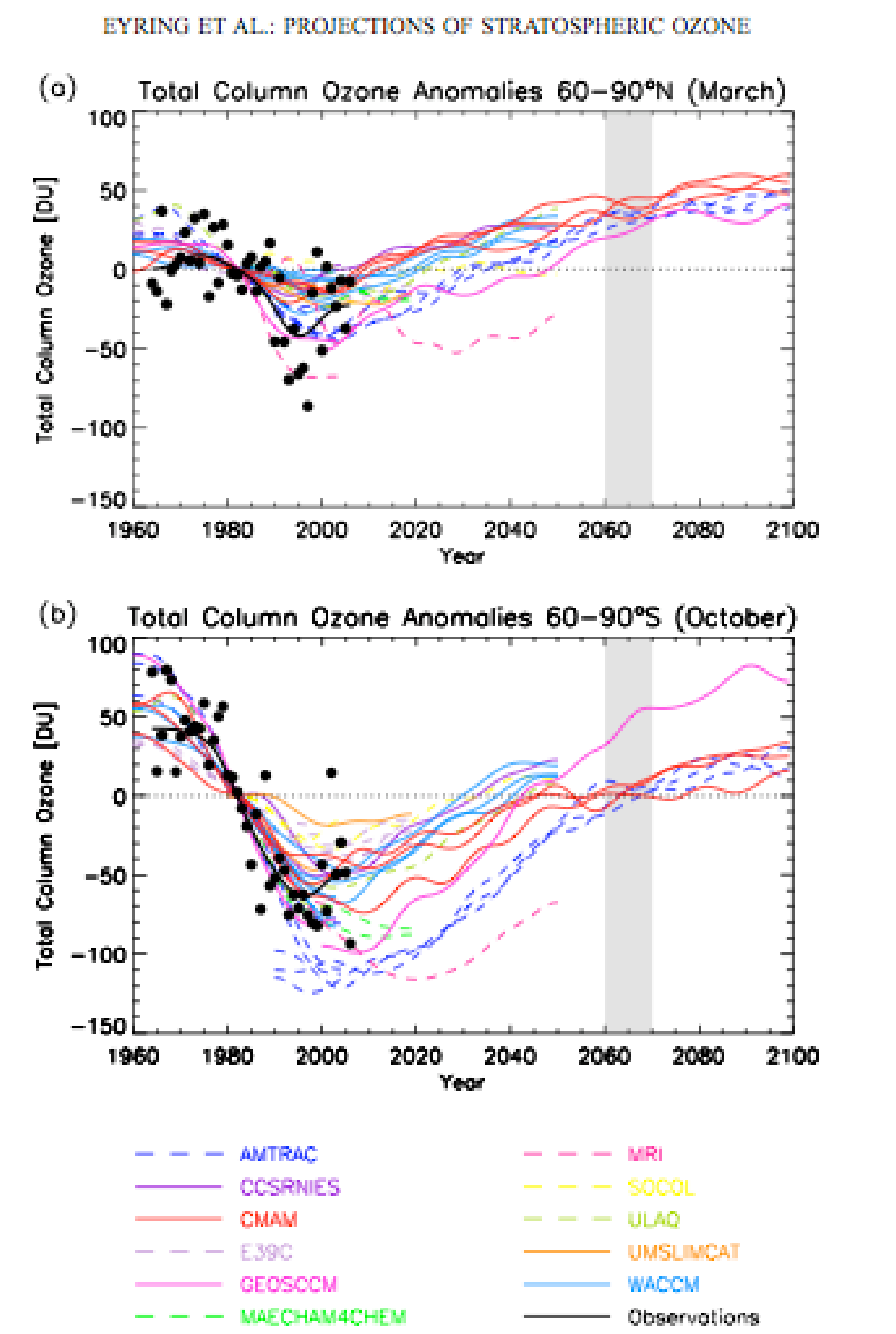


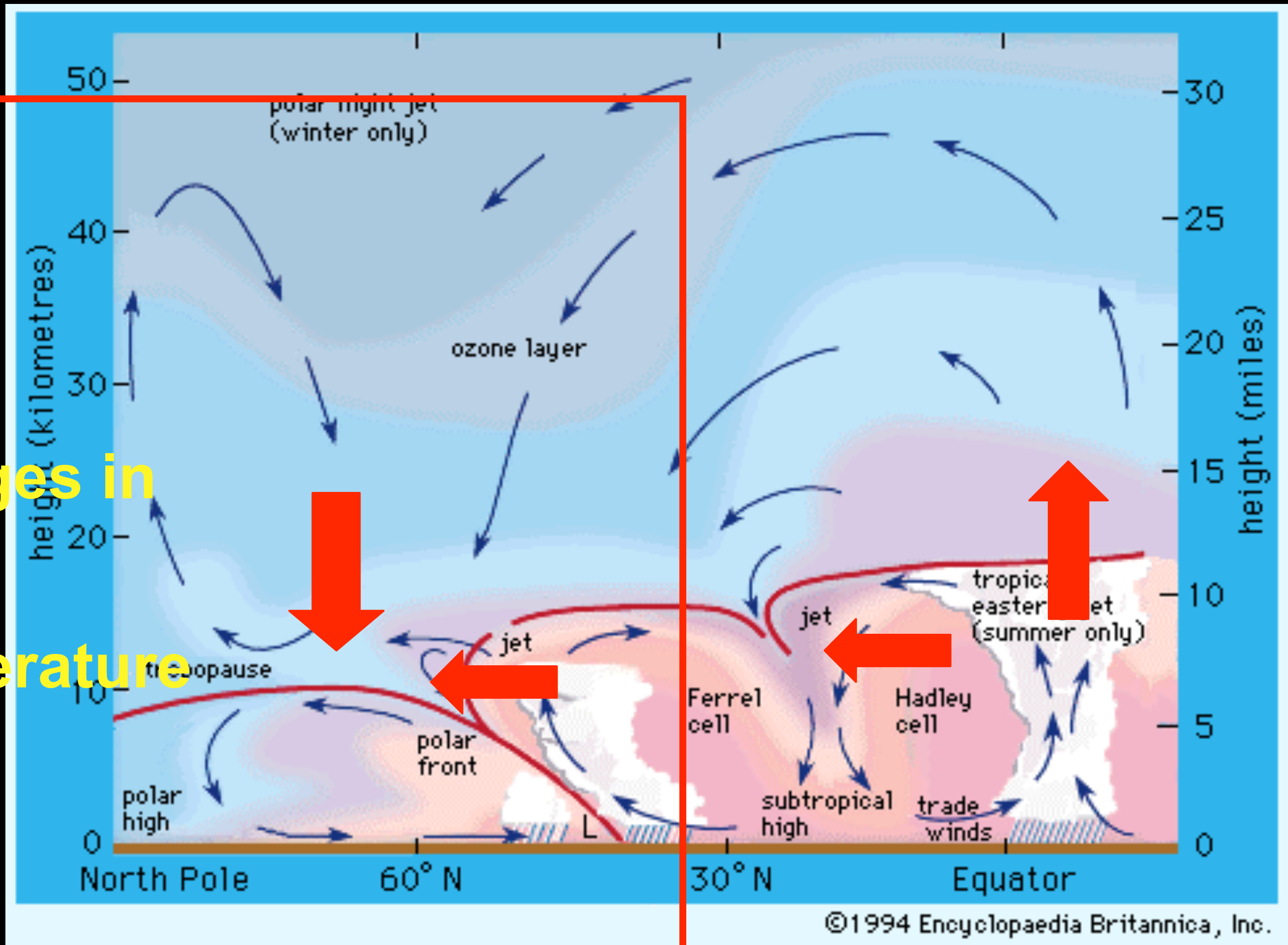
Fig. 3. Top panel: monthly mean H_2O vapor anomalies from HALOE (16–20 km, 20° S–20° N) in the tropics (black line) and POAM III (14–18 km) at middle to high NH latitudes (red line). Both lines represent three month mean water vapor VMRs, while black circles are monthly mean HALOE values (Update from Randel et al., 2006). Bottom panel: Time series of monthly mean 50 hPa eddy heat flux anomalies in each hemisphere and globally (added from both hemispheres).



Changing Circulation and Ozone Recovery

Coupled CCMs project a large range of different ozone recovery behavior in the polar regions in the 21st century

Cartoon Of Some Key Stratospheric And Climate Changes



- Cooling
- less strat H_2O
- changes in ozone
- temperature trends
- Shift of storm tracks, regional climates, SAM, NAM
- Mechanism? SST forcing? Wave forcing? other?

Modes of Variability in the Stratosphere and Troposphere

Stratospheric Harbingers of Anomalous Weather Regimes

Mark P. Baldwin* and Timothy J. Dunkerton

Observations show that large variations in the strength of the stratospheric circulation, appearing first above ~50 kilometers, descend to the lowermost stratosphere and are followed by anomalous tropospheric weather regimes. During the 60 days after the onset of these events, average surface pressure maps resemble closely the Arctic Oscillation pattern. These stratospheric events also precede shifts in the probability distributions of extreme values of the Arctic and North Atlantic Oscillations, the location of storm tracks, and the local likelihood of mid-latitude storms. Our observations suggest that these stratospheric harbingers may be used as a predictor of tropospheric weather regimes.

Weak vortex -> warmer, 'floppier'

Strong vortex -> colder, 'tighter'

Connections of stratosphere/troposphere on seasonal time scales. What about long term?

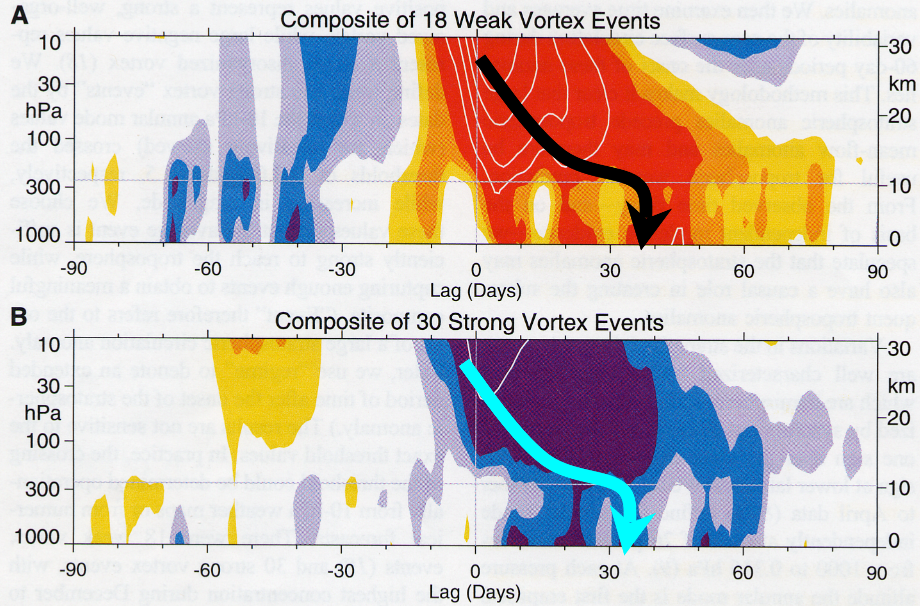


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross −3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between −0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

Box 3.3: Stratospheric-Tropospheric Relations and Downward Propagation

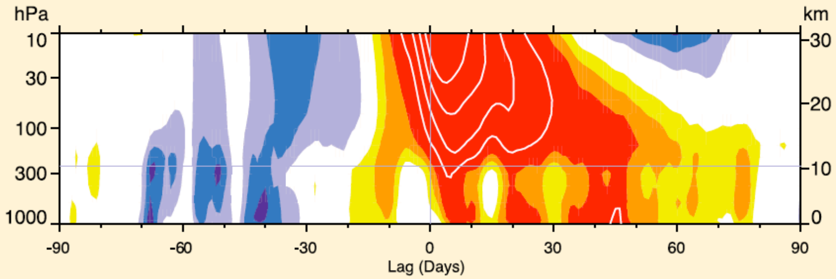
The troposphere influences the stratosphere mainly through planetary-scale waves that propagate upward during the extended winter season when stratospheric winds are westerly. The stratosphere responds to this forcing from below to produce long-lived changes to the strength of the polar vortices. In turn, these fluctuations in the strength of the stratospheric polar vortices are observed to couple downward to surface climate (Baldwin and Dunkerton, 1999, 2001; Kodera et al., 2000; Limpasuvan et al., 2004; Thompson et al., 2005). This relationship occurs in the zonal wind and can be seen clearly in annular modes, which explain a large fraction of the intra-seasonal and interannual variability in the troposphere (Thompson and Wallace, 2000) and most of the variability in the stratosphere (Baldwin and Dunkerton, 1999). Annular modes appear to arise naturally as a result of internal interactions within the troposphere and stratosphere (Limpasuvan and Hartmann, 2000; Lorenz and Hartmann, 2001, 2003).

The relationship between NAM anomalies in the stratosphere and troposphere can be seen in Box 3.3, Figure 1, in which the NAM index at 10 hPa is used to define events when the stratospheric polar vortex was extremely weak (stratospheric warmings). On average, weak vortex conditions in the stratosphere tend to descend to the troposphere and are followed by negative NAM anomalies at the surface for more than two months. Anomalously strong vortex conditions propagate downwards in a similar way.

Long-lived annular mode anomalies in the lowermost stratosphere appear to lengthen the time scale of the surface NAM. The tropospheric annular mode time scale is longest during winter in the NH, but longest during late spring (November–December) in the SH (Baldwin et al., 2003). In both hemispheres, the time scale of the tropospheric annular modes is longest when the variance of the annular modes is greatest in the lower stratosphere.

Downward coupling to the surface depends on having large circulation anomalies in the lowermost stratosphere. In such cases, the stratosphere can be used as a statistical predictor of the monthly mean surface NAM on time scales of up to two months (Baldwin et al., 2003; Scaife et al., 2005). Similarly, SH trends in temperature and geopotential height, associated with the ozone hole, appear to couple downward to affect high-latitude surface climate (Thompson and Solomon, 2002; Gillett and Thompson, 2003). As the stratospheric circulation changes with ozone depletion or increasing greenhouse gases, those changes will likely be reflected in changes to surface climate. Thompson and Solomon (2005) showed that the spring strengthening and cooling of the SH polar stratospheric vortex preceded similarly signed trends in the SH tropospheric circulation by one month in the interval 1973 to 2003. They argued that similar downward coupling is not evident in the NH geopotential trends computed using monthly radiosonde data. An explanation for this difference may be that the stratospheric signal is stronger in the SH, mainly due to ozone depletion, giving a more robust downward coupling.

The dynamical mechanisms by which the stratosphere influences the troposphere are not well understood, but the relatively large surface signal implies that the stratospheric signal is amplified. The processes likely involve planetary waves (Song and Robinson, 2004) and synoptic-scale waves (Wittman et al., 2004), which interact with stratospheric zonal wind anomalies near the tropopause. The altered waves would be expected to affect tropospheric circulation and induce surface pressure changes corresponding to the annular modes (Wittman et al., 2004).



Box 3.3, Figure 1. *Composites of time-height development of the NAM index for 18 weak vortex events. The events are selected by the dates on which the 10 hPa annular mode index crossed –3.0. Day 0 is the start of the weak vortex event. The indices are non-dimensional; the contour interval for the colour shading is 0.25, and 0.5 for the white lines. Values between –0.25 and 0.25 are not shaded. Yellow and red shading indicates negative NAM indices and blue shading indicates positive indices. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere. Modified from Baldwin and Dunkerton (2001).*

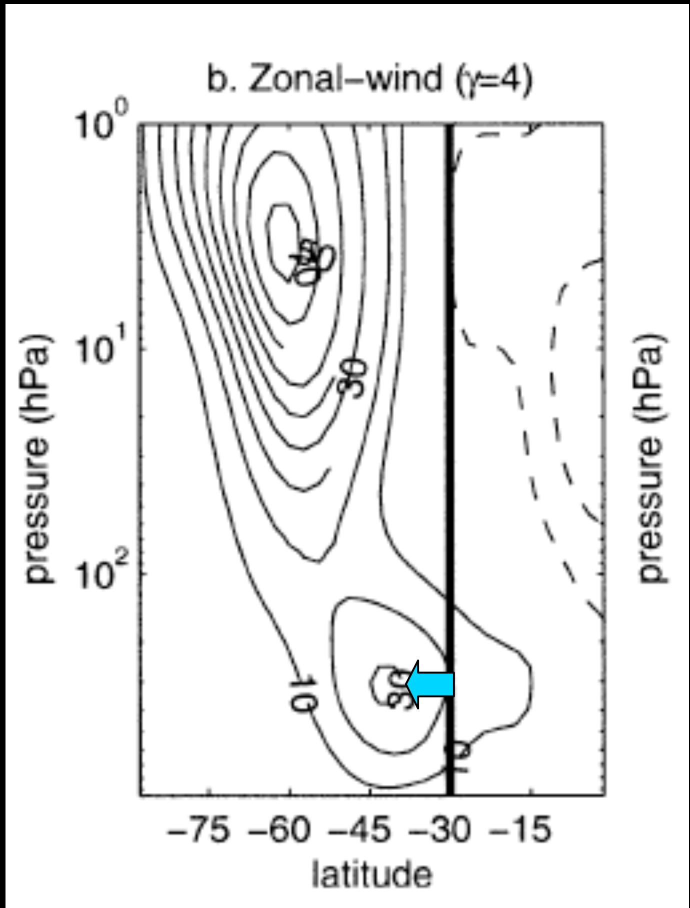
Highlighted in IPCC (2007) Chapter 3.

Mechanism(s)?

Planetary waves? Synoptic waves? Role of jets?

Many important papers by Baldwin, Dunkerton, Thompson, Polvani, Kushner, Haynes, Shepherd, Robinson, others…

How Does the Fluid Dynamics Work?



Stratosphere–Troposphere Coupling in a Relatively Simple AGCM: The Role of Eddies

PAUL J. KUSHNER

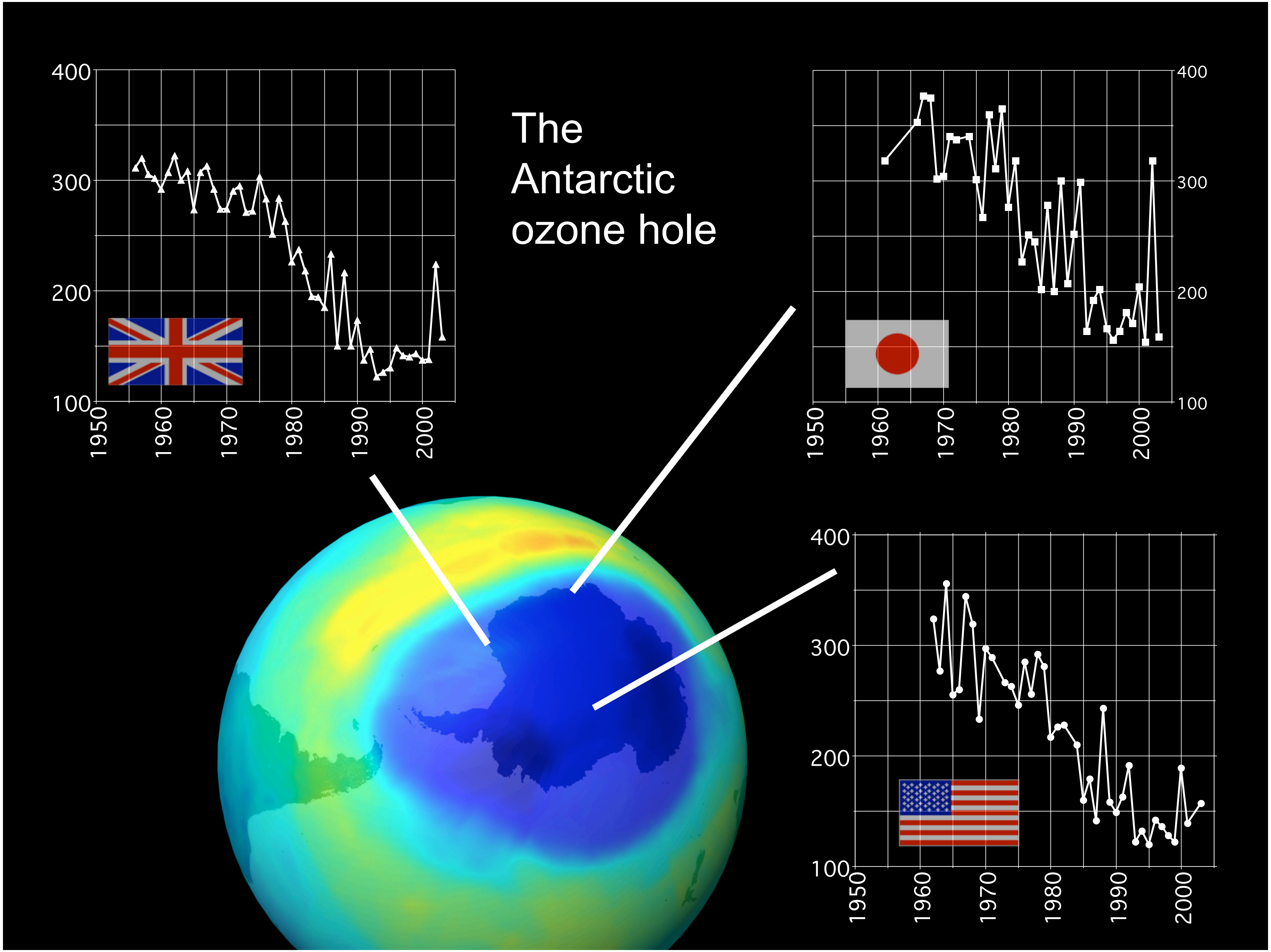
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

LORENZO M. POLVANI*

Department of Applied Physics and Applied Mathematics and the Department of Earth and Environmental Sciences, Columbia University, New York, New York

(Manuscript received 16 January 2003, in final form 29 July 2003)

- Position of the jet moves as polar stratosphere cools?
- "Downward control": change in the stratosphere moves down to the lower atmosphere through conservation of mass/momentum.
- More complex models?
- Initiation and/or amplification by coupling through eddies (waves)?

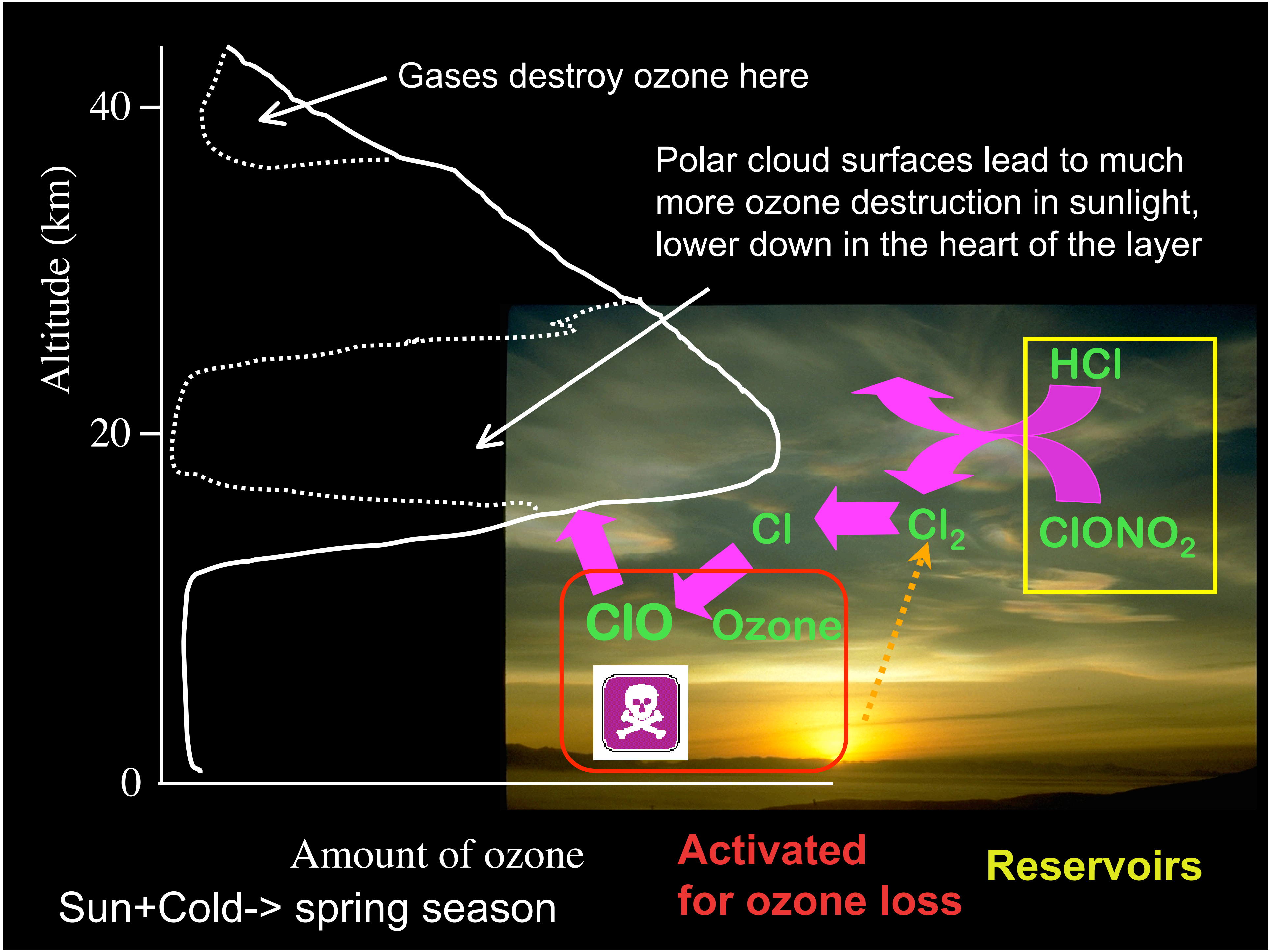

The
Antarctic
ozone hole
400
300
200
100
1950
1960
1970
1980
1990
2000
400
300
200
100
1950
1960
1970
1980
1990
2000
400
300
200
100
1950
1960
1970
1980
1990
2000

Clouds that form in the cold polar stratosphere allow surface (heterogeneous) chemistry to take place, enhancing ozone destruction by manmade chlorine.

Key reaction is
$HCl + ClONO_2 \rightarrow Cl_2 + HNO_3$

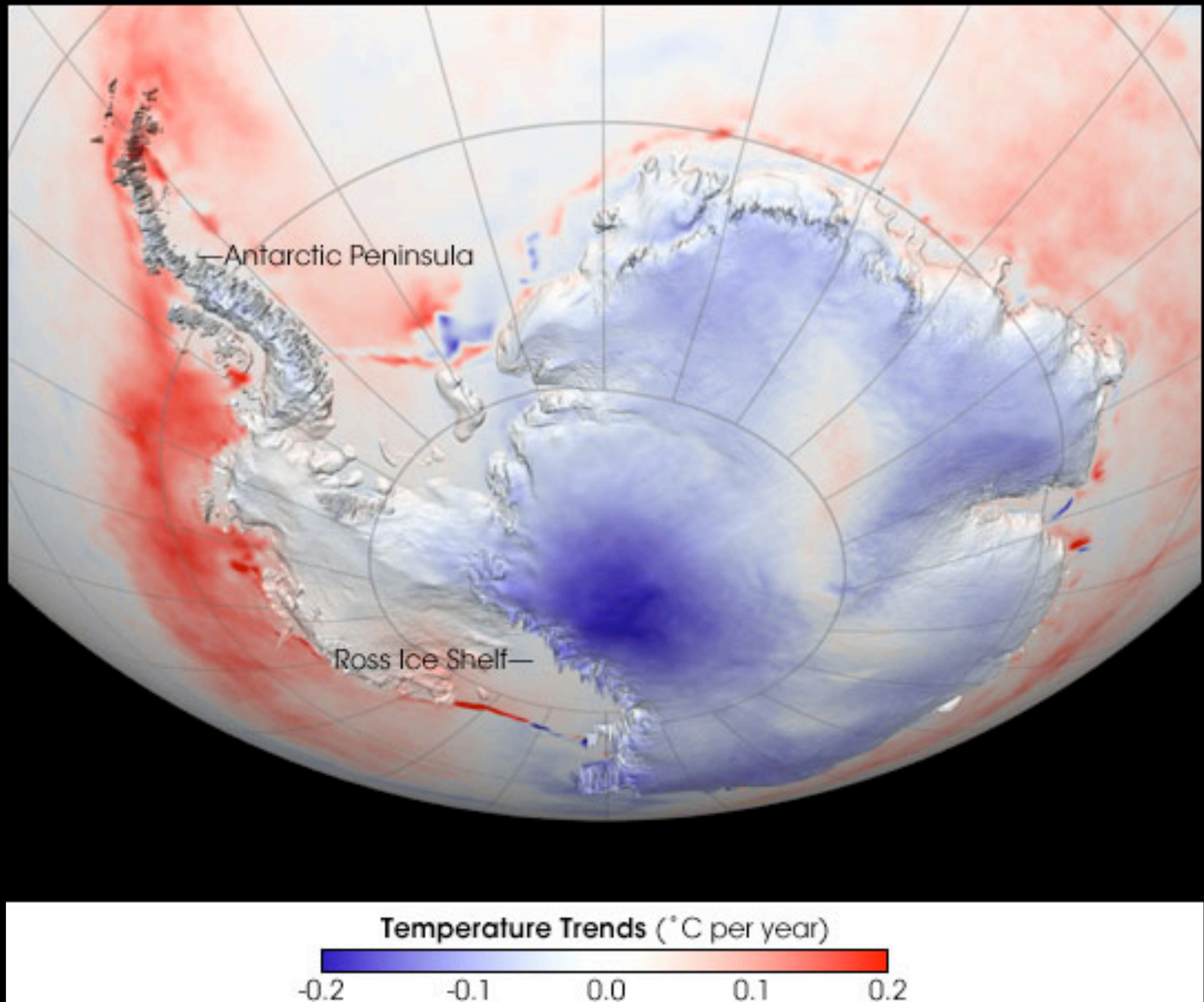
(Solomon et al., Nature, 1986).

Surface chemistry under the very cold conditions of Antarctica



Gases destroy ozone here
Polar cloud surfaces lead to much more ozone destruction in sunlight, lower down in the heart of the layer
40
20
0
Altitude (km)
Amount of ozone
HCl
$ClONO_2$
Cl_2
Cl
ClO
Ozone
Activated for ozone loss
Reservoirs
Sun+Cold-> spring season

Antarctic Surface Climate: Why So Different from the Rest of the World?

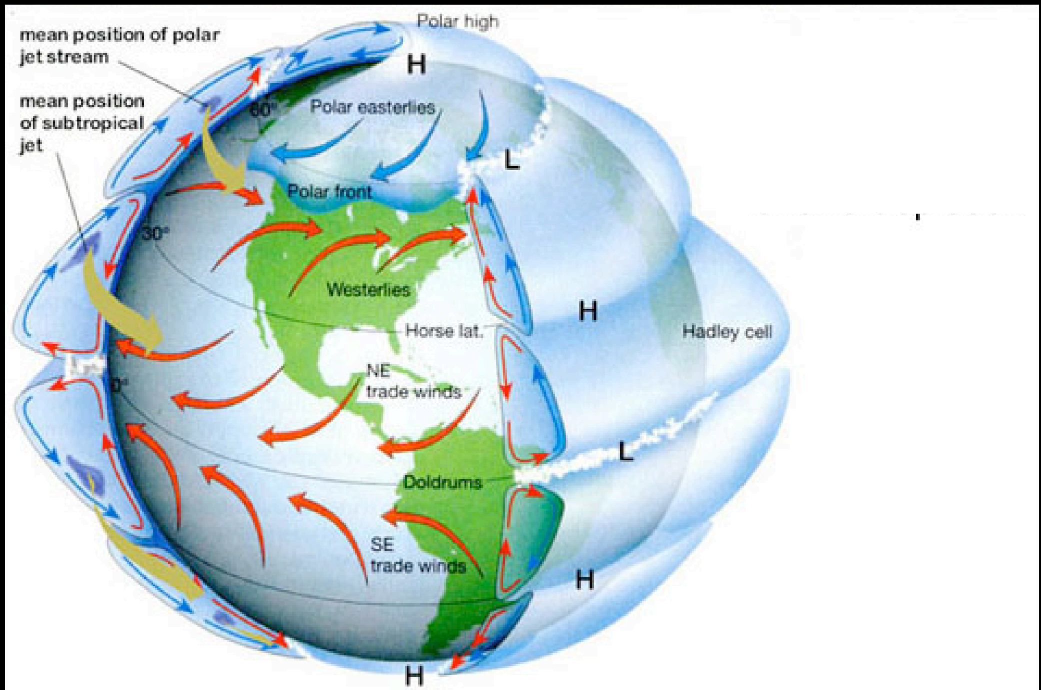


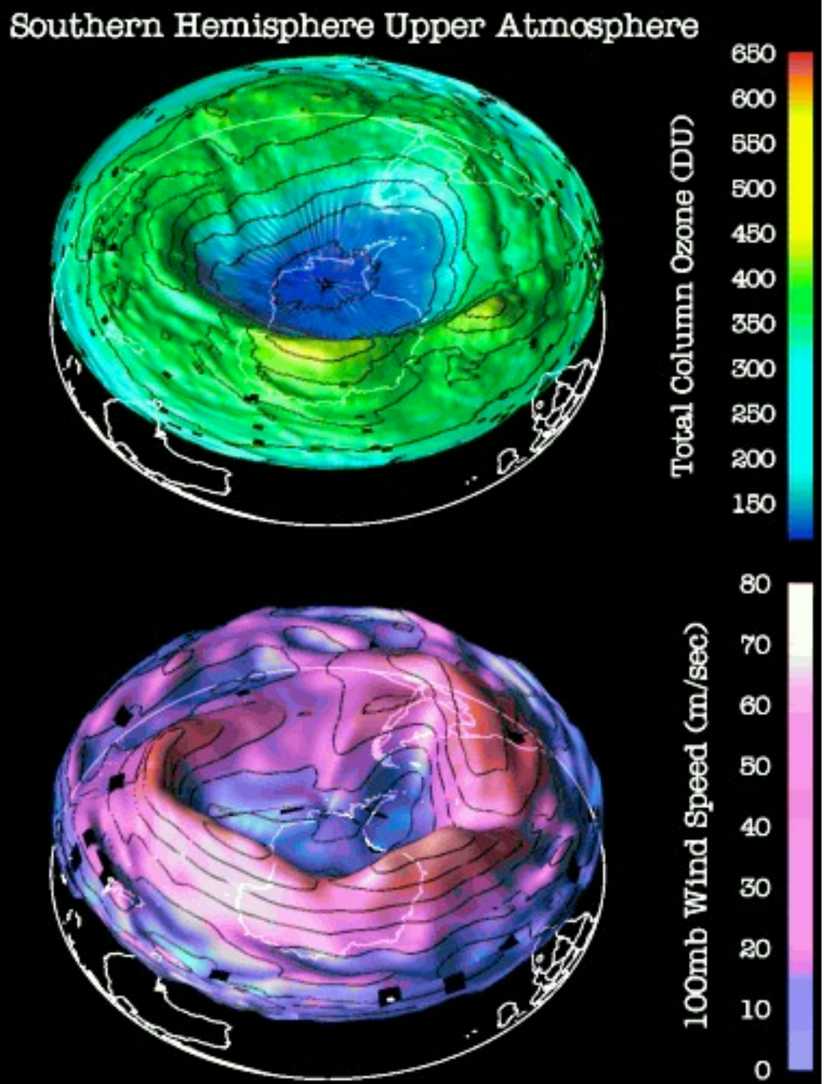
Summer skin temperature trends 1982-2004 from AVHRR

http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17257

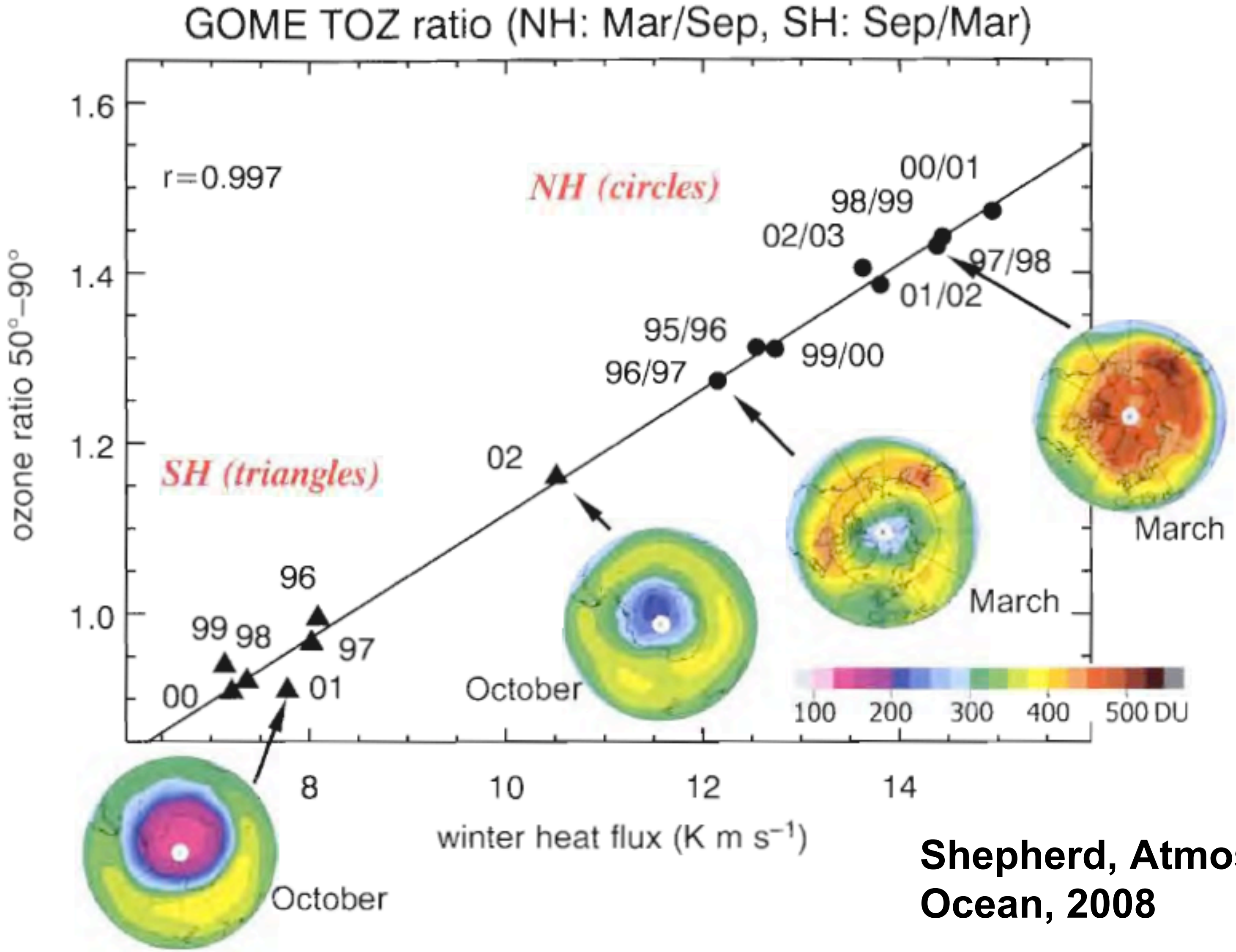
Ozone and Climate in the Vortex

A fundamental aspect of temperature, wind, and climate variability in the polar regions





Poles Apart: How ozone used to be and how it is now



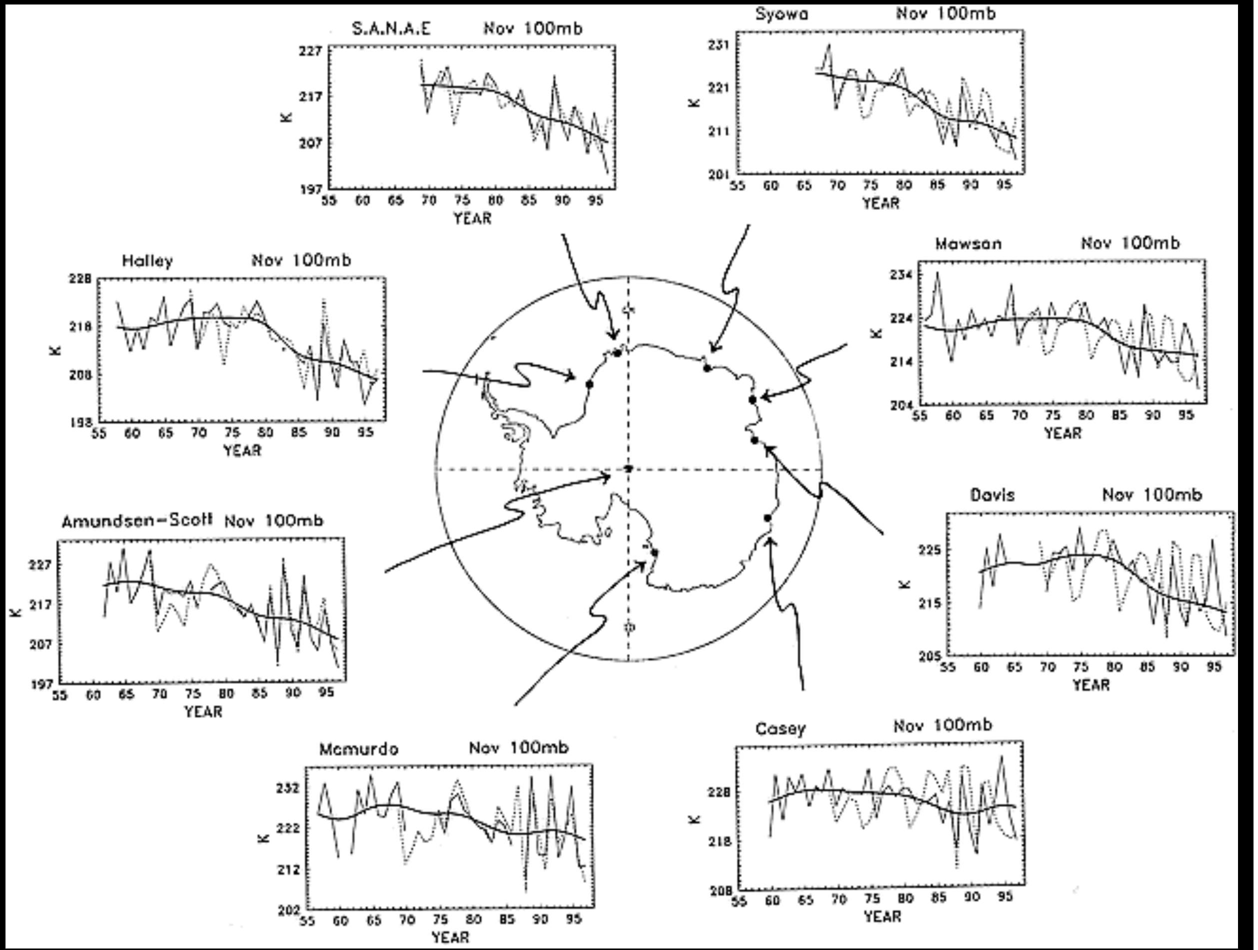
Shepherd, Atmos. Ocean, 2008

Ozone losses in the Arctic are much less severe than the Antarctic.

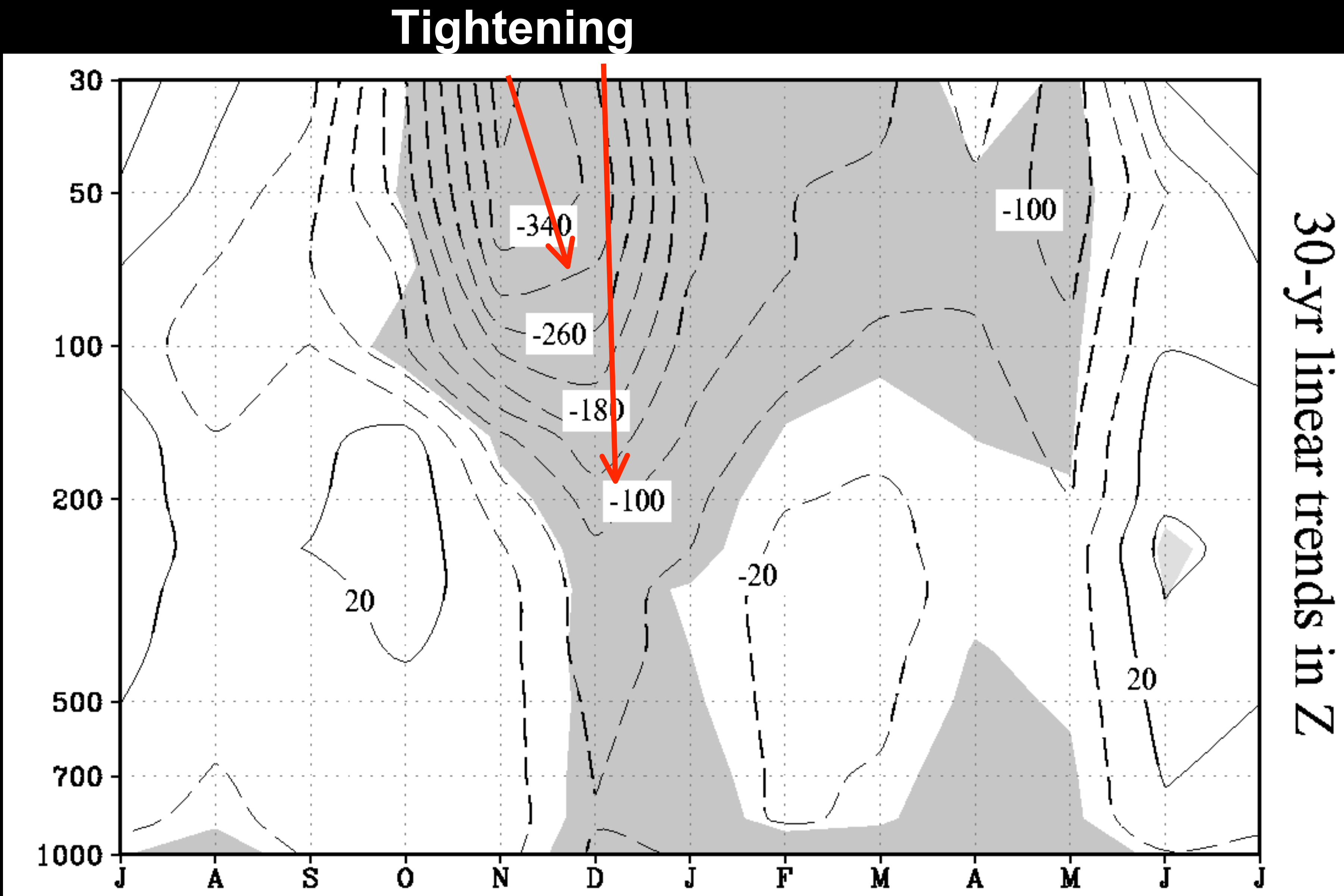
Ozone Depletion Changes The Antarctic Stratosphere

With so much less ozone, the Antarctic spring stratosphere gets much colder (5-10°C in November) and 'tighter', a remarkable change in stratospheric climate.

These cooling trends are very large…do they propagate down to affect the troposphere, and even surface climate?

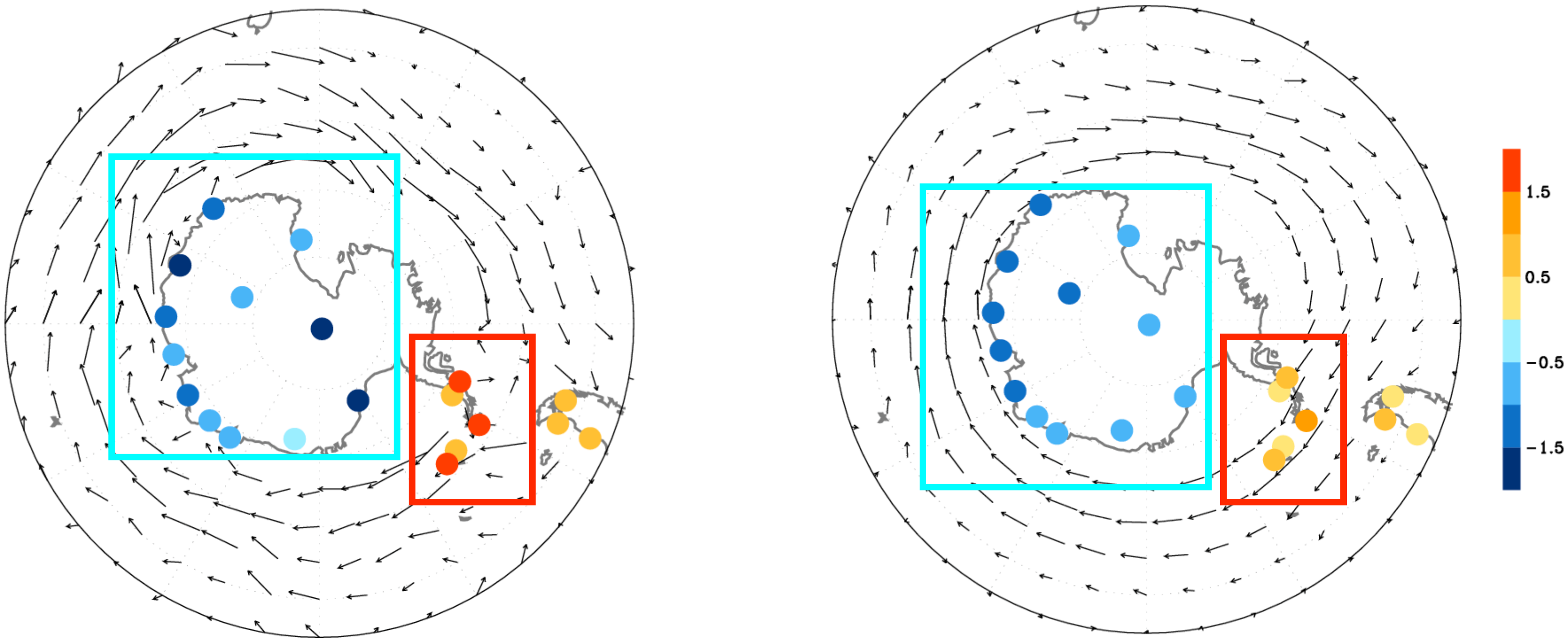


Recent SH climate change



Recent surface climate trends and the vortex

Total trends | Congruent with SAM



Recent trends in surface temperature and wind (Dec-May 1969-2000).
Stronger vortex: cold air stays bottled up in the vortex, so the plateau gets colder while the peninsula gets warmer

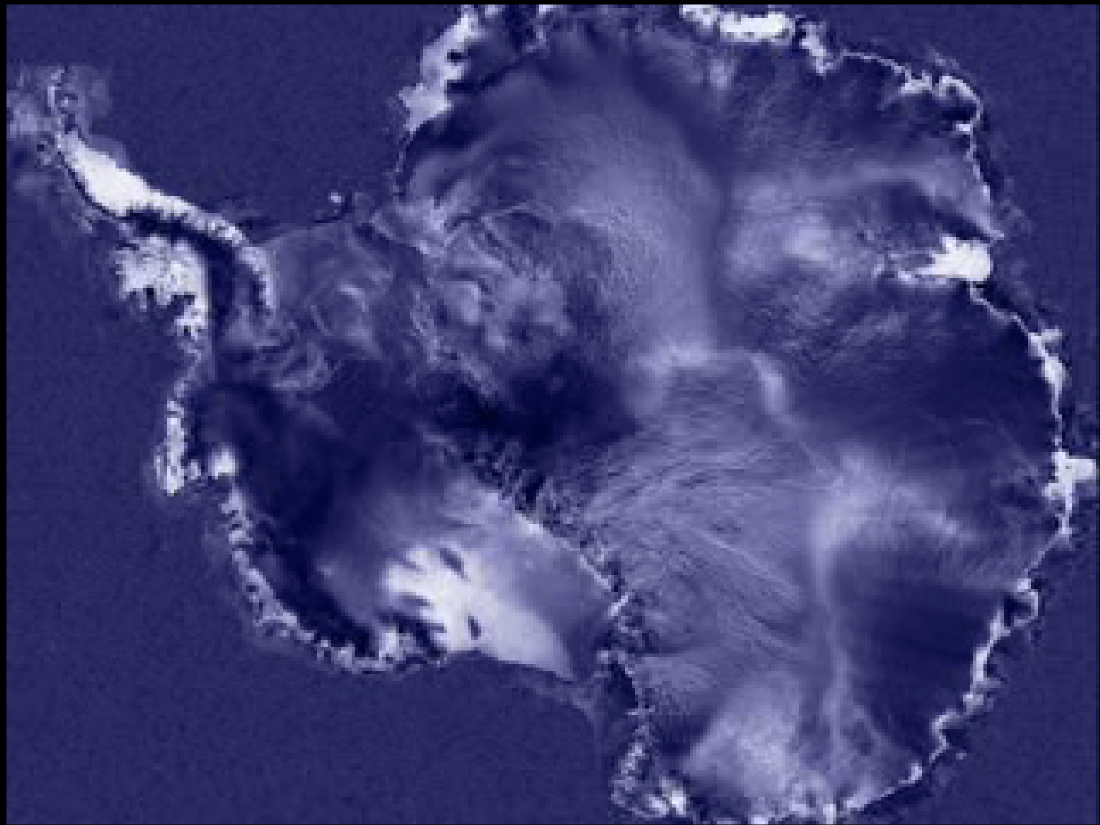
Thompson and Solomon Science 2002

Ice

Do we understand what is happening to ice shelves?

Satellite imagery shows disintegration of an area of about 3250 km^2 over 35 days in early 2002.

The Larsen B ice shelf, Antarctica.



Source: NASA

Variability in the Antarctic climate

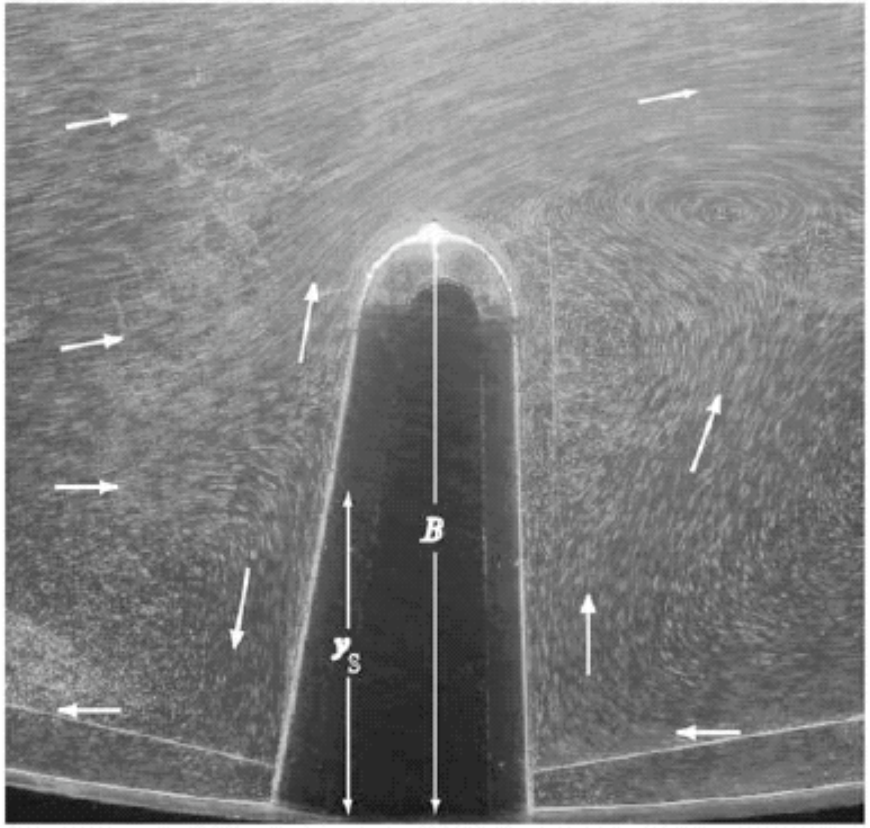
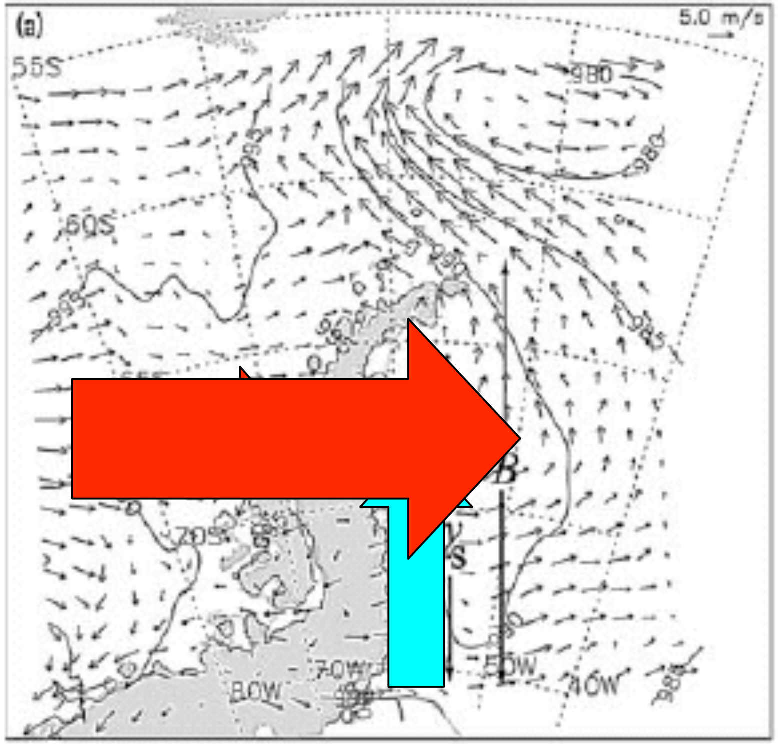


Figure 2. Horizontal streamline photograph of simulated low-level westerly flow (left to right) around a cape in the Southern Hemisphere, with $\mathbb{F} \approx 1/3$. The length y_S defines the position of the stagnation point from the base of the cape and B is the length of the cape. See color version of this figure in the HTML.



Effects of the peninsula topography on Antarctic flow patterns. Competition: westerlies and blocking.

Variability in the Antarctic climate

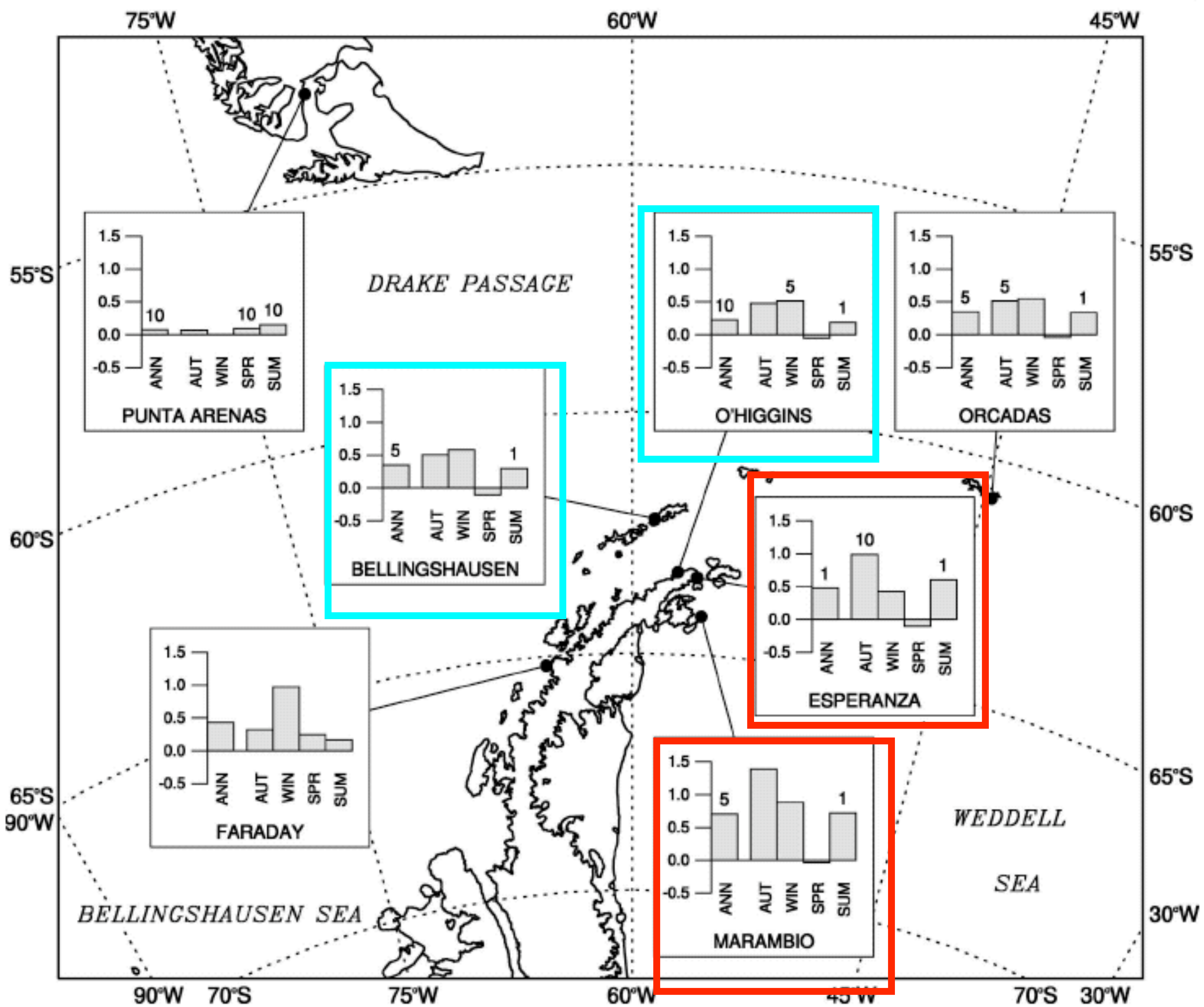
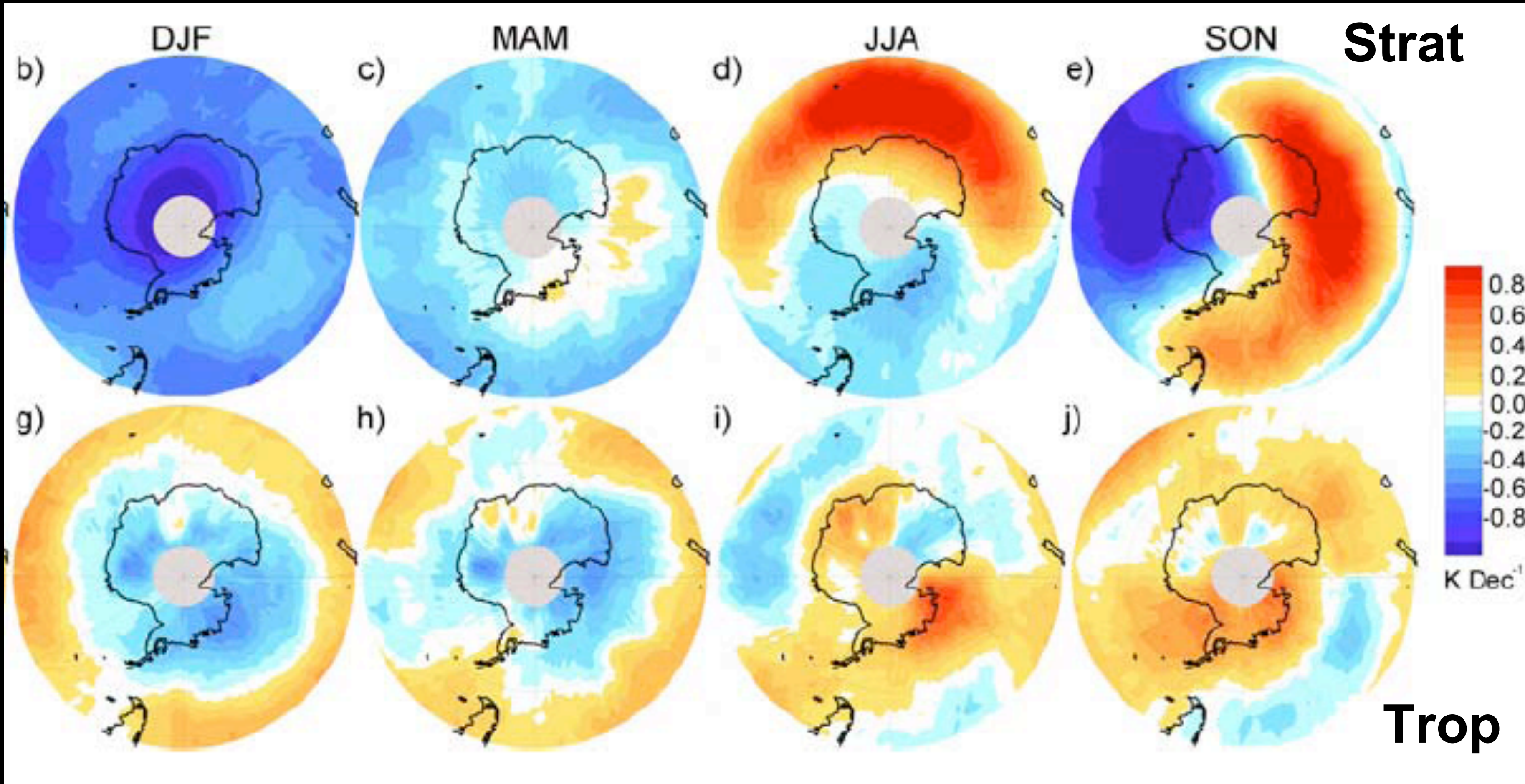


FIG. 1. The northern Antarctic Peninsula and southern South American region showing the location of stations examined in this study. The graphs show the change in annual and seasonal—autumn: March–May (MAM), winter: June–August (JJA), spring: September–November (SON), and summer: December–February (DJF)—near-surface temperature coincident with the positive trend in the SAM that began in the mid-1960s. The trends are calculated over 1965–2000, except for Bellingshausen (1968–2000) and Marambio (1970–2000). Units are °C decade^{-1}. Values are shown if the significance level of the trend is at the <1%, <5%, or <10% level.

Largest warming trends on the east side of the Peninsula in summer and autumn, due to stronger westerly flow (SAM), overwhelming blocking.

Satellite Data Provide A Key Check



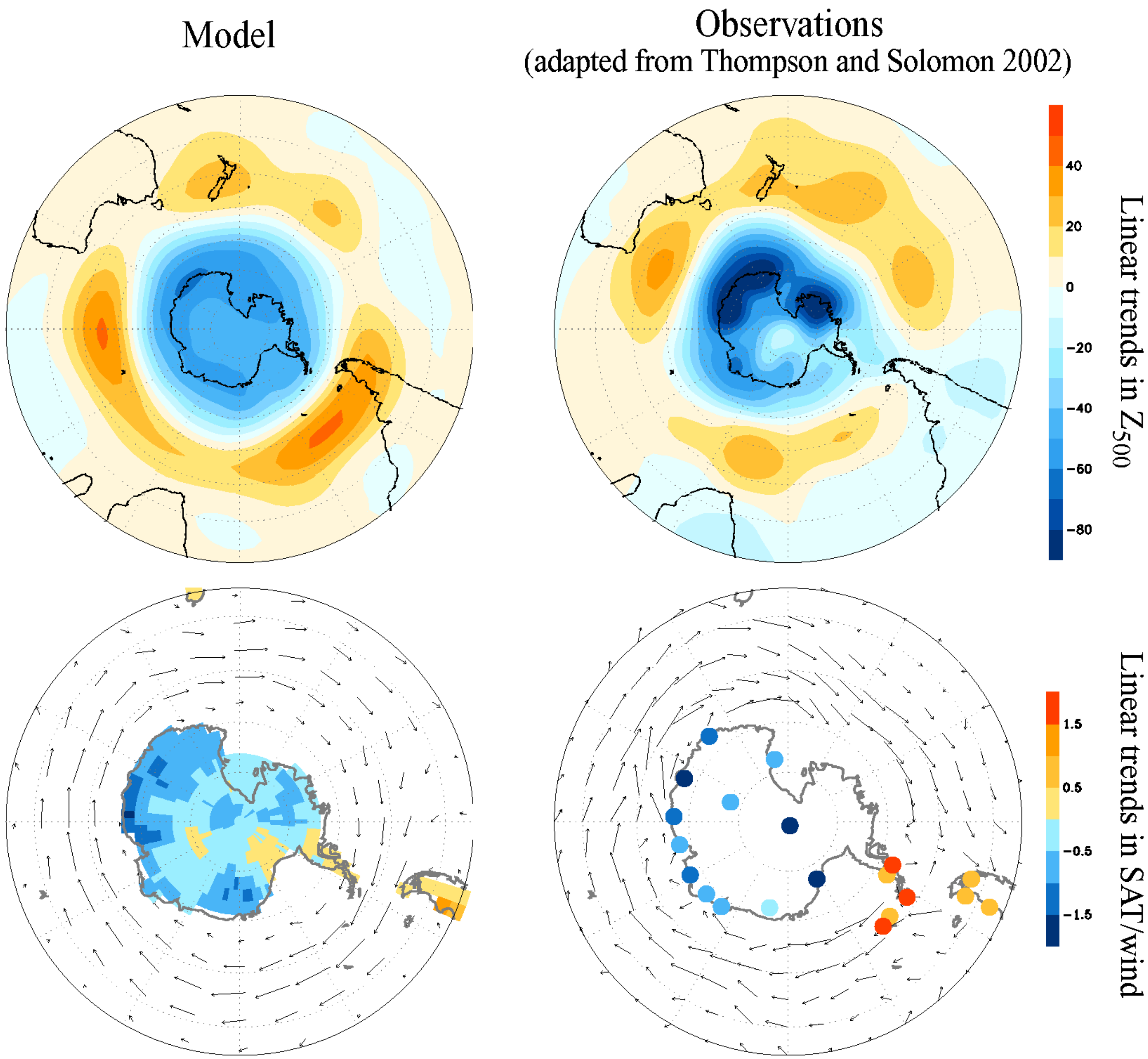
Summer season (DJF) cooling extends from the stratosphere to the troposphere. There is a lot of structure. [Johanson and Fu, Geophys. Res. Lett., 2007]

Model/Measurement Comparison

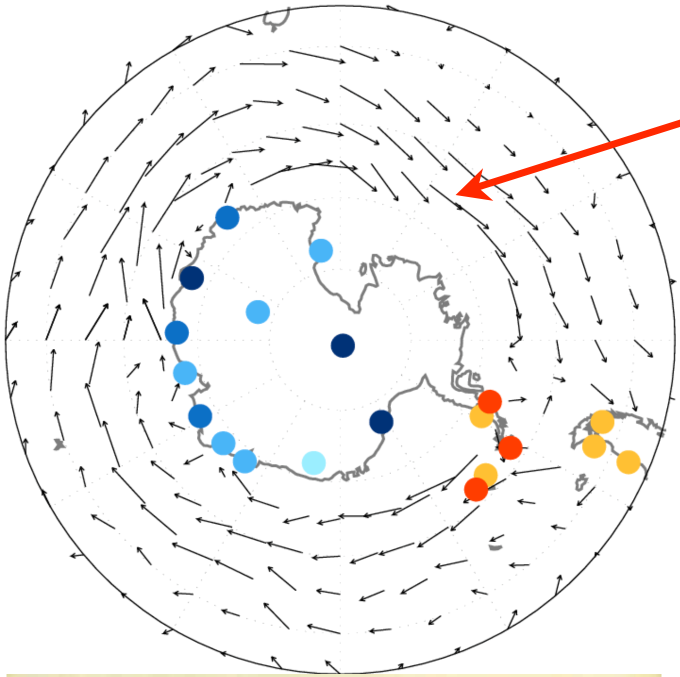
Hadley Center GCM forced with obsvd ozone depletion

(Gillett and Thompson, 2003).

{GHGs can also contribute to strengthening the vortex, but ozone has a much bigger effect.}



Couplings: Winds And Ozone, and Climate Variability and Change

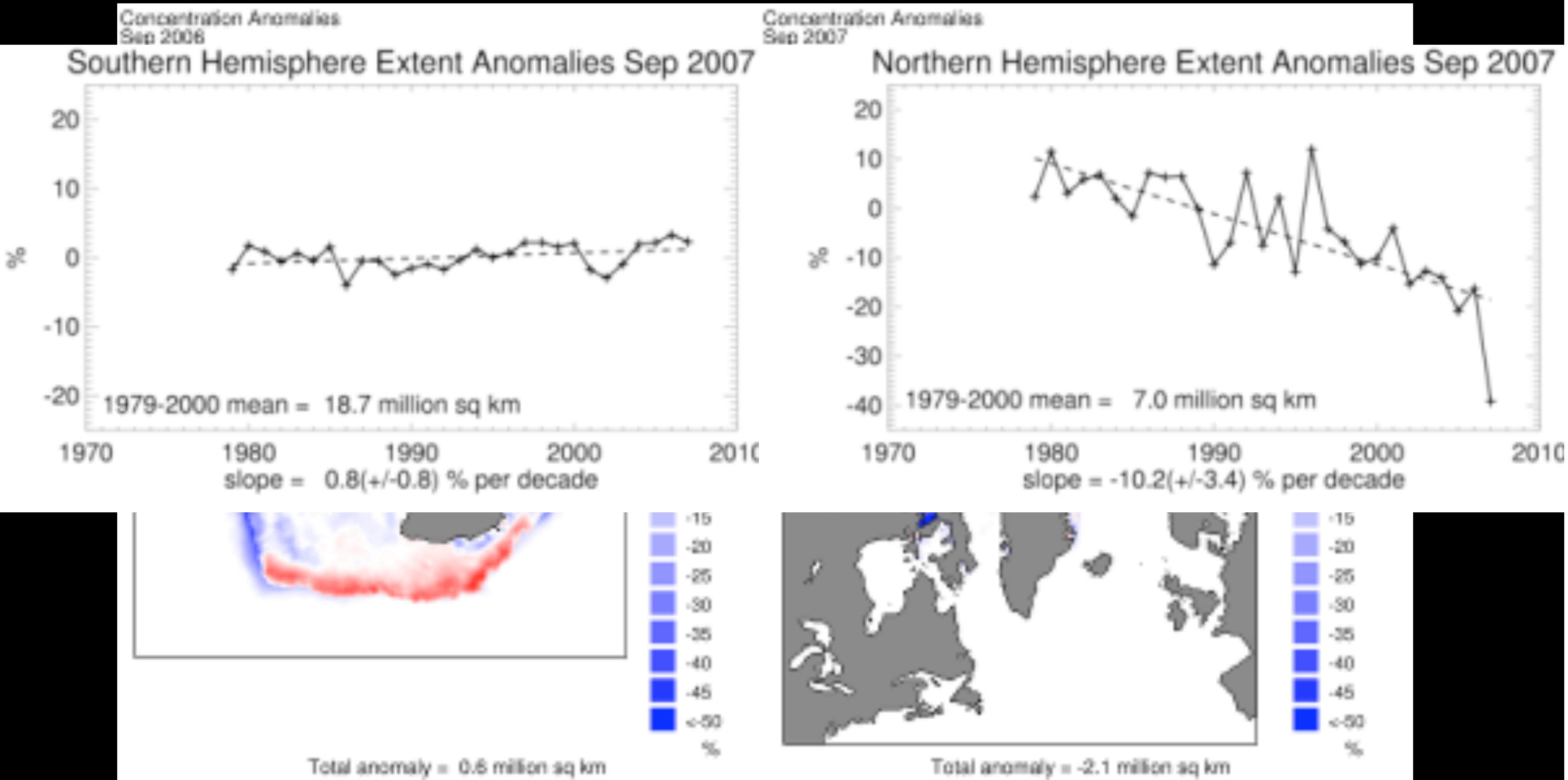


Stronger avg westerlies

Links to SH rainfall and perhaps Australian drought?

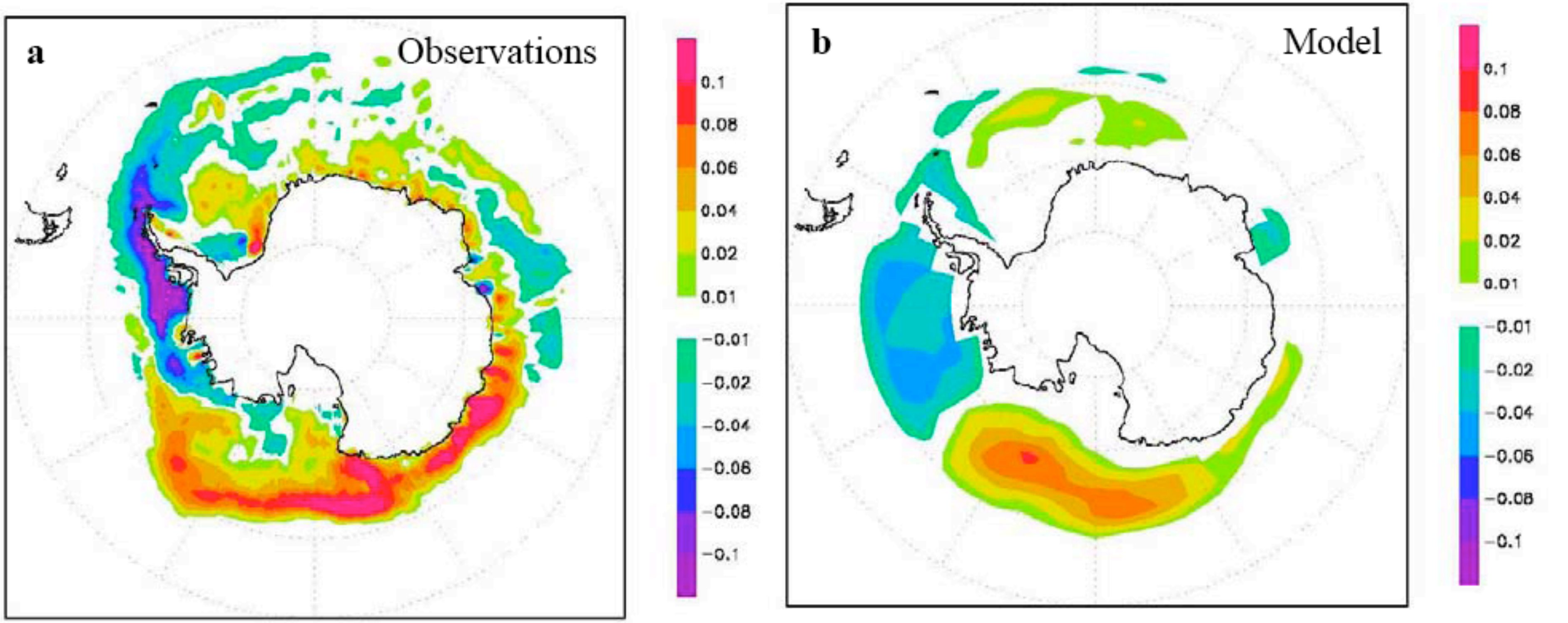
How do changes in wind stress affect ocean circulation and carbon and heat transport?

Arctic and Antarctic sea ice trends



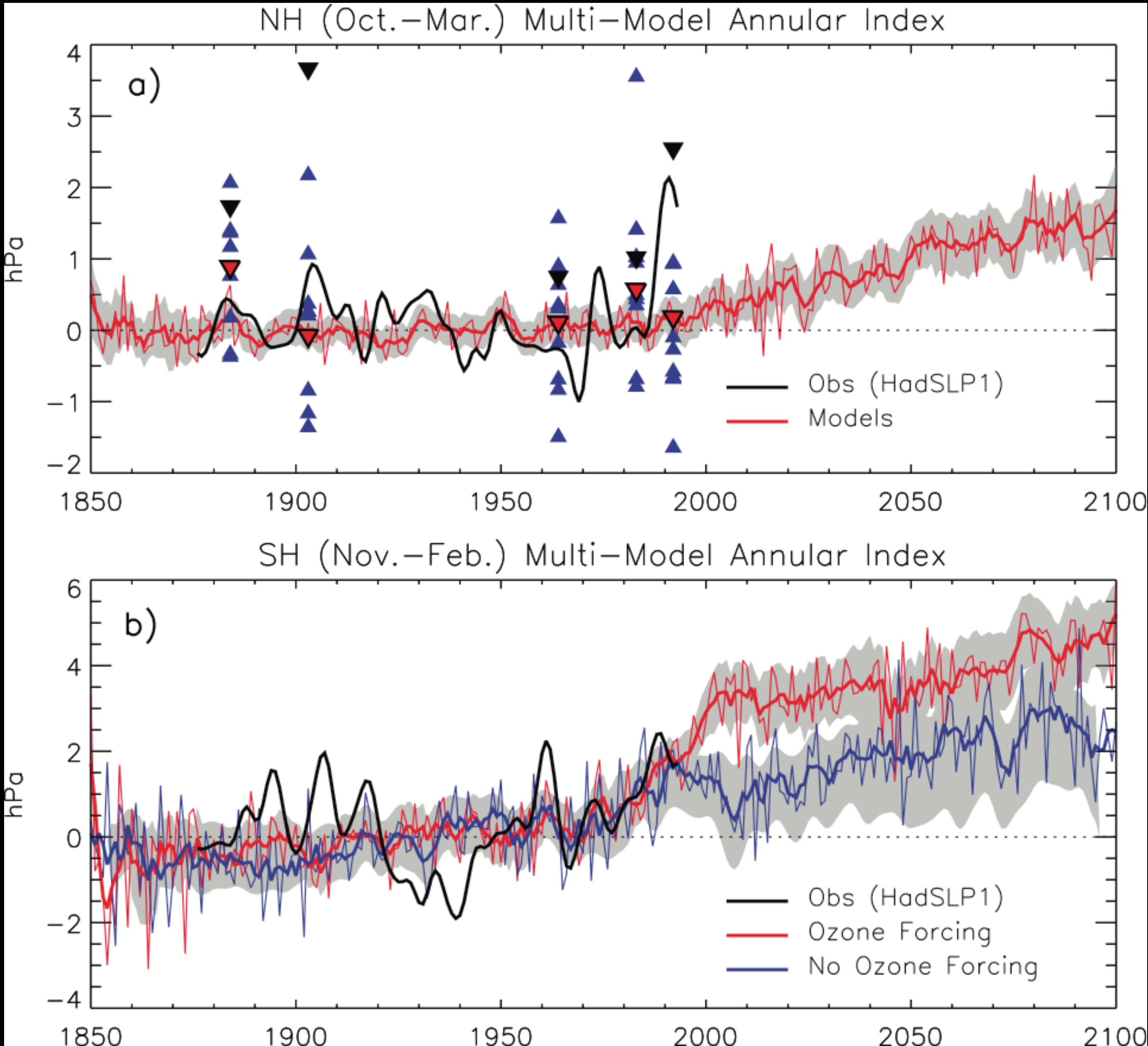
Overall trends very different. Ozone and SAM has affected the air temperatures and circulation patterns in SH summer (and probably fall as well). Is this affecting sea ice?

Arctic and Antarctic sea ice trends for 1980-2000 vs model with data assimilation to capture SAM trends:



Goosse et al, in press, Clim. Dyn., 2008

Increases in sea ice extent driven by SAM changes 1980-2000 (circulation, ozone?). Model also shows decreases for 1950-1980 (warming, GHG?).



NH?

SH√

Miller et al. JGR 2005; IPCC (2007) Ch 10

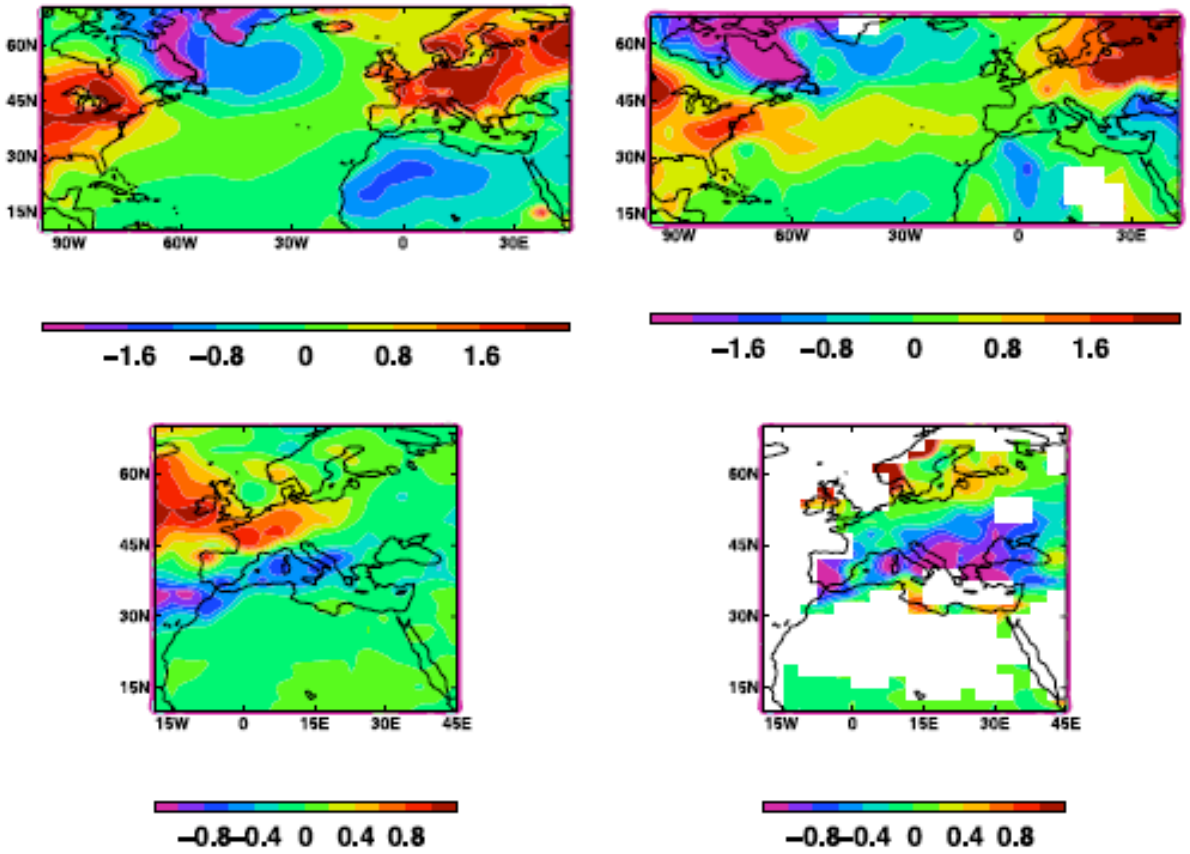
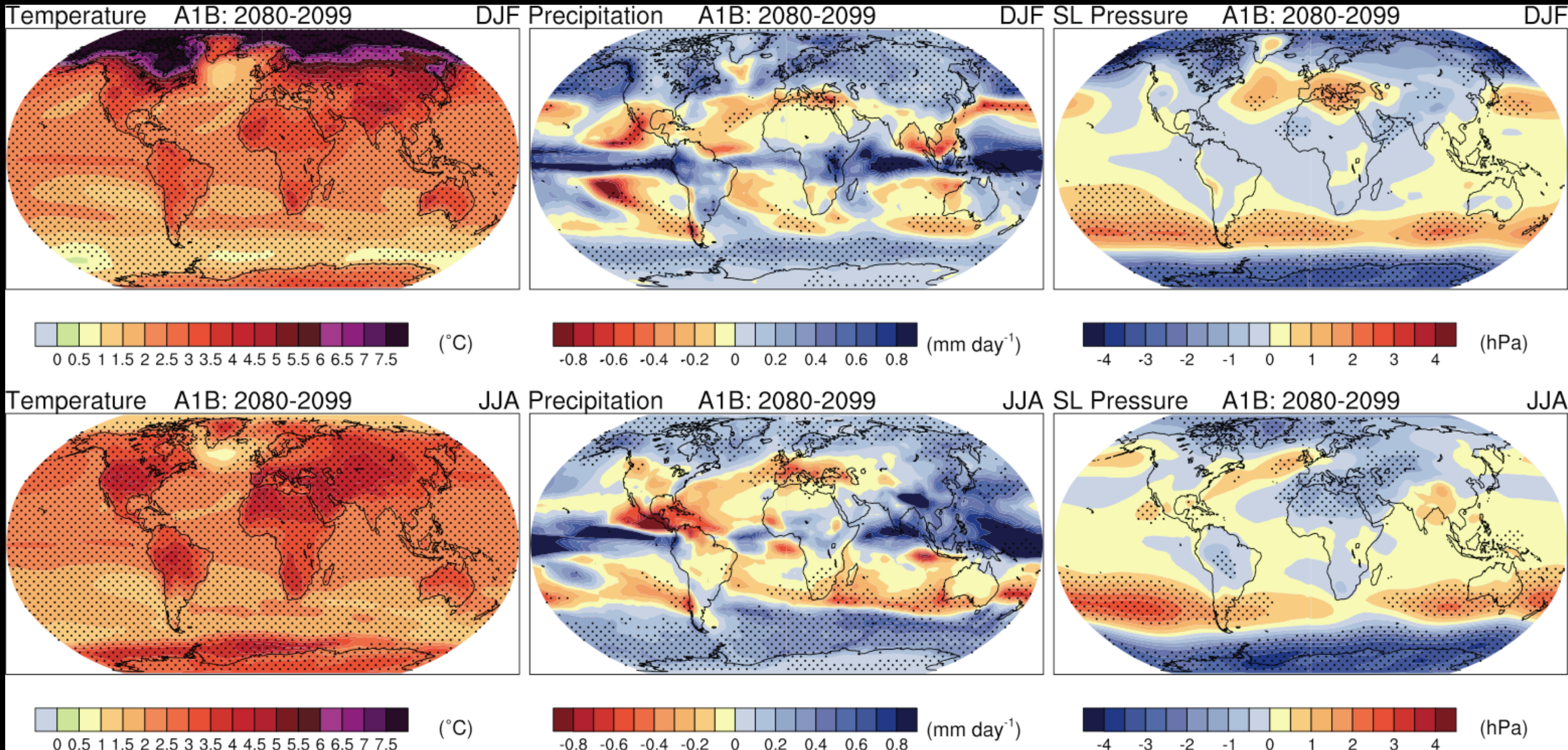


Figure 4. Surface climate response to the stratospheric circulation trend and comparison with observed changes. Upper left, modelled winter surface temperature change. Upper right, observed winter surface temperature change (K). Lower left, modelled winter precipitation change. Lower right, observed winter precipitation change over land (mm day^{-1}). Differences between 1990–95 and 1965–70 are shown. Model results are the difference between perturbed and control experiments.

Scaife: if you can't model it, prescribe it….

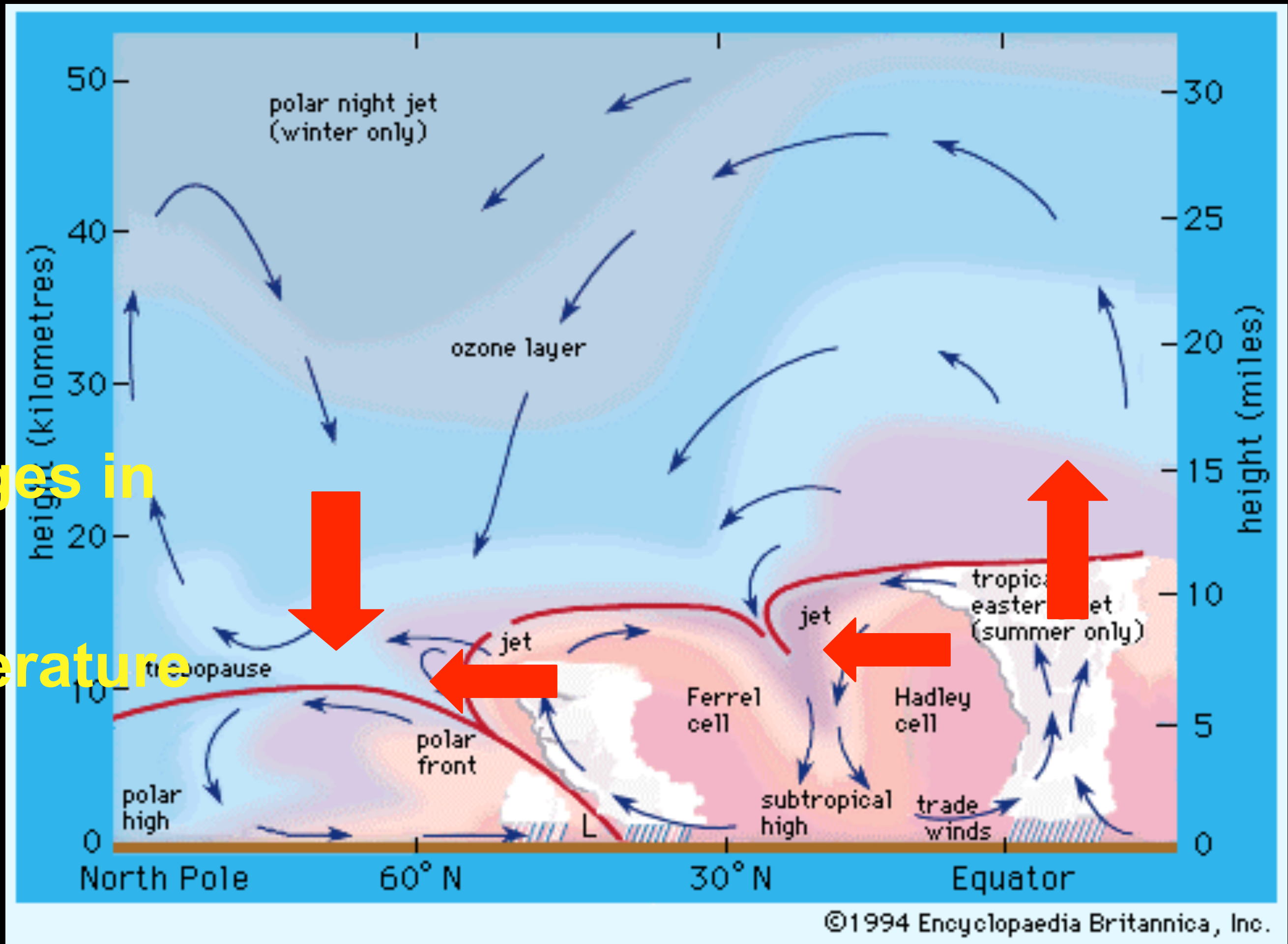
Large impact of the stratosphere on NH climate changes?

Climate Changes of IPCC (2007)



IPCC (2013): To do better on many aspects of structure/regional behavior, will benefit from a better understanding of the stratosphere

Cartoon Of Some Key Stratospheric And Climate Changes



- changes in ozone
- temperature trends

- Cooling
- less strat H_2O

- Shift of storm tracks, regional climates, SAM, NAM

- Mechanism(s)? SST forcing? Wave forcing? other?

Thanks for your attention, and for your support of the IPCC process