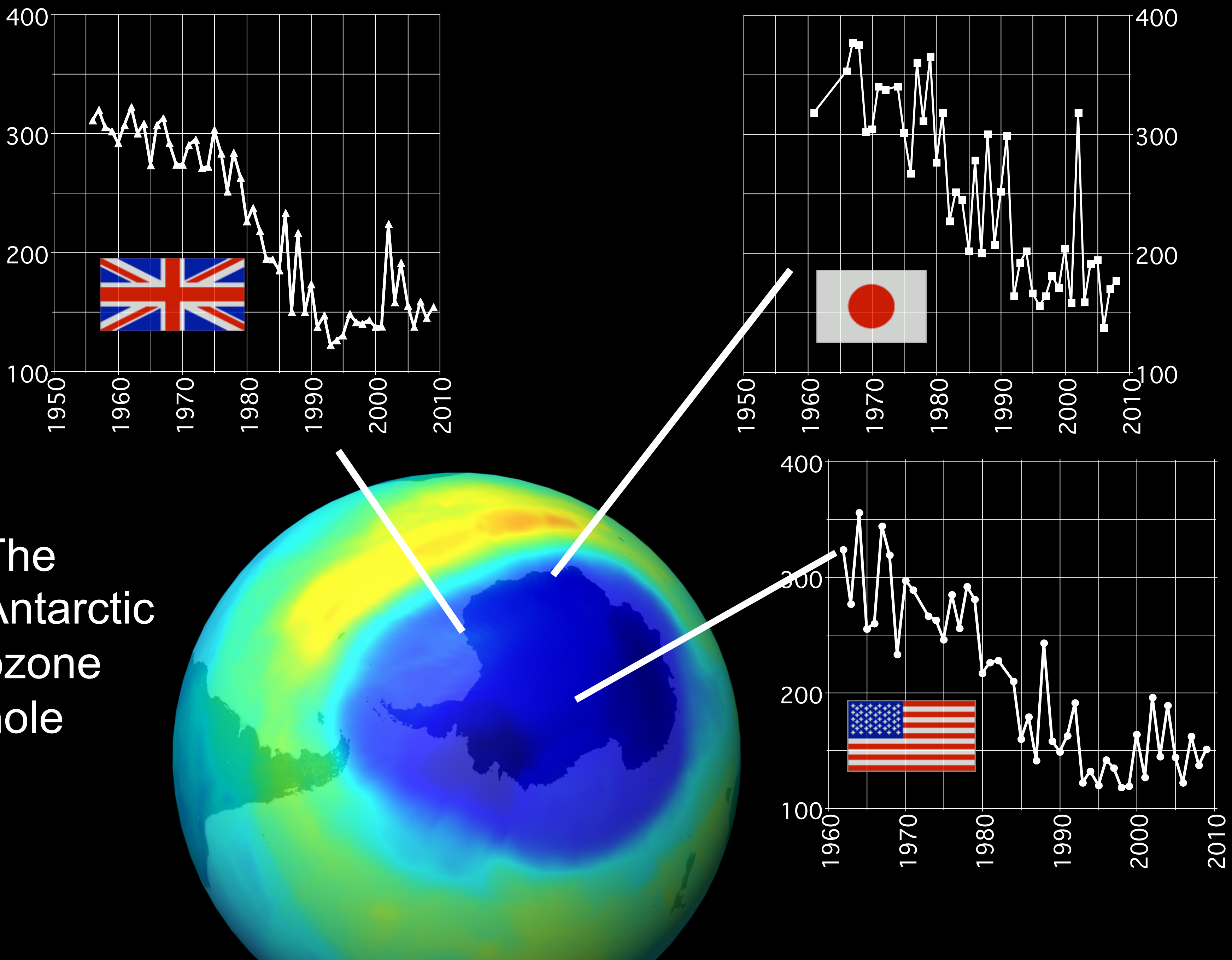
Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change

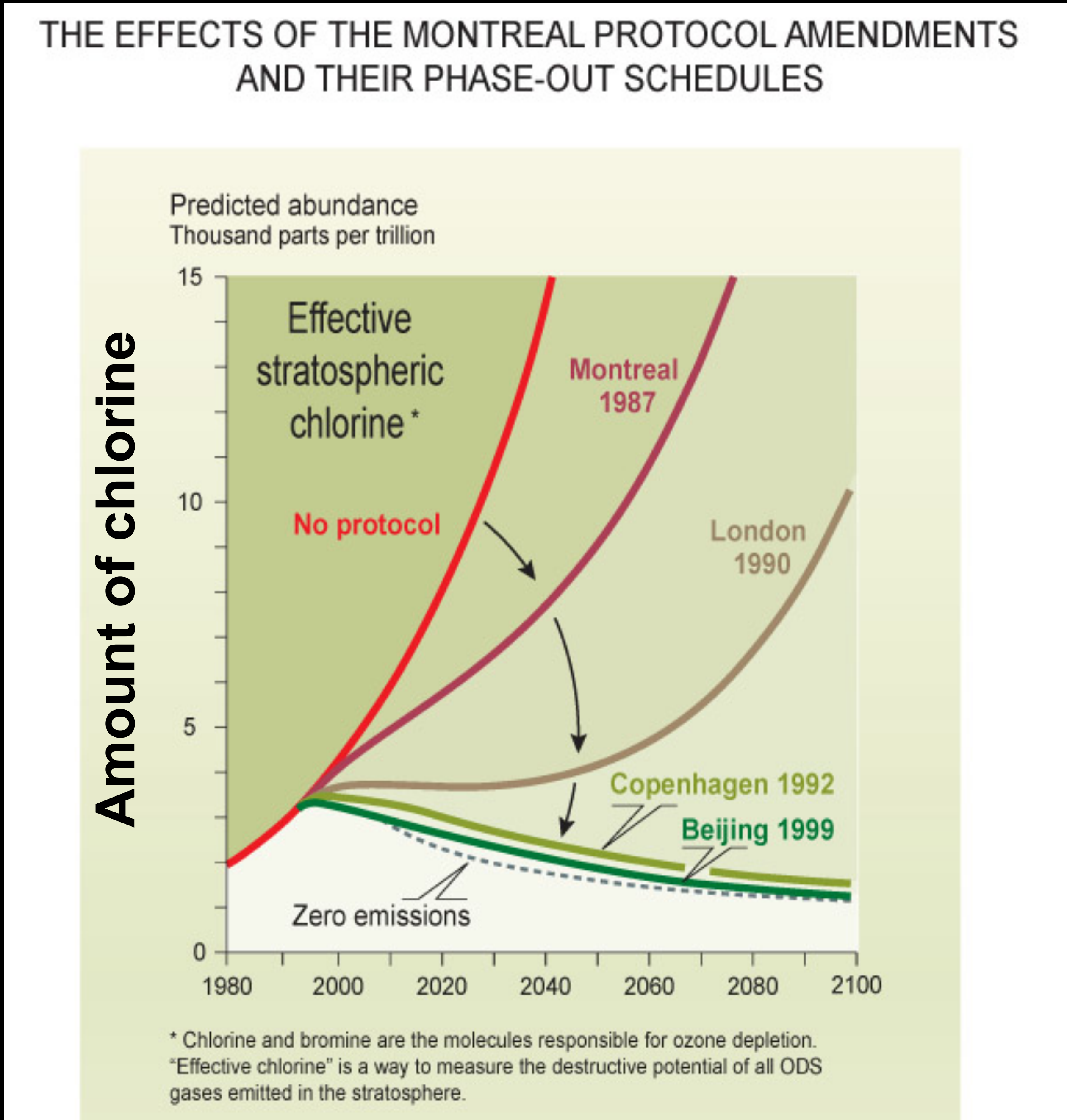
Susan Solomon presenting

Antarctic ozone depletion and southern hemisphere surface climate, not just in Antarctica but also at lower latitudes (Australia, southern Africa….)

Bandoro et al., J. Clim., in press, 2014

The Antarctic ozone hole





Concern about ozone depletion led the nations of the world to agree to a Montreal Protocol to freeze and then phaseout CFC emissions. CFCs will slowly decay over the 50 years+.

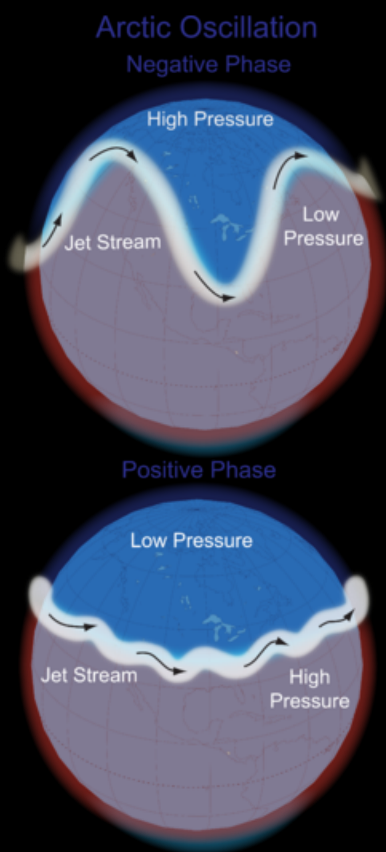
Ozone and Climate in the Vortex

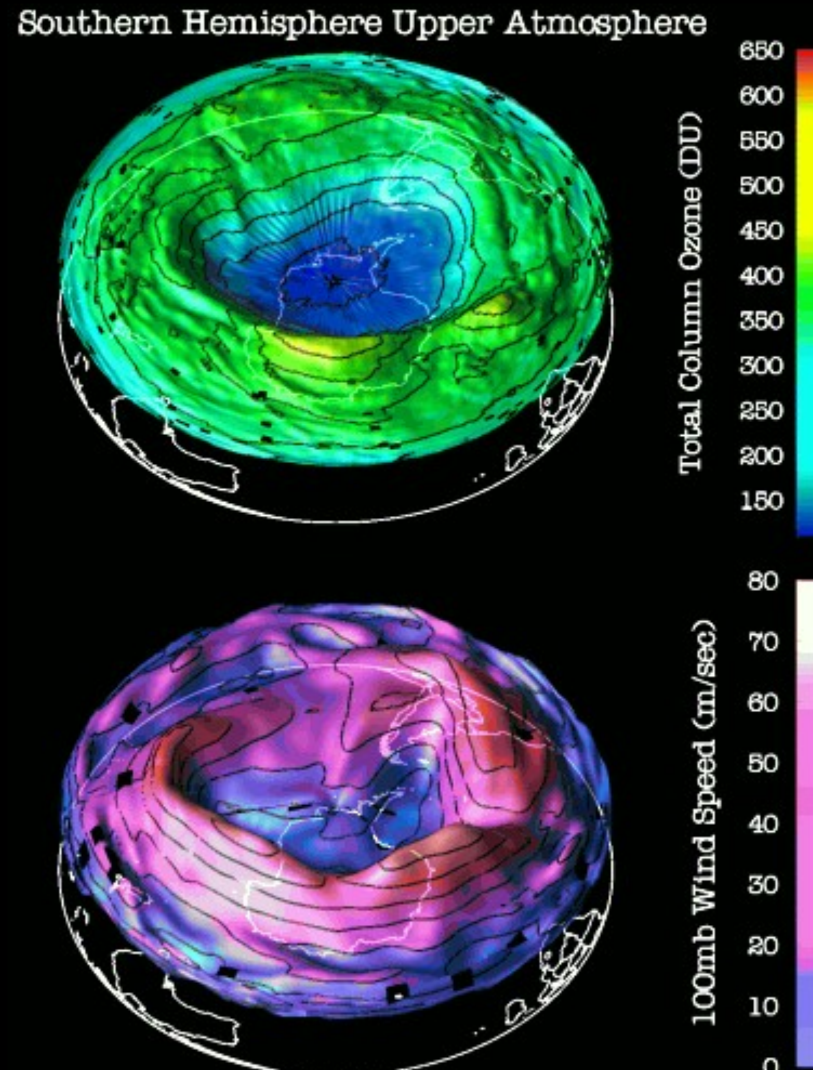
A fundamental aspect of temperature, wind, and climate variability in the polar regions

Annular modes

NAM (and NAO) and SAM

EOF1

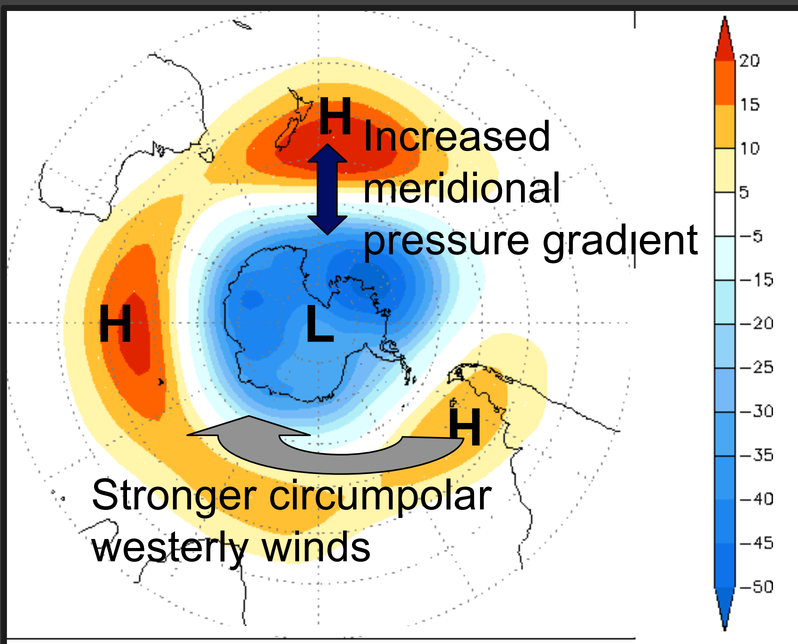




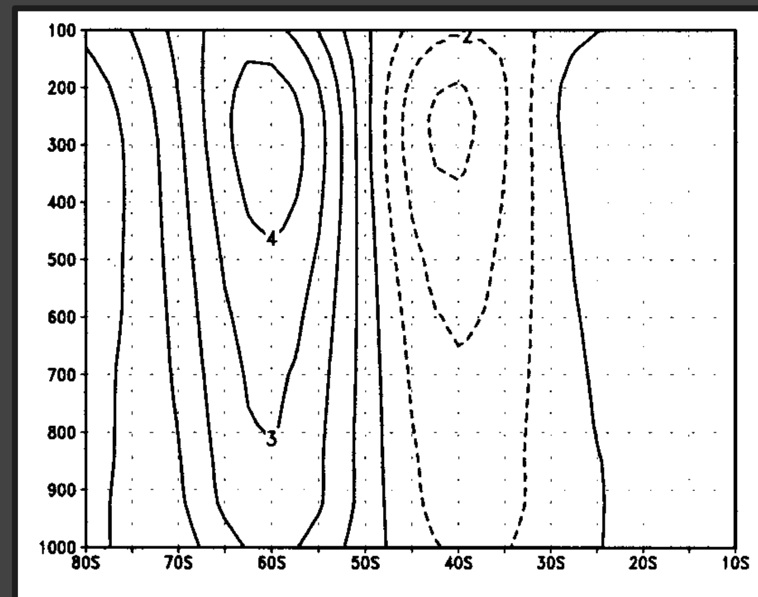
The Ozone Hole and Antarctic Climate Change

Southern Annular Mode:

- Dominant mode of atmospheric variability in SH
- North-South vacillation of mid-latitude jet
- Positive phase:
  - Strengthened westerlies at high-latitudes
  - Weakened westerlies in mid-latitudes



EOF 1 of monthly 850 hPa geopotential height (m)



EOF 1 of monthly zonal mean zonal winds (m/s)

Lorenz & Hartmann, 2001. J. of Atmos. Sci.

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.

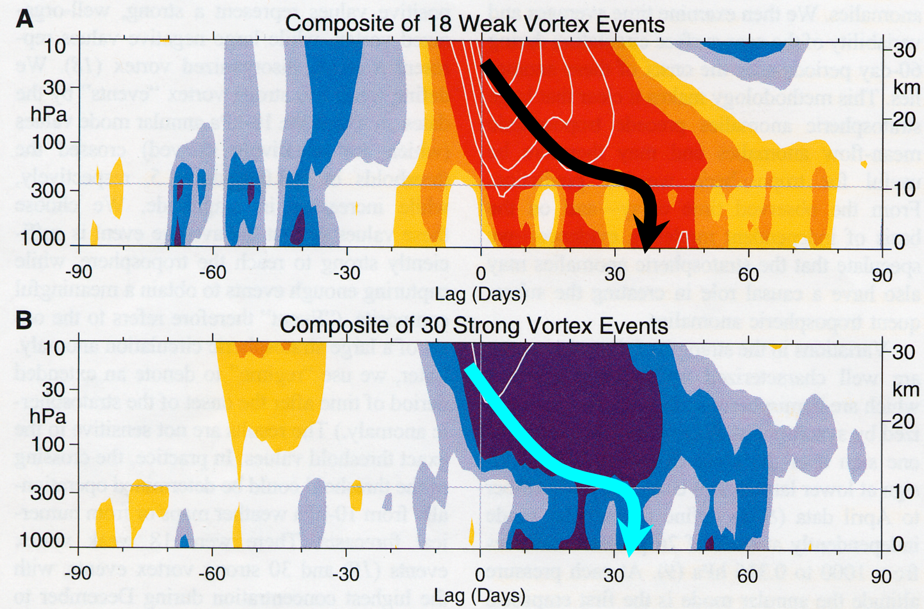


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross −3.0 and +1.5, respectively. The indices are nondimensional; the contour 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.

Weak vortex -> warmer, ‘floppier’ at the poles

Strong vortex -> colder, ‘tighter’ at the poles

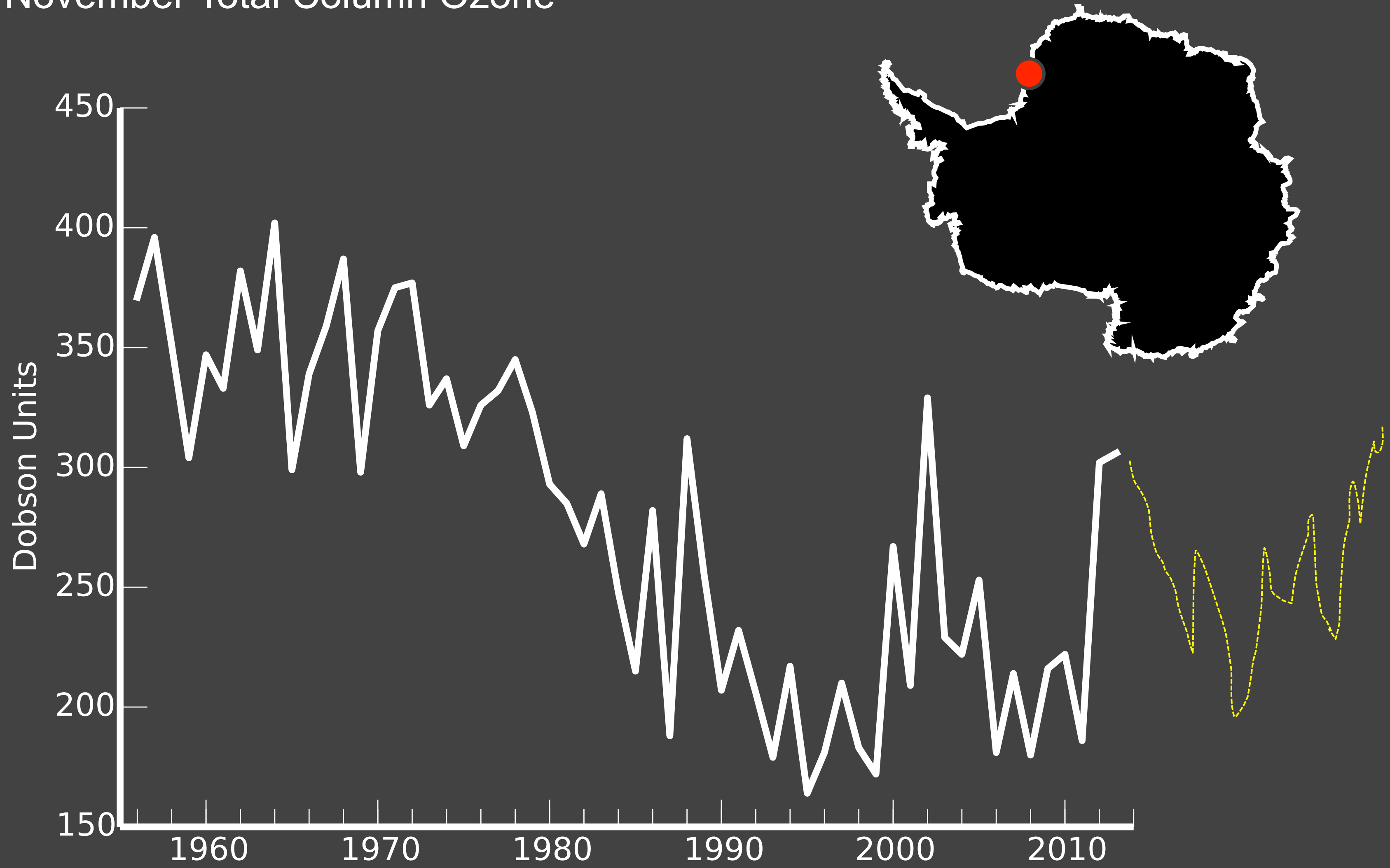
What about lower latitudes?

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

Annular modes

Interannual variability and trends in ozone depletion

Halley November Total Column Ozone

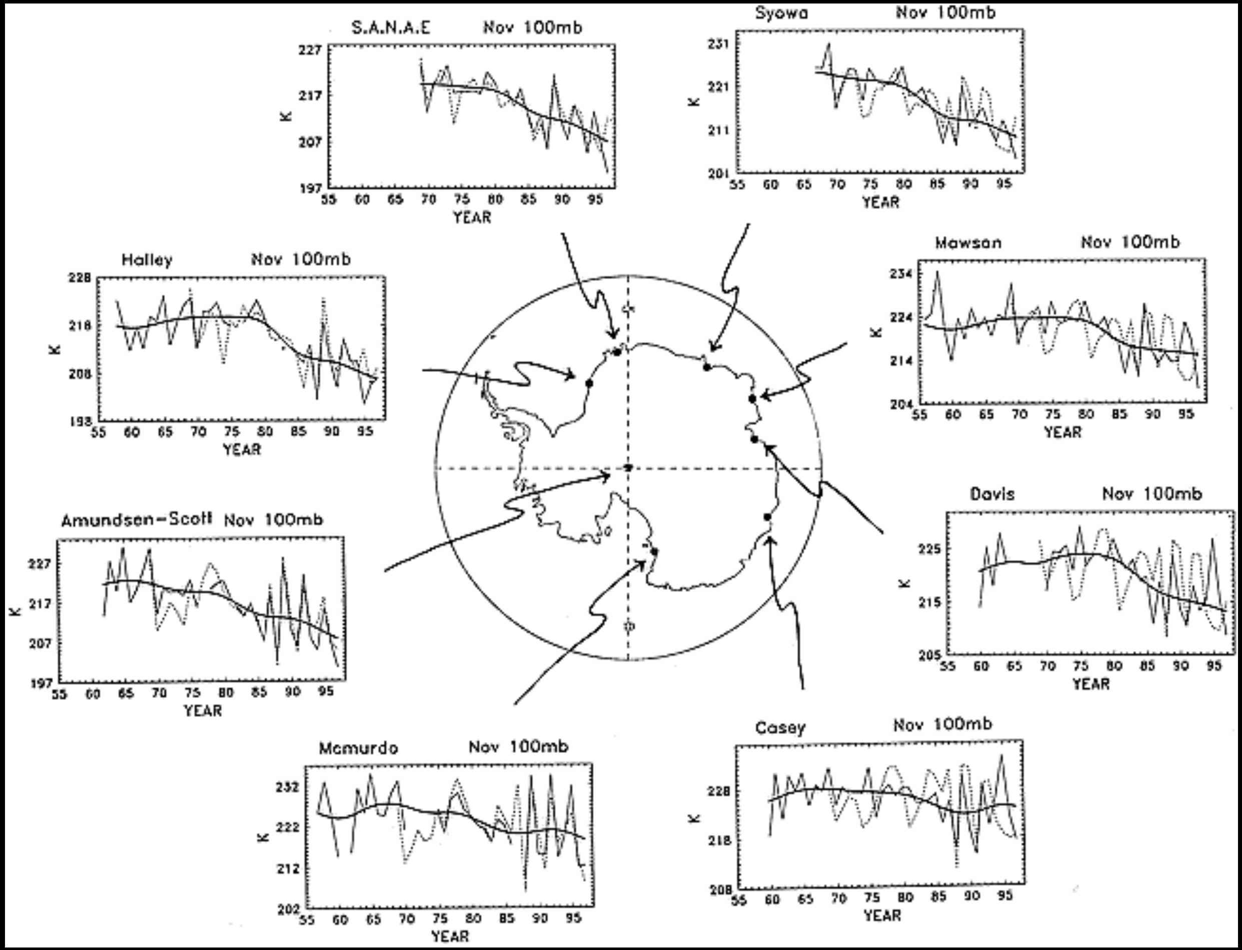


Ozone Hole Cools And Tightens

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.

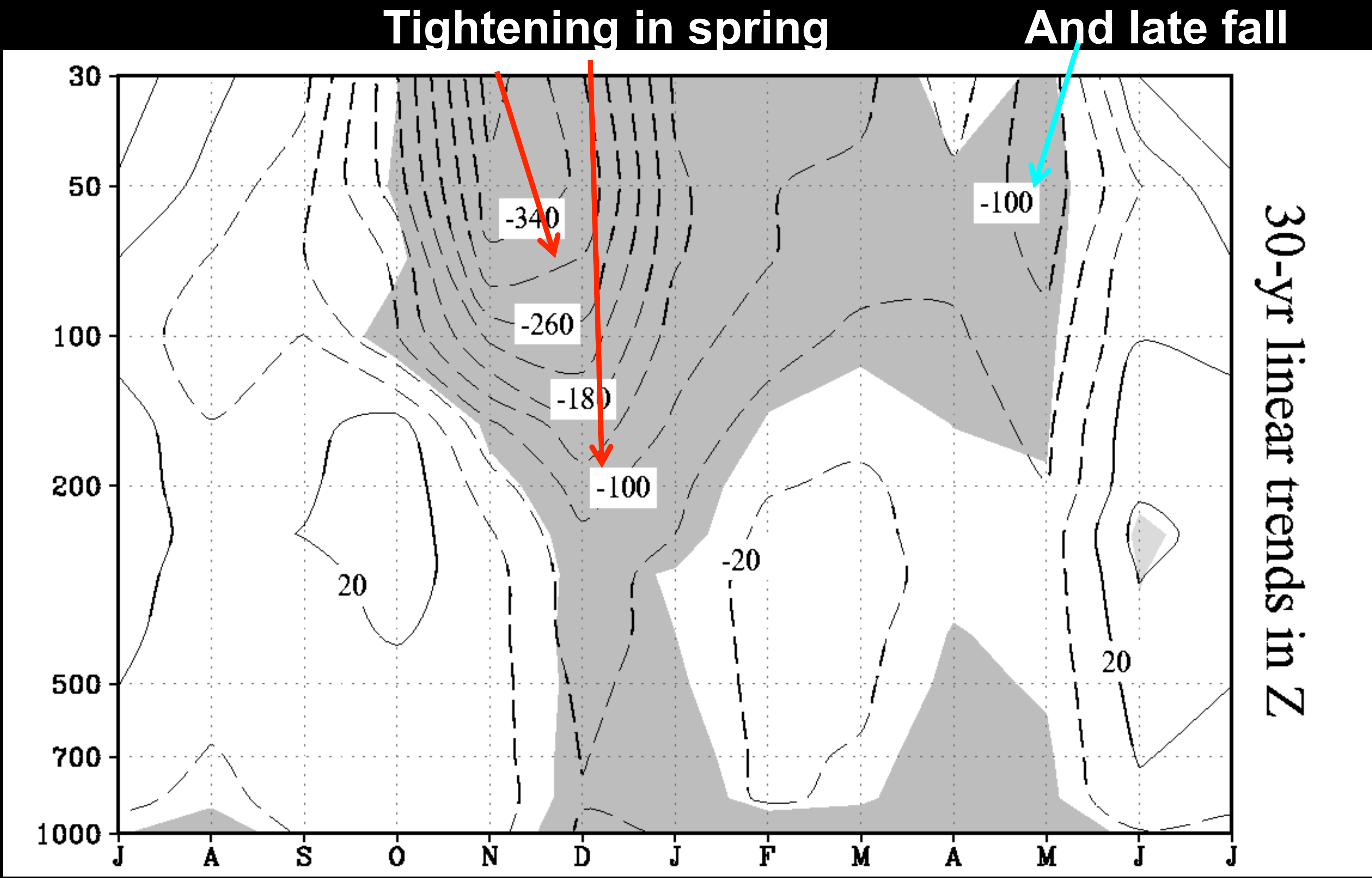
These cooling trends are very large…do they propagate down to affect the troposphere, and even surface climate?



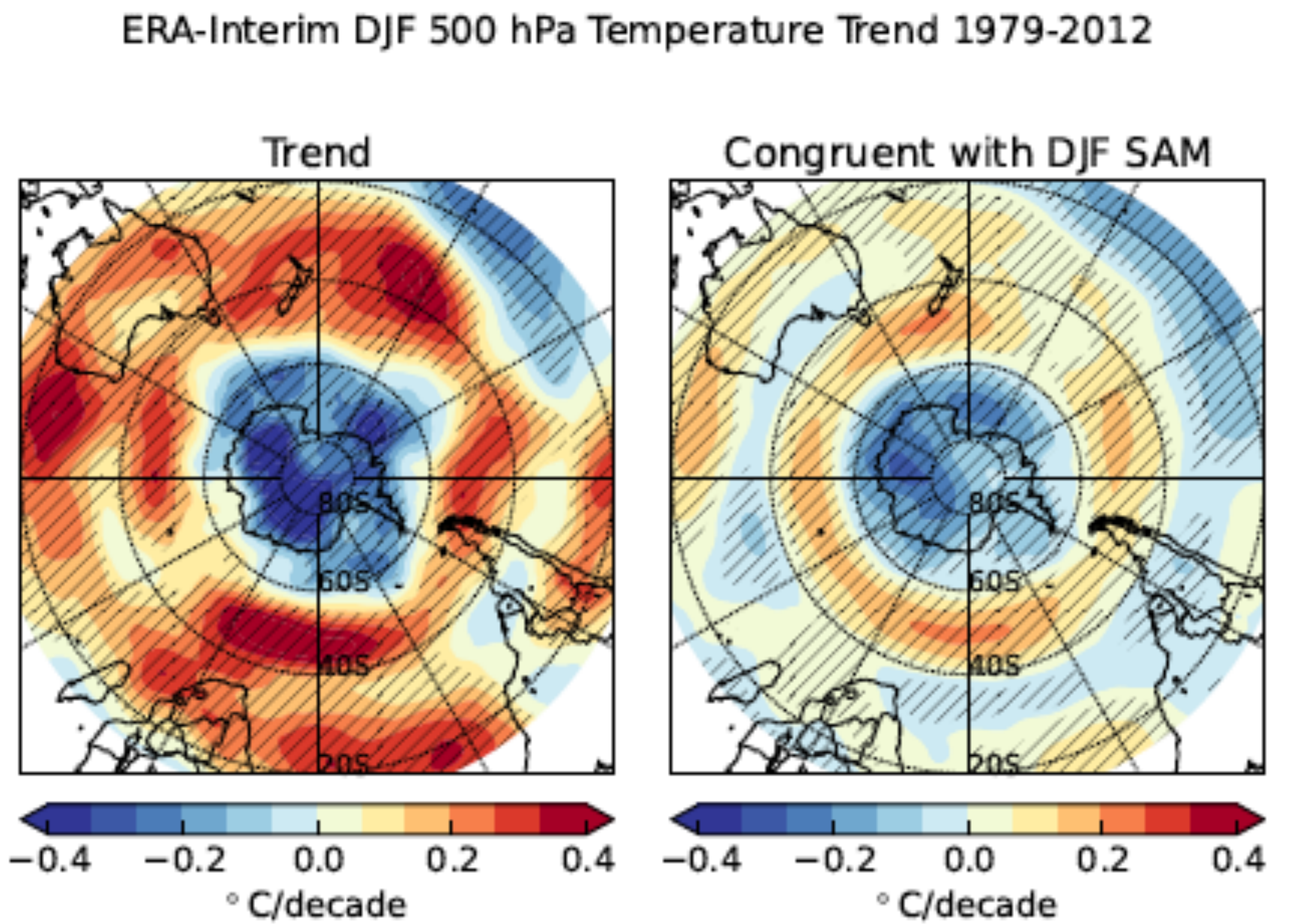
Randel and Wu

Recent SH climate change

Thompson and Solomon, Science, 2002



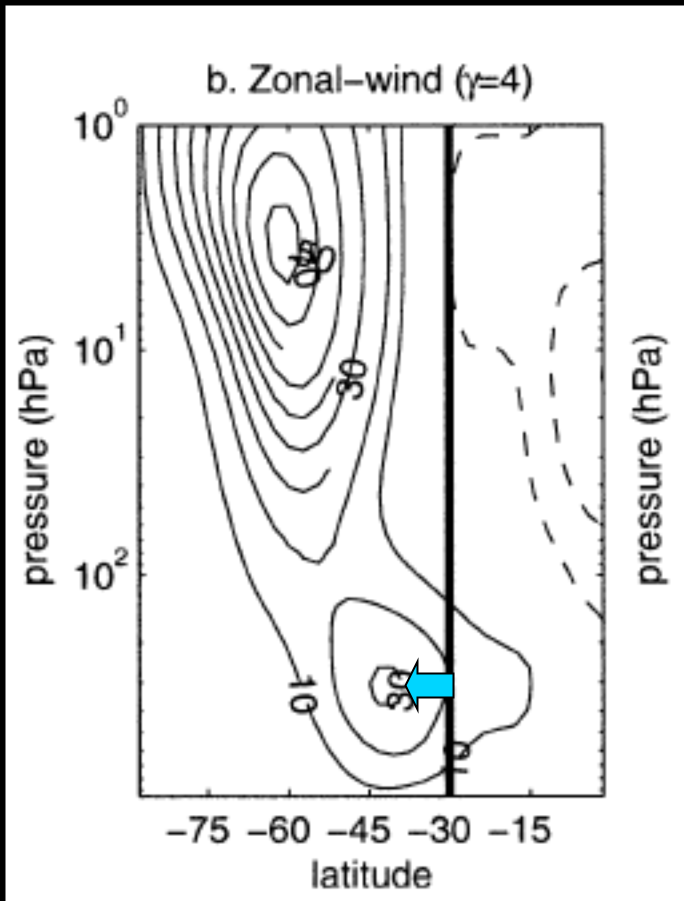
Results: 500 mbar

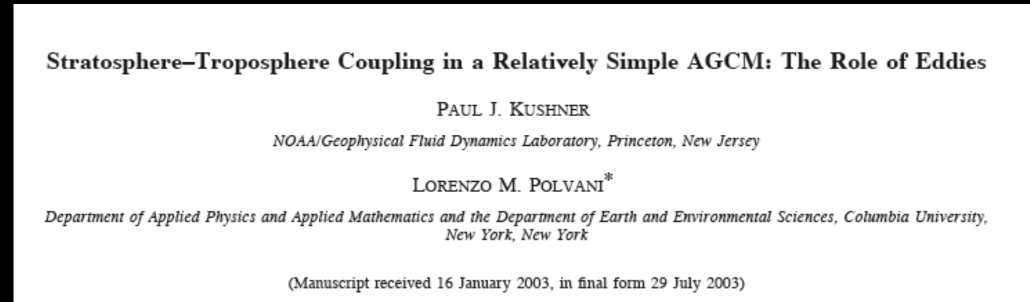


500 mbar Z and T look like (and are congruent with) SAM changes

Bandoro et al., J. Clim., in press, 2014

How Does the Fluid Dynamics Work? Still A Subject of Research…




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)

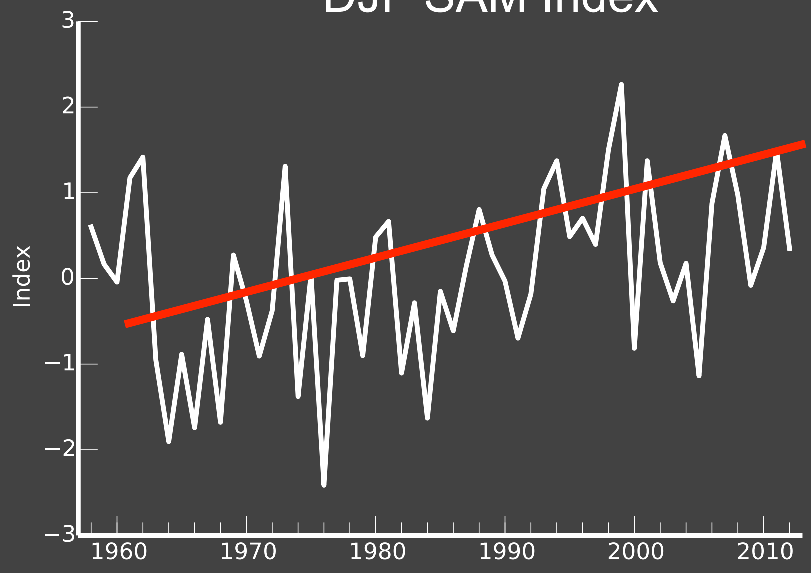
- Position of the jet moves as polar stratosphere cools
- Initiation, amplification by coupling through eddies (waves), eddy feedback

The Ozone Hole and Antarctic Climate Change

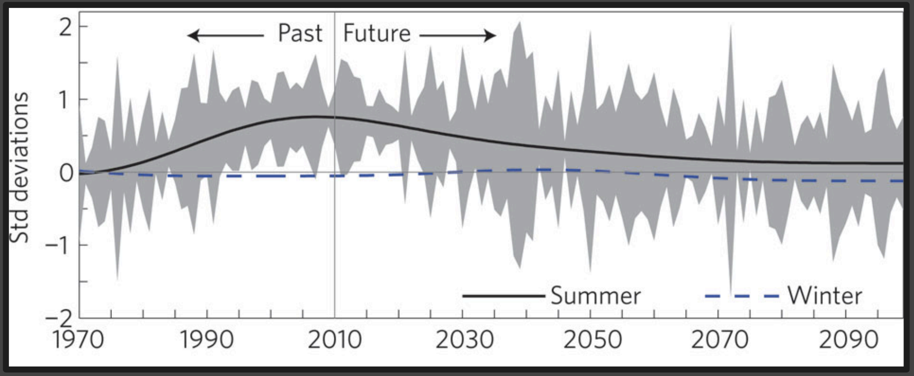
Stratosphere-troposphere coupling via the SAM:

- Observed positive trend in summer SAM
- Ozone depletion affects eddy heat and momentum fluxes that drive the SAM
- Despite debate in exact mechanisms, models agree large part of summer SAM trend is due to O_3 loss

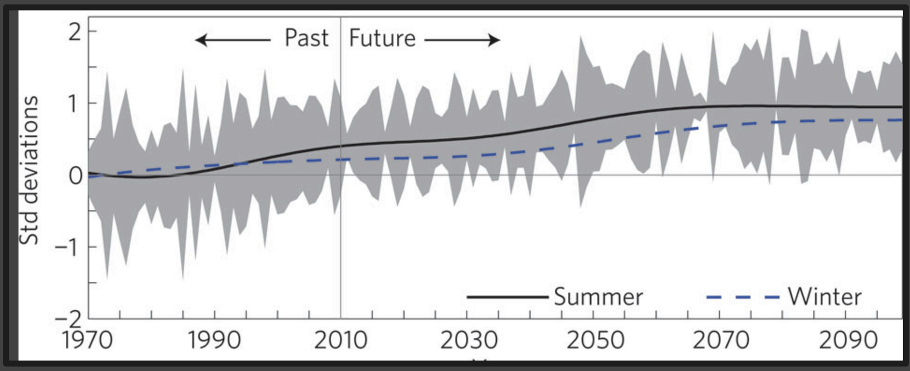
DJF SAM Index



O_3 Only

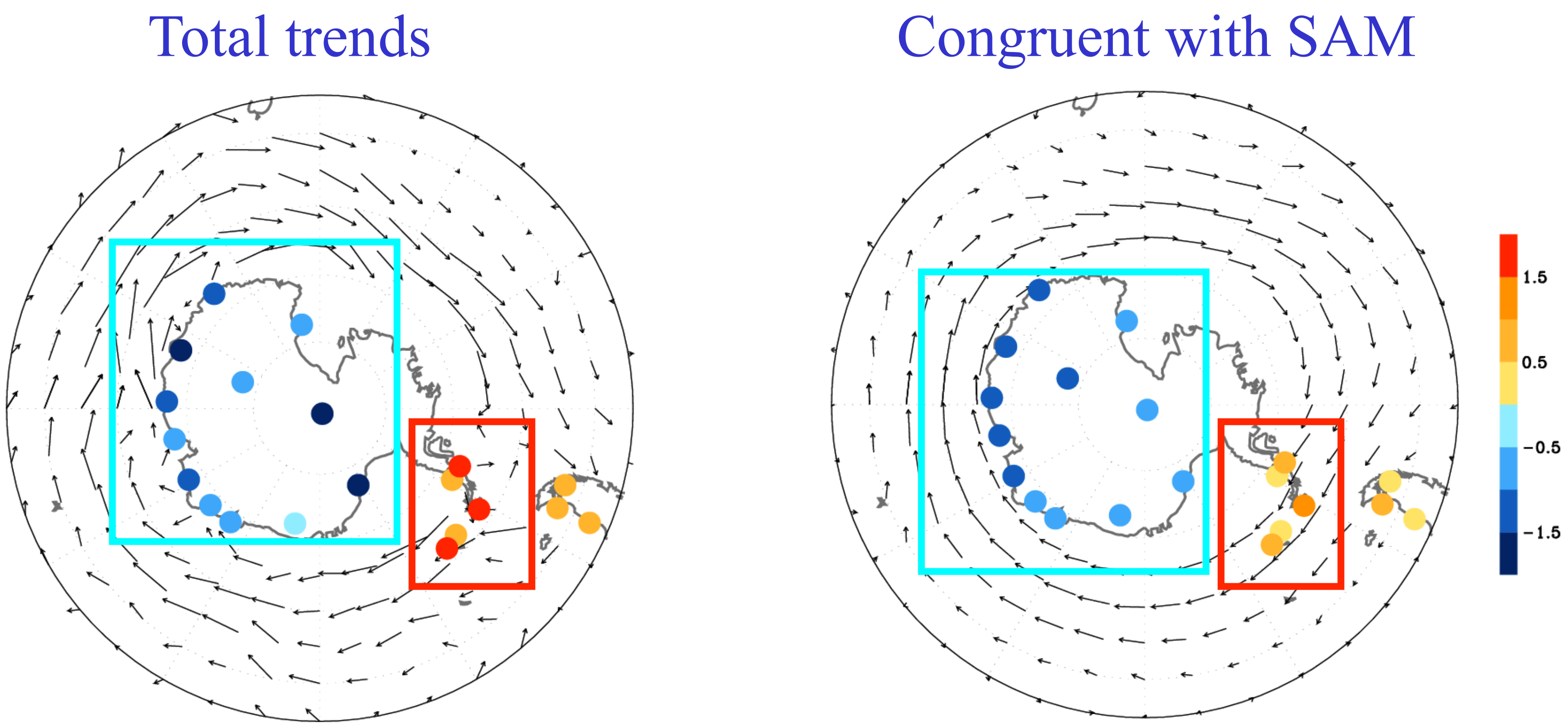


GHG Only



Mclandress et al., 2011. J. of Clim.

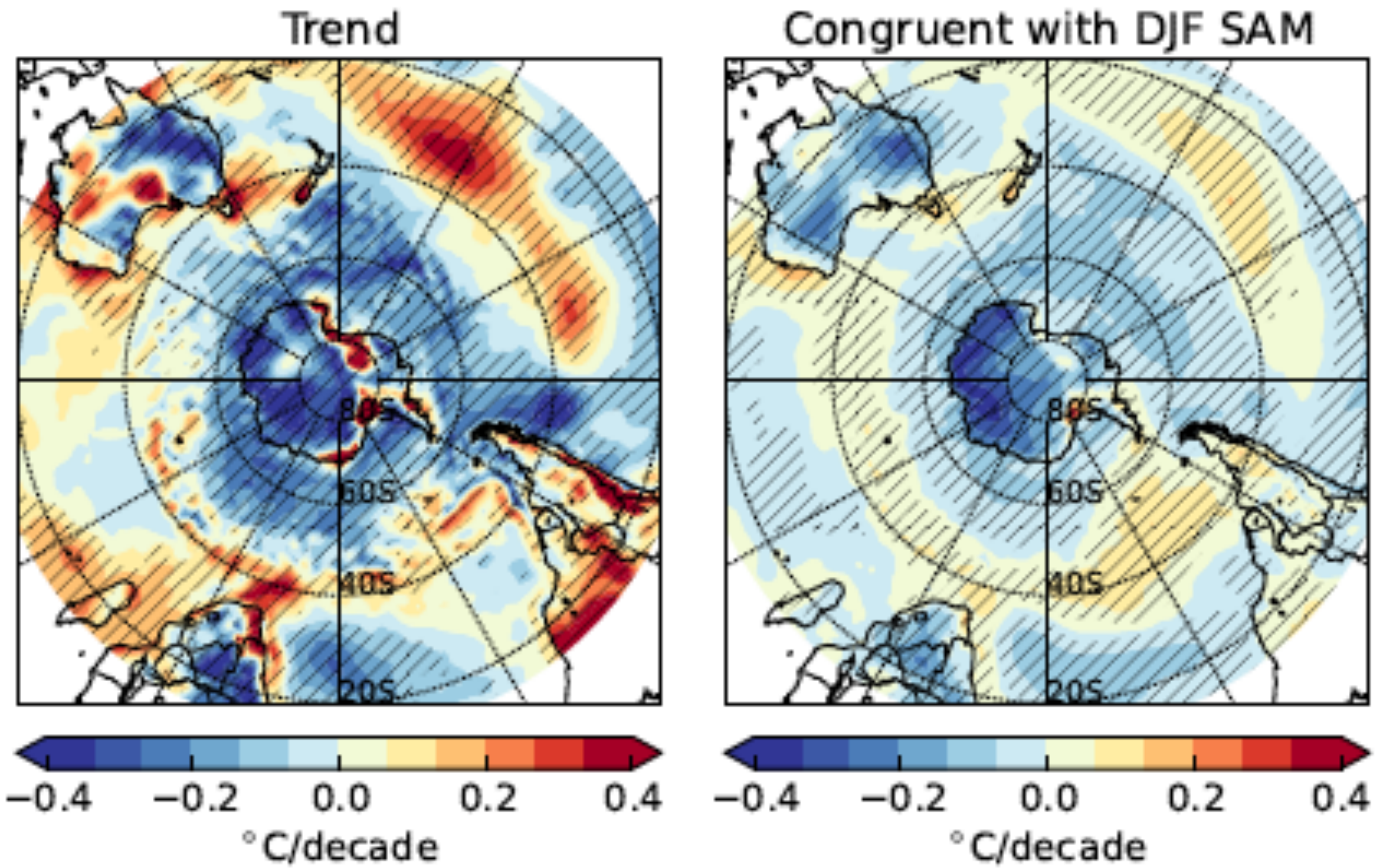
Circulation, surface temperature, and the vortex



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

Results: Surface T

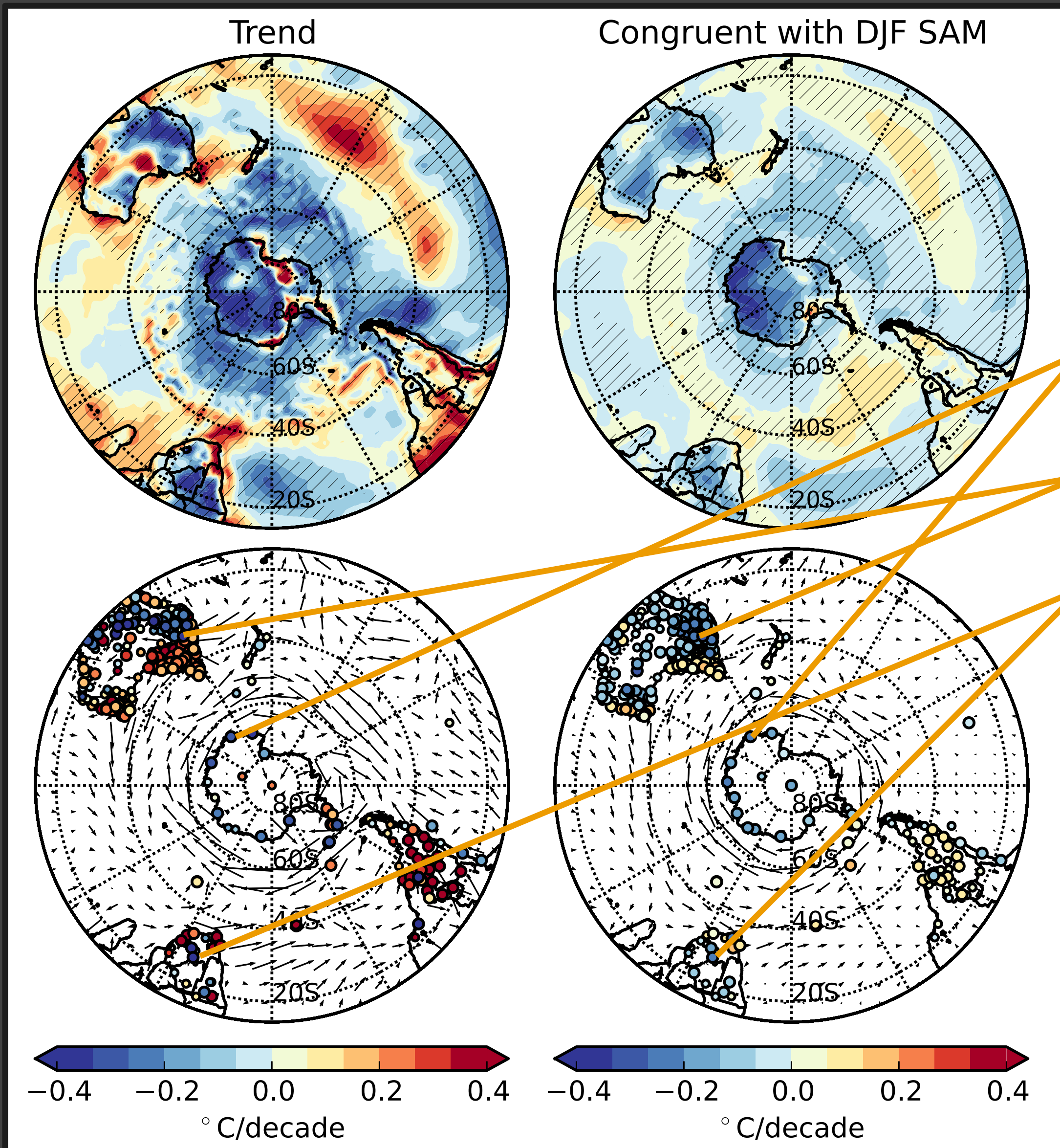


500 mbar Z and T look like (and are congruent with) SAM changes
But surface doesn't *look* like SAM outside of Antarctica…a mystery….

Bandoro et al., J. Clim., in press, 2014

SH Summer Climate Change 1979-2012

DJF Surface Air Temperature Trends



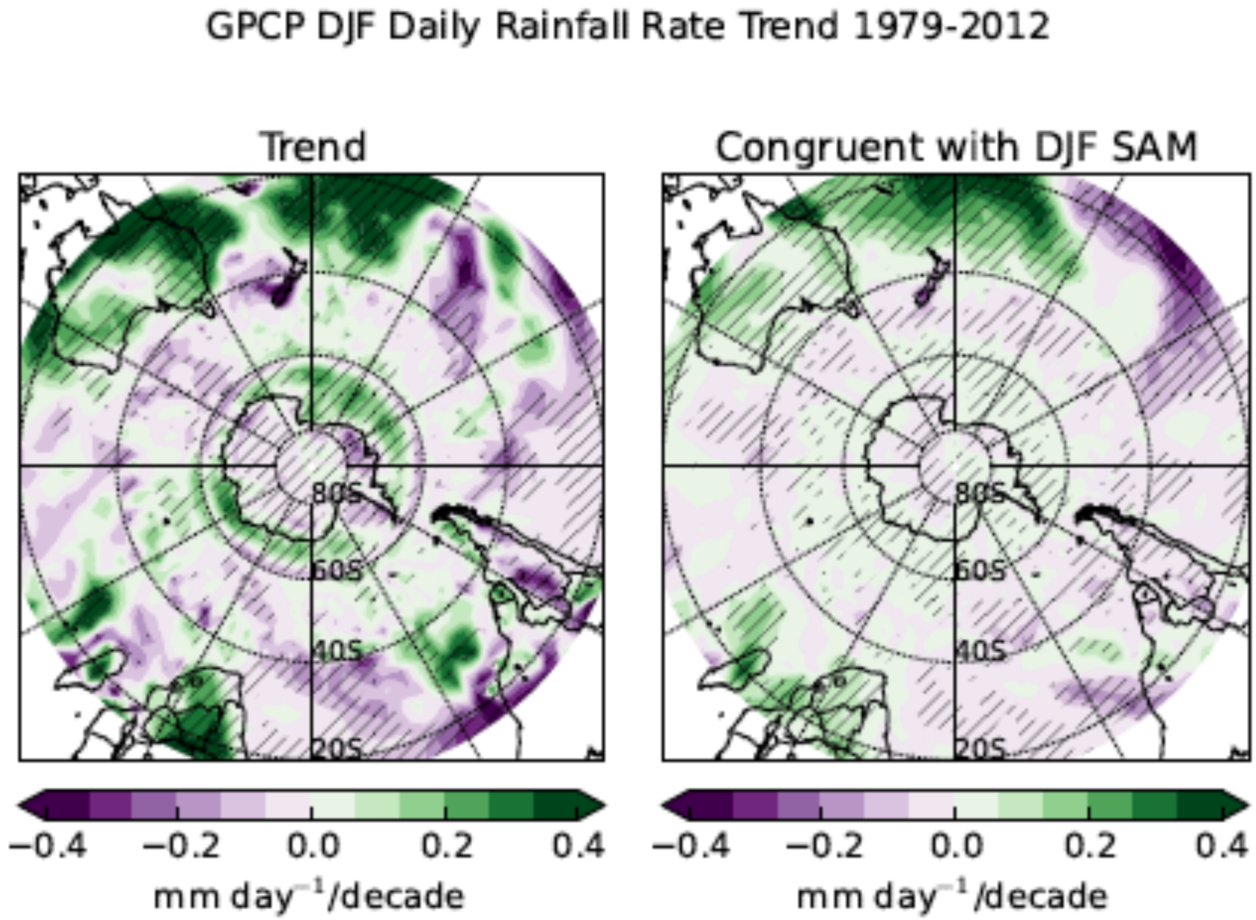
34 year Changes (°C)

Station	DJF Trend	SAM Congruent
Casey, Antarctica	-1.10	-0.92
Brogo Dam, Australia	-1.12	-0.88
Blomfoetein, South Africa	-1.16	-0.86

Top: ERA-Interim

Bottom: GHCN stations with 925 hPa ERA-Interim winds

Rainfall Connection

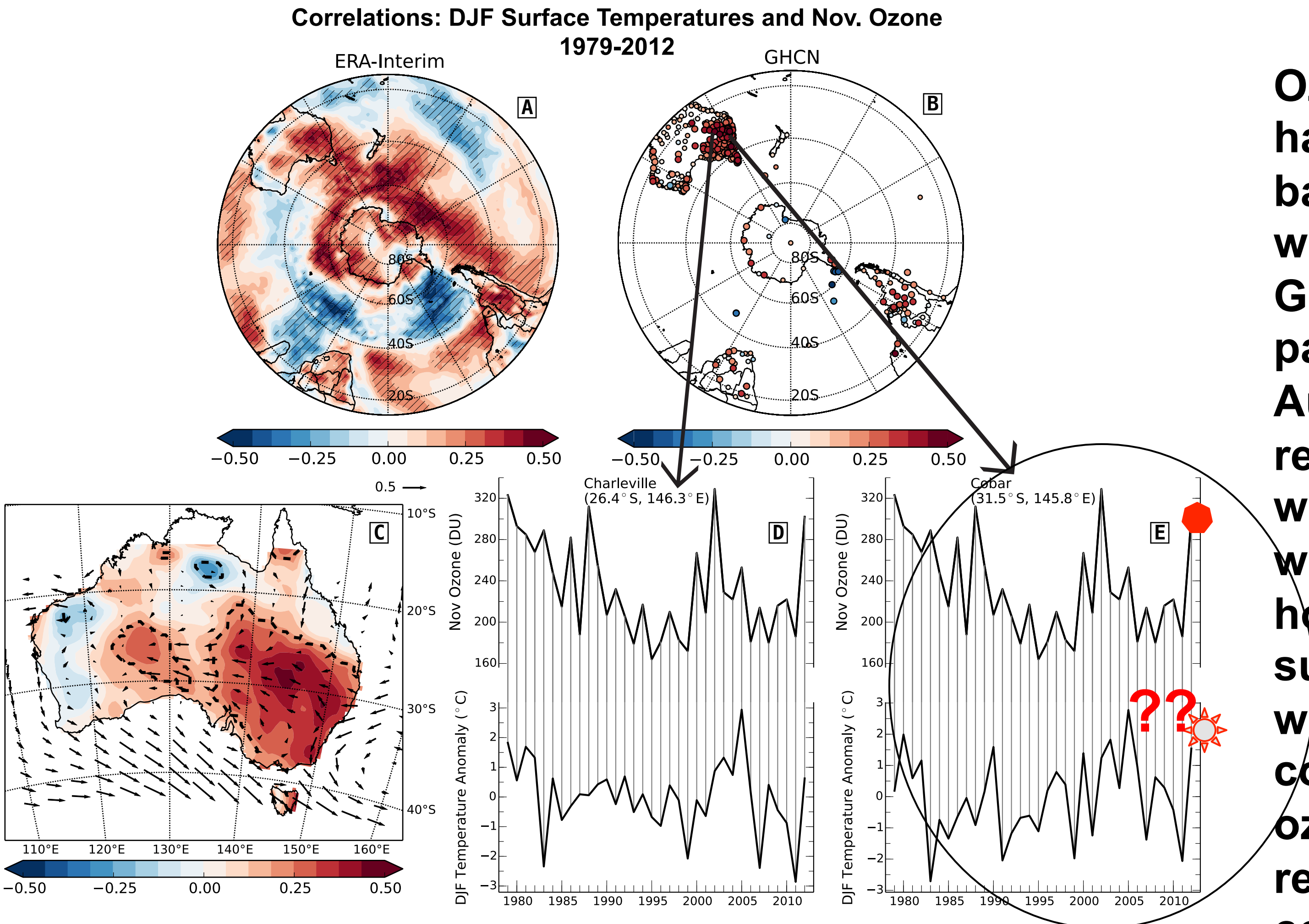


Why? SAM affects moisture flow and influences precip as well as warm air advection
Dry interiors of SH continents → summer temperatures strongly depend on precip

Bandoro et al., J. Clim., in press, 2014

ENSO effect checked → small impact

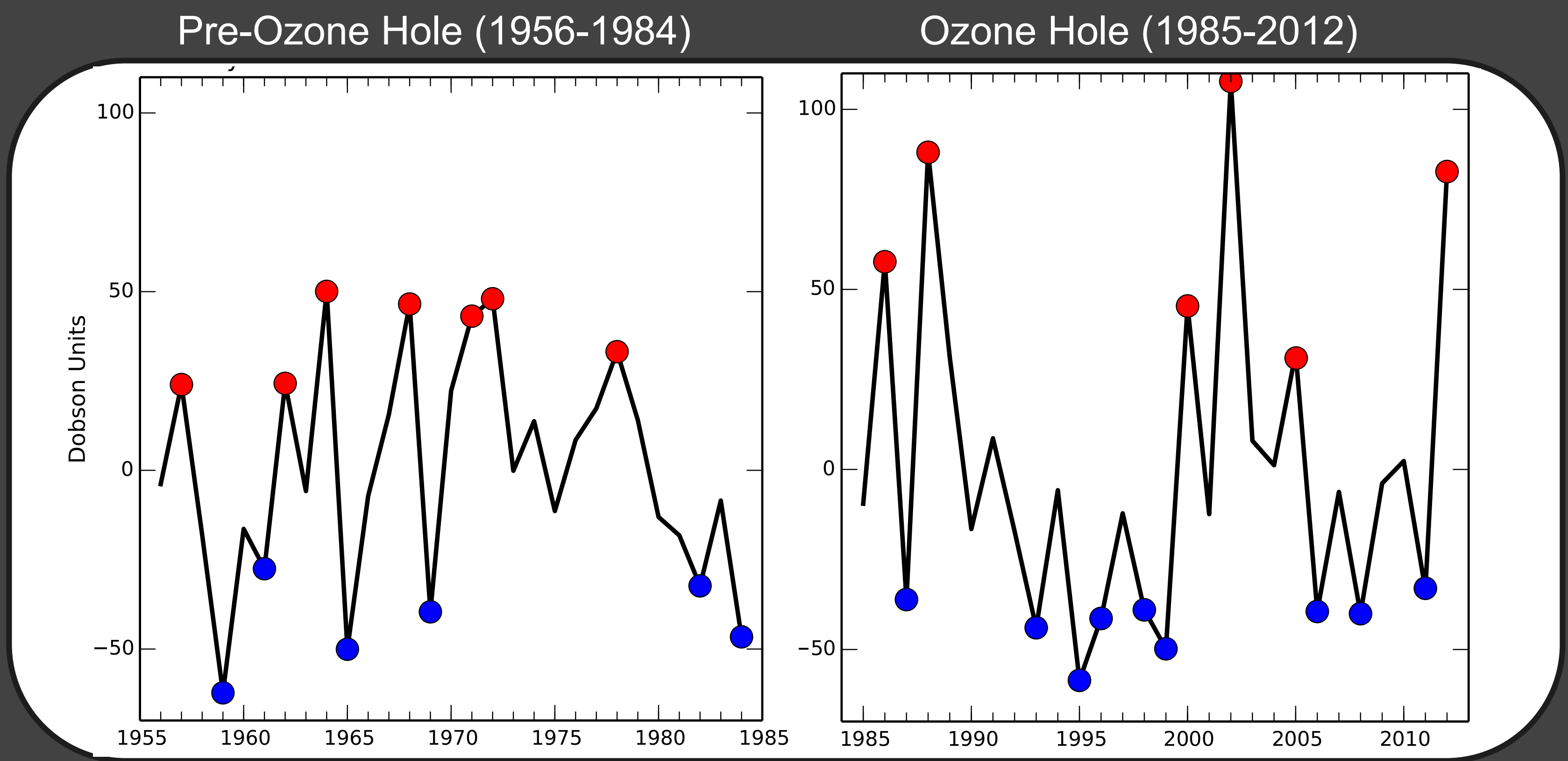
Correlation of DJF summer temps with past Nov ozone:



Ozone hole has 'held back' summer warming from GHG over parts of Australia; recent years with relatively weak ozone holes → hot summers, with more to come as ozone hole recovers in coming decades

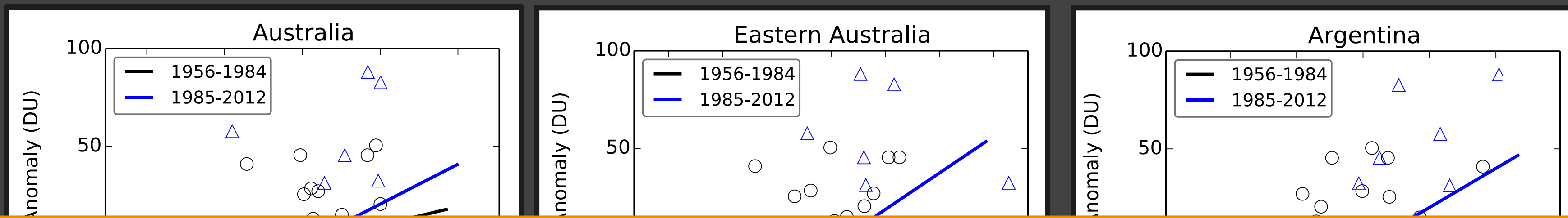
Bandoro et al., J. Clim., in press, 2014

Pre-Ozone Hole and Ozone Hole Eras



- High and low ozone years are those in which the detrended anomalies exceed ± 0.8 standard deviations

Pre-Ozone Hole and Ozone Hole Eras

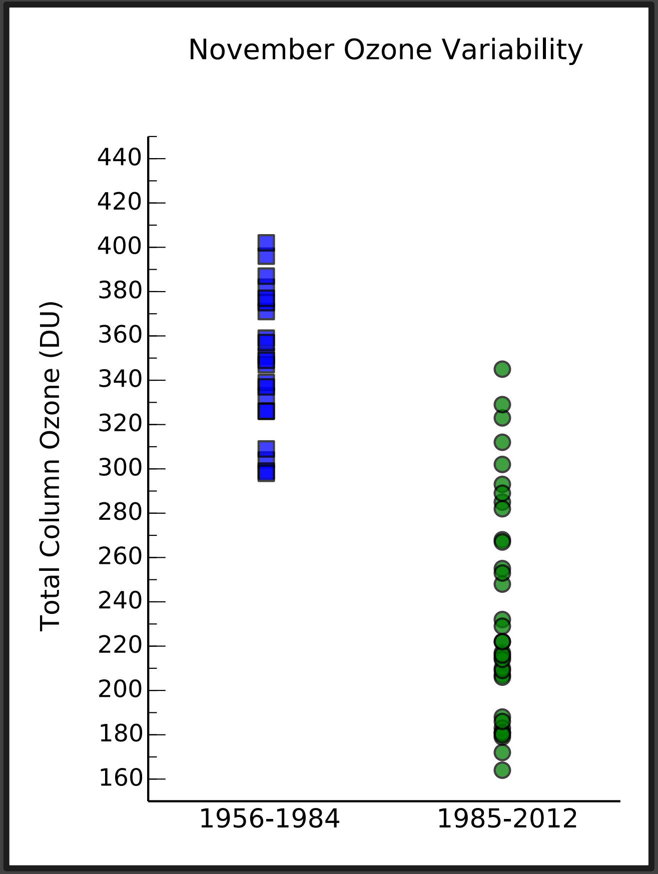


Region	Summer surface temperature correlations (1985-2012)	
	ENSO	Nov O_3
Australia	0.34	0.34
Eastern Australia	0.36	0.45
Argentina	0.31	0.39
South Africa	0.33	0.36
Botswana	0.42	0.49

Summer variance explained by Nov. O_3 between 1985-2012 is comparable to, and even greater than, that of ENSO in several mid-latitude regions.

Why no link in pre-ozone hole era?

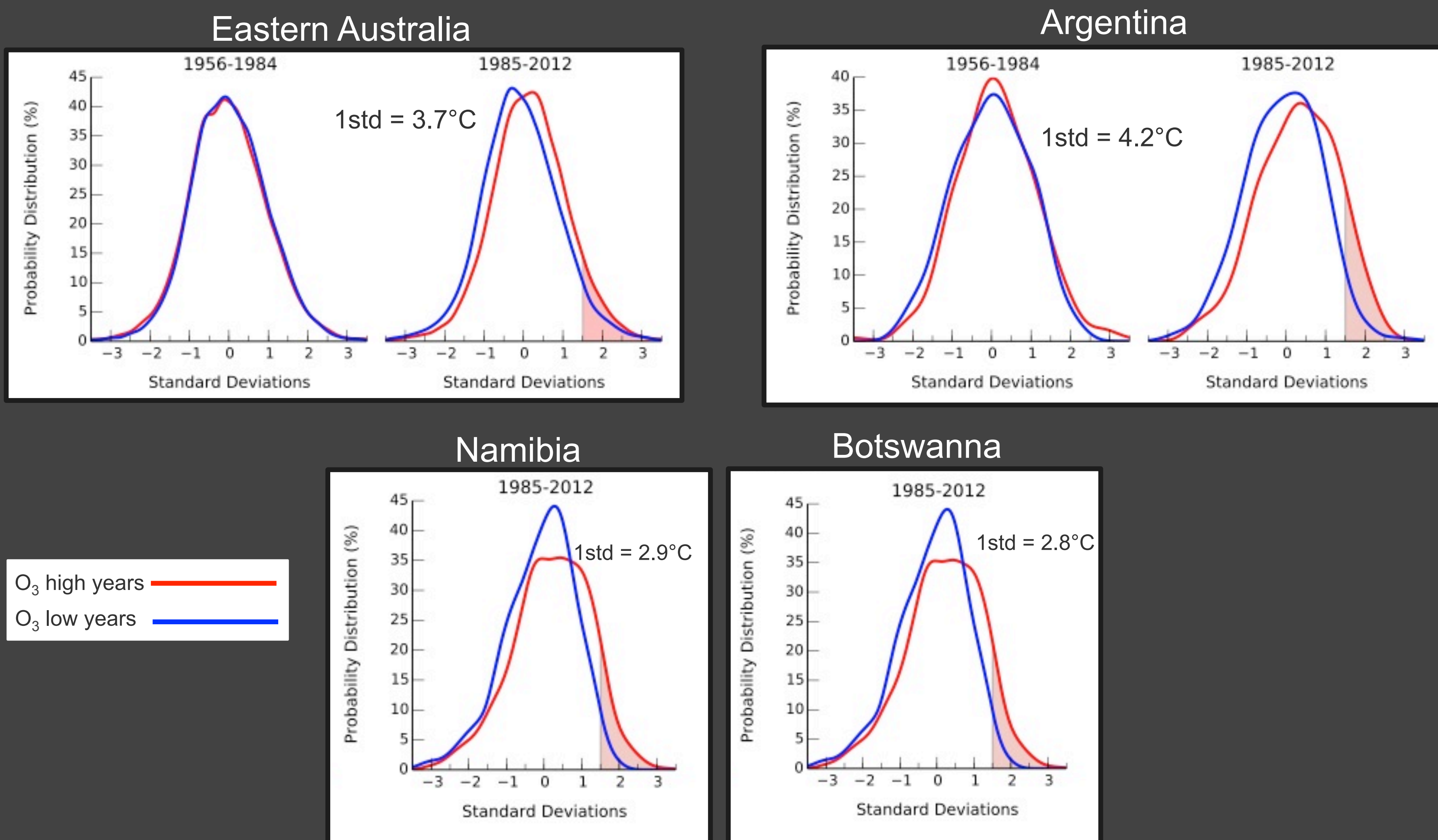
Variability of ozone level prior to halogen loading affected by dynamics. Now have additional chemistry on PSCs and are dynamically coupled.



1. In context of *Shaw et al. (2011)*, who noted that the ozone hole acts to extend the lifetime of the polar vortex, leading to an increased coupling between the stratosphere and troposphere in the SH, and consequently the summertime SAM.

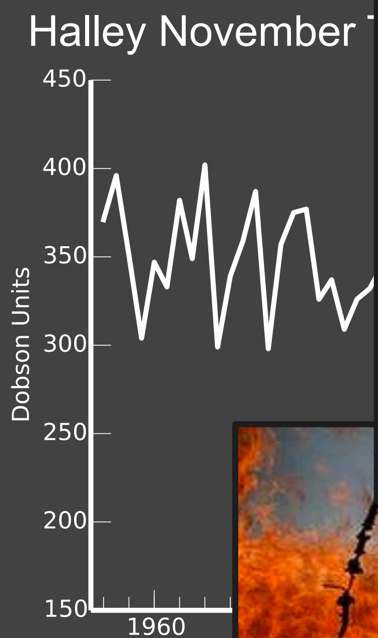
2. The larger interannual variability in the ozone hole era has caused the signal in surface temperatures to emerge by larger associated year-to-year variability in the SAM.

Maximum Daily Summer Temperatures

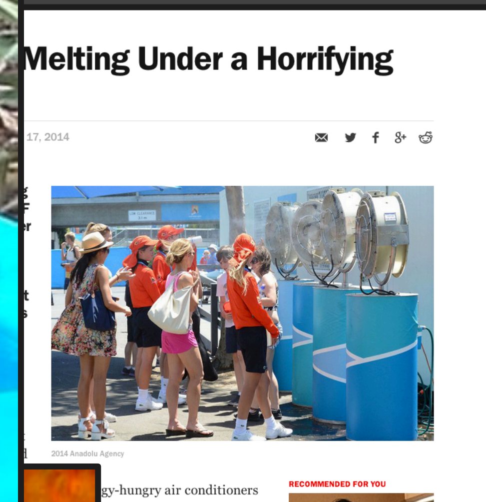


- Since onset of the ozone hole, high November O_3 years are more often followed by summers with hotter extremes

Maximum Daily Summer Temperatures



Su	
2013/	
2012/	
2011/	
2002/	
1999/	
1995/	
1988/89	0.61

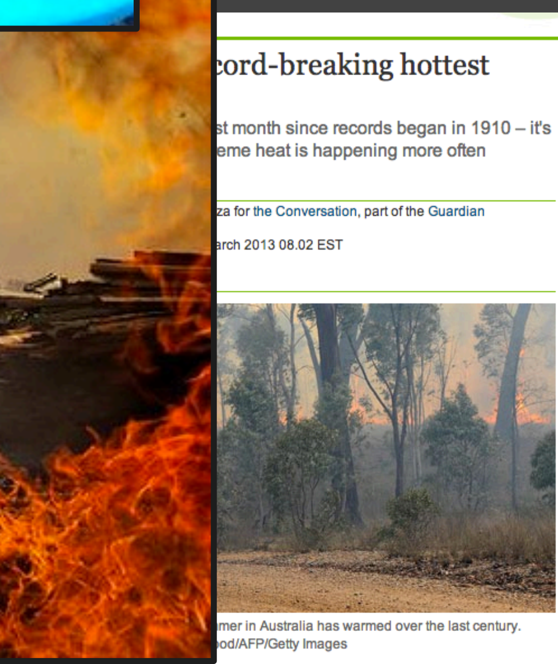

Melting Under a Horrifying

17, 2014

2014 Anadolu Agency

gy-hungry air conditioners

RECOMMENDED FOR YOU


cord-breaking hottest

st month since records began in 1910 – it's
eme heat is happening more often

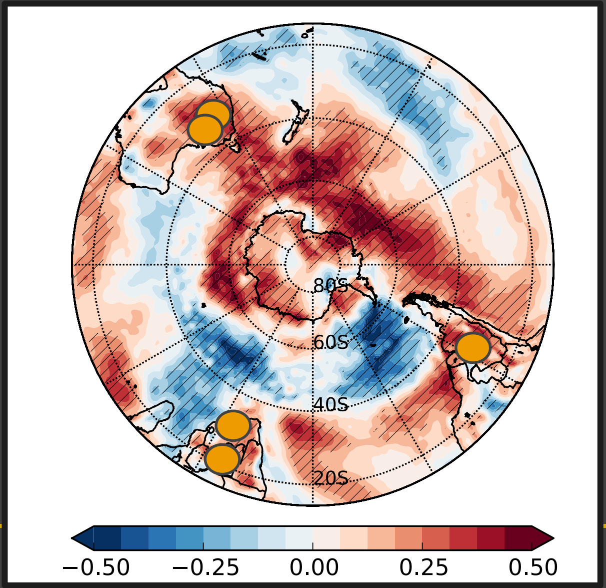
za for the Conversation, part of the Guardian

arch 2013 08.02 EST

mer in Australia has warmed over the last century.
od/AFP/Getty Images

Maximum Daily Summer Temperatures

Summer event and location $T_{max} > \overline{T} + 1.5STD$	Frequency of occurrence following: High O3 spring (%)	Low O3 spring (%)
>40.6°C in Charleville, Australia	5.1	2.7
>42.5°C in Bourke, Australia	8.0	2.7
>38.8°C in Bloemfontein, South Africa	10.0	6.6
>37.8°C in Maun, Botswana	7.3	1.0
>35.0°C in Cordoba, Argentina	8.0	4.1

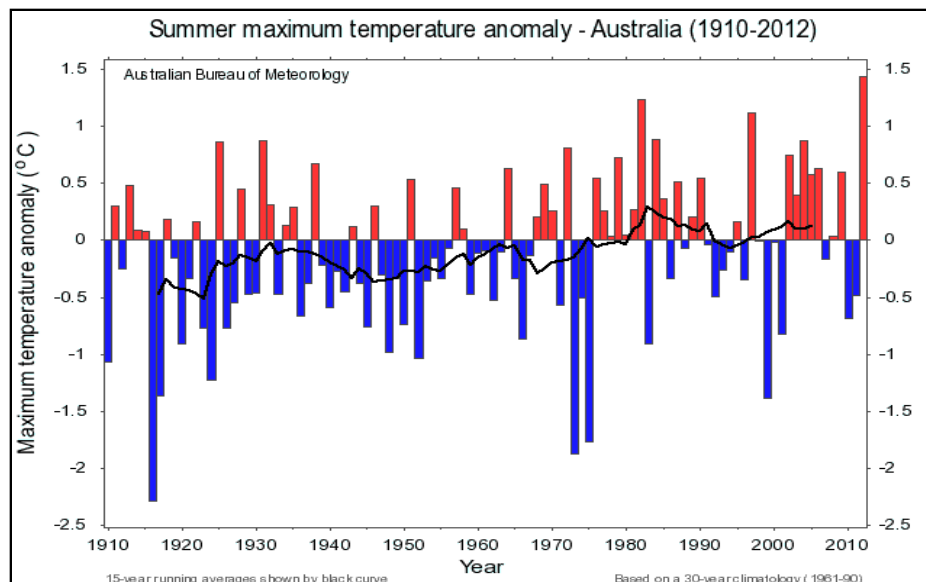


- In the ozone hole era, extremely hot summer days occurred more frequently in the summers following elevated levels of November polar ozone

TABLE 6. Frequency of summer extreme hot events in the years following high and low Antarctic spring total column ozone between 1985 and 2012. Results are given as percentage of days during the summer when the daily maximum temperatures exceeded the threshold indicated in the left column, which was chosen to be 1.5 standard deviations of the DJF seasonal mean over the period. Station data for the Australian stations was obtained from the ACORN-SAT database, and the other stations from the GHCN daily database.

Summer event and location	Frequency of occurrence (%) following High spring O_3	Low spring O_3
>40.6°C in Charleville, Australia (26.4°S, 146.3°E)	5.1	2.7
>42.5°C in Bourke, Australia (30.1°S, 135.6°E)	8.0	2.7
>40.7°C in Cobar, Australia (31.5°S, 145.8°E)	9.8	3.1
>38.2°C in Wagga Wagga, Australia (35.5°S, 147.5°E)	10.0	6.6
>38.8°C in Bloemfontein, South Africa (29.1°S, 26.1°E)	7.0	2.6
>37.8°C in Maun, Botswana (20.0°S, 23.3°E)	7.3	1.0

How much hotter would Australian (and other SH midlatitude) summers have been without the ozone hole to hold GHG-induced warming back?

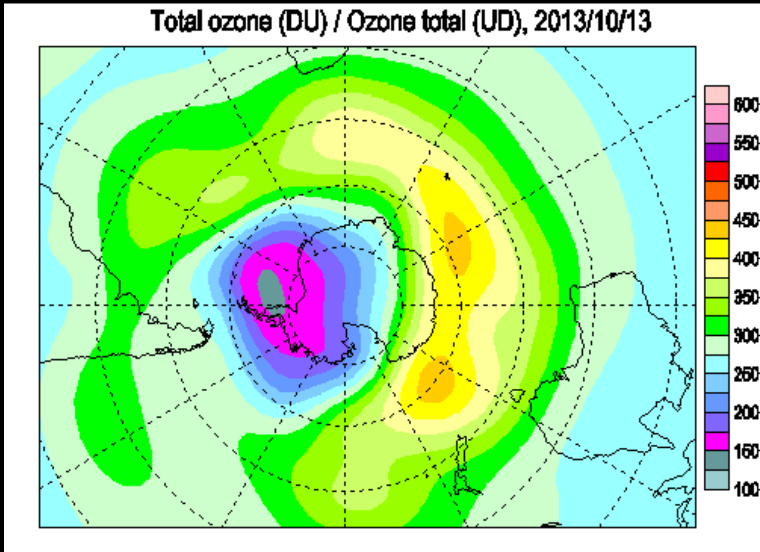


Conclusions:

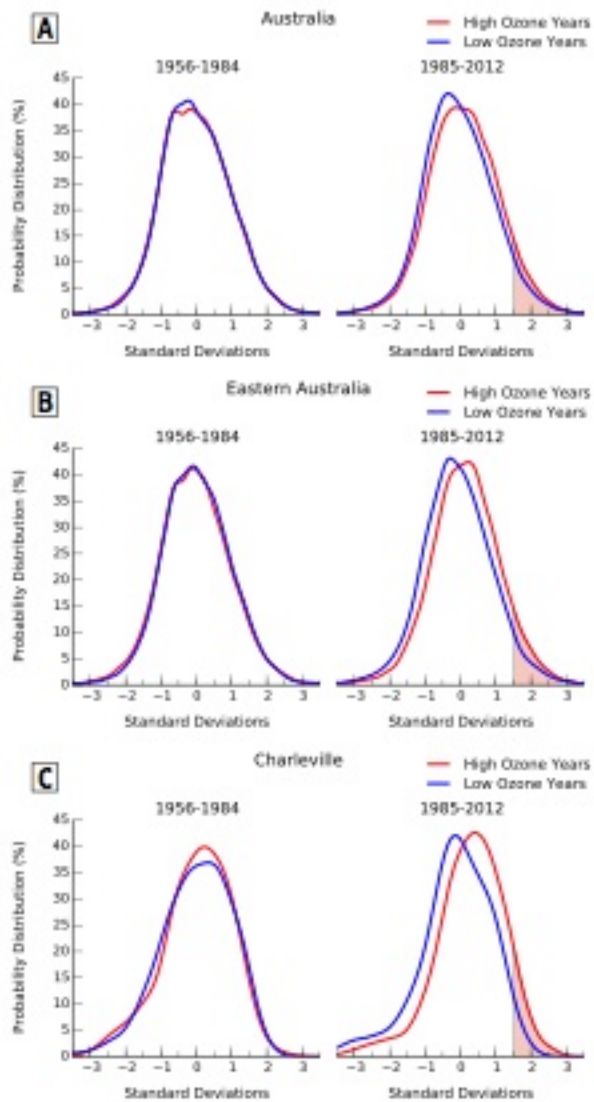
The ozone hole is caused mainly by chlorofluorocarbons emitted by humans.

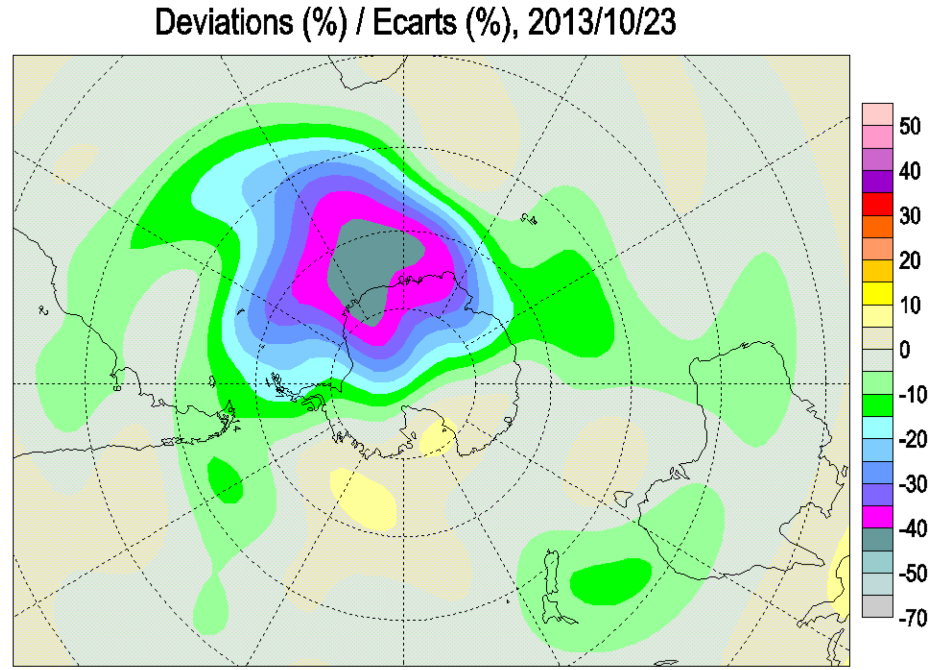
The ozone hole affects summer surface climate not only over Antarctica, but also over parts of Australia and southern Africa.

Ozone has been holding back these dry places from the full effects of global warming, due to precip changes.



Environment Canada
http://es-ee.tor.ec.gc.ca/e/ozone/Curr_allmap_s.htm





http://es-ee.tor.ec.gc.ca/e/ozone/Curr_allmap_s.htm

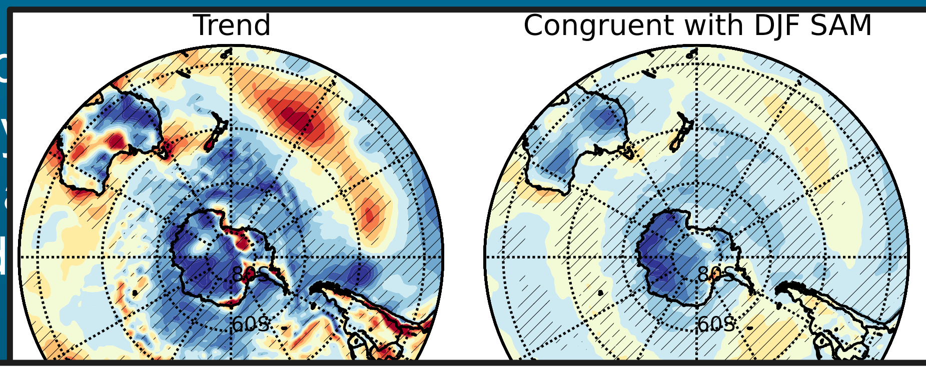
- **Composite summer daily max data for high vs low ozone years**

→ Remarkable changes in extremes

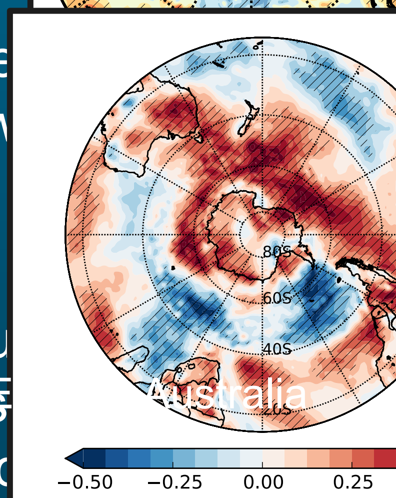
Conclusions

- Antarctic ozone depletion has impacted summer surface temperatures outside the pole, with an associated long-term cooling in regions of Australia and southern Africa.

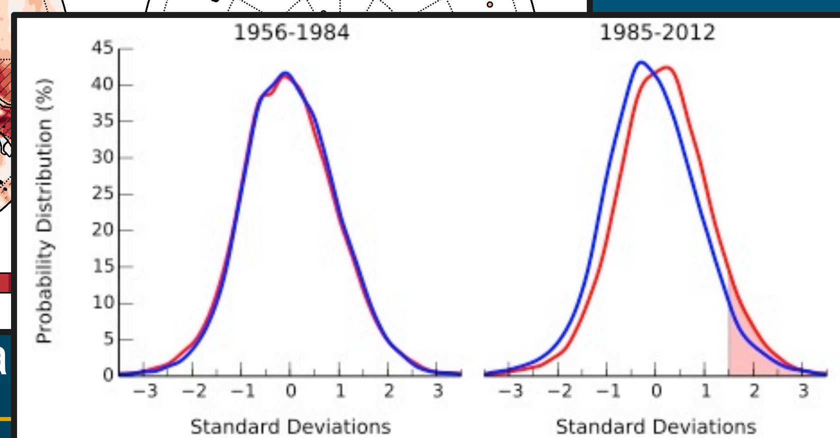
- In the decad … ozone hole, anomalously … antly correlated with hotter … arge regions of the SH, and



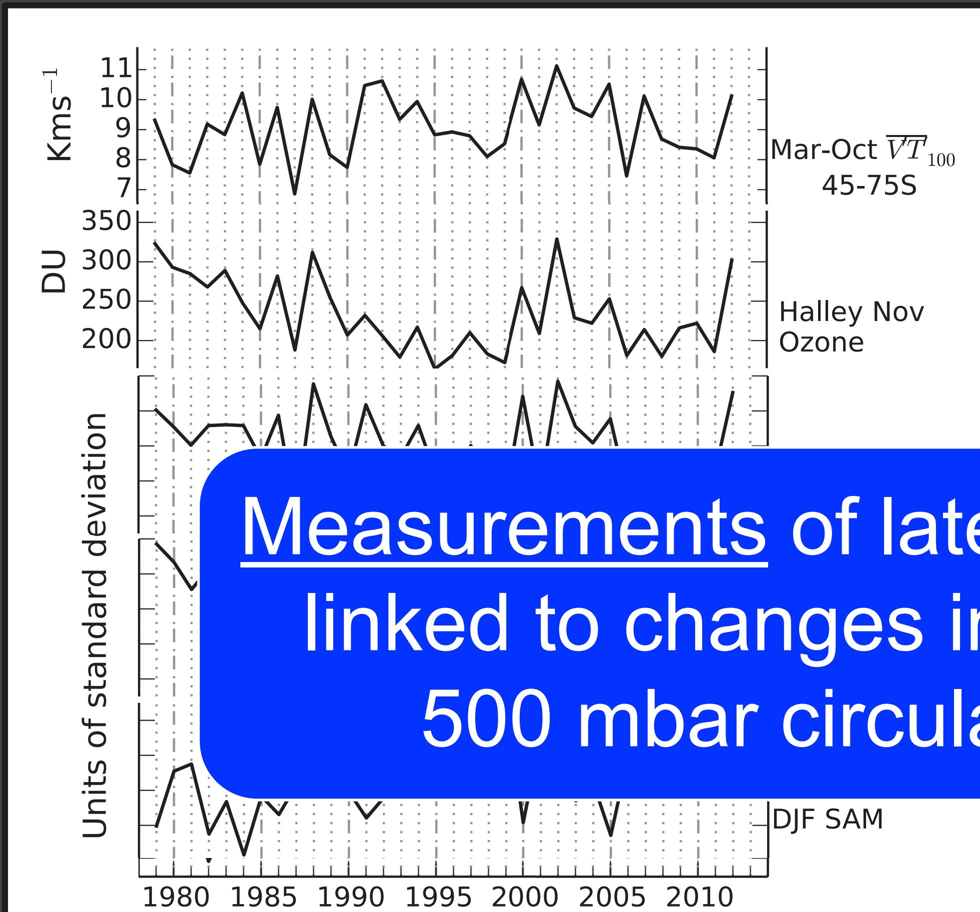
- Higher leve … followed by summers w … ents.



- In the next … y recover, bu … era. Our results … depletion, c … time surface temperatures in ma



Stratosphere-Troposphere Coupling



Detrended Correlation Coefficients

	Mar-Oct $\overline{v'T'}_{100}$	Nov O_3	Nov Z_{30}	DJF Z_{30}
Nov O_3	0.49			

Measurements of late springtime ozone are linked to changes in following summer's 500 mbar circulation. Surface T?

High poleward heat transport

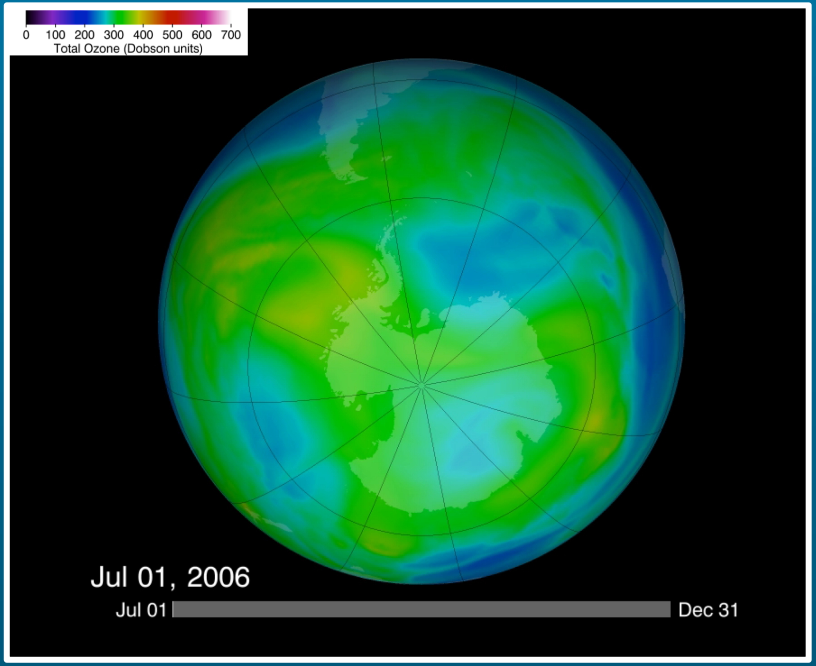
High spring ozone

Weaker stratospheric polar vortex in spring and summer

Negative SAM phase (equatorward jet shift)

The Ozone Hole

- Large stratospheric springtime O_3 loss over Antarctica
- Result from anthropogenic emissions of ozone depleting substances



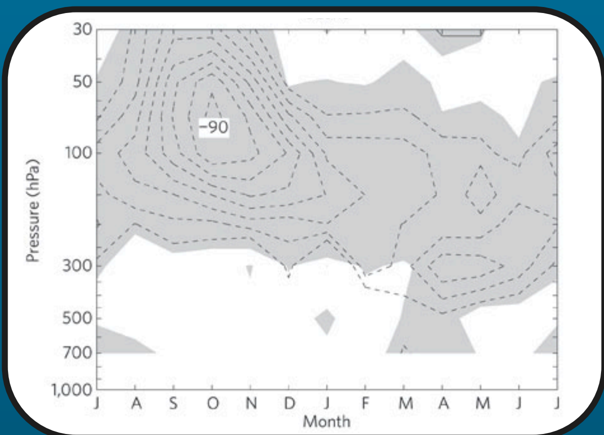
How has the ozone hole impacted both the long-term changes and interannual variability of summer surface temperatures outside of Antarctica?

http://ozonewatch.gsfc.nasa.gov/monthly/SH.html

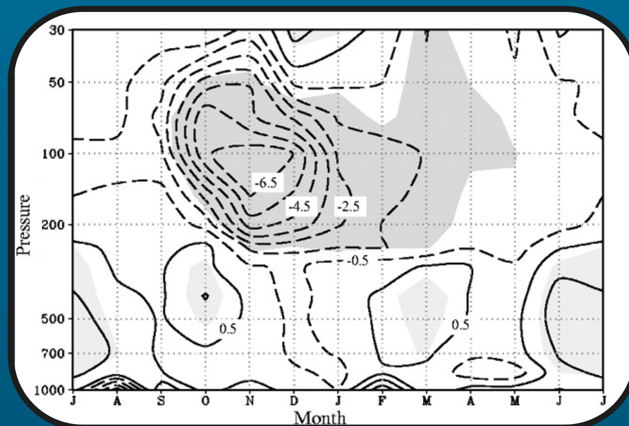
The Ozone Hole and Antarctic Climate Change

Previous studies [*Thompson & Solomon (2002)*, *Gillett & Thompson (2003)*] found that ozone depletion has affected summer surface climate in Antarctica.

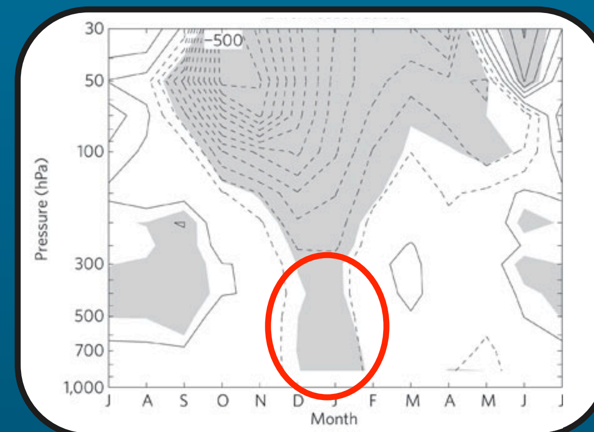
Ozone Trend (%)



Temperature Trend (K)



Geopotential Height Trend (m)



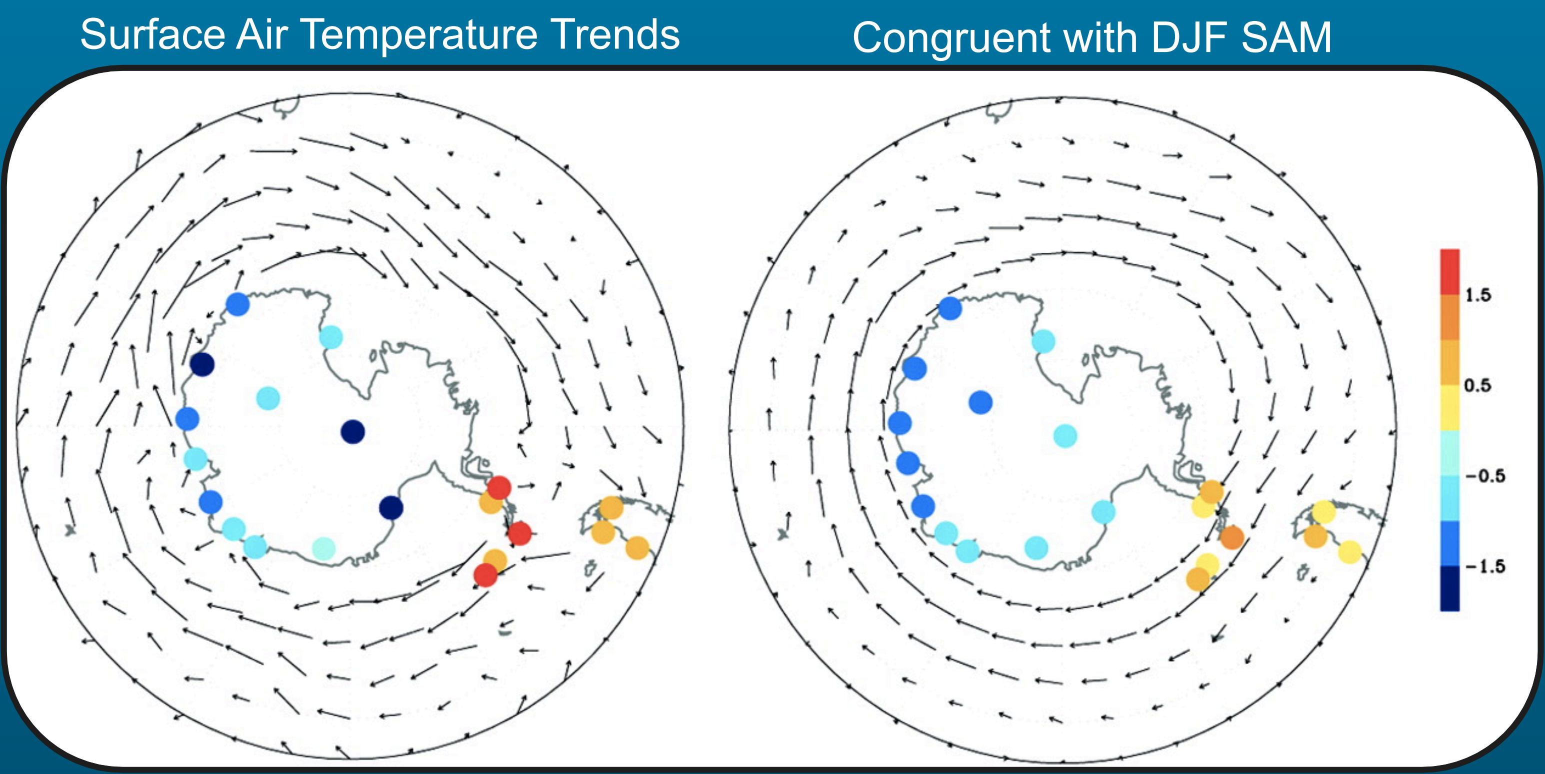
Ozone loss → Stratospheric cooling (Increased pole-to-equator *ΔT*) → Strengthened and longer lived polar vortex

∂u_g R ∂T

Circulation changes extend downwards to the surface in summer (DJF)

Thompson et al., 2011. Nature Geo., Gillett & Thompson, 2003. Science.

The Ozone Hole and Antarctic Climate Change



What are the long-term changes outside of the polar region linked to the circulation changes from ozone depletion?

Thompson & Solomon, 2002. Science

Datasets

ERA-Interim reanalysis

Global Historical Climatology Network (GHCN)

Australian Climate Observations Reference Network Surface Air Temperature (ACORN-SAT)

Halley station total column ozone

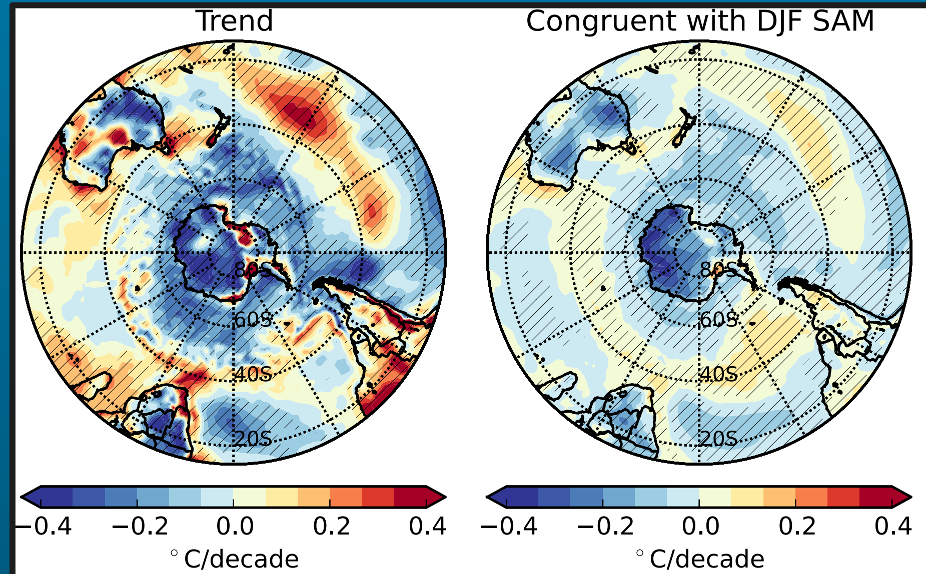
Marshall Southern Annular Mode index

El Niño Southern Oscillation index

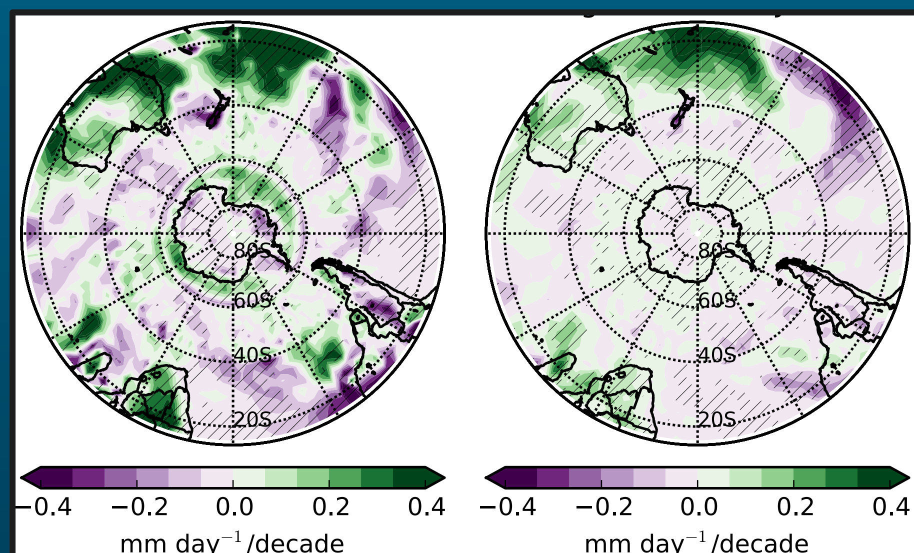
Global Precipitation Climatology Project (GPCP)

SH Summer Climate Change 1979-2012

DJF Surface Air Temperature Trends



DJF Precipitation Trends



Top: ERA-Interim, Bottom: GPCP

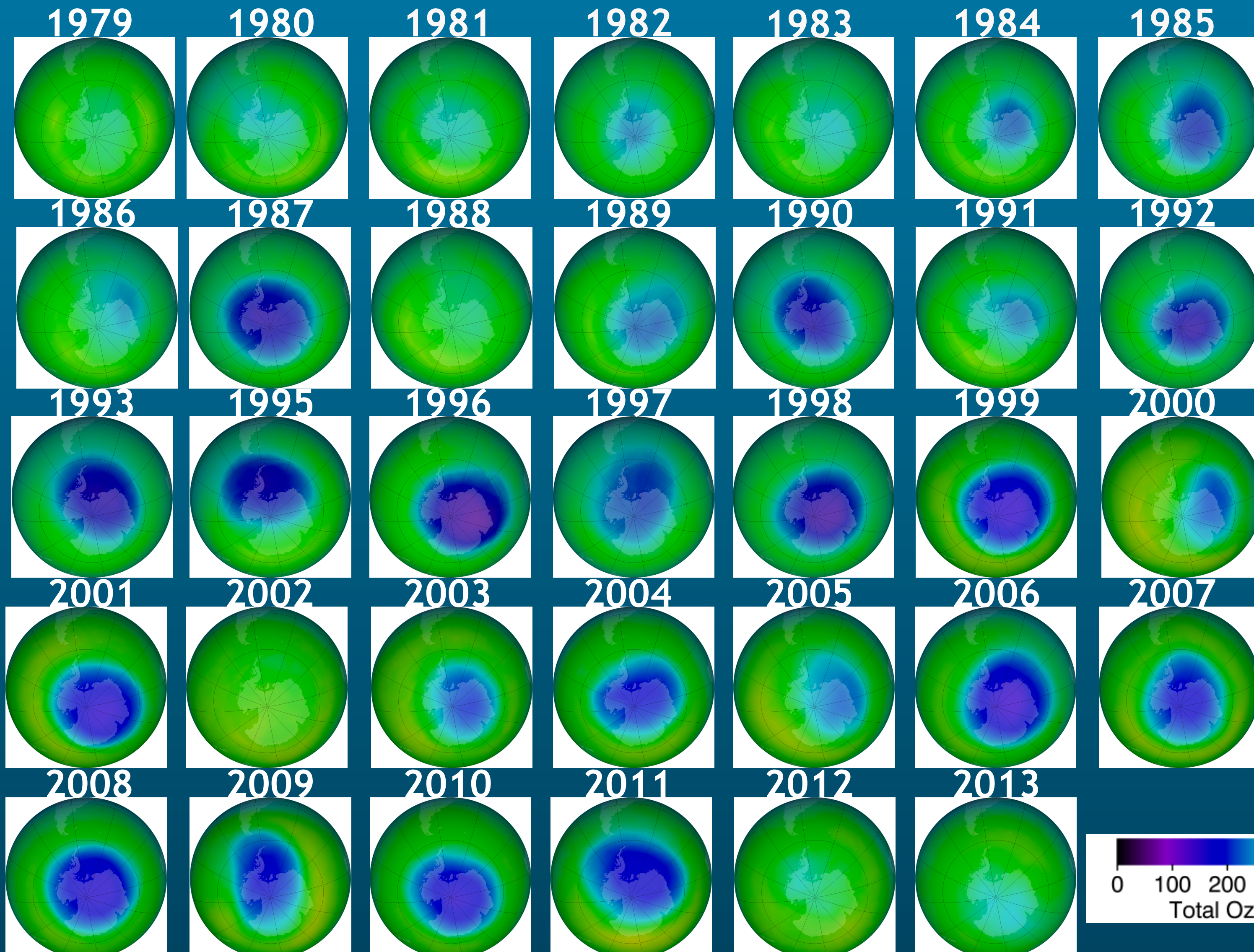
Summary of Long-term Changes:

- Significant changes in summertime surface temperature and precipitation outside of polar region congruent with the changes in SAM

- Surface trends, unlike the forcing, are not zonally-symmetric indicating the importance of modulating mechanisms

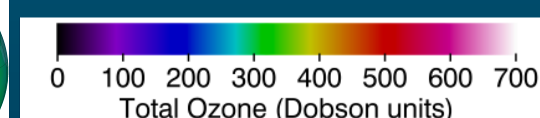
The long-term changes in summer surface climate are linked to the decadal changes in circulation forced by the ozone hole. What about the interannual variability?

Interannual variability in ozone depletion



November Total Column Ozone

Tail-end of the ozone hole season



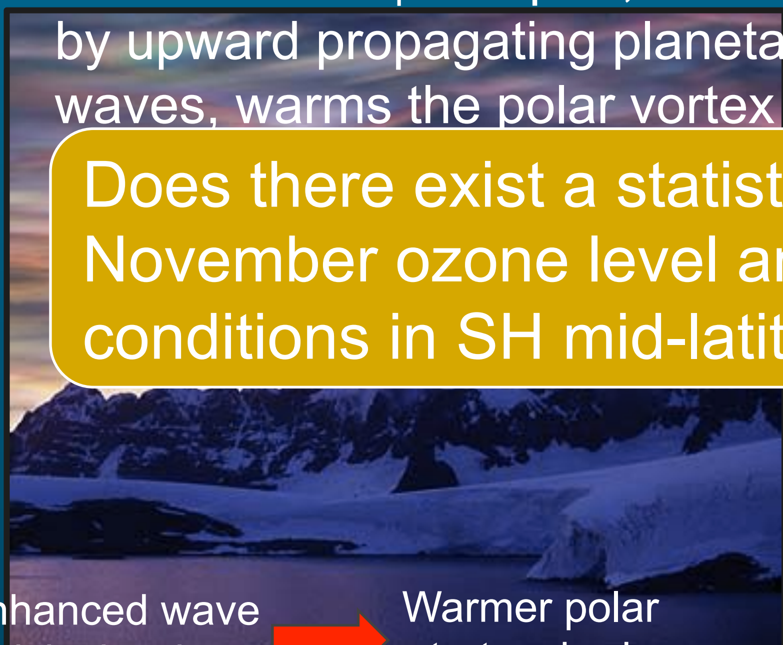
http://ozonewatch.gsfc.nasa.gov/monthly/SH.html

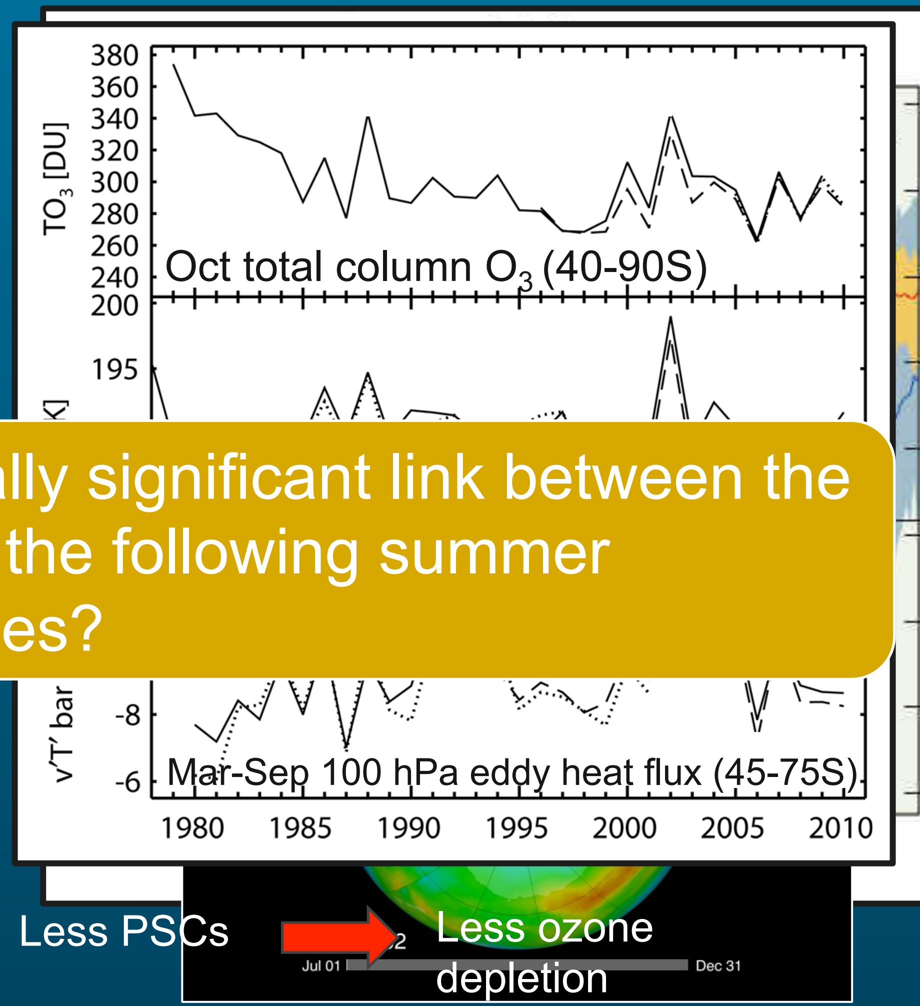
Interannual variability in ozone depletion

Why do some years have higher ozone loss than others?

- Key prerequisite for ozone loss is cold temperatures
- Poleward heat transport, induced by upward propagating planetary waves, warms the polar vortex

Polar Stratospheric Clouds





Does there exist a statistically significant link between the November ozone level and the following summer conditions in SH mid-latitudes?

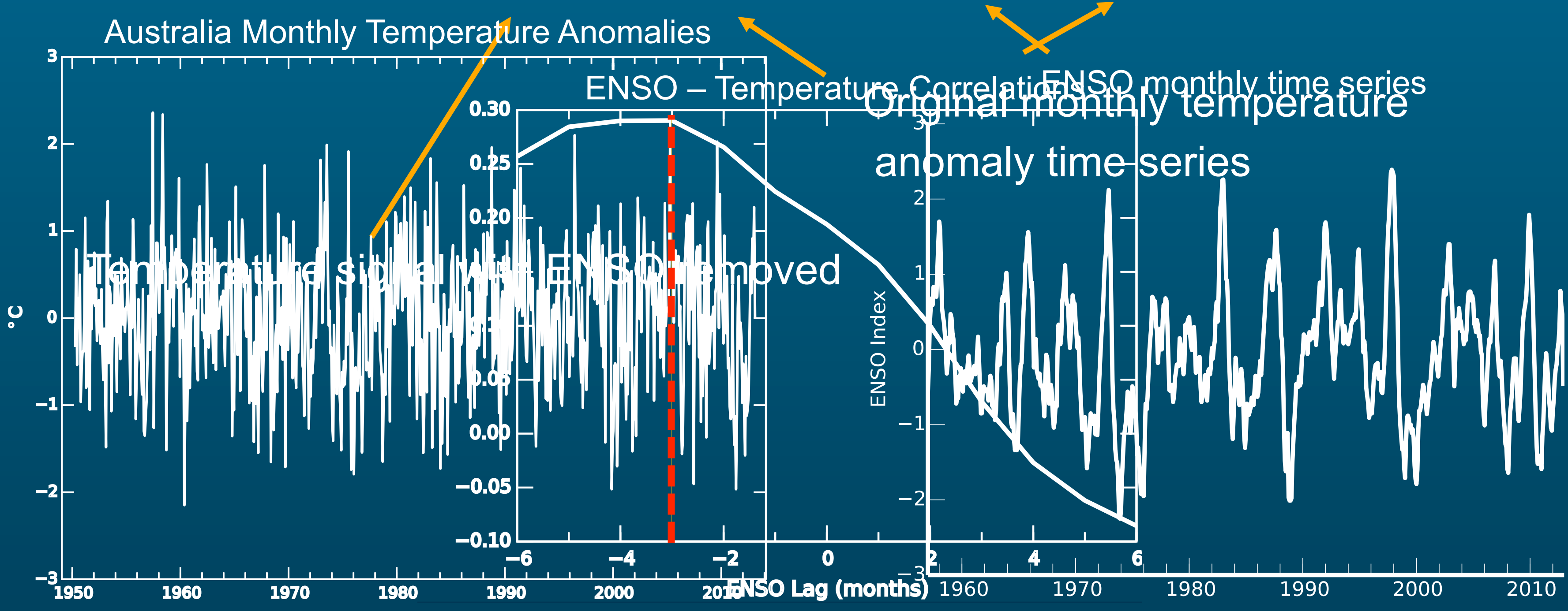
Enhanced wave activity in winter and spring → Warmer polar stratospheric temperatures → Less PSCs → Less ozone depletion

Data and Methods

ENSO removal:

- The effects of ENSO on interannual and interdecadal time scales have similar circulation changes associated with SAM
  - Filter out ENSO prior to analysis

$$T_c(t) = T_s(t) - ENSO(t-L) \cdot R$$



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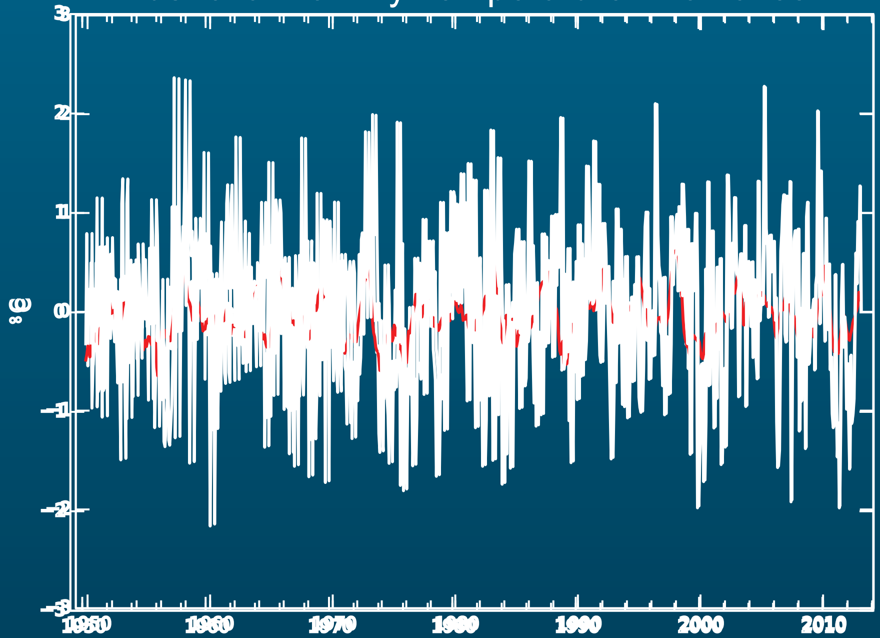
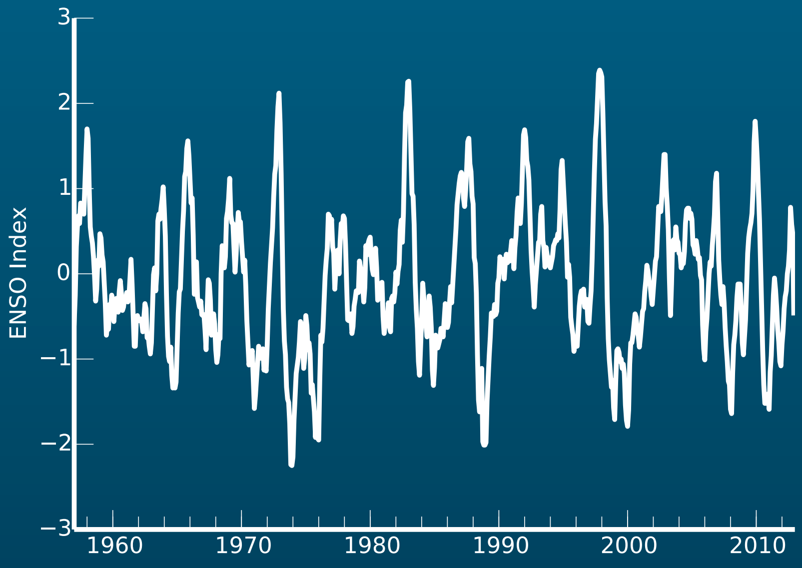
← Regression of anomalies onto lagged ENSO

Australia Monthly Temperature Anomalies

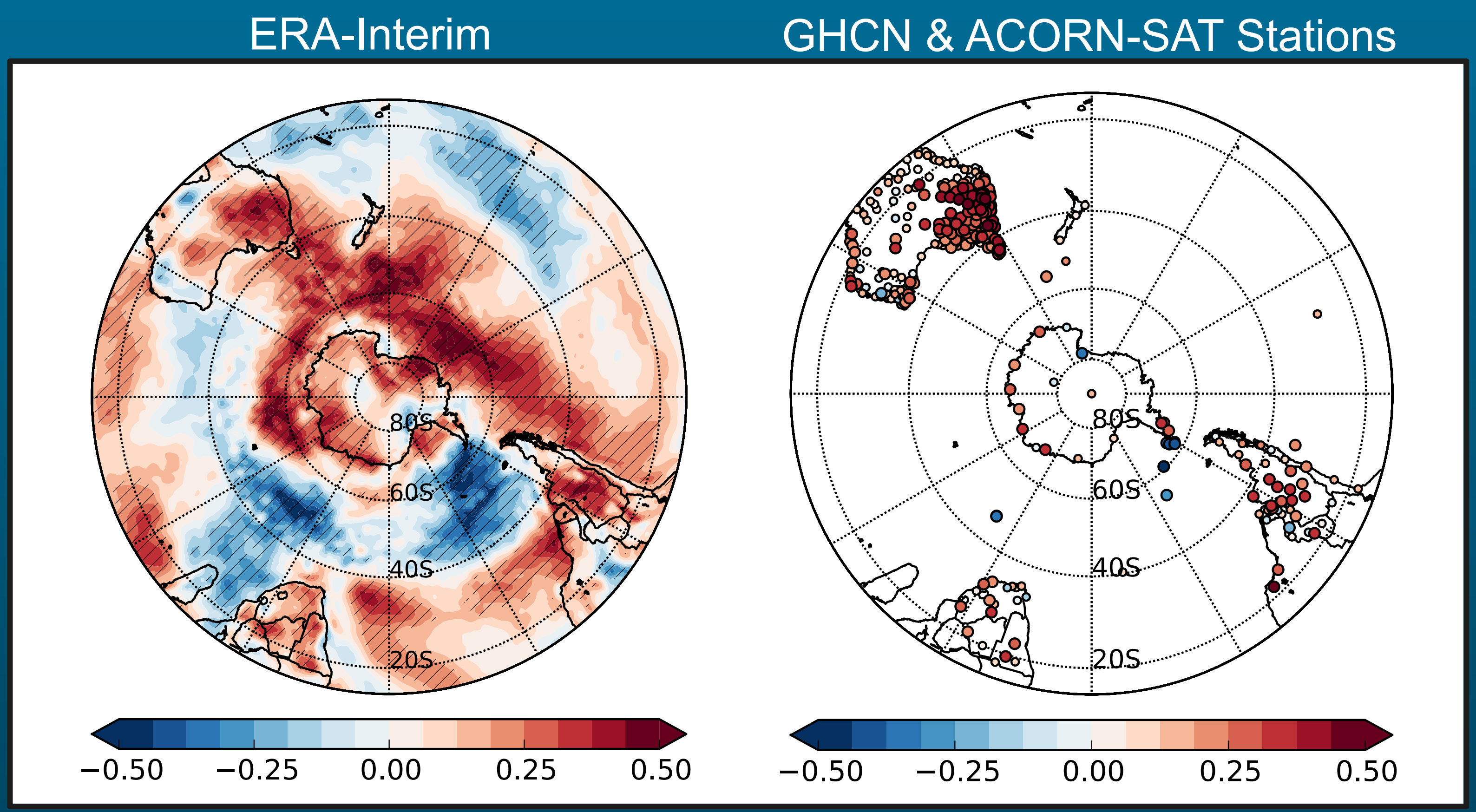


ENSO monthly time series



Springtime Ozone and SH Surface Temperatures

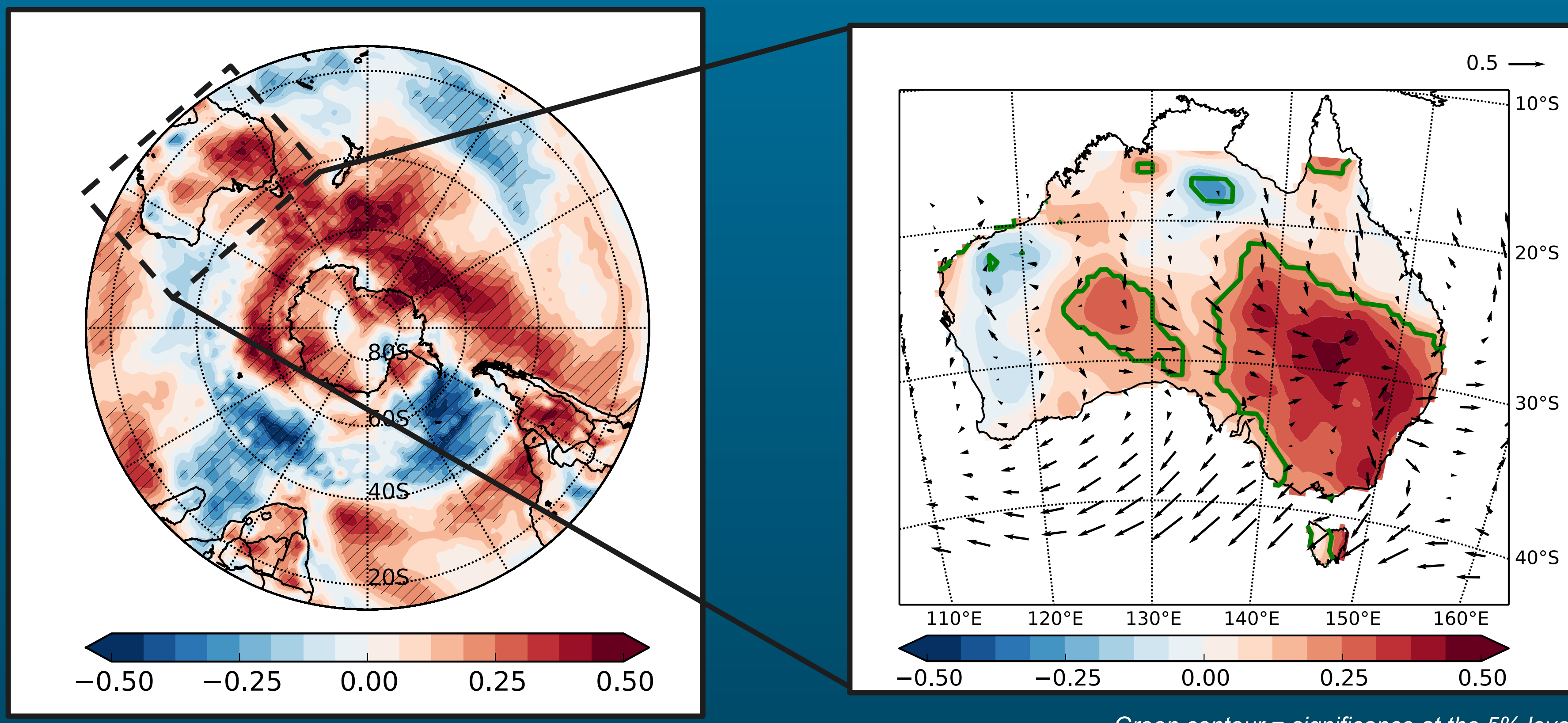
Correlations for November Ozone and Detrended
DJF Surface temperature Anomalies 1979-2012



Hatching = significance at the 10% level.

Springtime Ozone and SH Surface Temperatures

Correlations for November Ozone and Detrended
DJF Surface temperature Anomalies



Green contour = significance at the 5% level.
Arrows = correlation vectors with wind