The observed trend in the Southern Annular Mode: is it the ozone hole or is it greenhouse gases?

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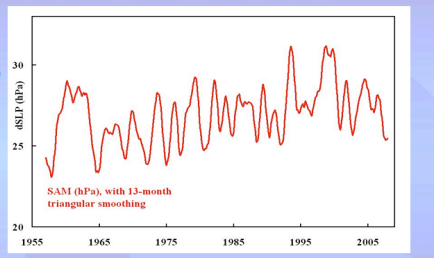
Acknowledge: G Marshall, M Allen, G Bodeker

Motive - the obvious trend in SAM (sea level pressure difference mid-latitudes - pole)

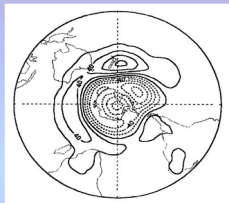


Method - multiple linear regression

- **multiple** - simultaneous fit to several indices
- **linear** - single coefficient multiplies each index
- **regression** – least-squares, minimises sum of squares of residuals
- **code courtesy of Myles Allen**
- **includes red-noise model** - accounts for autocorrelation
- **outputs the significance of each coefficient** - two-sided t-test

The Southern Annular Mode (SAM)

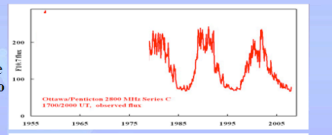
- **is the leading southern hemisphere Empirical Orthogonal Function (EOF) of variability in wind, tropospheric height, sea-level pressure**



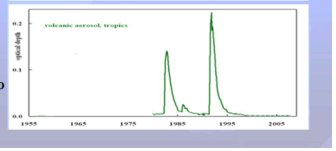
EOF1 of monthly mean sea-level pressure from NCEP reanalyses 1958-97 (Gong & Wang 1999)

- **SAM correlates well with sea-level pressure at 40°S minus 65°S**
- **so, we use SLP data from 6 stations at each latitude, from 1957 to 2005** (Marshall 2002)
- unaffected by SH reanalysis errors in pre-satellite era (before 1978)

- important because the solar cycle since 1978 happens to anti-correlate with linear trend

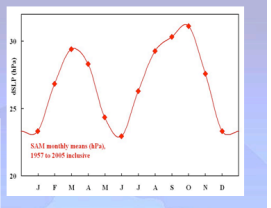


- and volcanic aerosol since 1978 happens to correlate with the solar cycle

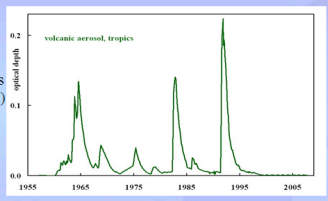


Rapidly-varying indices: seasonal cycle, stratospheric volcanic aerosol QBO, ENSO, solar cycle

- **seasonal cycle:** variability in SAM is dominated by its seasonal cycle. Seasonal cycle is best represented by the monthly means of the whole data set.

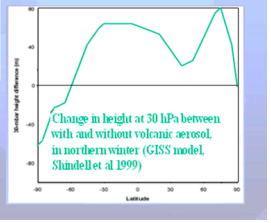


- **volcanic aerosol:** Satellite measurements (SAGE, SME) extrapolated via ground-based solar pyrometer (Sato et al)



Why should volcanic aerosol matter?

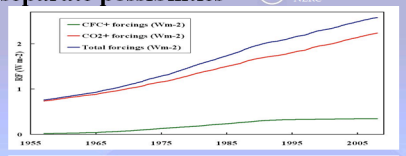
- **in sunlight it cools below** (reflects sunlight) **but warms above** (ozone sees the sunlight twice)
- **in darkness it warms below** (the normal greenhouse effect)
- **more aerosol = less height difference, tropics minus pole**



Trend index: we test 3 separate possibilities of long-term change

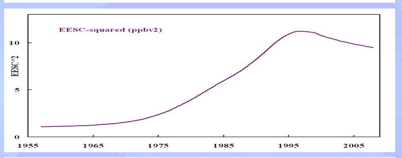
1. Increased greenhouse gases

Radiative forcing calculated from well-mixed greenhouse gases (GISS website)



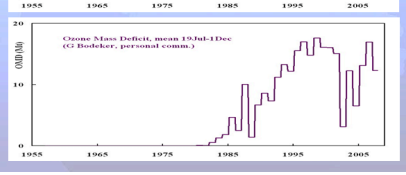
2. Effective equivalent stratospheric chlorine (EESC)

- Cl from CFCs that deplete ozone
- includes Br from halons
- lagged from tropospheric CFCs
- squared to represent polar reactions (ClO+ClO etc)

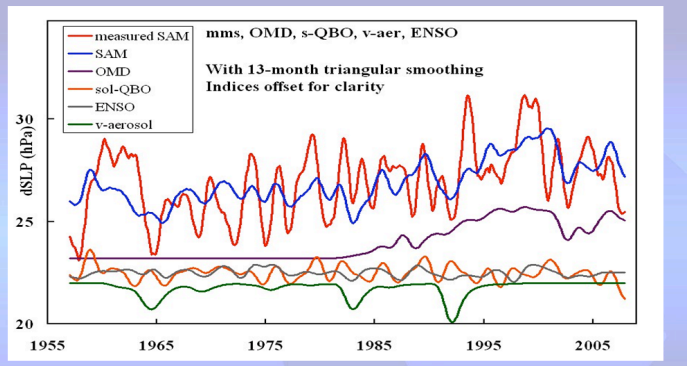


3. Ozone mass deficit (OMD)

- amount by which total ozone is less than 220 DU in the SH
- a measure of size times severity of the whole ozone hole



Results 1 - success



But, the observed SAM obviously includes some other inter-annually varying features
Planetary waves? - but we cannot diagnose these accurately in the SH before 1978
Ap (solar particle) index? - we tried this, but there was little improvement

Results 2 - significant correlation with GHGs, major increase in significance when replaced by EESC², further increase when replaced by Ozone Mass Deficit.

		t-value	Significance (%)
Results when also fitting ENSO, volcanic aerosol and solar-QBO indices	GHGs	3.8	99.7
	EESC²	4.3	99.9
	OMD	4.8	99.98

How much more likely?

- use Akaike Information Criterion (AIC):

For any one regression model *i*,

$$\mathbf{AIC} = n \ln(\textit{sum-sq-resids}/n) + 2(k+1)$$

where n is data points, k is degrees of freedom

Burnham & Anderson (1998):

$$\Delta_i = \mathrm{AIC}_i - \mathrm{AIC}_{min}$$

$$w_i = \exp(-\tfrac{1}{2}\Delta_i) / \left(\sum_{r=1 \to R} \exp(-\tfrac{1}{2}\Delta_r)\right)$$

where ***w* is AIC weight**

R is the number of regression models *r* considered

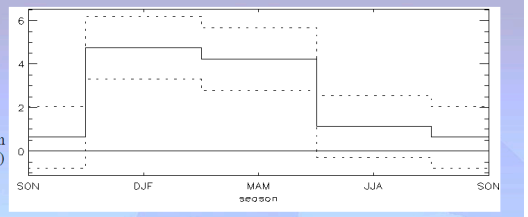
- denominator constant for given suite of models
- AIC weights for the suite sum to unity
- each weight is probability of that model being the best of the suite

Indices	AIC weight
Monthly means, ENSO, V- aerosol, Solar-QBO, **GHGs**	**0.013**
Monthly means, ENSO, V- aerosol, Solar-QBO, **EESC²**	**0.089**
Monthly means, ENSO, V- aerosol, Solar-QBO, **OMD**	**0.863**

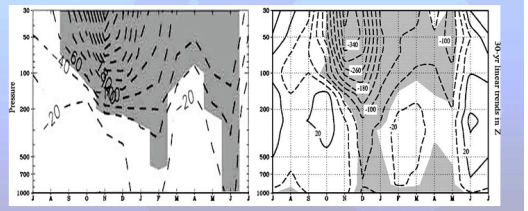
If regressions showed cause and effect, stratospheric ozone loss would be 7 to 70 times more likely to be the cause of the increase in SAM than greenhouse gases

Results 3 - cause & effect consistent with seasonal regressions

Seasonal regressions show maximum correlation with OMD in summer and autumn



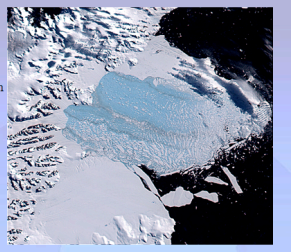
Consistent with earlier work showing stratosphere affecting troposphere in Antarctica



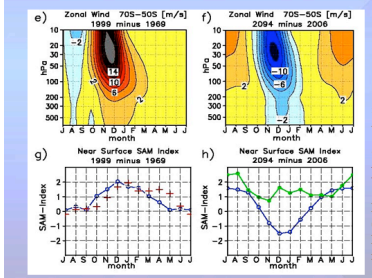
Modelled (left) and measured (right) trend in heights poleward of 65°S between 1969 and 1999 (Keeley, Gillettet al. GRL, Thompson & Solomon, Nature)

Why is this important?

1. Increase in sea level pressure diff. forces stronger near-surface winds, which brings warm air round Peninsula (Marshall et al., *J Clim* **19**, 5388, 2006), & brings more air over the Peninsula whose descent warms it (Van Lipzig et al., *J Clim* **21**, 1649, 2008) - melts ice shelves



Larsen ice shelf, Antarctic Peninsula /Weddell Sea, March 02



5. IPCC-AR4 models say SAM will continue to increase. But, they show trends in winter, and models with a better stratosphere show a partly opposite effect.

Perlwitz et al, *GRL* **35**, L08714, 2008, uses Goddard (GEOS) CCM, with full interactive stratospheric chemistry Blue lines in (g) & (h) are with actual and scenario CFCs, red crosses are Marshall SAM, green line is with fixed 1960s CFCs.

Conclusions:

A. SAM has a significant correlation with greenhouse gases
- major increase in significance when GHGs are replaced by EESC-squared
- further increase when replaced by the measured Ozone Mass Deficit

B. If regressions showed cause & effect, stratospheric ozone loss would be 7 to 70 times more likely to be the cause of the increase in SAM than greenhouse gases

C. Such cause and effect is consistent with the results of seasonal regressions

This is important because:

1. Increase in sea level pressure difference forces stronger near-surface winds
2. Brings warm air round Peninsula, melts ice shelves (Marshall et al., *J Clim* **19**, 5388, 2006)
3. Increases Antarctic Circumpolar Current - isolates cold productive water to south
4. Reduces capacity of the ocean to soak up extra CO_2 (Le Quere et al, *Science* **316**, 1735, 2007)
5. IPCC AR4 models say SAM will continue to increase
   - but models with a better stratosphere show partially opposite effect

- **our analysis says SAM should recover as ozone hole recovers** (Montreal Protocol)
- **will the Larsen ice shelf re-establish itself by 2100?**