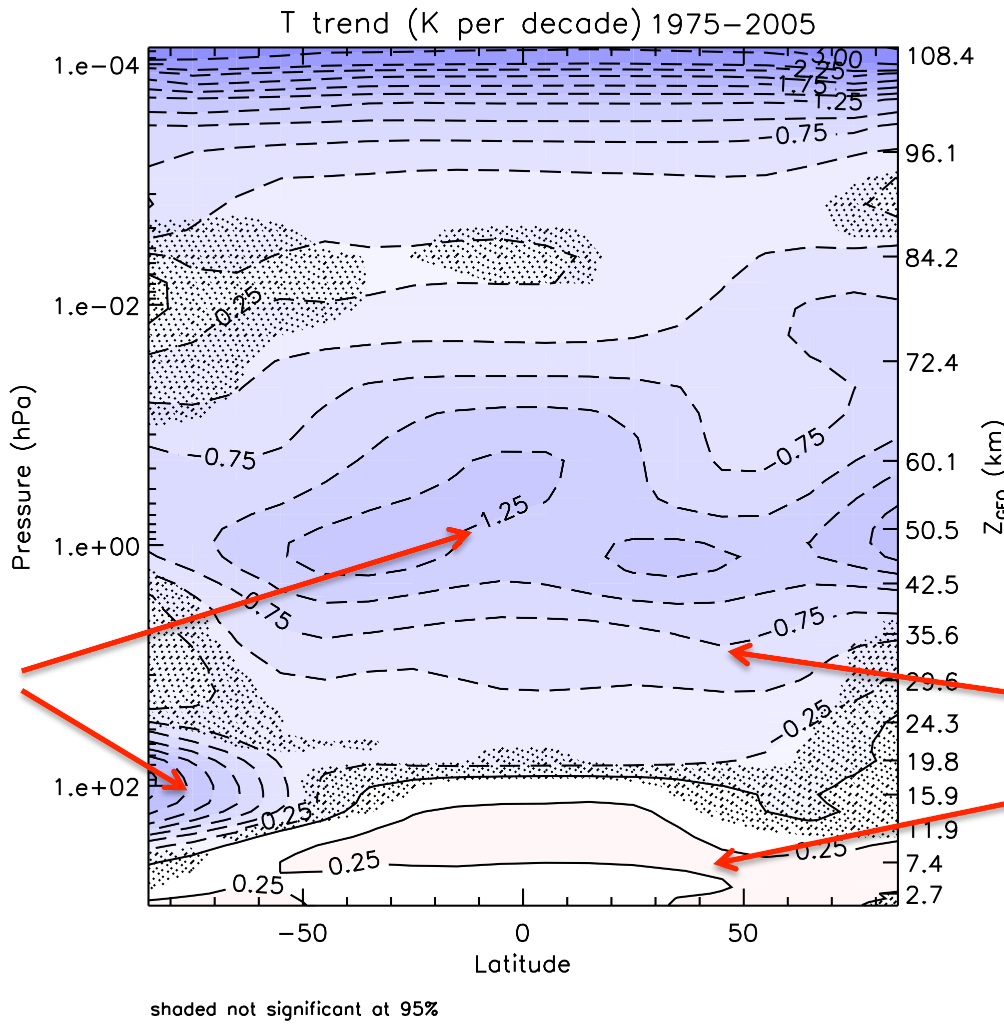
The role of the stratosphere in present and future climate change

Rolando Garcia
National Center for Atmospheric Research
Boulder, CO, USA

outline

- stratospheric temperature trends as “fingerprint” of climate change
- the role of ozone depleting substances (ODS)
- stratospheric ozone loss and present climate change
- ozone recovery and 21st century climate change

global T trends, 1975-2005



these local maxima are due to O_3 loss

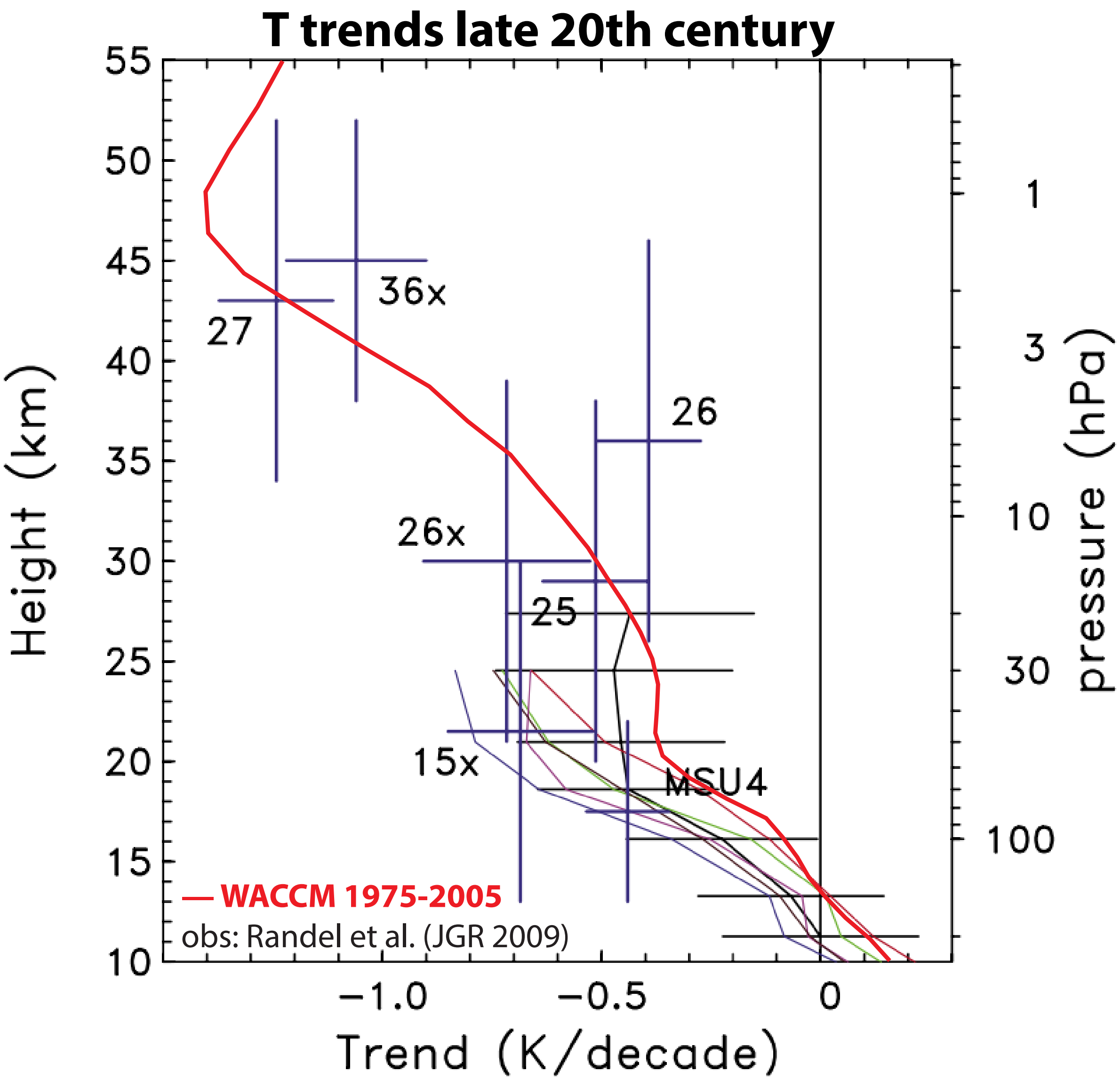
trend calculation using NCAR's Whole Atmosphere Community Climate Model (WACCM)

upper atmosphere cools

troposphere warms

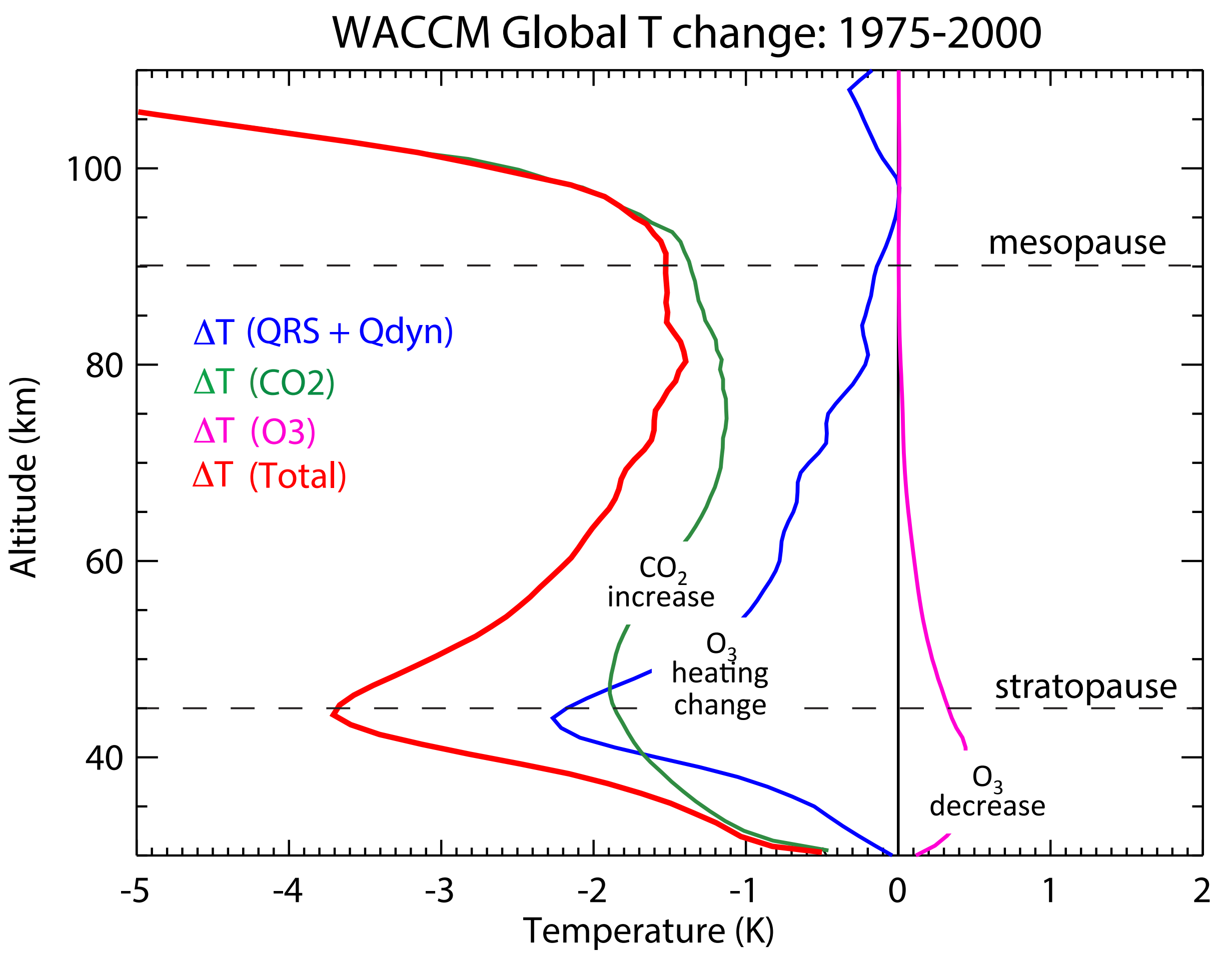
- trends in the late 20th century can be calculated accurately with comprehensive models
- the pattern of tropospheric warming/stratospheric cooling is a fingerprint of GHG-driven climate change

global-mean T trend profile vs. observations



- calculations agree well with observations within their uncertainties
- observations:
  MSU, SSU + radiosondes
  (Randel et al., 2009)

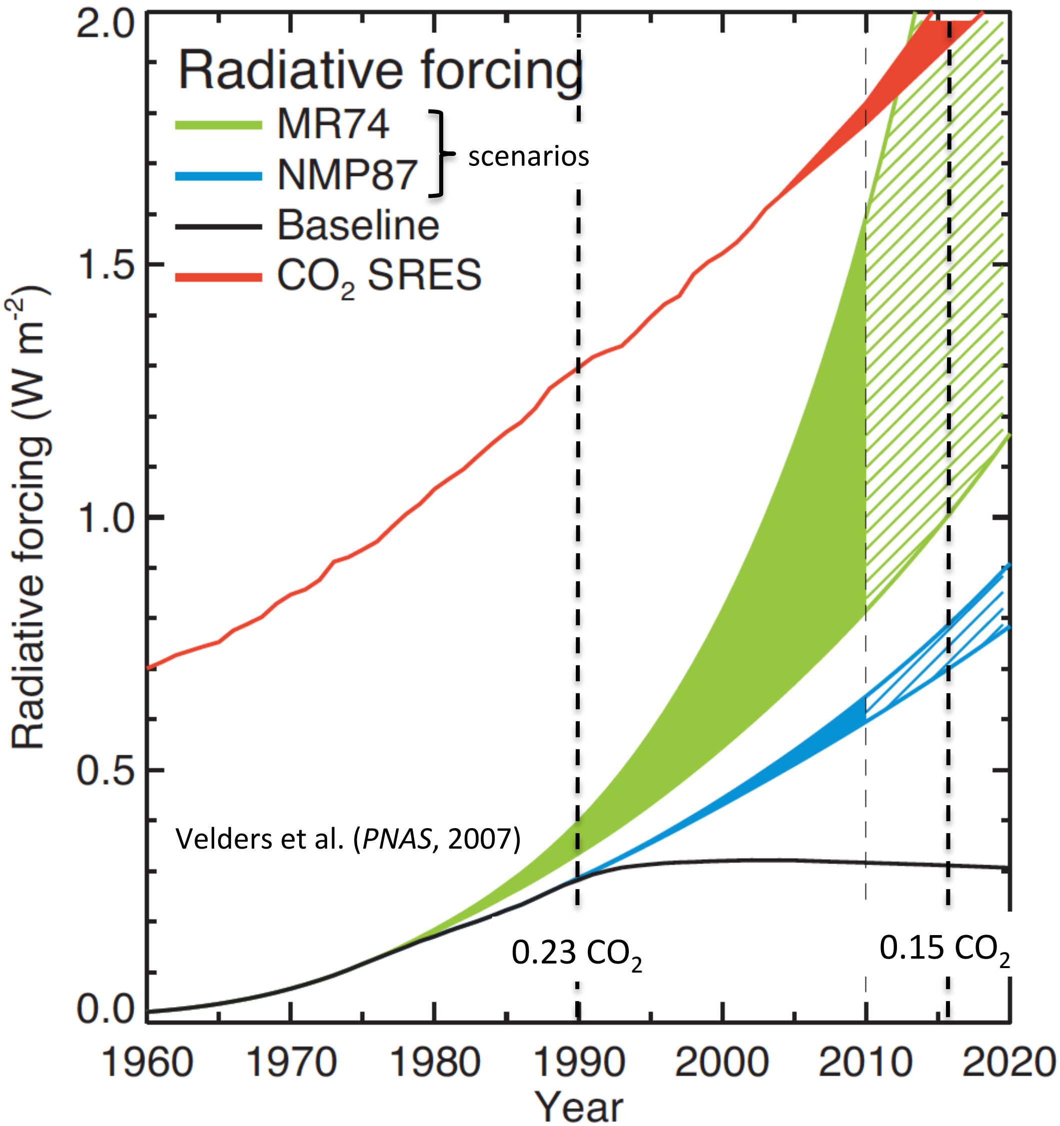
Attribution of T change



- ozone loss in the stratosphere plays a major role
- ozone decrease is driven by the increase in ODS

graph courtesy of M. López Puertas, Instituto de Astrofísica de Granada, Spain
NB: this is change over the period. For decadal trends, divide by 2.5 decades

ODS and climate



ODS *destroy ozone and they are also potent GHG*

Radiative forcing by ODS:

- 23% of CO_2 in 1990
- 15% of CO_2 today (2016)

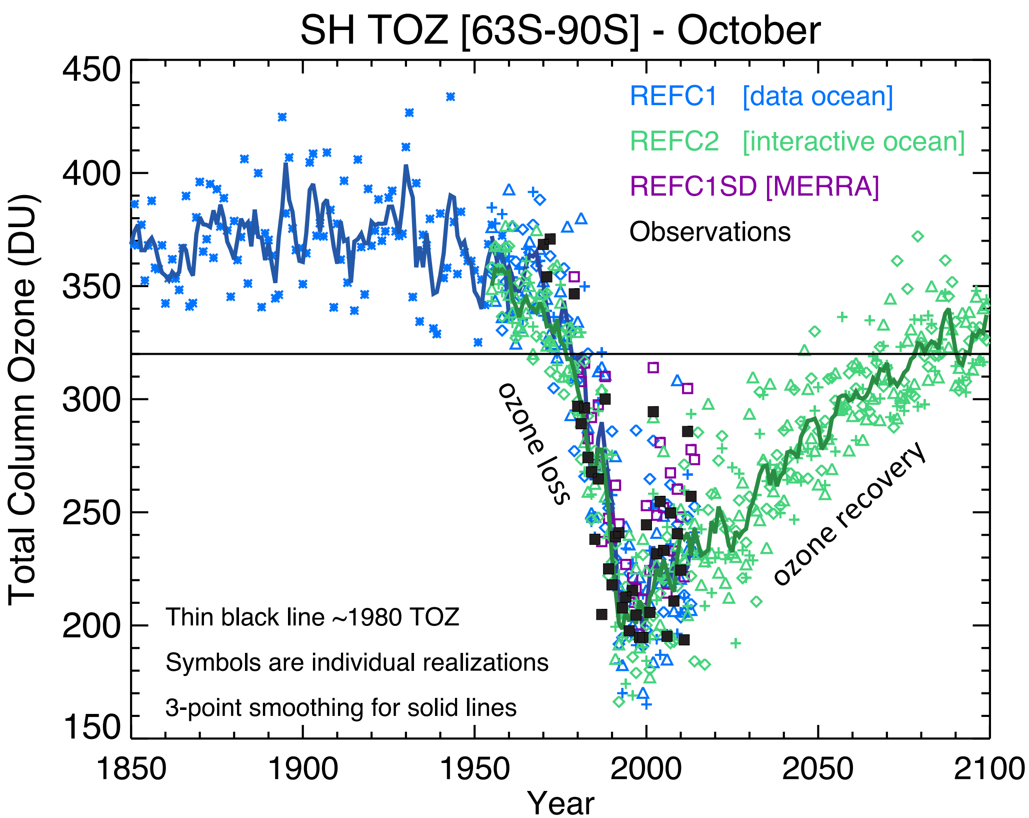
Without control of ODS:

- 35-110% of CO_2 today (2016), depending on growth scenario

→ Control of ODS is the largest contribution to the reduction of GHG emissions since the 1980s

- *However, the impact of ODS on ozone in the SH has had important climate consequences*

ozone loss over Antarctica



ozonsonde observations at Halley Bay: black squares

WACCM simulations:

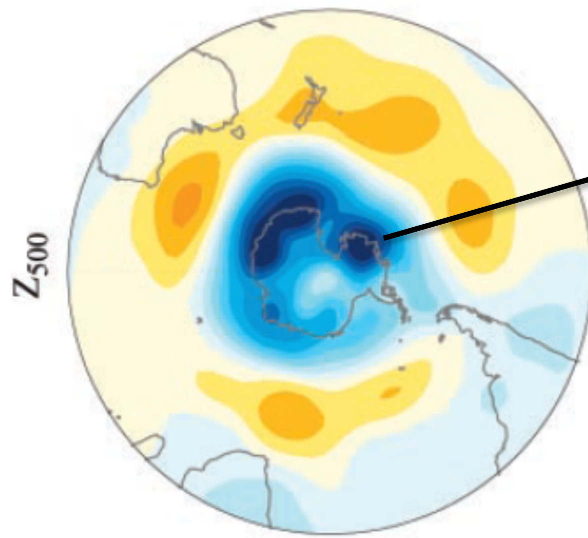
- dynamics constrained by MERRA
- free-running with specified SST
- free-running with interactive ocean

note ozone *loss and recovery*

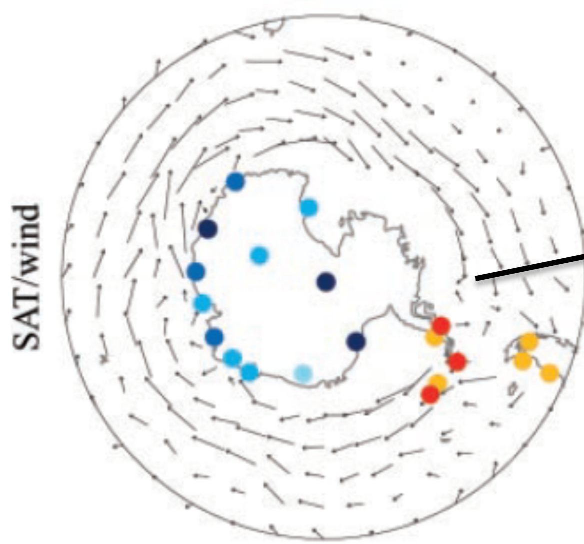
simulations: Whole Atmosphere Community Climate Model (WACCM)
graph courtesy of D. Kinnison, NCAR

impact of O_3 loss on tropospheric climate

Trend (1979-2000)

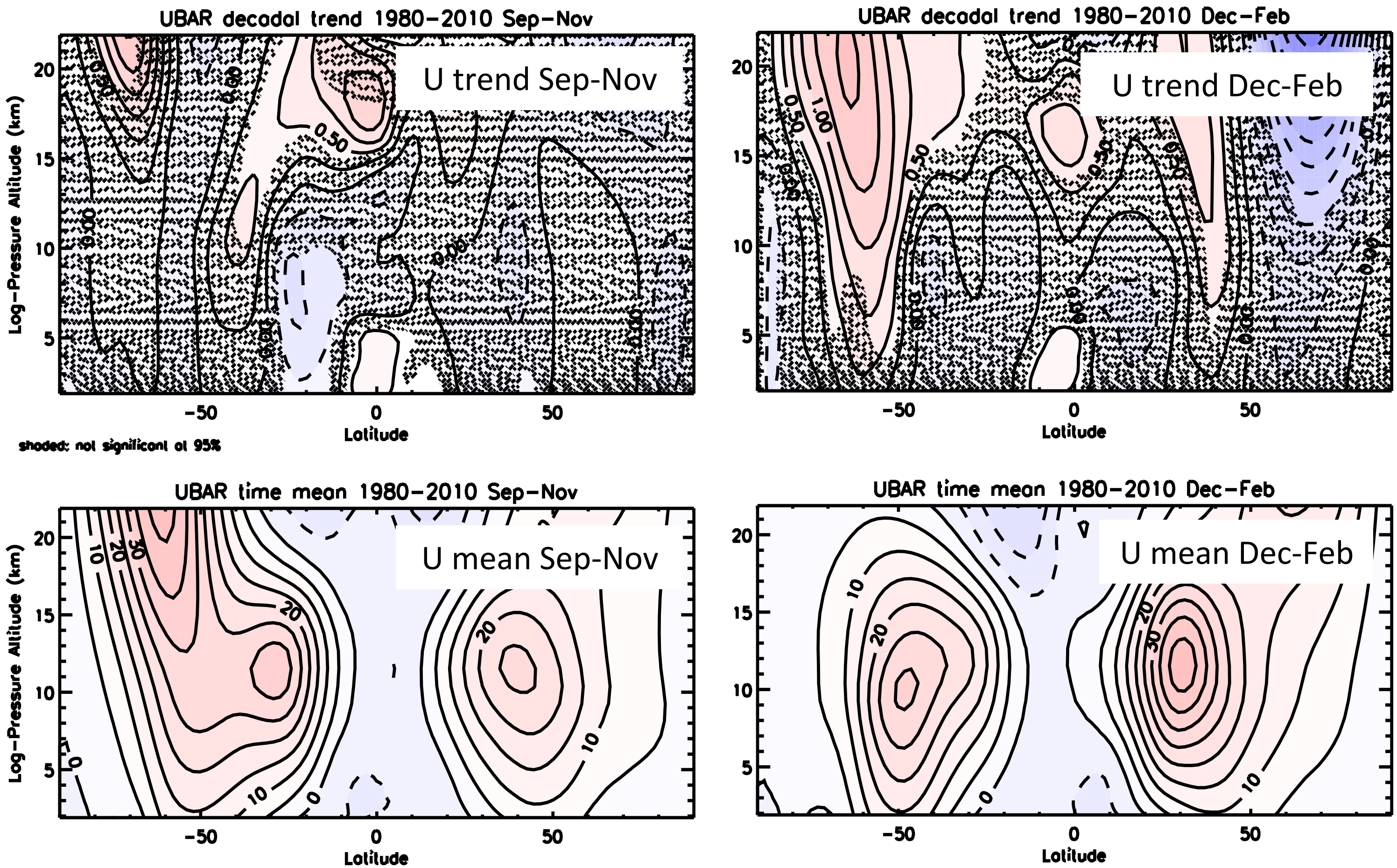


Thompson and Solomon (Science, 2002) showed that the tropospheric jet in the SH strengthens with the development of the Antarctic ozone hole



vertical structure of SH wind changes

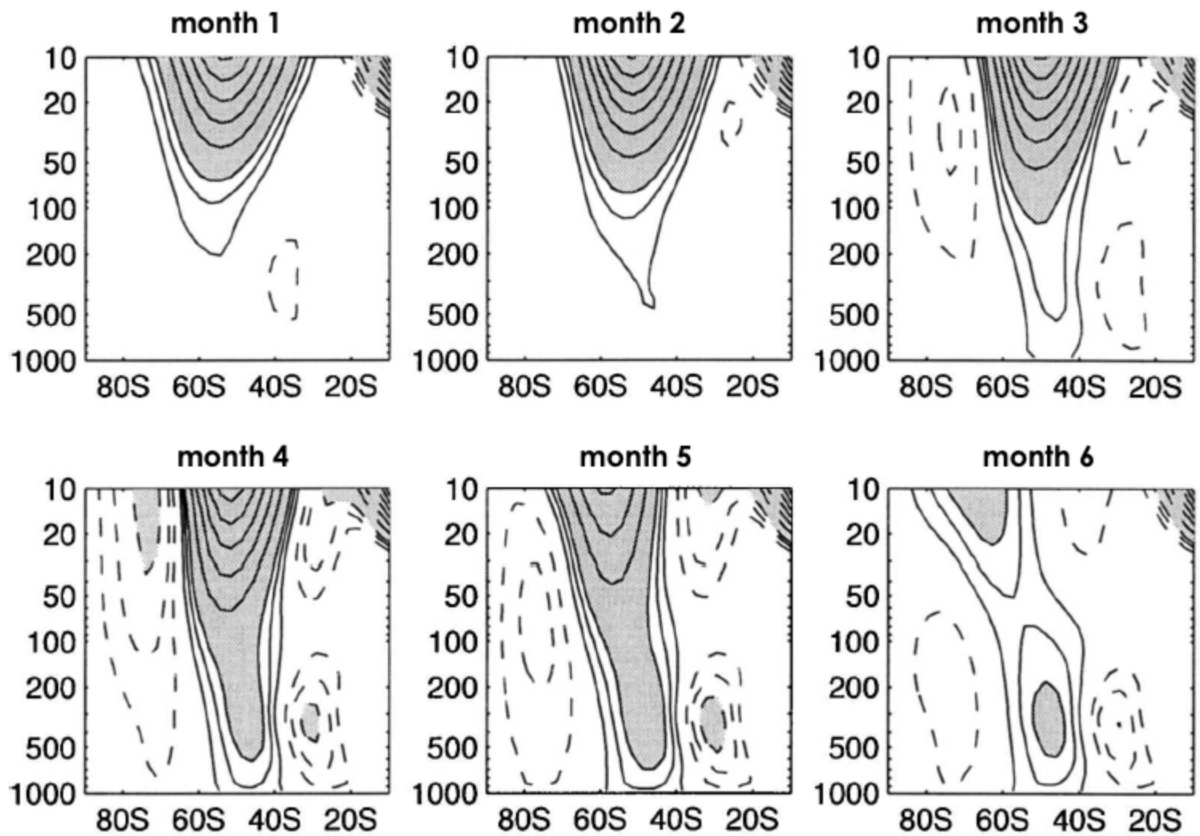
from MERRA reanalysis data, 1980-2010



- stratospheric jet intensifies in Sep-Nov
- changes extend into the troposphere in Dec-Feb → poleward jet shift

SH jet trend in a simple model

simple 3D model with specified cold anomaly in the polar stratosphere



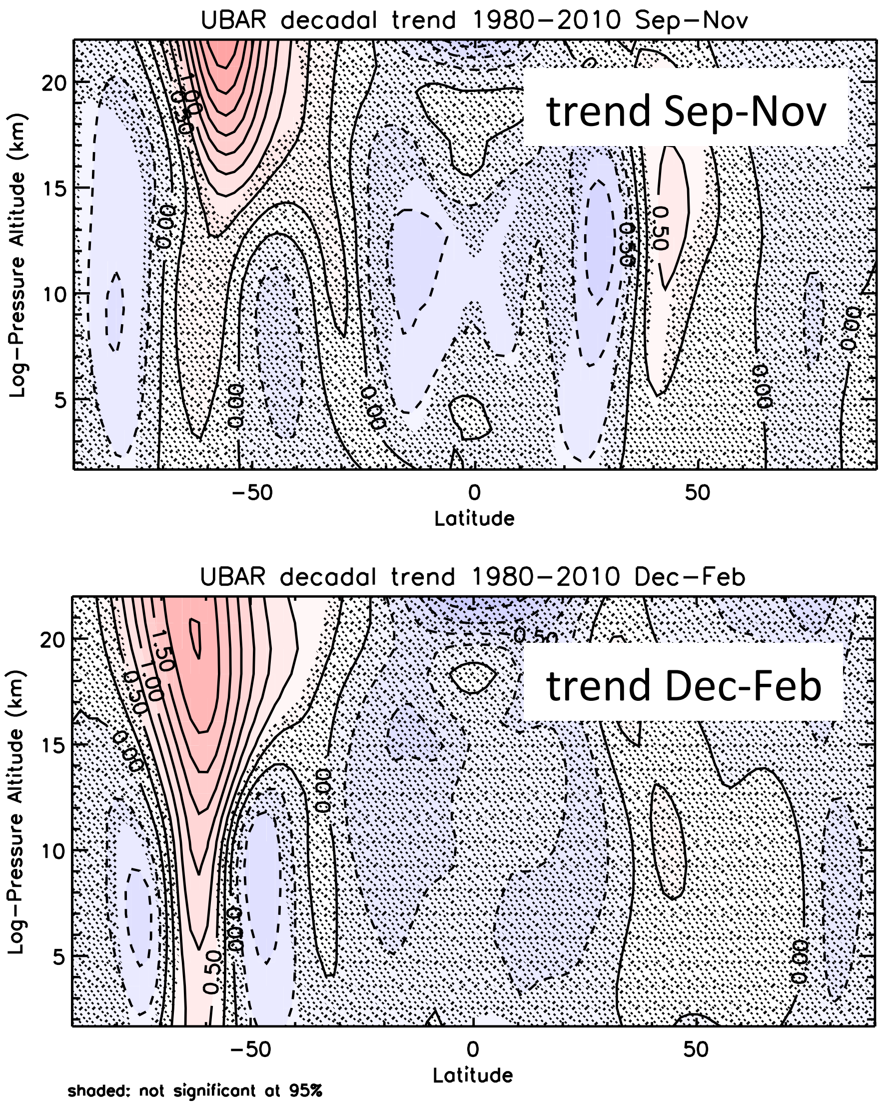
adapted from Kushner and Polvani (J. Clim; 2006)

ozone hole season

SH summer

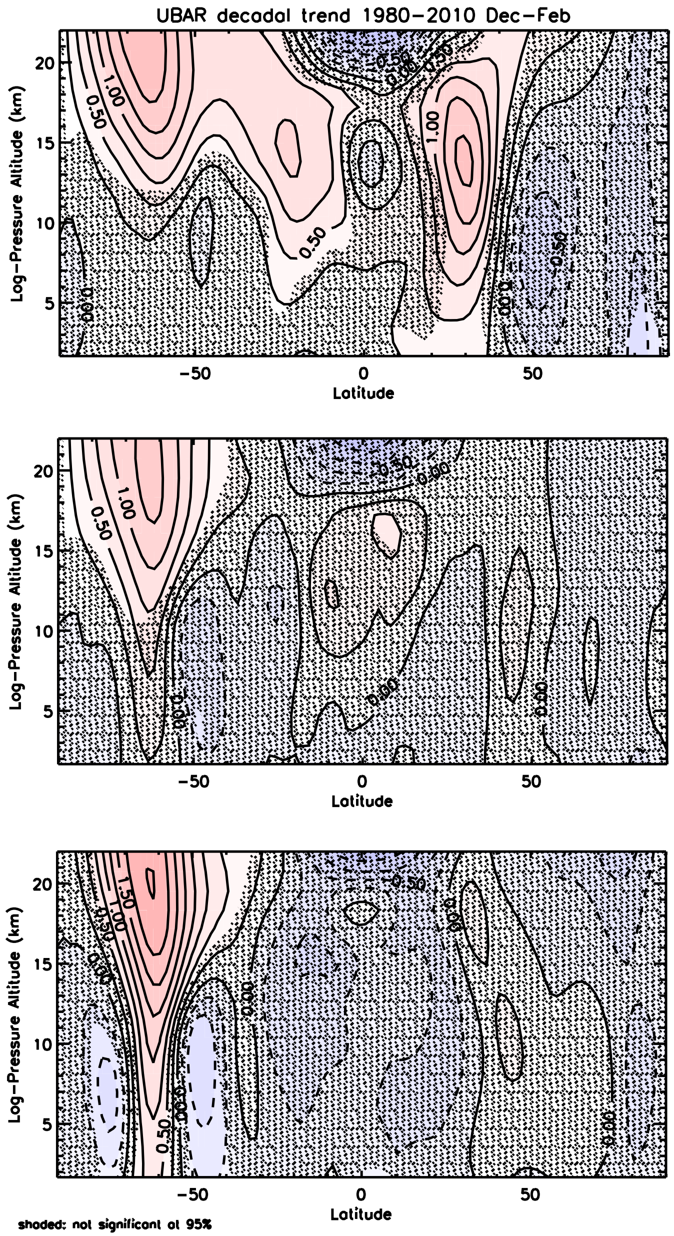
- the jet trends are reproduced in controlled simulations with a simplified model
- ozone loss → colder polar stratosphere → stronger polar stratospheric jet
- strong stratospheric jet → shift in the tropospheric jet (pattern develops over a few months)

SH jet trend in a climate-chemistry model



- WACCM U trend for 1980-2010
- the model is fully interactive, with coupled chemistry and coupled ocean
- inception and development of U anomalies is consistent with observations and simple model calculations shown before

SH jet trend in a chemistry climate model: variability

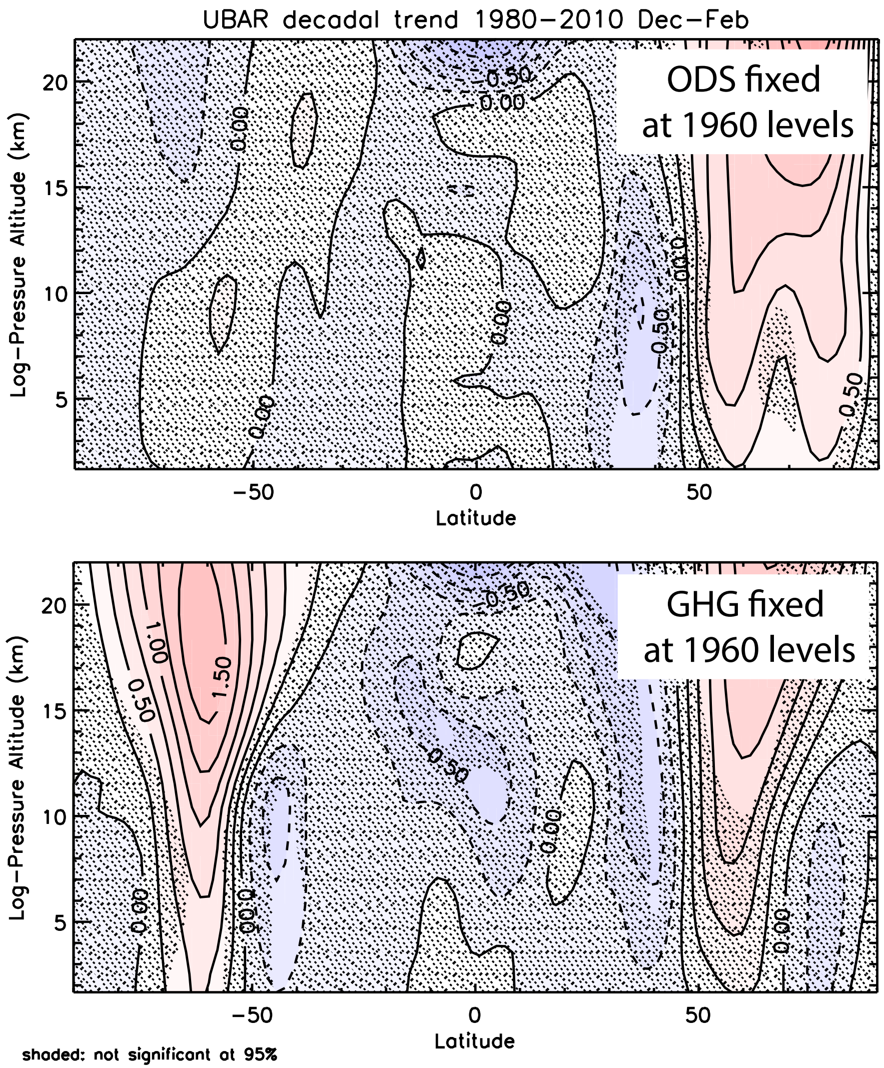


WACCM U trends Dec-Feb 1980-2010

- the plots show *three independent realizations* of the period 1980-2010 made with WACCM
- the jet above 10 km is always significantly stronger: driven directly by ozone loss
- extension into the troposphere varies among the simulations

SH jet trend is attributable to ozone loss

two WACCM simulations, 1980-2010

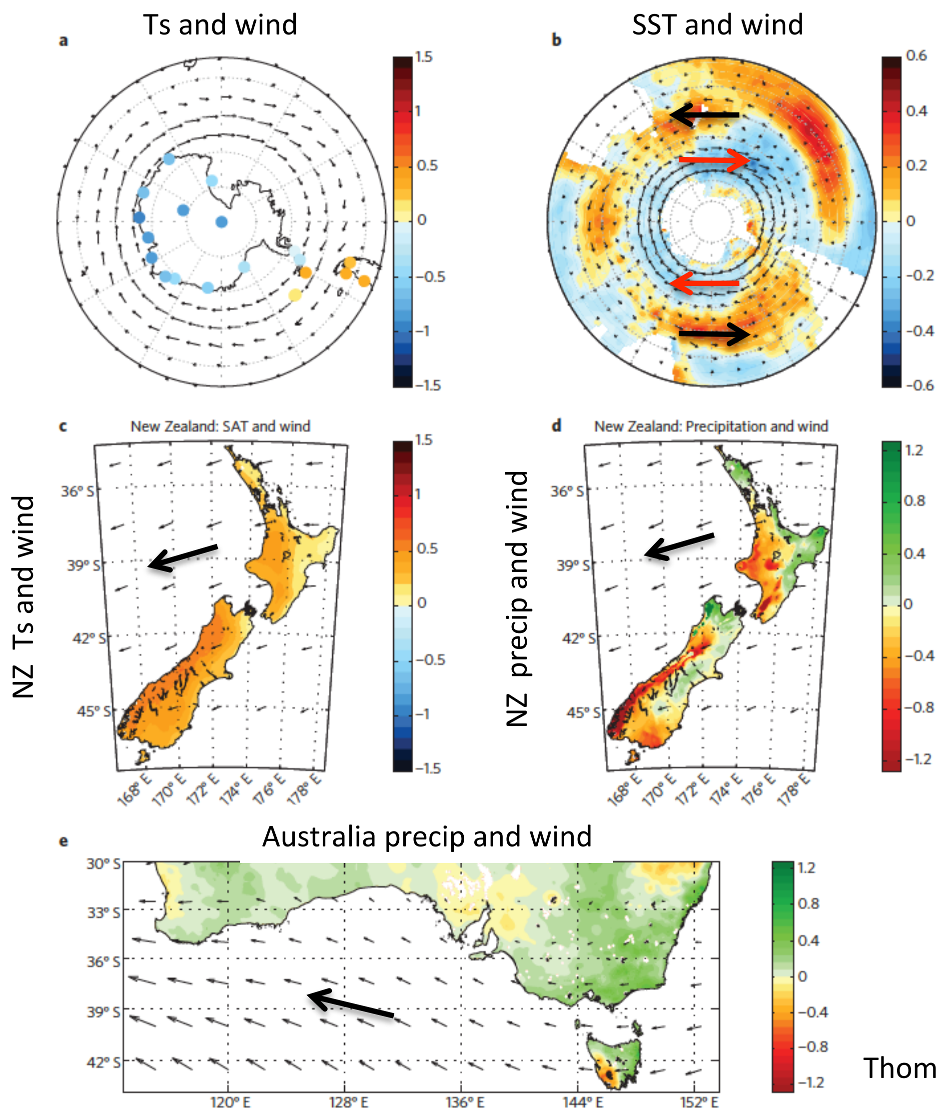


WACCM U trends
Dec-Feb 1980-2010

no ODS growth → no changes in SH jet

but SH jet changes occur even if well-mixed GHG (CO_2, N_2O, CH_4) do not change

consequences for SH climate: midlatitudes



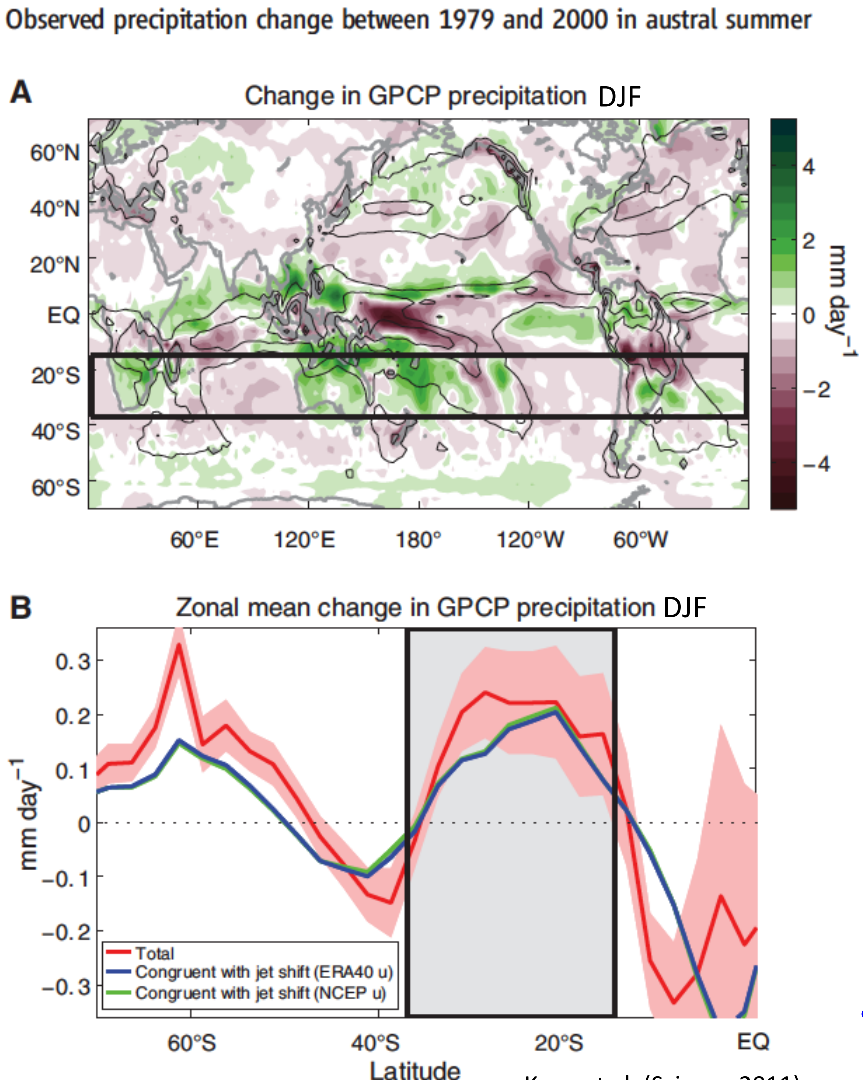
westerly anomaly

easterly anomaly

Thompson et al. (Nature Geosci., 2011)

Signature of the SAM in austral summertime climate variability. Results show regressions on the SAM index using DJF monthly mean data. **a**,**c**, Surface air temperatures (SAT; shading) and 925-hPa winds (vectors). **b**, Sea surface temperatures (SST; shading) and 925-hPa winds (vectors). **d**, **e**, Precipitation (shading) and 925-hPa winds (vectors). Shading interval is (**a** and **c**) 0.1 K; (**b**) 0.04 K; and (**d** and **e**) 0.08 mm day^{-1}. Data sources and analyses details are given in Methods.

consequences for SH climate: subtropics



Kang et al. (Science 2011)

observations:

- precipitation change 1979-2000

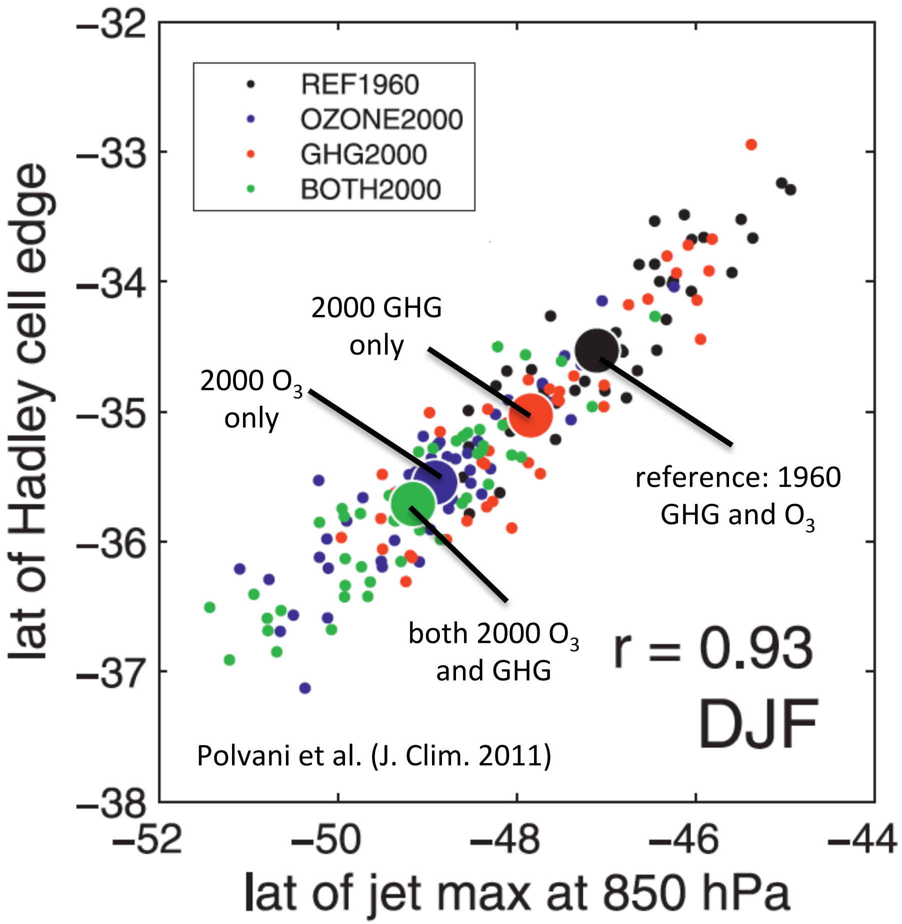
- zonal-mean precipitation change 1979-2000

  +

- zm precipitation change 1979-2000 congruent with change in the position of the jet

- *very similar results are obtained with models driven by observed ozone depletion*
- *change is attributable to expansion of Hadley cell*

SH jet and Hadley cell edge



50-year time-slice simulations (Polvani et al., J. Clim. 2011)

- the edge of the Hadley cell is strongly correlated with the position of the SH jet
- the effect is strongest when ozone loss is included in the simulations

Ozone recovery and SH climate: 2001-2050

The Impact of Stratospheric Ozone Recovery on the Southern Hemisphere Westerly Jet

S.-W. Son,[1*] L. M. Polvani,[1,2] D. W. Waugh,[3] H. Akiyoshi,[4] R. Garcia,[5] D. Kinnison,[5] S. Pawson,[6] E. Rozanov,[7,8] T. G. Shepherd,[9] K. Shibata[10]

In the past several decades, the tropospheric westerly winds in the Southern Hemisphere have been observed to accelerate on the poleward side of the surface wind maximum. This has been attributed to the combined anthropogenic effects of increasing greenhouse gases and decreasing stratospheric ozone and is predicted to continue by the Intergovernmental Panel on Climate Change/Fourth Assessment Report (IPCC/AR4) models. In this paper, the predictions of the Chemistry-Climate Model Validation (CCMVal) models are examined: Unlike the AR4 models, the CCMVal models have a fully interactive stratospheric chemistry. Owing to the expected disappearance of the ozone hole in the first half of the 21st century, the CCMVal models predict that the tropospheric westerlies in Southern Hemisphere summer will be decelerated, on the poleward side, in contrast with the prediction of most IPCC/AR4 models.

Son et al. (Science, 2008)

CCMVal: coupled chemistry-climate models
AR4: conventional climate models (no chemistry)

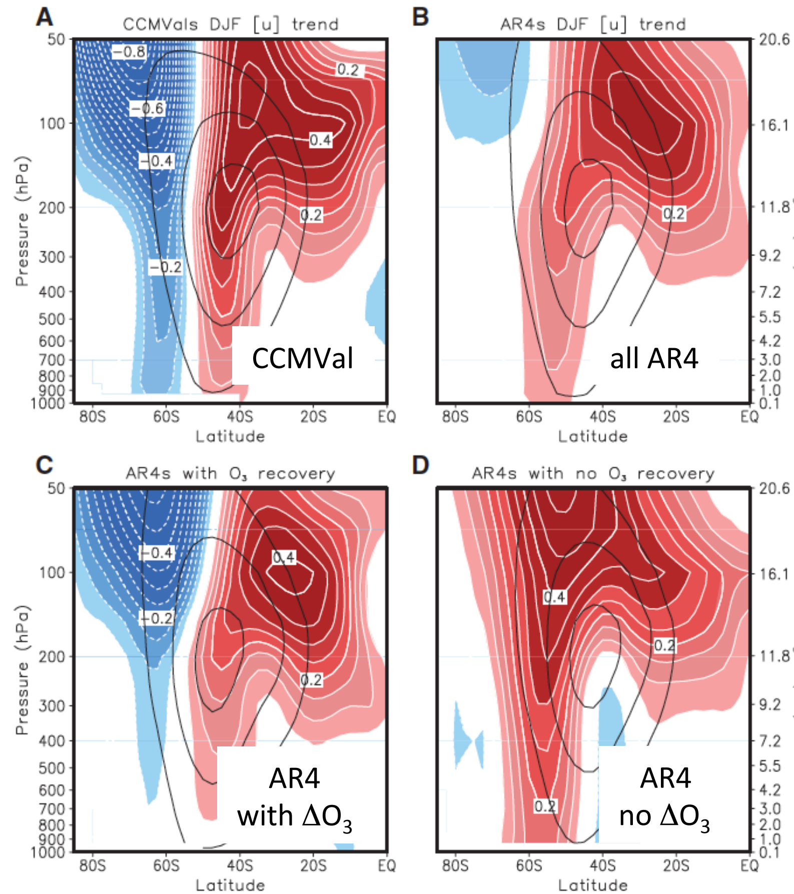
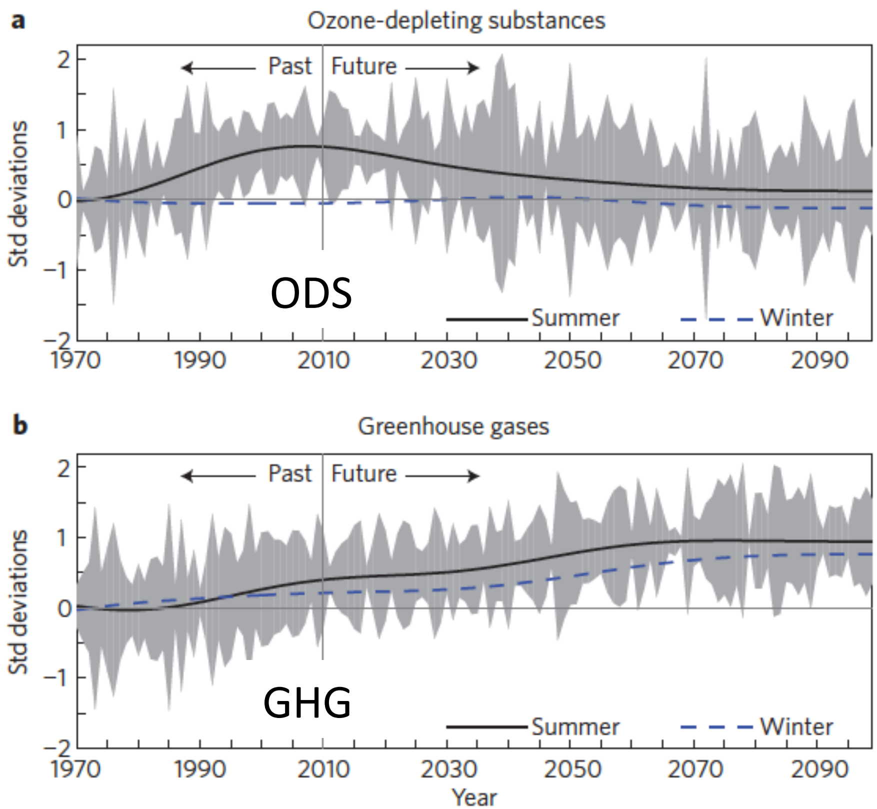


Fig. 2. Trends in December-to-February (DJF) zonal-mean zonal wind. The multimodel mean trends between 2001 and 2050 are shown for the CCMVal models (**A**), the AR4 models (**B**), the AR4 models with prescribed ozone recovery (**C**), and the AR4 models with no ozone recovery (**D**). Shading and contour intervals are 0.05 ms^{-1} $decade^{-1}$. Deceleration and acceleration are indicated with blue and red colors, respectively, and trends weaker than 0.05 ms^{-1} $decade^{-1}$ are omitted. Superimposed black solid lines are DJF zonal-mean zonal wind averaged from 2001 to 2010, with a contour interval of 10 ms^{-1}, starting at 10 ms^{-1}. EQ, equator.

ODS, GHG and the SAM



Time series of the southern annular mode from transient experiments forced with time-varying ozone-depleting substances and greenhouse gases.

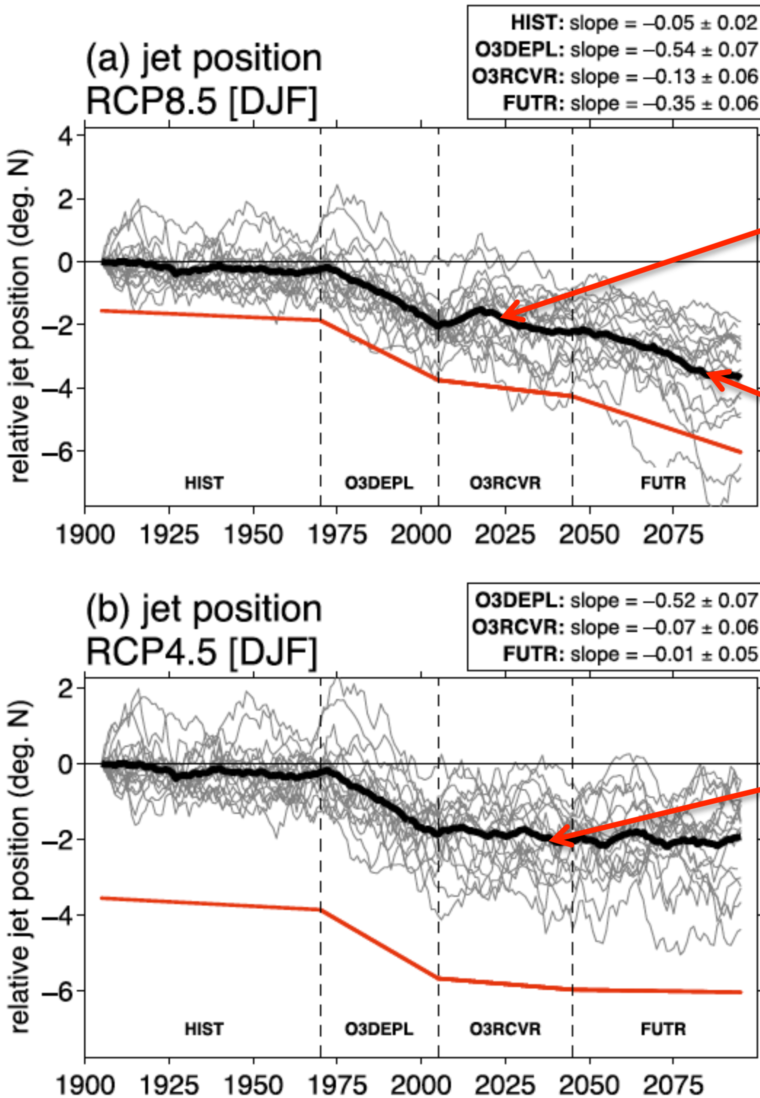
Thompson et al. (Science, 2011)

- evolution of the SAM in simulations by the Canadian Middle Amtosphere Model
- ODS produce positive SAM anomalies by destroying ozone, which cools the lower polar stratosphere
- GHG do the same by increasing IR cooling throughout the stratosphere
- the impact of GHG is small at present
- the impact of ODS is large at present but diminishes as ODS decrease and ozone recovers

→ in the 21st century, ODS and GHG have opposite impacts on the SAM

future SH climate change

analysis of 18 CMIP5 (AR5) models
Barnes et al. (J. Clim, 2014)



ozone recovery and GHG effects oppose each other over this period

a trend is seen again after the O_3 recovery period (but only in the extreme RCP8.5 scenario)

no trends anytime after O_3 recovery in the RCP4.5 scenario

(this is confirmed by WACCM simulations—not shown here)

Conclusions

- stratospheric temperature trends provide a clear fingerprint of anthropogenic climate change
- ozone destruction due to the growth of ODS in the 20th century has altered the climate of the SH
- SH climate change driven by stratospheric ozone loss extends to the surface
- ozone recovery in the 21st century will oppose the trend due to continued growth of GHG
- ozone recovery will reduce the role of the stratosphere in tropospheric climate change