Stratospheric water vapour and climate

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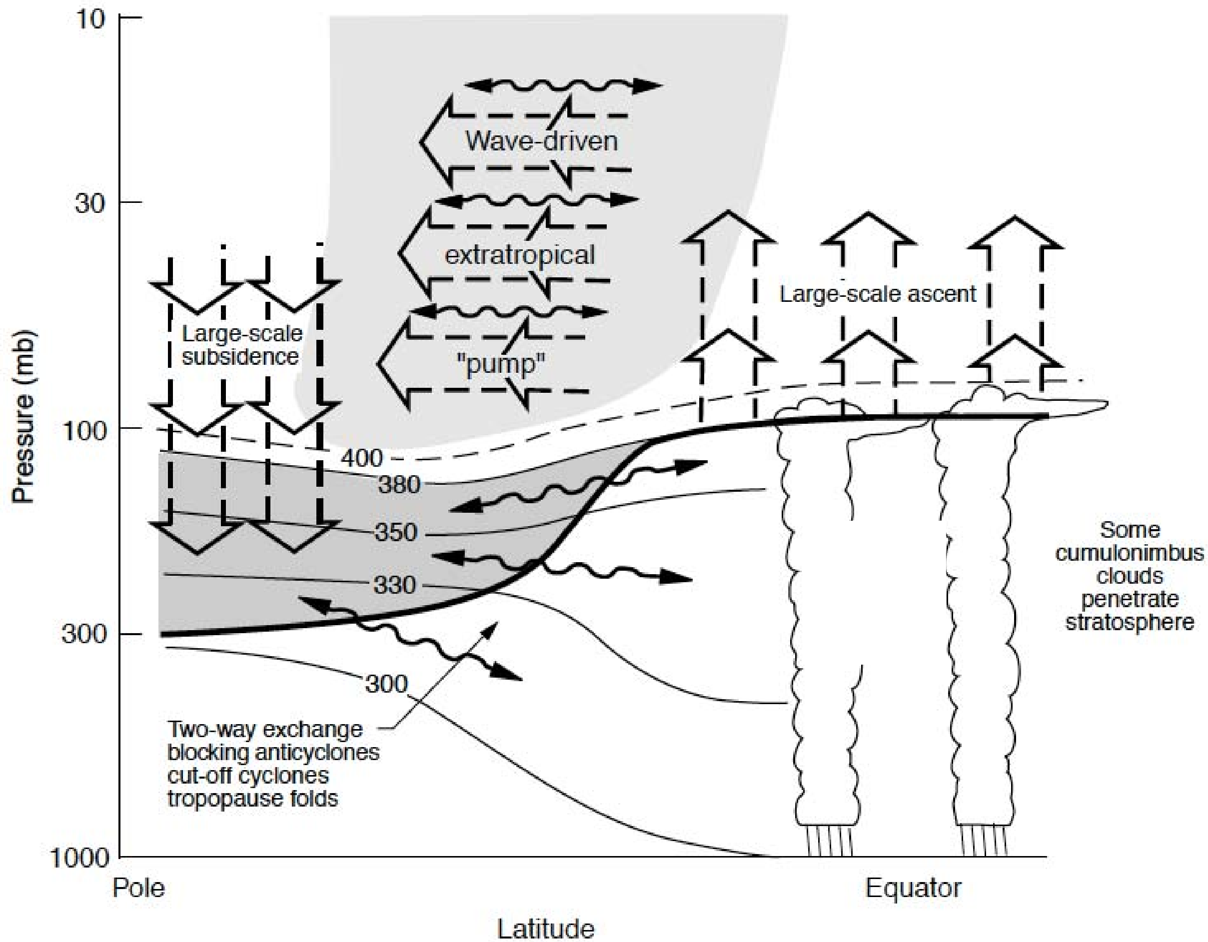
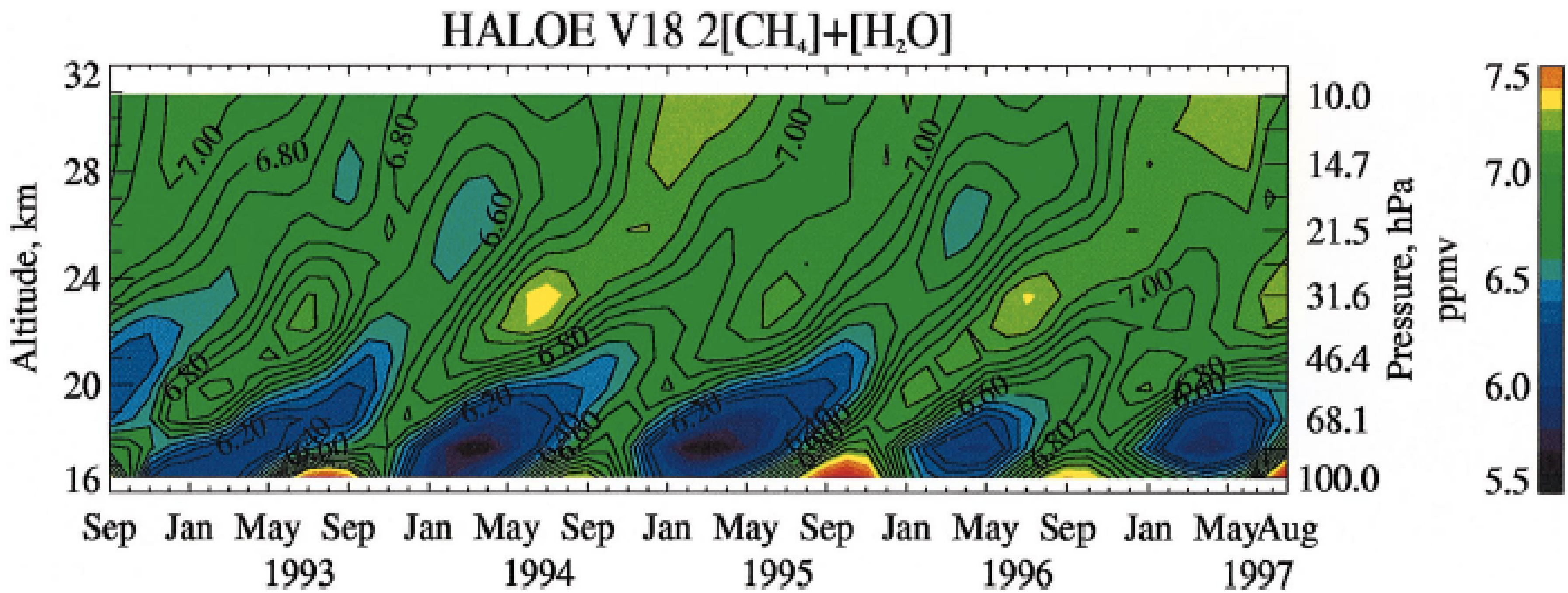
- The wave-driven stratospheric “Brewer-Dobson circulation”
  - Air enters the stratosphere through the cold tropical tropopause, where it is dehydrated



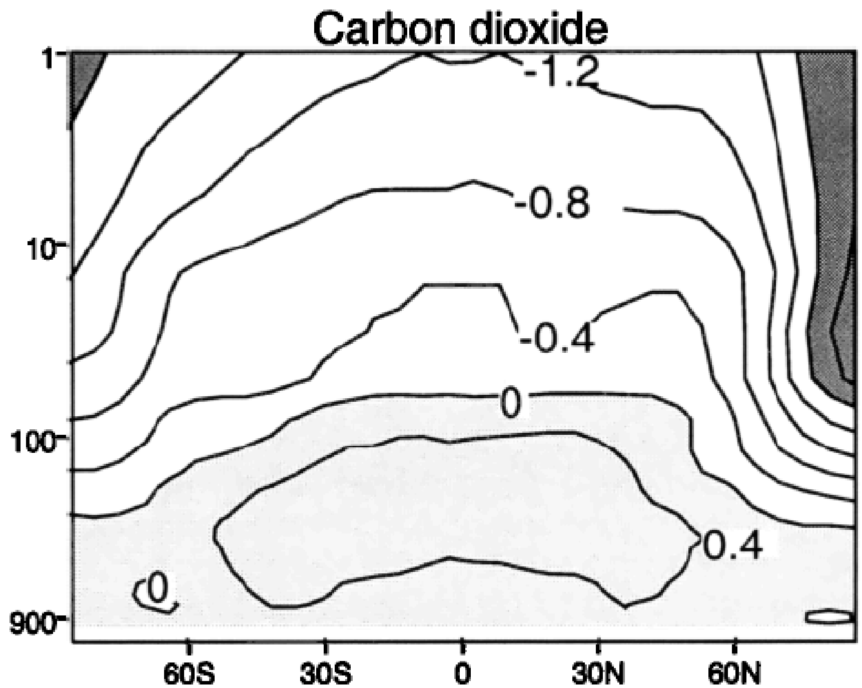
Holton et al. (1995 Rev. Geophys.)

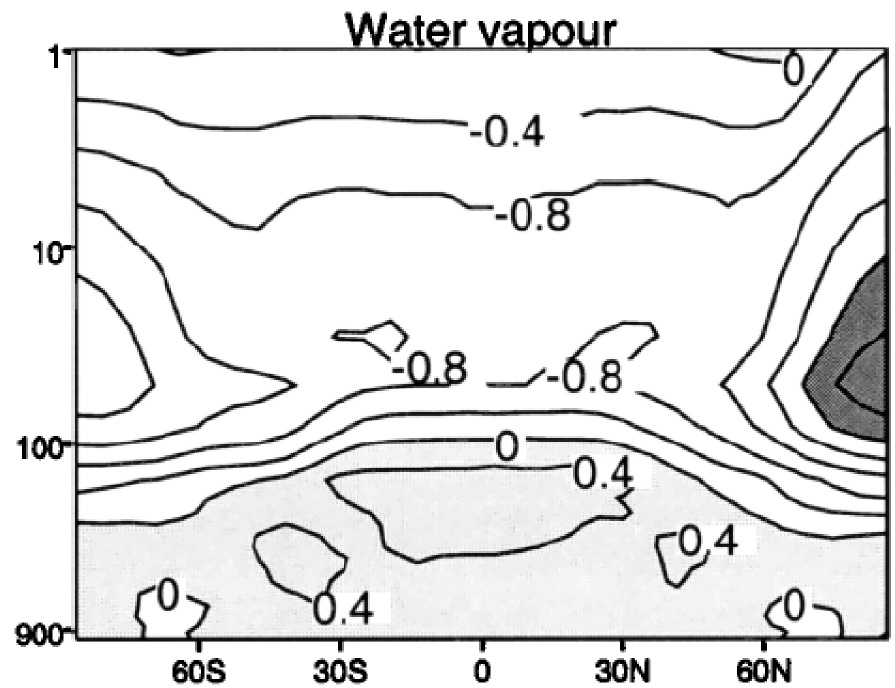
- The seasonal cycle in tropical tropopause temperature causes a seasonal cycle in dehydration, which is imprinted on the water vapour entering the stratosphere: the “water vapour tape recorder” (Mote et al. 1996 JGR)



Mote et al. (1998 JGR)

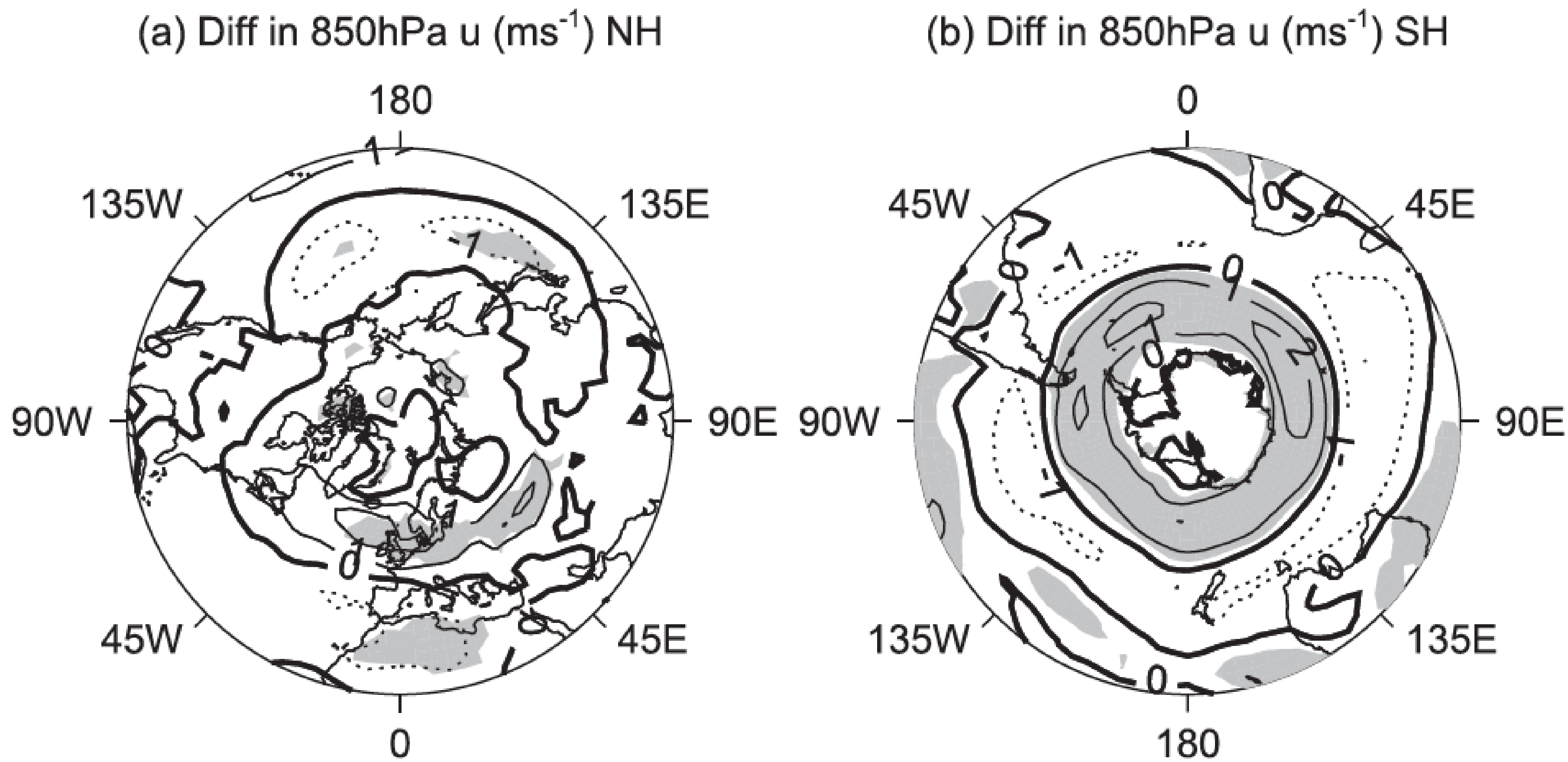
- Stratospheric water vapour is an important greenhouse gas
- A trend of 0.4 ppmv/decade (as was apparently observed over Boulder) over 1979-1997 would have led to global surface warming that was 44% of that from CO_2 alone
- Stratospheric cooling maximizes in lower stratosphere, has strong latitudinal structure; results from relatively low opacity compared to CO_2 (see Maycock, Shine & Joshi 2011 QJRMS)





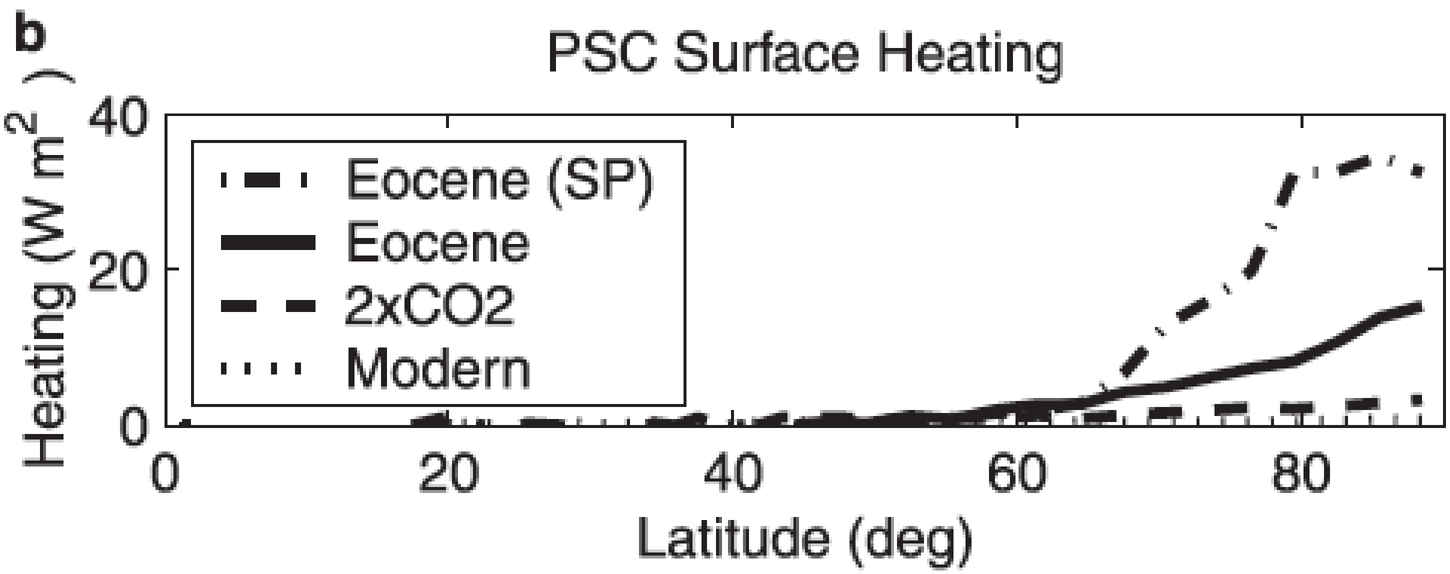
Forster & Shine (1999 GRL)

- Increases in stratospheric water vapour are predicted to lead to tropospheric circulation changes, especially in the DJF season, due to changes in the stratospheric wave-driven circulation
  - Here for doubled H_2O, without surface temperature changes



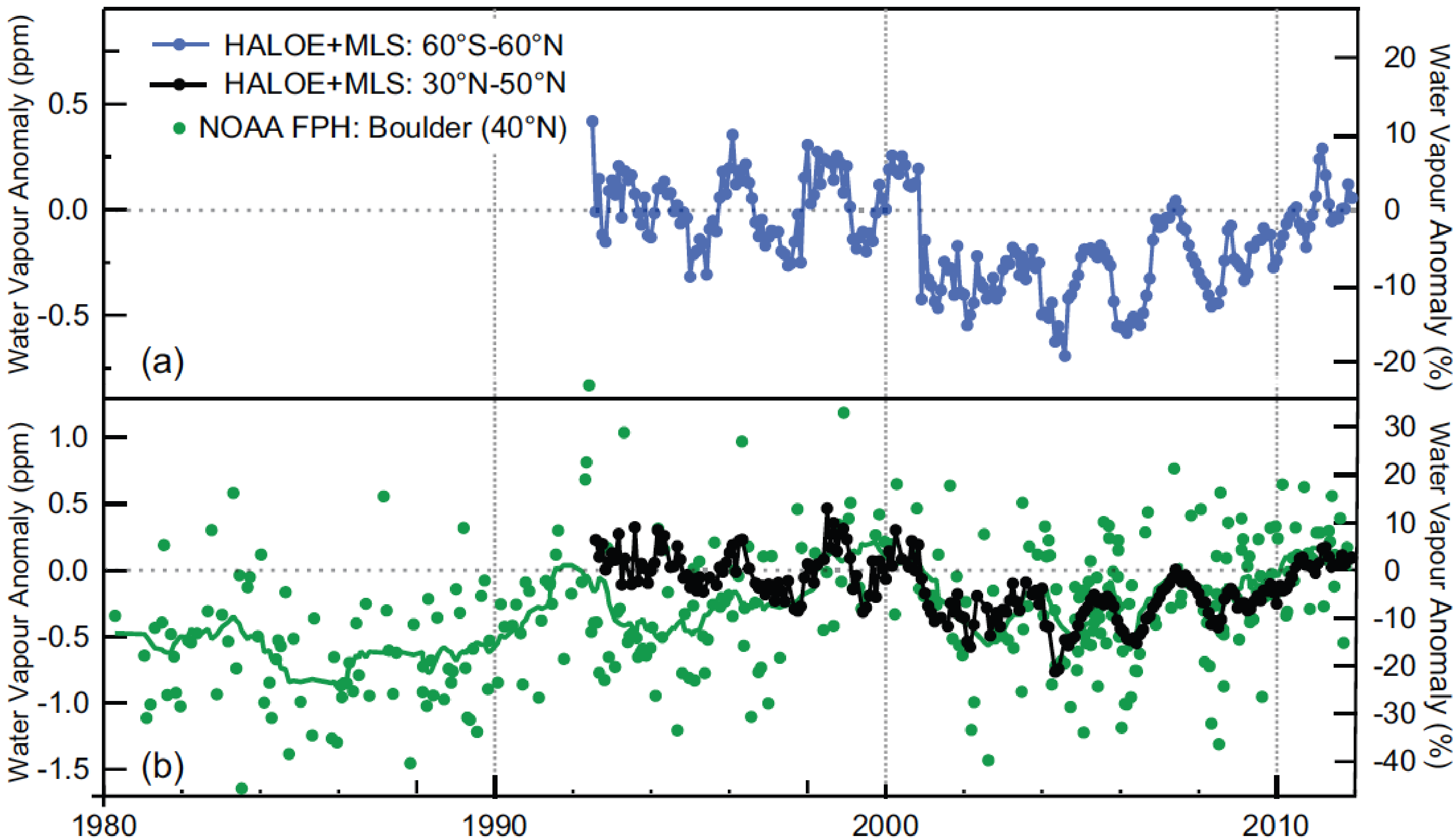
Maycock et al. (2013 J. Clim.)

- It has been argued that an increase in Polar Stratospheric Clouds (PSCs) could significantly enhance Arctic amplification, and may have been important during the Eocene
  - Would result from increased stratospheric water vapour due to a warmer tropical tropopause, together with colder polar stratospheric temperatures
  - N.B. The climate model used here is very simple!



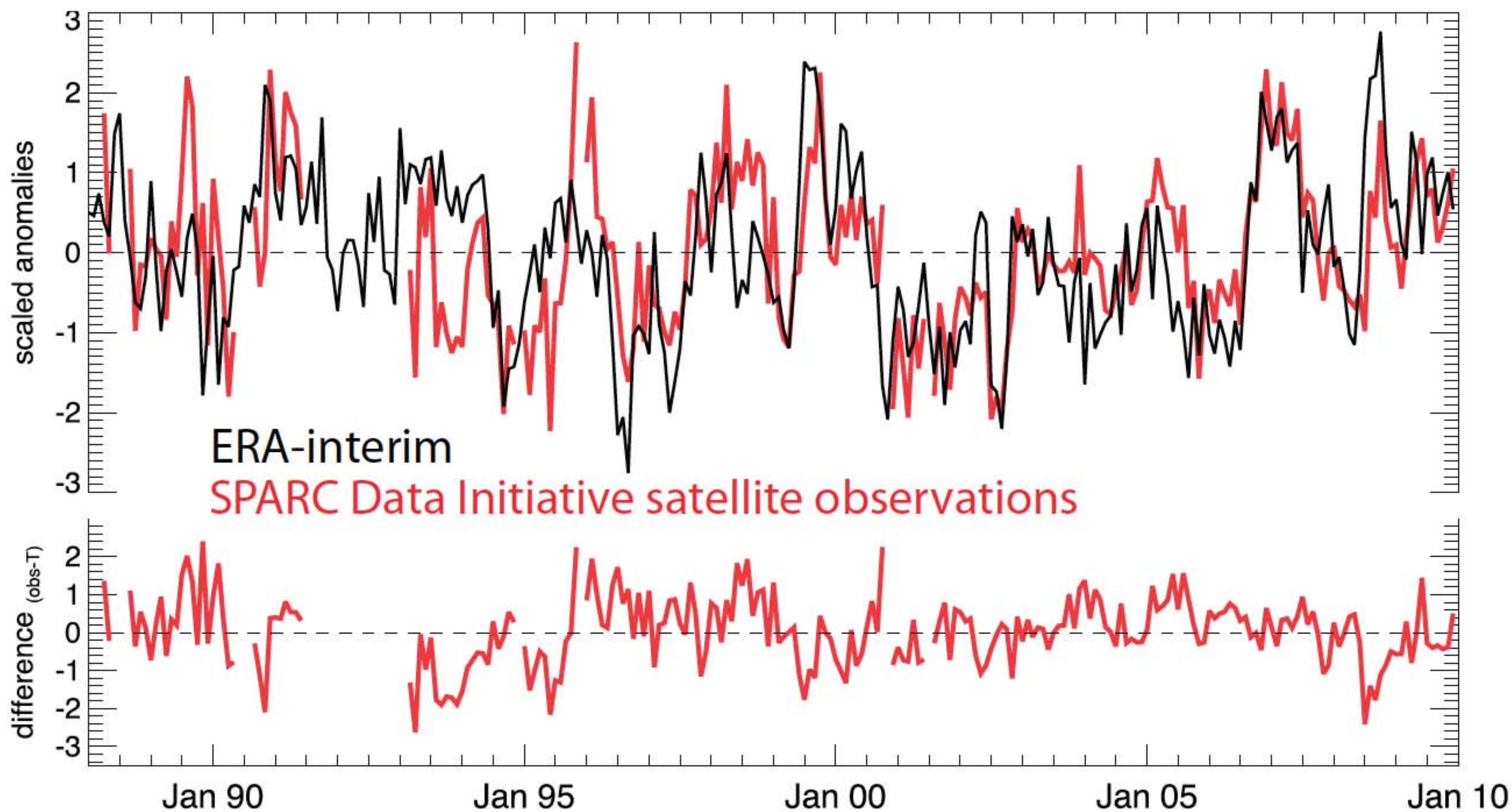
Kirk-Davidoff, Schrag & Anderson (2002 GRL)

- Observed lower stratospheric water vapour (16-18 km) shows rather interesting behaviour over recent decades



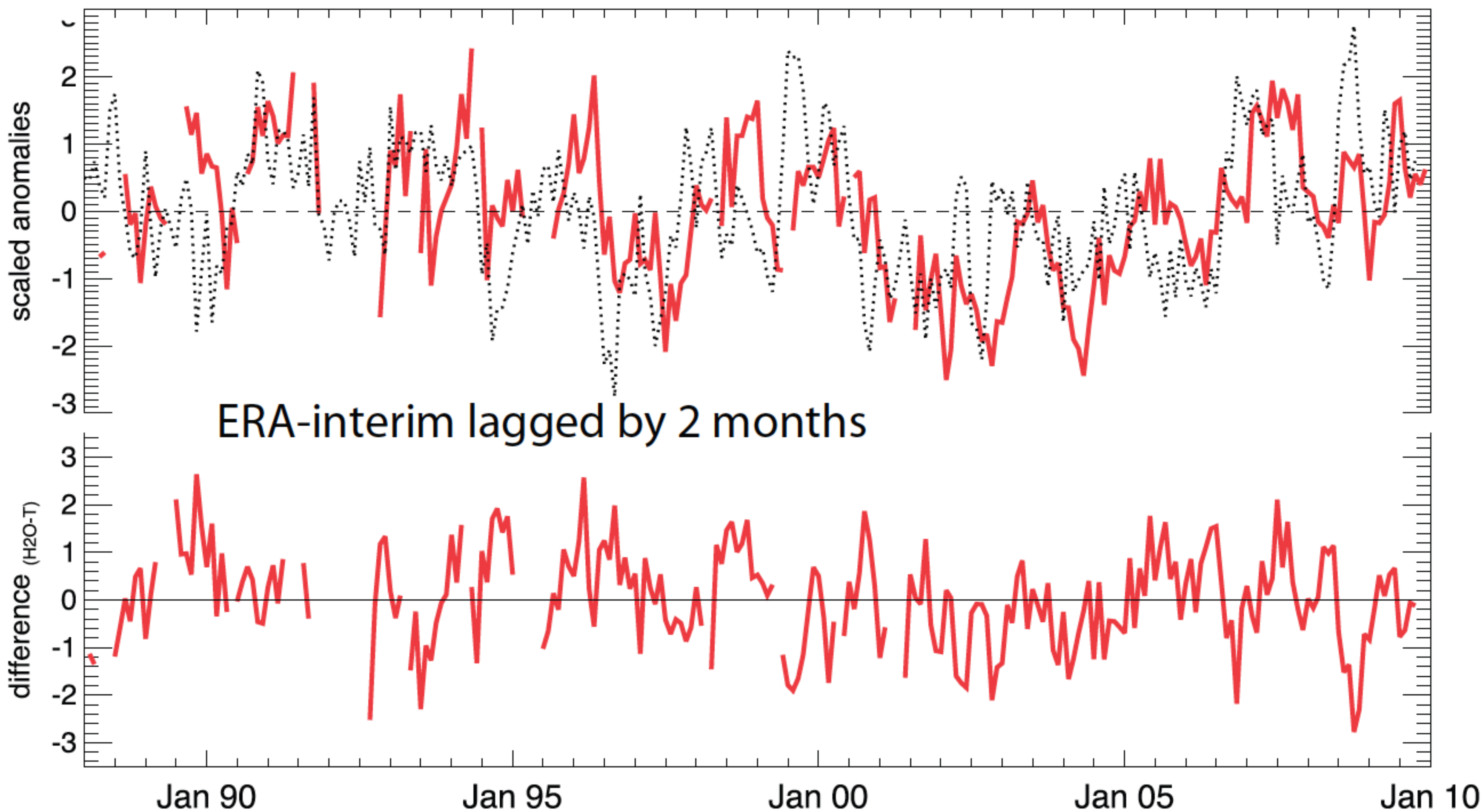
Chapter 2 of IPCC AR5 (2014)

- Satellite lower stratospheric tropical water vapour anomalies (red) follow temperature anomalies (black) over decadal timescales, and show no apparent trend over last 20+ years



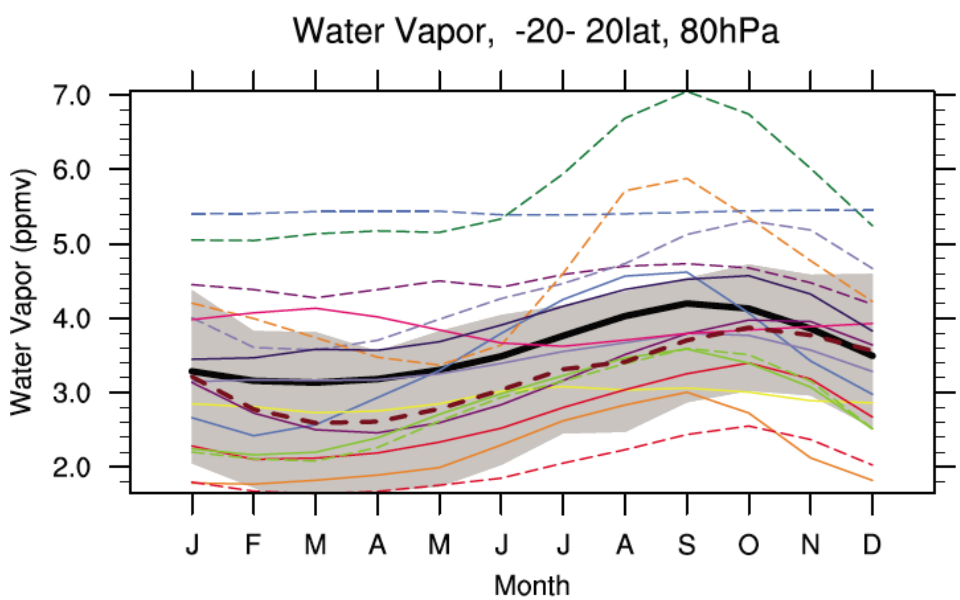
Hegglin et al., submitted

- Lower stratospheric *extratropical* water vapour anomalies do not follow tropical tropopause temperature quite so closely, but the decadal variability comes mainly from the entry values

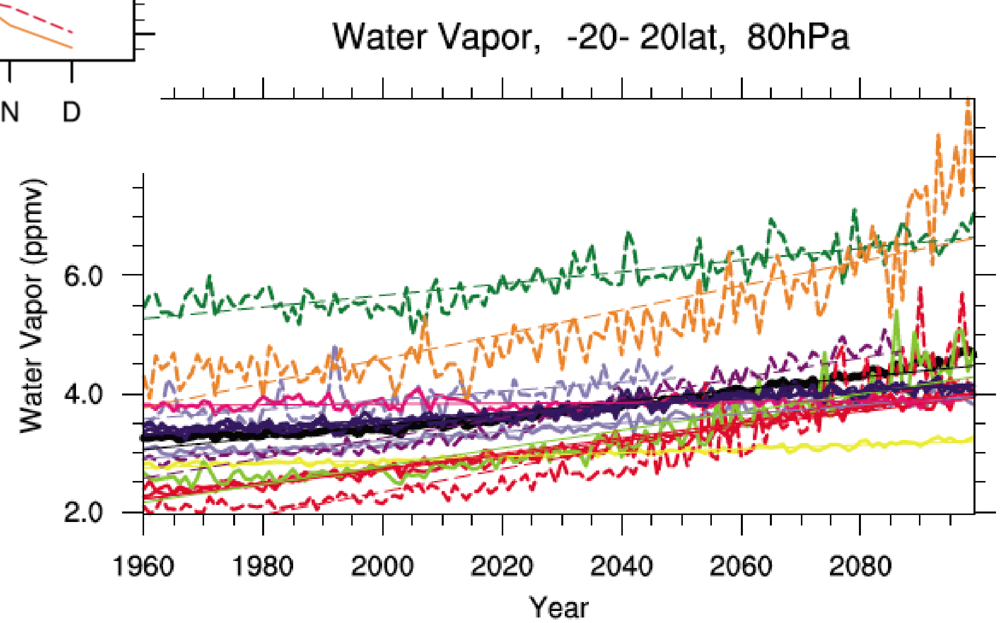


Hegglin et al., submitted

- Chemistry-climate models generally predict increased stratospheric water vapour entry values from climate change, but their performance in the TTL is not necessarily reliable

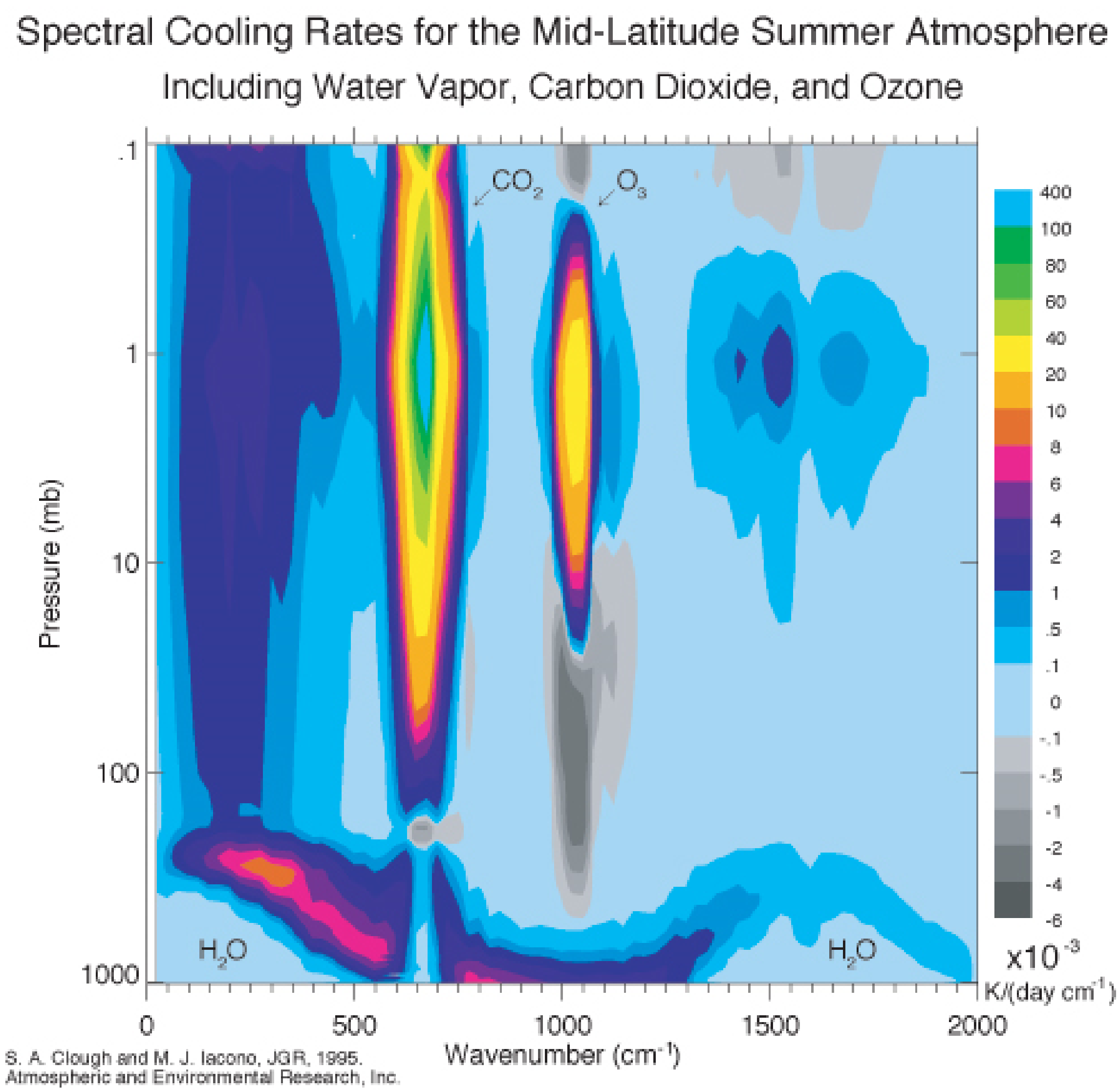


Thick black is multi-model mean, dashed black is HALOE satellite observations



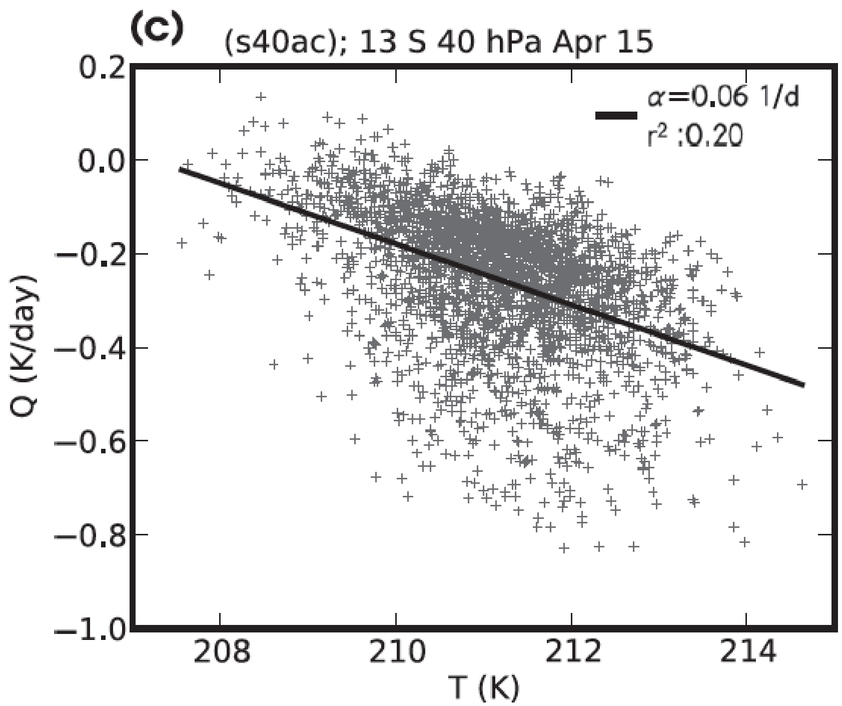
CCMVal-2 models, from Gettelman et al. (2010 JGR)

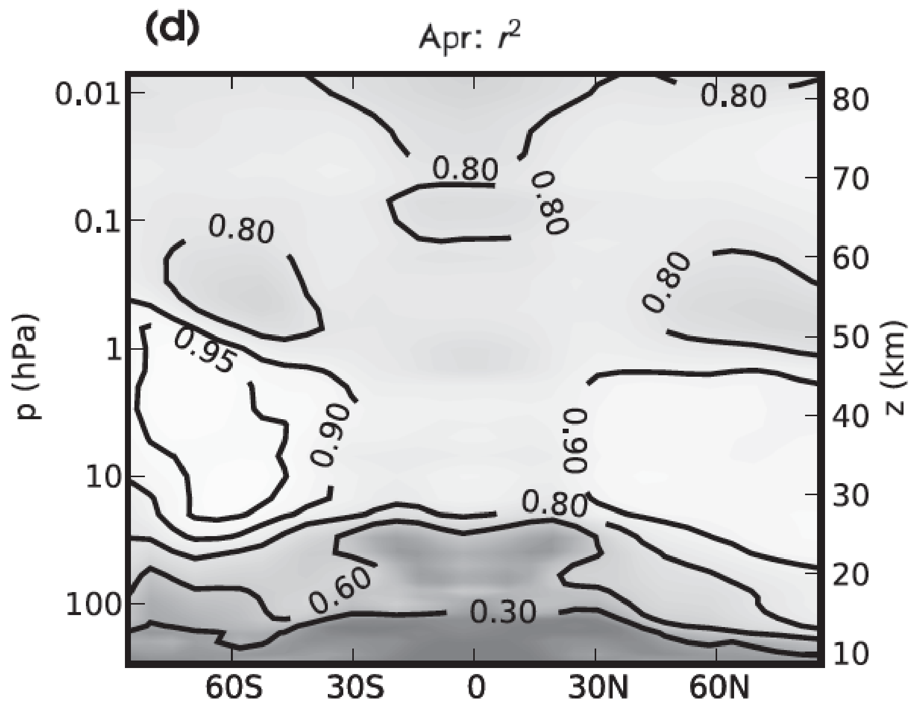
- The structure of infrared cooling rates around the tropopause is quite complicated, differing for the different gases



Clough & Iacono (1995 JGR)

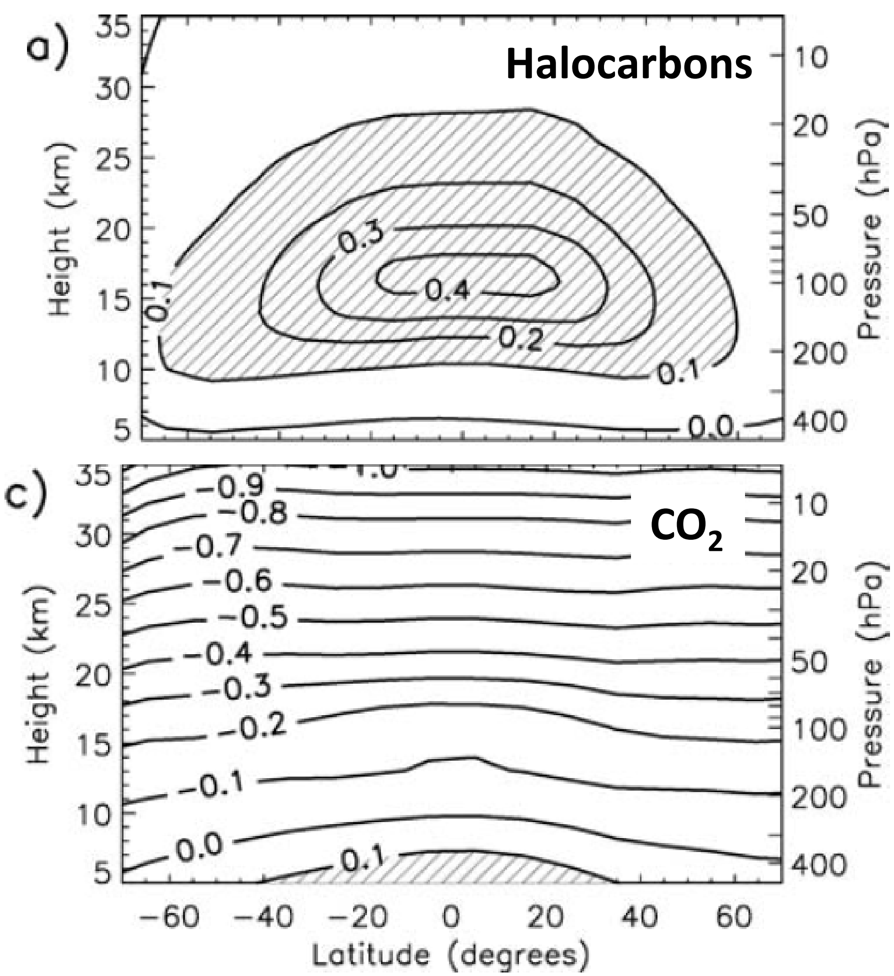
- Newtonian cooling is a reasonable approximation in most of the stratosphere, but not in the tropical lower stratosphere
- Scatter plots of modelled temperature and longwave cooling rates in tropical lower stratosphere (left); fraction of variance in Q explained by local temperature anomalies (right)



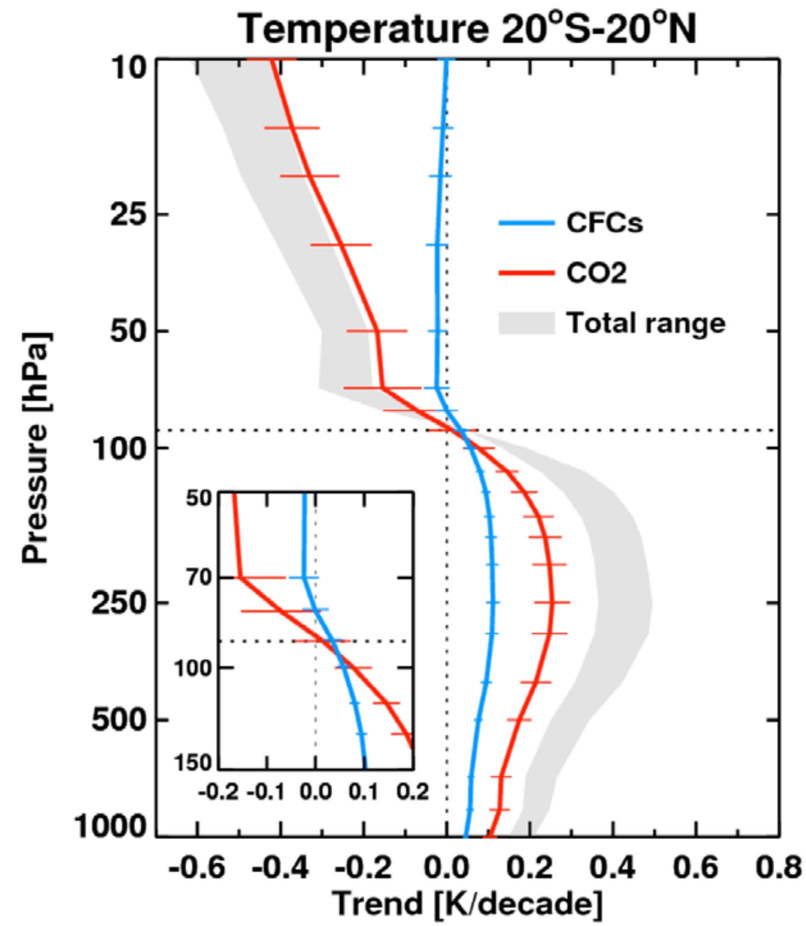


Hitchcock, Shepherd & Yoden (2010 JAS)

- Using a coupled CCM, the response over 1960-2010 to radiative changes in CFCs (right) did not show the expected warming in the tropical lower stratosphere (left, from a FDH calculation)

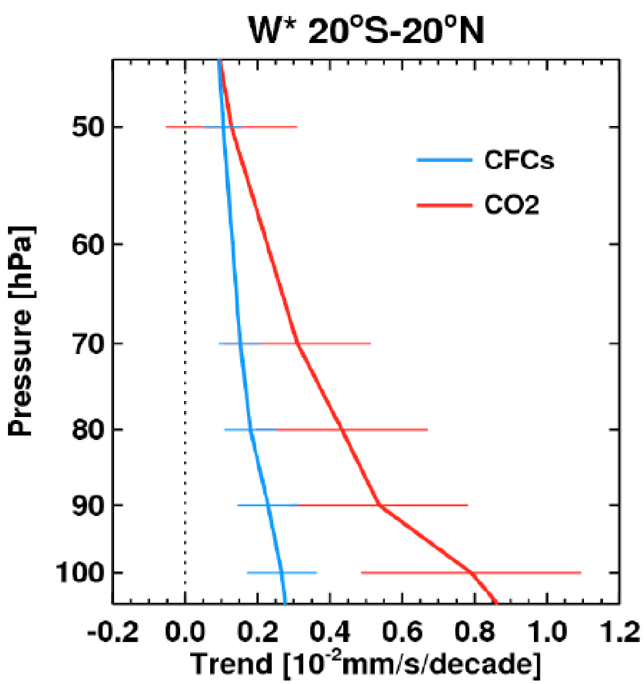


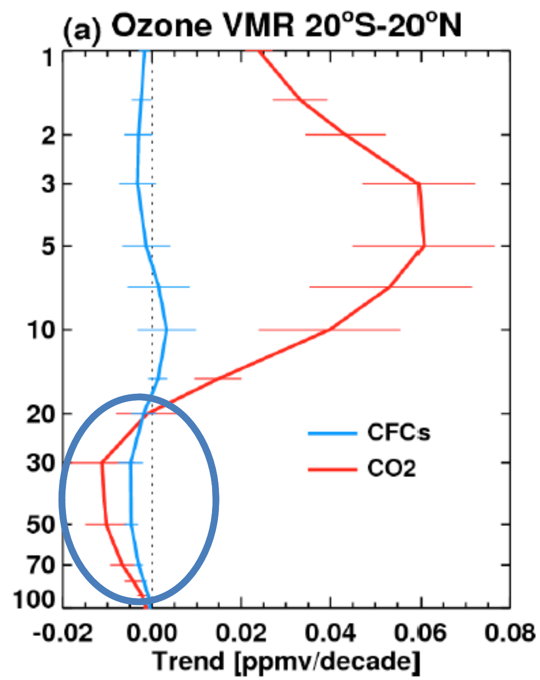
Forster & Joshi (2005 Clim. Change)

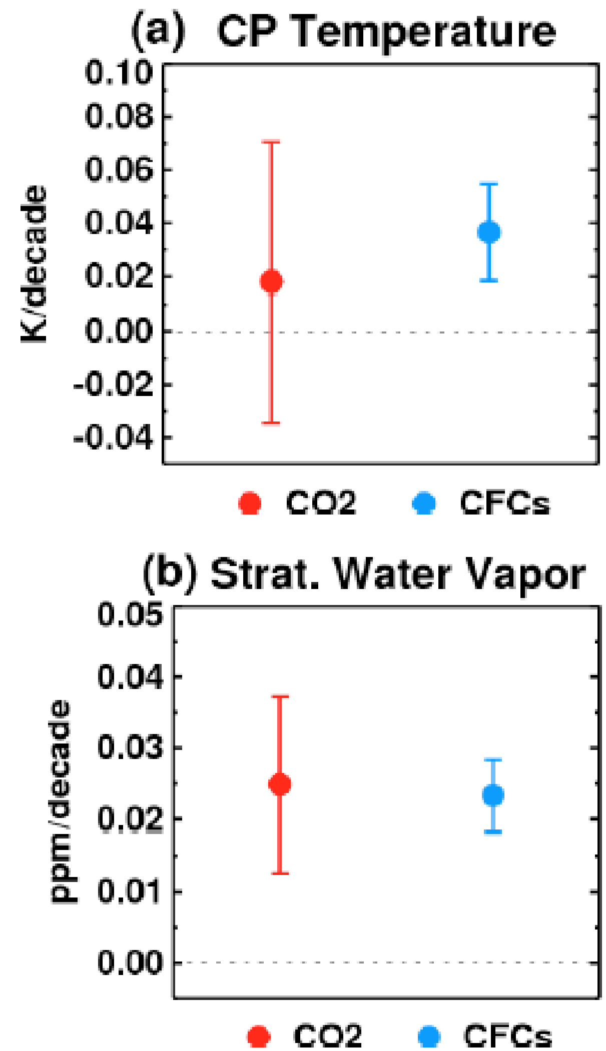


McLandress et al., to be submitted

- Over 1960-2010, CFCs had a comparable effect on stratospheric water vapour to that of CO_2 (vs 40% for surface warming), also on ozone through strengthened tropical upwelling
  - Implications for past vs future



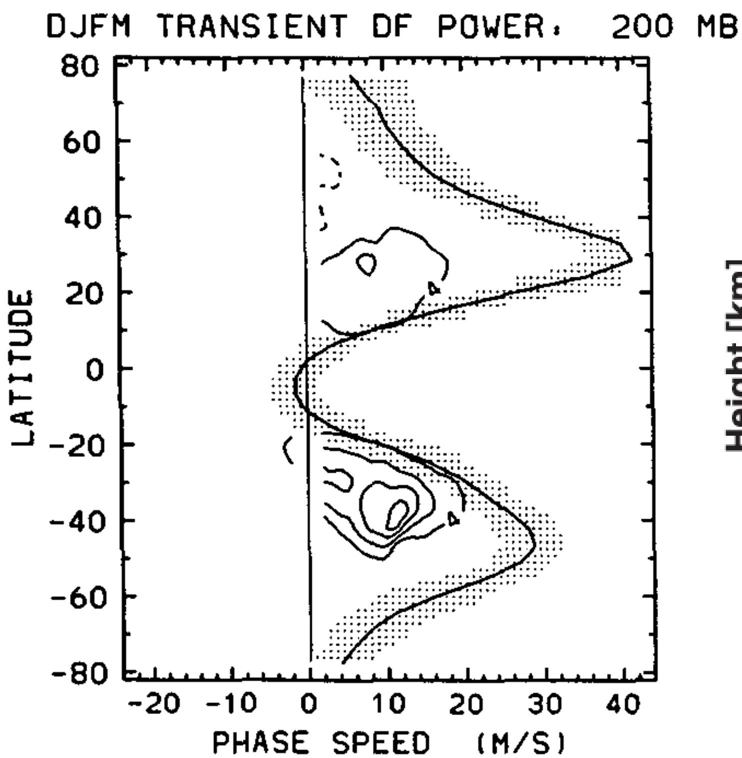




McLandress et al., to be submitted

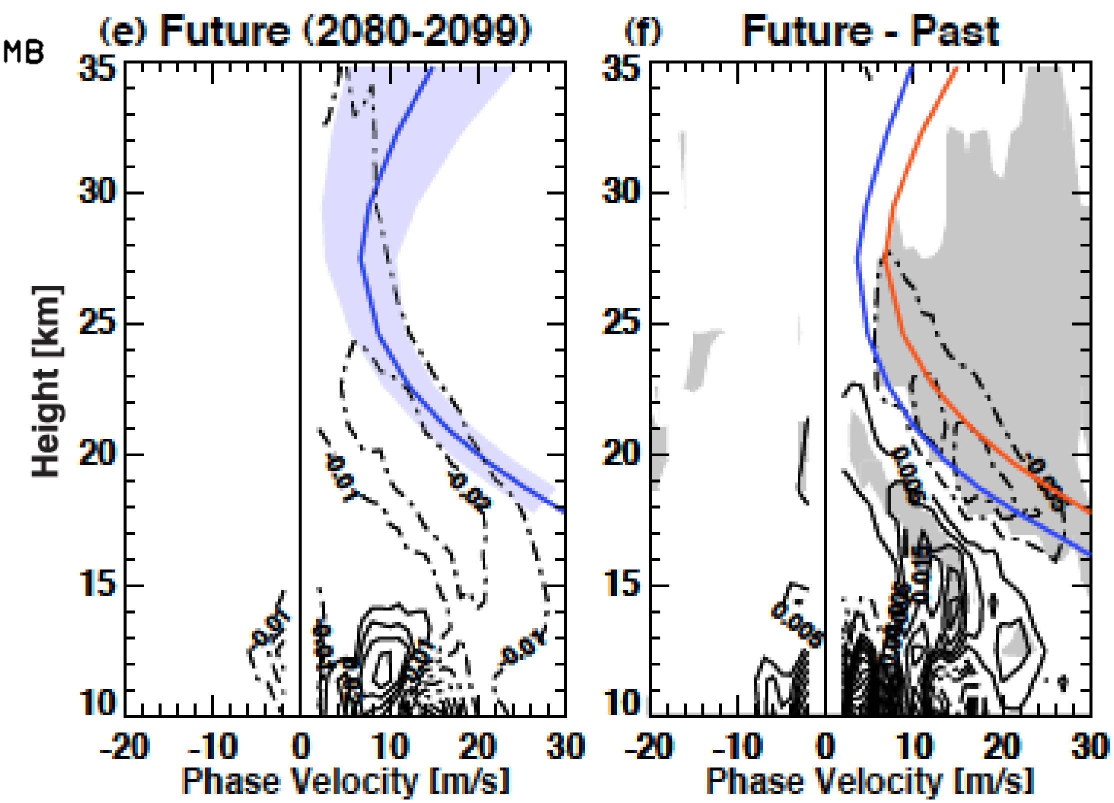
- A strengthened Brewer-Dobson circulation can be robustly expected from tropospheric warming, from rising Rossby-wave critical levels on the upper flank of the subtropical jet

E-P flux convergence



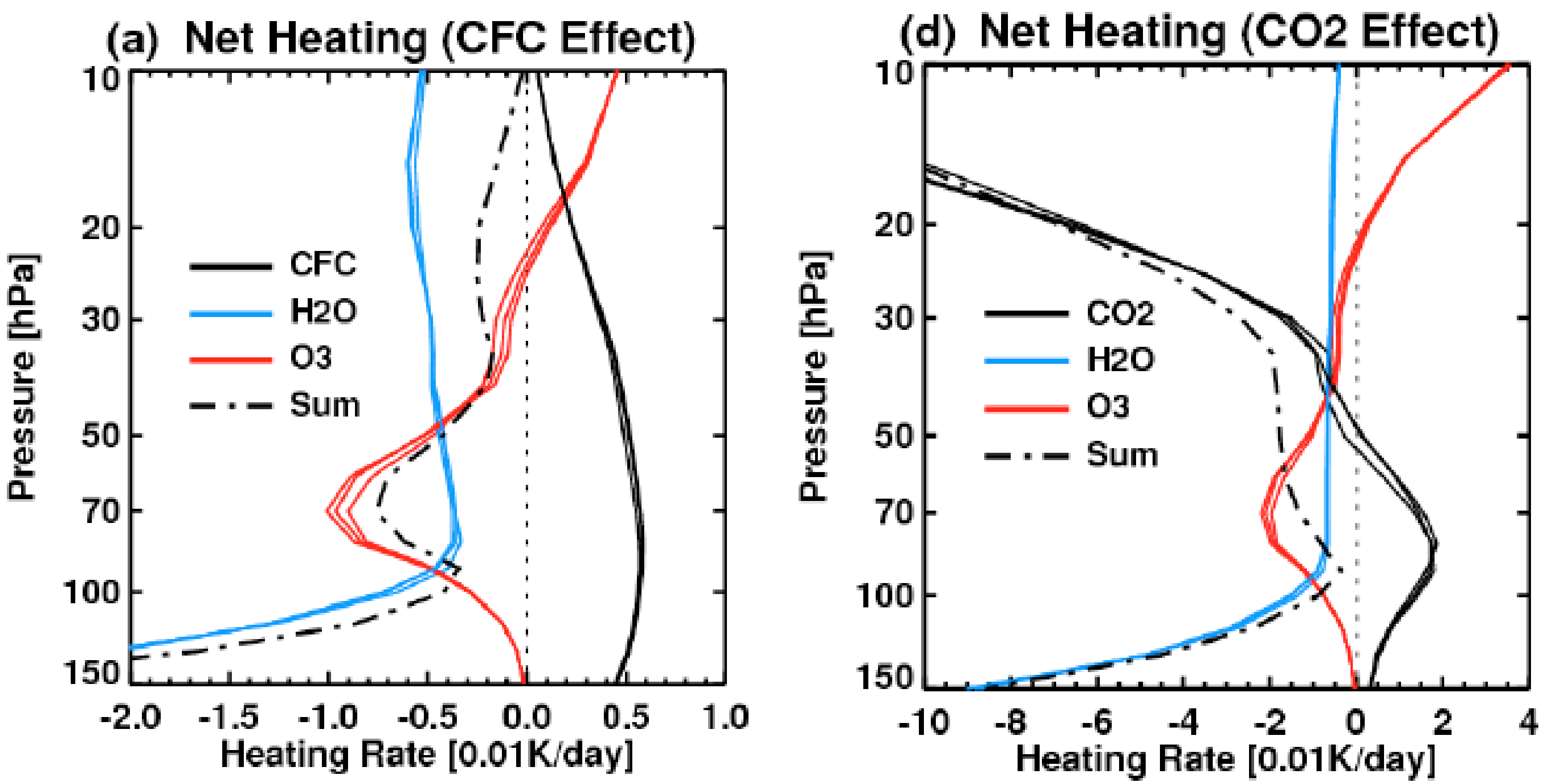
Observed climatology, from Randel & Held (1991 JAS)

Synoptic-scale waves (DJF 30°N)



CMAM simulations, from Shepherd & McLandress (2011 JAS)

- Together, the cooling from lower stratospheric water vapour increases and ozone decreases more than offsets the warming from CFCs (figures show instantaneous tropical heating rates)
- Water vapour and ozone feedbacks are similarly important in the response to CO_2 (right)

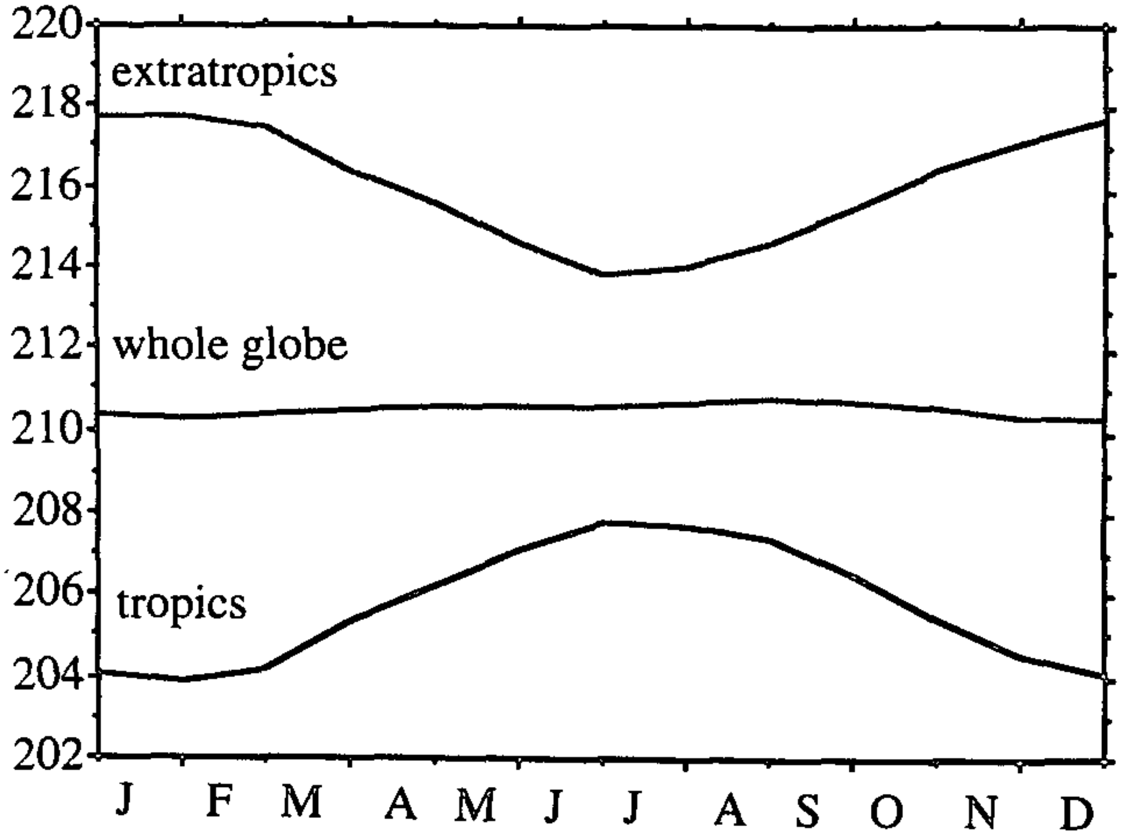


McLandress et al., to be submitted

Summary

- Stratospheric water vapour is important for climate
  - Not just radiative forcing, but also tropospheric circulation
- Most important region is lower stratosphere, where the main driver is tropical tropopause temperature (dehydration)
  - Significant variability is observed on decadal timescales
- Models predict a long-term increase from climate change, but the robustness of this prediction is unclear
  - The radiative balance around the tropical tropopause region is complex, with a *warming* from CO_2
- Water vapour and ozone feedbacks more than offset the expected local warming from halocarbons
- Water vapour and ozone feedbacks are similarly important in the response to CO_2
  - Shows importance of interactive ozone in climate modelling

- The seasonal variation in the BDC leads to a seasonal variation in lower stratospheric temperature
  - Tropical temperatures are lowest in boreal winter, when the tropical upwelling is the strongest



MSU Channel 4 temperature (approx 100 hPa)

Compensation between tropics and extratropics suggests the influence of the BDC

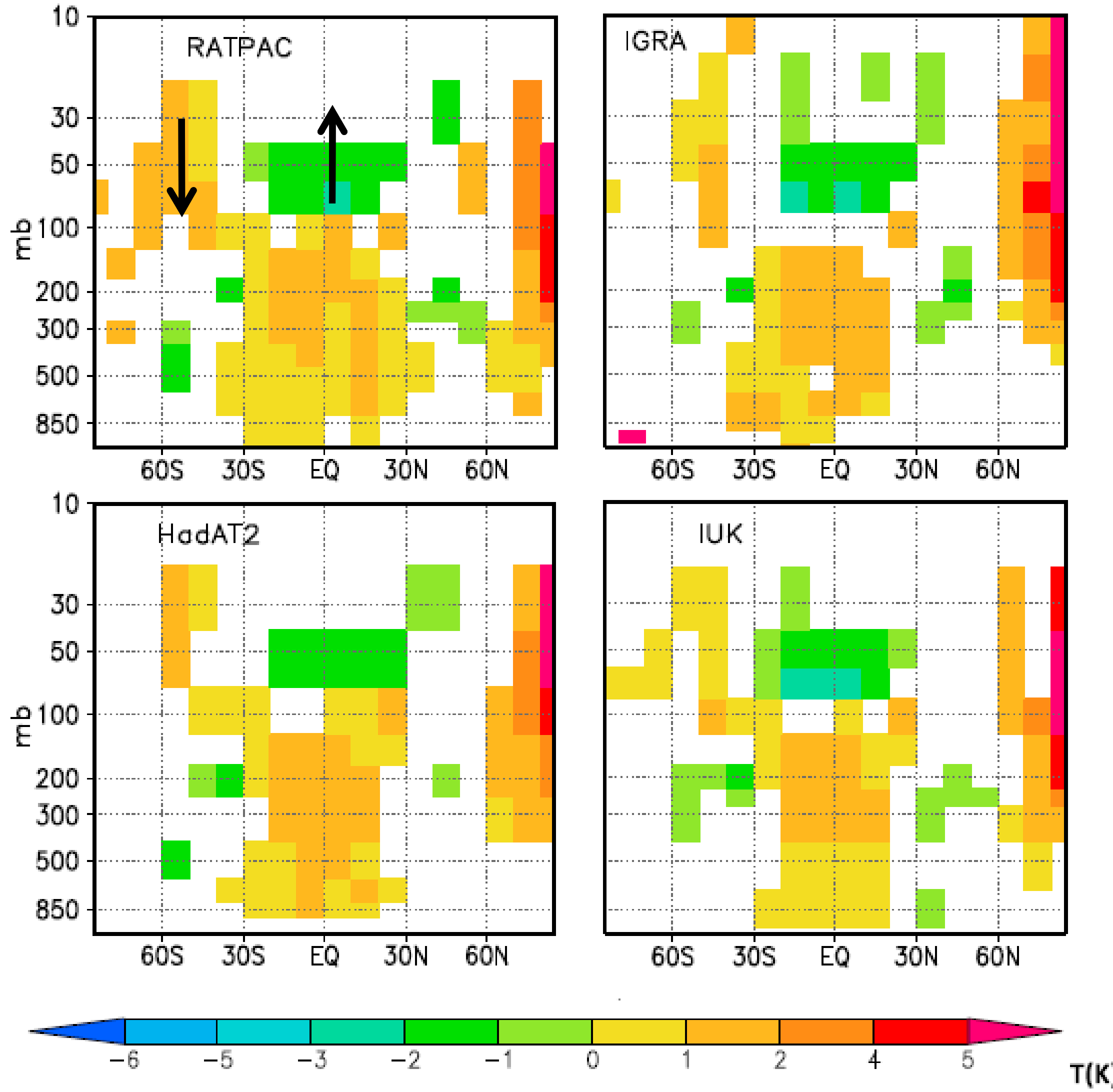
Yulaeva, Holton & Wallace (1994 JAS)

- Radiosonde observations reveal variations in the BDC associated with El Niño

Regression of DJF temperature onto Nino 3.4 index

These stratospheric features must be dynamically driven

Free & Seidel (2009 JGR)



- Tropical tropopause temperature also controls stratospheric water vapour on interannual timescales

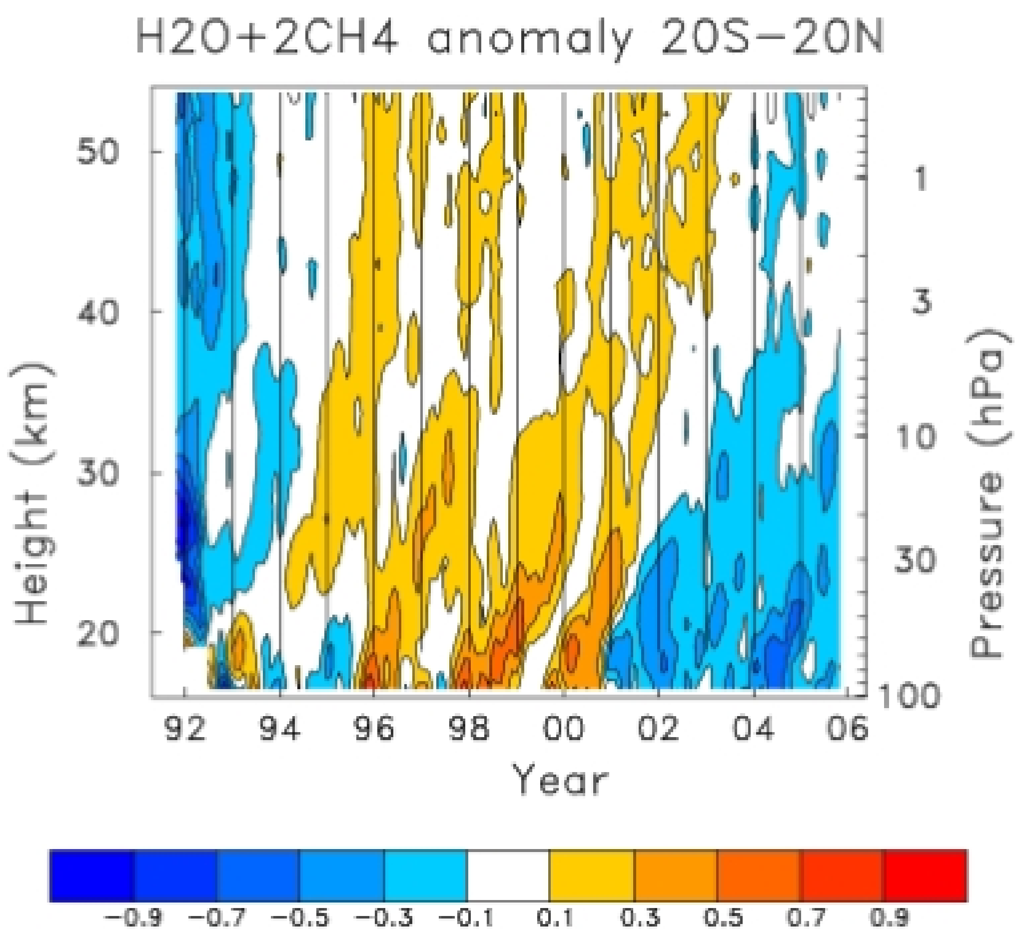
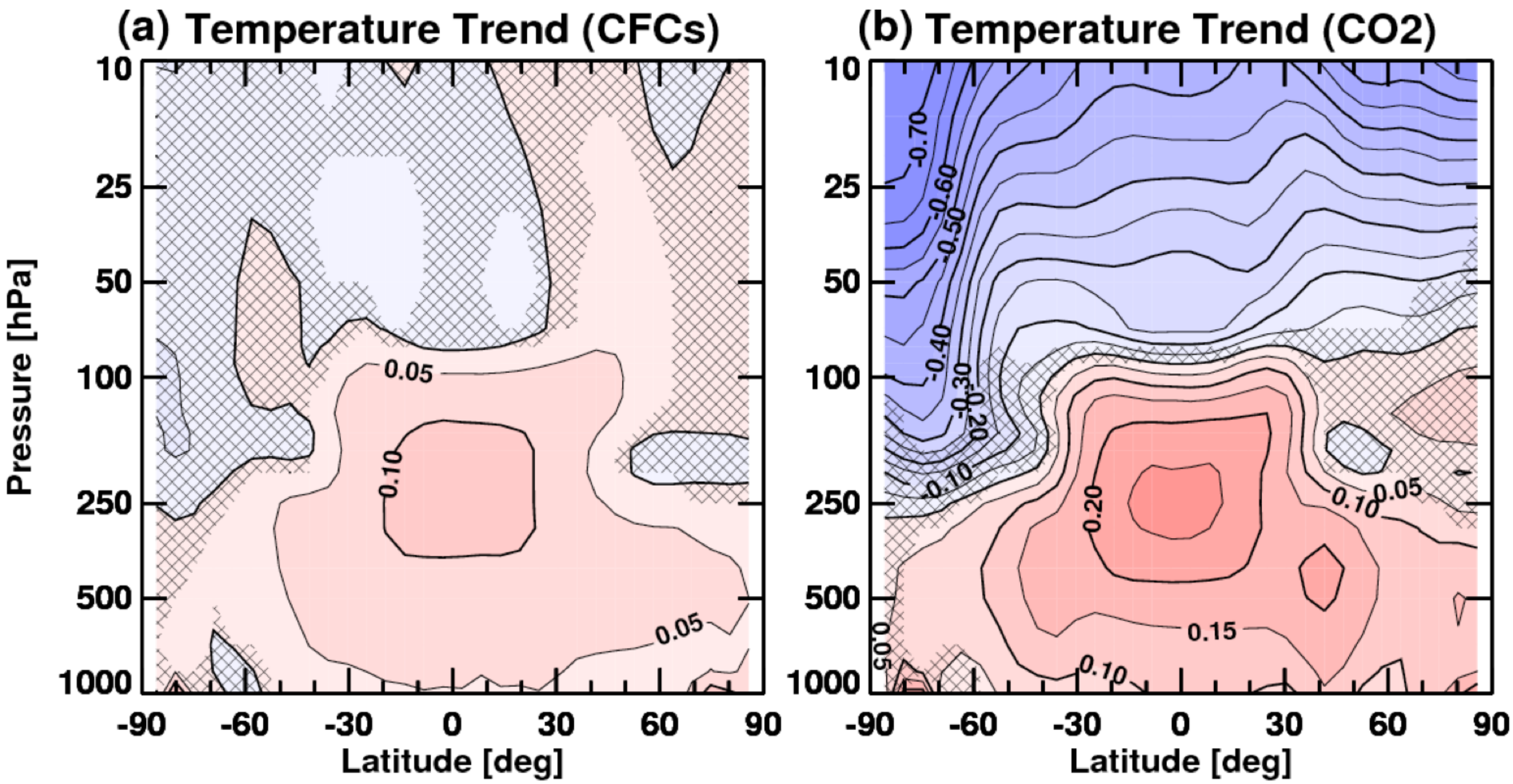


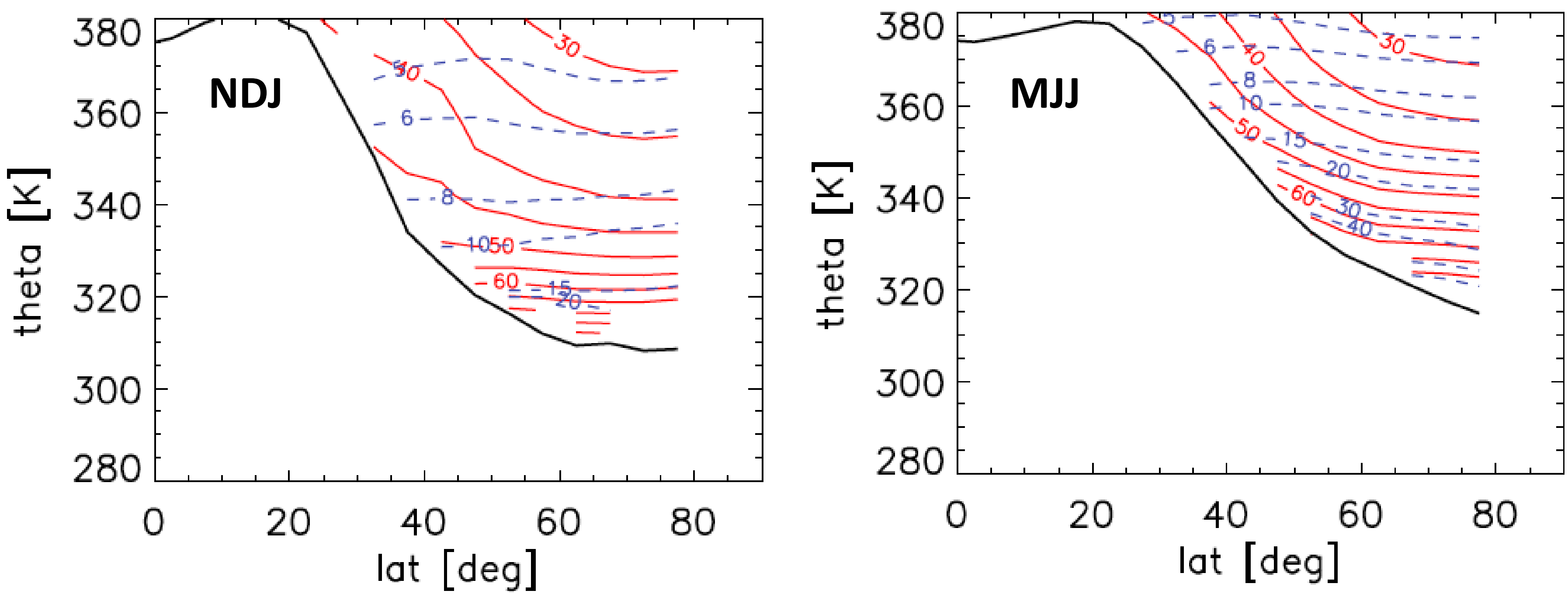
Figure shows interannual anomalies in the "tropical tape recorder" as seen in HALOE measurements from the UARS satellite

Updated from Randel et al. (2004 JAS)



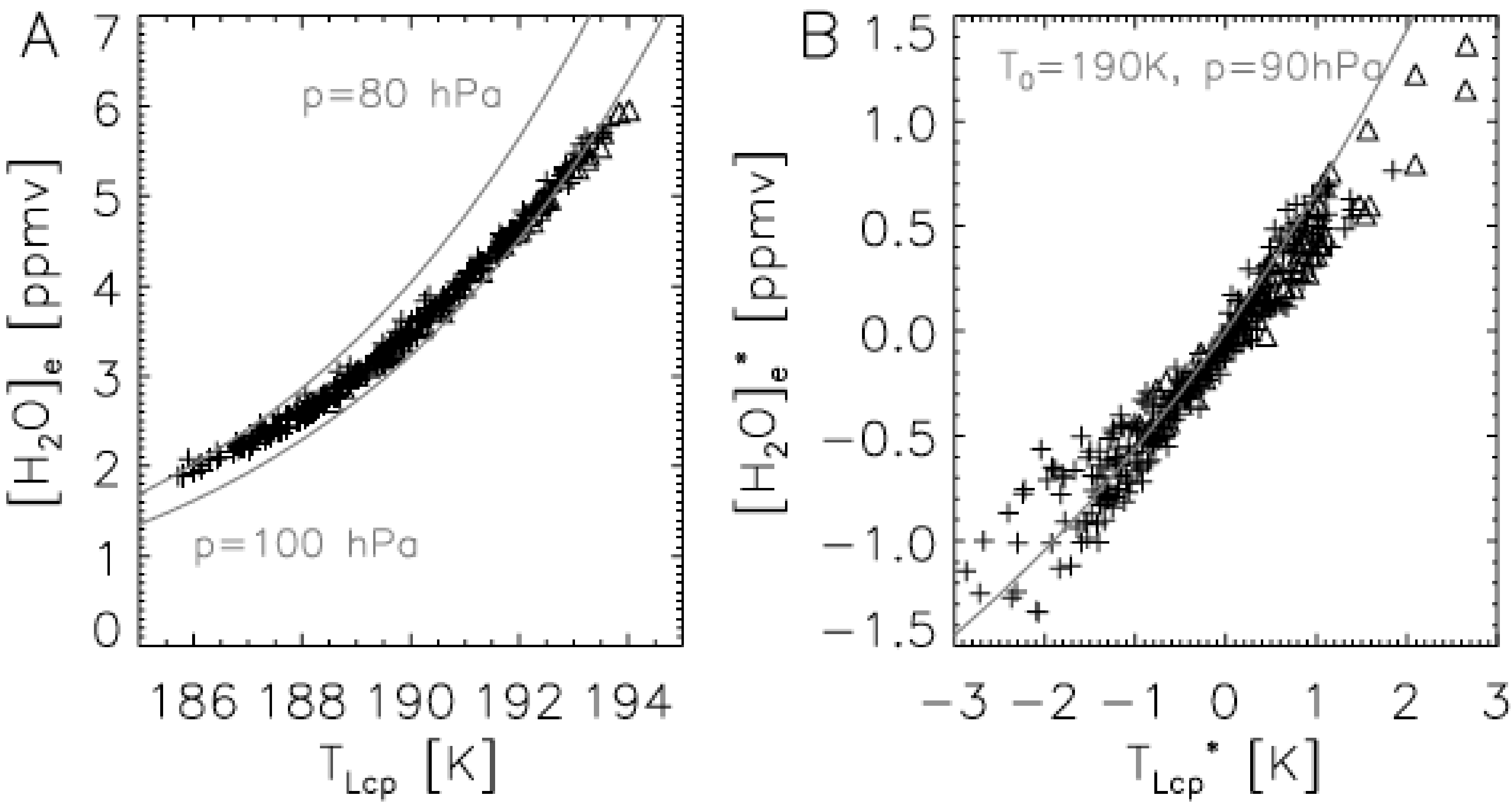
McLandress et al., to be submitted

- Spatial distribution of water vapour in the lowermost stratosphere is quite different from that of other long-lived tracers, because of the role of tropical dehydration
  - Shows H_2O (blue dashed) and CO (red solid) from ACE-FTS, screened by ozone values to identify stratospheric air



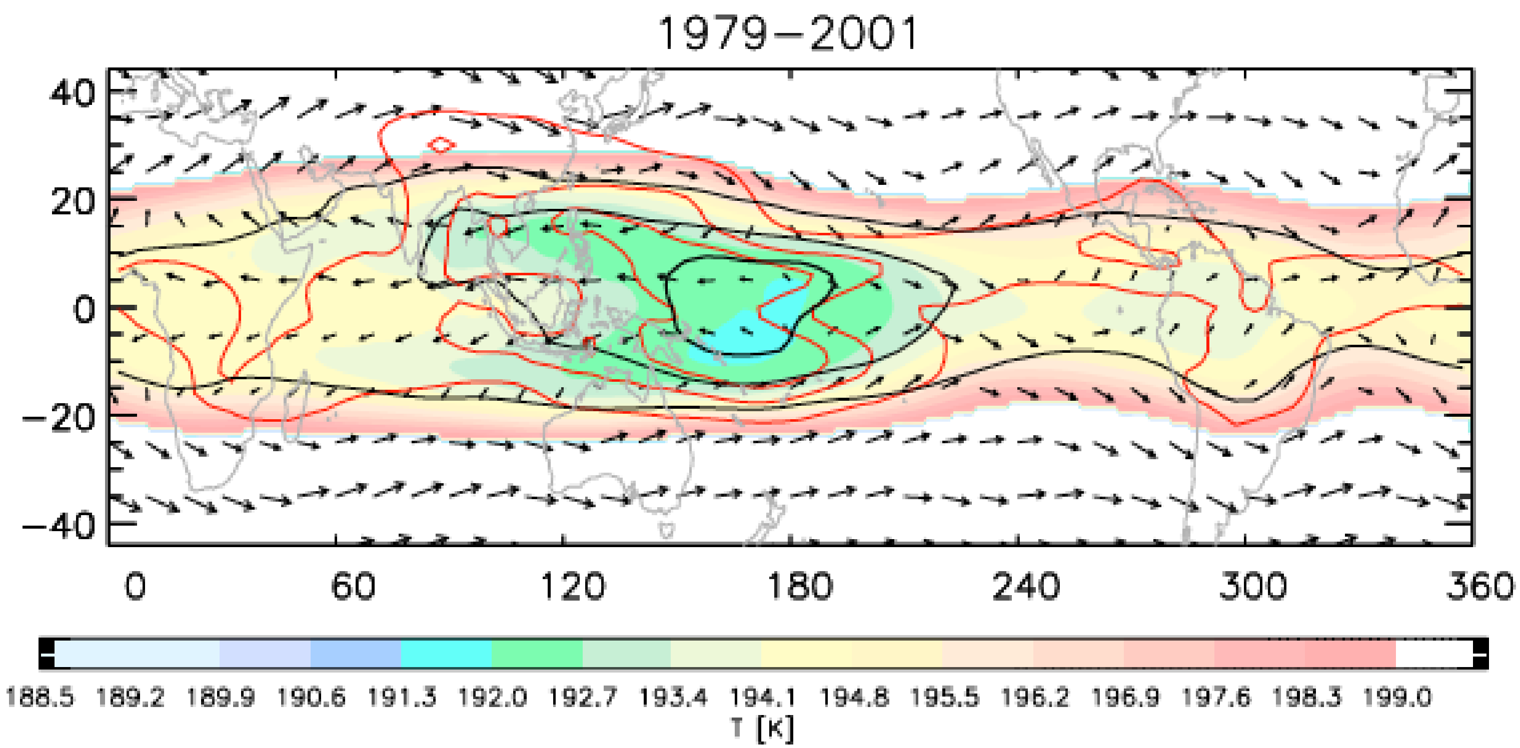
Hoor et al. (2010 ACP)

- Relationship between Lagrangian cold-point temperature and entry value of stratospheric water vapour is nonlinear (left), but is reasonably linear for year-to-year anomalies (right)



Fueglistaler & Haynes (2005 JGR)

- The entry value of stratospheric water vapour is controlled by the "Lagrangian cold point temperature", which is mainly located over the western tropical Pacific
  – Colours and arrows show temperatures and winds at 90 hPa
  – Black contours show PDFs of location of "final" dehydration



Fueglistaler et al. (2005 JGR)