The stratospheric water vapour puzzle

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DAMTP **CC*f*CS**

Stratospheric water vapour

Alan Brewer

551·510.5

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)

1. INTRODUCTION

Between 1943 and 1945 the writer made some 16 ascents into the stratosphere over Southern England during which humidity measurements were made by means of a frost-point hygrometer. On some of the ascents the carbon dioxide (CO_2) content of the air of the stratosphere was measured by using the hygrometer at the CO_2 point. The hygrometer has been described by Brewer, Dobson and

Dry air observed by Brewer corresponds to frost point of ~195K

‘Troposphere-stratosphere exchange of trace constituents: the water vapor puzzle’ (Holton 1984).

Brewer (1949) -- ‘Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere’

Mean temperatures too high to account for observed concentrations of water vapour -- Newell and Gould-Stewart (1981) -- ‘A stratospheric fountain’

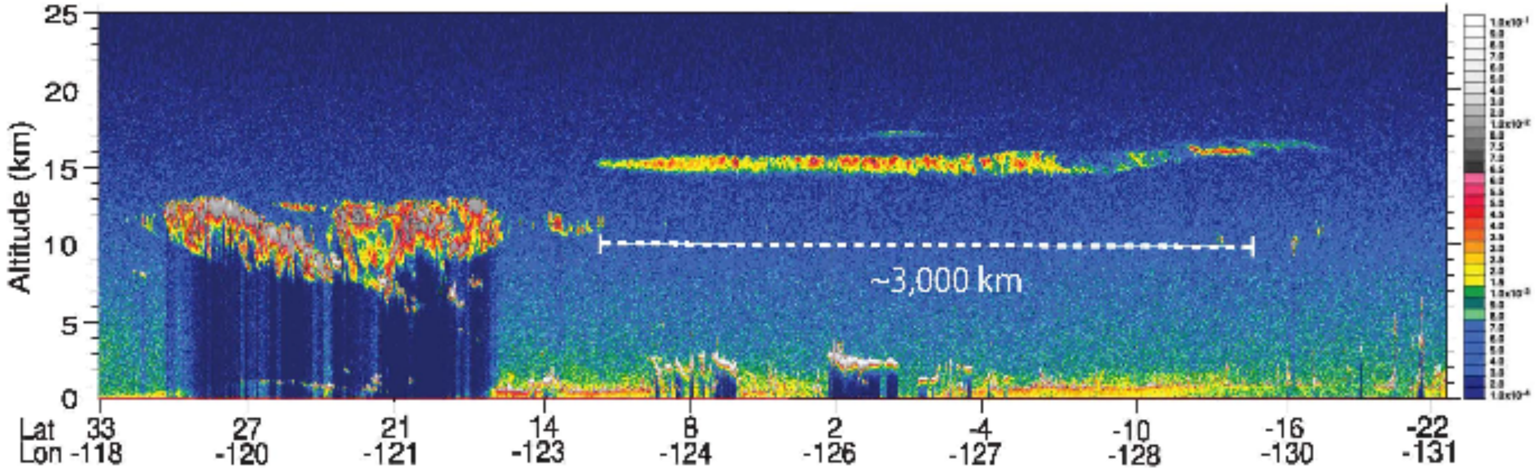
Importance of convective-scale -- convective penetration of stratosphere without hydration of stratosphere -- Danielsen (1982) -- ‘A dehydration mechanism for the stratosphere’

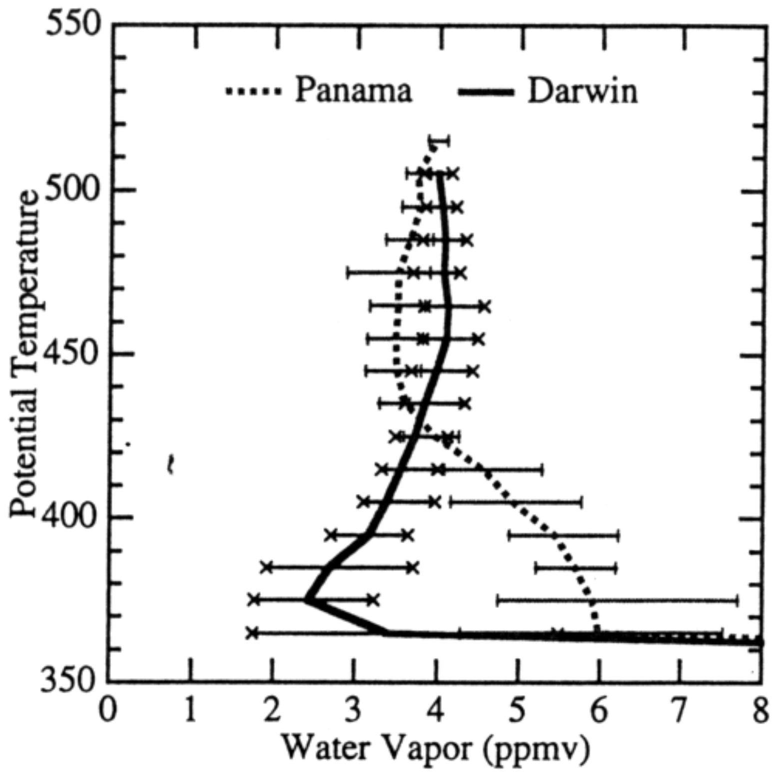
Geographical/seasonal differences in water vapour profiles – Kelly et al (1993)

Water vapour trend from 1960s to 1990s? Sharp drop in 2000. Stratospheric water vapour important for tropospheric climate and stratospheric ozone chemistry

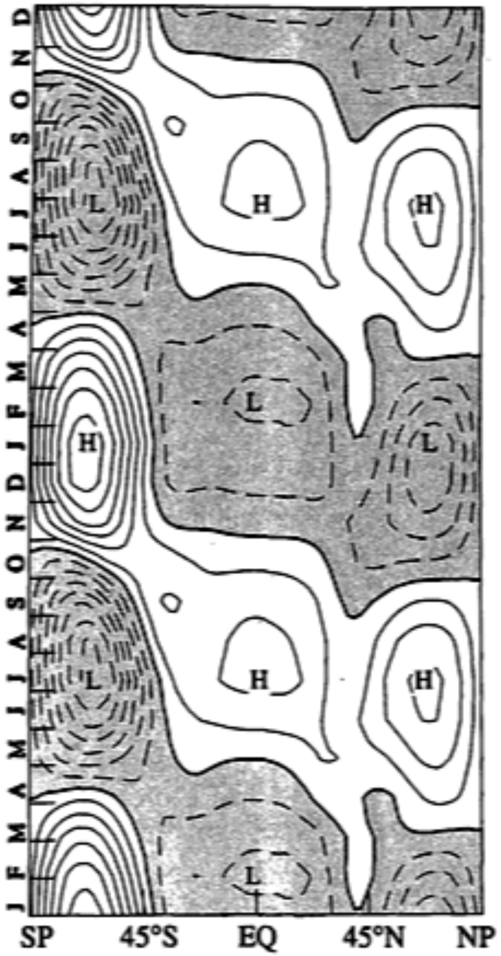
CALIPSO 28 January 2009

(Taylor et al 2011)





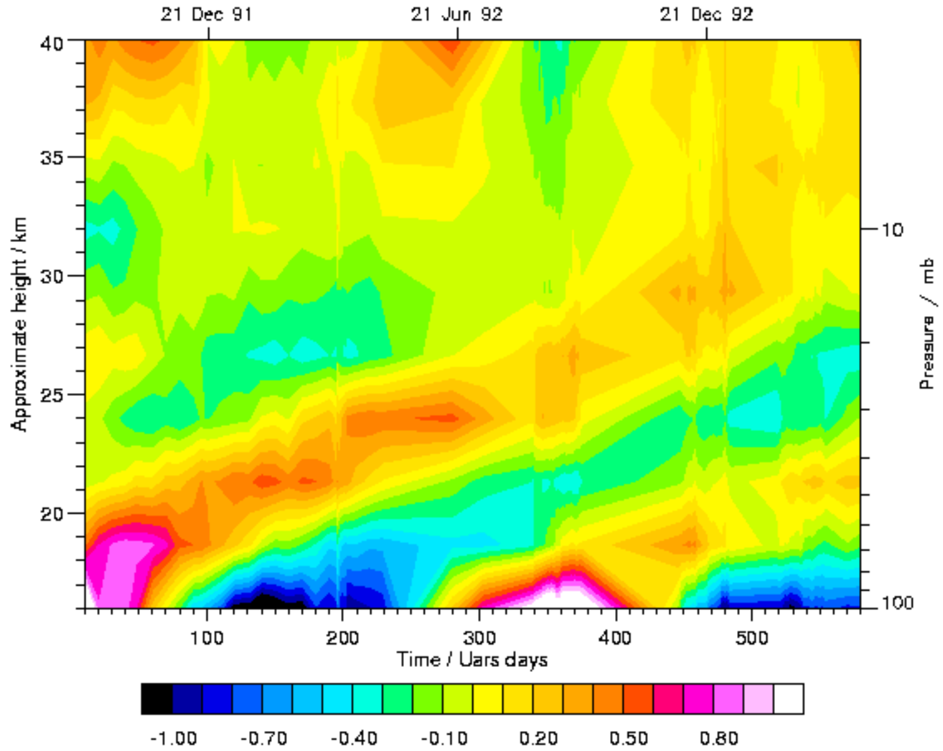
Panama (July) and Darwin (January) water vapour profiles (ER-2)
(Kelly et al 1993)



Seasonal variation of tropical tropopause temperature

Yulaeva et al (1994)

‘Tropical tape recorder’



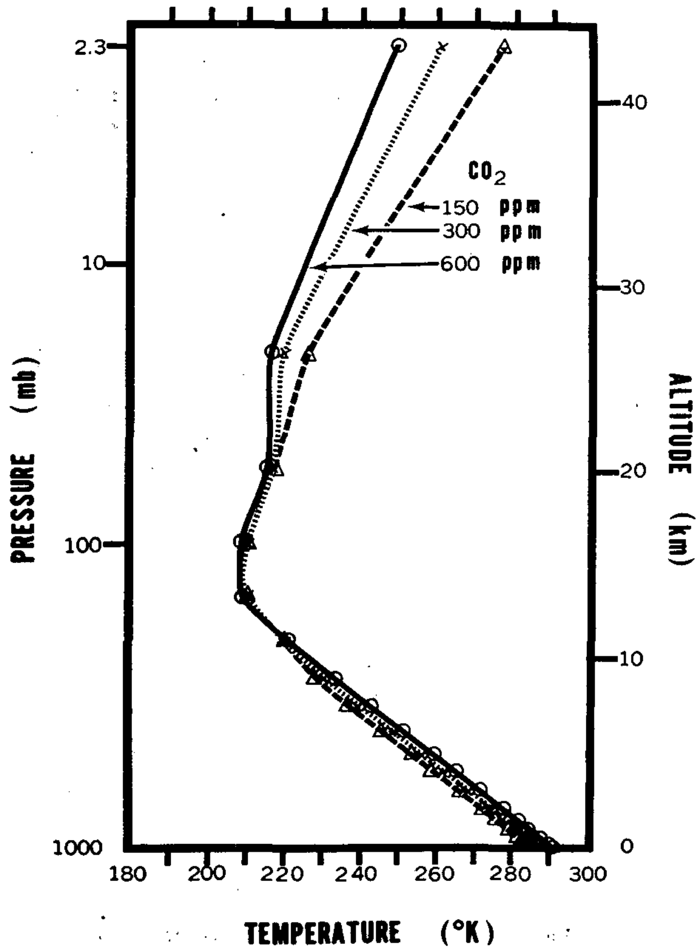
Variation of tropical water vapour observed by MLS instrument on UARS

Mote et al (1996)

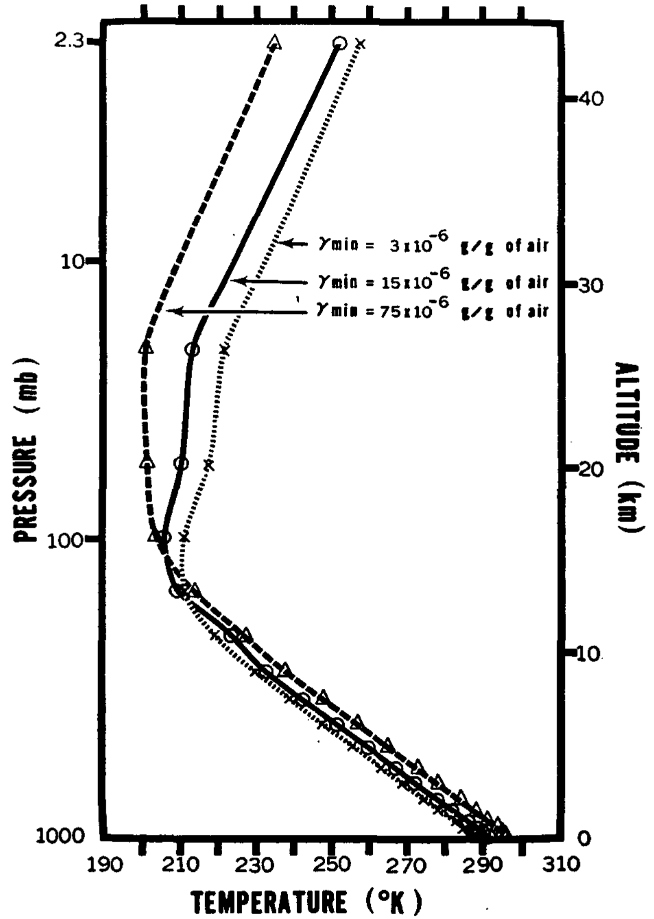
Effects of CO_2 increase/ stratospheric H_2O increase

Manabe and Wetherald (1967)

Changing CO2



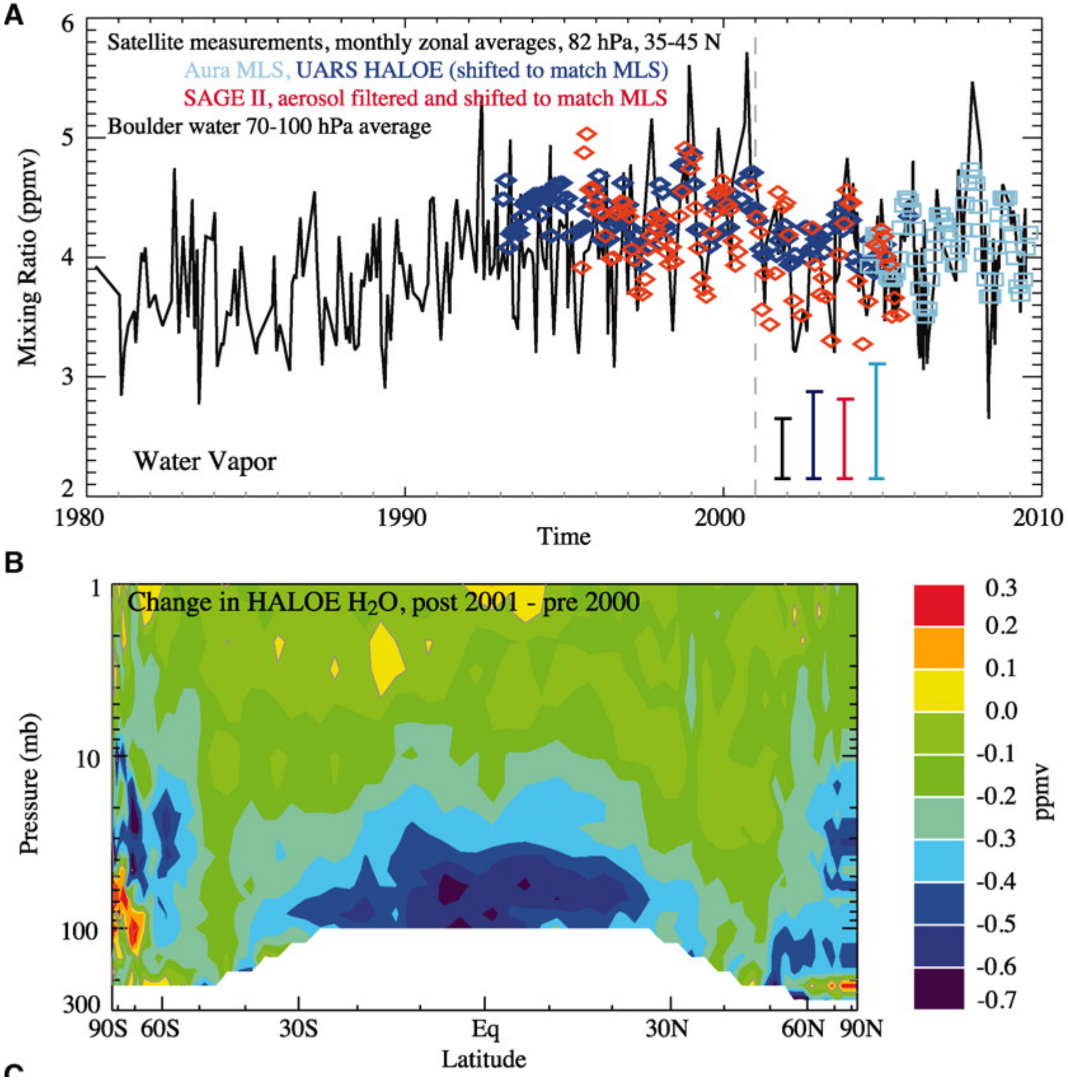
Changing stratospheric H2O

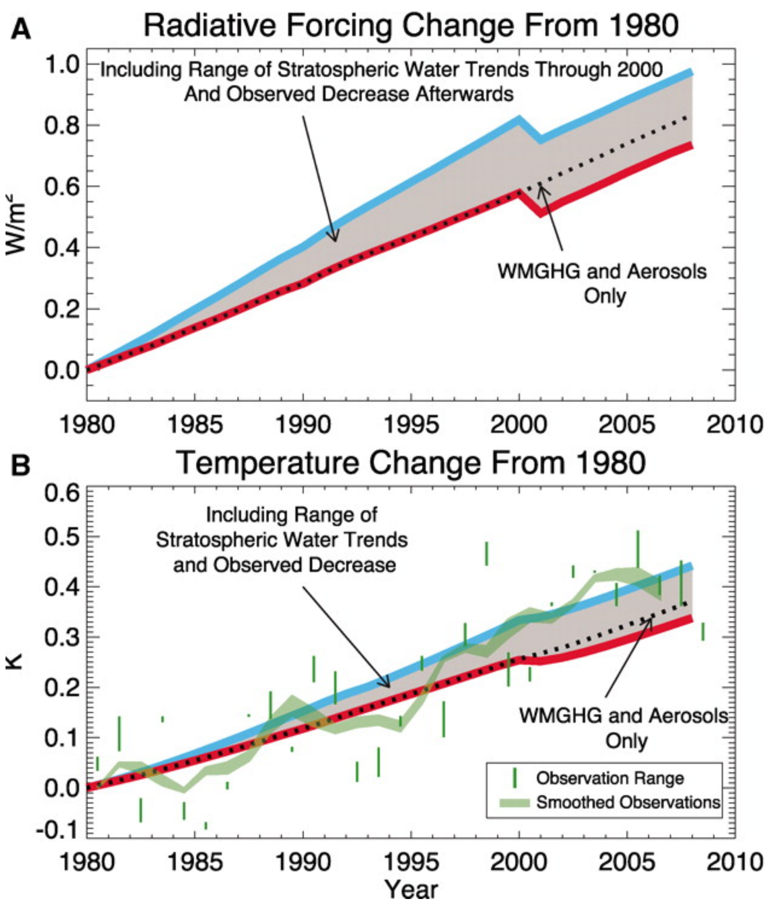


(many subsequent calculations)

Interannual/decadal changes in stratospheric water vapour

(Solomon et al 2010)



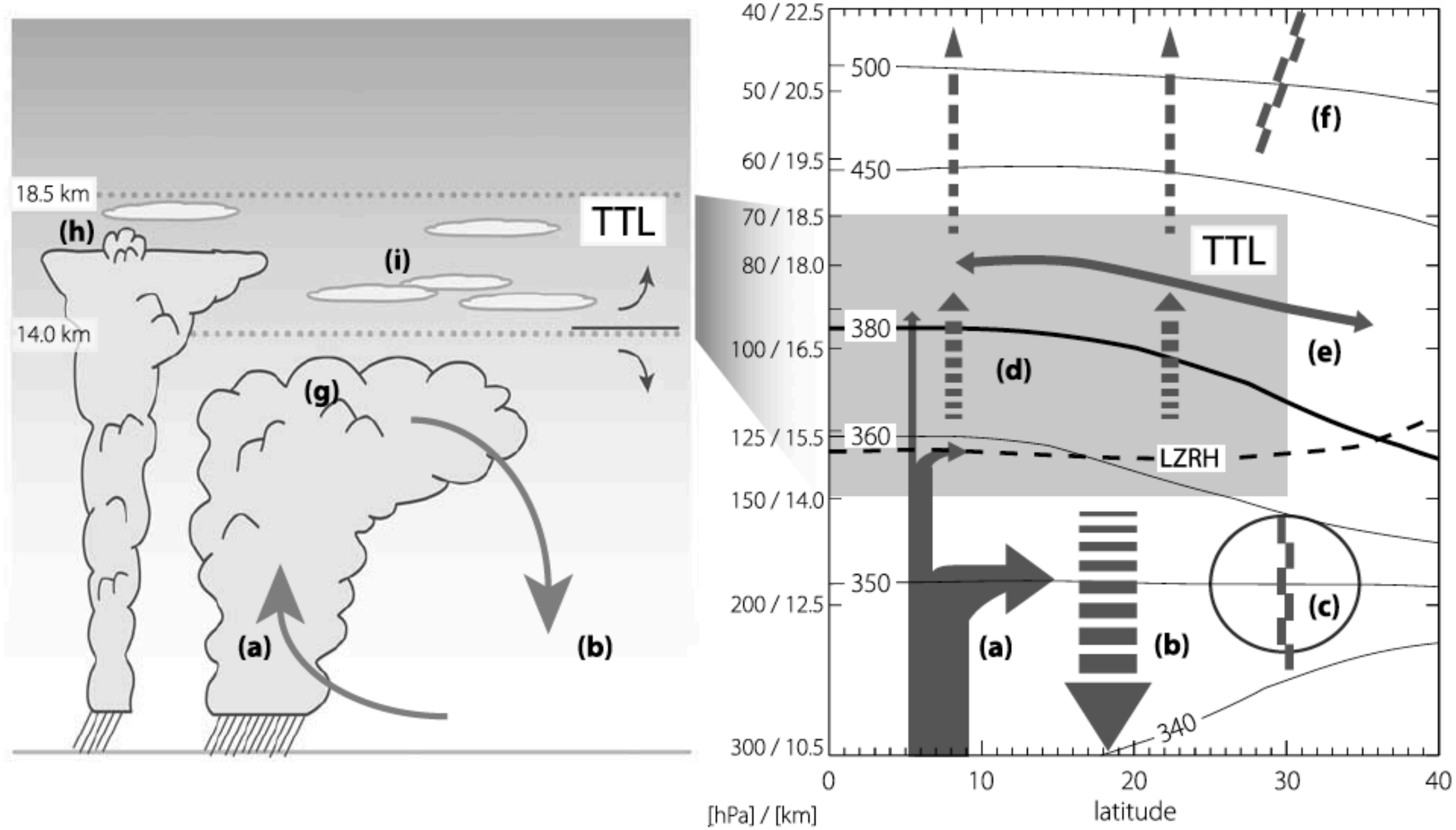


What determines annual, interannual and longer term variations in stratospheric water vapour?

- Temperatures (spatial scales? time scales? resolved by different observations and by re-analysis datasets? or not?)
- Transport (pathways? rates? convective penetration?)
- Dehydration efficiency (homogeneous vs heterogeneous nucleation? changes in background aerosol?)
- What processes are captured by climate models?

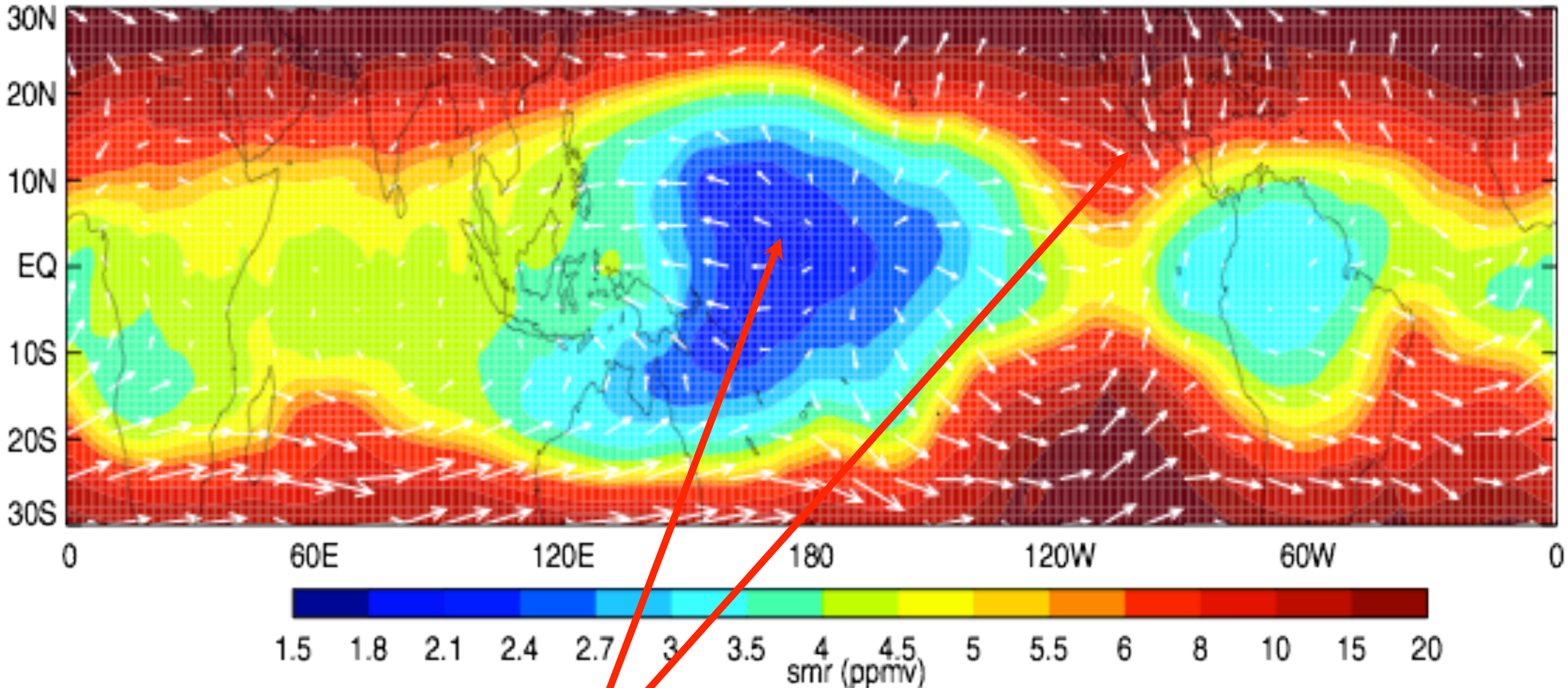
Tropical Tropopause Layer (TTL)

Fueglistaler et al (2009)



Transport from troposphere to stratosphere and dehydration is a 3-D process

Horizontal variation of smr



[ERA-Interim, January 2001]

In tropical upwelling regions, saturation mixing ratios vary by almost one order of magnitude.

3-D circulation is important! e.g. Holton and Gettelman 2001

The relation between Eulerian temperature field and atmospheric water vapour is strongly modulated by transport.

3-D view of dehydration

Schematic models: Holton and Gettelman (2001), Plumb (2002)

Trajectories from GCM: Hatsushika and Yamazaki (2003)

Trajectories from operational analysis/re-analysis data:

Jensen and Pfister (2004), Fueglistaler et al (2004), Bonazzola and H (2004)

Fueglistaler, Bonazzola, H and Peter (2005), Fueglistaler and H (2005), …..

Liu, Fueglistaler and H (2010), ….

Dessler and Schoeberl (2011), …

Ploeger et al (2011), …

Lagrangian approach to relating temperatures to stratospheric water vapour

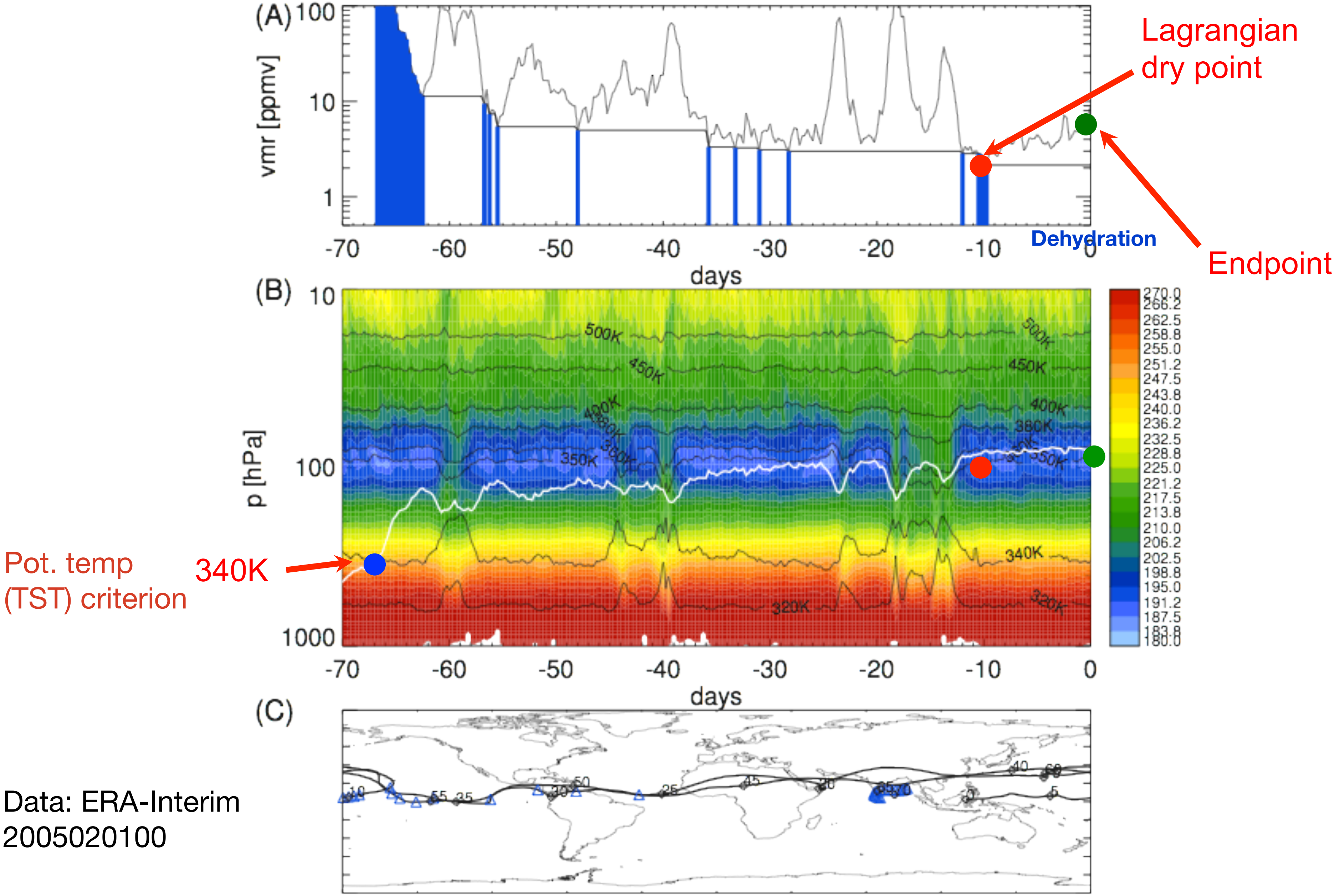
(e.g. Liu et al 2010)

(i) Back trajectories (using ECMWF re-analysis data) are started in the lower stratosphere

(ii) Those that can be traced back to the troposphere within integration time (1-year) form the Troposphere-to-Stratosphere (TST) ensemble

(iii) Find Lagrangian Dry Point (LDP) of the TST-ensemble (note T, lat, lon, pres, time) - this is the last point at which trajectories encounter 100% RH before the endpoint

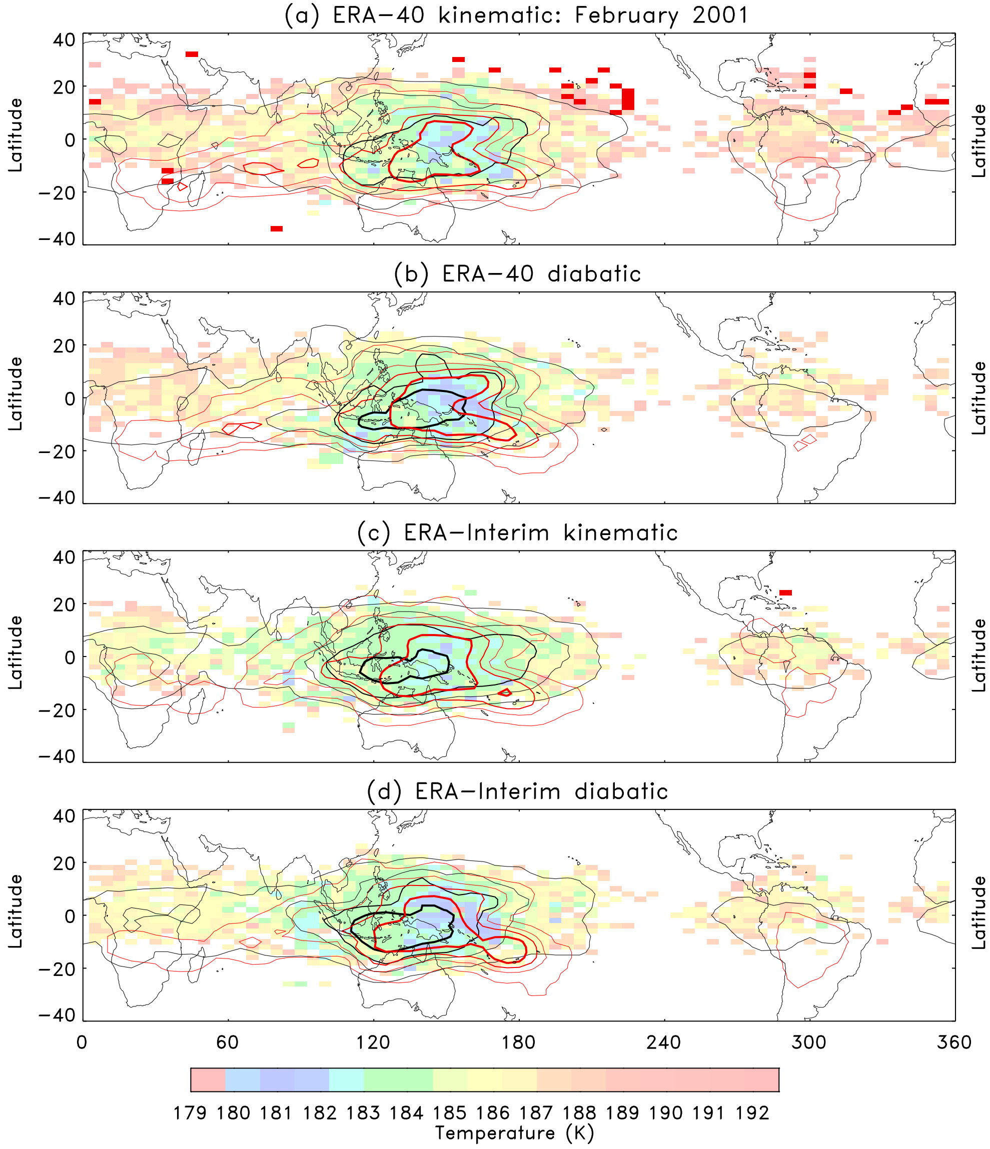
Results are assumed to be statistically representative (large ensembles of trajectories calculated - usually on the order of $10^6 – 10^7$). Individual trajectories are not accurate.

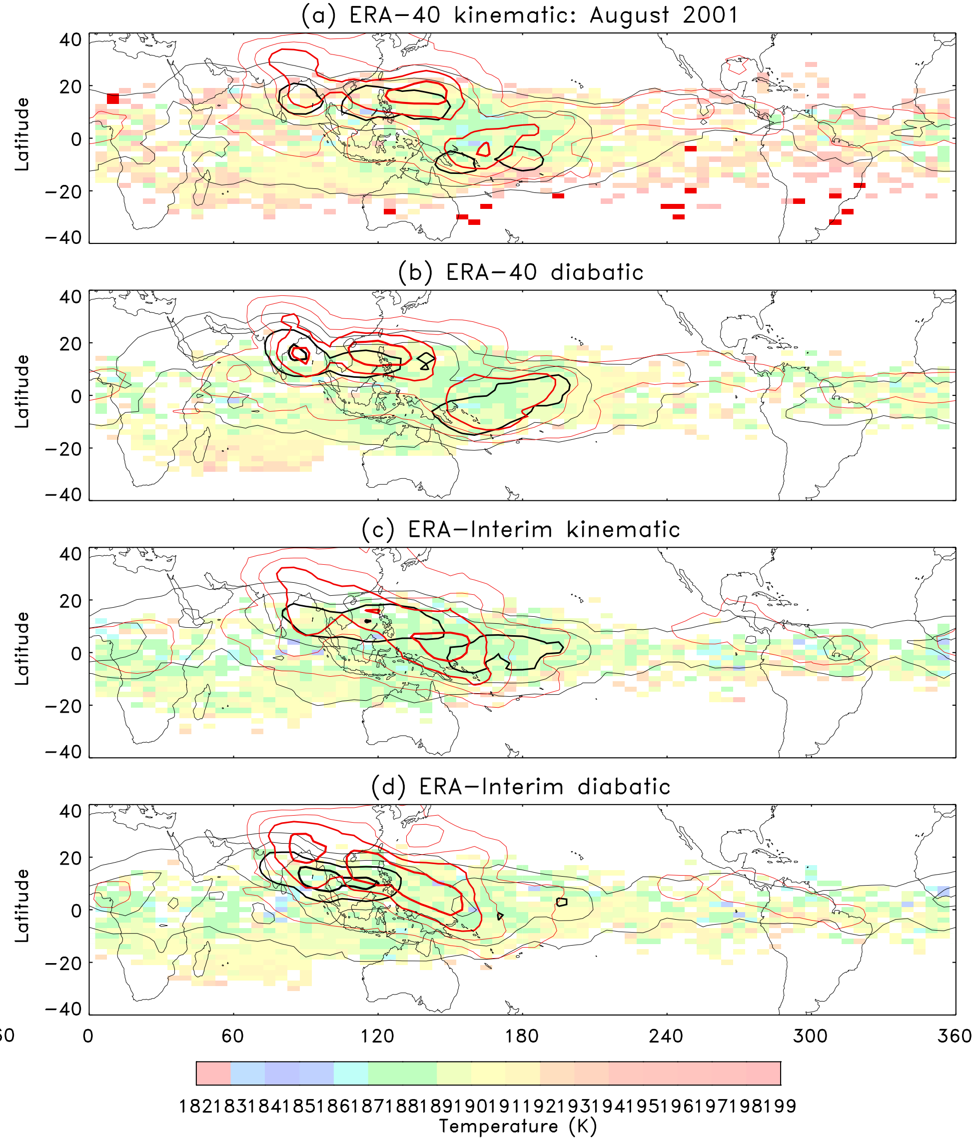


Data: ERA-Interim
2005020100

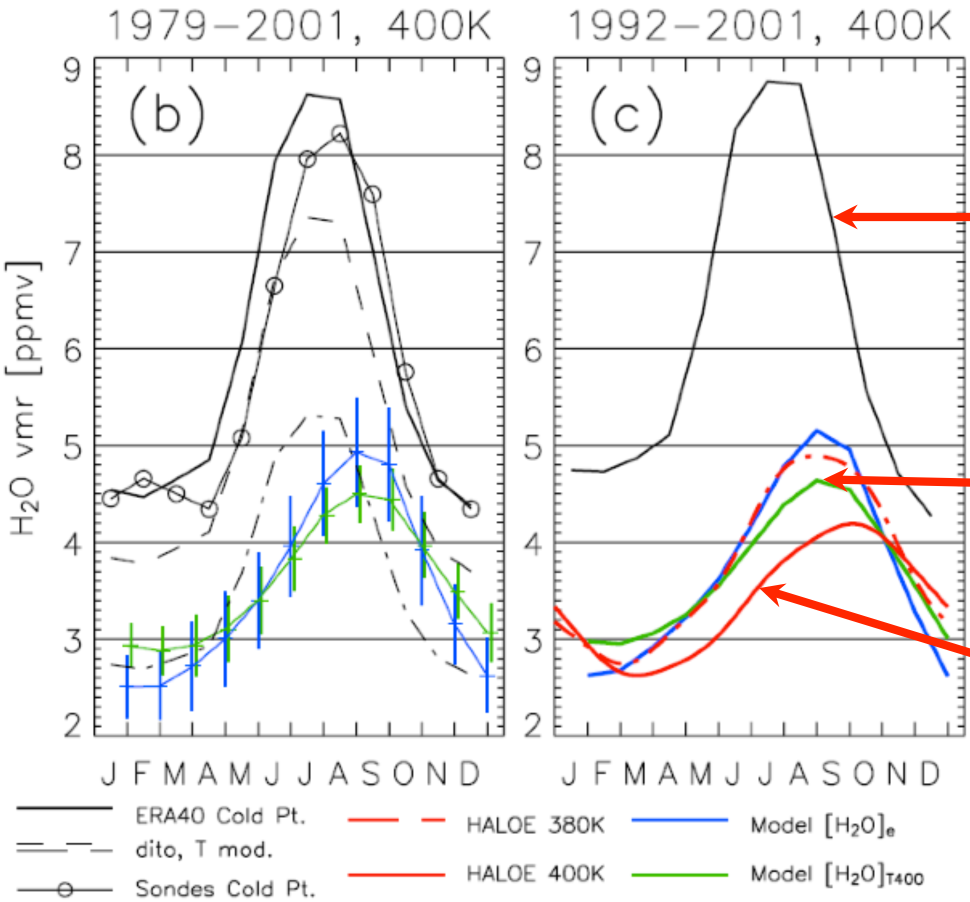
LDP distribution

Liu (2009)





Previous results using ERA-40 data



Climatologically averaged annual cycle of tropical mean (30˚S - 30˚N) water vapour on 400K

Estimate from local Eulerian column minimum temperature

Estimate using trajectories

Observation (HALOE)

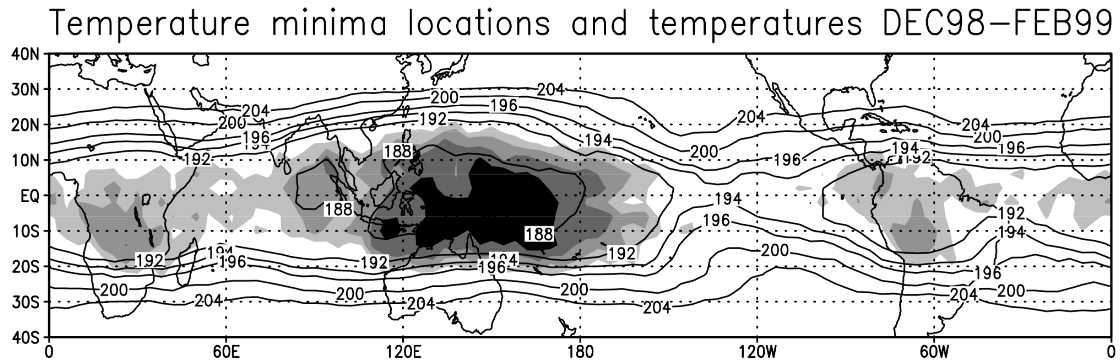
Tropically averaged model results are in quite good agreement with observations!

(a) Vertical propagation too fast

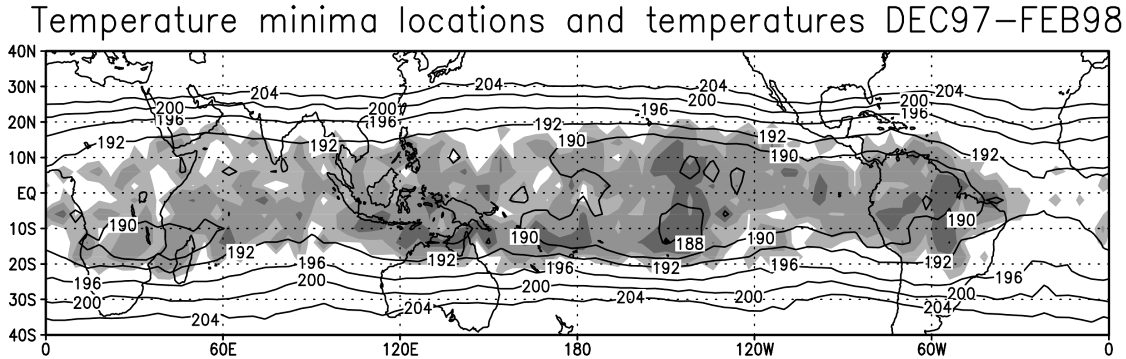
(b) Results have a moist bias

Fueglistaler *et al.* 2005, JGR

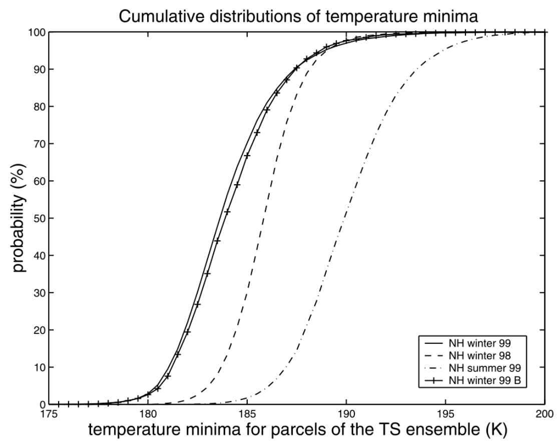
La Nina (1998-99)

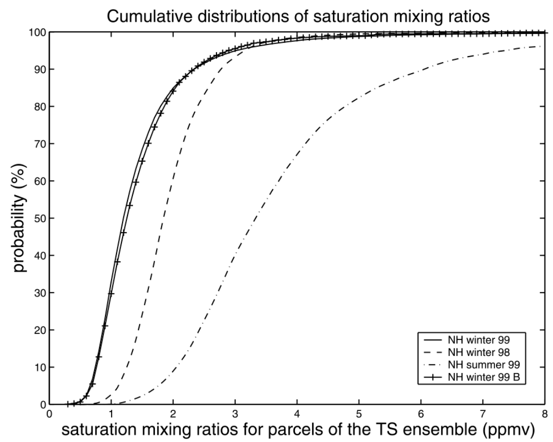


El Nino (1997-98)

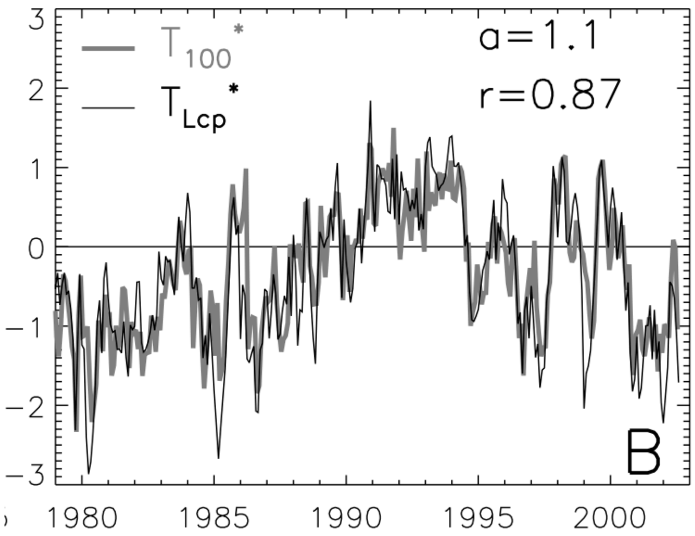


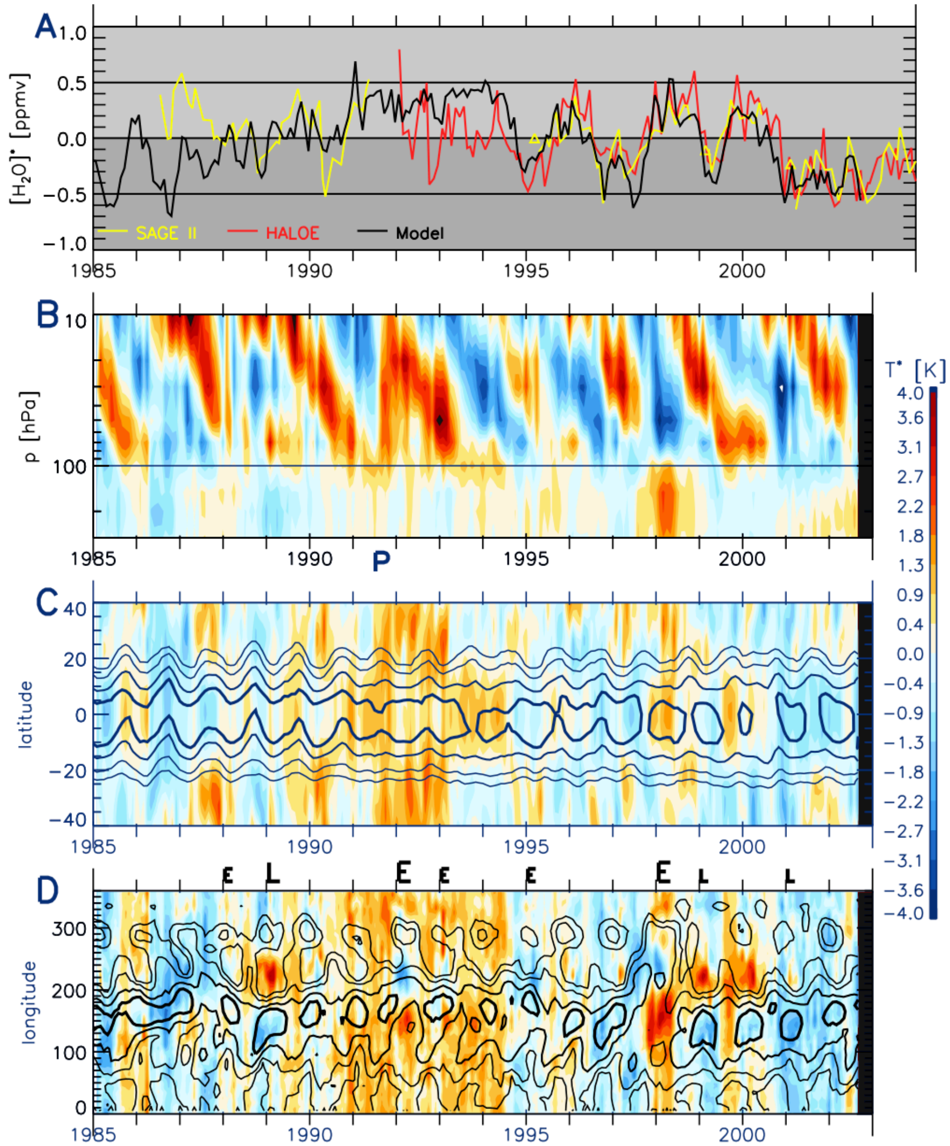
Bonazzola and H (2004)





Interannual variability
(Fueglistaler and H 2005)



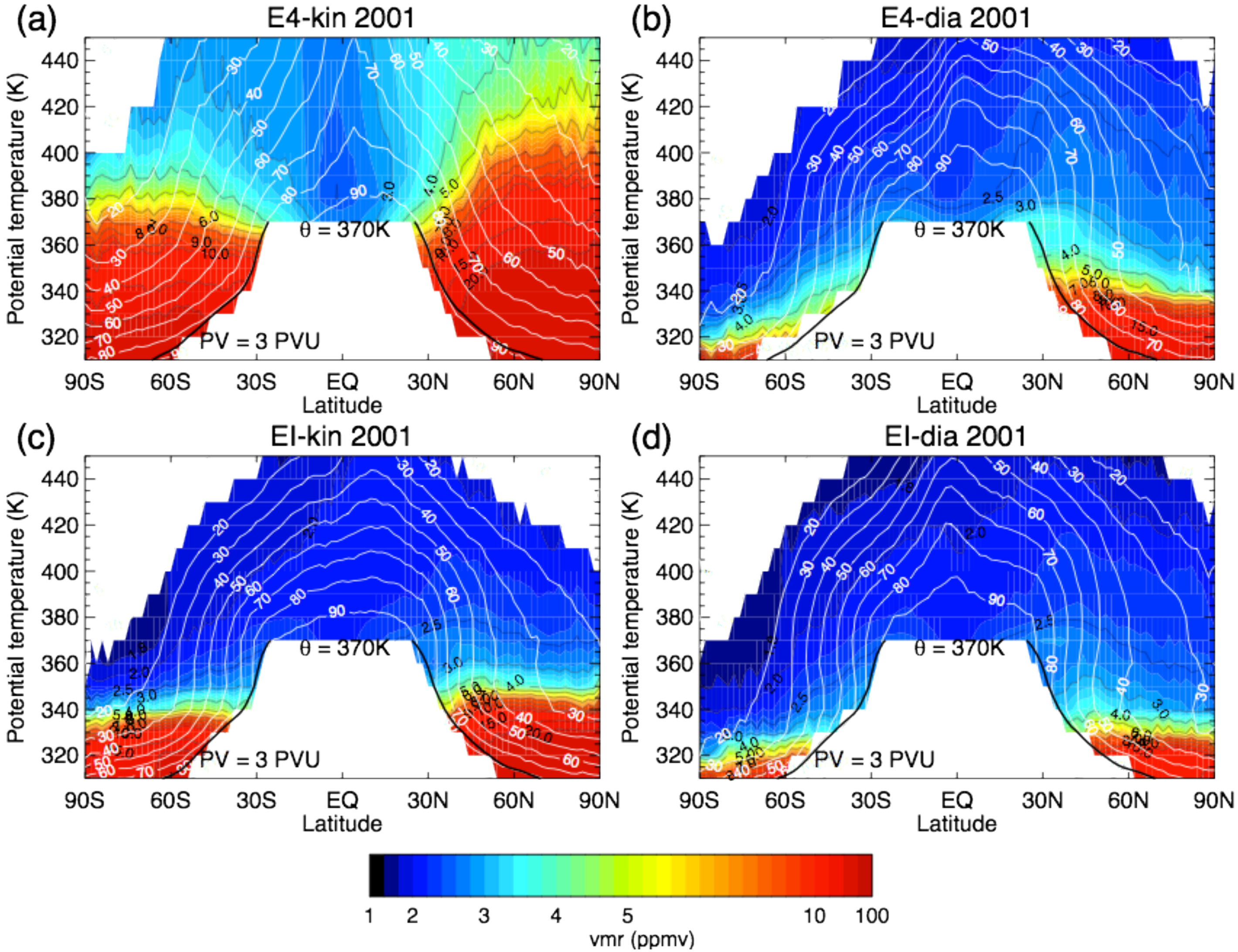


Dependence on data and trajectory type

Liu *et al.*, 2010

LDP water vapour from TST-ensemble only

6-hourly T159L60



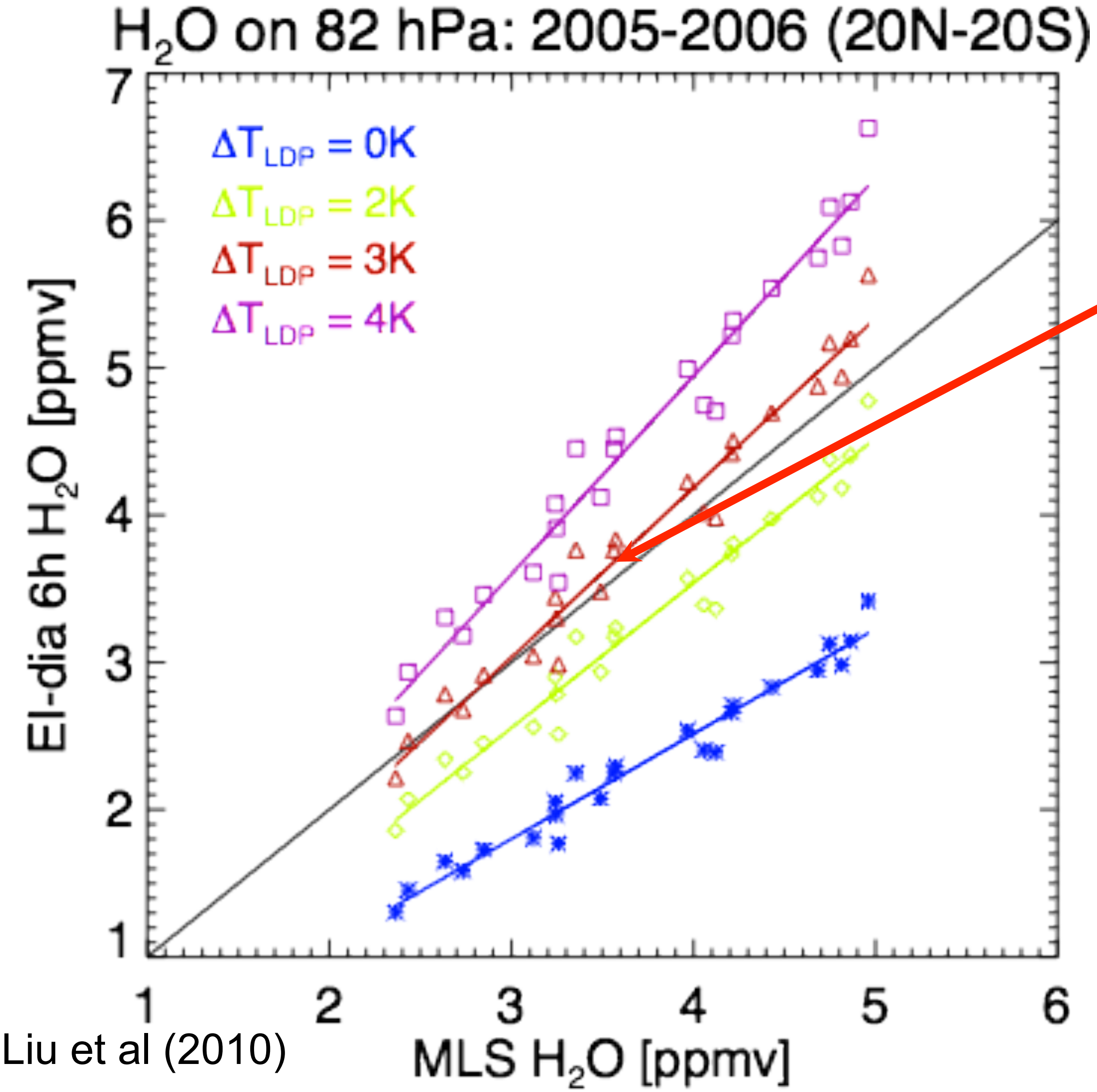
E4 - ERA-40
(3D-var assimilation ends 2002)

EI - ERA-Interim
(4D-var assimilation 1989 - present)

kin - kinematic
(vertical velocity calculated from continuity equation)

dia - diabatic
(vertical motion from heating rates)

Simple LDP correction



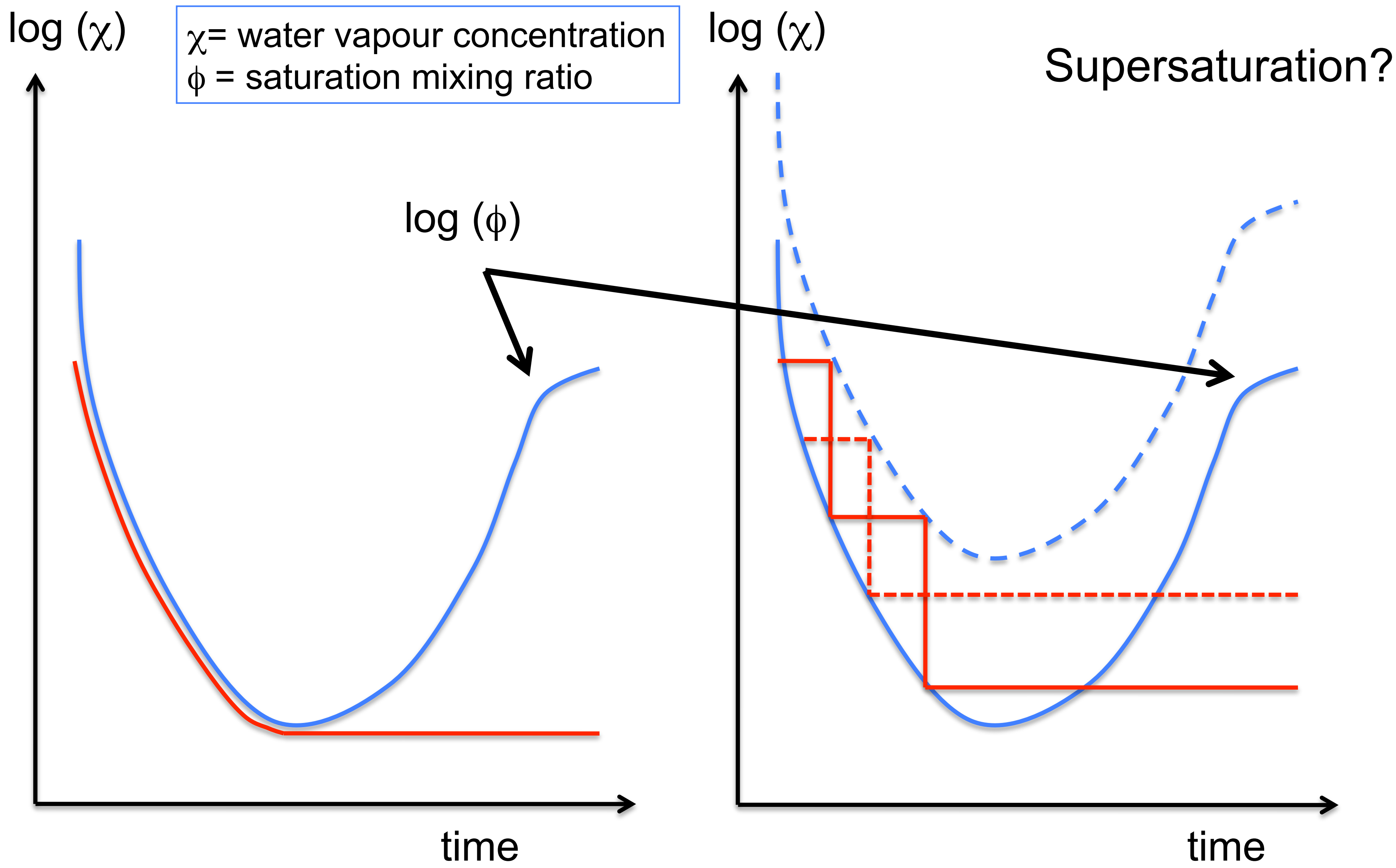
Liu et al (2010)

Increase LDP temperature by +3K to bring results to agreement with MLS!

(Surprisingly, such a simple LDP temperature correction can correct much of the bias in both the mean and amplitude)

Liu et al (2010) -- summary

- The simplest advection-condensation model (dehydration at 100% relative humidity, immediate and complete sedimentation of condensates) is **dry biased** - Good news, since in better agreement with what we might expect for such a model. Previous results showing moist bias less easy to understand.
- After considering errors incurred in applying the model (errors in reanalysis temperature and transport), we estimate that a Lagrangian Dry Point temperature correction of ~**3K** is sufficient to bring results into agreement with observations.
- How to explain the dry bias in the A-C model? Quantify roles of microphysics/mixing/convective penetration.



instantaneous condensation to local saturation mixing ratio

160% supersaturation followed by instantaneous condensation to local saturation mixing ratio given supersaturation is equivalent to given temperature correction

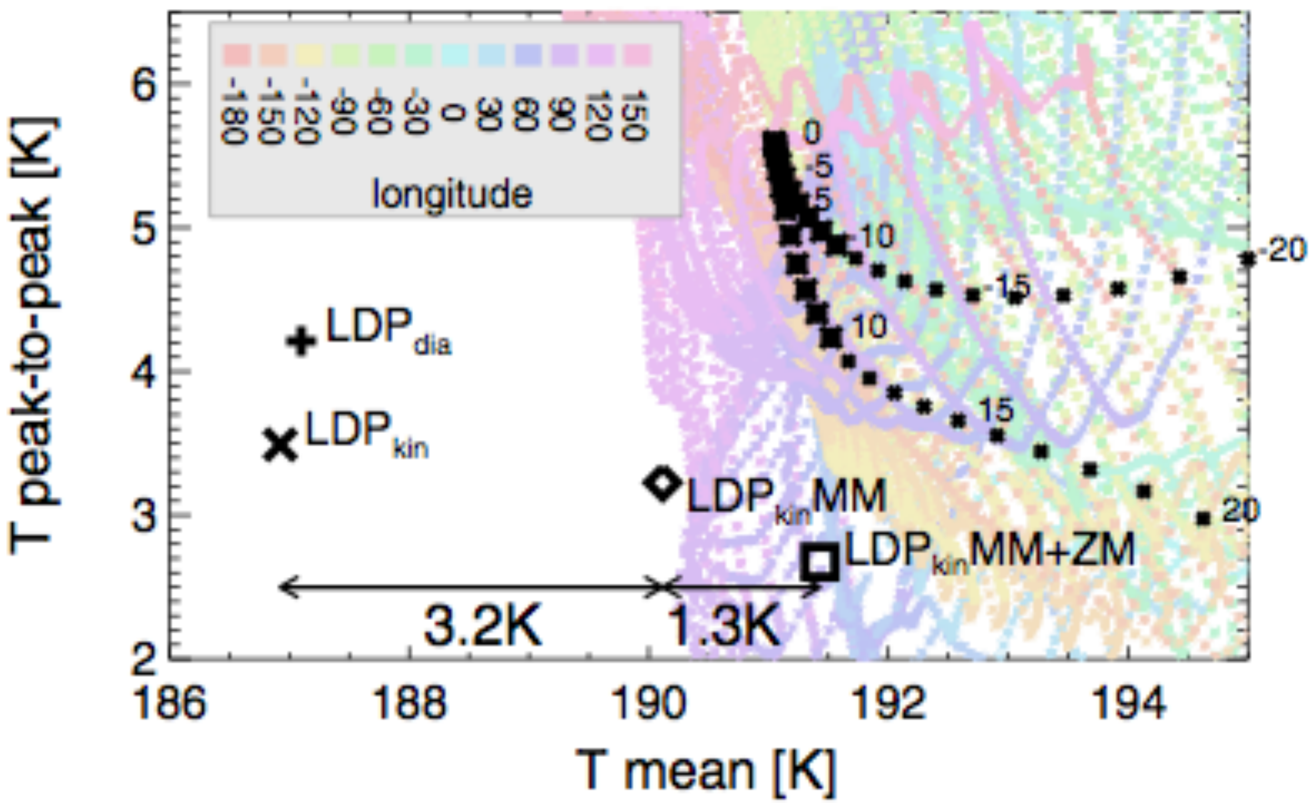
$$e_s(T) = e_s(T_0)\exp[\frac{L_v}{R_v}(\frac{1}{T_0} - \frac{1}{T})] \propto \exp(-\frac{6300\mathrm{K}}{T})$$

supersaturation $\alpha > 1$

↕

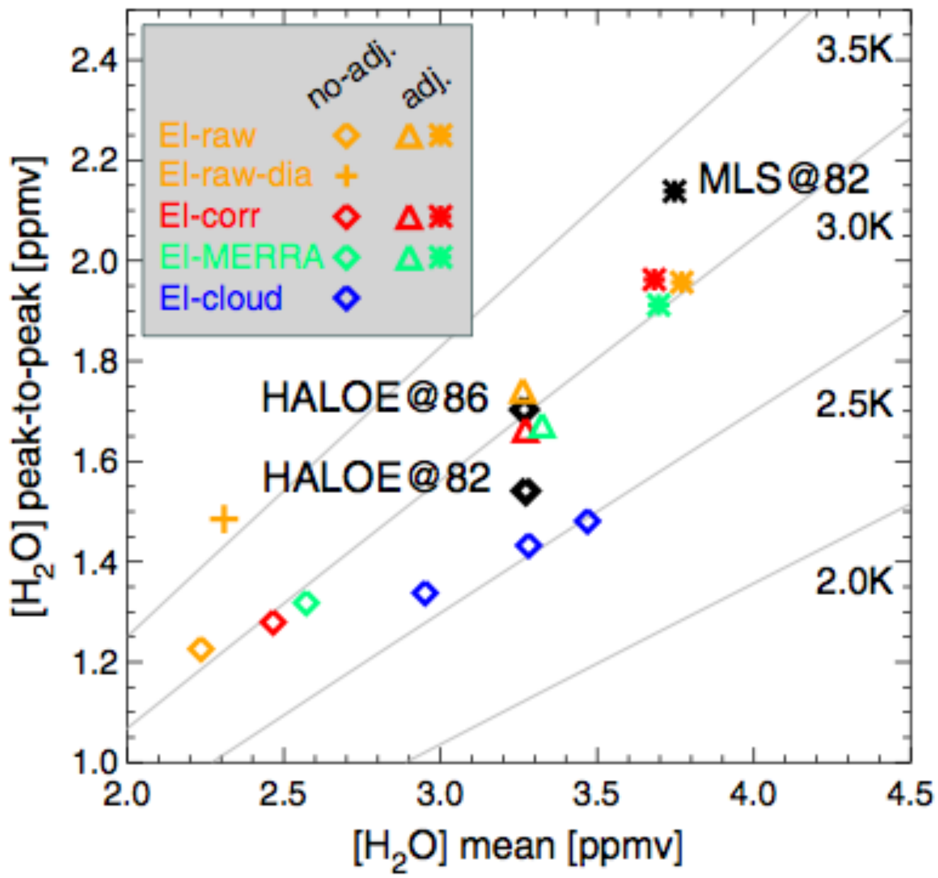
temperature correction $\Delta T \sim T^2 \log \alpha / 6300\mathrm{K} \sim (6\mathrm{K}) \log \alpha$

Update on LDP analysis of annual cycle



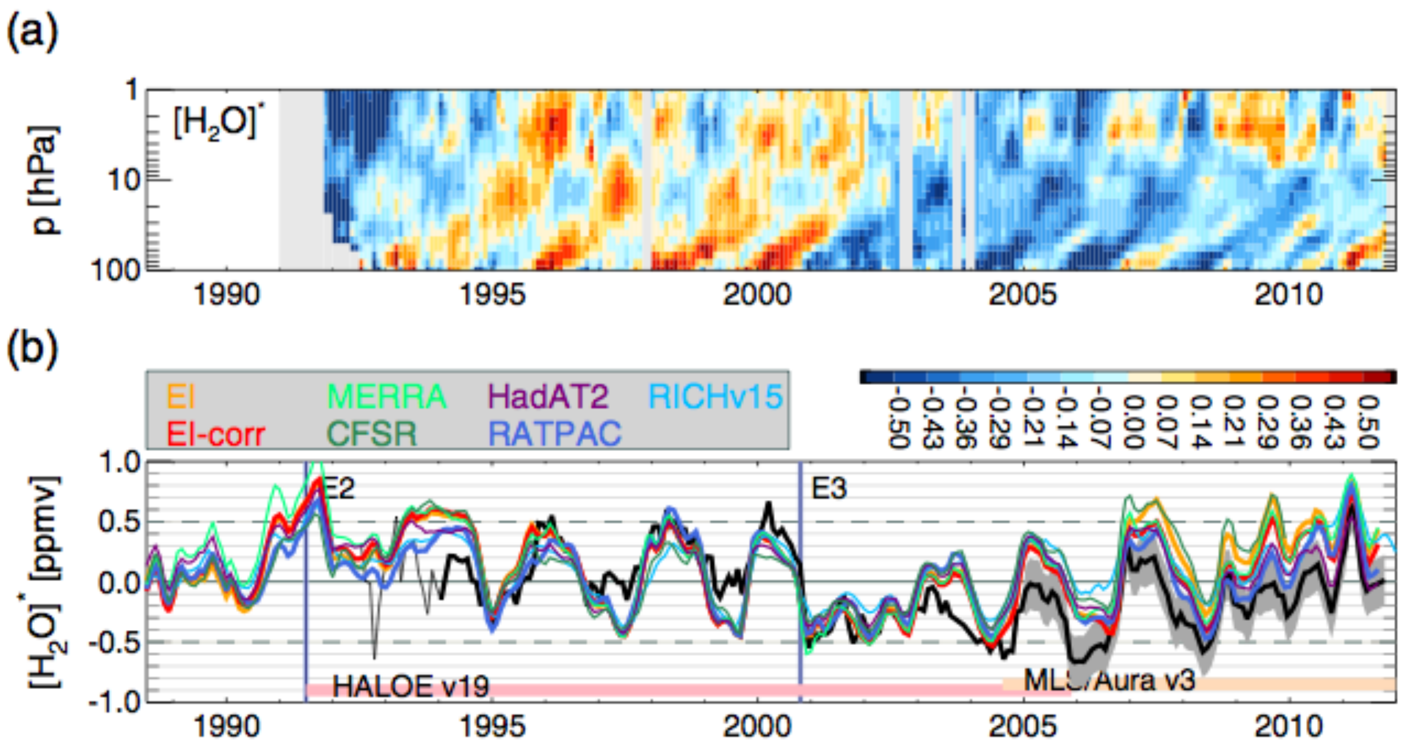
Fueglistaler et al (2013)

Comparison of LDP predictions with observations



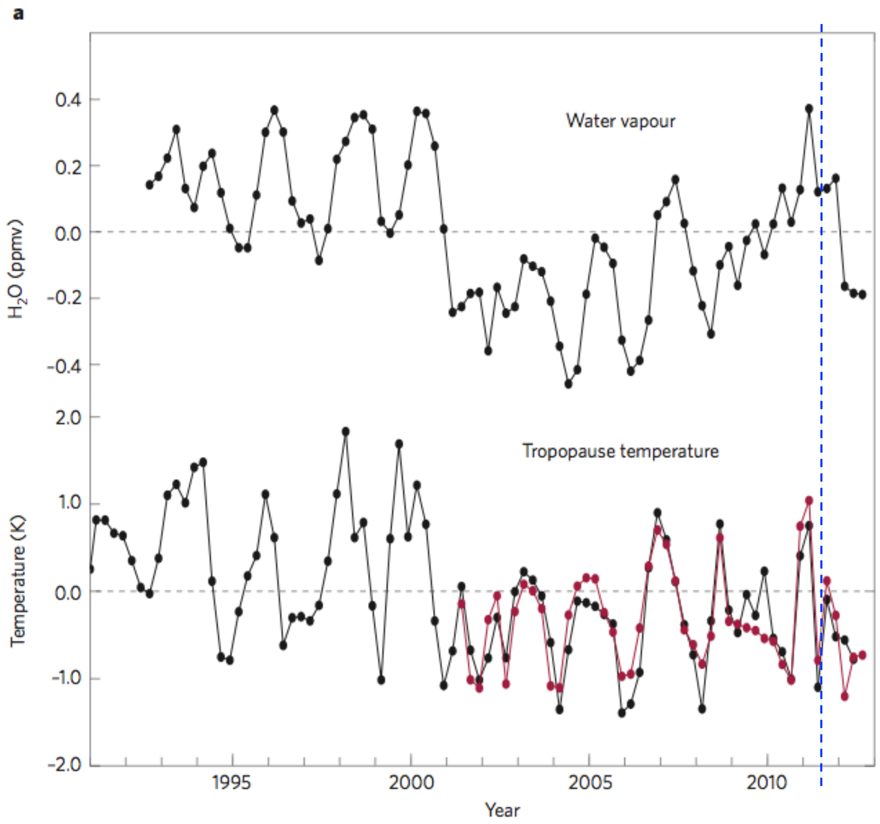
Fueglistaler et al 2013

LDP predictions of interannual variability



Fueglistaler et al 2013

Recent interannual variability

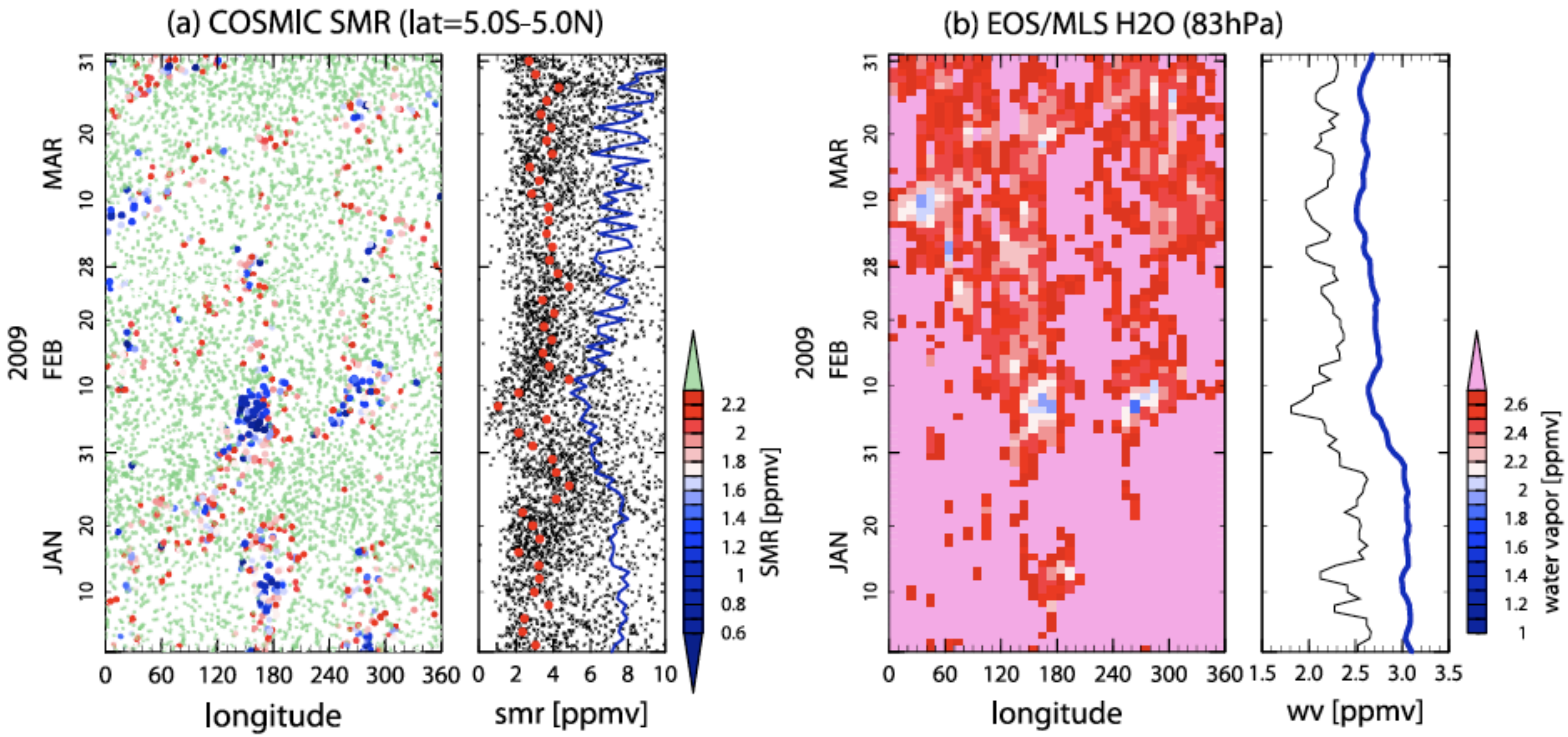


Randel and Jensen (2013)

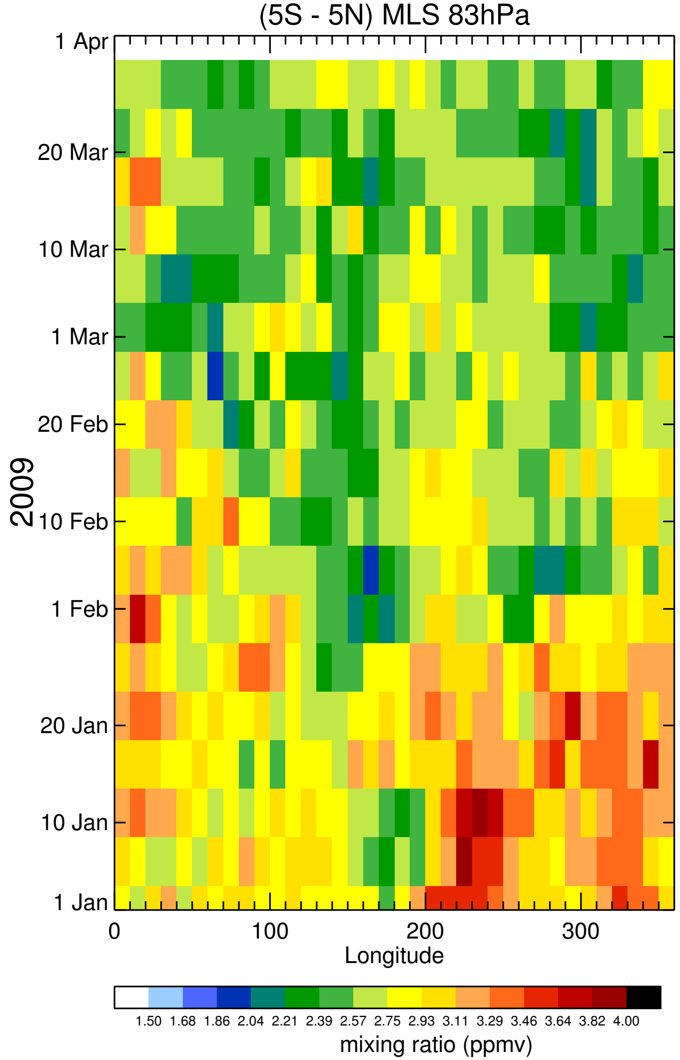
post-2011 drop

Role of localised cold events in large-scale dehydration?

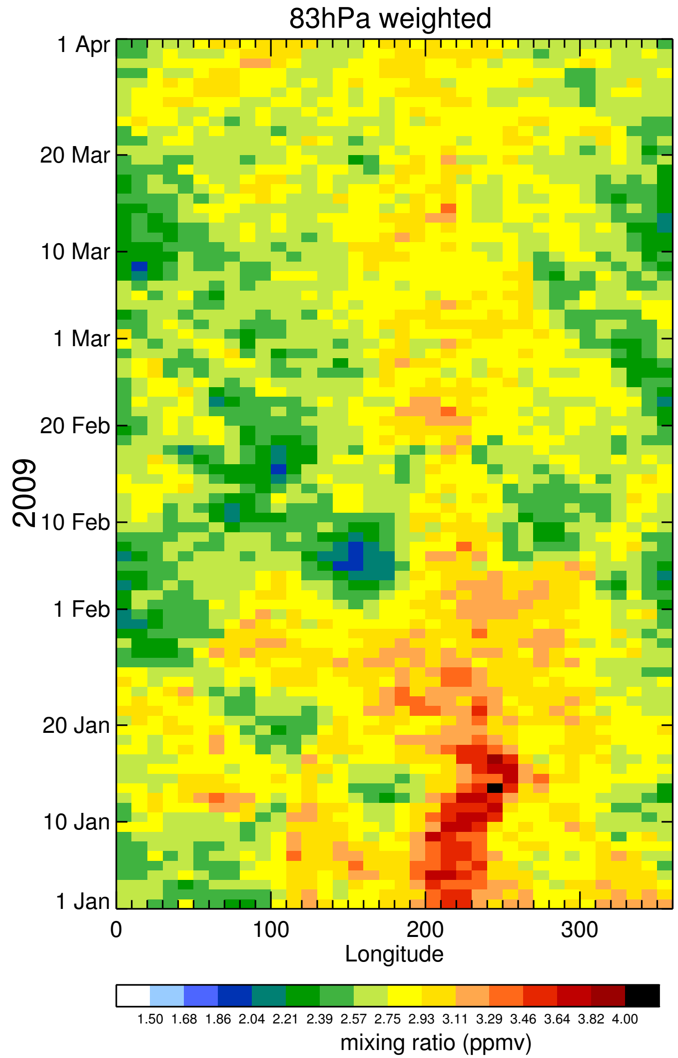
Takashima et al (2010)



MLS 83hPa

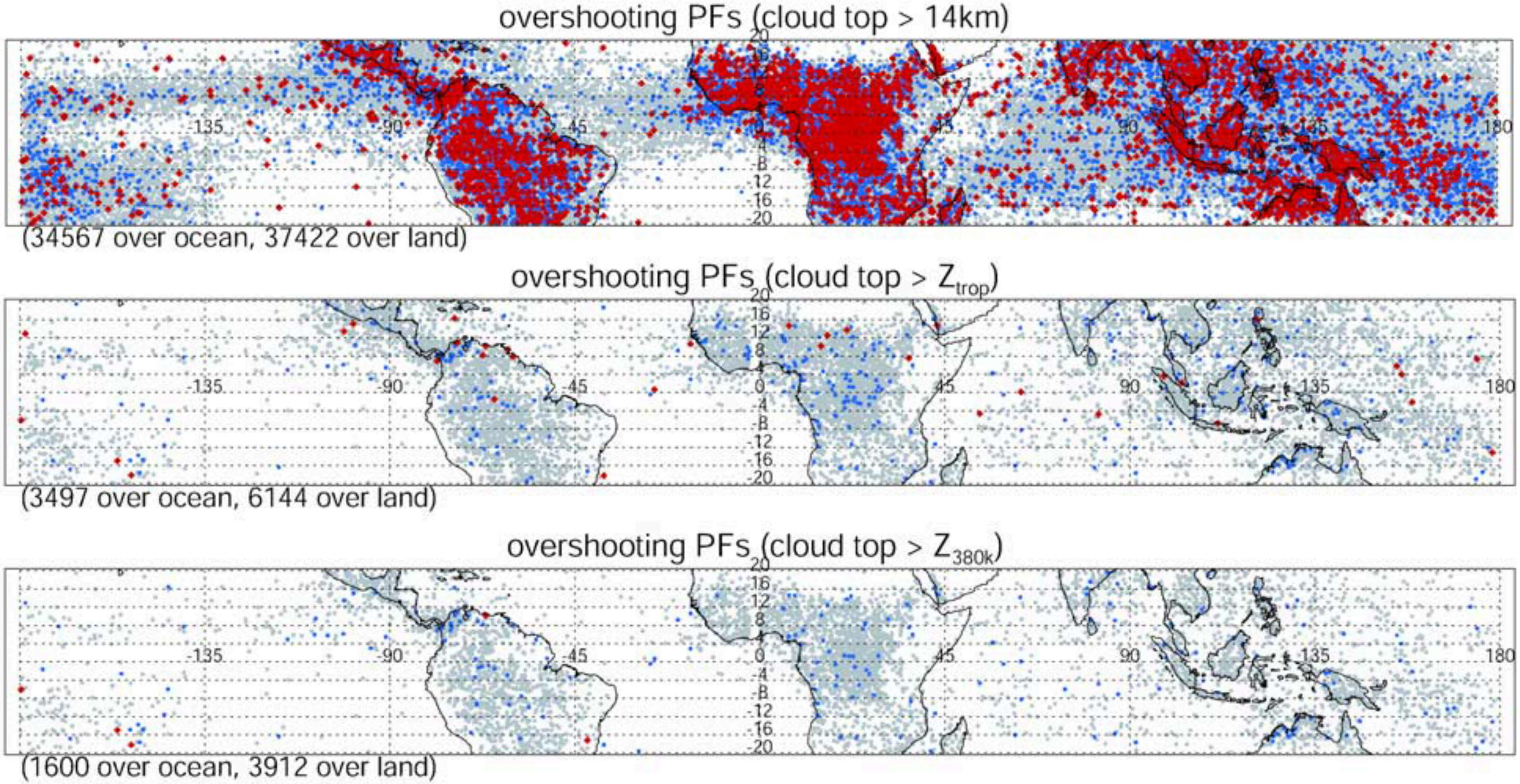


Trajectory reconstruction



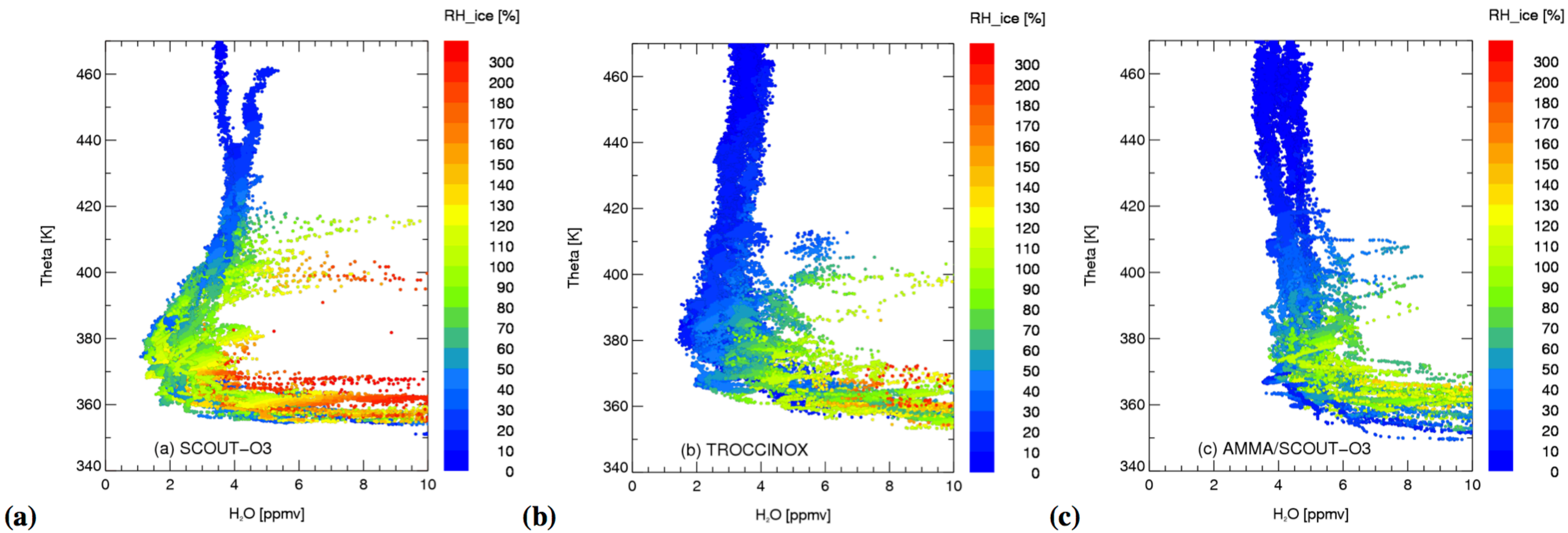
(Sue Liu, personal communication)

Role of overshooting convection?



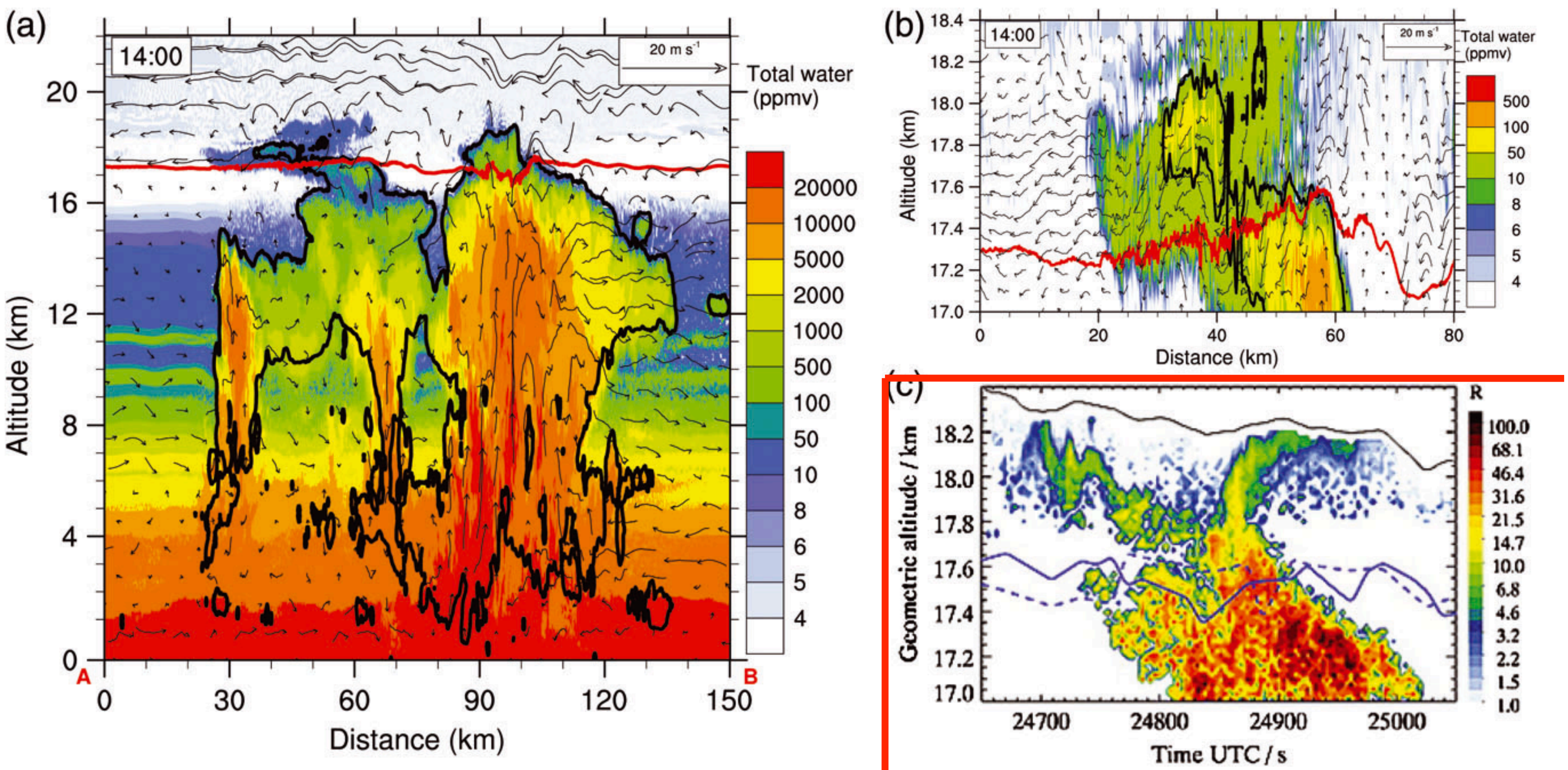
Liu and Zipser (2005)

Moistening effect of convection



Schiller et al (2009)

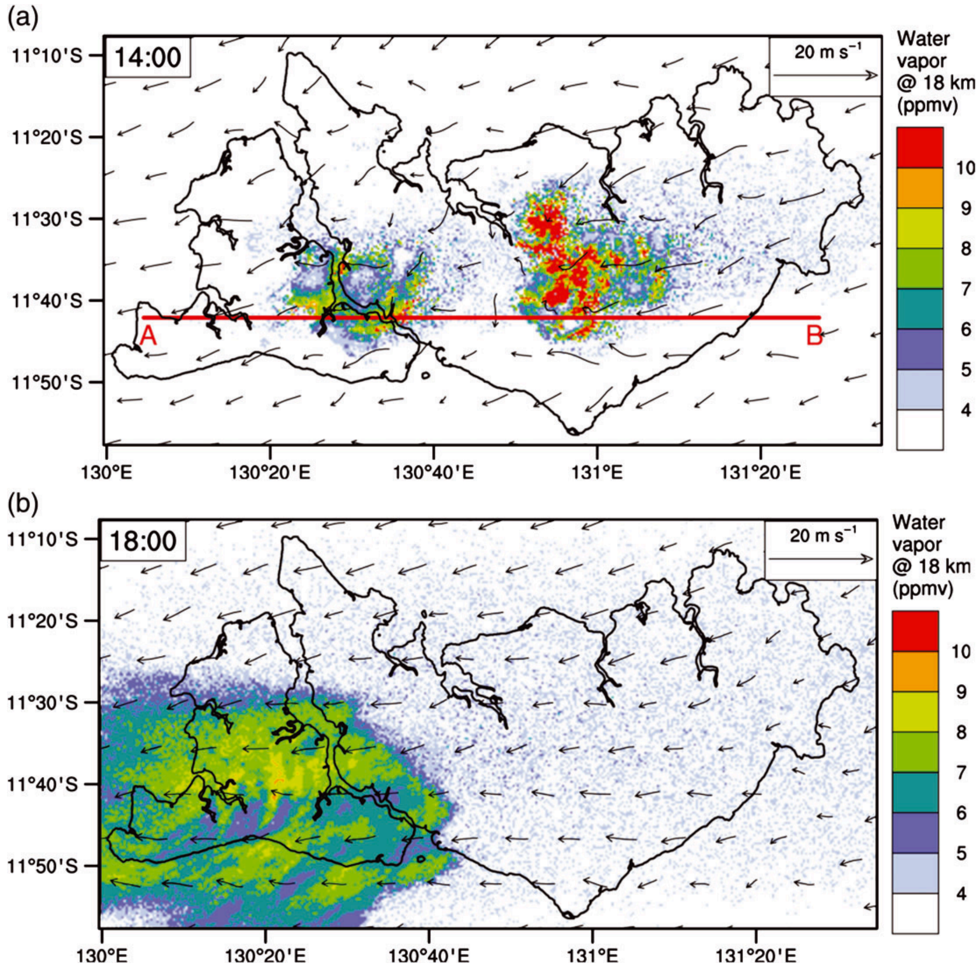
Numerical simulations of "Hector" system



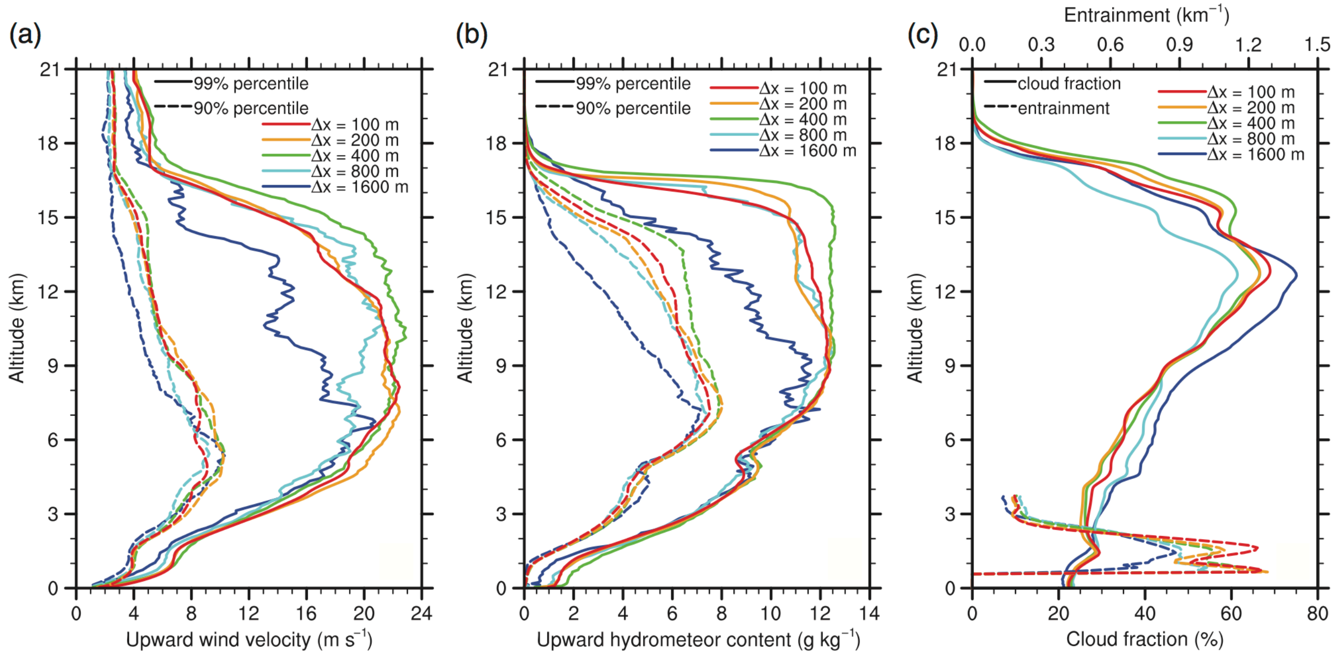
Dauhut et al (2015)

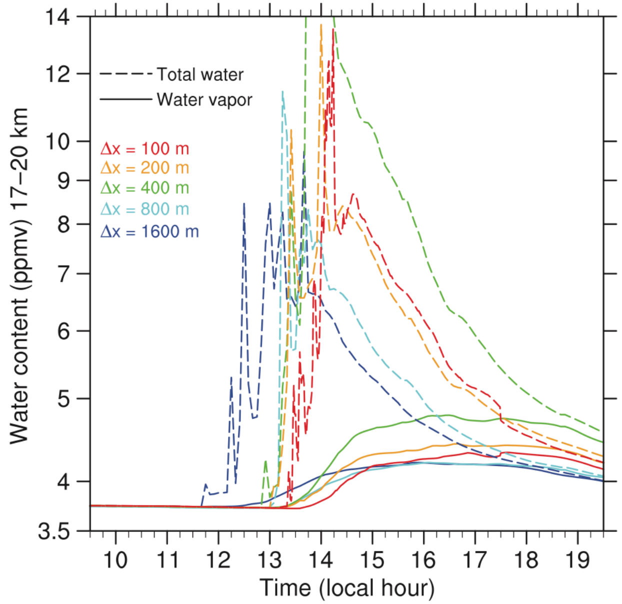
[1.3 x 10^9 grid points on 16000 processors]

Observations -- Corti et al (2008)



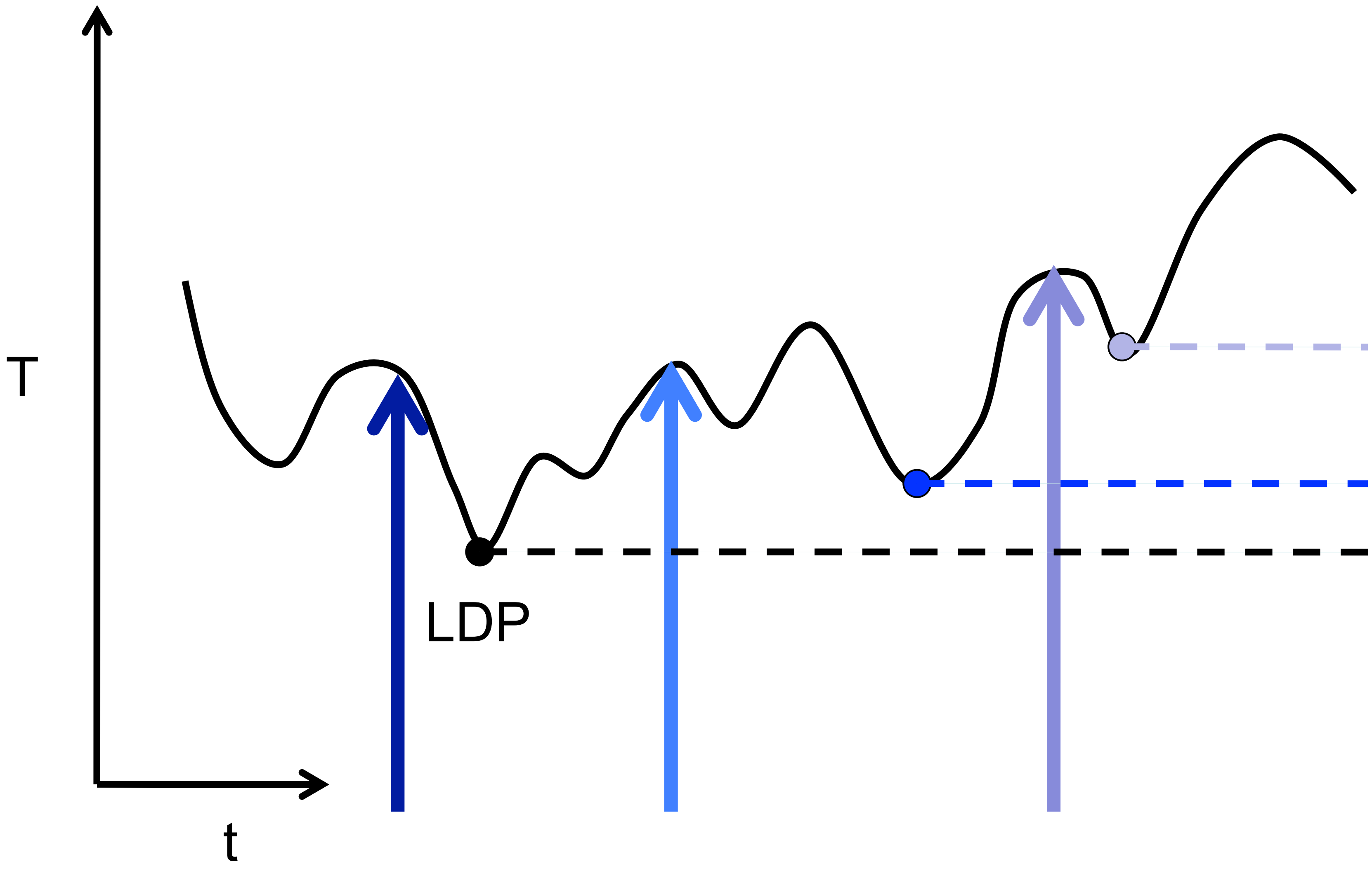
Dauhut et al (2015)



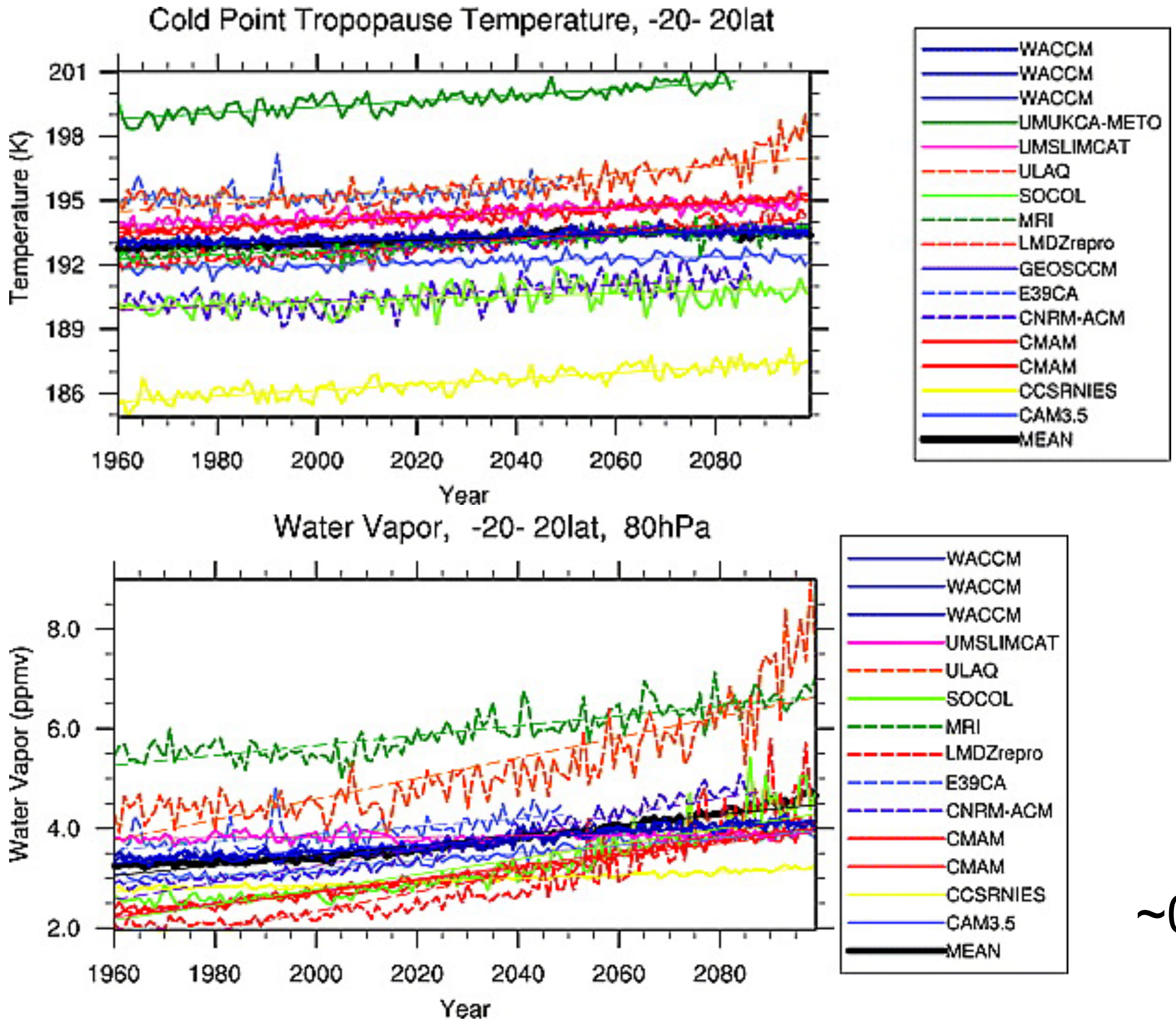


Dauhut et al (2015)

Implication of convective injection?



CCMVal model predicted trends



Gettelman et al (2010)

~0.5-1K/100yrs

~0.5-1ppmv/100yrs

Summary

- Tropical TST is 3-dimensional process and Lagrangian approach is a useful way to explore and quantify.
- Annual mean and annual cycle can be captured with constant temperature correction – what physical effects is this capturing?
- Time variation (less than one month) of temperature field is very important.
- Large part of interannual variability in stratospheric water vapour is captured by Lagrangian Dry Point calculation – the temperature constraint is strong on interannual time scales.
- There is observational evidence for convective moistening but none for convective drying. Extrapolation from localised observations/modelling of convective moistening to the large scale is difficult.
- Models predict increasing stratospheric water vapour.
- Is this simply a temperature effect? (Longitudinal structure important – Garfinkel et al 2013)
- Are other changes important on longer time scales (e.g. aerosol?, gravity waves – Kim and Alexander 2015? 'ice lofting' – Dessler et al 2016)