Insight into tropical troposphere-to-stratosphere transport from analysis data

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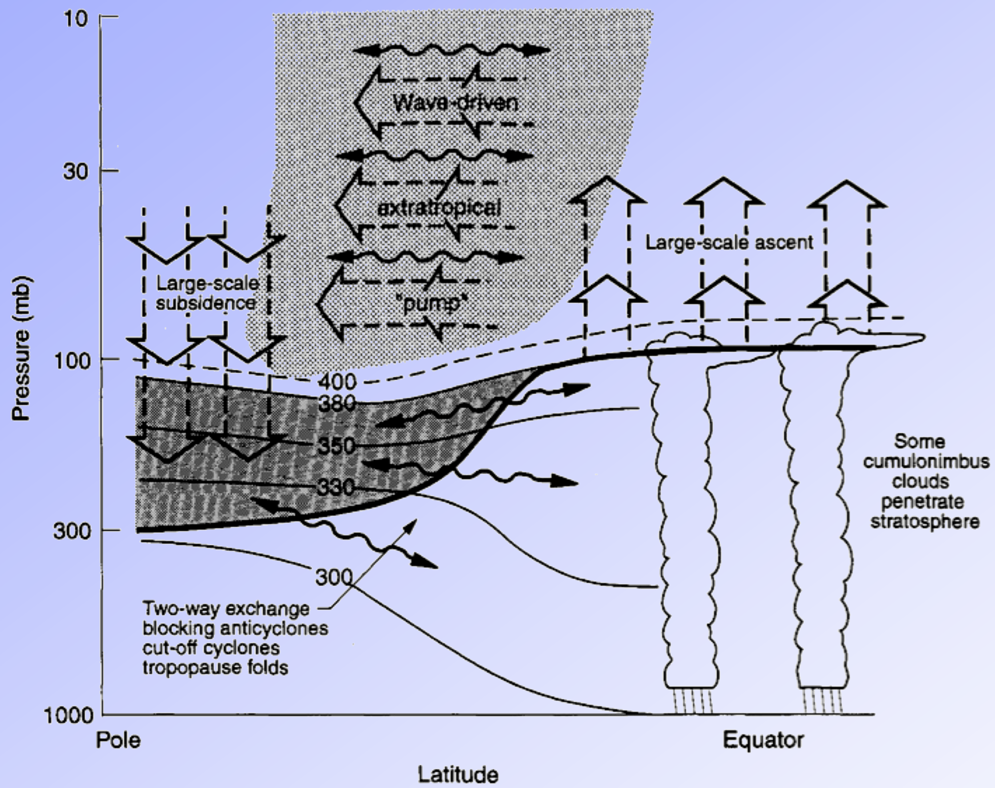
Overview

- Introduction.
- Stratospheric water vapour and tropical troposphere-to-stratosphere transport.
- Age of air, constraints from other tracers, heat balance.
- Summary and outlook.

Stratosphere-troposphere exchange



The Holton et al. [1995] view.

Quantitative questions:

Mass flux (into ‘overworld’/‘lower-most stratosphere’).

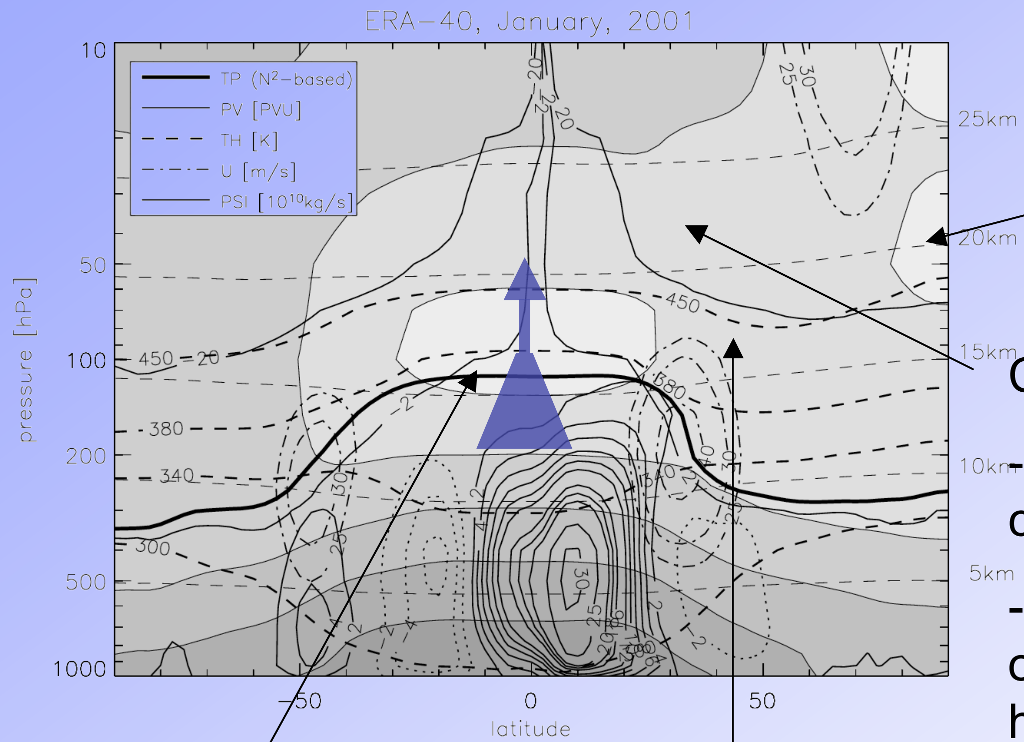
Convective transport vs. radiative ascent.

Tracer flux (e.g. water vapour, VSLS).

Qualitative questions:

Processes that control structure of low latitude UT/LS, processes that control troposphere-stratosphere transport.

Stratospheric H_2O



Chemistry:

-Principal source of OH (HOx chemistry).

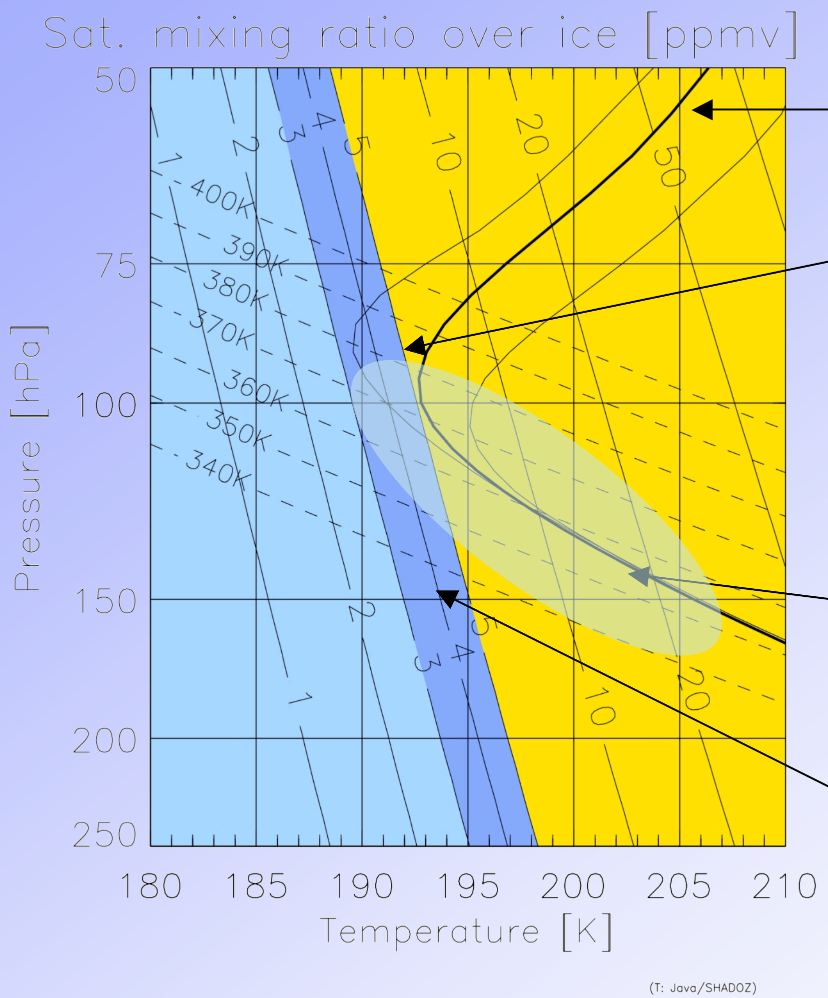
- heterogeneous chemistry on Polar strat. clouds ('ozone hole').

Radiation:

H_2O trend of 20 years leads to forcing of 0.29 Watt/m^2, strat.cooling of -0.8K [Forster and Shine, 2002]. Impact on tropospheric circulation [e.g. Joshi, Charlton, Scaife, 2006].

"Bottleneck" for stratospheric H_2O; **entry mixing ratio $[H_2O]_e$.**

The bottleneck for stratospheric H_2O



Tropical T-profile (Java).

Conditions at tropical tropopause.
(seasonal variation, absolute values?).

X10 !

Conditions around subtropical tropopause (quasi-isentropic exchange limited, transport barrier).

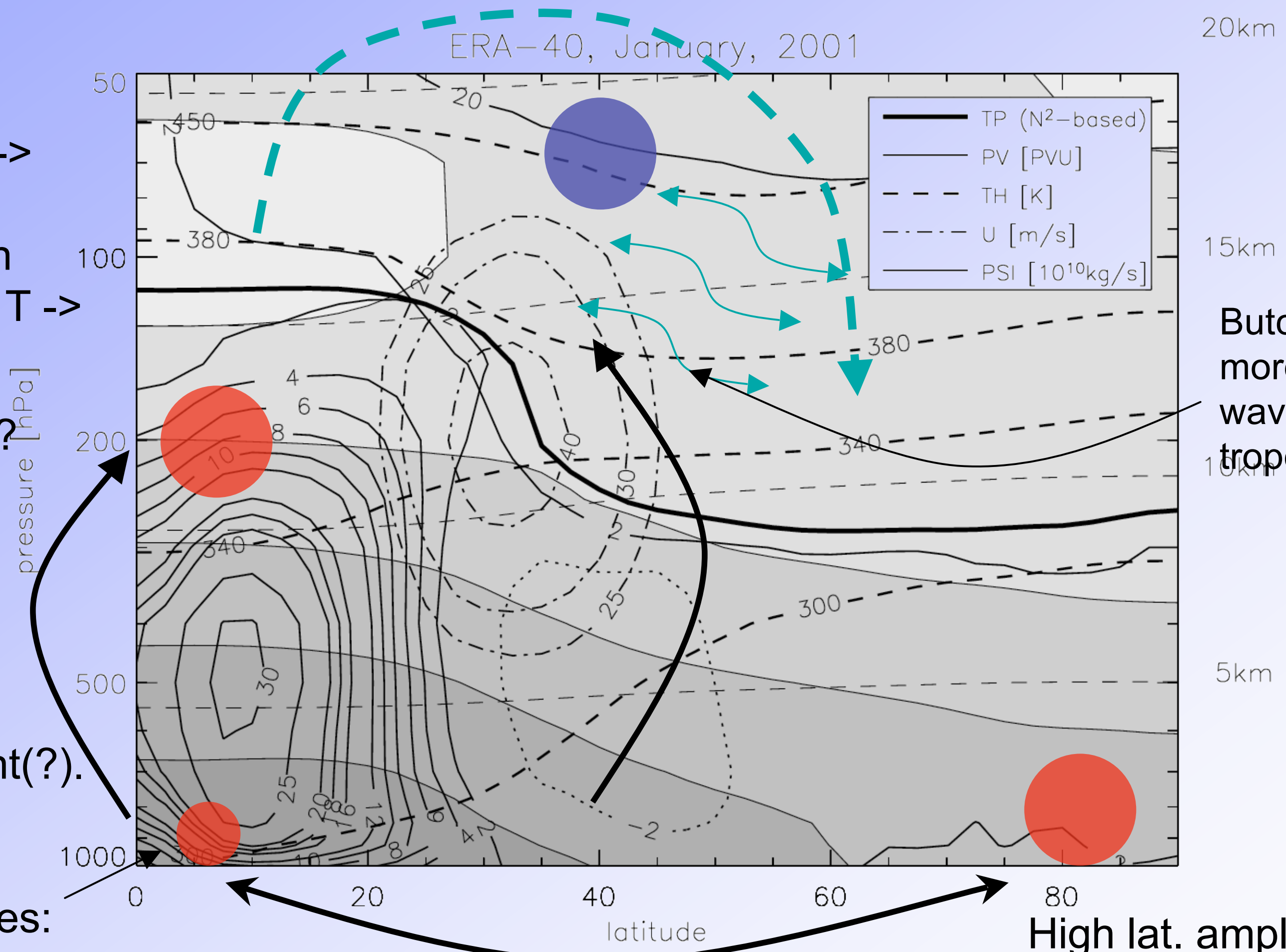
Observations in stratosphere: 3-5 ppmv.

Motivation: Increasing GHG …

… induce T changes (●, ●)

Strat. Circulation -> ozone -> feedback on tropopause T -> $[H_2O]_e$.

Q: ↗ or ↘ ?



Butchart&Scaife 2001: more GHG -> more wave driving; colder tropopause(?).

Moist adiabatic adjustment(?).

Q_e increases:
-convective height?
-CAPE?

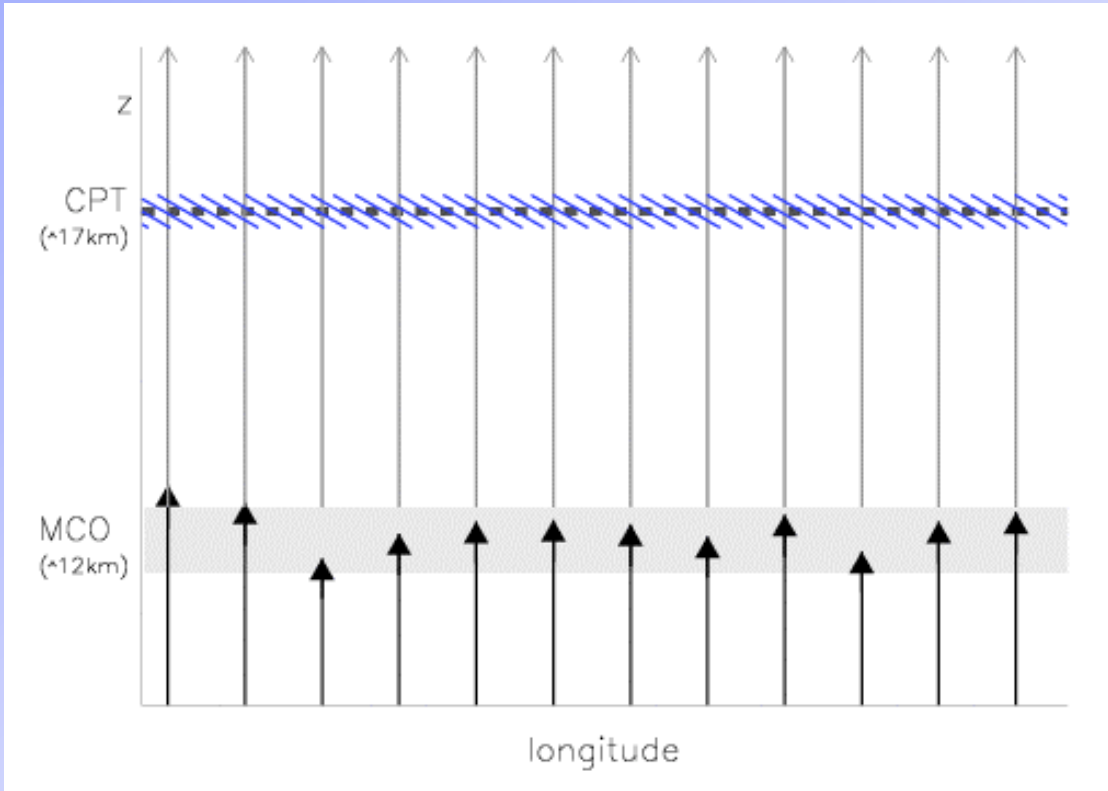
Lat. T-gradient decreases (?).

High lat. amplification (ice albedo feedbacks).

Water vapour content is closely tied to temperature history …

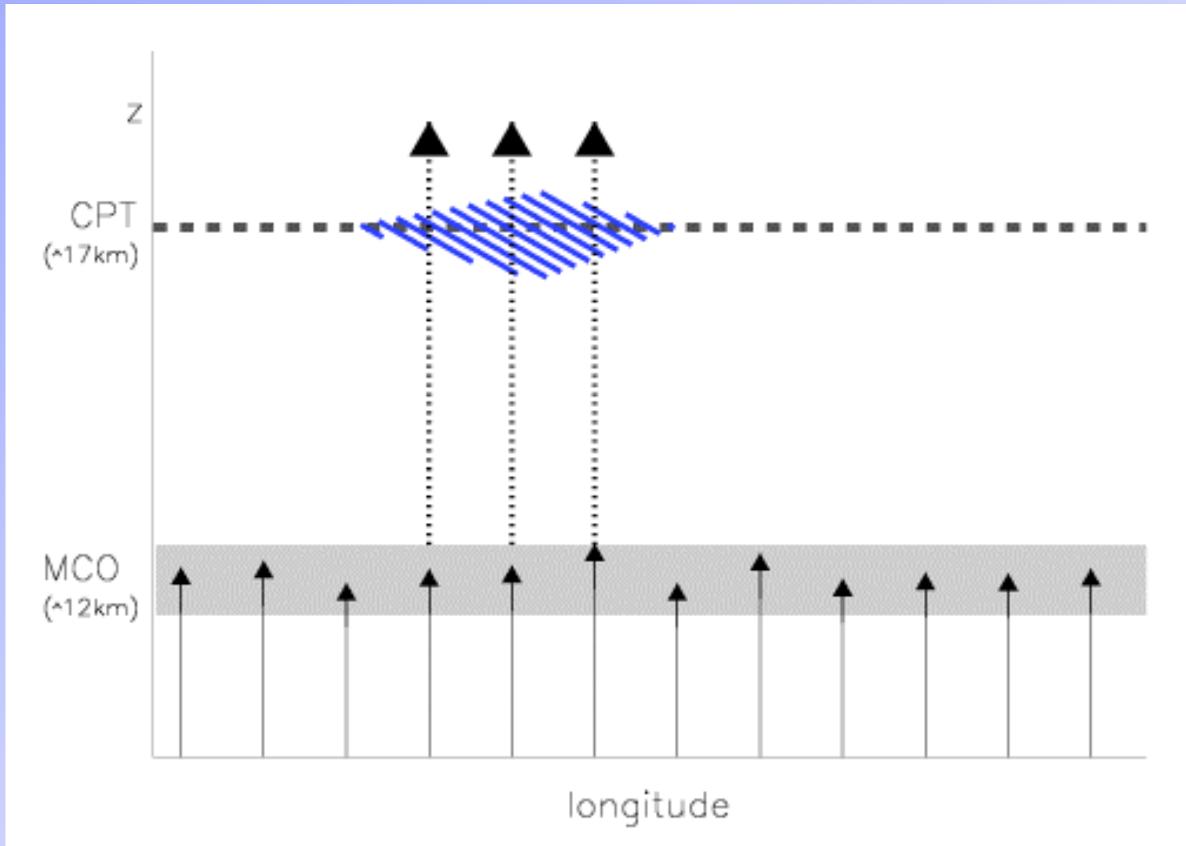
- …, and the latter is tied to ‘transport pathways’.
- Hence, information about one of the two may be used to constrain the other. (This mutual relationship has the potential to create great confusion!)
- Stratospheric H_2O is a classical example where attempts have been made to explain one of the two via the other.
- Stratospheric H_2O is also a simple case inasmuch as - in contrast to tropospheric H_2O - there is a clear coldpoint, and no further rehydration/dehydration in large parts of the stratosphere (apart from CH_4 oxidation). (Also: after passage through coldpoint mixing processes cannot change ‘global’ mean concentrations.)

Hypotheses of transport and dehydration: Brewer 1949



Deduces stratospheric circulation (entry in tropics) based on midlatitude stratospheric H_2O observations. No details about convection/large scale ascent etc.

Hypotheses cont.: Newell and Gould-Stewart, 1981

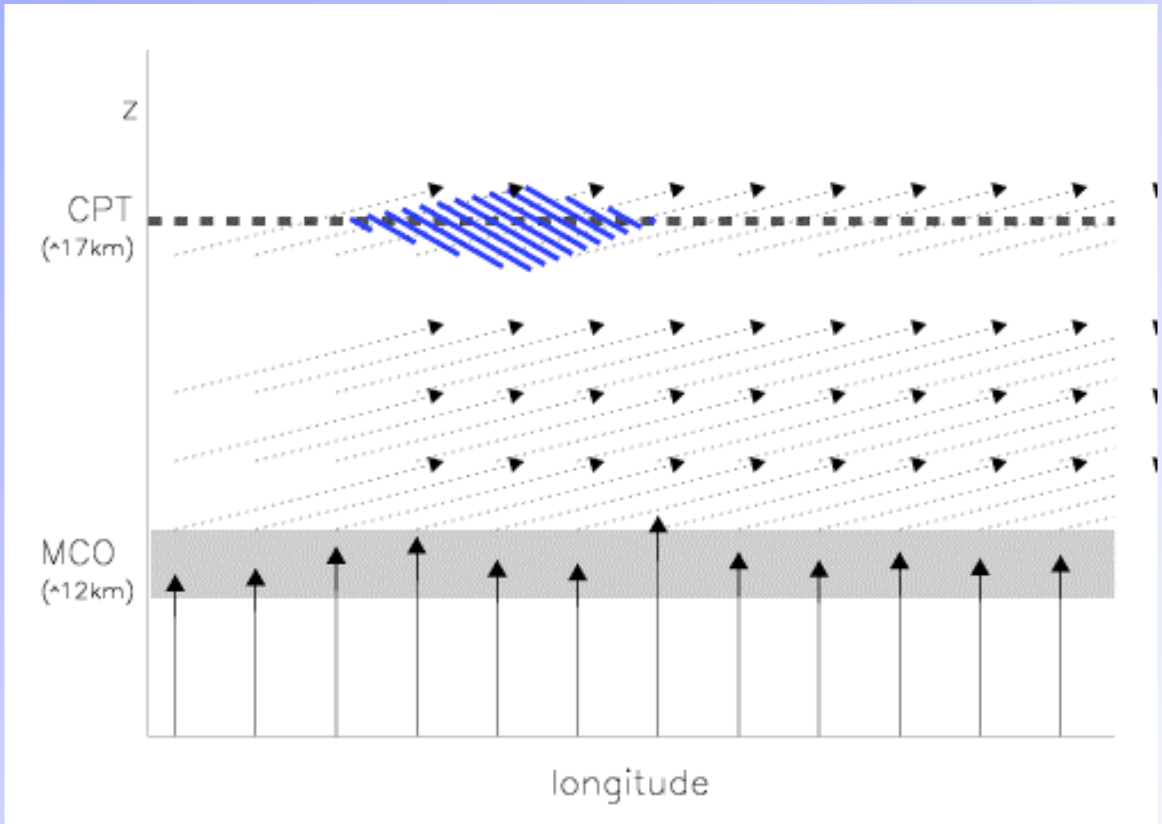


Say stratosphere is drier than expected from ‘typical’ tropopause T’s -> preferrential entry during times and areas of lowest T’s.

->’Fountain’.

What’s wrong: use of 100hPa T’s; physical mechanism for fountain NEVER substantiated. But: there may indeed be zonal asymmetries in upwelling.

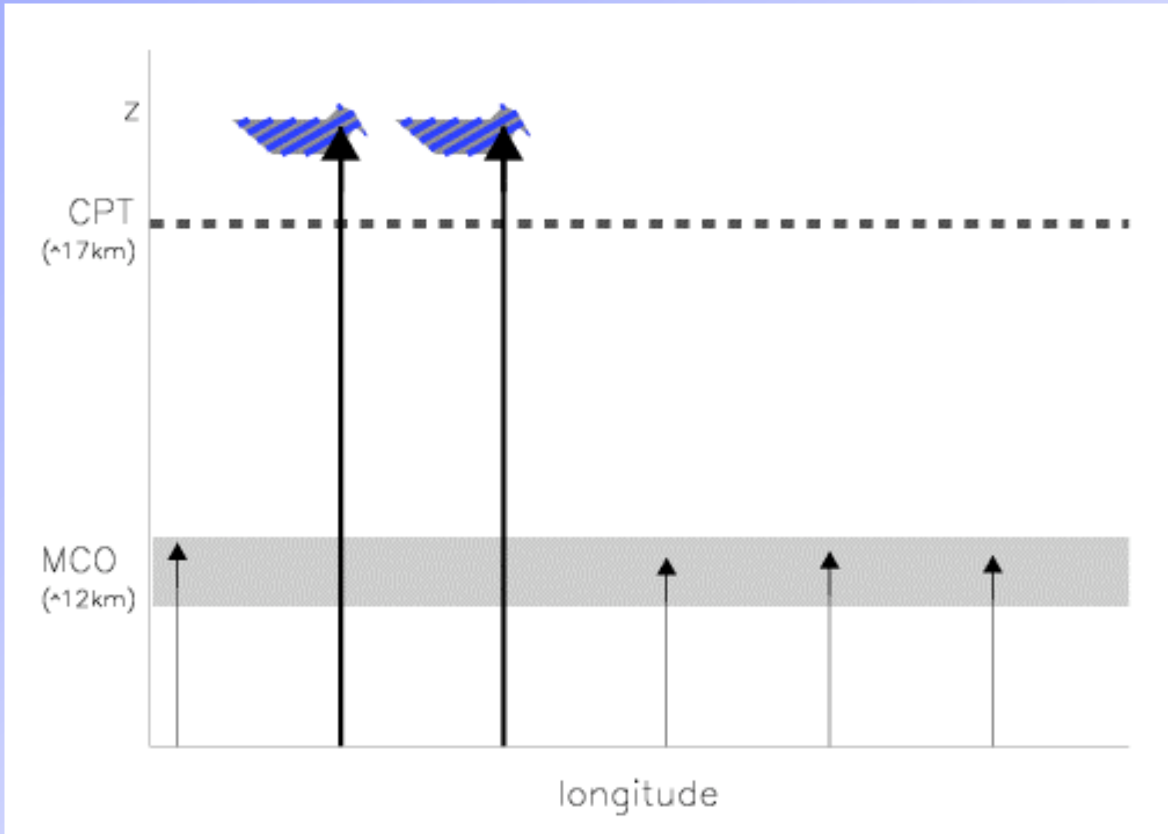
Hypotheses cont.: Holton and Gettelman, 2001



Modification of NG81: horizontal transport instead of vertical ensures exposure to low T's.

Simple model (distance-height) to illustrate the point.

Hypotheses cont.: Danielsen 1980’s-90’s

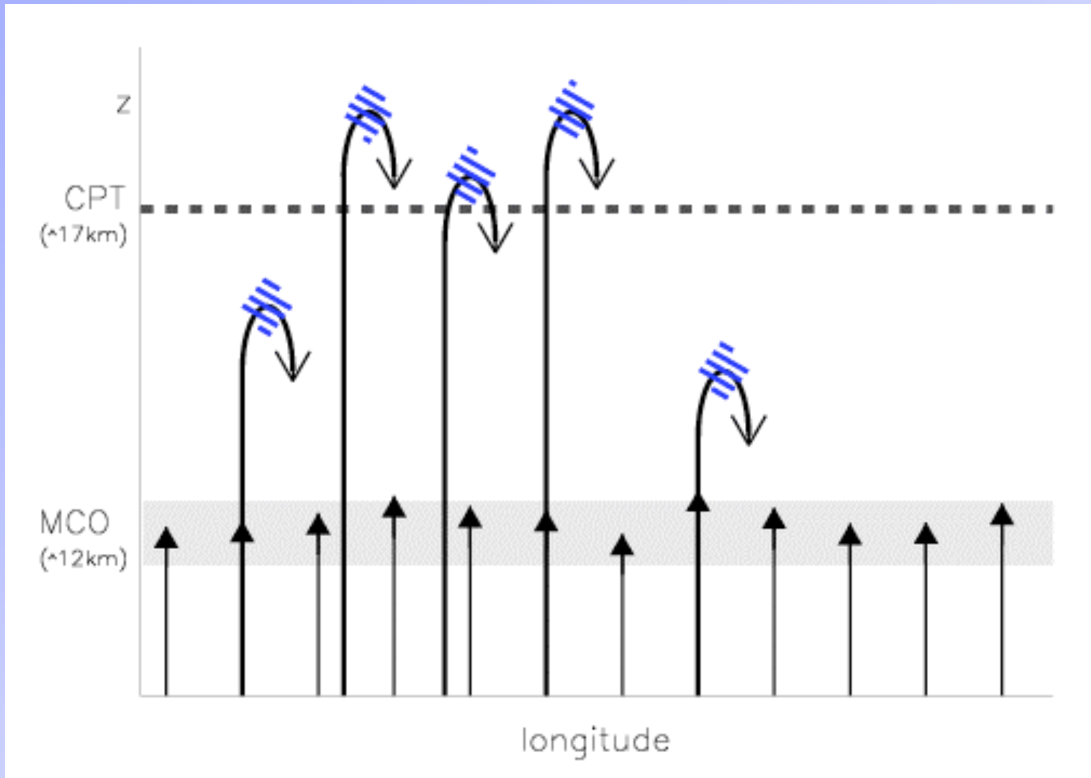


Radiatively driven circulation (and cooling) in clouds in lower stratosphere produce dehydration

‘Hygropause confusion’ - natural explanation by Mote et al., 1995.

Stratospheric drying also in Potter and Holton 1994 due to gravity waves. Pre-tape-recorder paper, increasing T’s in lower strat. make it increasingly unlikely that frostpoint is met again.

Hypotheses cont.: Sherwood and Dessler, 2001

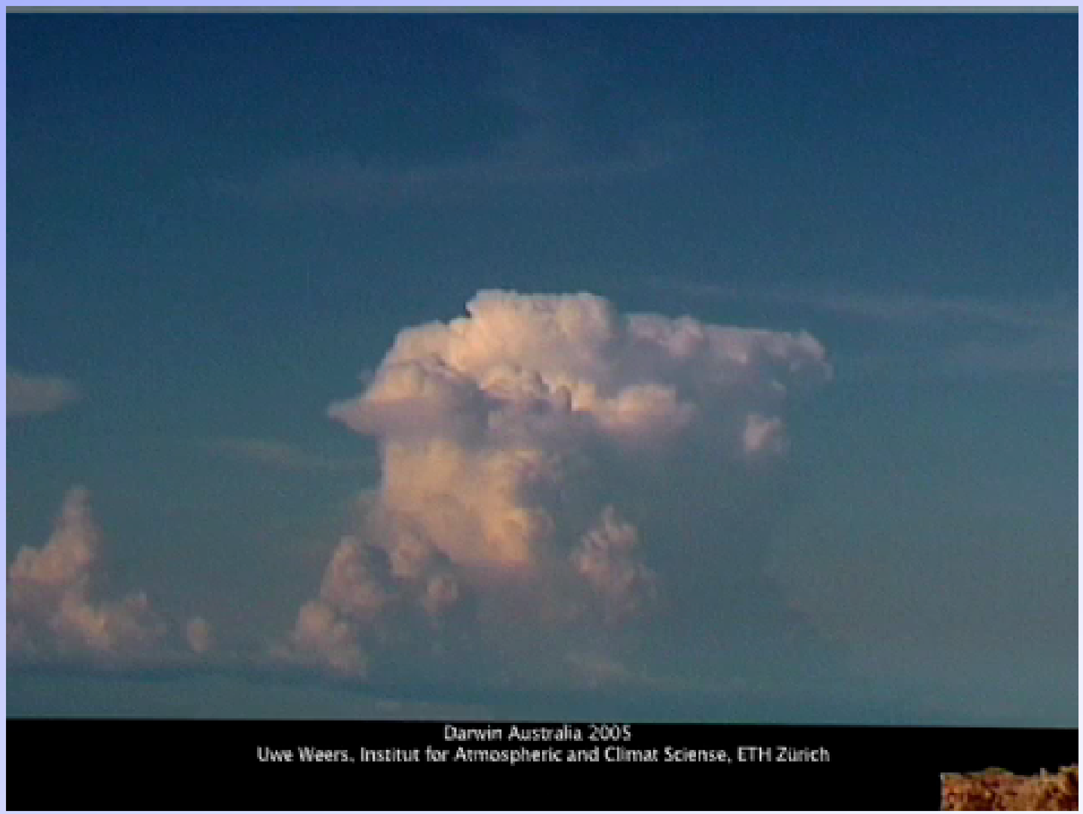


Overshooting (over LNB) convection has the potential for very dry air. This overhoot is supposed to mix with ambient TTL air, leaving air often subsaturated even at ‘coldpoint’.

Control of $[H_2O]_e$

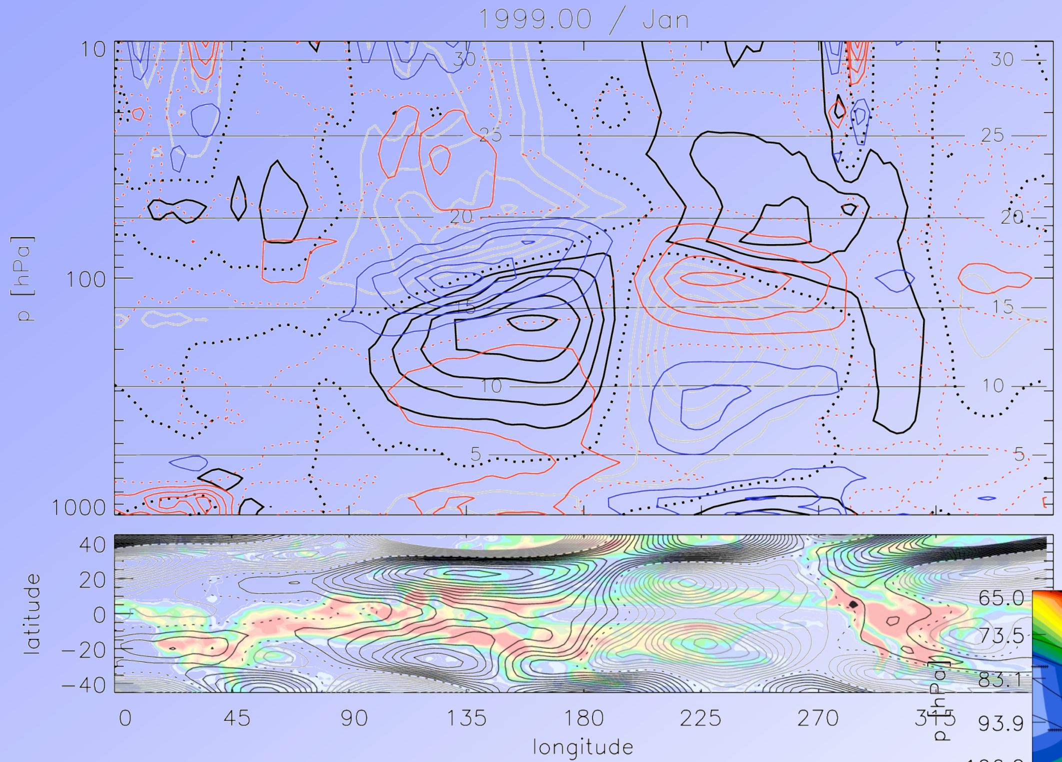
- Hypotheses are all based on idealized models. What is needed is a model with global T's and transport as close to the real atmosphere as possible, then we can quantify match/mismatch.
- (Re-)Analysis data seems the natural choice. Caveat: known deficiencies for example in representation of convective transport.
- To predict $[H_2O]_e$ one needs to know: T-history, cloud microphysics (nucleation, sedimentation efficiency etc.), transport pathways (global scale, convective vs. radiative ascent).

The big unknown: Deep convection

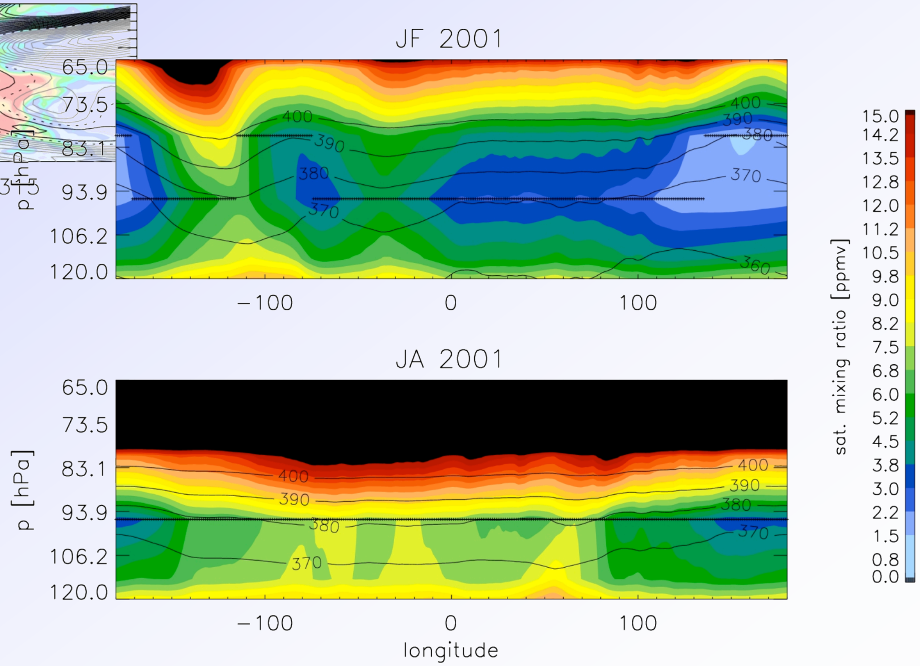


Direct (detrainment) and indirect effects (waves); both are a challenge, particularly in TTL where approx. all terms of heat balance eqn. are of same order (more later).

The zonal structure



Zonal T-anomalies (red,blue) and geopot. height anomalies (black, grey). Upper level Rossby and Kelvin waves as response to localized tropospheric heating [e.g. Gill, 1980].



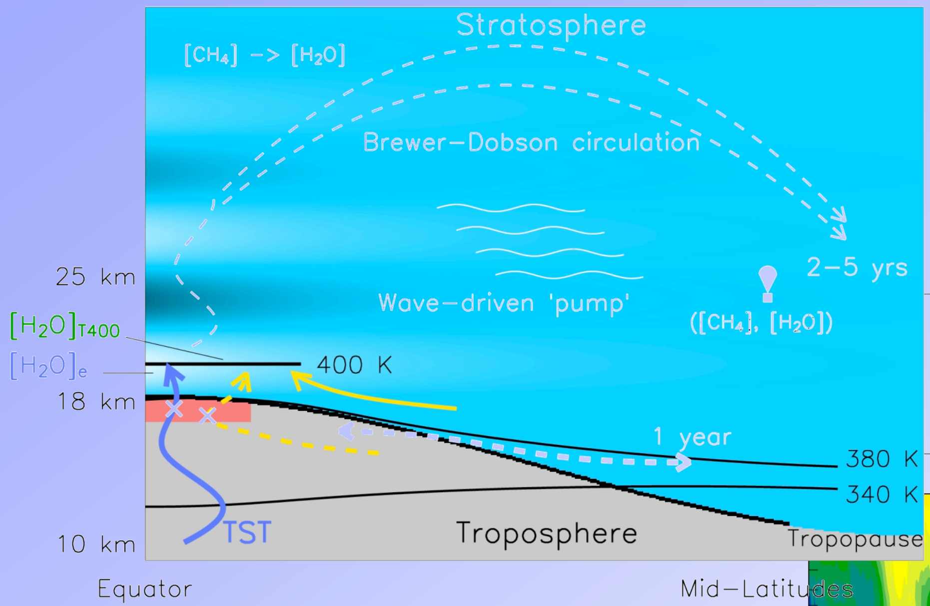
Zonal structure of **saturation** mixing ratio in tropics.

A quantitative approach …

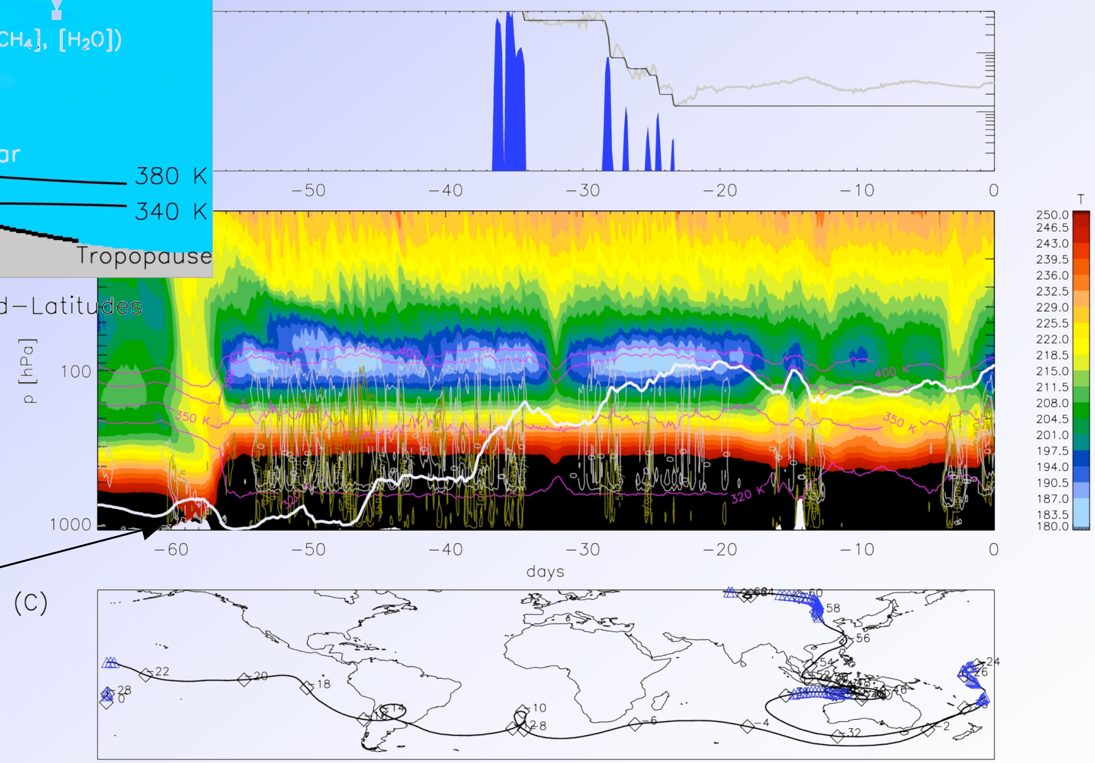
Predict [H2O]e based on (re-) analysis data (much improved vertical resolution, realistic tropopause T's).

- Use trajectories to track pathways.
- Begin with simplest cloud microphysics (nucleation at saturation, complete fall-out).
- Compare with observations: evidence for missing processes?

Method

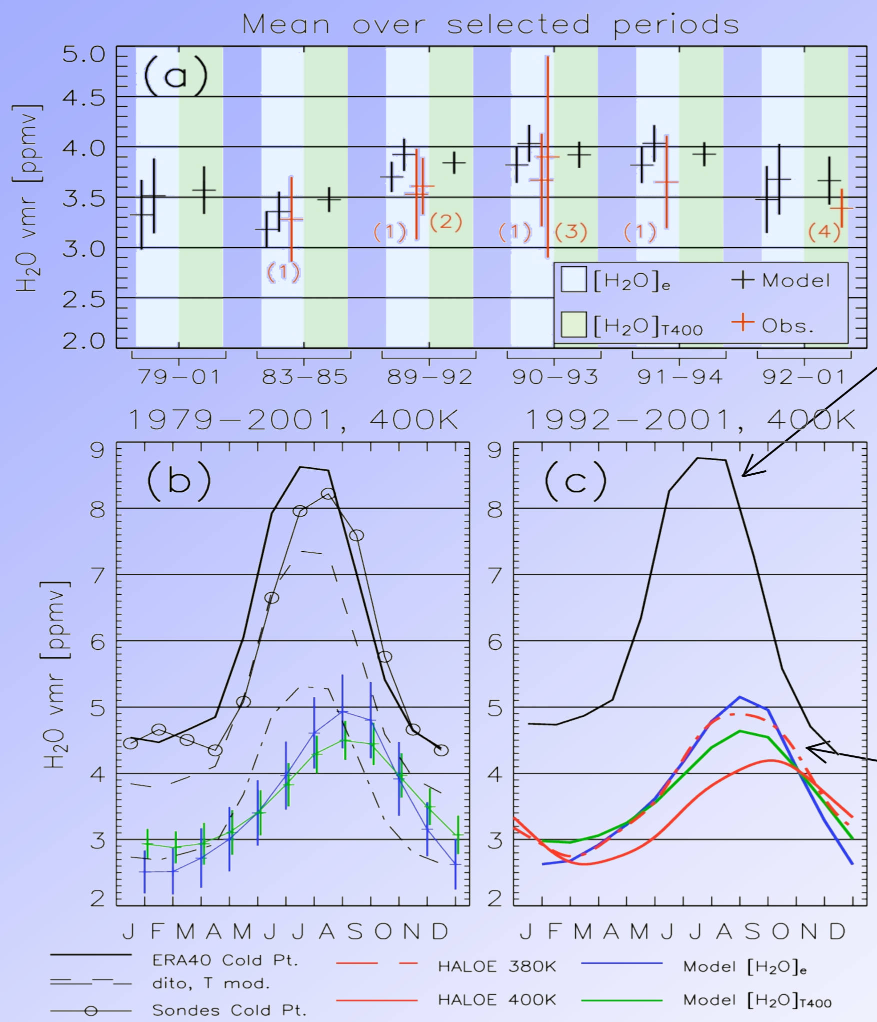


Schematic [Fueglistaler et al., 2005]



Sample trajectory (ECMWF op. analysis, 3hr)

Results: Seasonal cycle $[H_2O]_e$



Predictions of $[H_2O]_e$ from:

Tropical (5d time mean) cold point temperatures.

+ time variation

+ transport

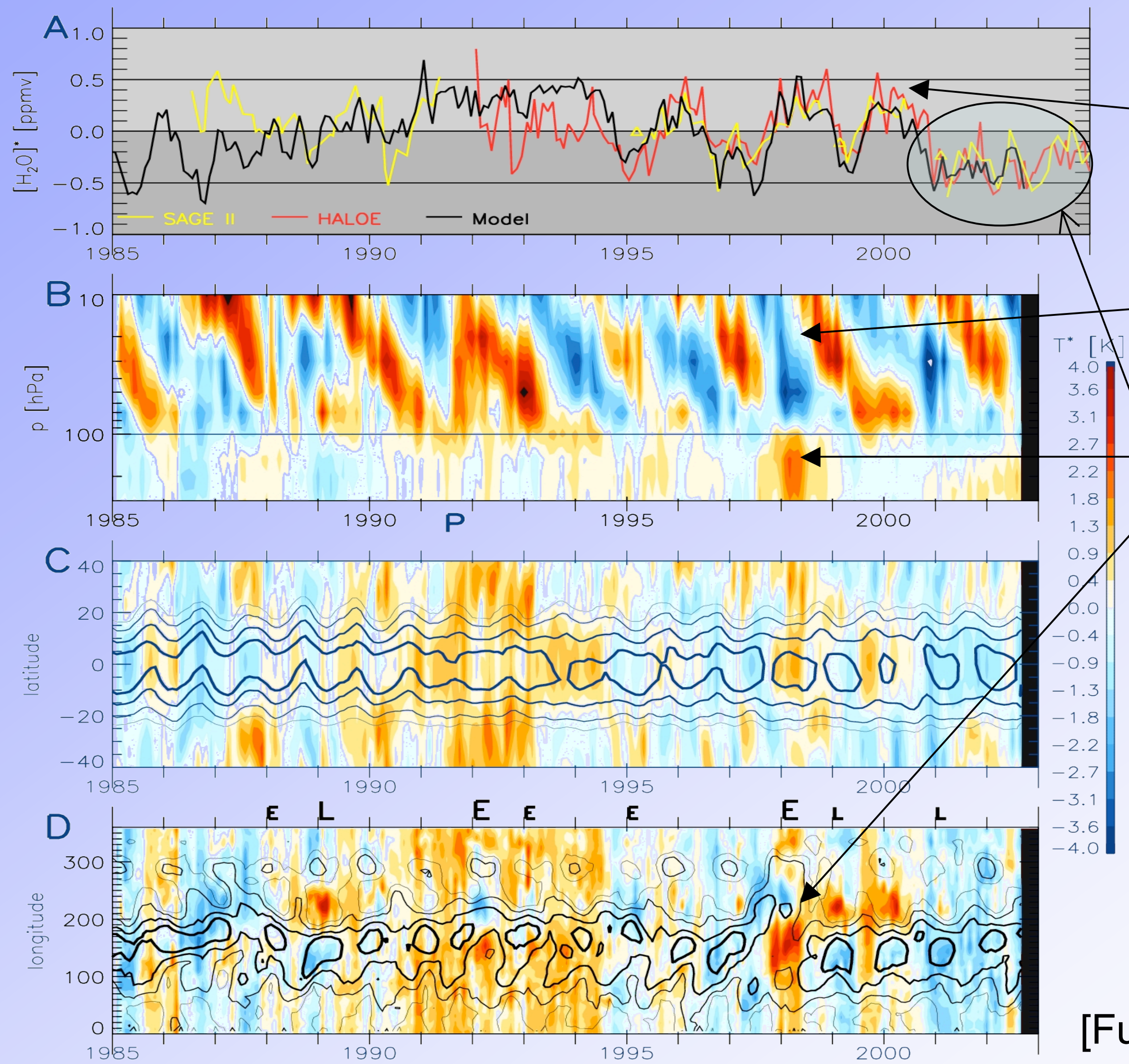
= Annual mean and seasonal variability to within 0.25 ppmv; small phase shift.

Model predictions.

Observations (HALOE).

[Fueglistaler et al., 2005].

Results: Interannual variability of $[H_2O]_e$



SAGE II, HALOE, MODEL

QBO

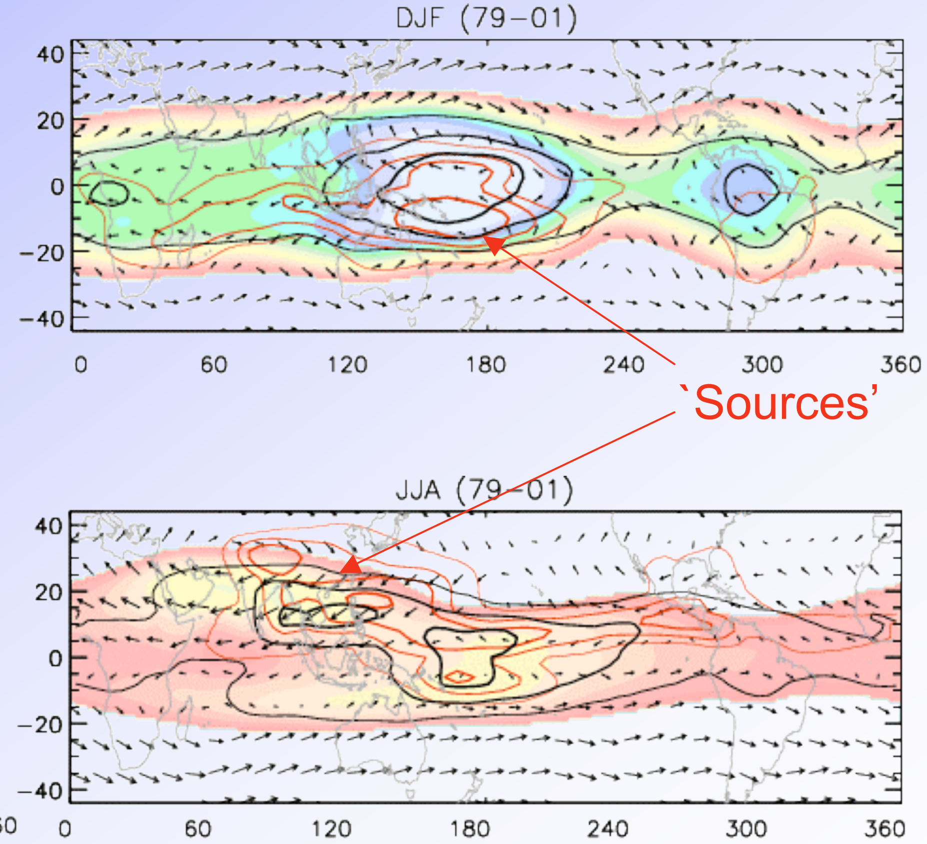
ENSO

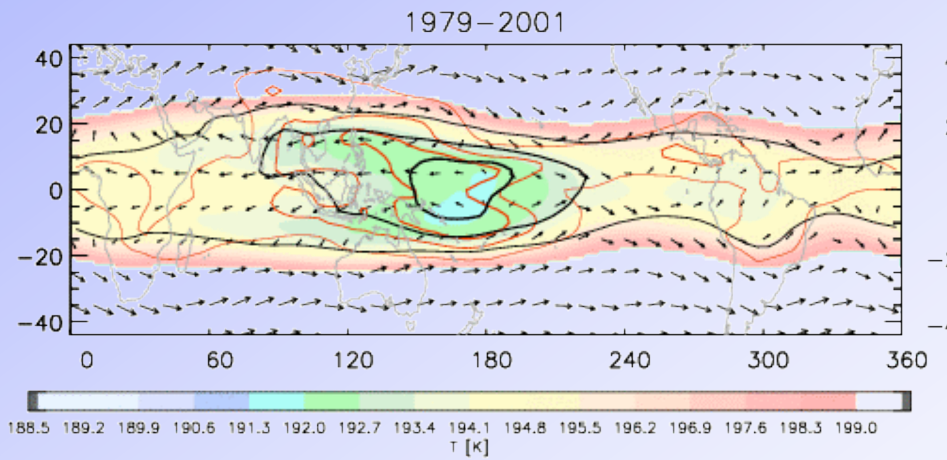
Dry phase since mid-2000 ('trend reversal'): **T-effect**, **Cause**? (QBO; BD?; Ozone?)

[Fueglistaler and Haynes, 2005]

Locations of entry into TTL and final dehydration

Entry into TTL (red contour lines) and final dehydration (black contour lines) are both localized, and show seasonal variability as expected from ITCZ/monsoons (fountains into TTL).





[Fueglistaler et al., 2005]

Pathways of TST

Measure? Using `boxes’ is not adequate.

-> total length of trajectory between entry into TTL and cold point, and the maximal zonal shift.

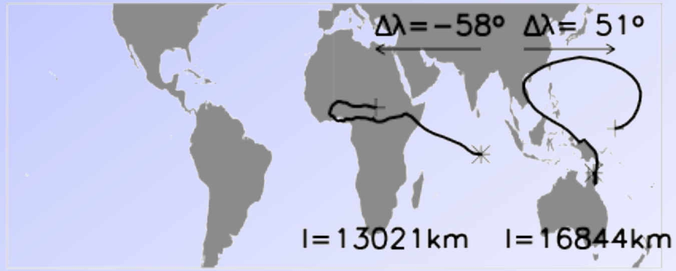
Results:

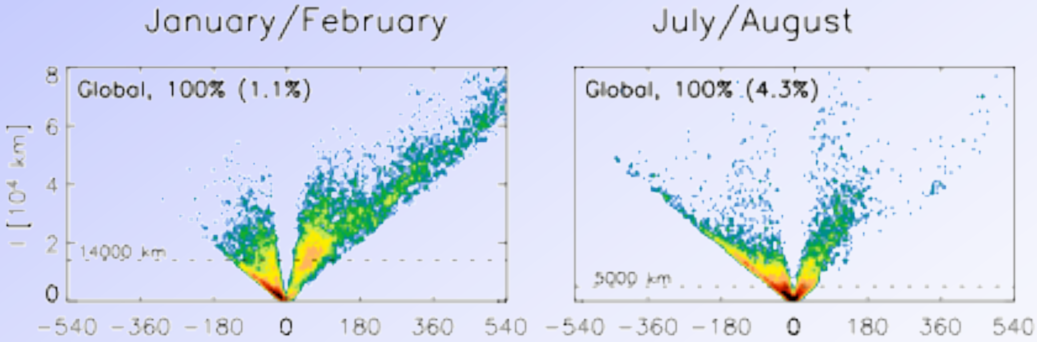
- Typically 5-10’000 km long.

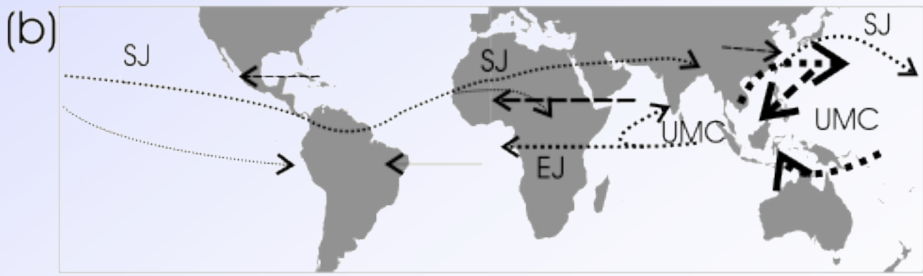
- Upper level monsoon circulations (UMC, anticyclones).

- Equatorial Easterlies (EJ).

- Subtropical jets (SJ).







[Fueglistaler et al., 2004]

Summary [H2O]e

- Systematic approach to describe pathways of tropical troposphere-to-stratosphere transport [Fueglistaler et al., 2004; Bonazzola and Haynes, 2004].
- Physical predictions of $[H_2O]_e$ and its seasonal and interannual variations [Fueglistaler et al., 2005; Fueglistaler and Haynes, 2005] yields good agreement with observations on global scale.
- Variations highly correlated with tropical mean tropopause T's, 'trend' not explained.
- Transport: 'TTL fountain' [Fueglistaler et al., 2004] over Western Pacific (supplies about 70% of strat. air). Real or model/assimilation artefact?

-> Analysis data seems to predict [H2O]e quite well -> 'good' temperature fields, transport good … but: how good? It may be that overshooting convection is NOT crucial for [H2O]e, and hence conclusions on transport may be premature.

- Are there other observations that could constrain TST?

Age of air

`Age of air’ is zero at the tropical tropopause by conventional definition.

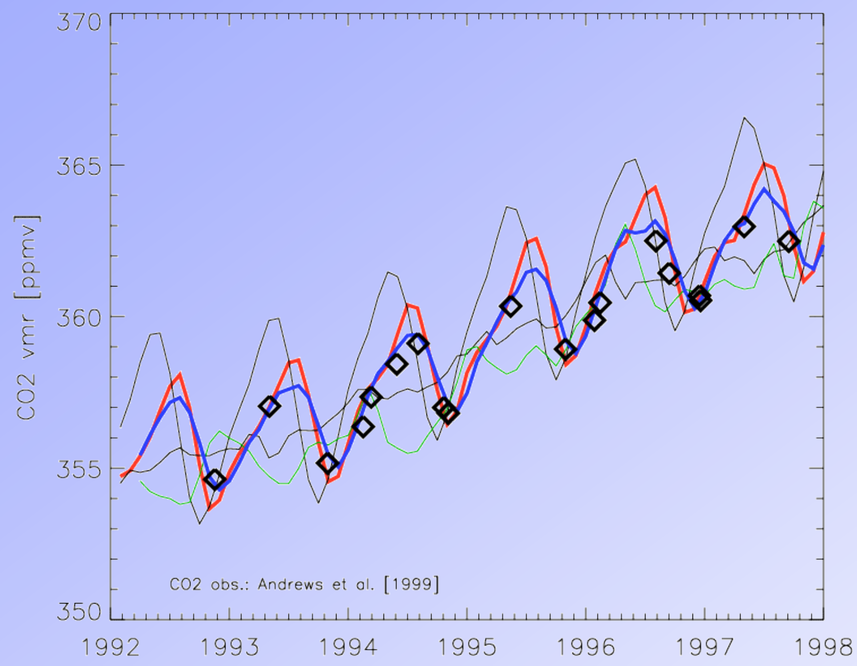
But: Observations e.g. of CO_2 suggest a time lag between boundary layer and tropopause of order 2 months [Boering et al. 1994, and others].

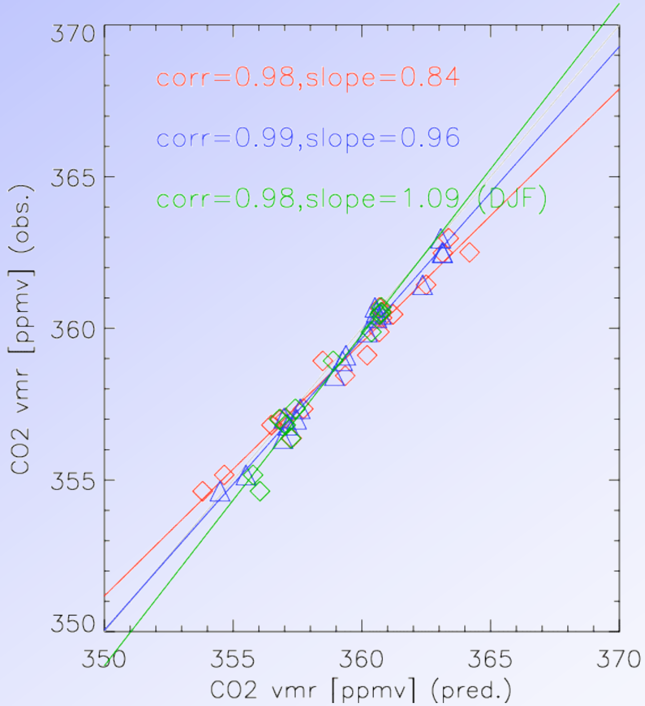
-> This may be indicative of (vertical) transport processes (suggestive for ‘slow ascent’, but Sherwood and Dessler show that it also works with deep convection …)

-> Adjust definition of `age’ to time e.g. elapsed since free troposphere, assuming there is a transport regime change at the base of the TTL.

(Reality: probably continuum …)

Carbon dioxide at tropopause



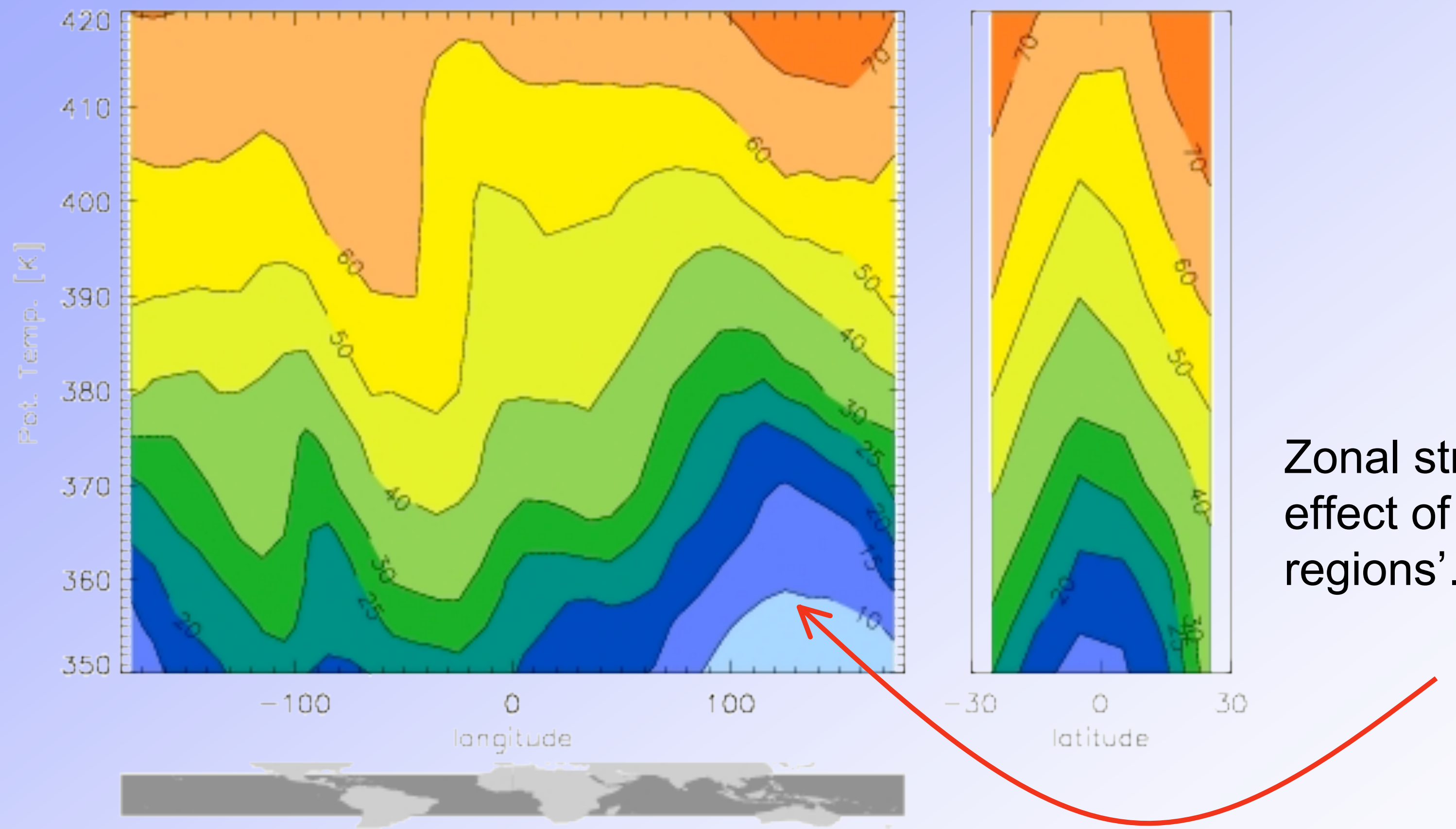


- The Boering et al. fit (blue) uses unrealistic boundary conditions (avg. of Mauna Loa/Samoa, recall ‘source regions’).
- Surface observations (not shown) at Christmas Island (green) cannot be reproduced.
- Simple model using trajectories (red) yields worse agreement.

-> Better surface CO_2 description necessary for conclusions.

Age of air from trajectory calculations

(boreal winter)



Zonal structure: effect of 'source regions'.

(Operational analysis data, 3hr wind fields)

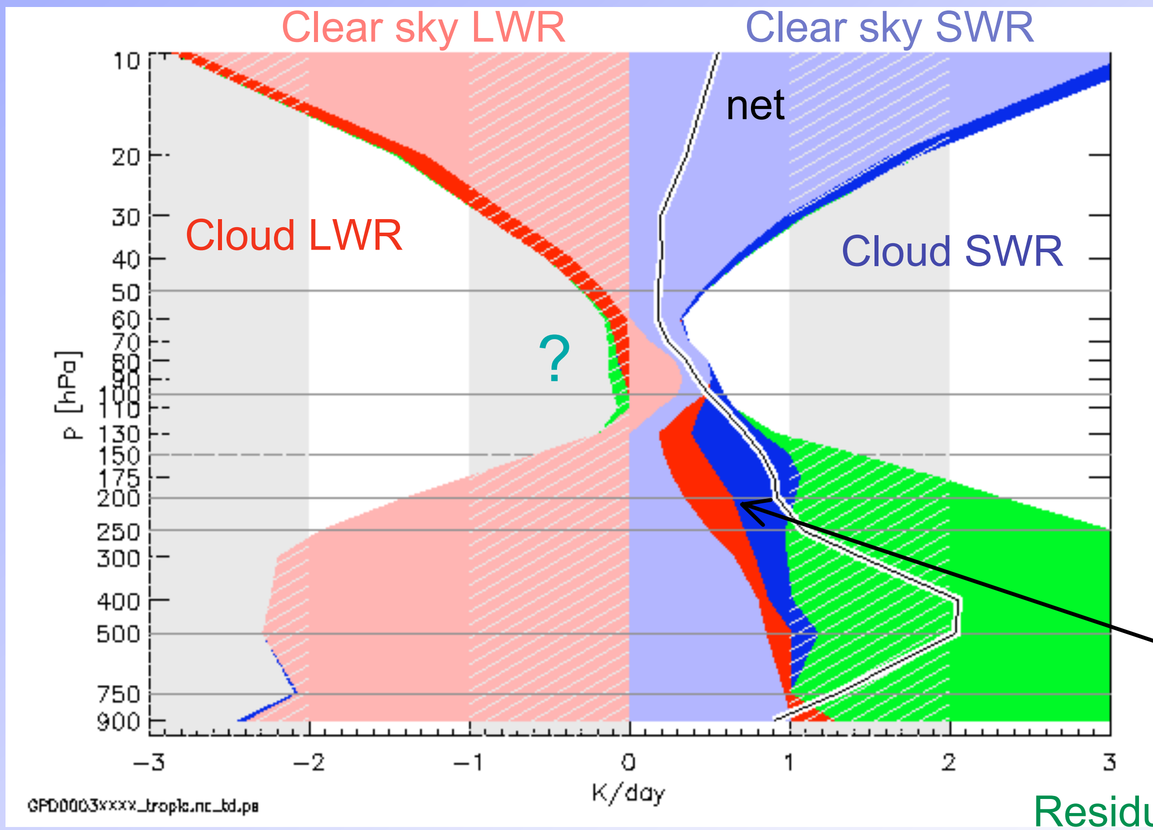
The heat balance in the TTL

$$\mathrm{d}T/\mathrm{d}t - Q/c_\mathrm{p} + v\nabla T - \omega\left(\kappa T/p - dT/dp\right) = 0$$

Diabatic terms Q: $Q_{\text{rad-clear}} + Q_{\text{rad-cloud}} + Q_{\text{latent}}$

TTL: Transition from (moist) convective regime in troposphere to radiatve regime in stratosphere. If (modelled) transport across TTL is supposed to be realistic, then so must be the terms of the heat balance.

The heat balance in the TTL: Diabatic terms in ERA-40 model



Stratosphere:

Radiation, small cloud effect (see also Fueglistaler and Fu, 2006)

TTL:

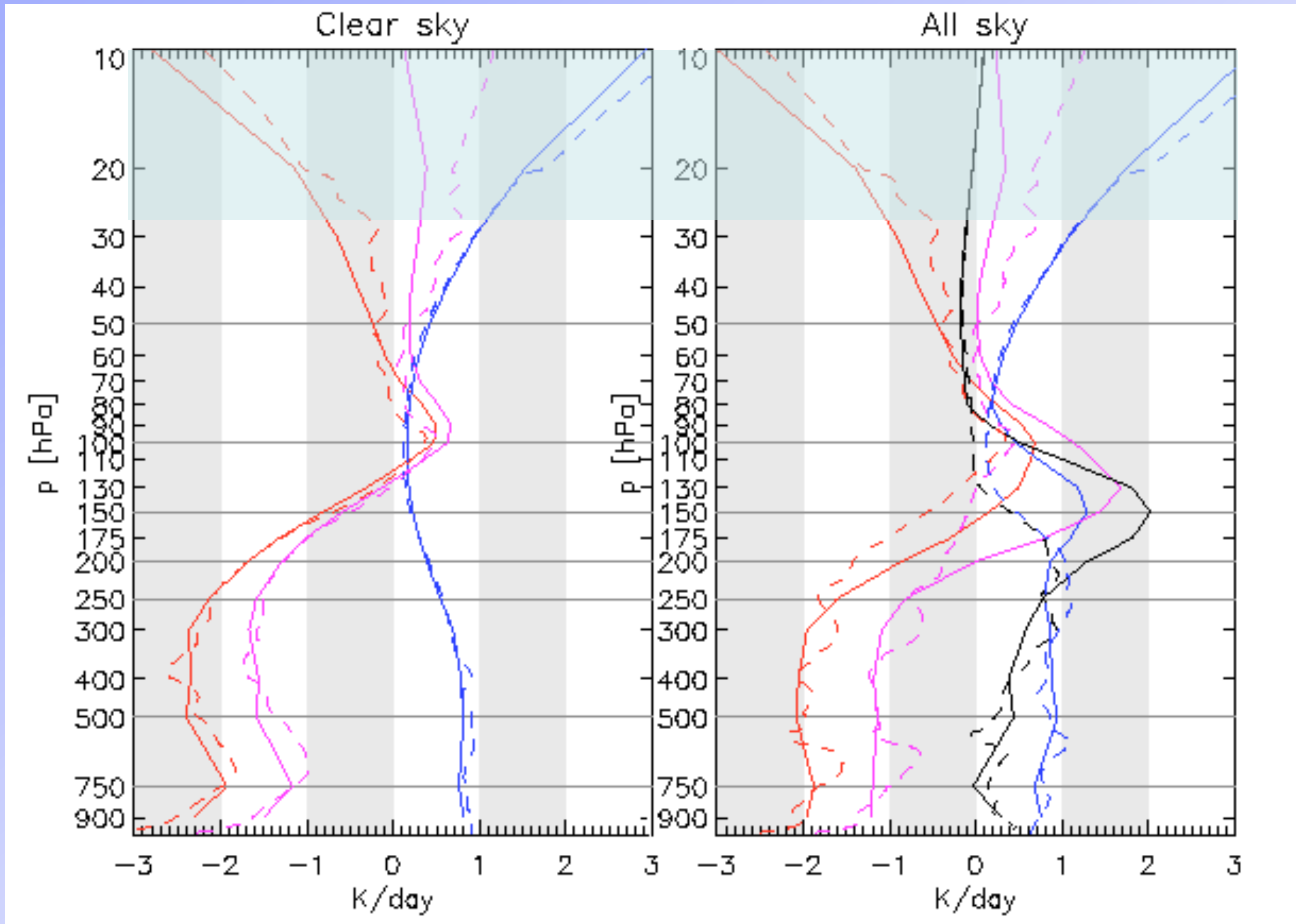
Top: radiation (plus weird sink!); base: **all terms similar order**.

Very large cloud radiative effect!

Residual = latent heat, diffusion, …

(March 2000, tropical average 10S-10N)

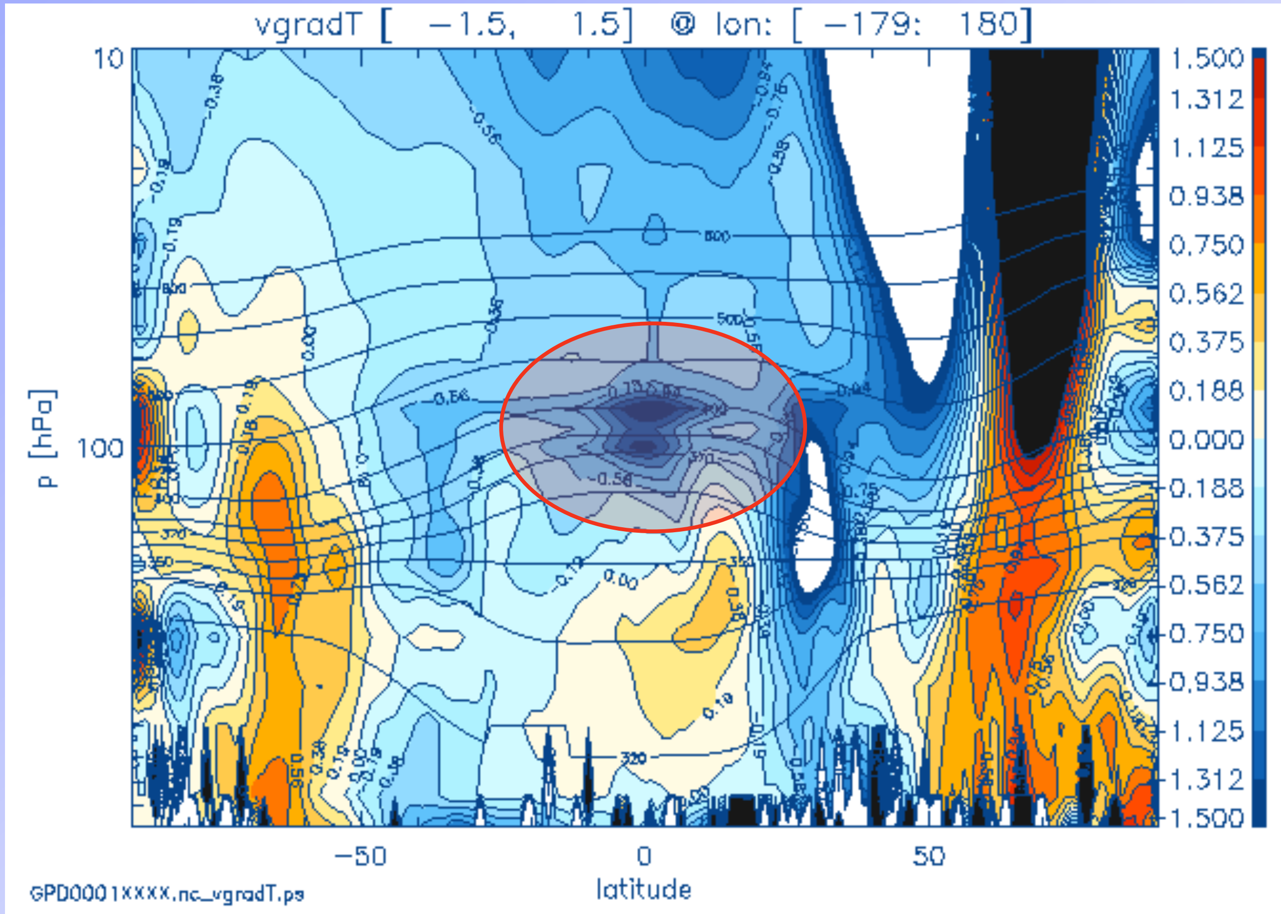
The radiative heat balance over tropical Western Pacific



LWR, SWR, total, cloud.

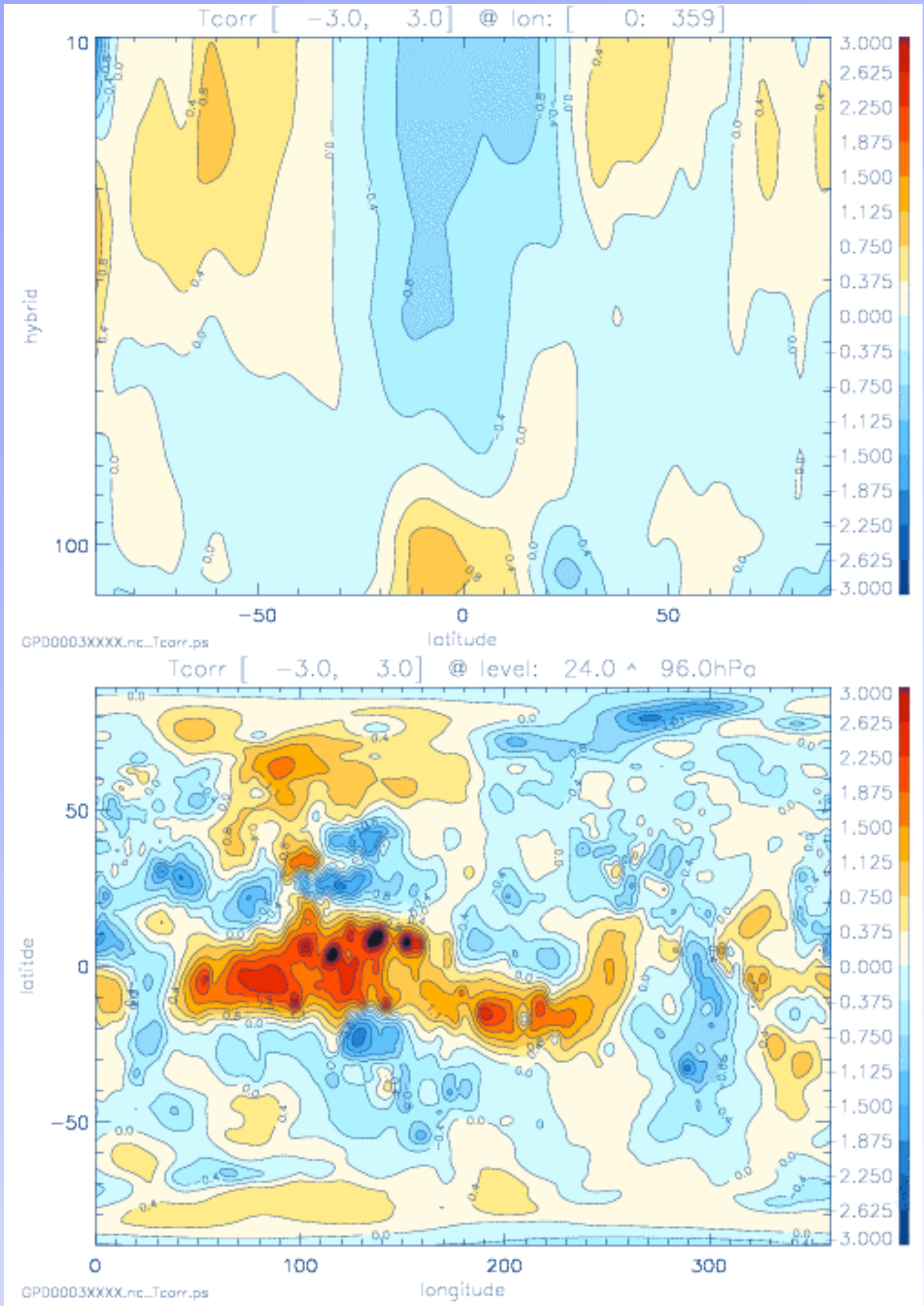
ECMWF (solid) comparison with Fueglistaler and Fu [2006] calculations (dashed) for Manus (clouds from radar).

Horizontal advection



At tropopause, Vgrad(T) is of order 1K/day, same order as radiative terms.

Zonal mean -V*grad(T), January 2000, ERA-40



The trouble with the heat balance in assimilated data (preliminary)

Assimilation increment (assimilation - forecast) is a large term in the heat balance. Clear correspondence to convection.

Summary

• High quality temperature fields from assimilated data allow to predict $[H2O]_e$ and to **quantify** discrepancies to observations.

•$[H2O]_e$ to within 0.25 ppmv of observations, seasonal and interannual variability. (+)

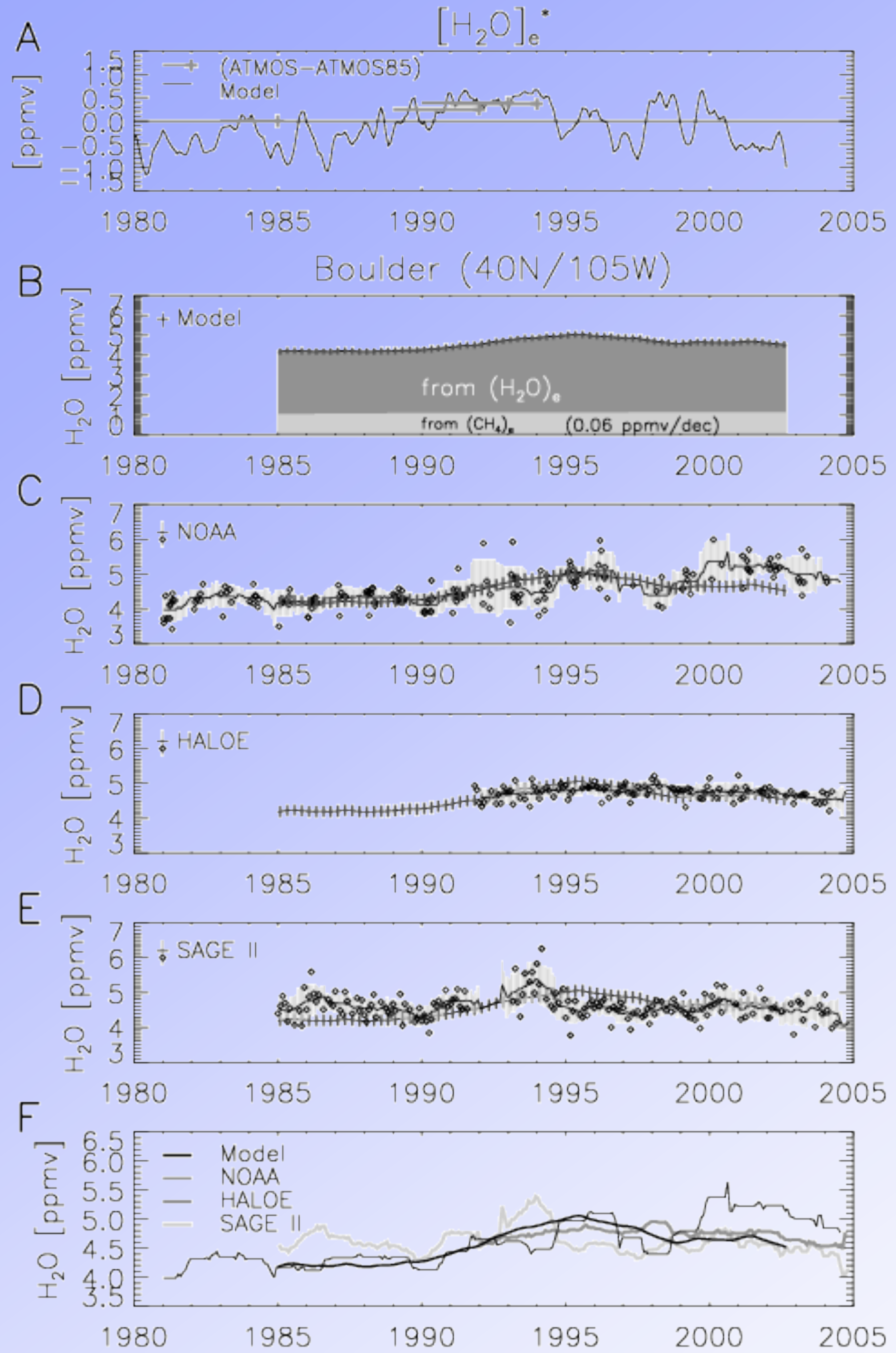
• [H2O] phase problem at 400K (method). (-)

• Proposed long term trend not seen. (?)

• Other tracers may be needed to constrain transport pathways, e.g. CO_2 and ‘age of air’.

•The heat balance in the TTL requires our attention: all terms are of same order, and model calculations that do not take the global TTL structure into account may NOT allow conclusions. What can we learn from assimilation increments?

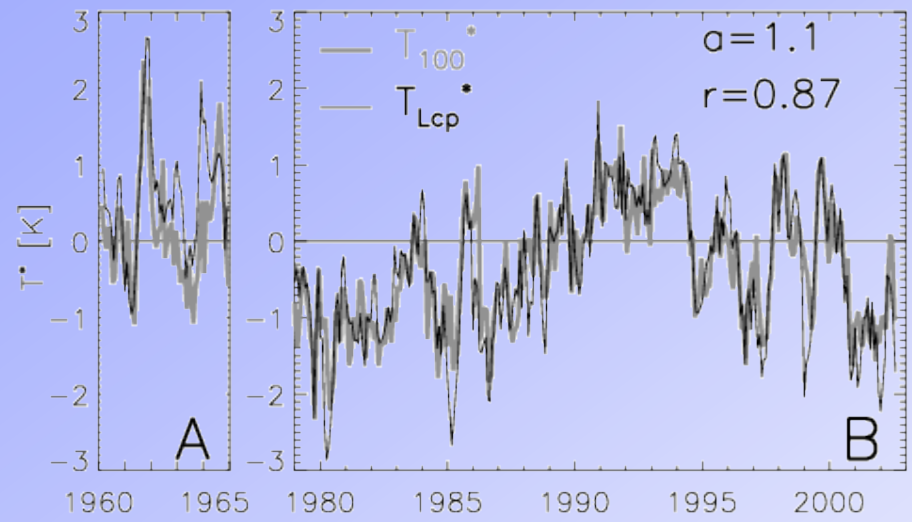

Thank you.

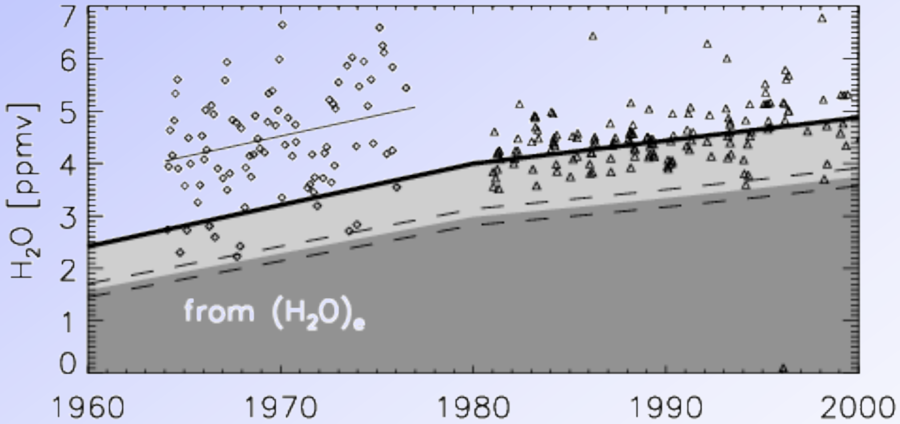


H2O over Boulder, CO

[Fueglistaler and Haynes, 2005]

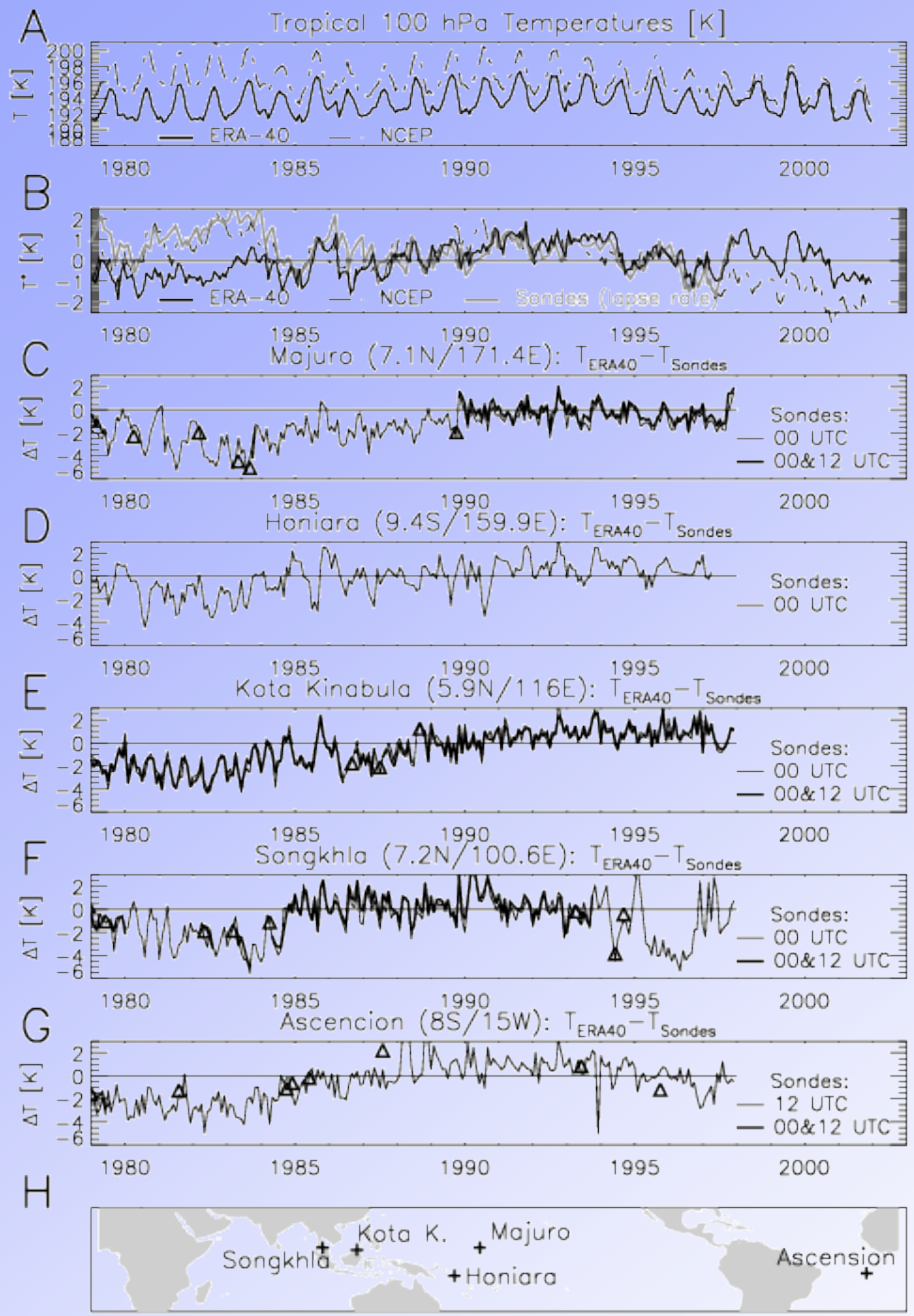
The stratospheric H2O trend





[Fueglistaler and Haynes, 2005]

ERA-40 temperatures



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