The Diabatic Heat Budget of the Upper Troposphere/Lower Stratosphere

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Outline

PART I: Introduction & Motivation

PART II: Results

- ERA-Interim, ERA-40
- Comparisons

PART III: Summary and Outlook

PART I: Introduction and motivation

The (zonal mean) thermodynamic energy equation

$$\underbrace{\mathrm{d}T/\mathrm{d}t}_{\text{Temperature tendency}} - \underbrace{Q/c_{\mathrm{p}}}_{\text{Diabatic terms}} + \underbrace{v\nabla T - \omega\left(\kappa T/p - dT/dp\right)}_{\text{Advective terms}} = 0$$

Advective terms

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

Temperature tendency

+ Diffusion and turbulent mixing.

Stratospheric Heat Balance

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

Diabatic terms dominated by radiation: Clear sky rad. transfer calculation + effects of (underlying) clouds.

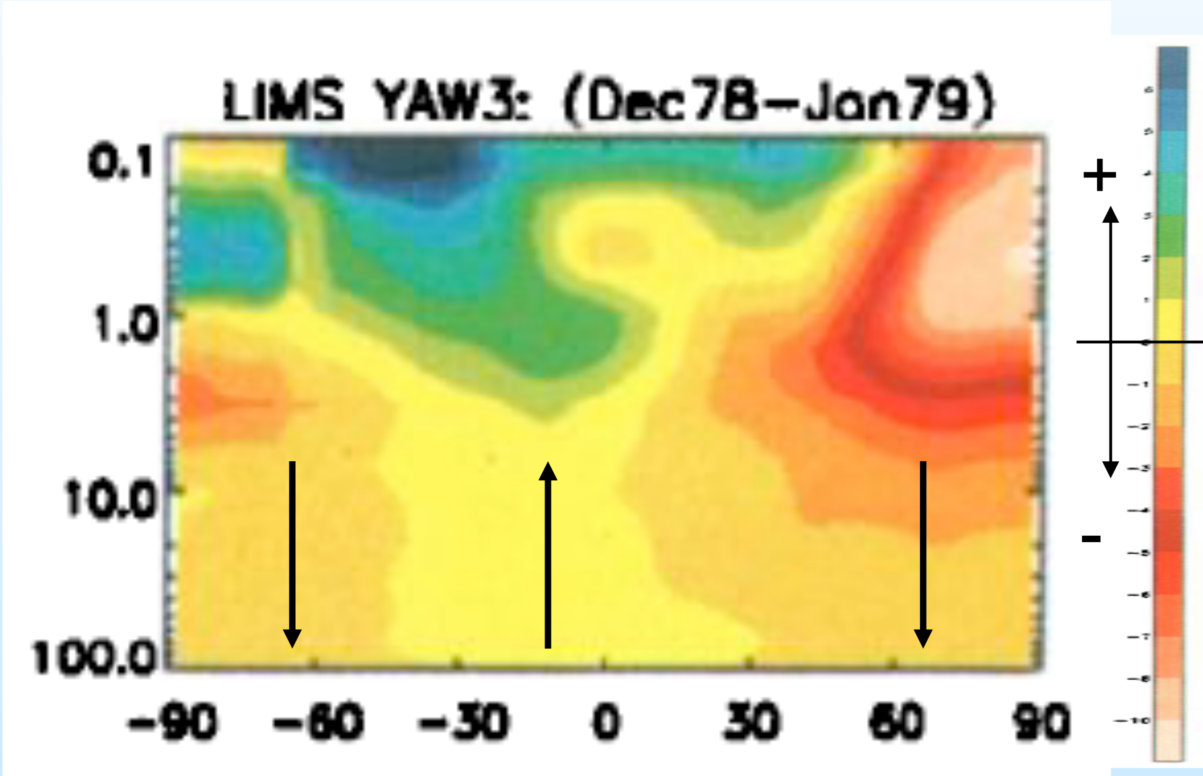
Requires: accurate temperature and tracer profiles, rad. transfer code.

TEM framework: Q <-> w*

Stratospheric Heat Balance

Extensive literature
(selected):

- Kiehl and Solomon 1986, Solomon et al. 1986.
- Gille and Lyjak [1986, 1987]
- Olaguer et al. 1992
- Mlynczak et al. 1997.
- …



[Mlynczak et al. 1997, from plate 2]

Focus typically on stratospheric overworld (i.e. p <= 100hPa).

Transition from Troposphere to Stratosphere

Focus on `entry' region - TTL etc. gate to the stratosphere for tracers (H2O, VSLS)

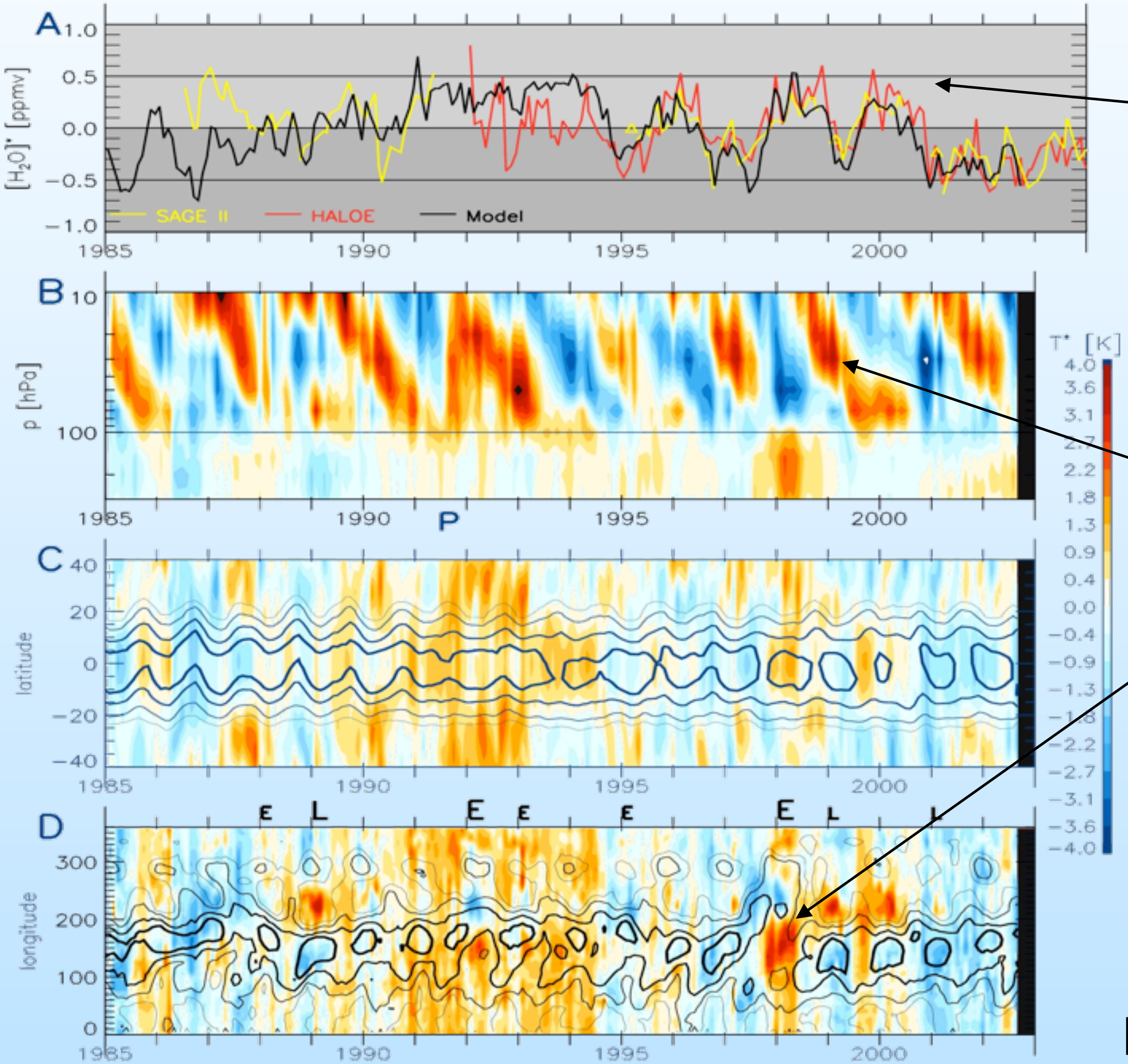
"Never ending" debate: Role of convection.

Best available data for interpretation/analysis of observations (remote & in situ): assimilated meteorological data - widely used (Eulerian /Lagrangian studies), but issues with resolved scales etc.

Why we are interested in understanding the heat balance of the TTL:

For example stratospheric water vapour.
(Plus many other …)

Interannual variability of stratospheric water $[H_2O]_e$



SAGE II, HALOE,
MODEL

Variations well understood - we see the effects of

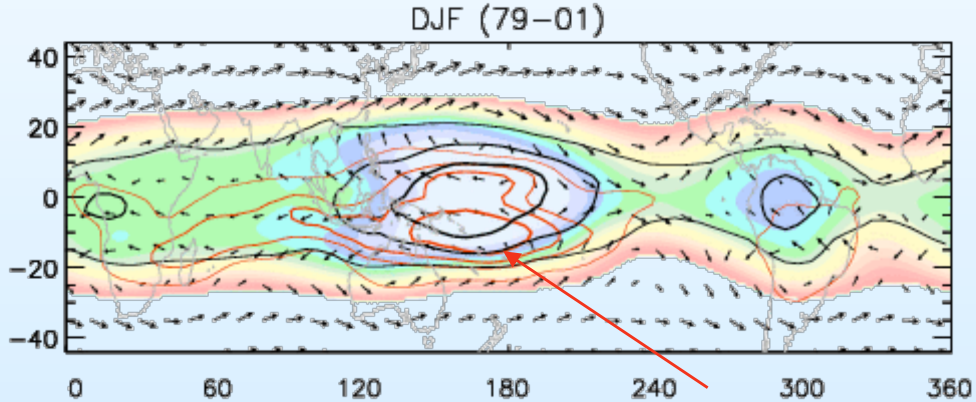
- QBO
- B-D
- ENSO
- Volcanoes

on temperature and circulation in the TTL, which control stratospheric water.

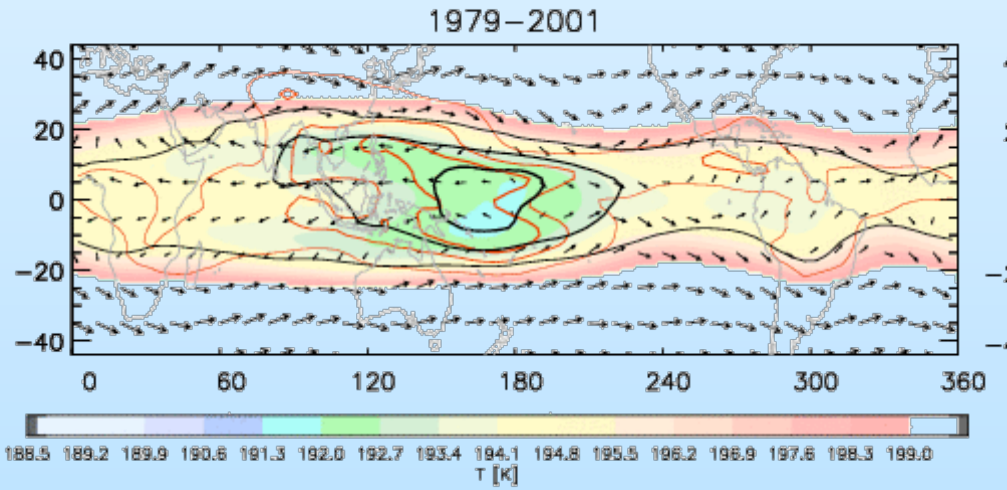
[Fueglistaler and Haynes, 2005]

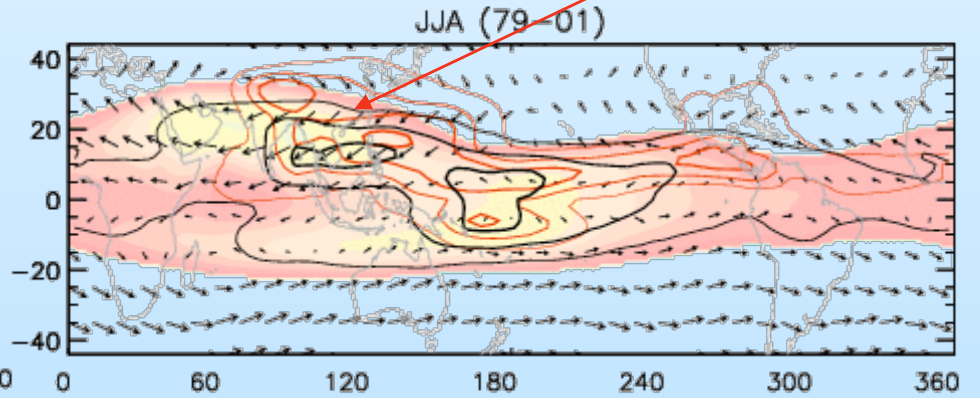
Locations of entry into TTL and final dehydration

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).



`Sources'

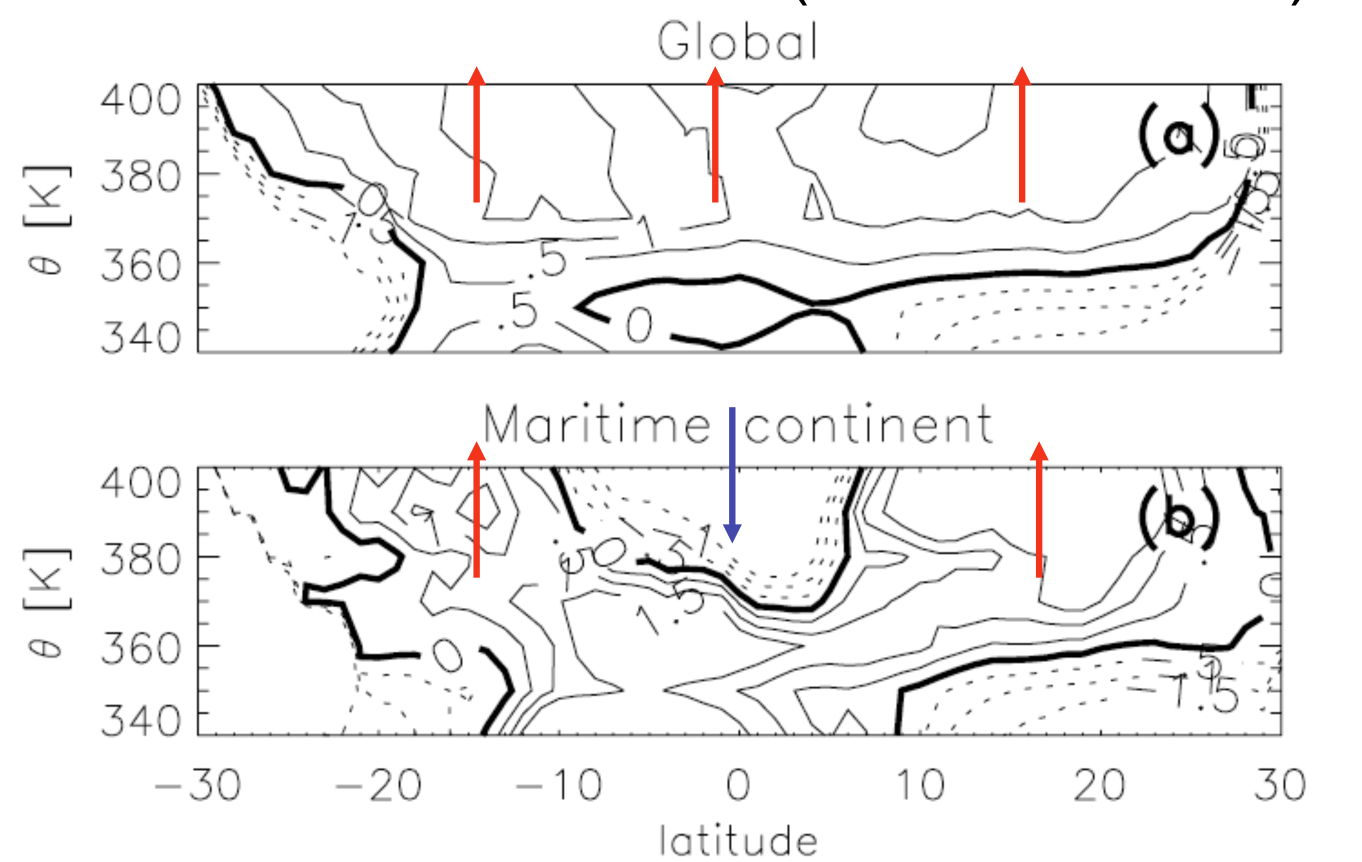




[Fueglistaler et al., 2005]

A drain?

(Sherwood 2001)



Most hypotheses rejected since then (see also Fueglistaler and Fu, 2006).

But: why can we see it in ECMWF analyses?

[Fueglistaler et al. 2004]

Q: Are our models really ‘fit’ to predict the future?

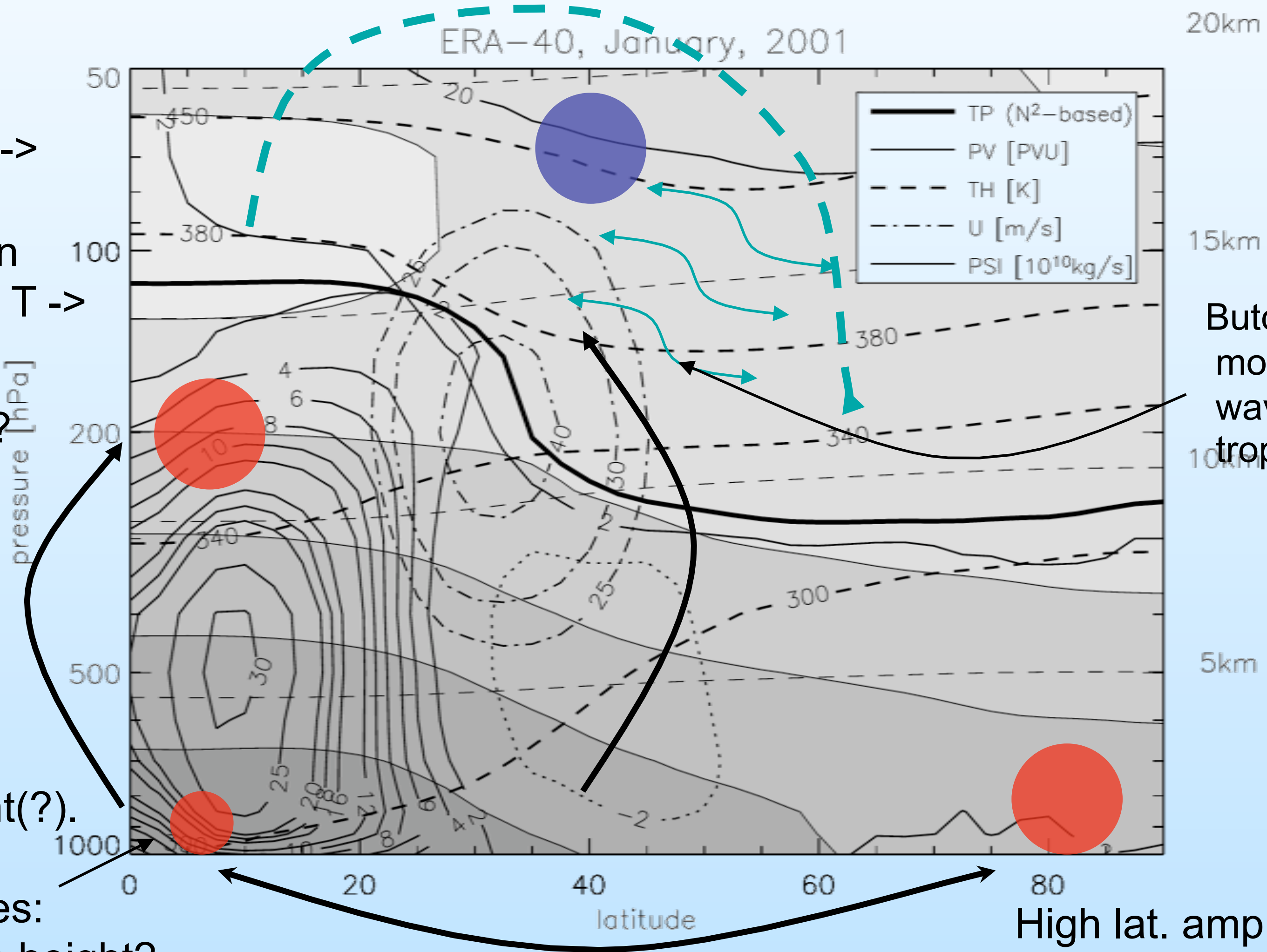
In addition to being able to predict ENSO, QBO and B-D changes, it is crucial that the terms of the energy balance - in particular also in the TTL - are correct; else the response (in temperature, and circulation) will not be of the correct order (or even sign).

The future - need to understand UT/LS heat budget

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

Q: ↗ or ↘ ?

Temp. changes (●, ●)



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

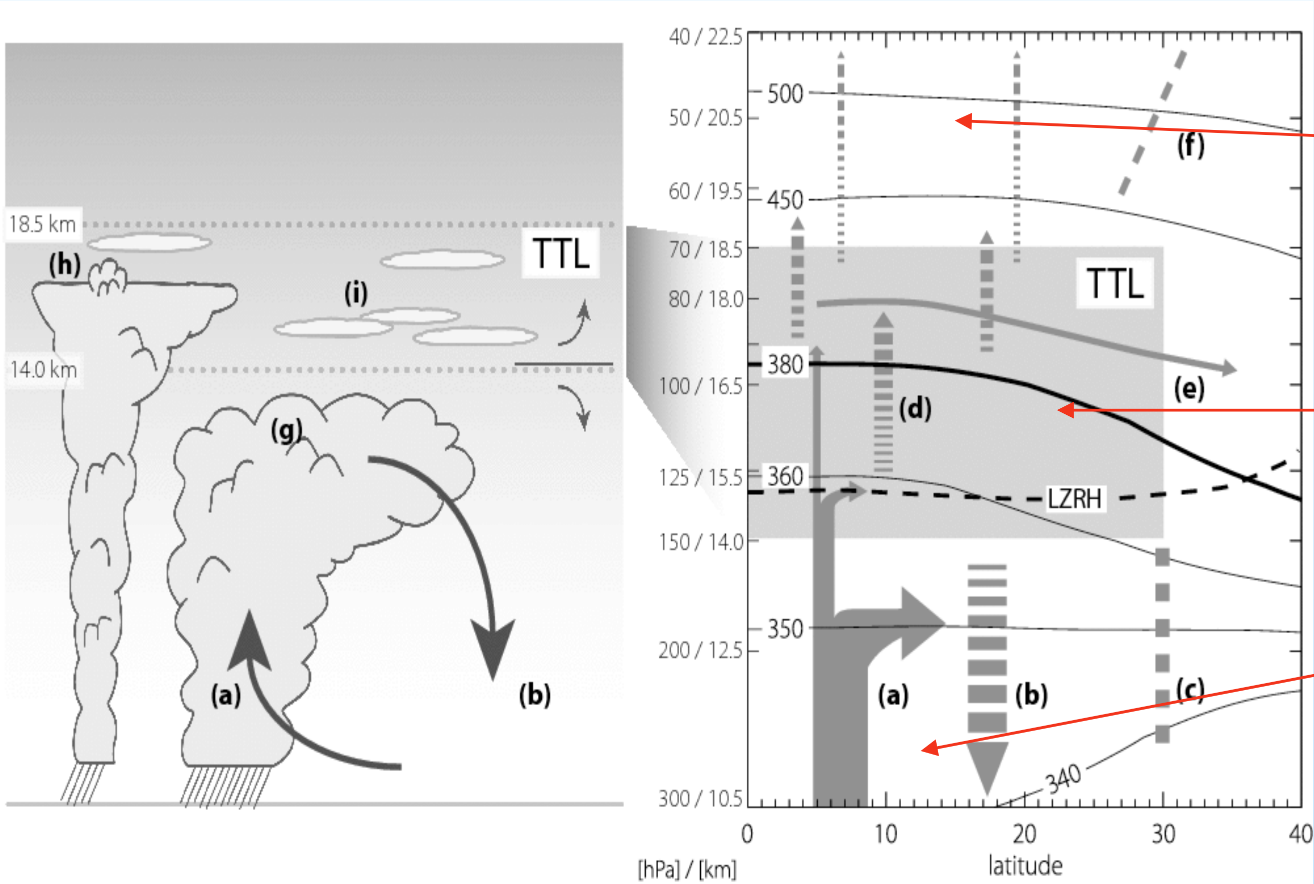
Moist adiabatic adjustment(?).

Θ_e increases:
-convective height?
-CAPE?

Lat. T-gradient decreases (?).

High lat. amplification (ice albedo feedbacks).

Diabatic processes



Stratosphere:
Radiation(gas -phase)

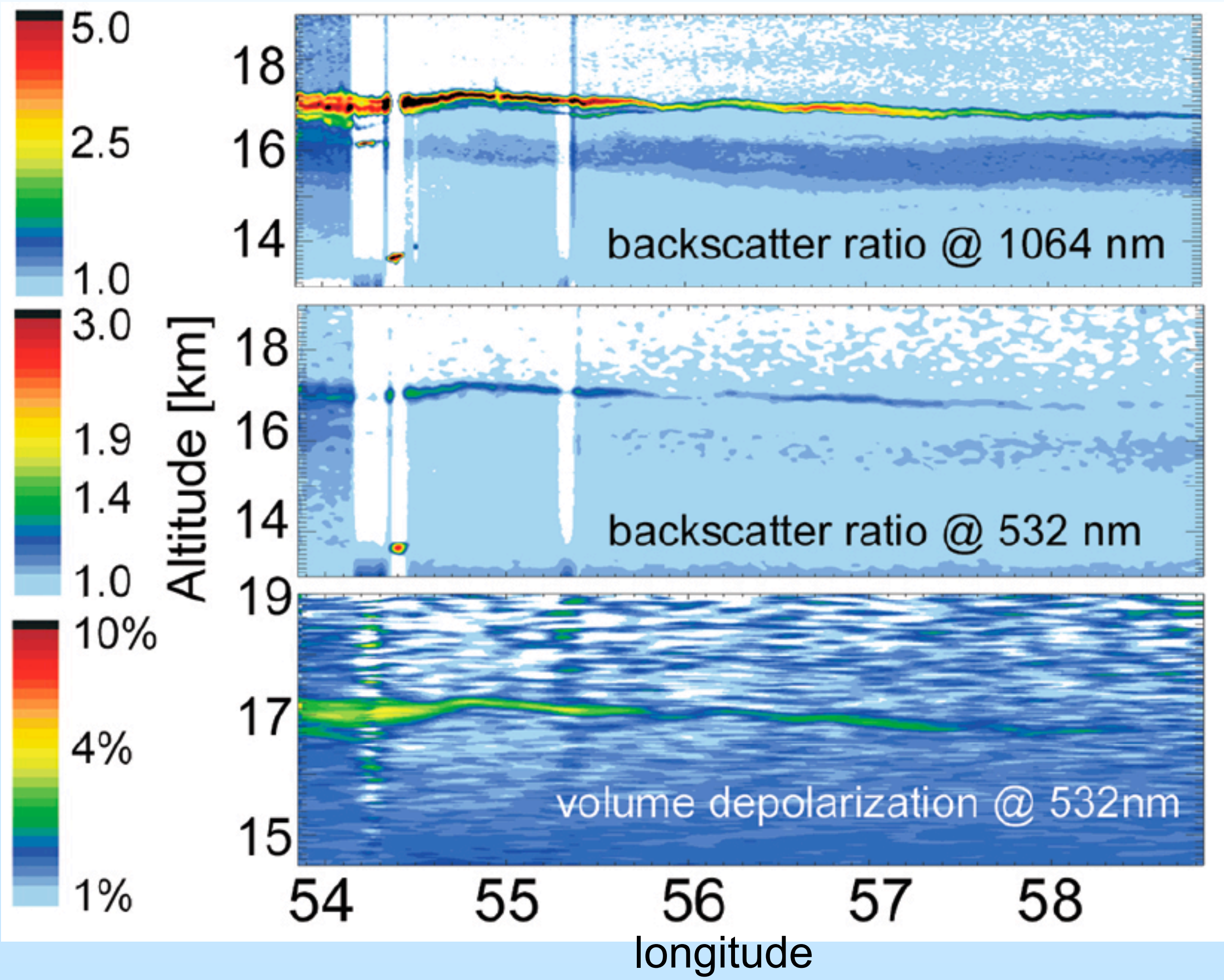
TTL: all

Troposphere:

Latent heat balances radiative loss (gas -phase, also cloud effects)

[Fueglistaler et al., to appear in Rev. Geophysics]

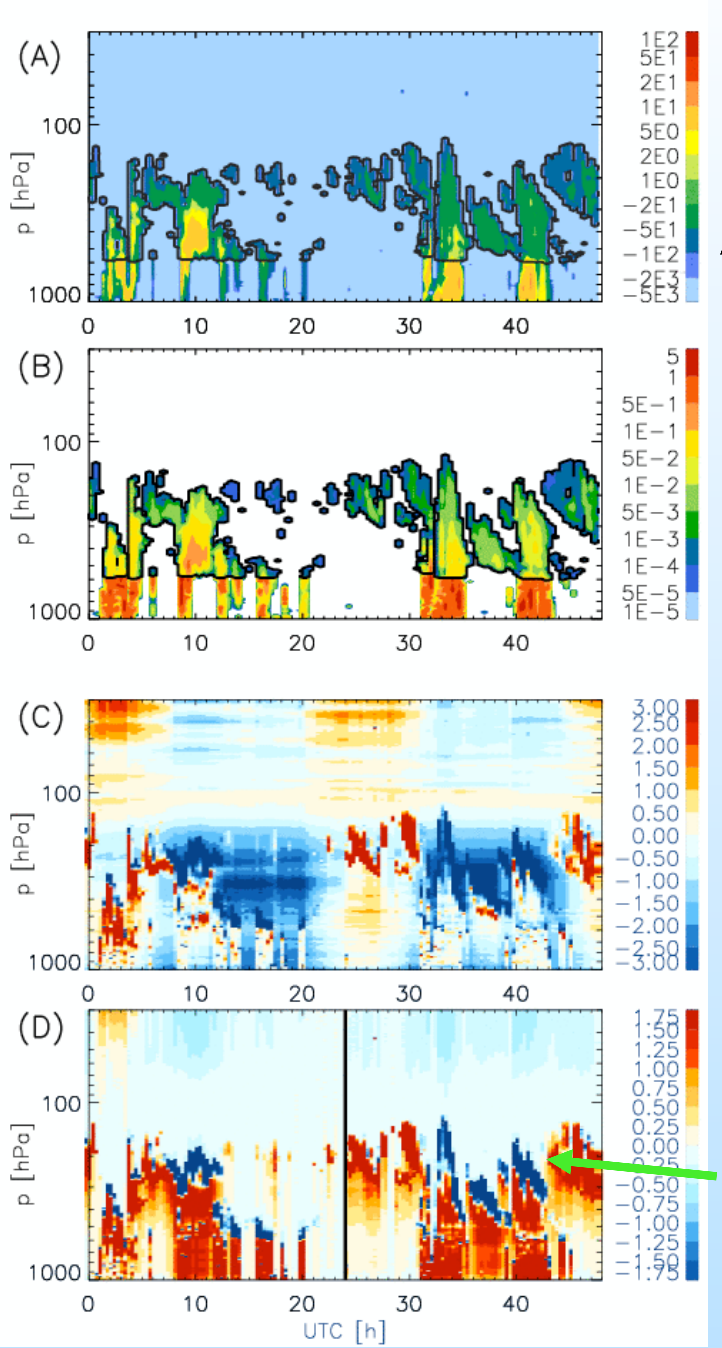
TTL-complications: Optically thin cirrus clouds



Widespread occurrence, difficult to model, radiative effects not well quantified.

[Peter et al., ACP, 2003]

Optically thick clouds



ARM millimeter cloud radar Manus (WP), 2 day sample.

Retrieved condensed phase.

Radiative heating/cooling from rad. transfer calculation.

Net cloud radiative effect.

Cooling + Heating!

[Fueglistaler and Fu, 2006]

Strongly modify local radiative heating, and have effect on stratosphere (modification of upwelling fluxes).

Sensitive to vertical structure, time of day, particle sizes /number density -> radiative effects not well quantified.

Thermal effects of convection

- Latent heat release
- Adiabatic adjustments
- Excitation of waves
- Turbulent mixing (cooling when overshooting of Level of neutral buoyancy, LNB)

Focus of convective parameterizations to date is not accurate representations of impact on TTL!

PART II: Analyses of assimilated data

Assimilated (meteorological) data

Much improved over last decade.

[u/v/T]: observations + model, w problematic

Q: Model only (conv. param., rad. transfer code etc.)

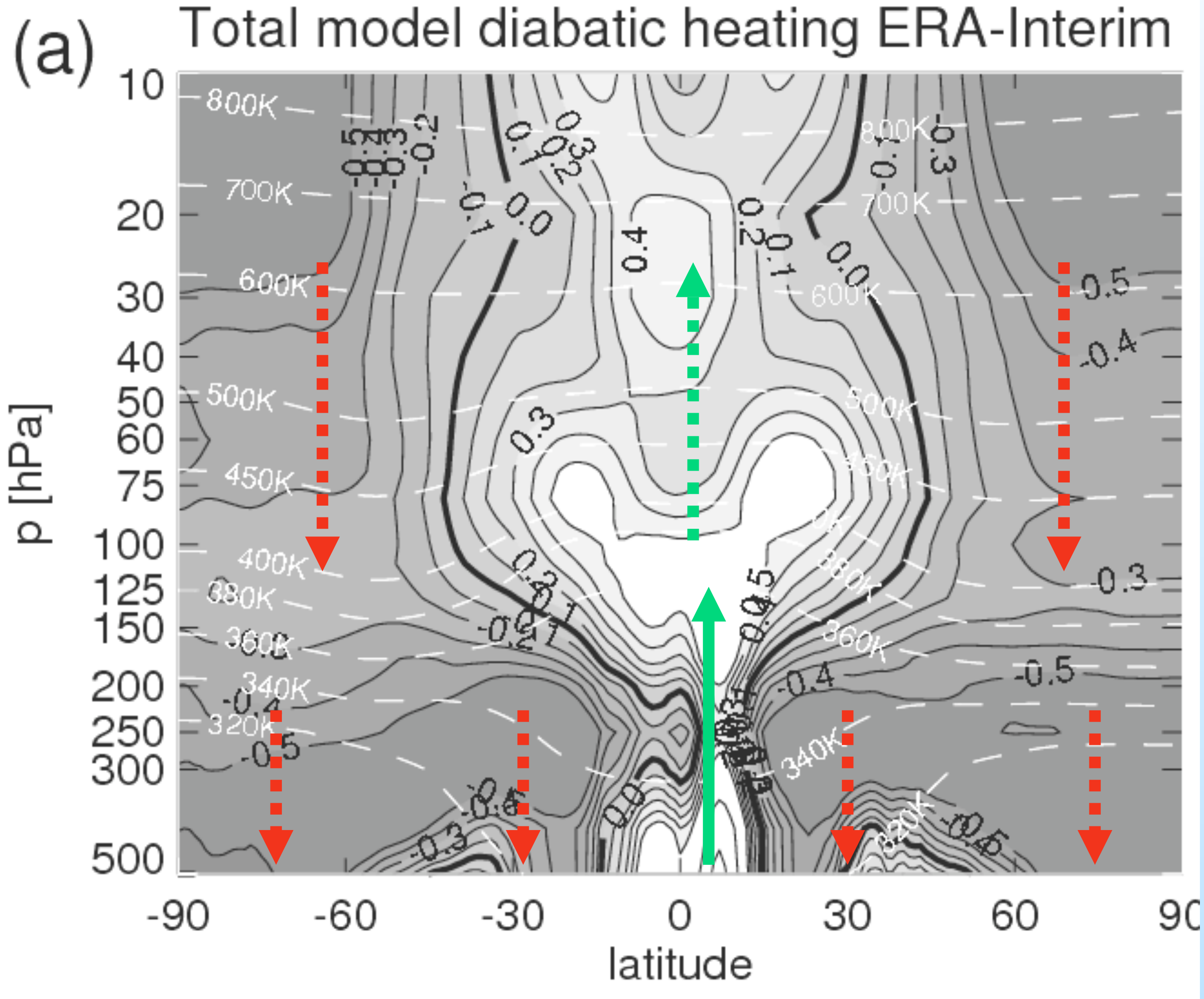
Here we show data from new **ERA-Interim**, and compare also with widely used **ERA-40**.

Changes from ERA-Interim to ERA-40 (see also presentation by B. Legras):

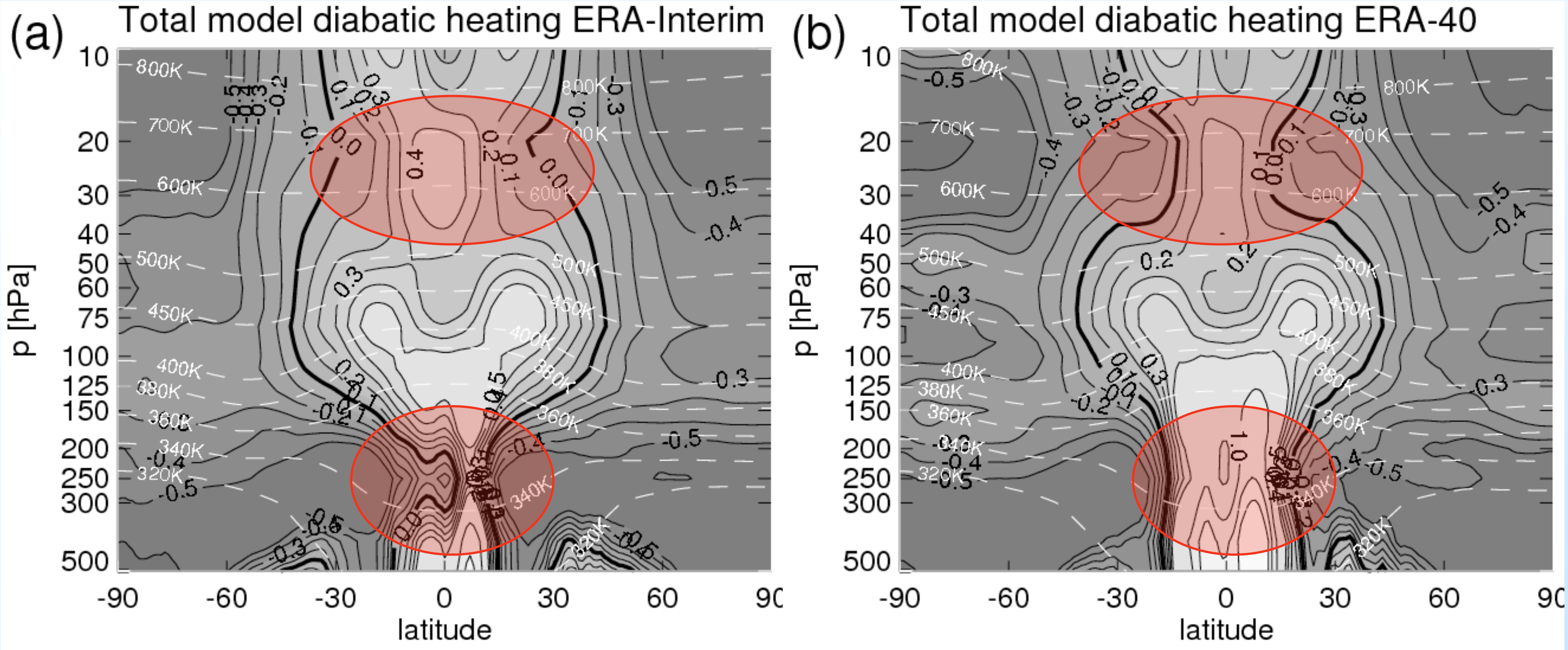
- 4D-var
- assimilation
- model cycle

For details see articles by Simmons, Uppala et al. in ECMWF newsletter, or Fueglistaler et al. 2008 (submitted to QJRMS).

Total diabatic heating (annual mean)



Total diabatic heating (annual mean, comparison)

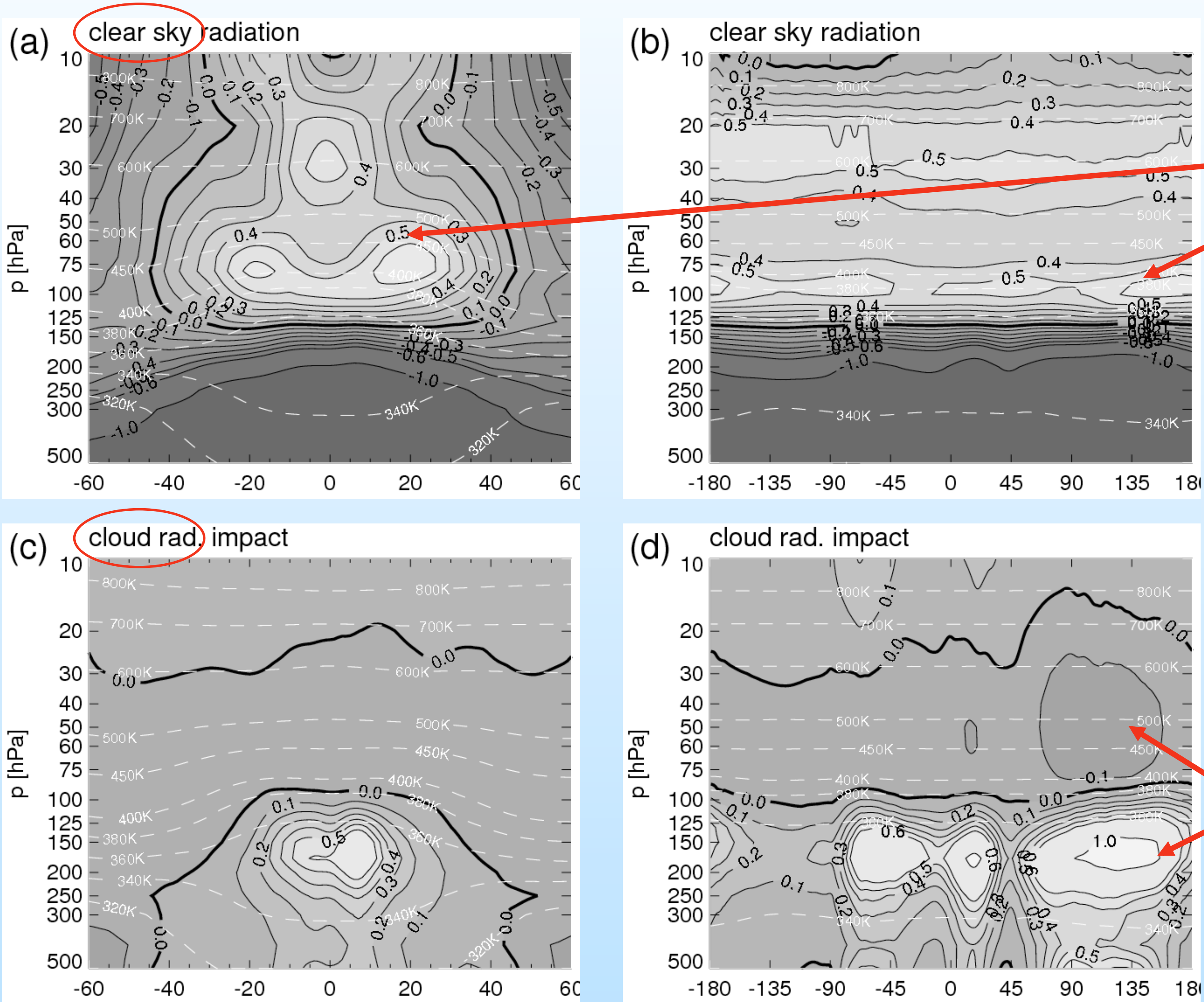


ERA Interim, 2000

ERA-40, 2000

Zonal mean

Equatorial



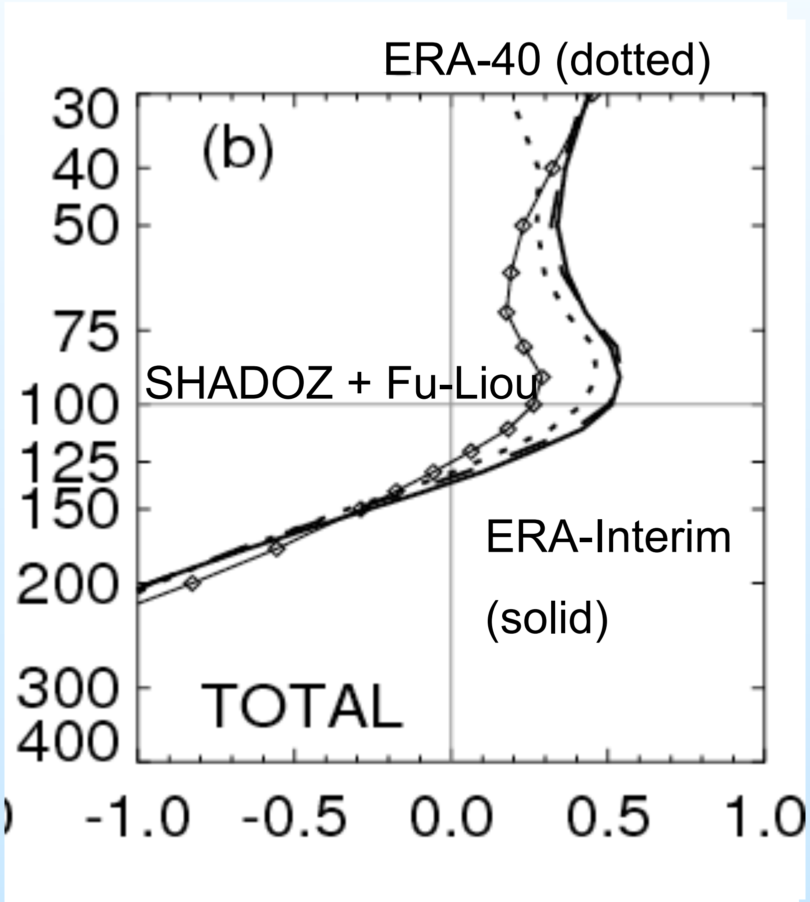
latitude

longitude

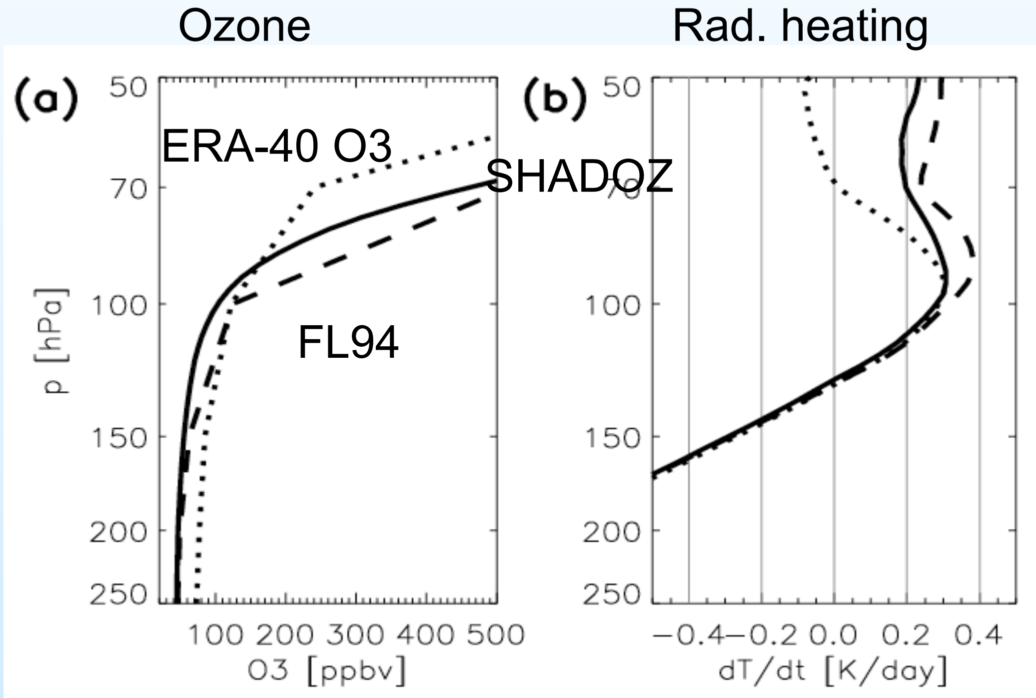
Clear sky rad. heating: maxima in lower stratosphere over subtropics. Maxima at tropopause over Western Pacific (`fountain region'; because of low T's; but zonal mean O3 climatology)

Clouds: radiative effects play a major role between 200 and 100hPa; small reduction in lower equatorial stratosphere over most cloudy regions (WP)

Clear sky radiative heating (tropics)



Qclear differences at tropopause are large (Factor 2).



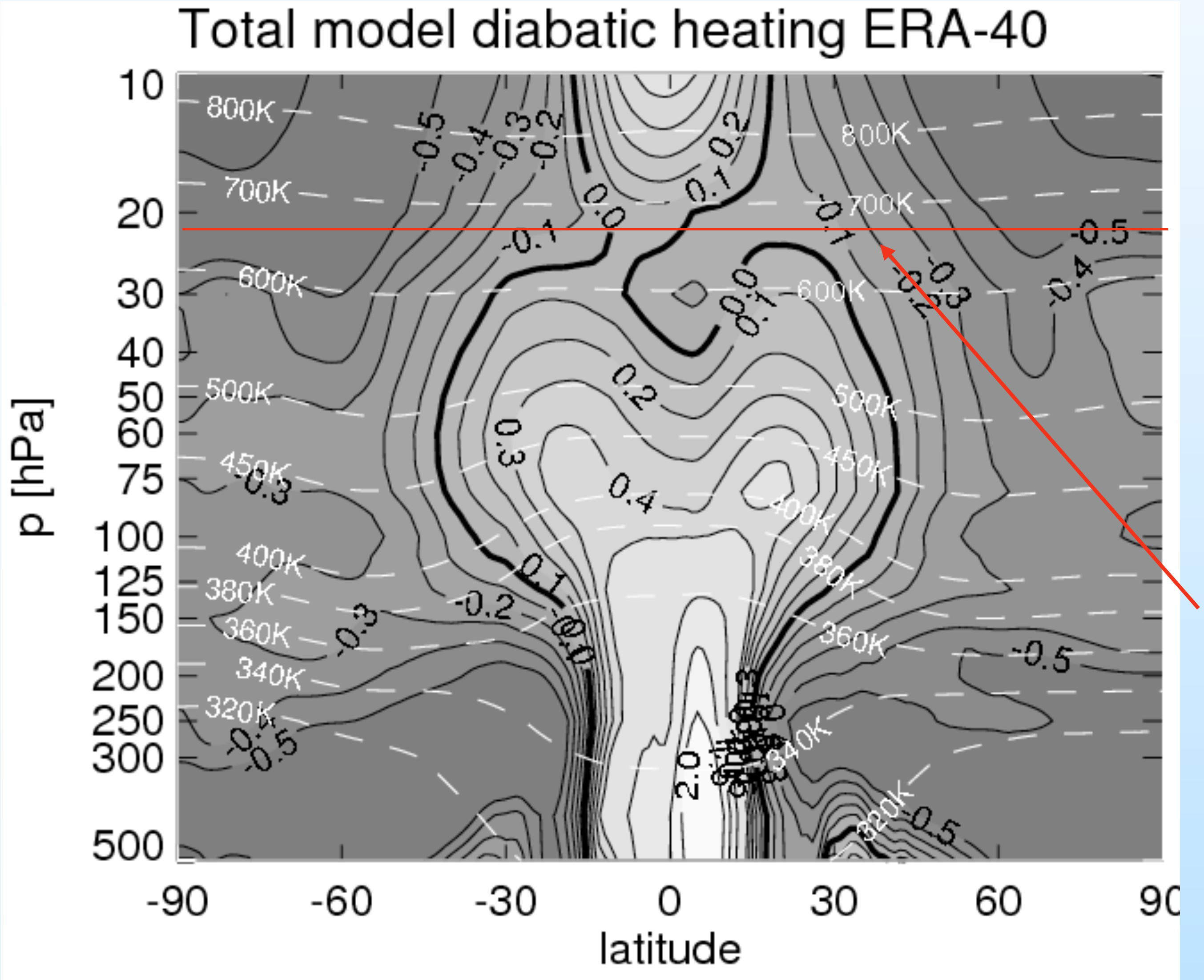
ECMWF uses Fortuin + Langematz (FL94) O3 climatology for rad. transfer calculation.

SHADOZ has lower O3 at tropopause, gives approx. 0.1K/day less heating. Note: ERA-40 ozone field is strongly biased (-> use of climatology).

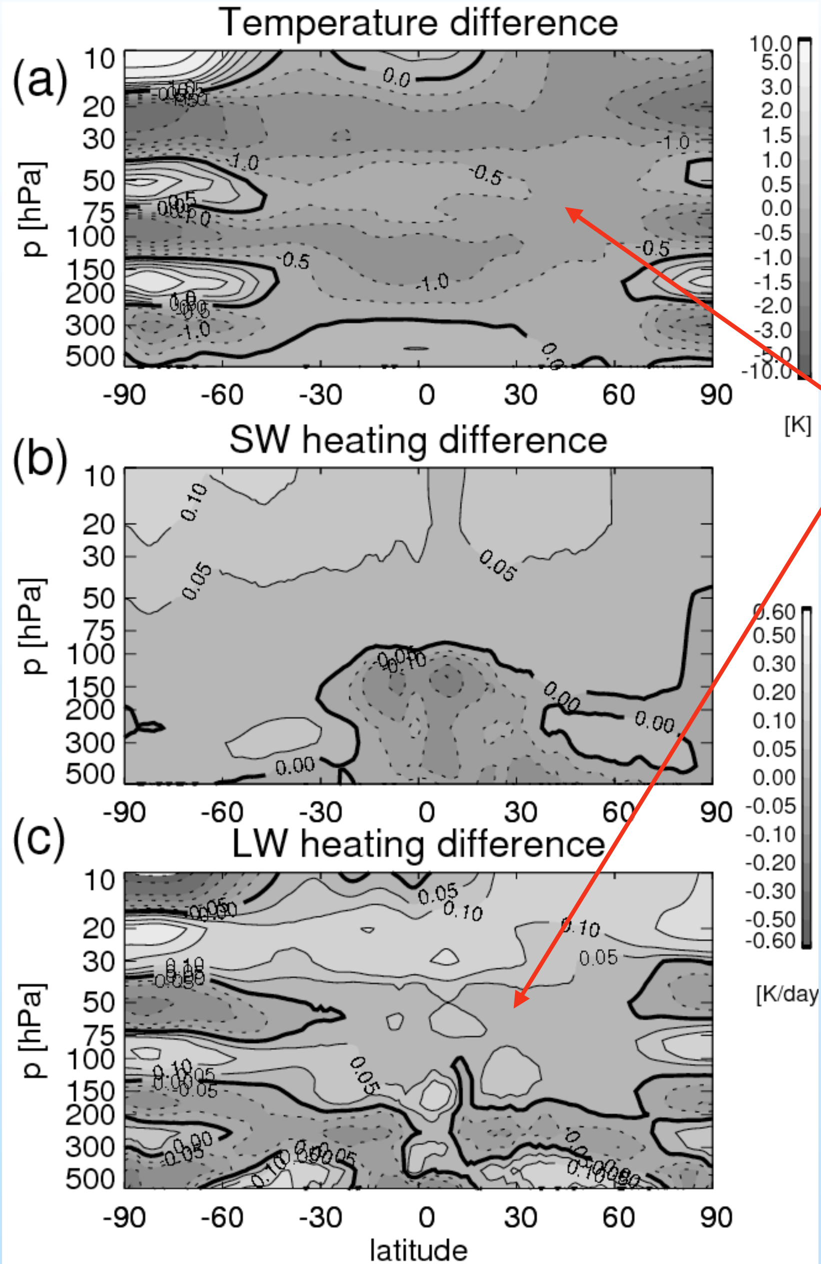
+ differences in rad. transfer code.

Uncertainty: +/- 25-50% (?)

Example: ERA-40 problems



ERA-40 has biases in vertical temperature structure which affects calculated LW heating /cooling. Depending on QBO phase, radiative heating becomes highly unrealistic (here year 1997).



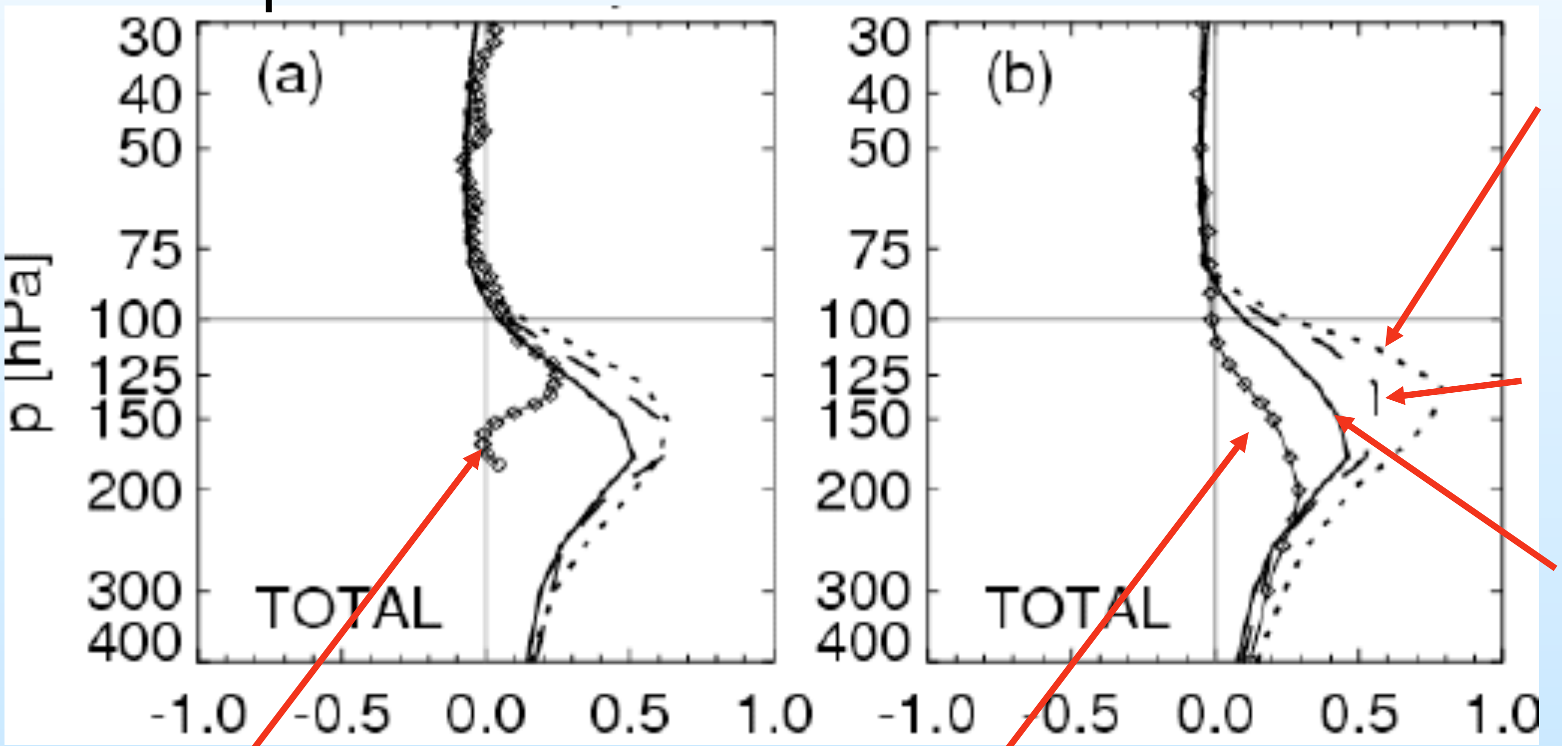
Problems in ERA-40 radiative heating are due to problems in (assimilated) temperature (affecting LW).

(Oscillatory patterns in Q^{rad} have origin in LW, and arise from incorrect temperature structure.)

Cloud radiative effects: highly uncertain

Tropics

ARM TWP “Manus”



ERA-40

EXP-471

ERA-Interim

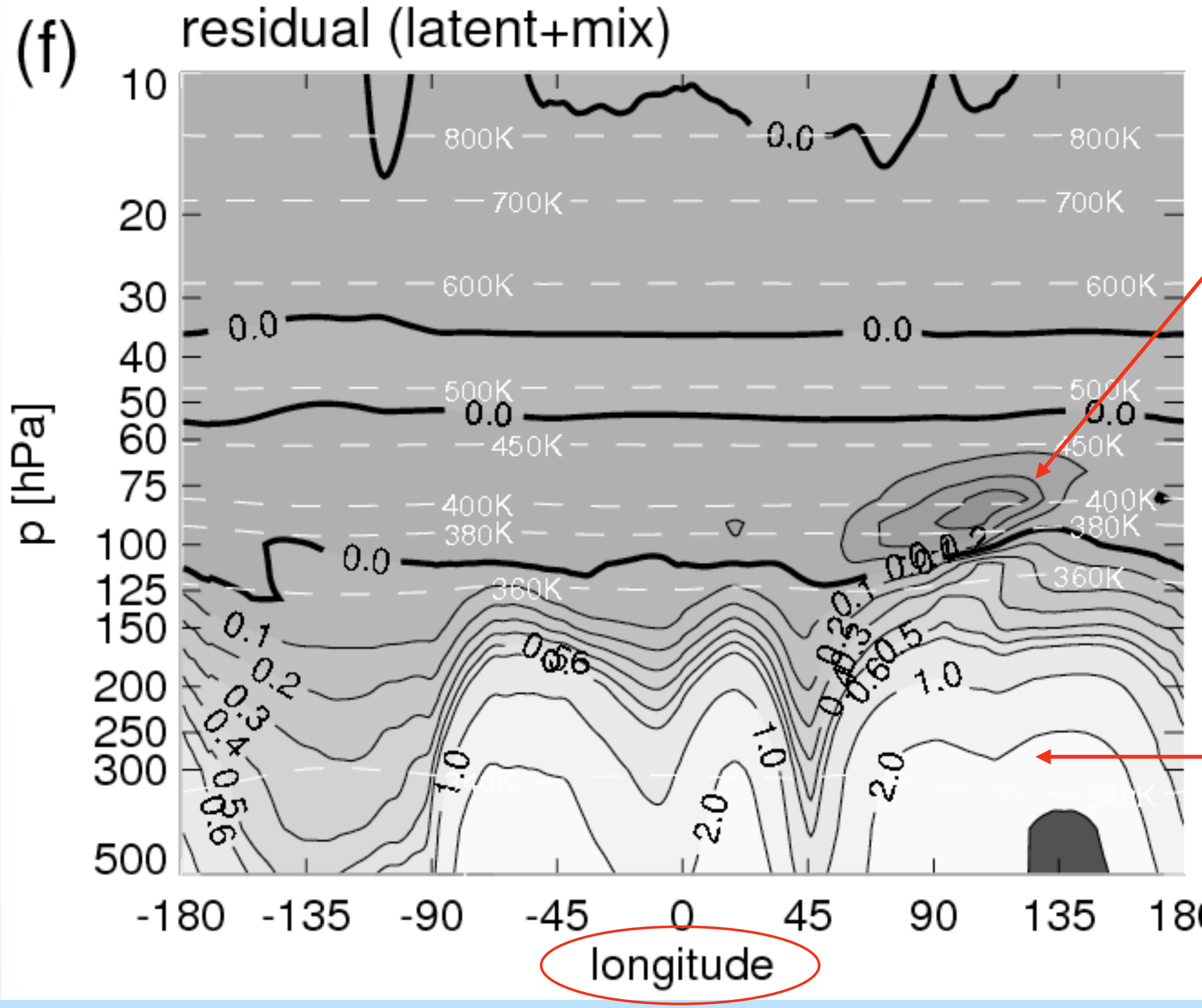
dT/dt [K/day]

dT/dt [K/day]

ISCCP/LITE [Corti et al 2005]

ARM MCR [Fueglistaler and Fu, 2006]

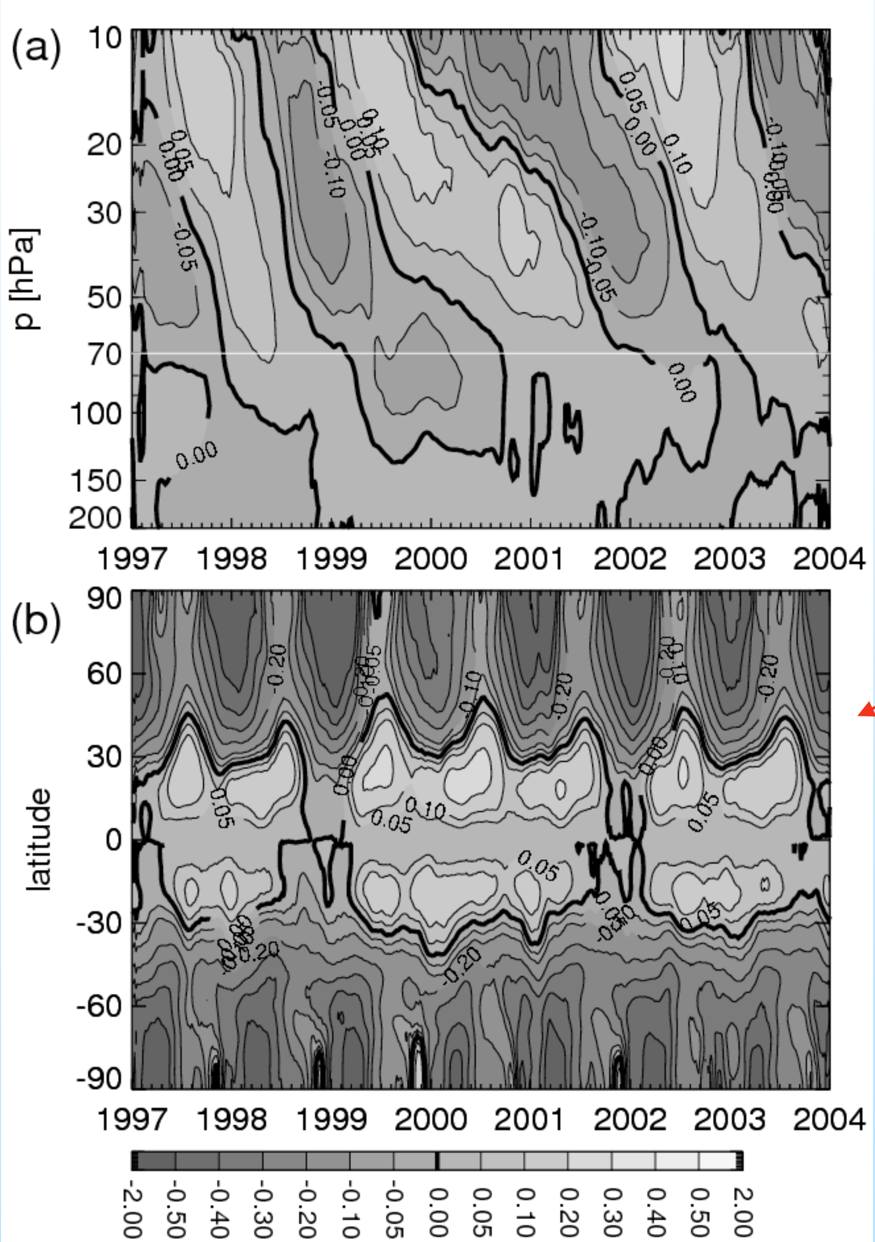
Residual (latent + mixing) over tropics



Unexpected: some convective, but mainly CAT! (low Richardson number)

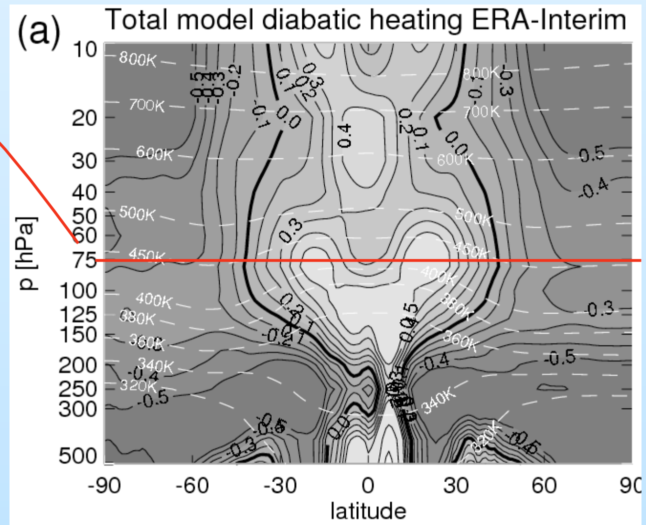
Expected: (massive heating over WP, IO, AF, SA)

‘Double peak structure’ of radiative heating

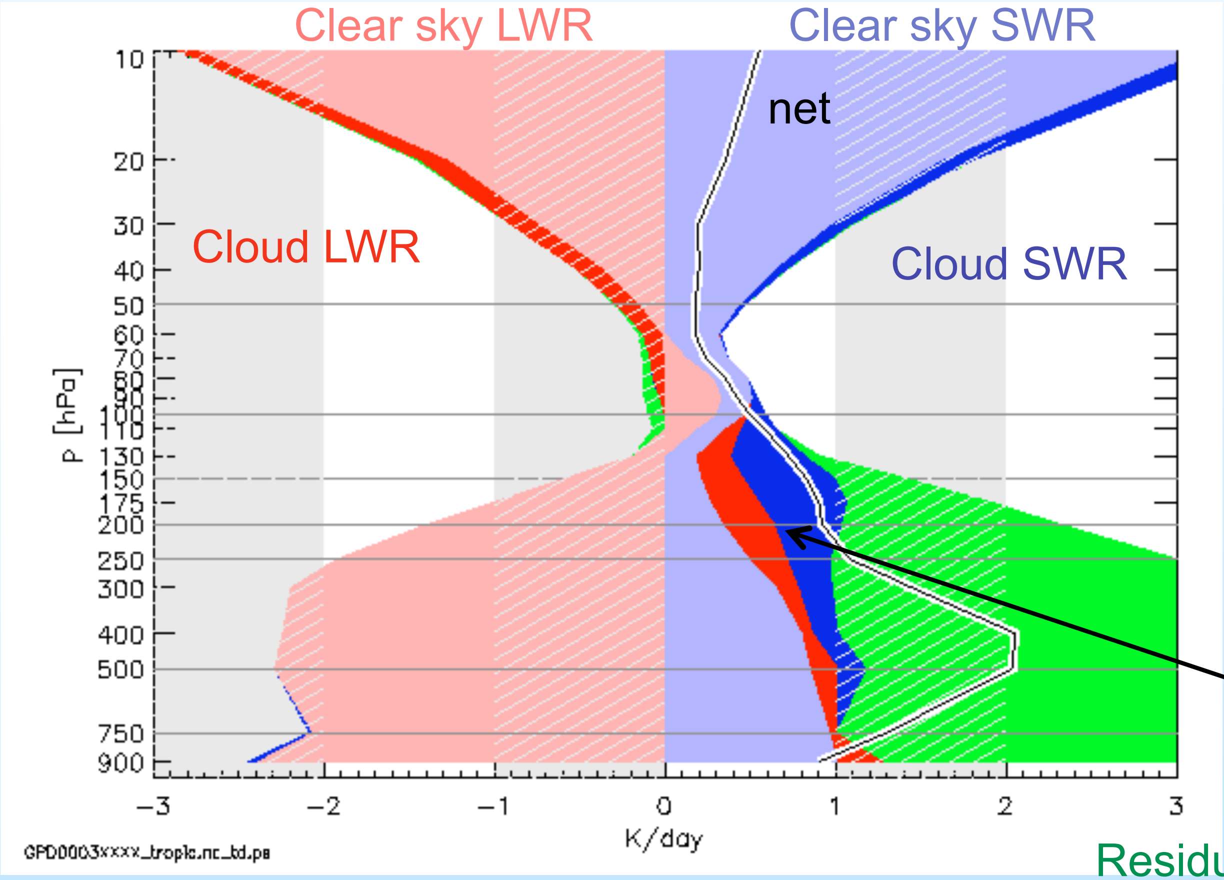


QBO strongly modulates structure of radiative heating at low latitudes, but maxima over subtropics at 70hPa robust feature.

(subtract equatorial value)



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



Stratosphere:

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

TTL:

Top: radiation (plus mixing); base: **all terms similar order**.

Very large cloud radiative effect!

Residual = latent heat, diffusion, …

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

Role of the assimilation temperature increment

Simplify for finite quantities:

$$\delta T + Q/c_p + \delta T_{adv} = 0$$

$$\delta T + Q^{model}/c_p + \delta T_{adv}{}^{model} + \delta T^{assimilation} = 0$$

if $\delta T_{adv} = \delta T_{adv}{}^{model}$ then:

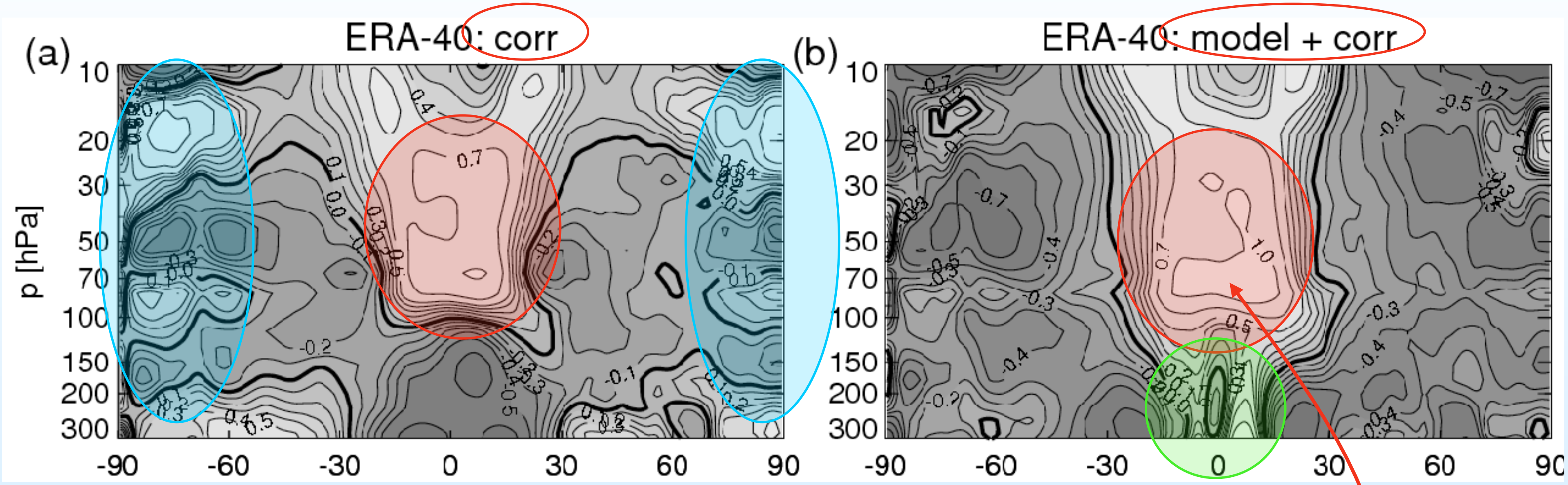
$$Q^{model}/c_p + \delta T^{assimilation} = Q^{true}/c_p$$

Implications:

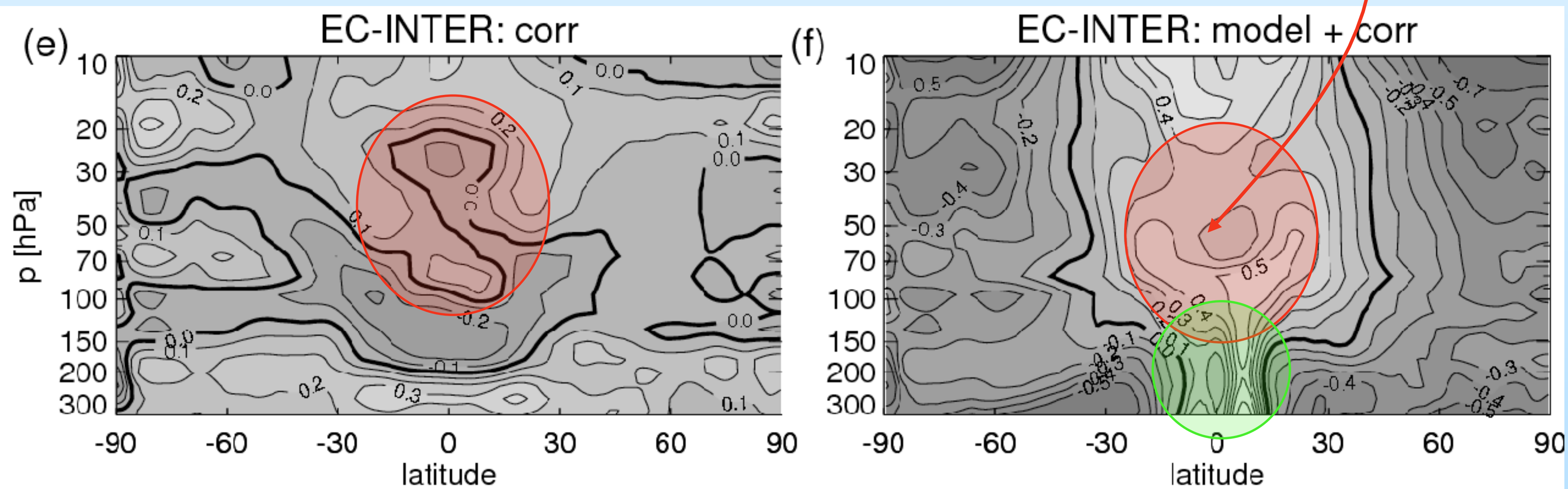
Adding the assimilation increment to the model diabatic heating recovers the true diabatic heating.

If two analyses have same $\delta T_{adv}{}^{model}$, but different Q^{model} (for many reasons), then the above sum should converge (not necessarily towards Q^{true}).

-> compare ERA-Interim and ERA-40.



ERA-40: Diab. circ. twice as strong,
structure lost.



Adding assimilation increment to model diabatic heating yields for ERA-40 and Interim:

- Overall structure more similar, but amplitude in ERA-40 twice that of ERA-Interim.

- ERA-40 lost structure in low latitude stratosphere (I.e. maxima over subtropics at 70hPa)

- Oscillations at poles reduced

- Convection: Interim bottleneck at 200hPa removed, ERA-40 excessive heating removed

We conclude that the `too strong BD' in ERA-40 is indeed (also) in the diabatic circulation, and that the **error must originate in the advective term**. The ultimate cause remains unknown. It is likely that assimilation causes too much oscillatory motion, and vertical and horizontal heat fluxes are exaggerated.

PART III: Summary and Outlook

Outlook I:

Open question:

If we determine TEM w* from v/T, does that correspond to $Q_{model}+Q_{assim}$, or …?

Not clear whether w* is not affected by the same deficits as diabatic heating terms. This would be not-so-good news for analyses based on ERA-40 w*.

Outlook II:

Assimilated data is still not good enough to identify unequivocally ‘missing model physics’, but is making rapid progression towards this goal.

(Caveat: the more complex the assimilation process, the harder it is to understand what the corrections physically mean.)

Outlook III:

For stratosphere, new ECMWF interim reanalysis is a big step forward.

For TTL, questions remain:

- too little convection

- Role of clouds in model very important for layer 200-100hPa (other models apparently have the same effect), but this cloud radiative heating is associated with large uncertainties (depends to a good deal on parameterizations, which were optimized with other aspects in mind).


Thank you!