Evaluation and intercomparison of reanalysis diabatic heating in the tropical UTLS

Jonathon Wright
Department of Earth System Science, Tsinghua University

with contributions from

Stephan Fueglistaler
Princeton University

Xiaoyi Sun
Tsinghua University

Masatomo Fujiwara
Hokkaido University

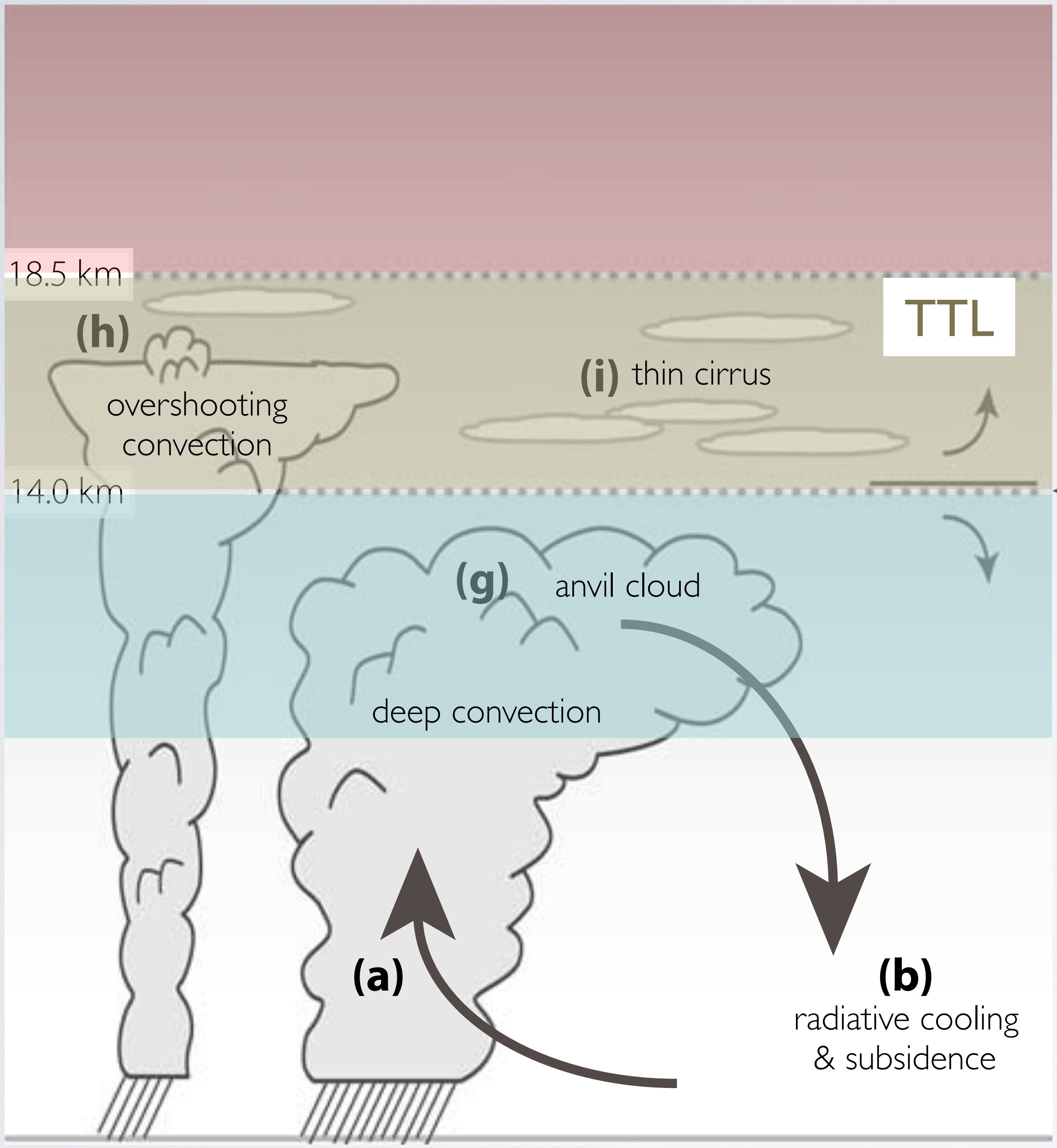
清華大學

S·RIP SPARC Reanalysis Intercomparison Project

Diabatic heating: motivation

- Understanding the circulation of the UTLS requires an understanding of the diabatic heat budget
- The terms in the diabatic heat budget are impossible to measure directly and must be simulated using numerical models
- The distribution of diabatic heating in the tropical UTLS has substantial implications for transport, mixing, thermodynamic structure, and composition
- Vertical and horizontal distribution of diabatic heating heating and cooling affect the preferred locations and characteristics of cross-tropopause exchange simulated by trajectory and chemical transport models
- It remains unclear to what extent biases (or missing contributions) in diabatic heating imprint on circulation patterns in the UTLS
- Differences in diabatic heating may help to identify and solve problems in the reanalysis model or data assimilation system

The tropical UTLS



Lower stratosphere (LS)

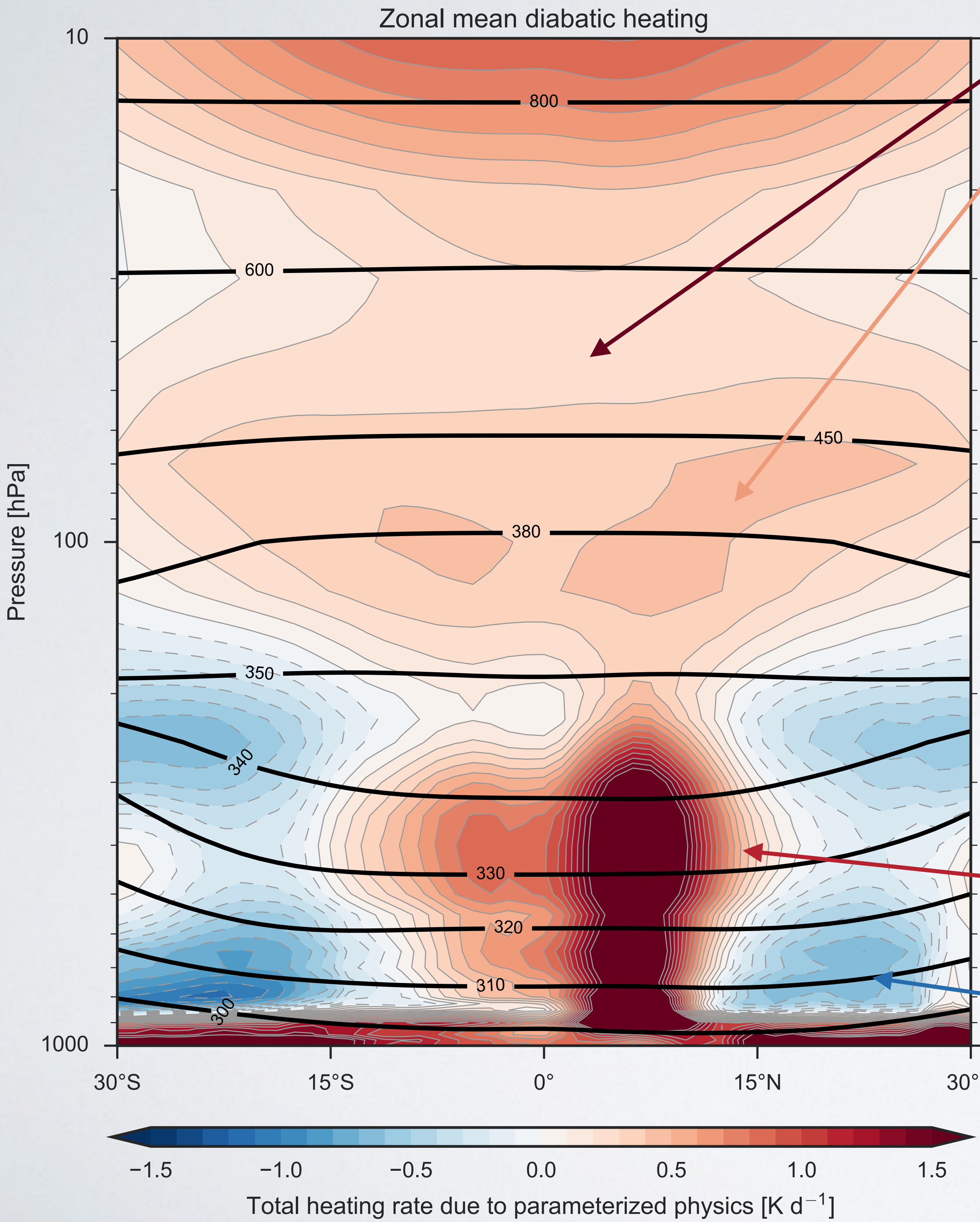
Tropopause transition layer

Level of zero net radiative heating (LZRH)

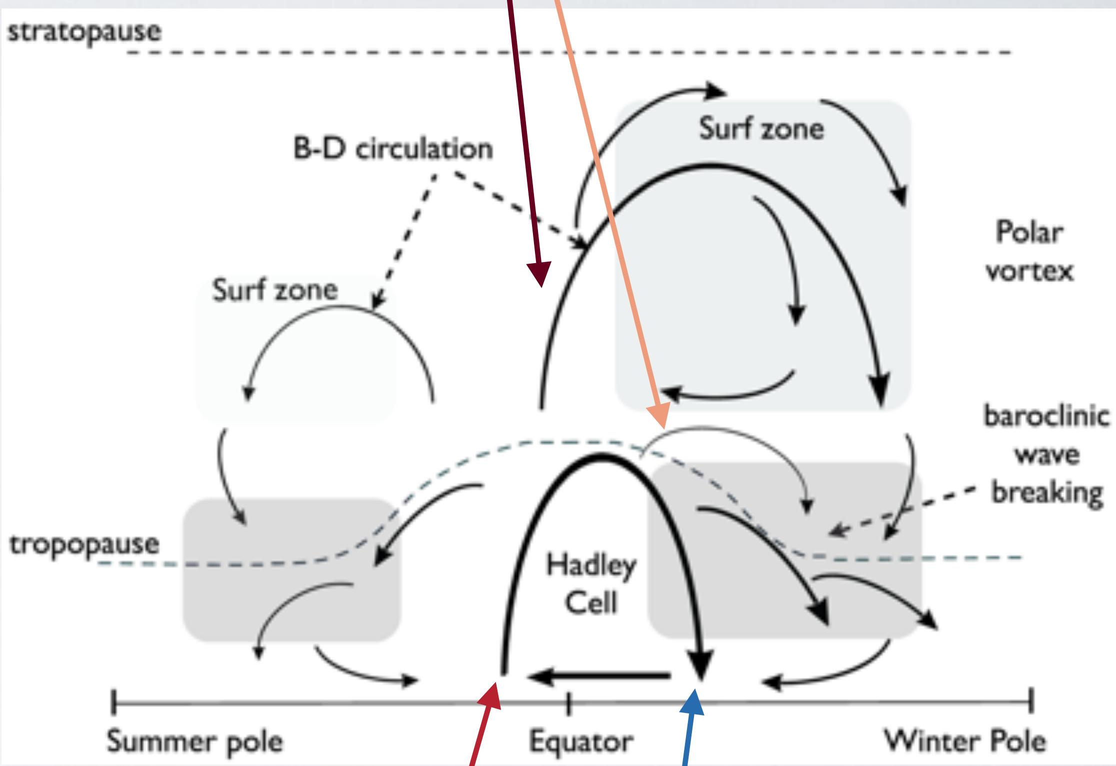
Upper troposphere (UT)

Fueglistaler et al., *Rev. Geophys.* 2009

Diabatic heating and the large-scale circulation



tropical stratospheric heating: deep and shallow branches of Brewer-Dobson circulation

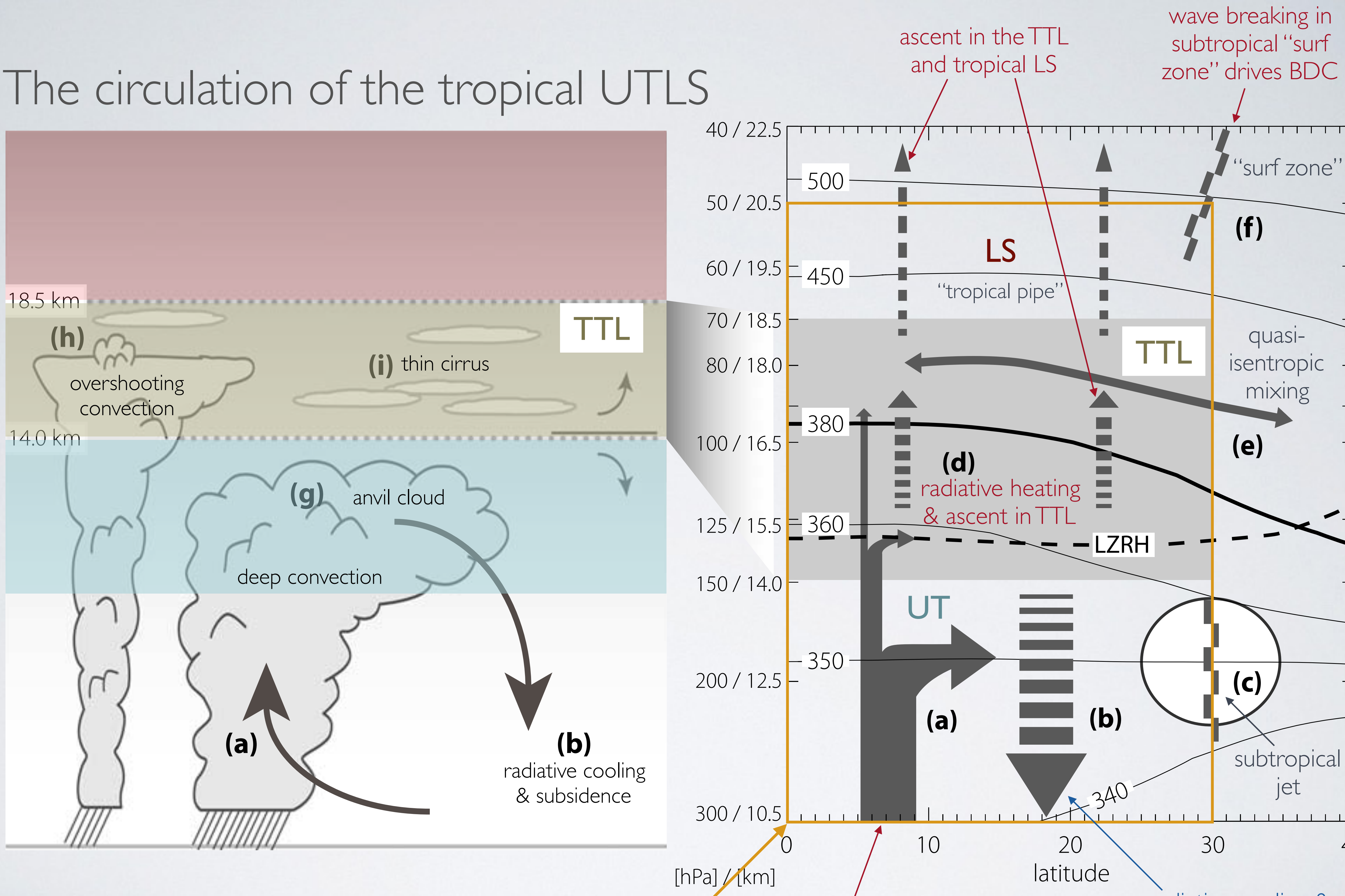


tropical tropospheric heating: upward branch of Hadley cell

subtropical tropospheric cooling: downward branch of Hadley cell

Data from JRA-55

The circulation of the tropical UTLS



Focus domain: 30°S–30°N, 50~300 hPa

Fueglistaler et al., *Rev. Geophys.* 2009

Role and components of diabatic heating

Thermodynamic energy equation:

$$\frac{\partial T}{\partial t} + \overbrace{\mathbf{v} \cdot \nabla T}^{\text{horizontal advection}} - \overbrace{\omega \left(\frac{\kappa T}{p} - \frac{\partial T}{\partial p} \right)}^{\text{vertical advection}} = \overbrace{\frac{Q}{c_p}}^{\text{diabatic heating}}$$

$$\underbrace{\boxed{\frac{Q}{c_p}}}_{\text{total}} = \underbrace{\boxed{\frac{Q_{\text{rad}}}{c_p}}}_{\text{radiation}} + \left(\underbrace{\boxed{\frac{Q_{\text{lat}}}{c_p}}}_{\text{moist physics}} + \underbrace{\boxed{\frac{Q_{\text{mix}}}{c_p}}}_{\text{turbulence}} \right)$$

Can also split Q_{rad} into long-wave (LW) // short-wave (SW) or clear-sky // cloudy radiative components

Diabatic heating: assimilation increments

Reanalyses do not conserve energy!

Reanalyses also include a virtual diabatic heating term:

$$\frac{Q}{c_p} = \frac{Q_{\mathrm{rad}}}{c_p} + \left(\frac{Q_{\mathrm{lat}}}{c_p} + \frac{Q_{\mathrm{mix}}}{c_p} \right) \boxed{+ \frac{Q_{\mathrm{assim}}}{c_p}}$$

assimilation increment

observationally-influenced temperature analysis

model temperature forecast

$$\frac{Q_{\mathrm{assim}}}{c_p} = \frac{\boxed{T_{\mathrm{assim}}} - \boxed{T_{\mathrm{fc}}}}{\boxed{t_{\mathrm{fc}}}}$$

forecast length

The assimilation increment can help with bias identification — but not necessarily with bias attribution

Interpretation: the Newtonian cooling approximation

inverse of radiative relaxation time scale

radiative equilibrium temperature

$$\frac{Q_{\mathrm{rad}}}{c_p} \approx -\alpha \cdot (T - T_{\mathrm{eq}})$$

local temperature

Basic framework: the Newtonian cooling approximation

Radiative heating depends on temperature and composition

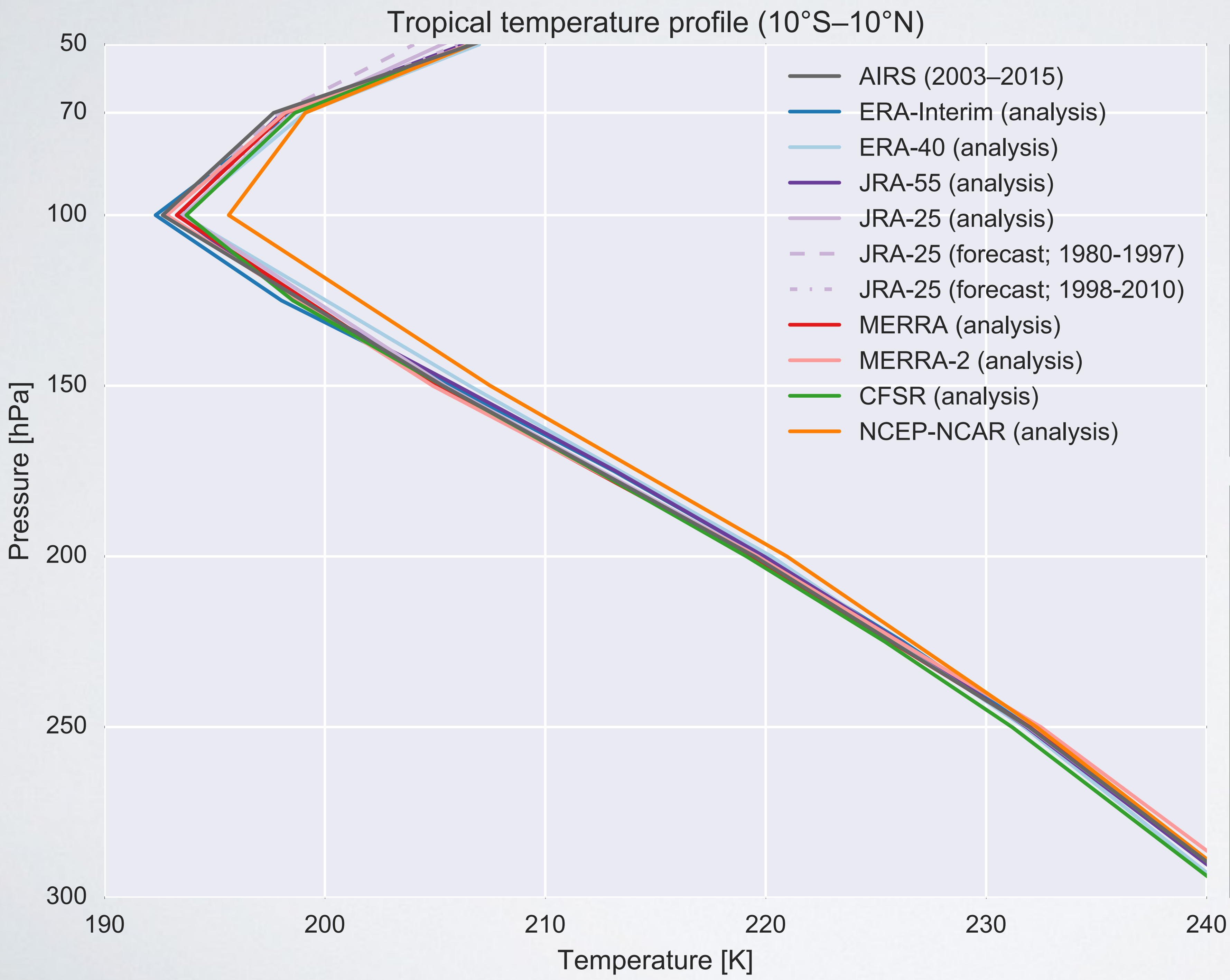
$$\frac{Q_{\mathrm{rad}}}{c_p} \approx -\alpha \cdot (T - T_{\mathrm{eq}})$$

All else equal, an increase in temperature reduces radiative heating (enhances radiative cooling) and vice versa.

Perturbations to atmospheric composition (or temperature above and below) affect radiative heating by modifying T_{eq}.

UTLS temperature structure in reanalyses

Differences in vertical resolution and physics affect temperatures in the TTL and LS



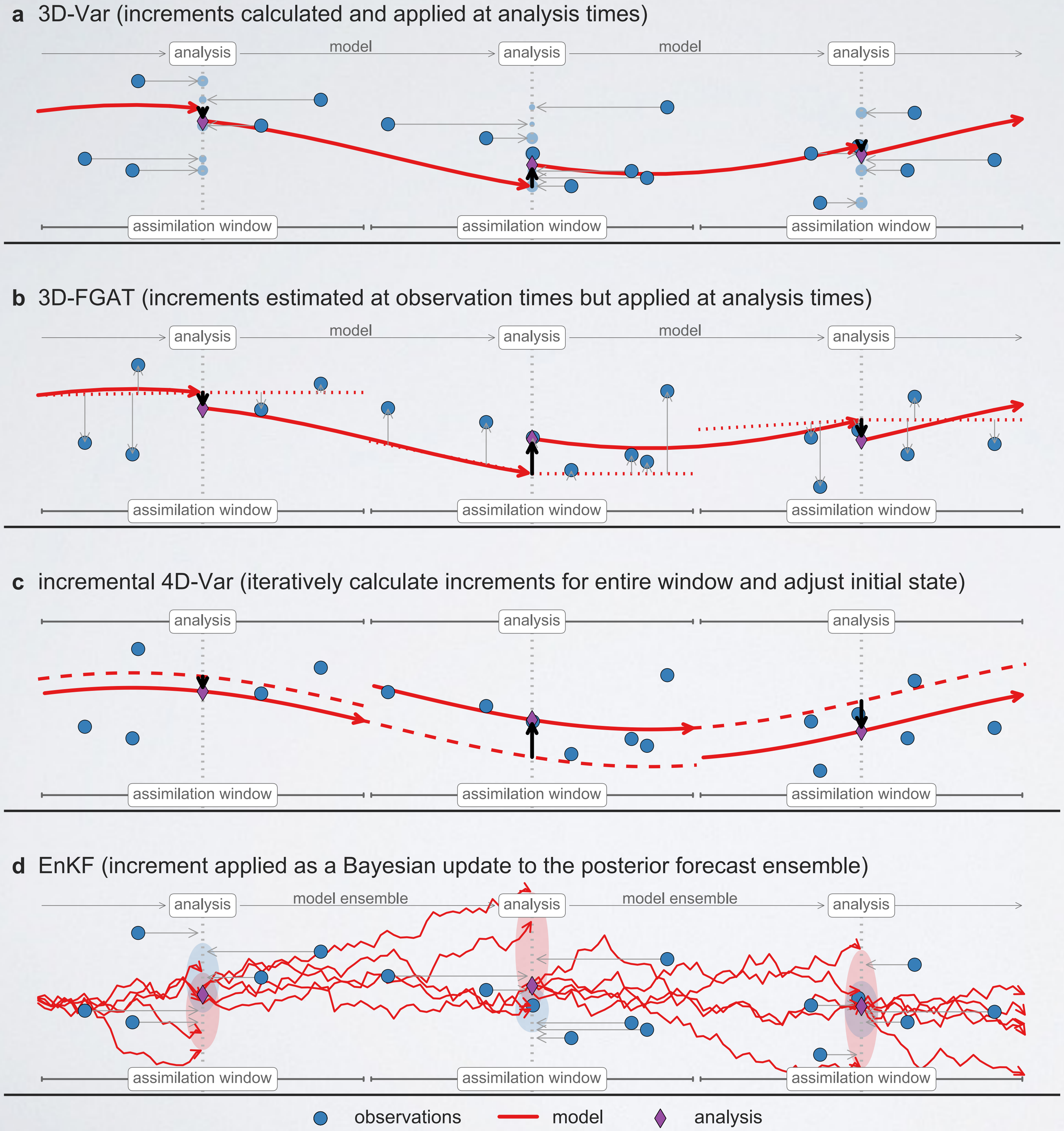
Tropical mean cold point tropopause temperatures can be substantially different — the mean tropical CPT in ERA-Interim is colder than most, while that in NCEP-NCAR is particularly warm

Both analyzed and forecast temperatures may affect radiative heating (radiation calculations occur during the forecast step) — model biases can have important effects, especially in the stratosphere

A brief introduction to data assimilation

Reanalyses: **atmospheric GCMs constrained by data assimilation**

Diabatic heating is calculated during the forecast step



3D-Var reanalyses:
JRA-25, (NCEP-NCAR)

3D-FGAT reanalyses:
ERA-40, CFSR, (NCEP-NCAR)

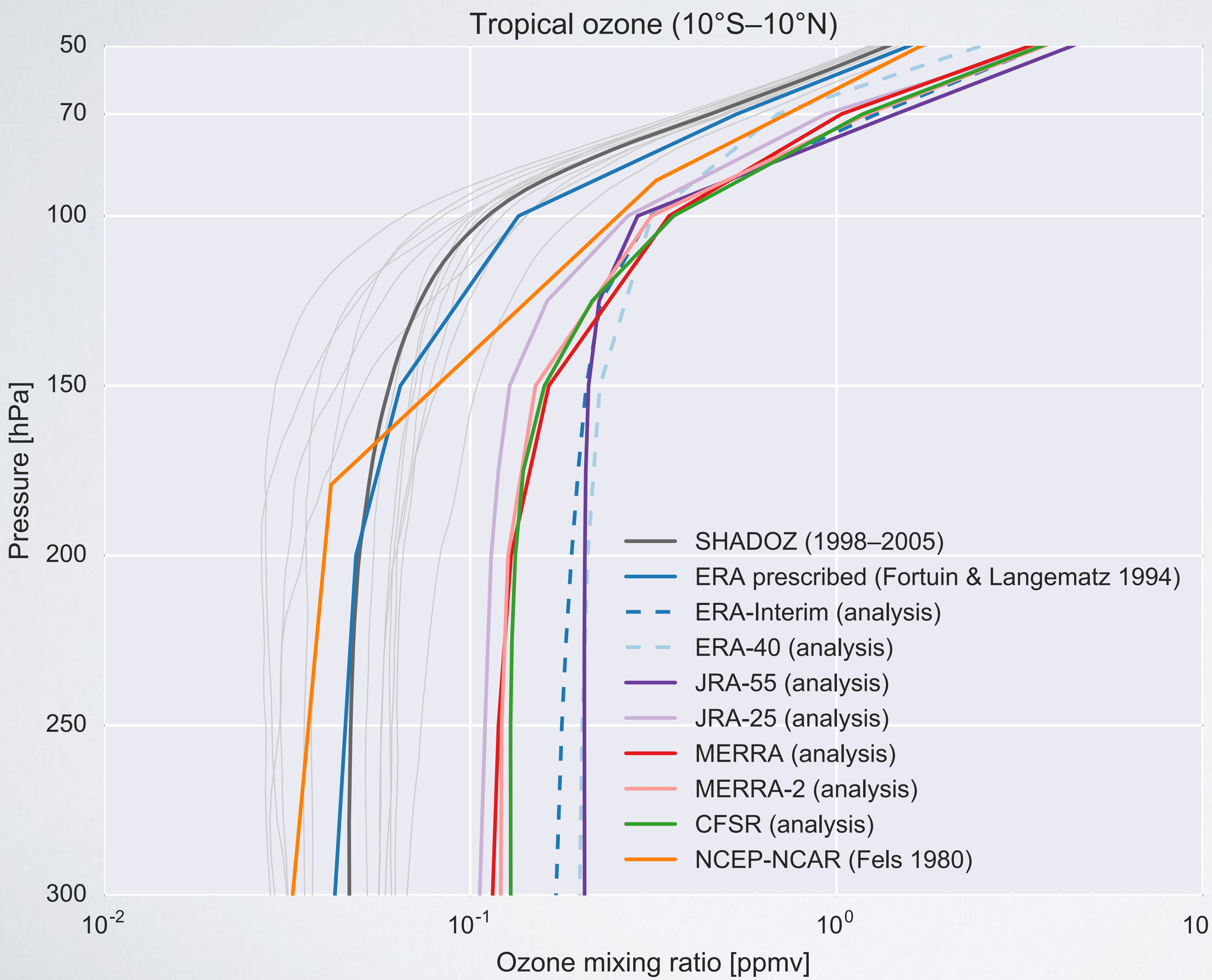
3D-FGAT (IAU) reanalyses:
MERRA, MERRA-2

4D-Var reanalyses:
ERA-Interim, JRA-55, *ERA-20C*

EnKF reanalyses:
NOAA-CIRES 20CR

UTLS composition in reanalyses

Ozone is an important potential source of uncertainty in Q_{rad}:



Prognostic ozone:
MERRA, MERRA-2, CFSR

Offline CTM:
JRA-25, JRA-55

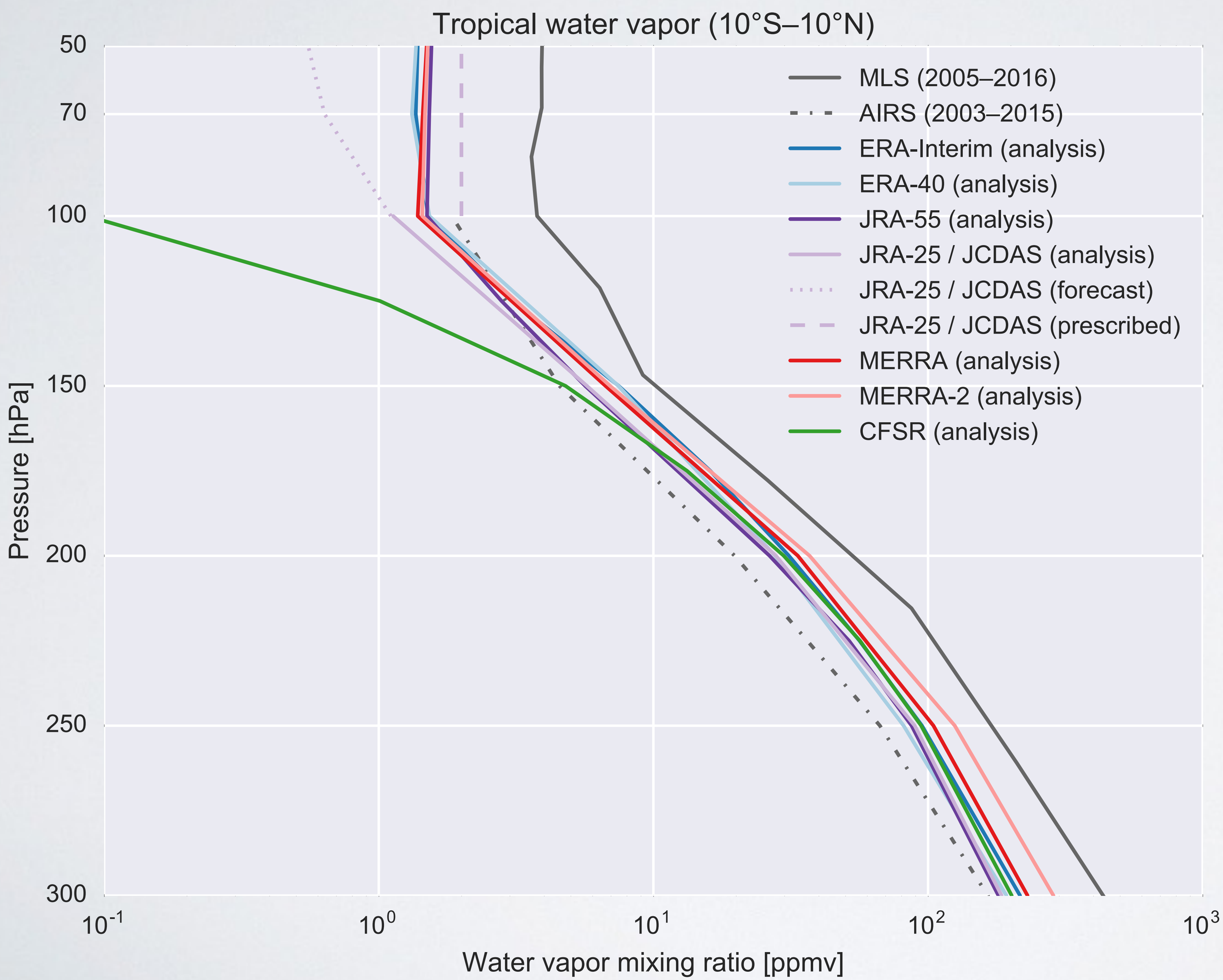
Monthly/zonal climatologies:
ERA-40, ERA-Interim, NCEP R1

Prognostic ozone models used by reanalyses overestimate ozone throughout the UTLS relative to observations

Climatologies are closer to observations, but exclude spatiotemporal variability

UTLS composition in reanalyses

Differences in water vapor and clouds may also affect Q_{rad}:



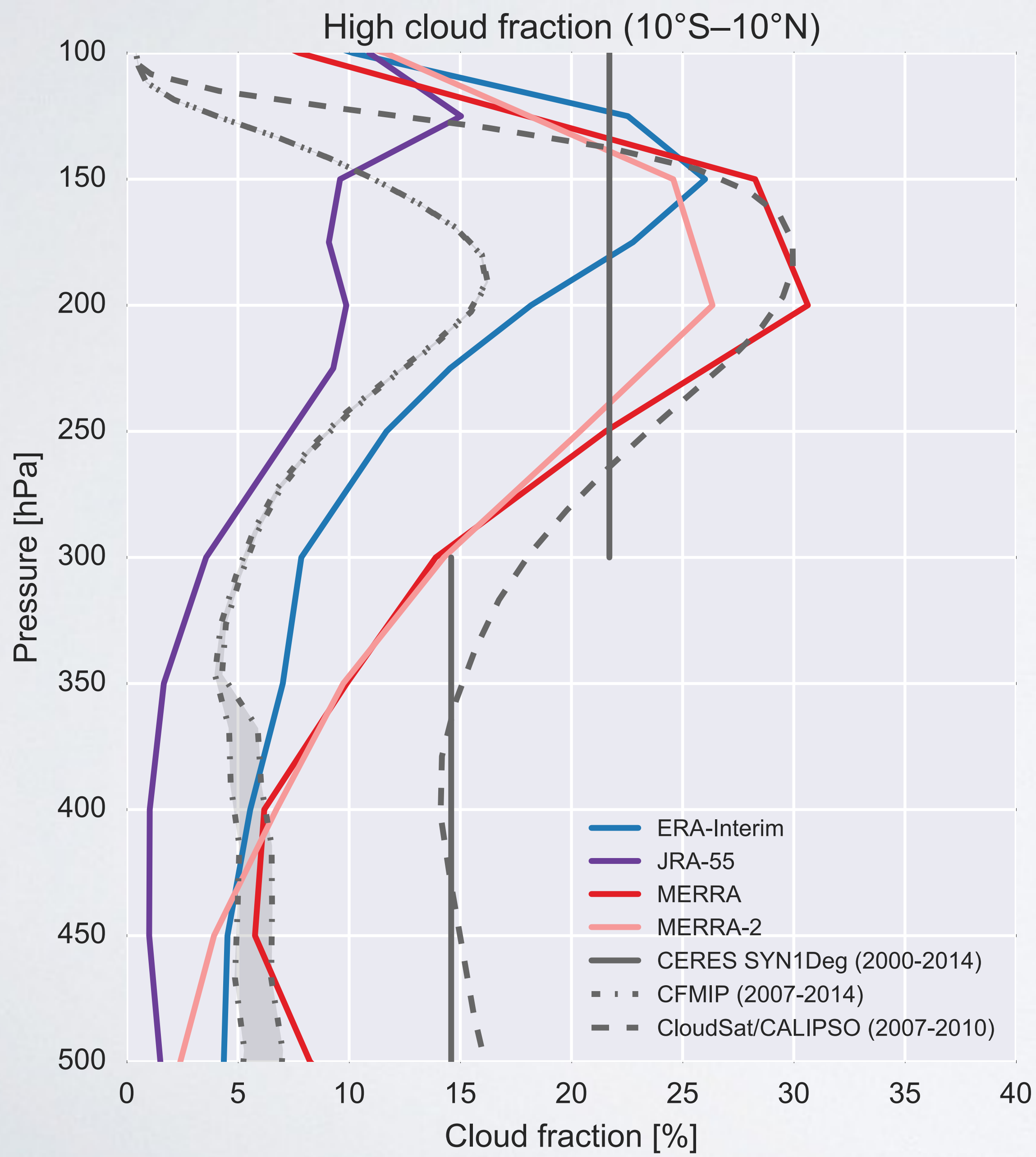
Reanalyses do not produce physically meaningful variations in humidity values above the tropopause — most systems use constant or climatological stratospheric water vapor in radiation calculations

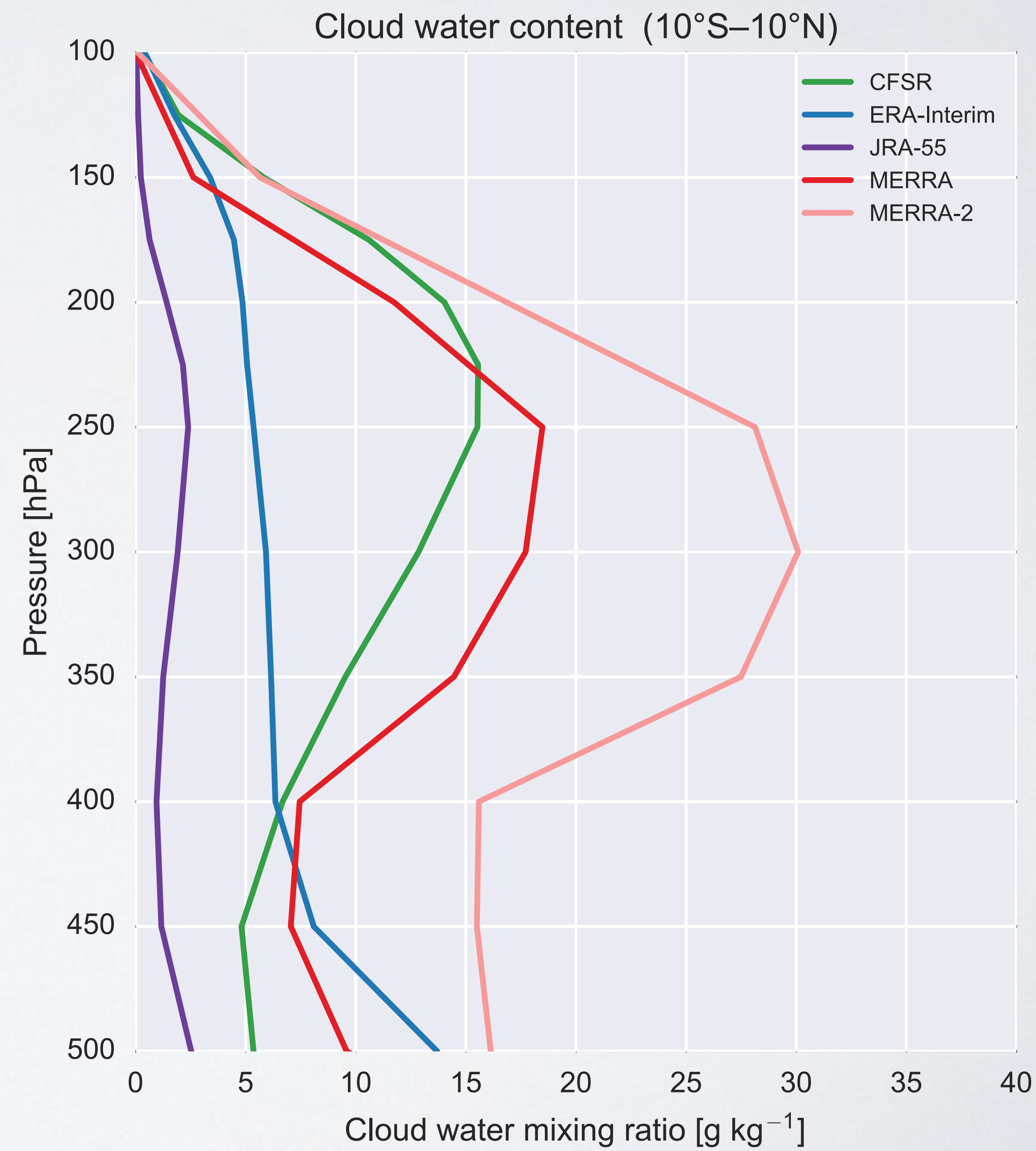
Observational constraints on water vapor are sparse in the UT as well, where radiosonde measurements are unreliable above 300 hPa. Mean profiles are consistent with satellite retrievals, but use with caution!

UTLS composition in reanalyses

Differences in water vapor and clouds may also affect Q_{rad}:

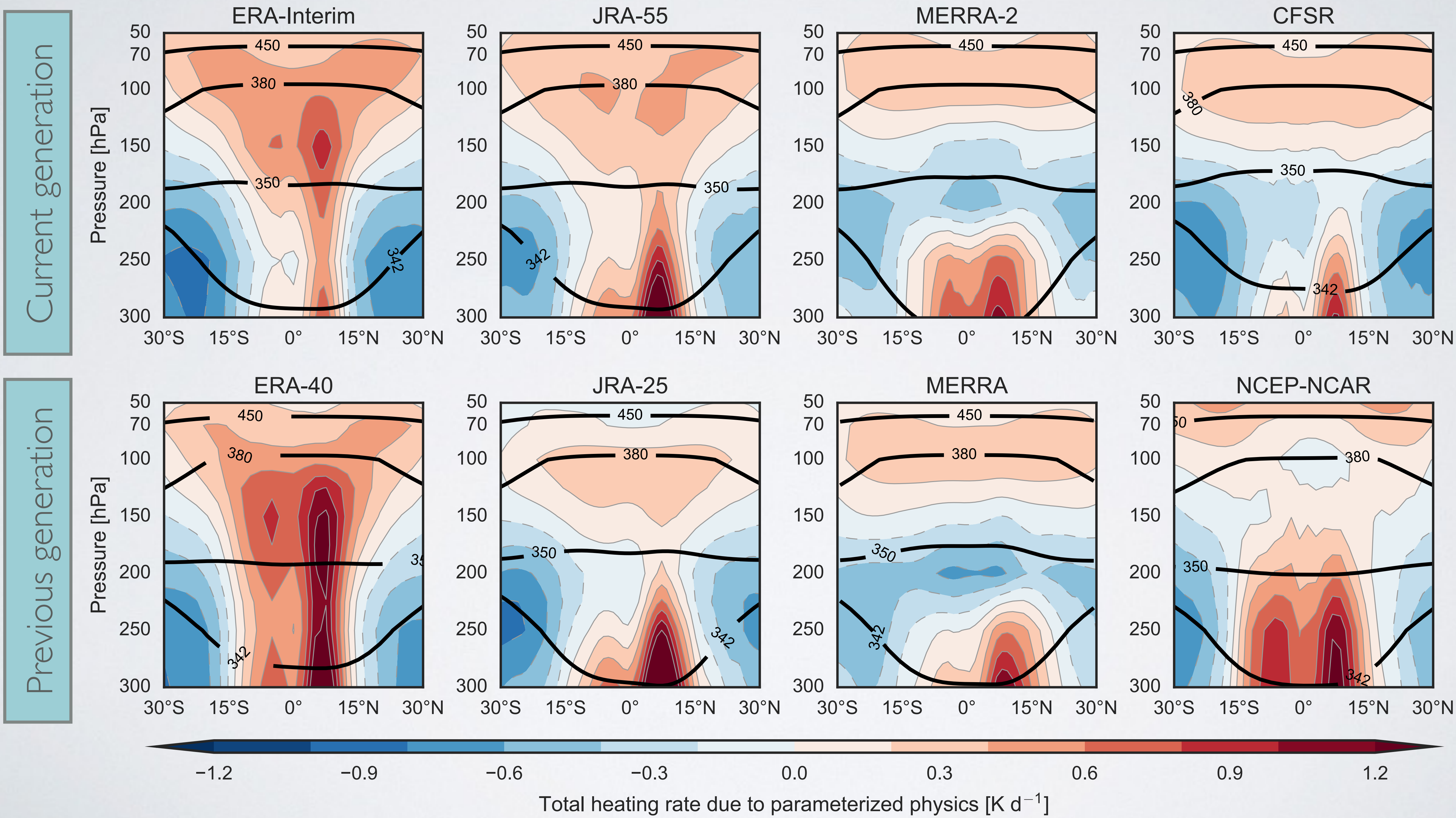
Vertical and horizontal distributions of cloud fraction and cloud water content (both liquid and ice) in the tropical UT and TTL differ substantially among reanalyses





Zonal mean diabatic heating

Take-home message: large differences exist in reanalysis diabatic heating rates in the tropical UTLS



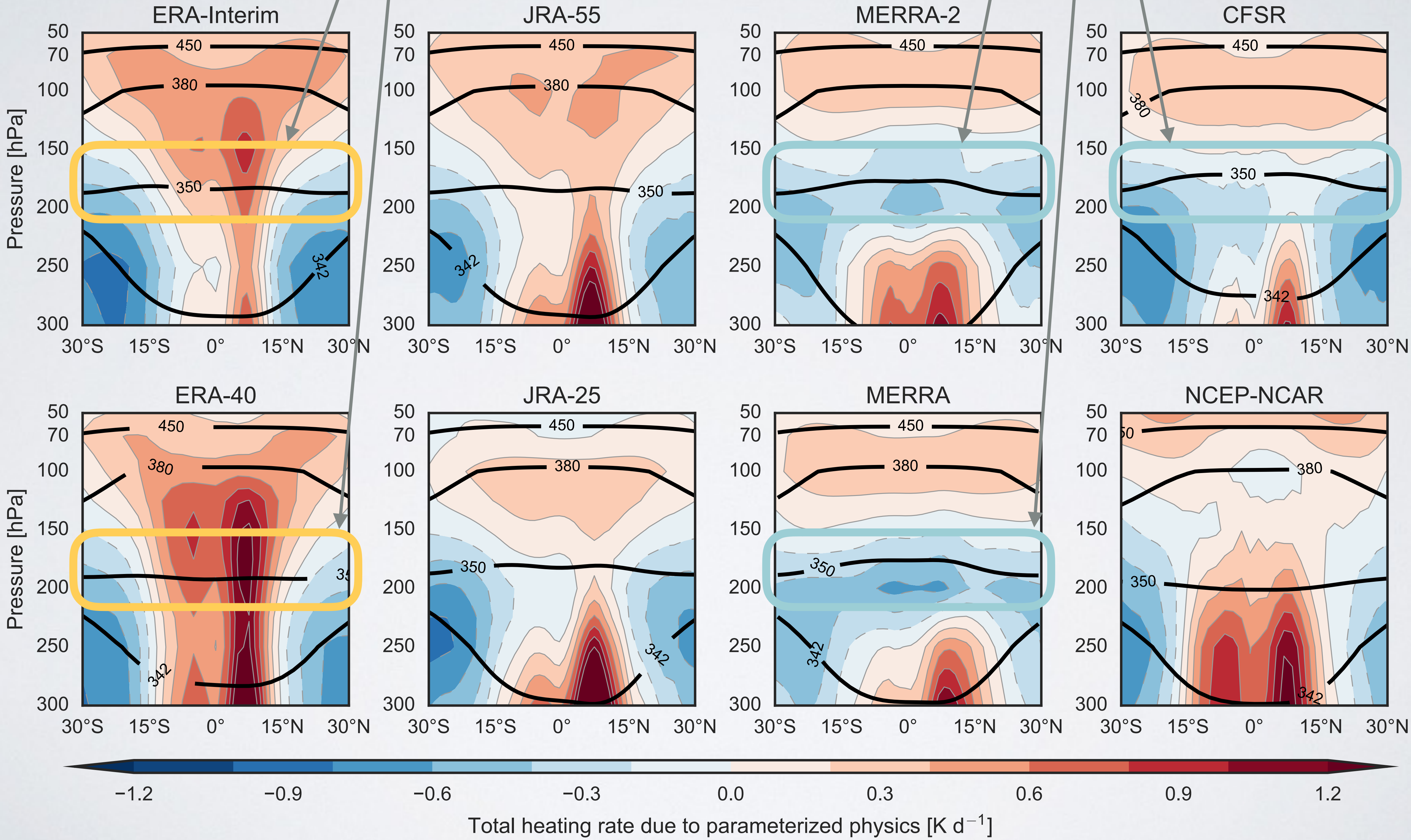
See also Wright & Fueglistaler, *ACP* 2013, doi:10.5194/acp-13-9565-2013

Zonal mean diabatic heating

Key differences…

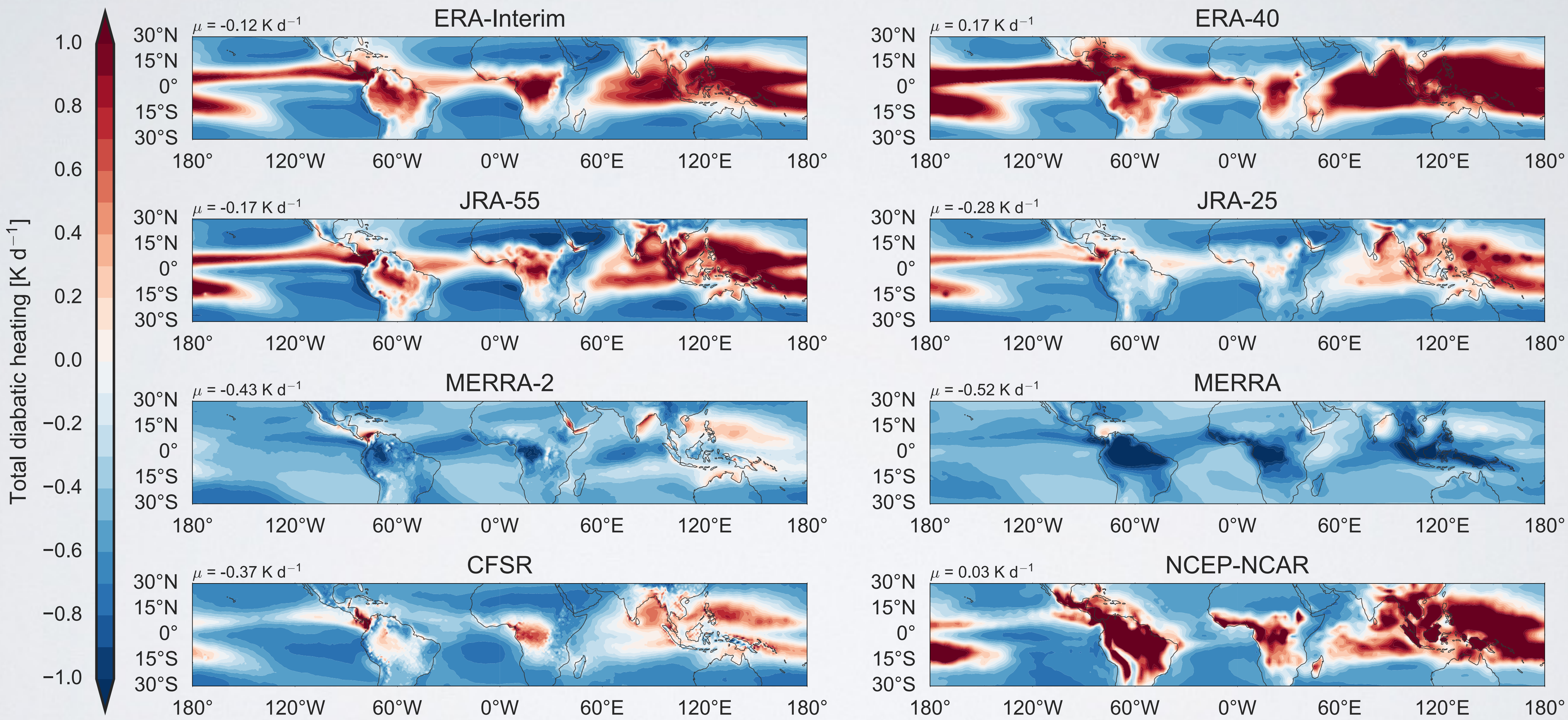
Contrasts with strong heating in ERA-I & ERA-40

Cooling above 200 hPa in tropics in MERRAs and CFSR — a transport barrier?



Time mean heating in the upper troposphere: 200 hPa

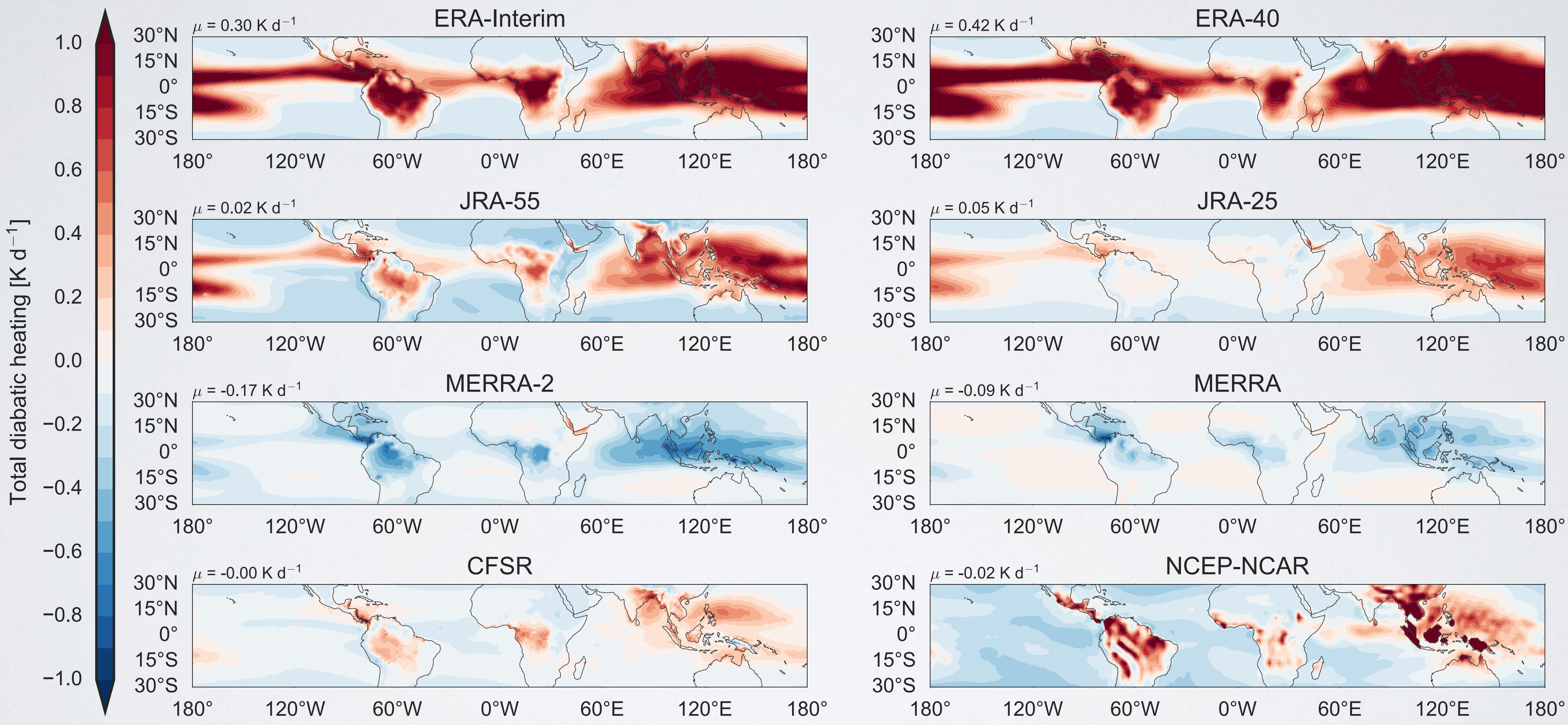
The strongest upper tropospheric heating in most systems is located in the deep convective regions of the tropics, especially over continents and in the maritime convergence zones



Heating in CFSR is more confined to the continents, while MERRA and MERRA-2 show strong cooling over most convective regions. This difference is particularly pronounced in MERRA.

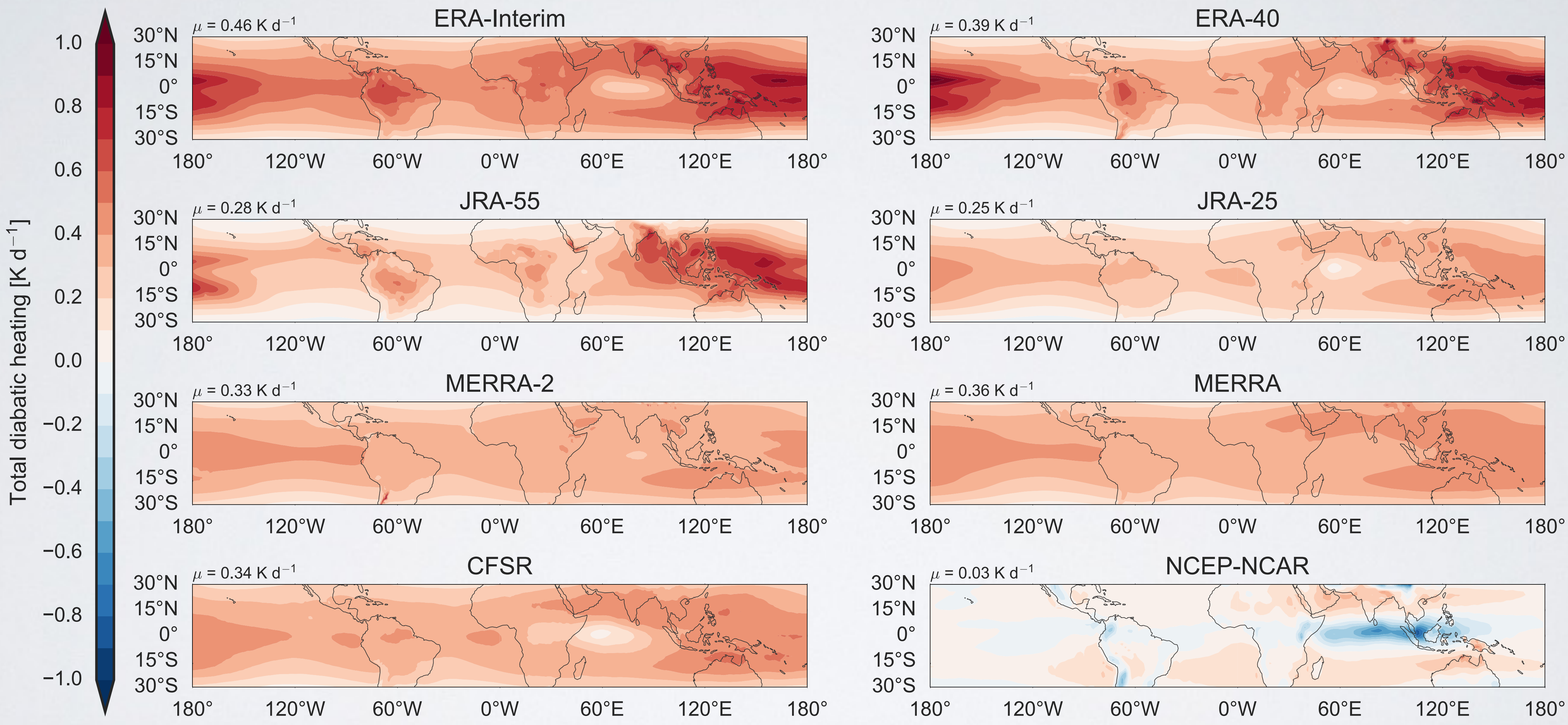
Time mean heating at the base of the TTL: 150 hPa

These qualitative differences are even more apparent at the base of the TTL, where MERRA and MERRA-2 have opposite spatial patterns of net heating and cooling relative to other systems



Time mean heating near the tropopause: 100 hPa

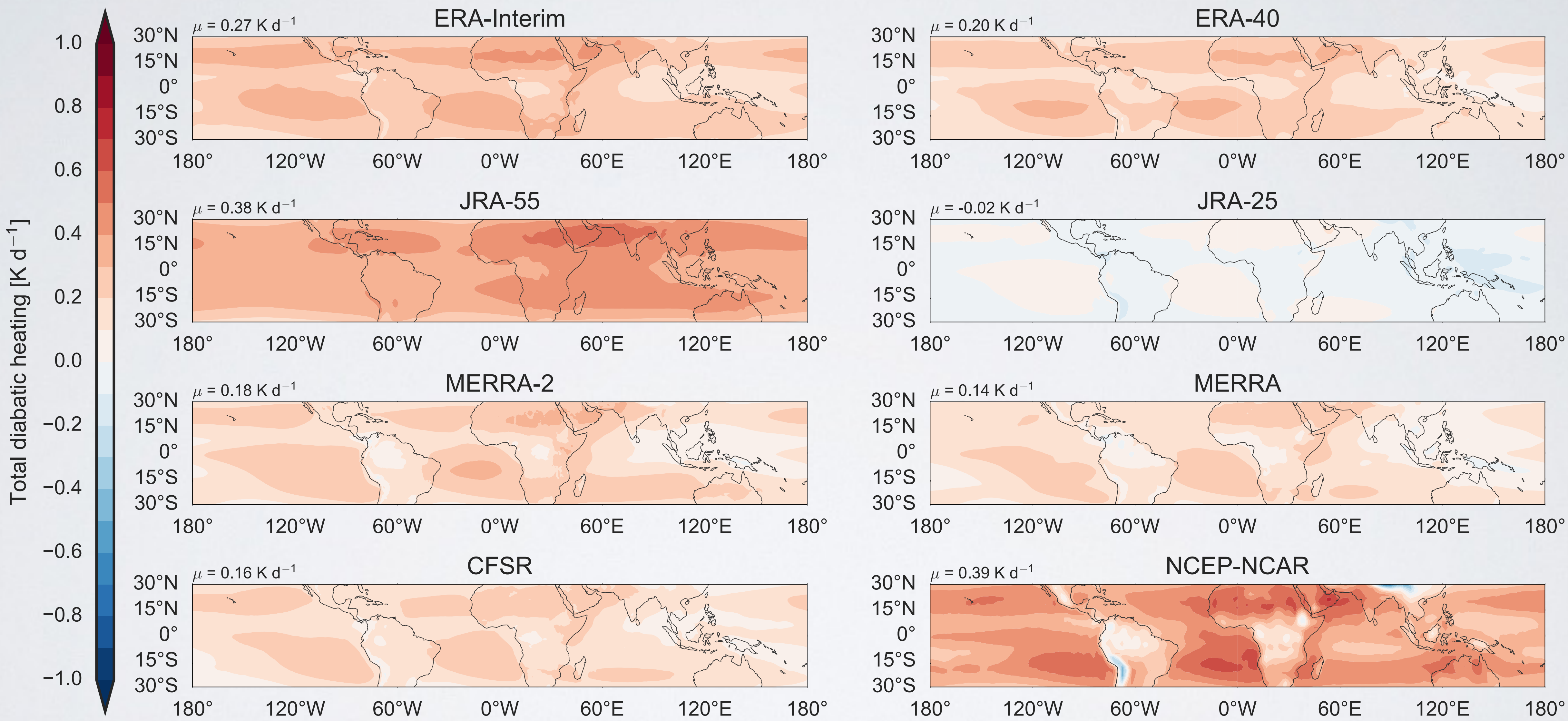
Diabatic heating becomes more similar amongst the newer reanalyses close to the tropopause, though the radiative response in convective regions still differs substantially in magnitude



NCEP-NCAR is quite different from the newer reanalyses at both 150 and 100 hPa, with deep convective effects penetrating to 150 hPa and a tropical core of radiative cooling at 100 hPa

Time mean heating in the lower stratosphere: 50 hPa

Differences near 50 hPa are more quantitative than qualitative, but imply different rates of ascent in the tropical Brewer–Dobson circulation — JRA-55 even produces net cooling at this level…

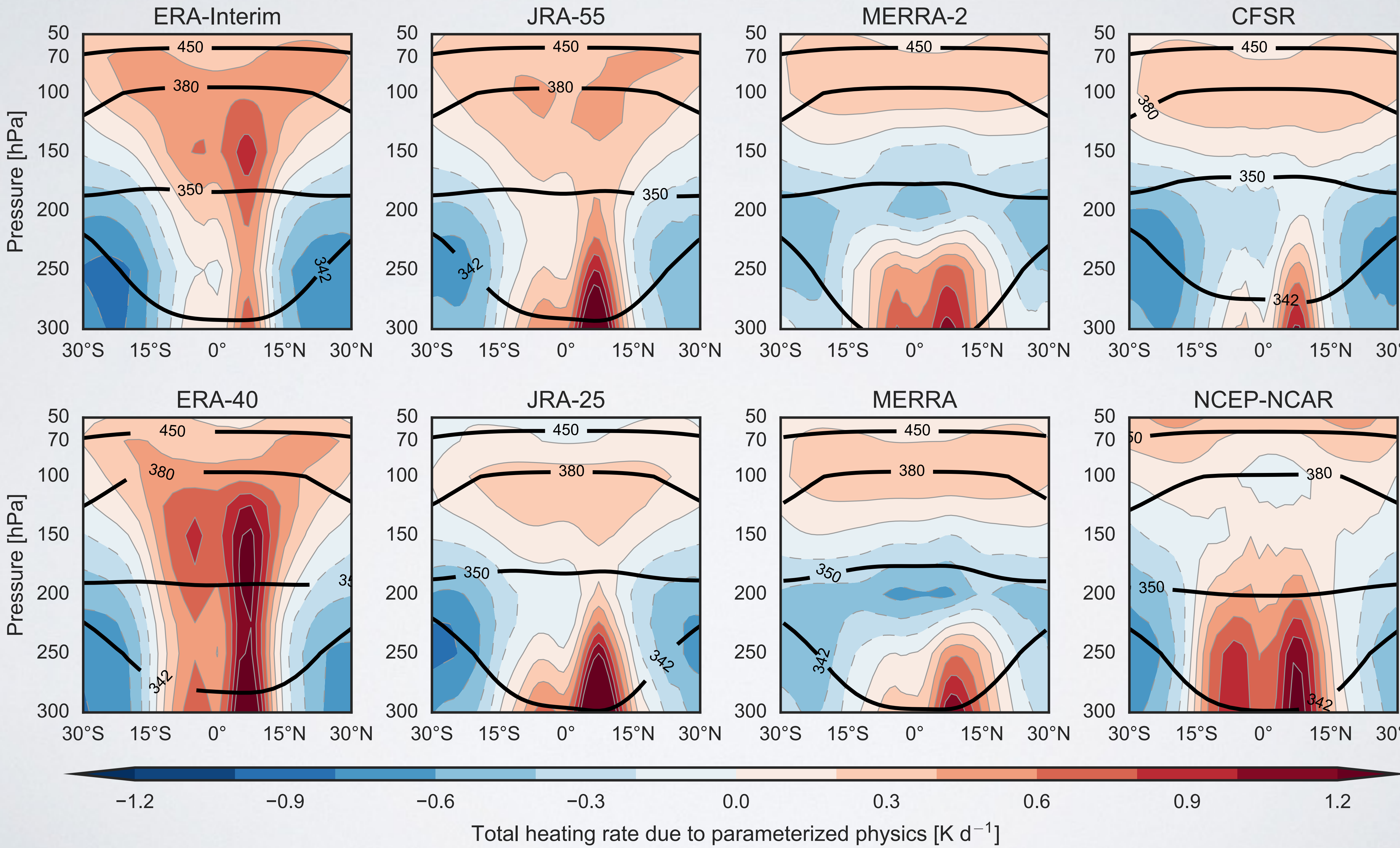


The cooling in JRA-25, which extends upward to about 30 hPa, causes large problems in transport model simulations of stratospheric composition — the deep BDC effectively doesn't exist!

Zonal mean diabatic heating

Key differences…

Reanalyses show both qualitative and quantitative differences in total heating in the tropical lower stratosphere

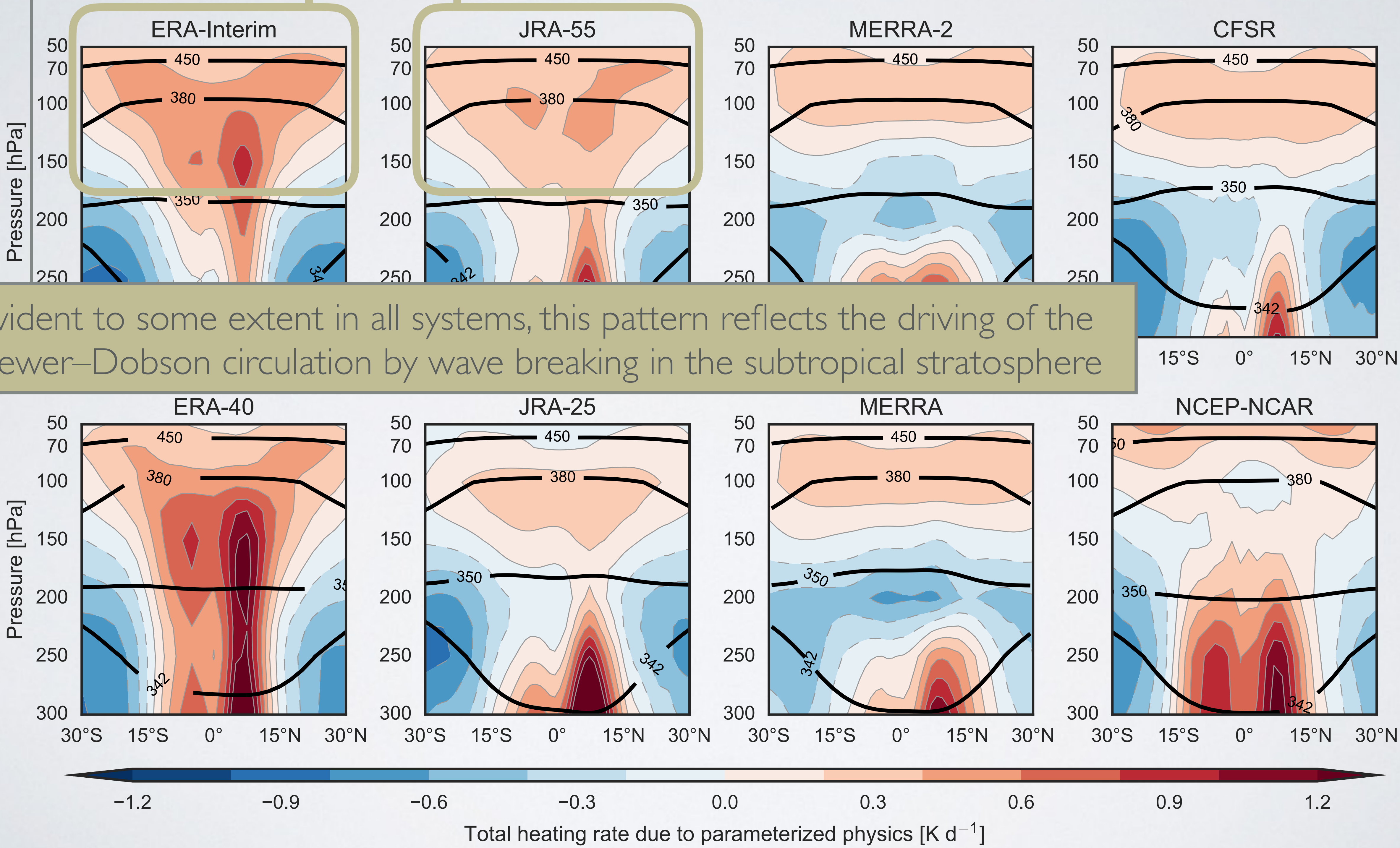


Zonal mean diabatic heating

Reanalyses show both qualitative and quantitative differences in total heating in the tropical lower stratosphere

ERA-Interim and JRA-55 show pronounced "V" shapes

Evident to some extent in all systems, this pattern reflects the driving of the Brewer–Dobson circulation by wave breaking in the subtropical stratosphere



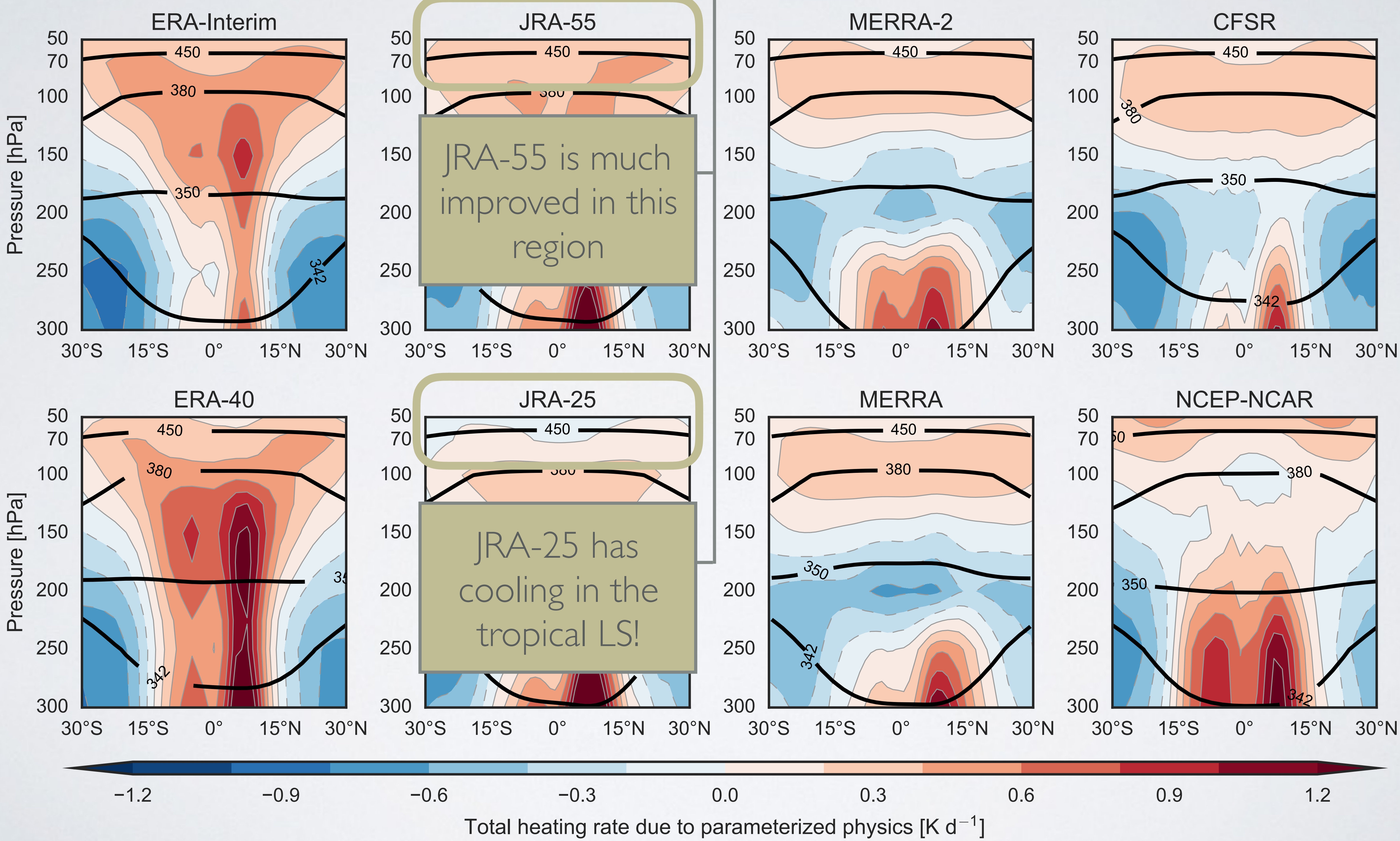
Zonal mean diabatic heating

Key differences…

Reanalyses show both qualitative and quantitative differences in total heating in the tropical lower stratosphere

JRA-55 is much improved in this region

JRA-25 has cooling in the tropical LS!

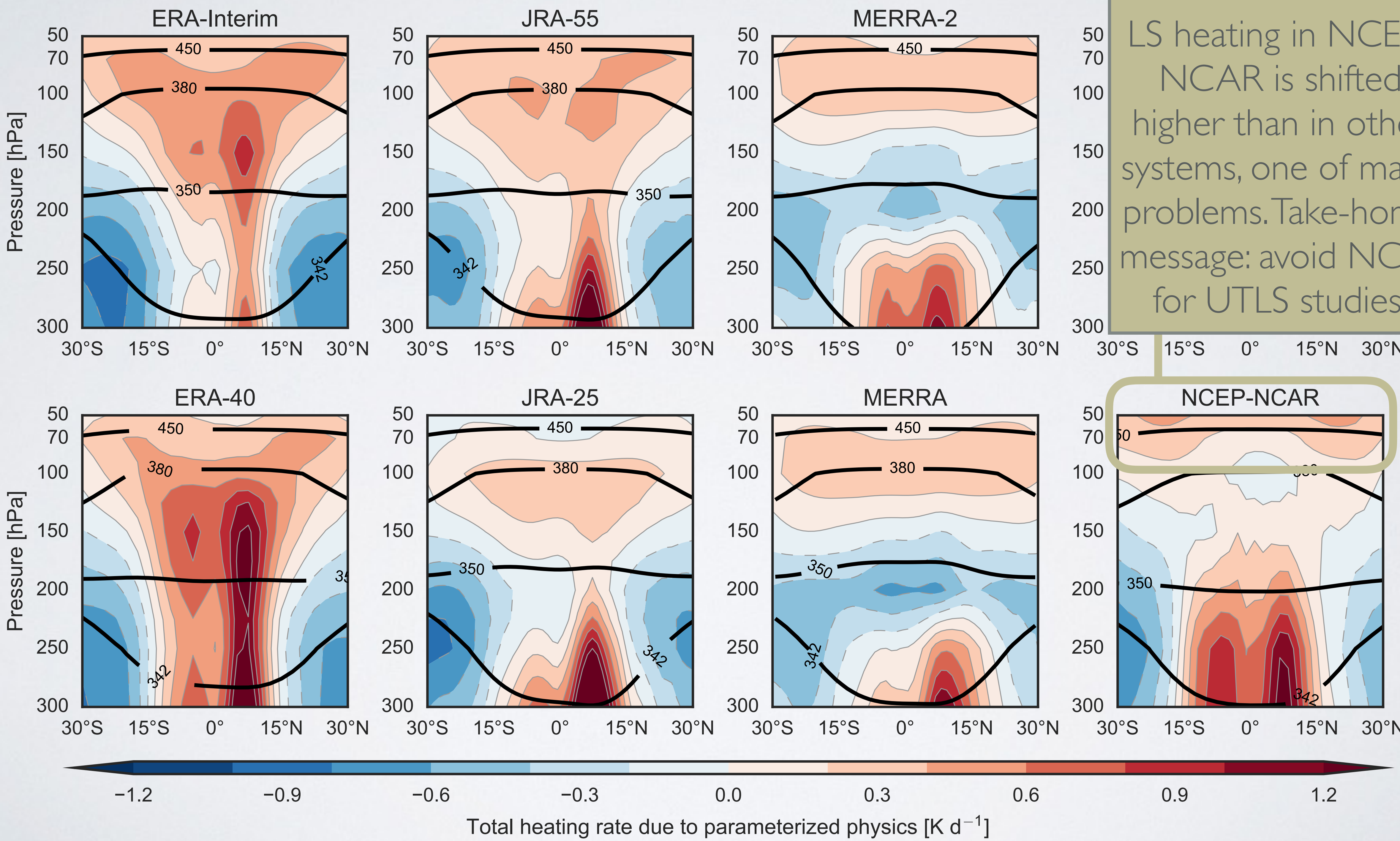


Zonal mean diabatic heating

Key differences…

Reanalyses show large differences in total heating in the tropical lower stratosphere

LS heating in NCEP-NCAR is shifted higher than in other systems, one of many problems. Take-home message: avoid NCEP for UTLS studies!

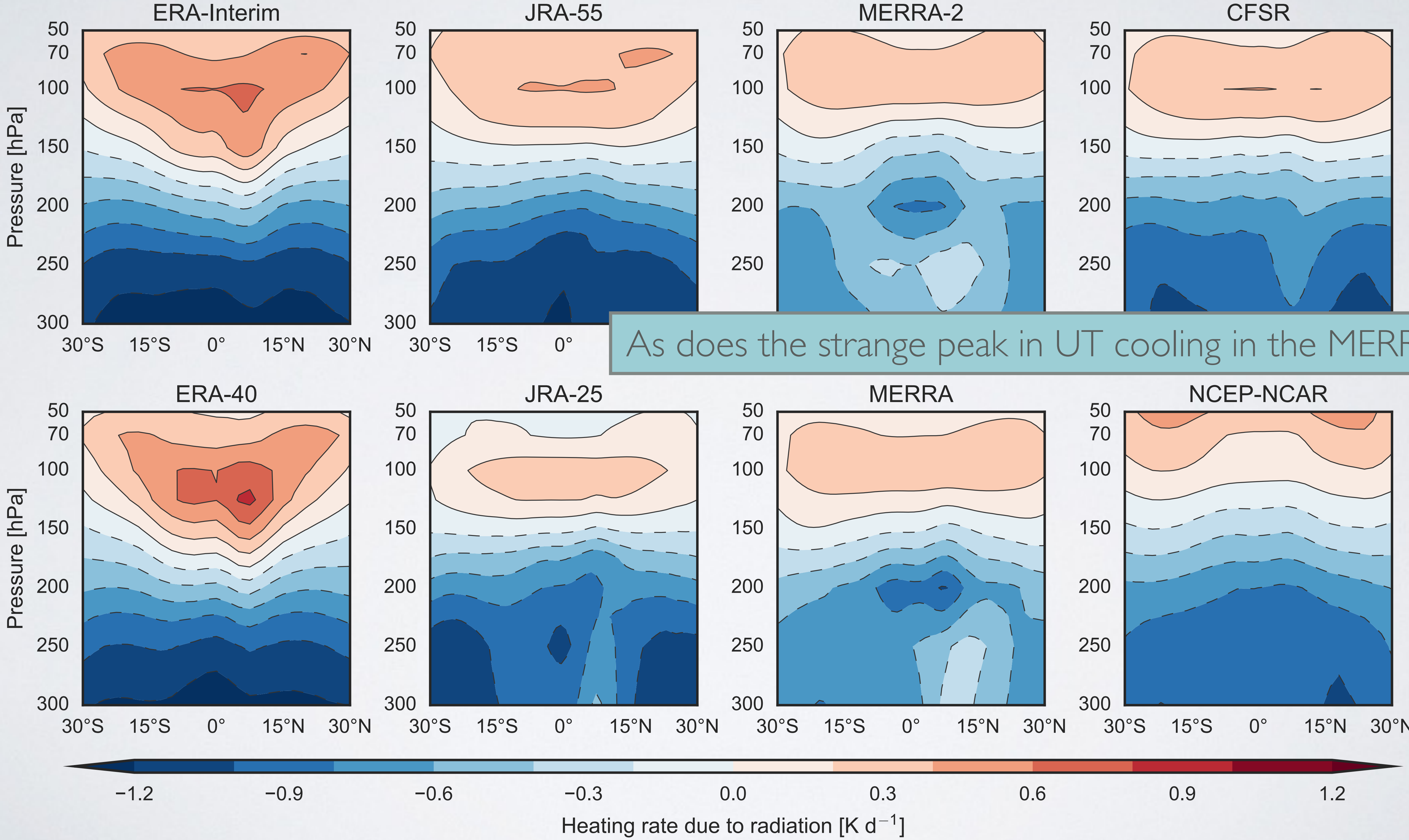


Zonal mean diabatic heating: radiation

We might expect radiative heating to be better constrained, but…

The different stratospheric signatures originate in radiative heating rates

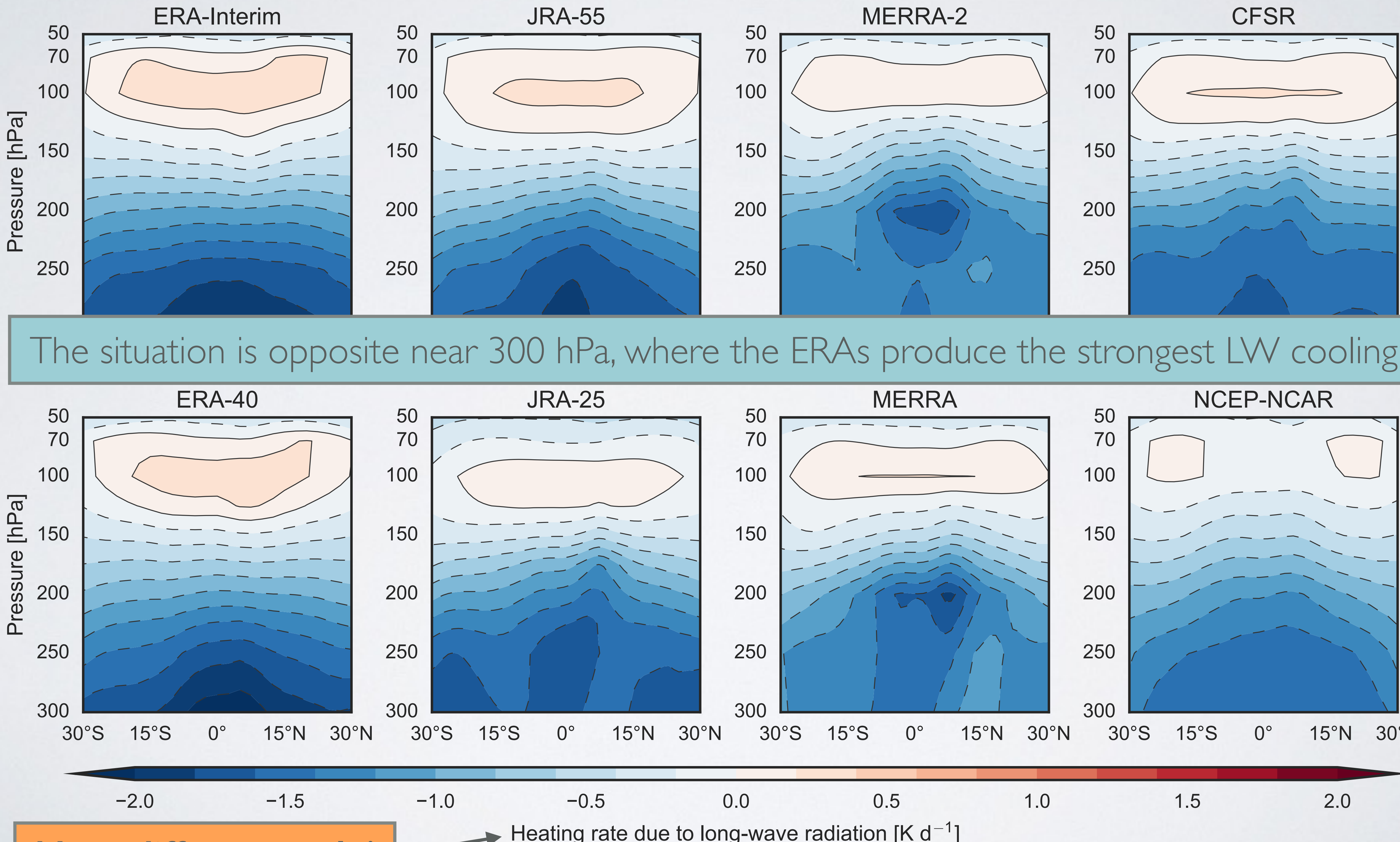
As does the strange peak in UT cooling in the MERRAs



Zonal mean diabatic heating: long-wave radiation

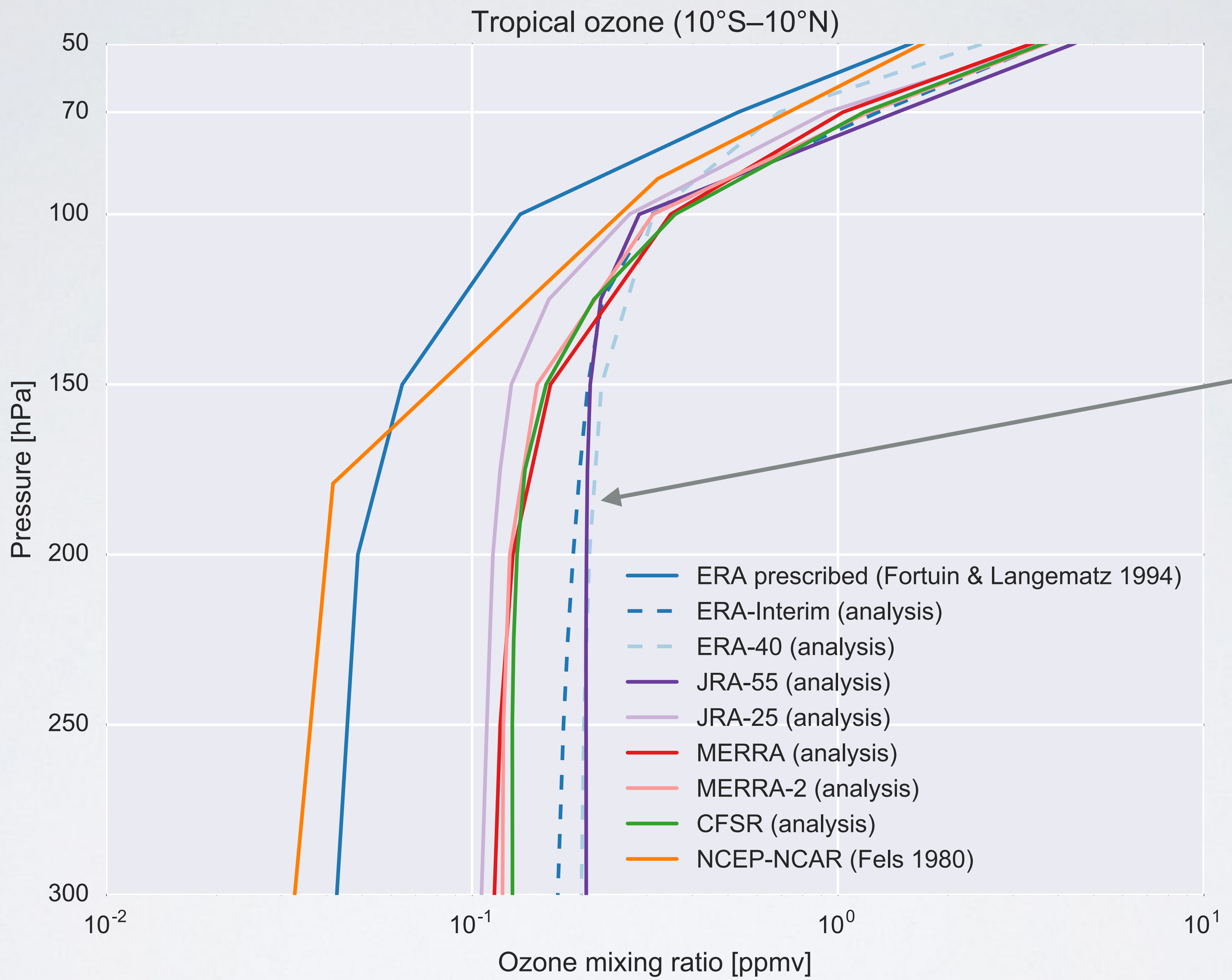
The ERAs have less LW cooling and more heating near 100~200 hPa than the MERRAs

The situation is opposite near 300 hPa, where the ERAs produce the strongest LW cooling



Note different scale!

Zonal mean diabatic heating: long-wave radiation

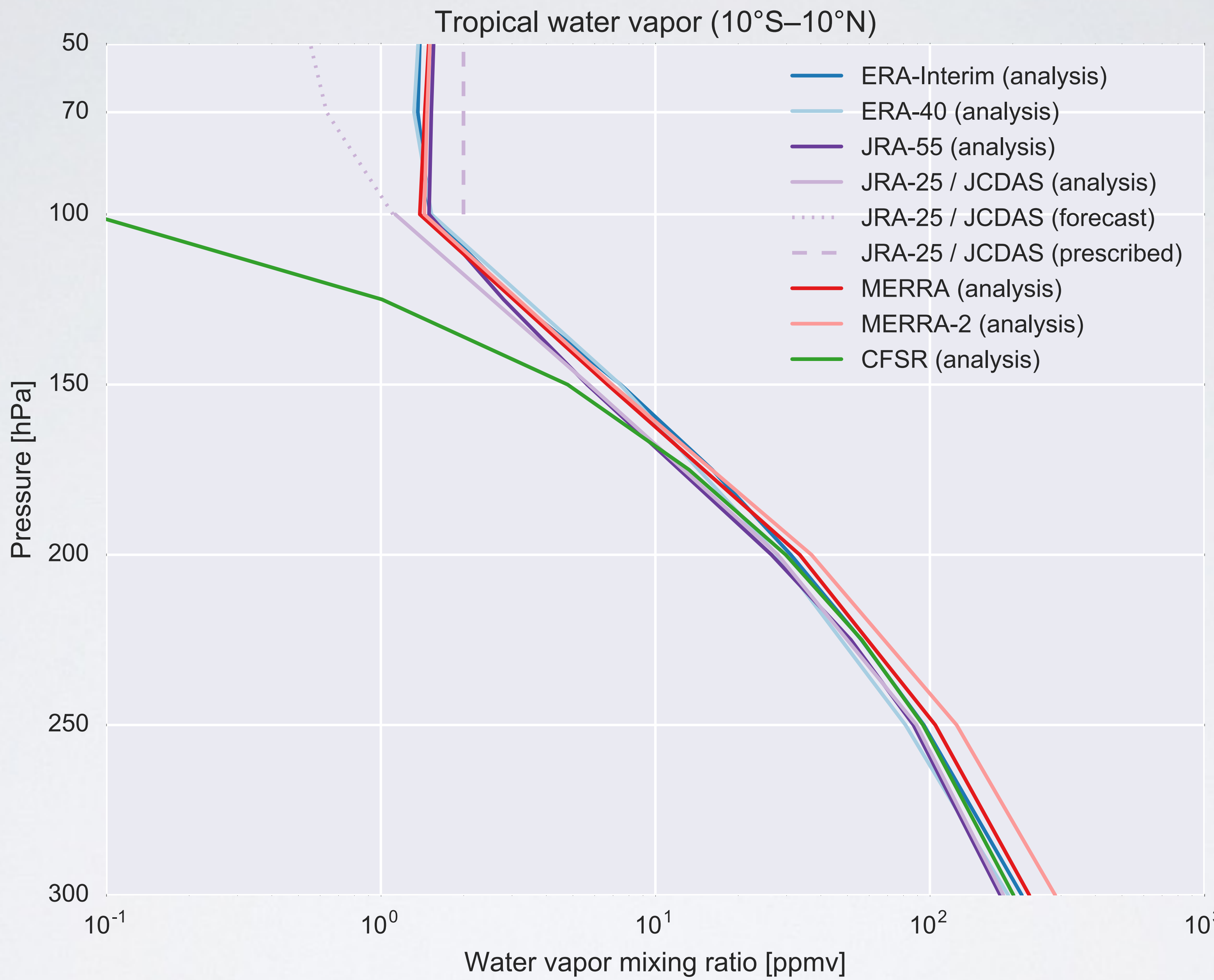


but what about JRA-55?

ERA-Interim and ERA-40 use a climatology with less UT ozone and hence less LW absorption

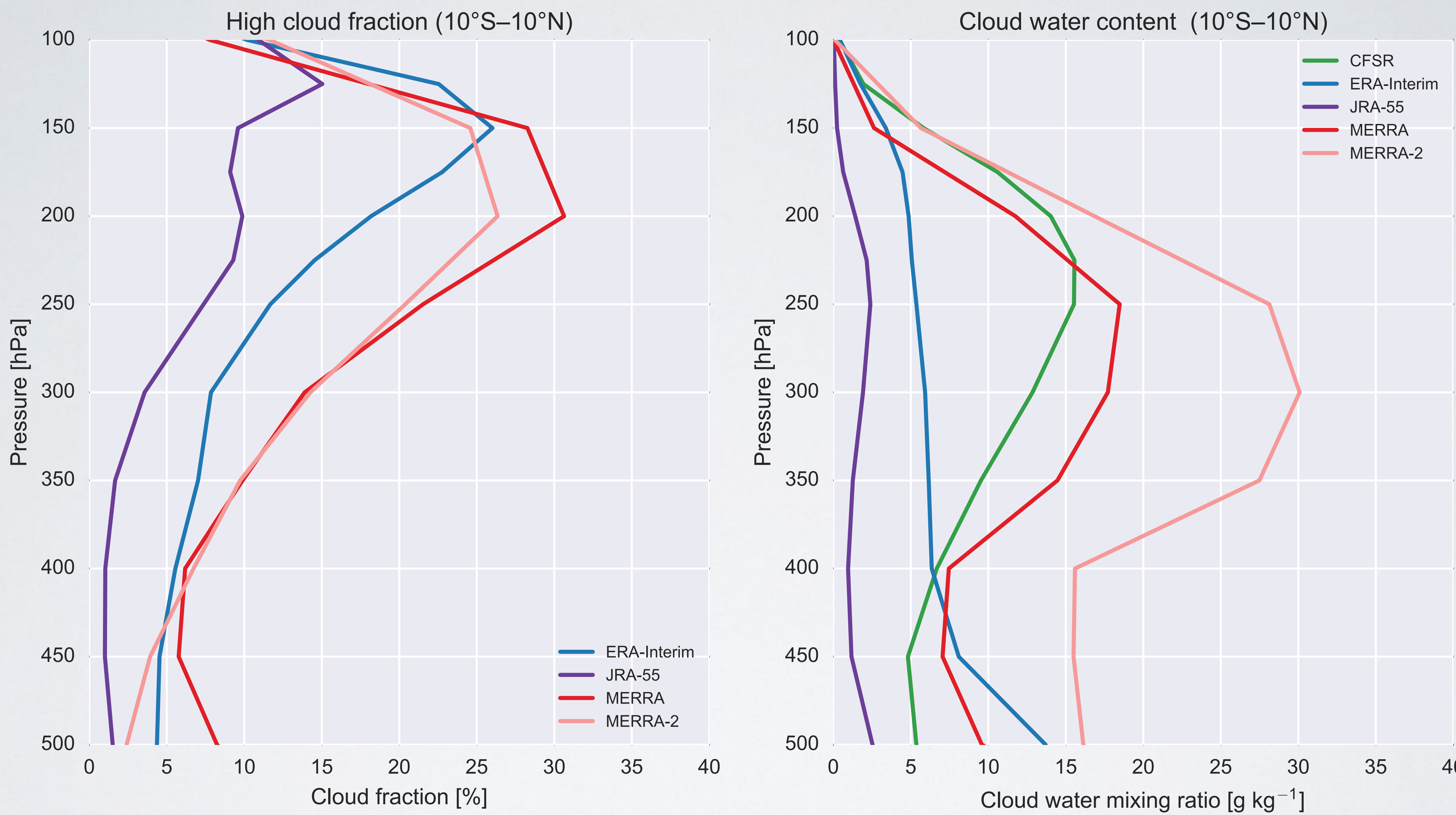
MERRA and MERRA-2 produce large amounts of UT ozone, consistent with more absorption

Zonal mean diabatic heating: long-wave radiation



MERRA and MERRA-2 also produce a more humid upper troposphere within the convective detrainment layer (200~300 hPa), also consistent with enhanced LW and SW absorption here

Vertical profiles of cloud fraction and cloud water

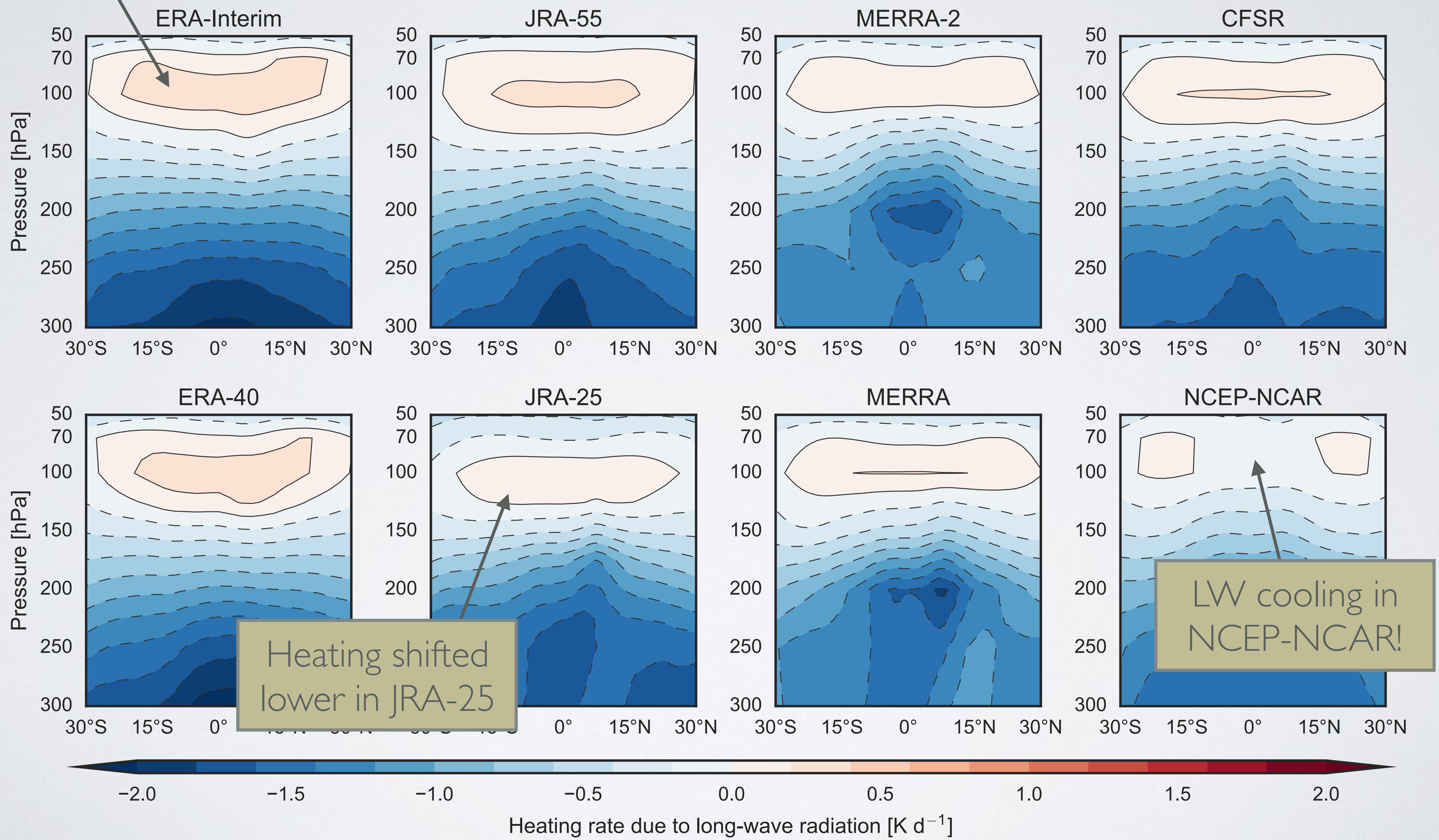


…but the main difference may be clouds: MERRA and MERRA-2 include more extensive and thicker clouds, with enhanced LW absorption in the cloud layer and enhanced emission above

Zonal mean diabatic heating: long-wave radiation

Strongest heating in ERA-Interim

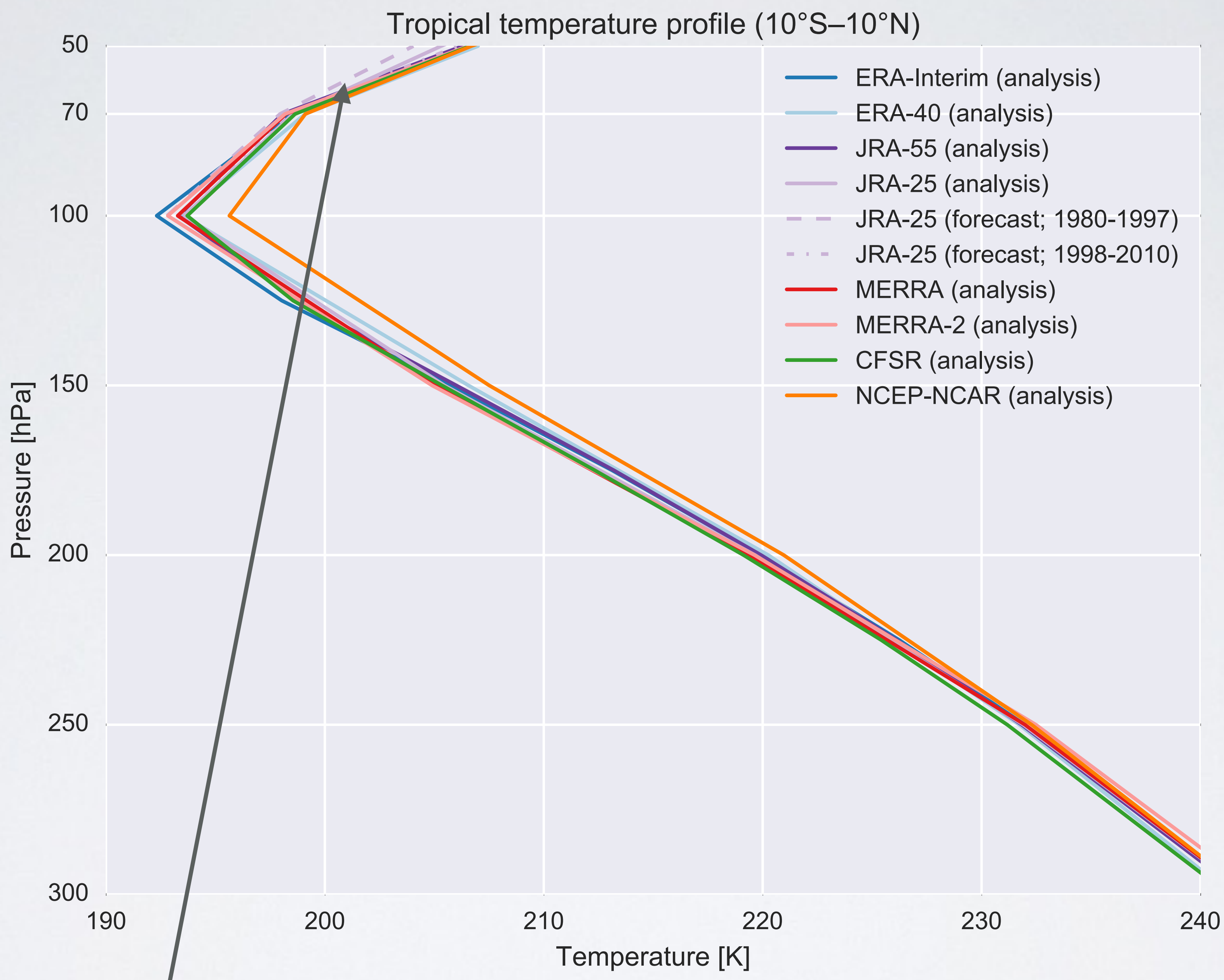
The differences near the cold point tropopause are also mainly from the LW components



Heating shifted lower in JRA-25

LW cooling in NCEP-NCAR!

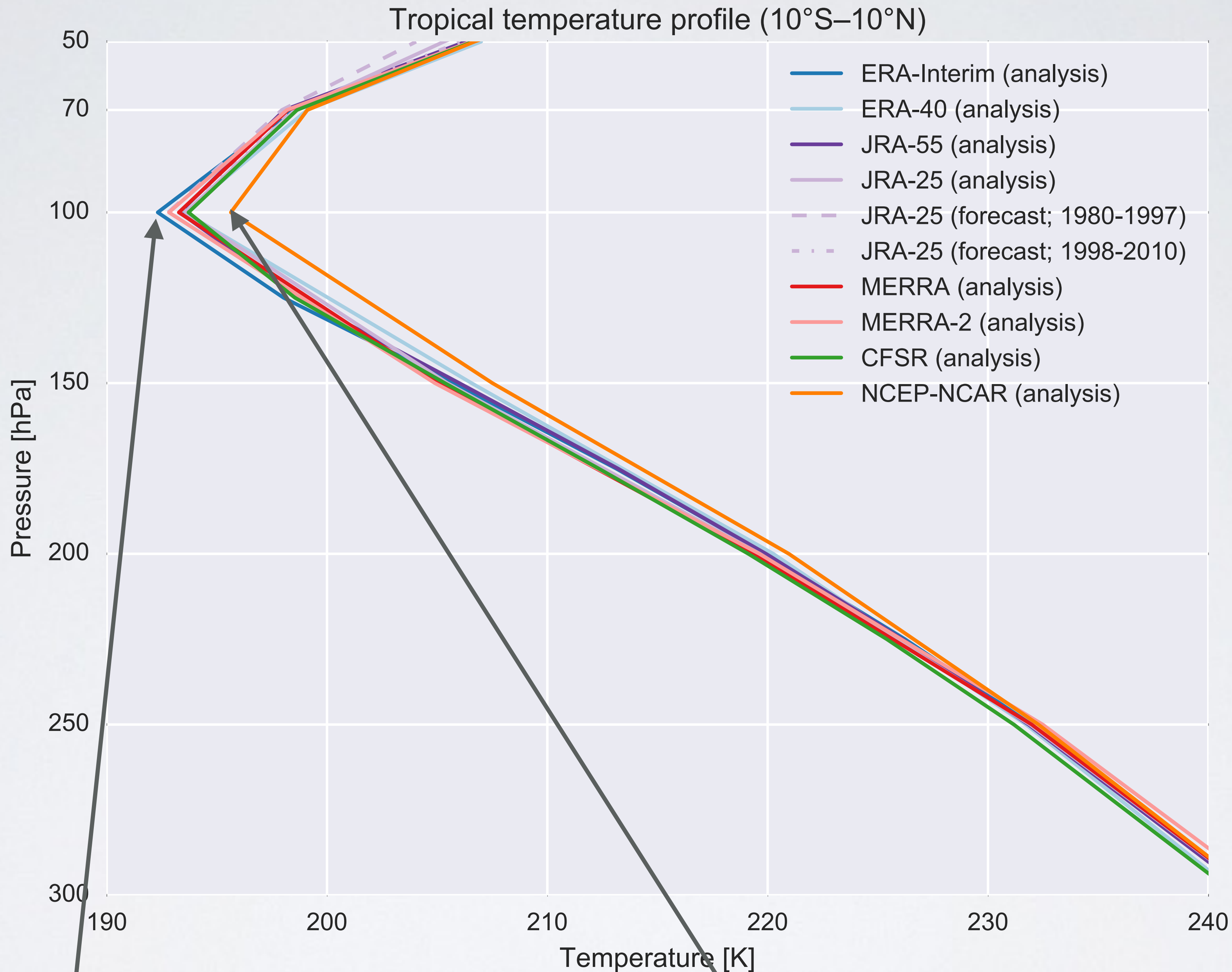
Zonal mean diabatic heating: long-wave radiation



The JRA-25 model has a cold bias in equilibrium T in the stratosphere — AMSU-A corrects the bias in T after 1998 but SSU was insufficient…

…however, warm analysis T combined with the cold bias in the radiative equilibrium T lead to radiative cooling in the stratosphere post-1998

Zonal mean diabatic heating: long-wave radiation

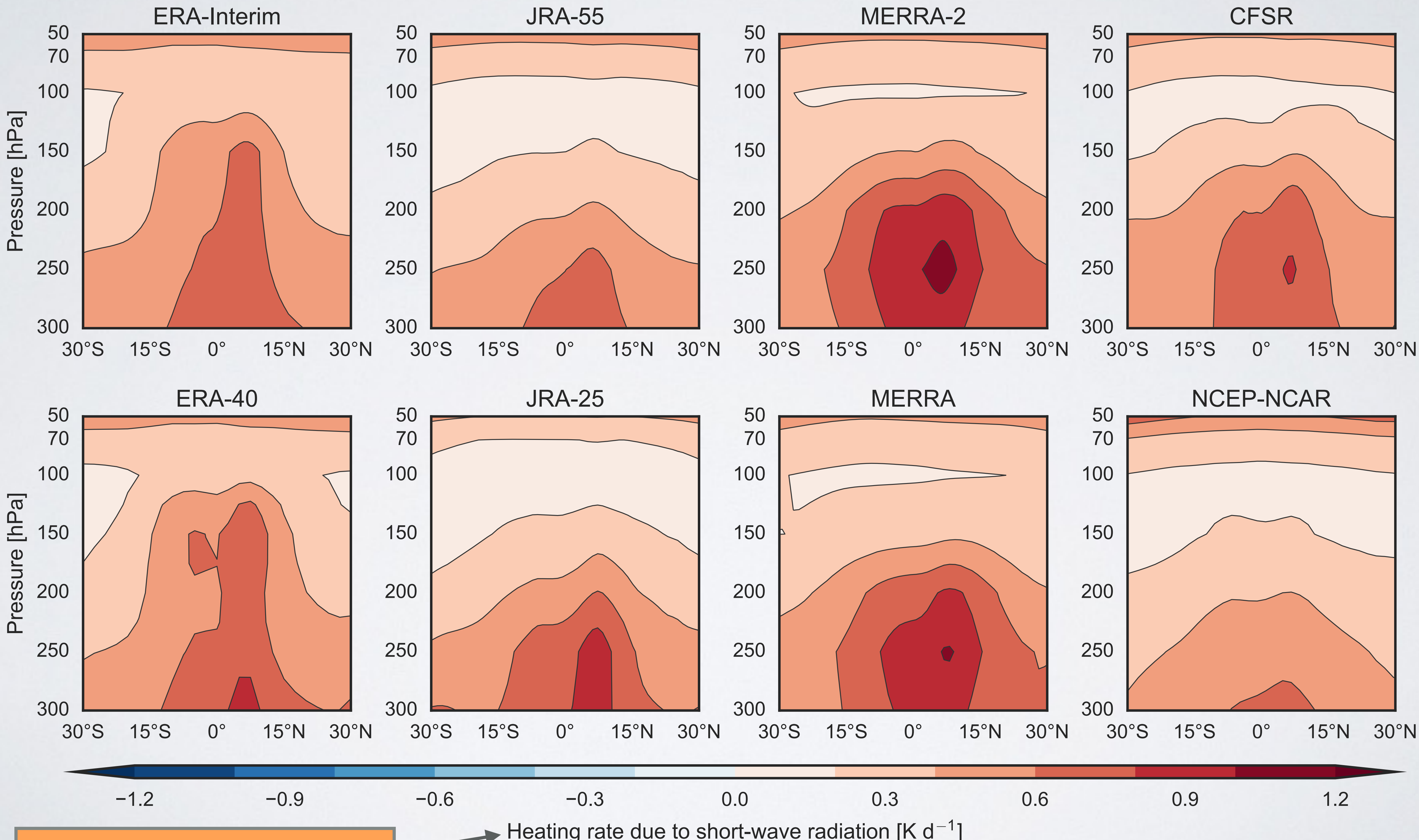


ERA-Interim is colder than other reanalyses at 100 hPa, consistent with enhanced LW heating

NCEP-NCAR has enhanced LW cooling near the tropopause due to a warm bias at 100 hPa

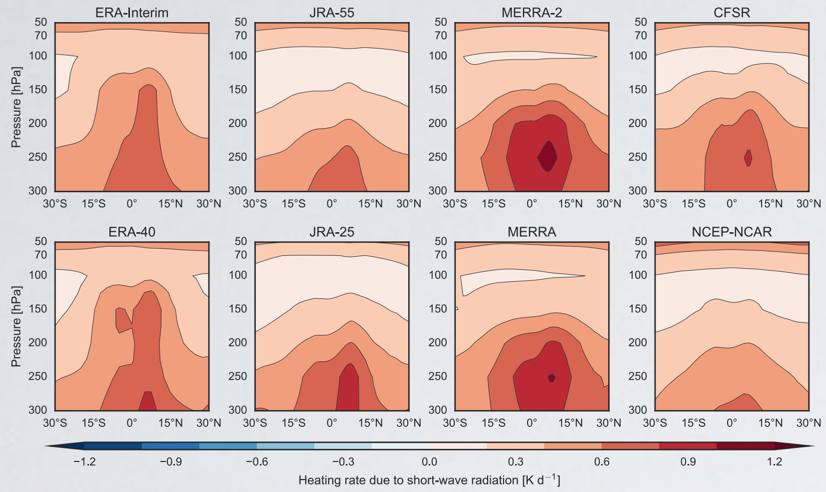
Zonal mean diabatic heating: solar radiation

Despite some small differences in the LS, differences in SW heating rates are evidently dominated by differences in cloud fields in the UT



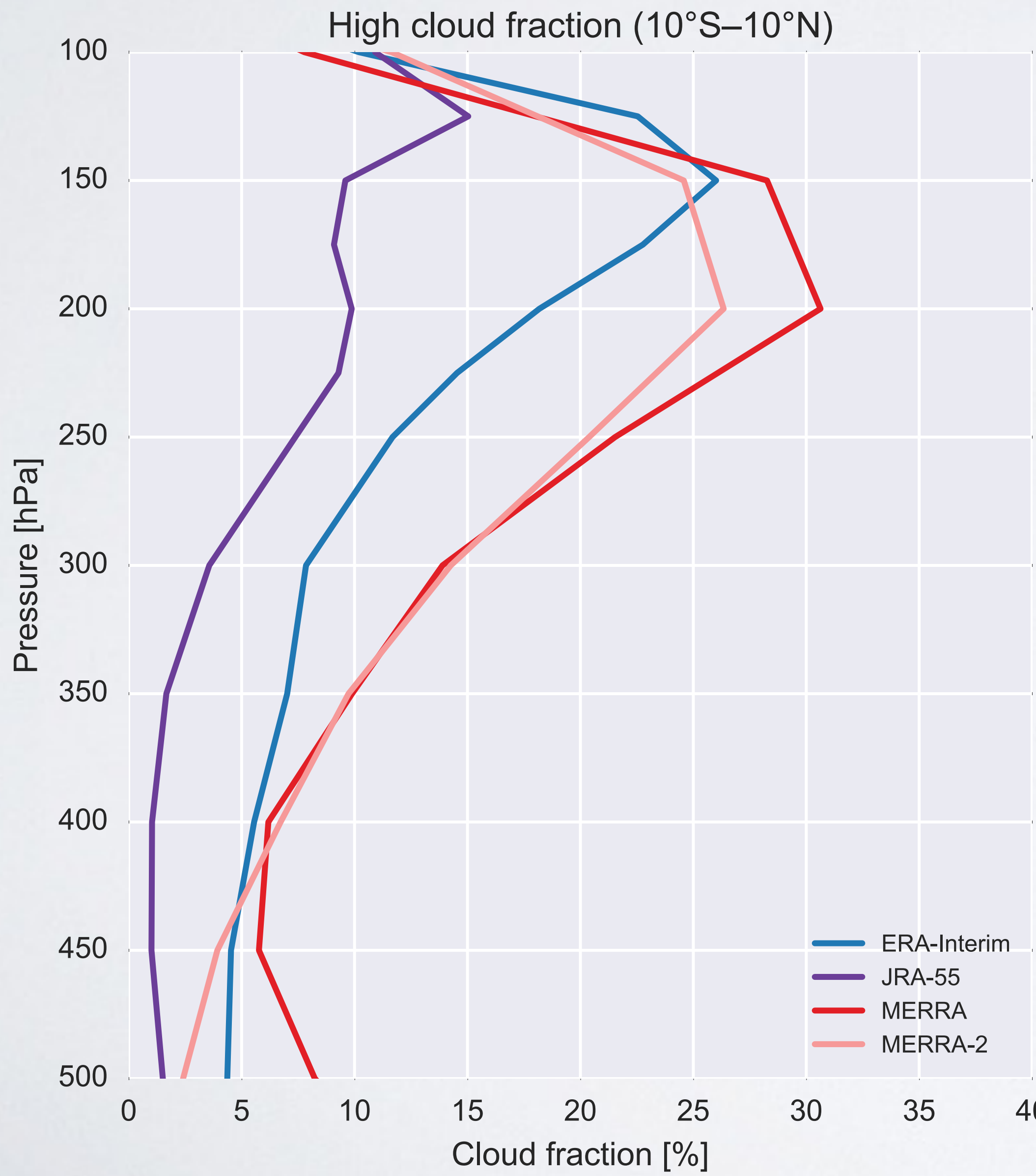
Back to the first scale

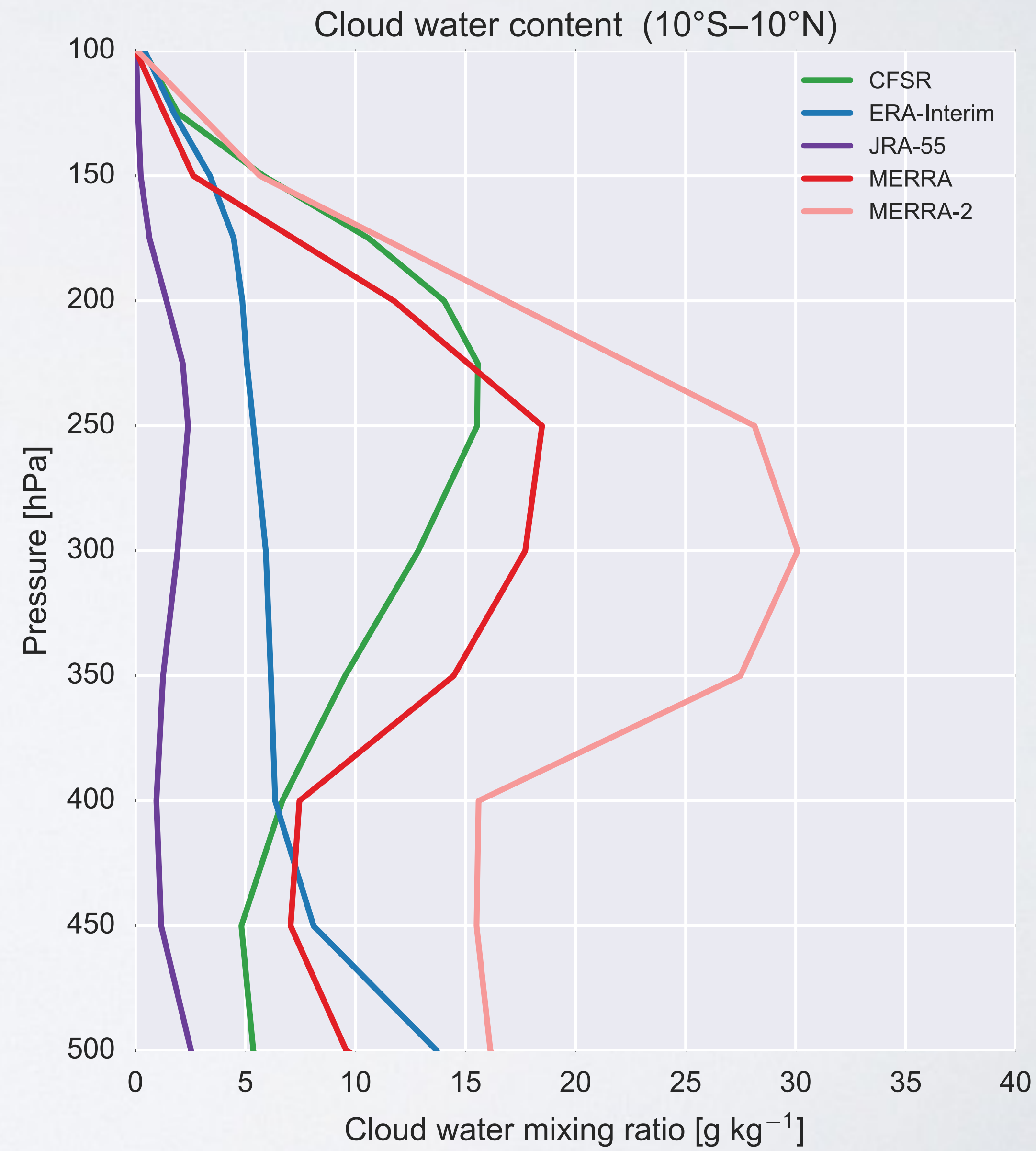
Vertical profiles of cloud fraction and cloud water



Differences in shortwave heating rates are broadly consistent with differences in cloud fields among these systems

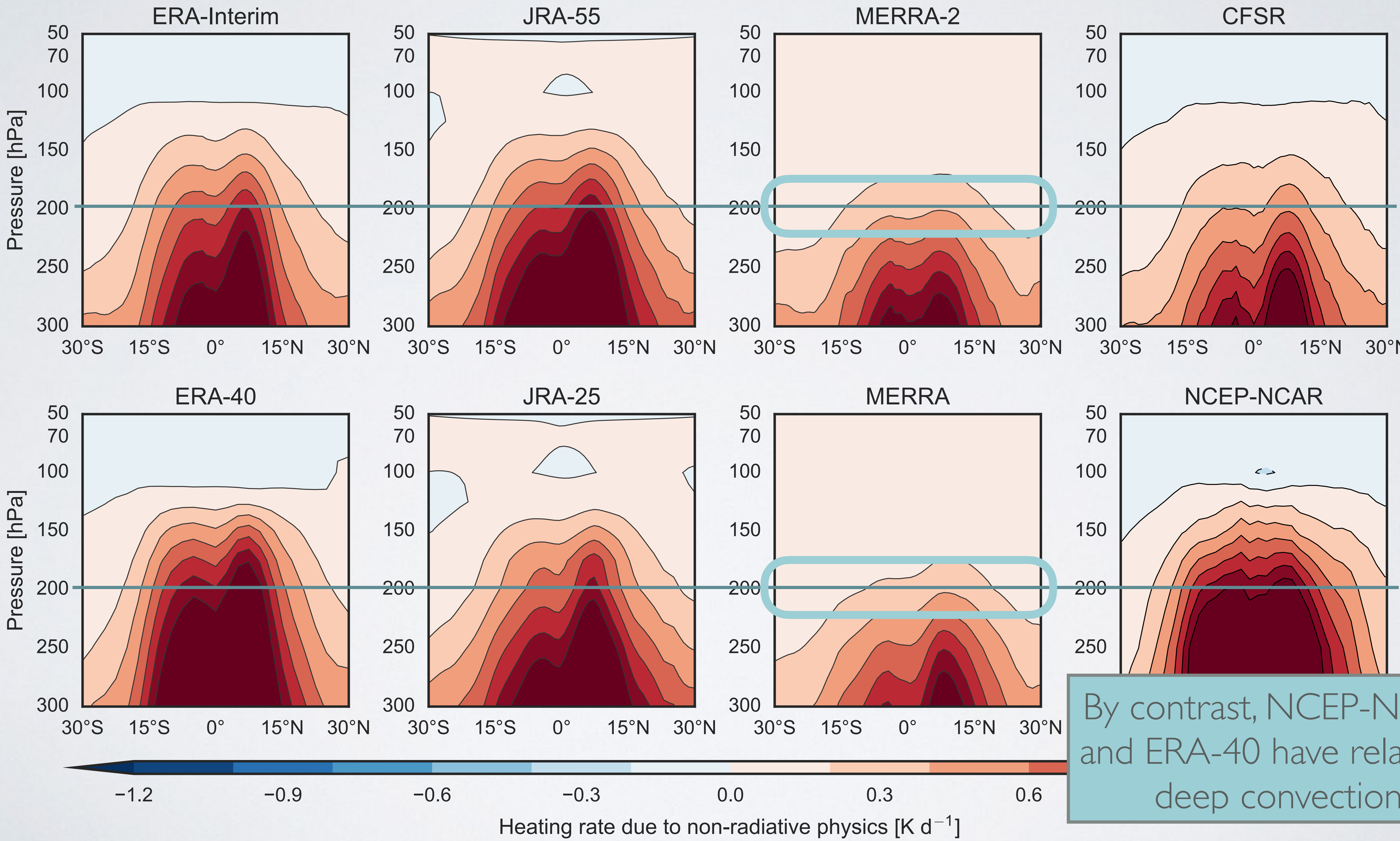
MERRA and MERRA-2 have more (and thicker) clouds in the UT, while ERA-Interim has more extensive clouds in the TTL





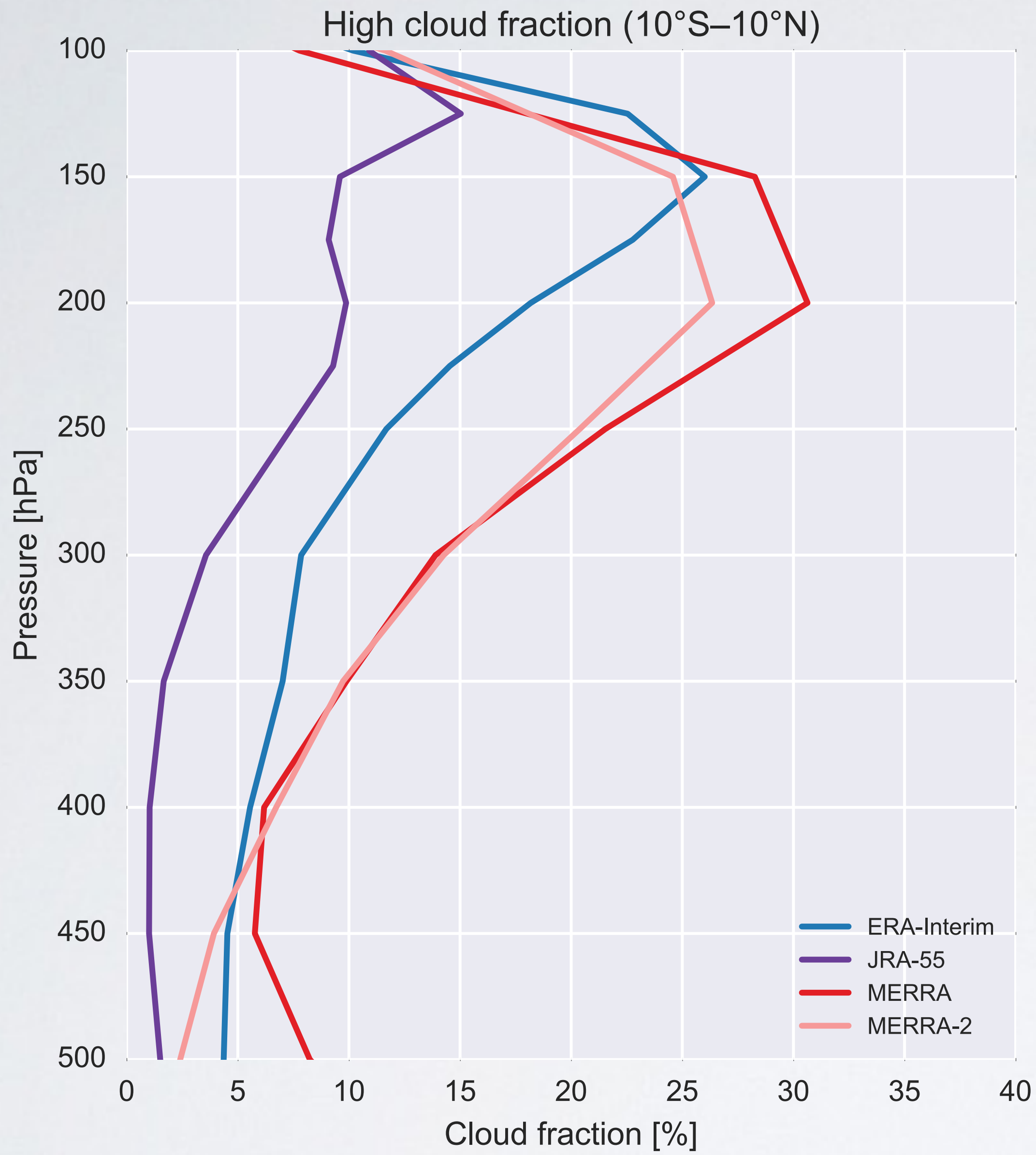
Zonal mean diabatic heating: residual (non-radiative physics)

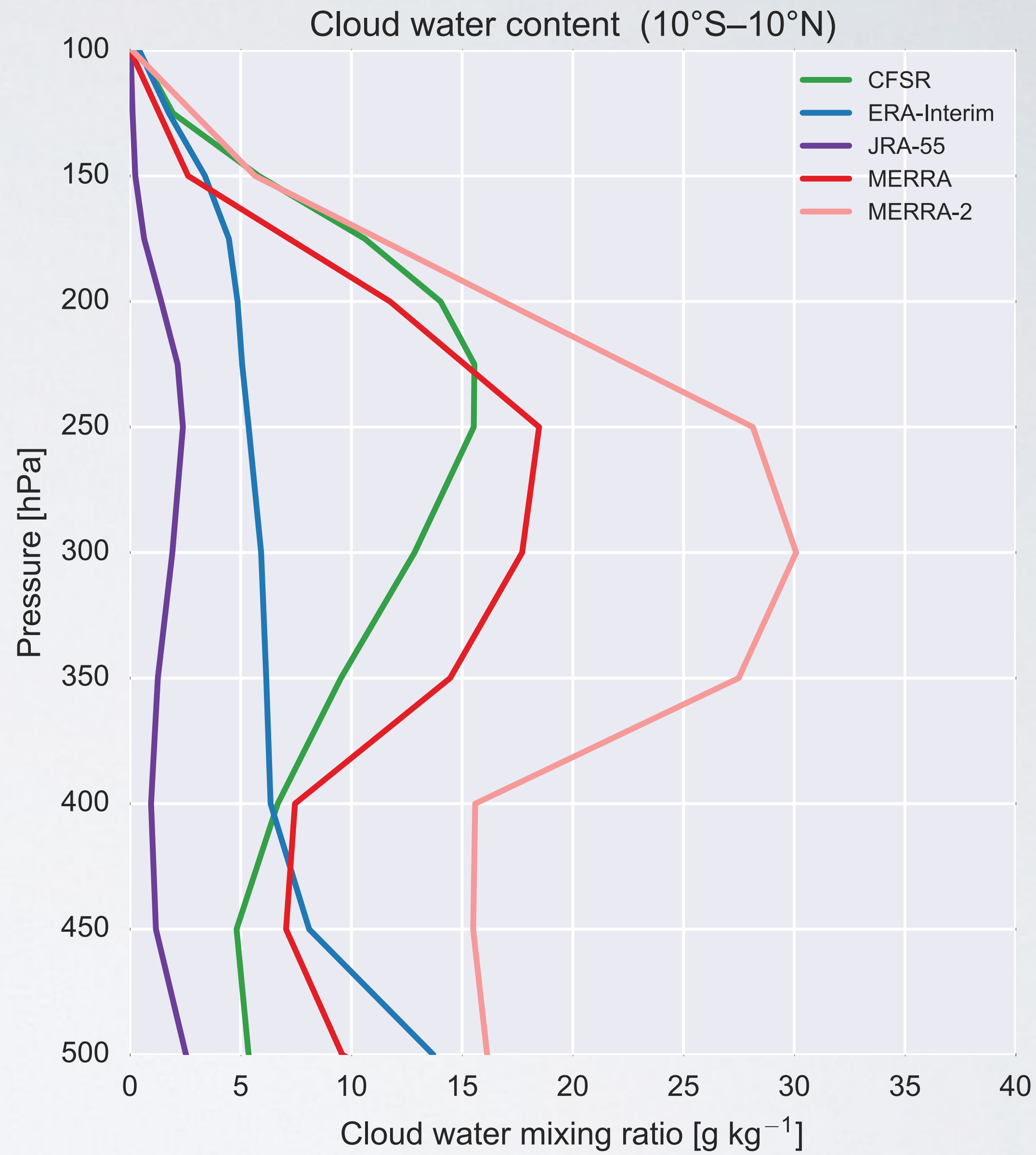
In addition to stronger LW cooling above the cloud top, MERRA and MERRA-2 have weaker latent heating near 200 hPa, indicating shallower clouds



By contrast, NCEP-NCAR and ERA-40 have relatively deep convection

Vertical profiles of cloud fraction and cloud water



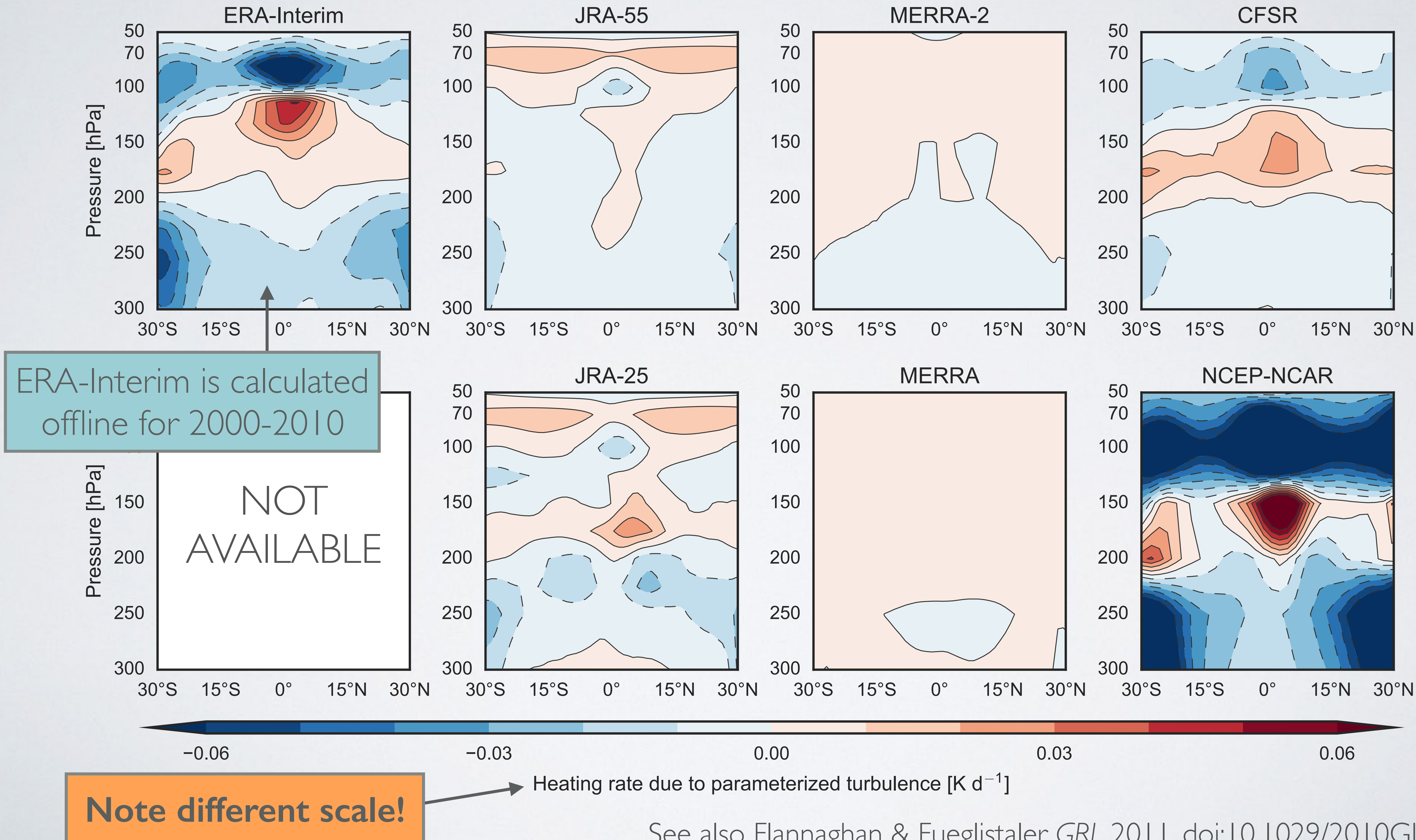


MERRA and MERRA-2 have thicker but lower anvil cloud layers, suggesting shallower convection

Shallower convection and weaker UT radiative cooling in MERRA and MERRA-2 may involve feedbacks, since radiative cooling in the UT acts to destabilize the tropical atmosphere

Zonal mean diabatic heating: shear–flow mixing

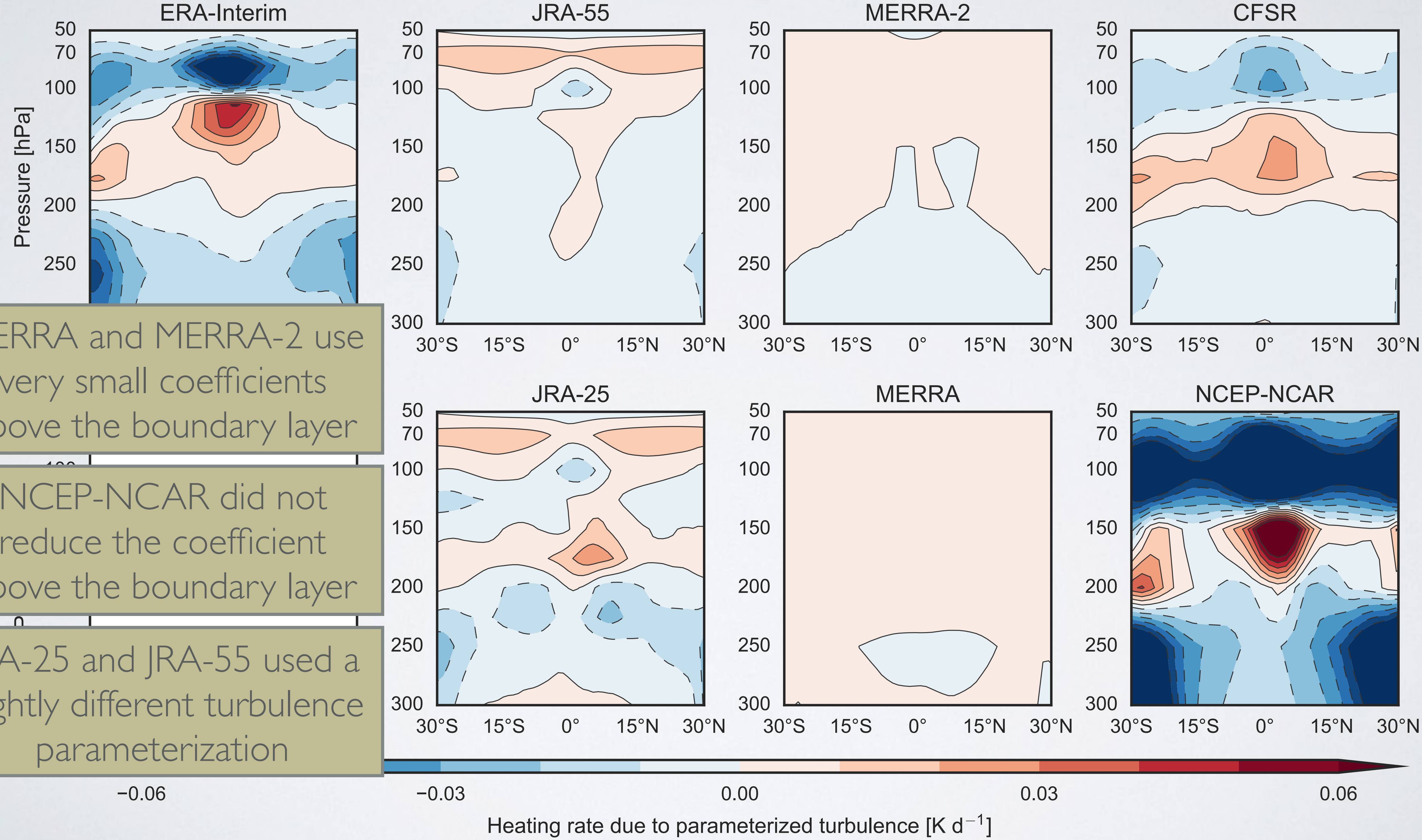
Most systems produce a local maximum in parameterized turbulent mixing across the tropical tropopause, though the strength of this mixing varies



See also Flannaghan & Fueglistaler, *GRL* 2011, doi:10.1029/2010GL045524

Zonal mean diabatic heating: shear–flow mixing

Differences mainly reflect assumptions about the magnitude of the vertical diffusion coefficient



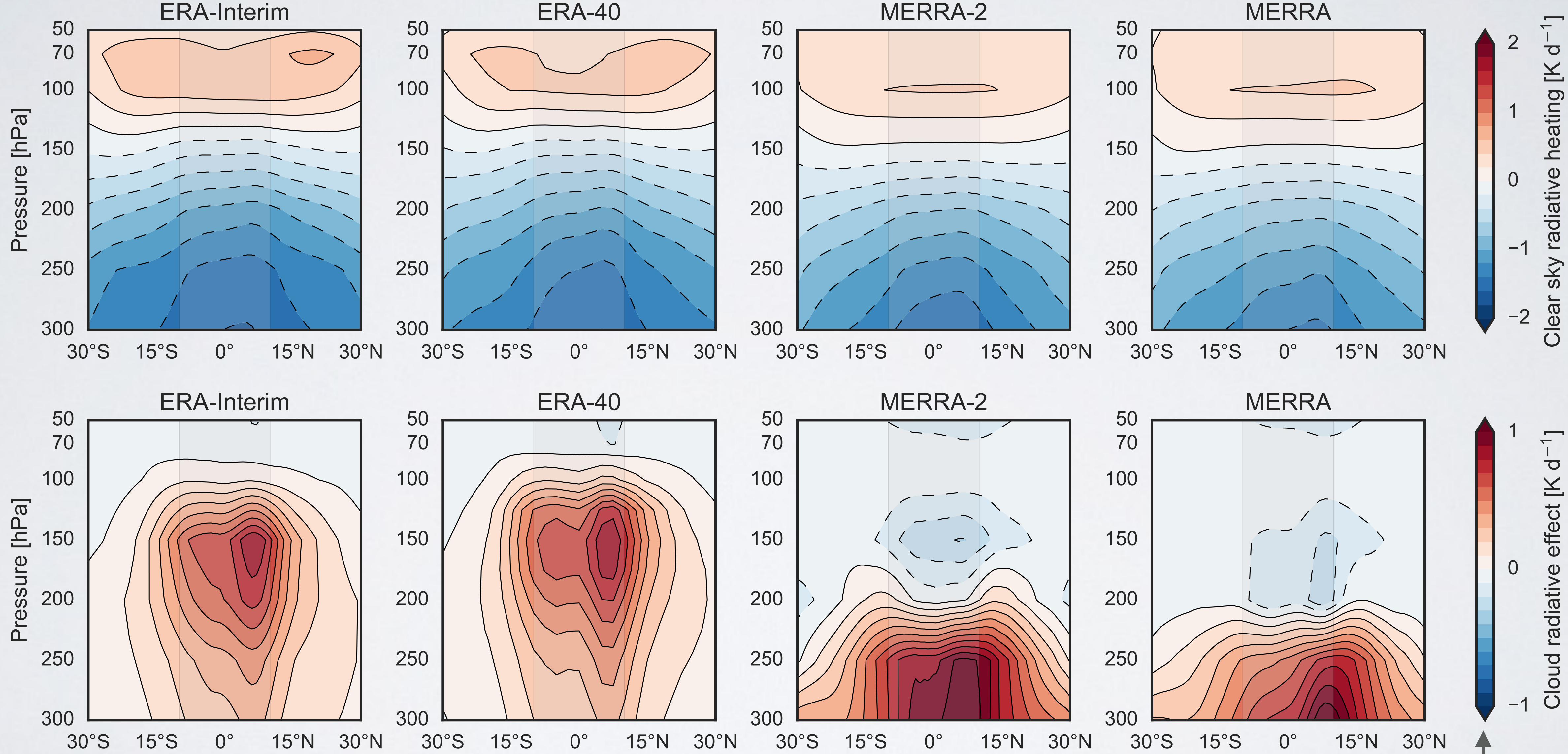
MERRA and MERRA-2 use very small coefficients above the boundary layer

NCEP-NCAR did not reduce the coefficient above the boundary layer

JRA-25 and JRA-55 used a slightly different turbulence parameterization

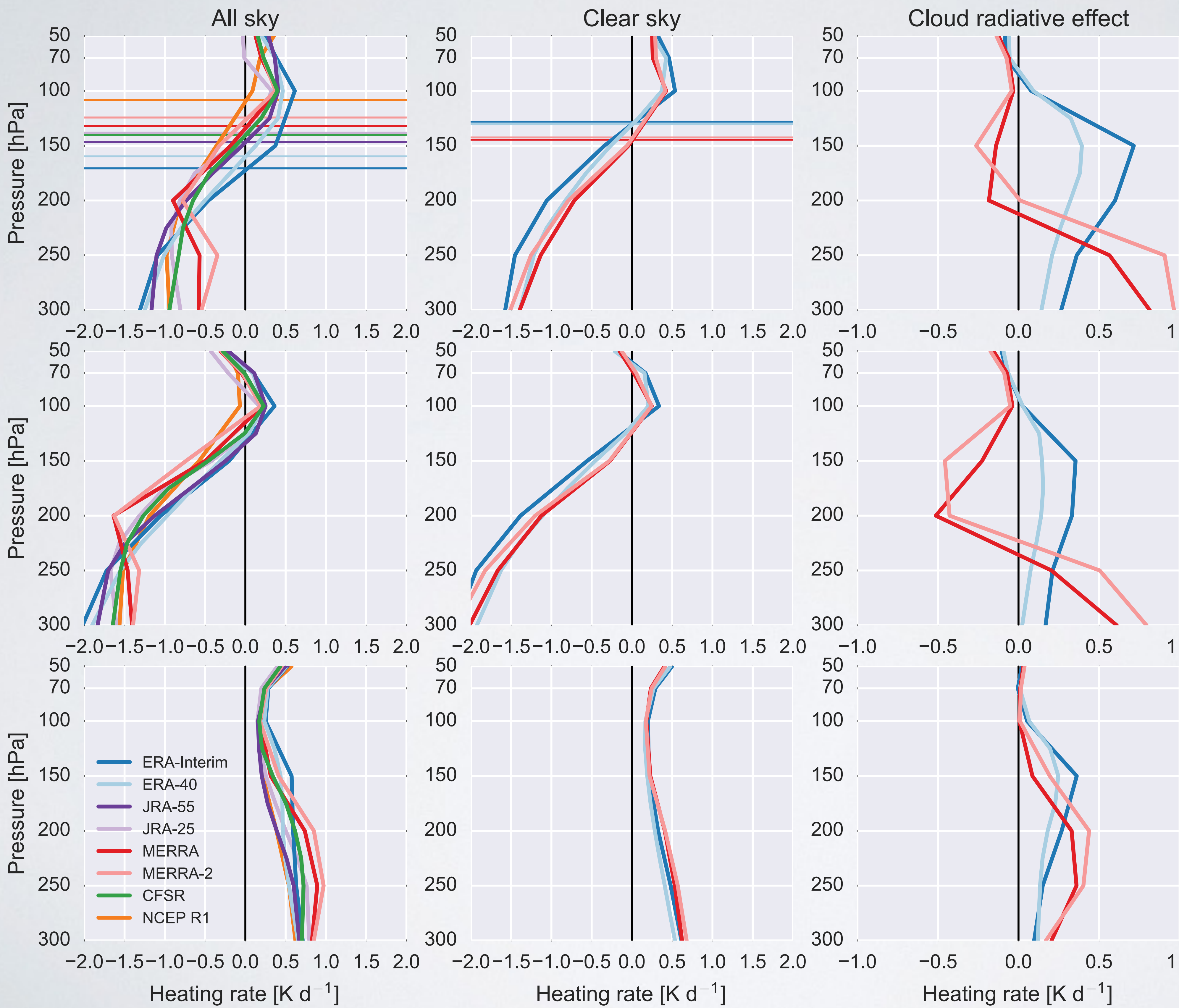
Zonal mean diabatic heating: cloud radiative effects

Both clear-sky radiative heating rates and cloud radiative effects contribute to these differences



Note different scales!

Tropical mean diabatic heating: radiation

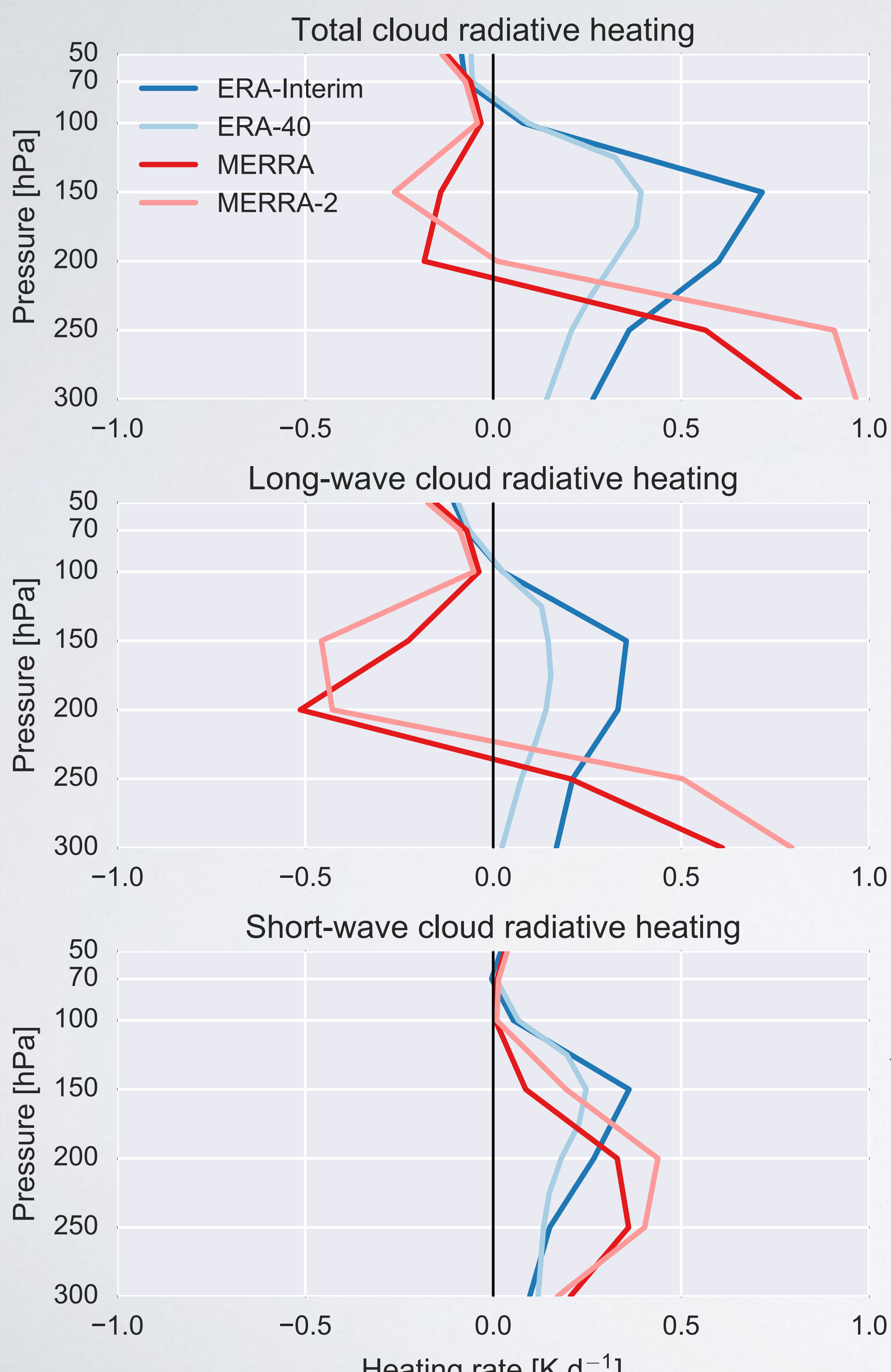


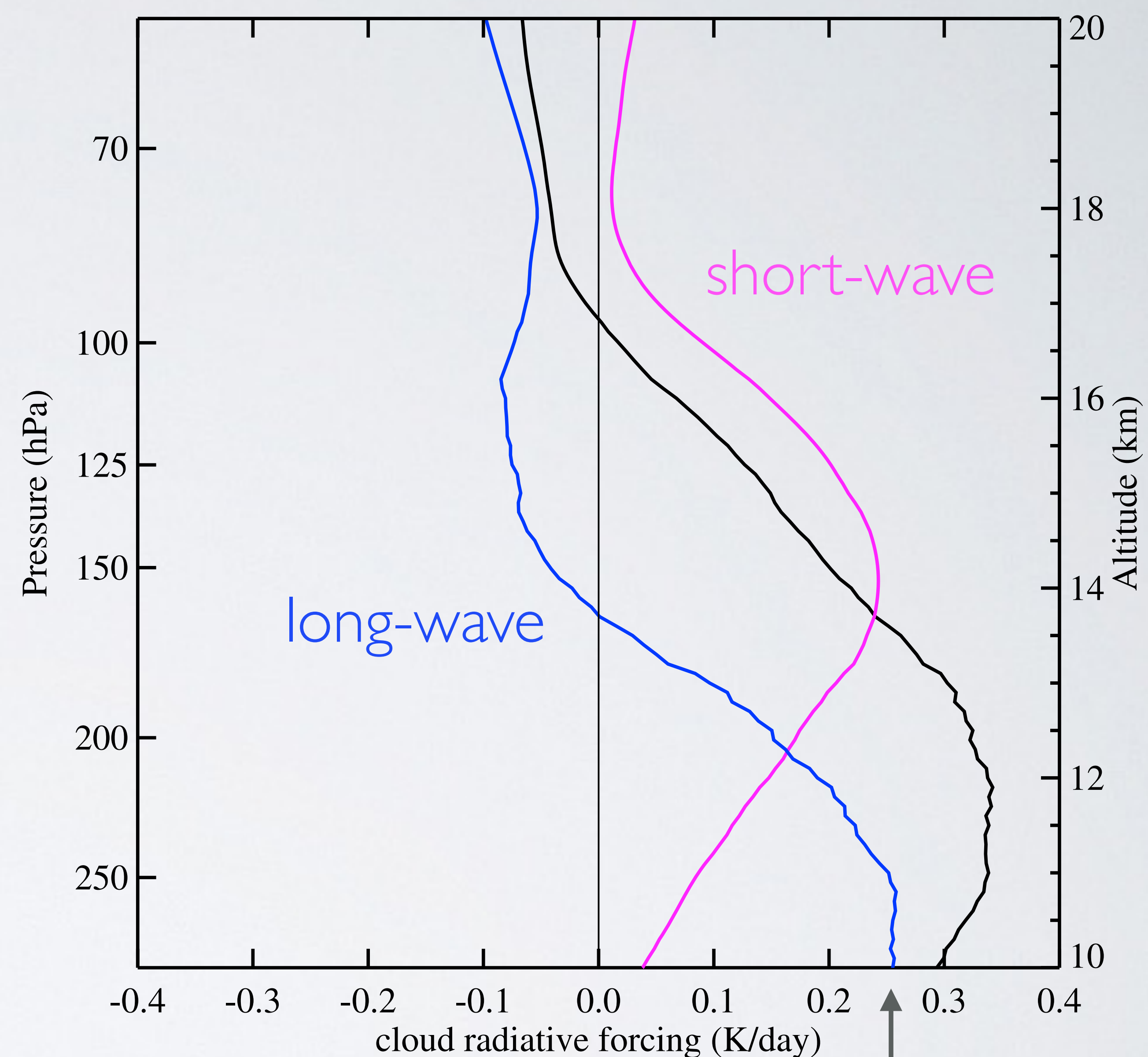
Differences change the LZRH location, with implications for transport through the TTL

Cloud effects are more pronounced, but clear-sky differences are influential too

The key factor in SW heating rates is the vertical location of anvil clouds

Zonal mean diabatic heating: cloud radiative effects





Reanalysis estimates: model radiative transfer and clouds

Observationally-based estimate: still requires a radiative transfer model but uses observations to specify cloud properties

Yang et al., *JGR* 2010, doi:10.1029/2009JD012393

Clouds: a closer look

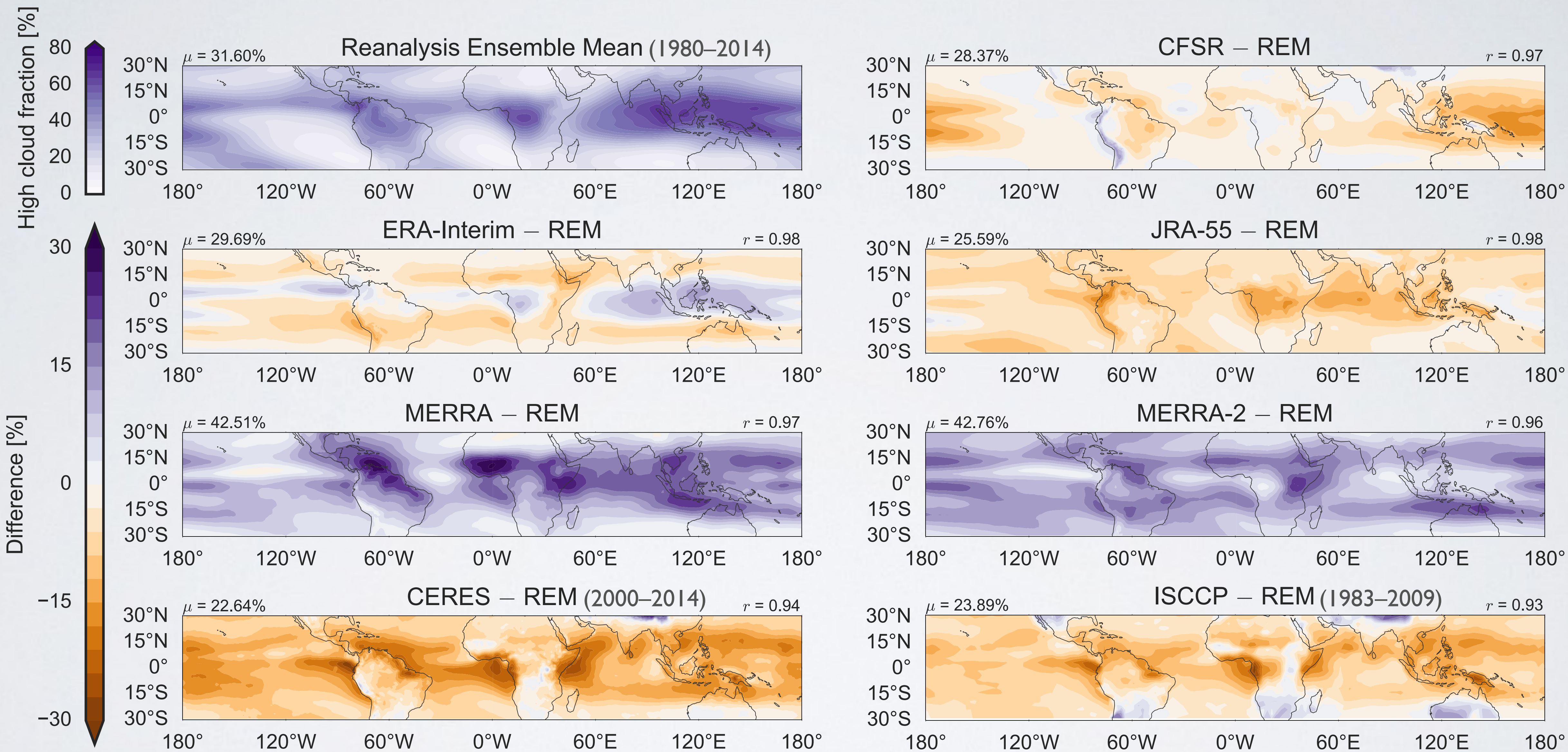
- Clouds play important roles in tropical climate and meteorology, and have strong relationships with sea surface temperature (SST), the radiation budget, and the atmospheric water cycle
- Some variables that influence clouds (temperature, tropospheric moisture, winds) are directly constrained in reanalyses, while others primarily reflect the model formulation
- Differences in reanalysis cloud fields depend in part on the physical parametrizations used in the forecast model (convection, large-scale clouds, inclusion of supersaturation), but also on the type of data assimilation
- In some cases, observational data only influence clouds indirectly via the forecast initial state; in others, observations influence clouds directly via adjustments applied either to the initial conditions or as tendency terms in a new forecast
- Differences in reanalysis-generated diabatic heating rates within the tropical UTLS are clearly heavily impacted by differences in cloud fields

Notes on clouds comparison

- Baseline is a reanalysis ensemble mean, constructed from CFSR, ERA-Interim, JRA-55, and MERRA-2
- Some comparisons against observations are provided for context, but biases may result from observing geometry, diurnal sampling, or other issues rather than problems in reanalyses
- All direct comparisons are performed for the overlapping time period and on an appropriate common grid (grid cell sizes in parentheses):
  - Reanalysis ensemble mean: January 1980–December 2014 (1°)
  - ISCCP D2: July 1983–December 2009 (2.5°)
  - CERES ISCCP-D2like: March 2003–December 2014 (1°)
  - AIRS: September 2002–December 2014 (1°)
- The definition of the 'high cloud fraction' variable varies, but examination of profiles suggests that this should not have much impact:
  - ~500 hPa and up: JRA-55, AIRS
  - ~440 hPa and up: ERA-Interim, CERES, ISCCP
  - ~400 hPa and up: CFSR, MERRA, MERRA-2
- All five of the reanalysis systems assume maximum–random overlap in distributing clouds for radiation calculations
- CFSv2 (CFSR after January 2011) uses McICA, but CFSR does not

Tropical distributions of high clouds

Reanalyses produce similar spatial distributions, but with large quantitative biases: MERRA and MERRA-2 have more clouds, JRA-55 has fewer, and ERA-Interim and CFSR are close to average

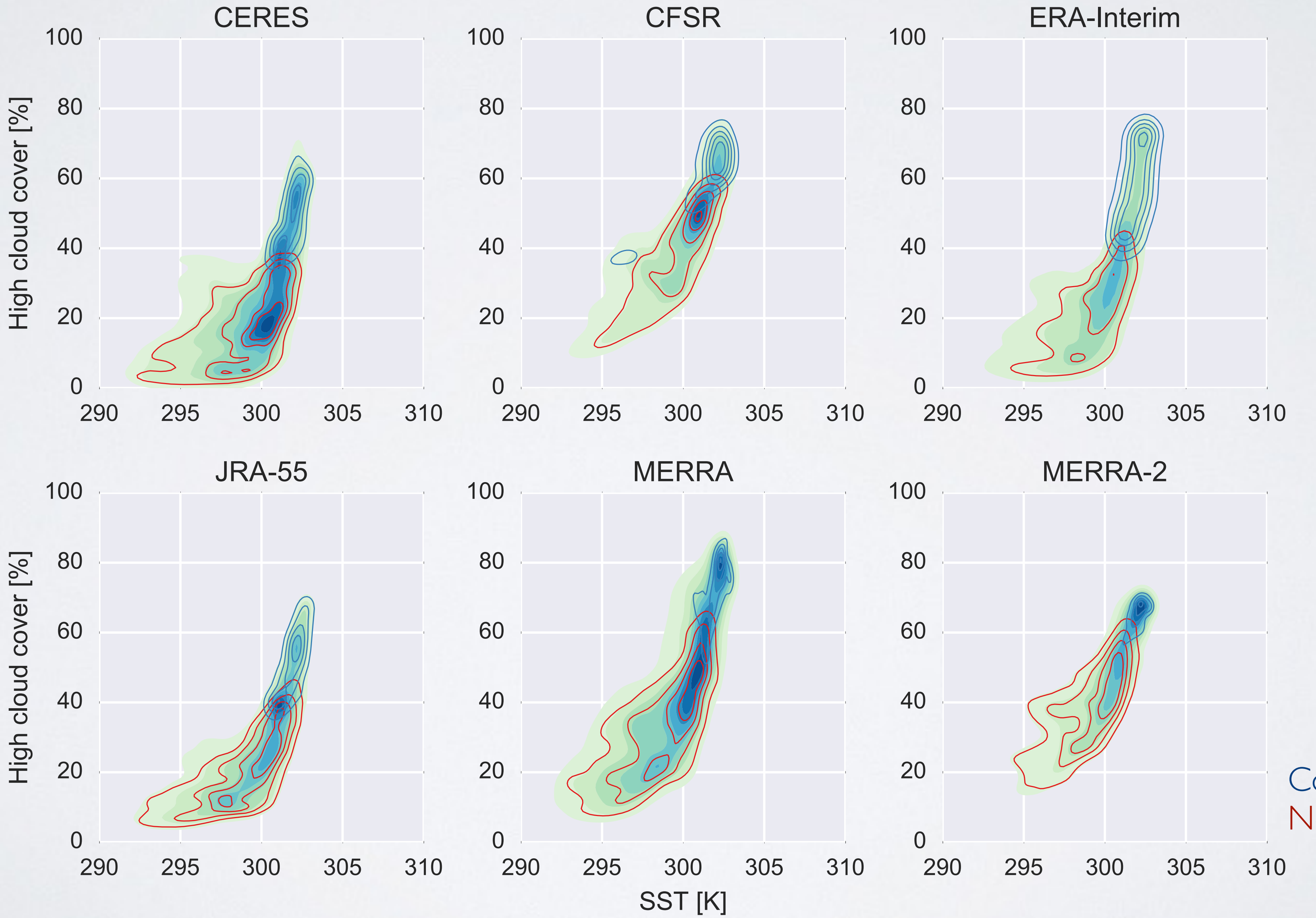


Observations indicate smaller cloud fractions, but evaluation of MERRA-2 cloud simulator suggests that this is a bias in IR observations — in which case most reanalyses underestimate high clouds!

High cloud cover versus SST

The spatial distribution of high clouds is controlled to leading order by the spatial distribution of deep convection, which in turn depends on the spatial distribution of tropical SSTs

All reanalyses produce larger high cloud fraction over warmer SSTs, but with some differences

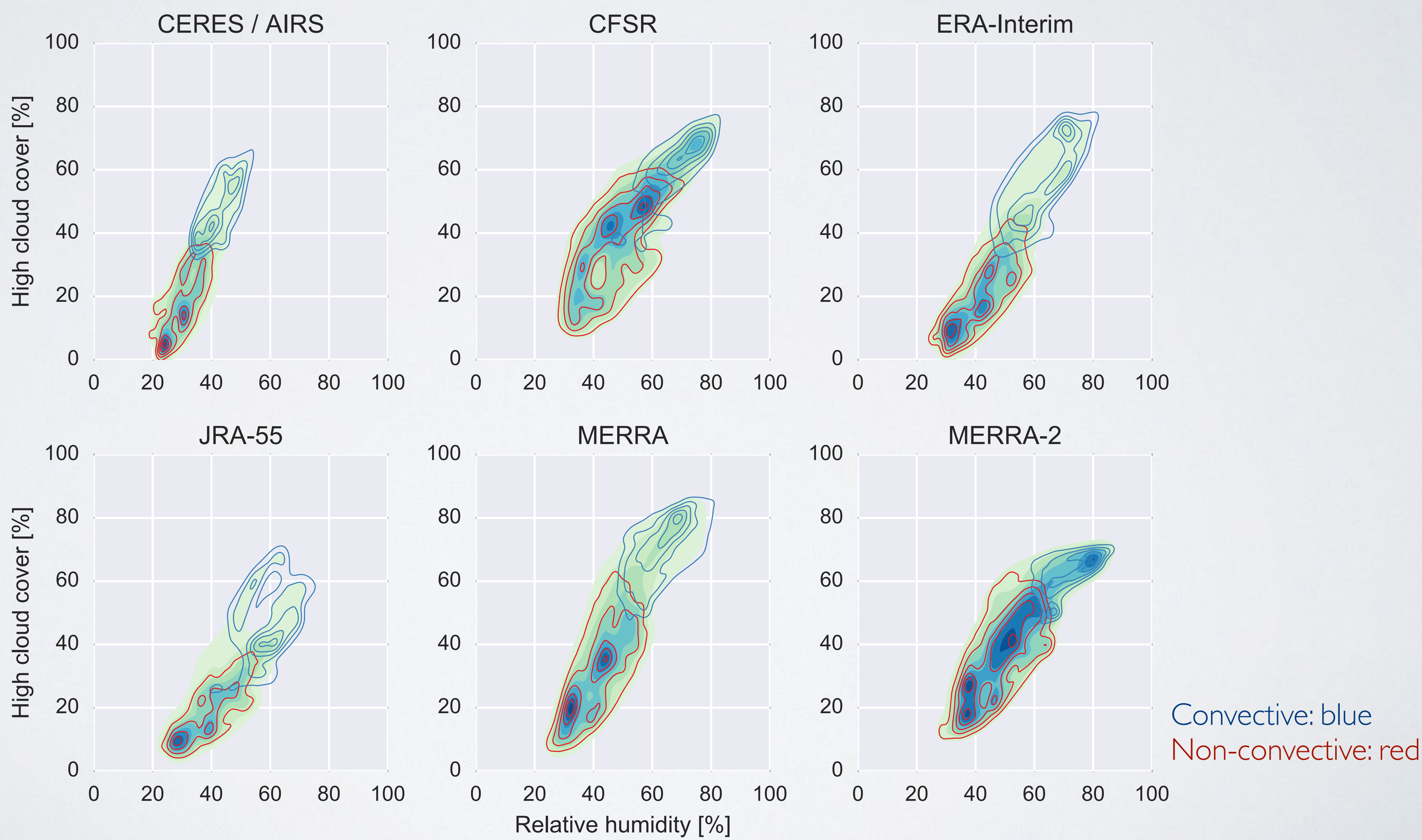


Convective: blue
Non-convective: red

High cloud cover versus relative humidity at 250 hPa

Upper tropospheric humidity is another key factor in determining the distribution of high clouds

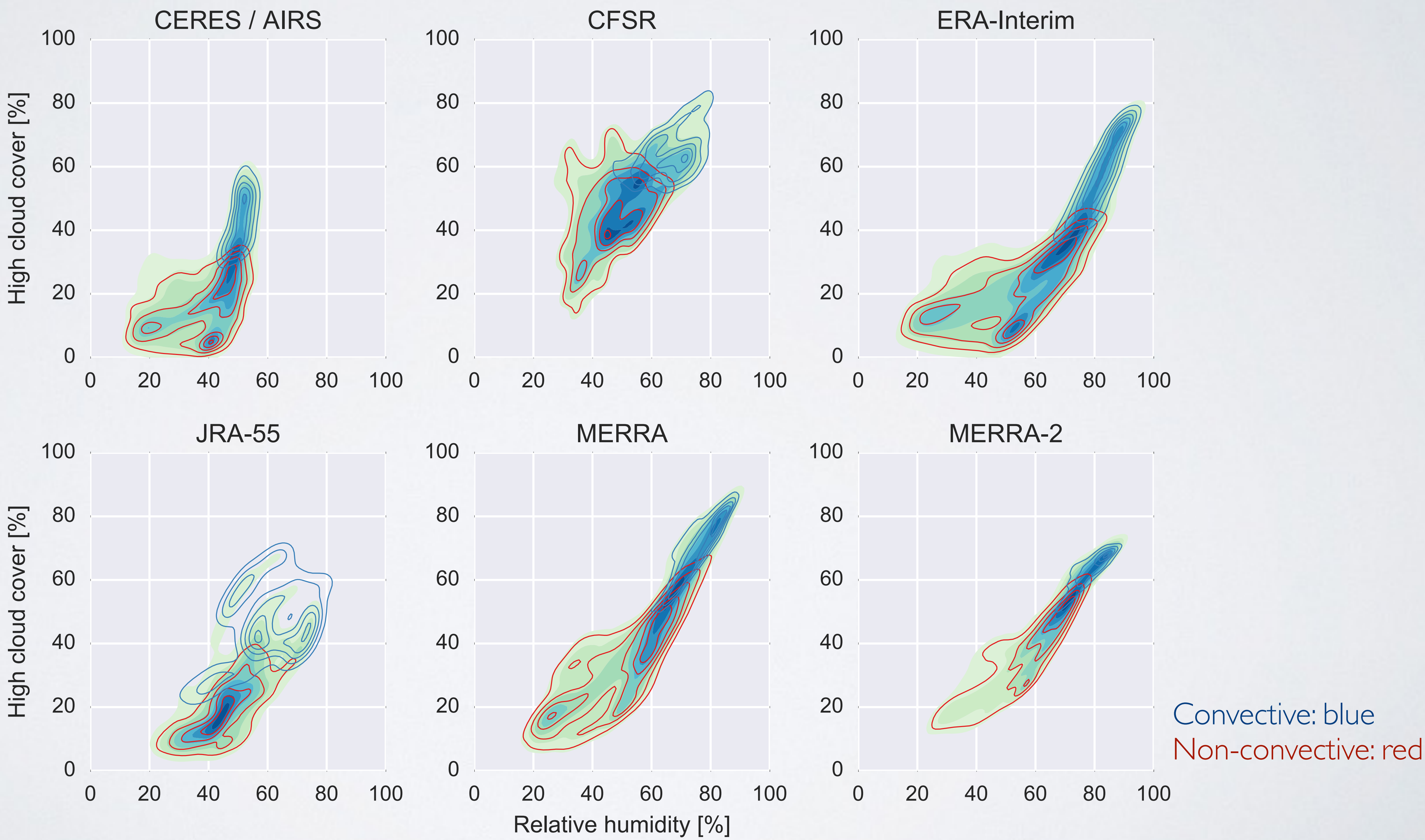
Reanalyses again produce broadly similar relationships between UTH and high cloud cover within the deep convective detrainment layer, with higher humidities corresponding to more clouds



High cloud cover versus relative humidity at 150 hPa

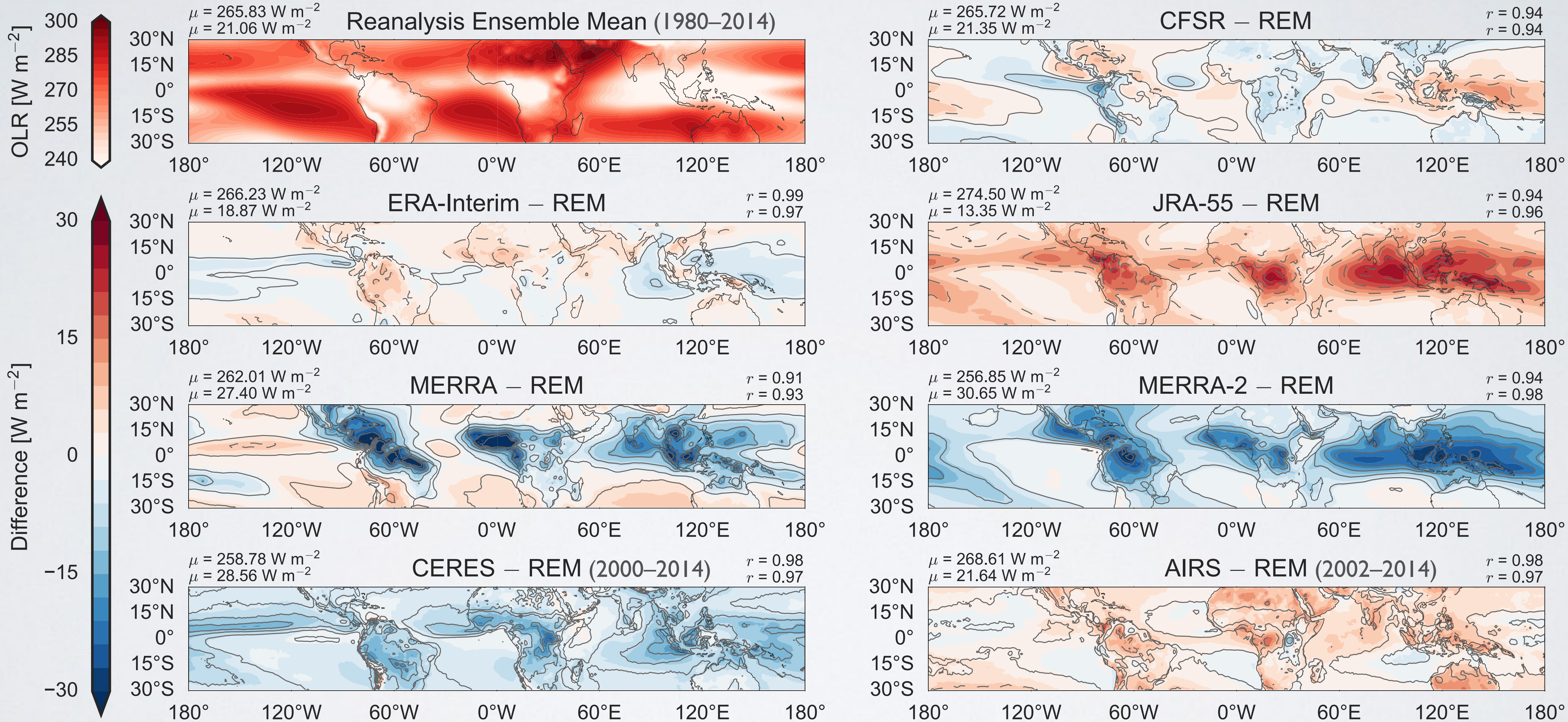
Upper tropospheric humidity is another key factor in determining the distribution of high clouds

Relationships with UTH at 150 hPa are different, with some following UTH at 250 hPa (deeper detrainment layers?) and some following SST (overshooting convection? thermal responses?)



Tropical distributions of long-wave cloud radiative effects

Biases in outgoing long-wave radiation and long-wave cloud radiative effects within the tropics are systematic and coherent, with tightly relationships to the distribution and extent of high clouds



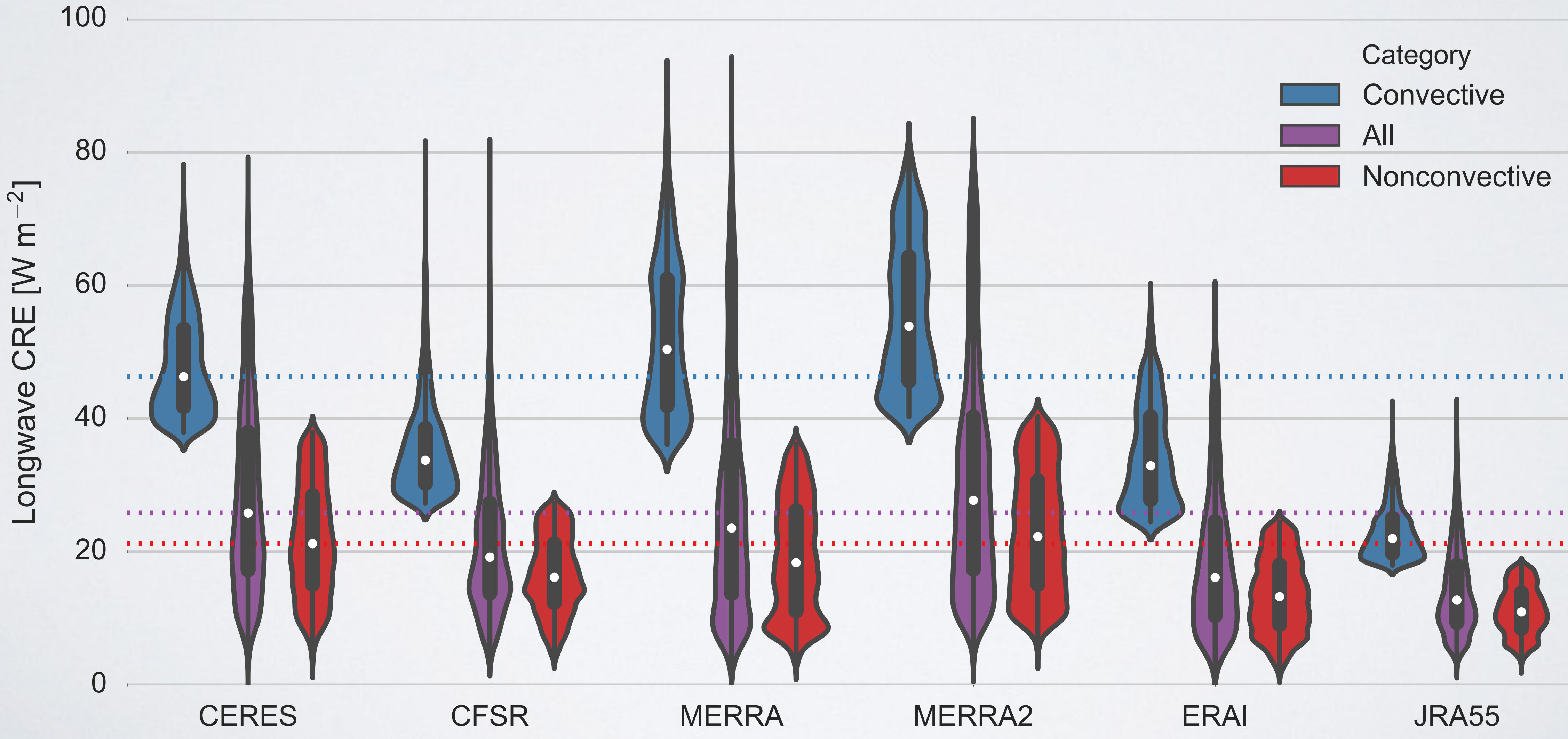
CERES indicates lower OLR and larger CRE than the REM, NOAA OLR shows even larger biases in both, and AIRS has a different diurnal sampling — MERRA-2 is most similar to observations

Tropical distributions of long-wave cloud radiative effects

Most reanalyses underestimate cloud long-wave effects in the TOA energy balance

MERRA-2 is the most realistic relative to CERES in both magnitude and range of LW CRE

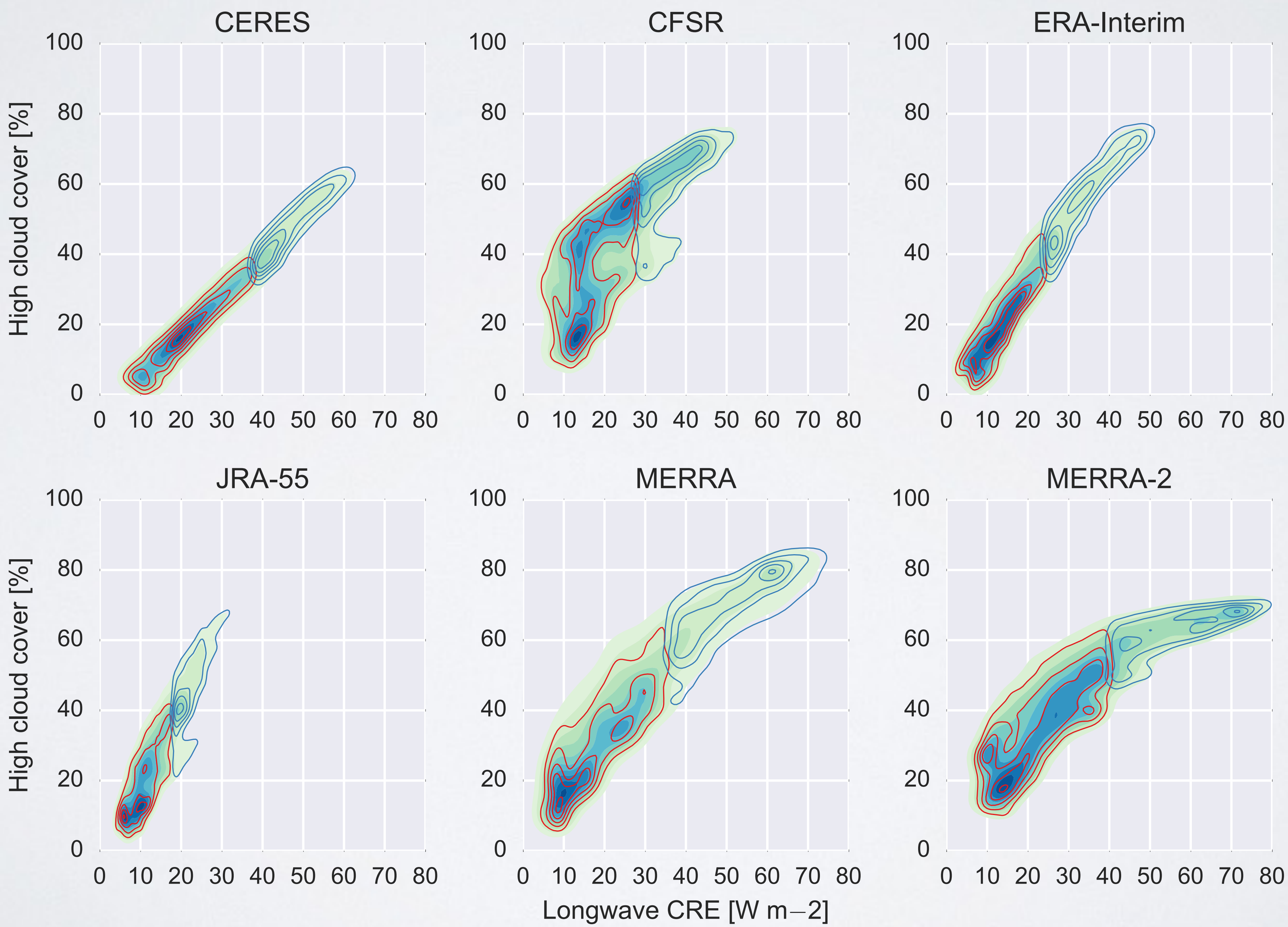
JRA-55 badly underestimates LW CRE (and thus overestimates OLR) in the tropics



High cloud cover versus long-wave CRE

Relationships between high cloud cover and long-wave CRE show some important differences

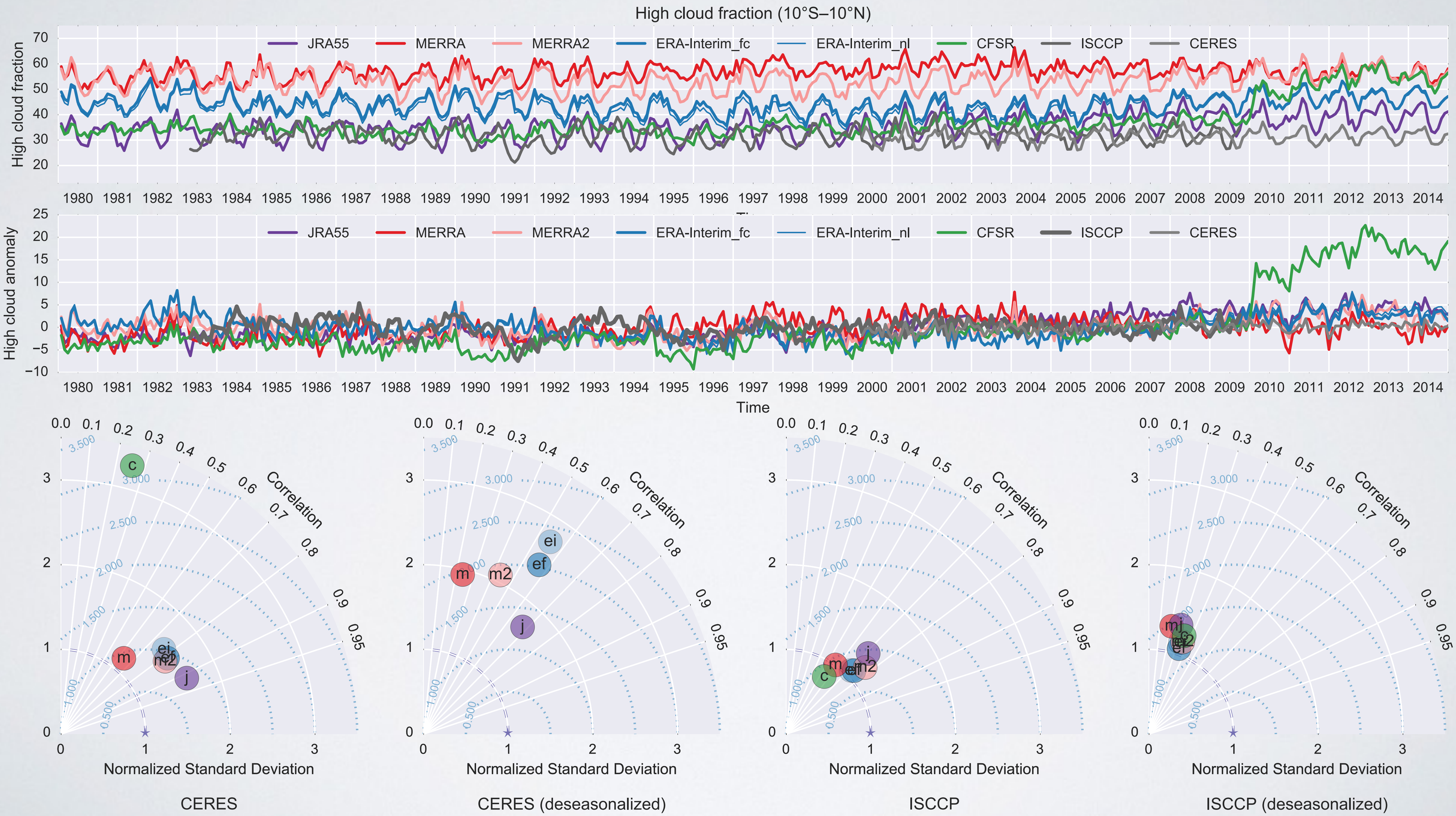
Differences in these relationships appear to be related to average cloud water paths in the upper troposphere — MERRA-2 has smaller cloud fractions but larger water paths than MERRA



Convective: blue
Non-convective: red

Temporal variability of tropical high clouds

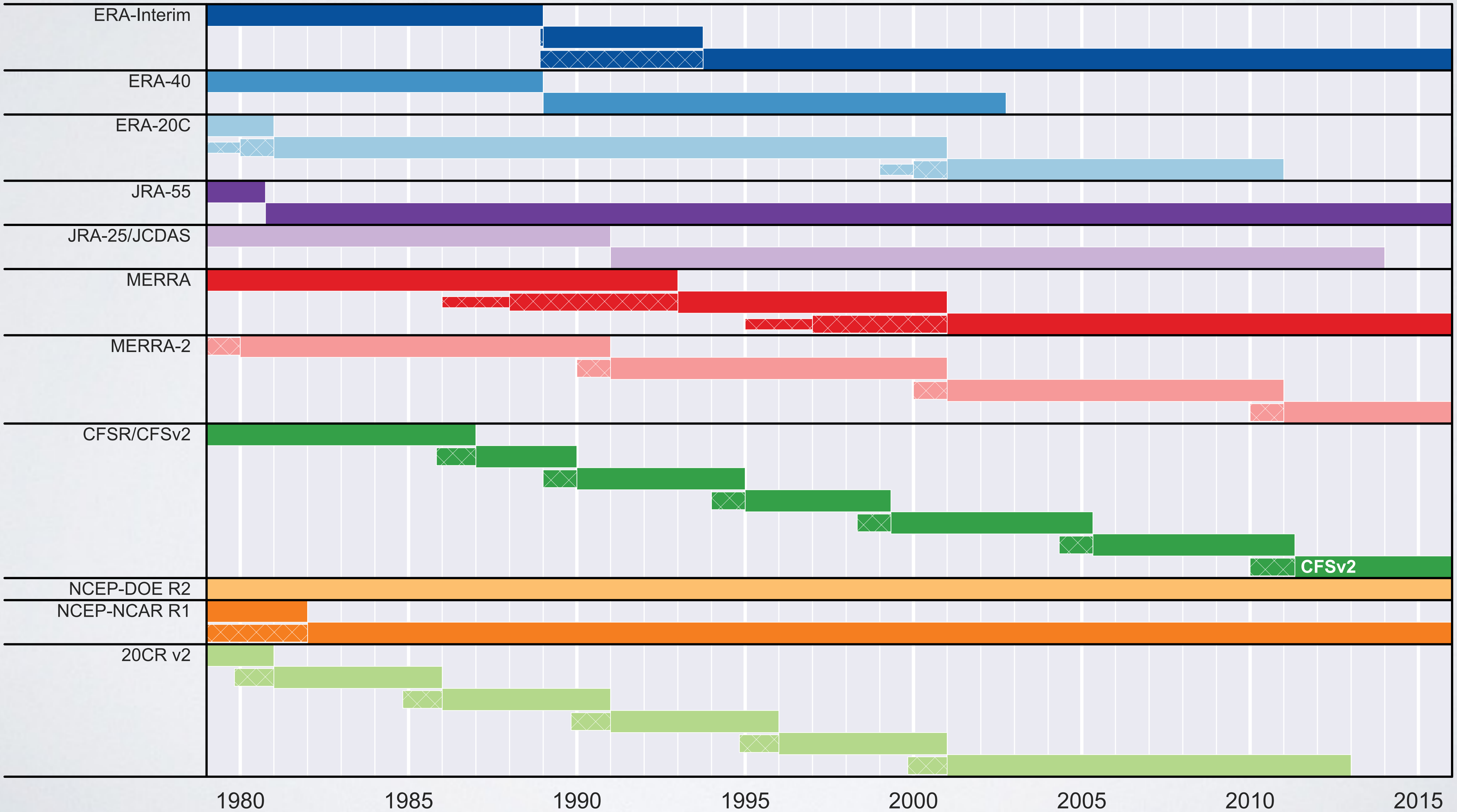
Reanalyses capture the seasonal cycle but interannual variations are structural rather than physical



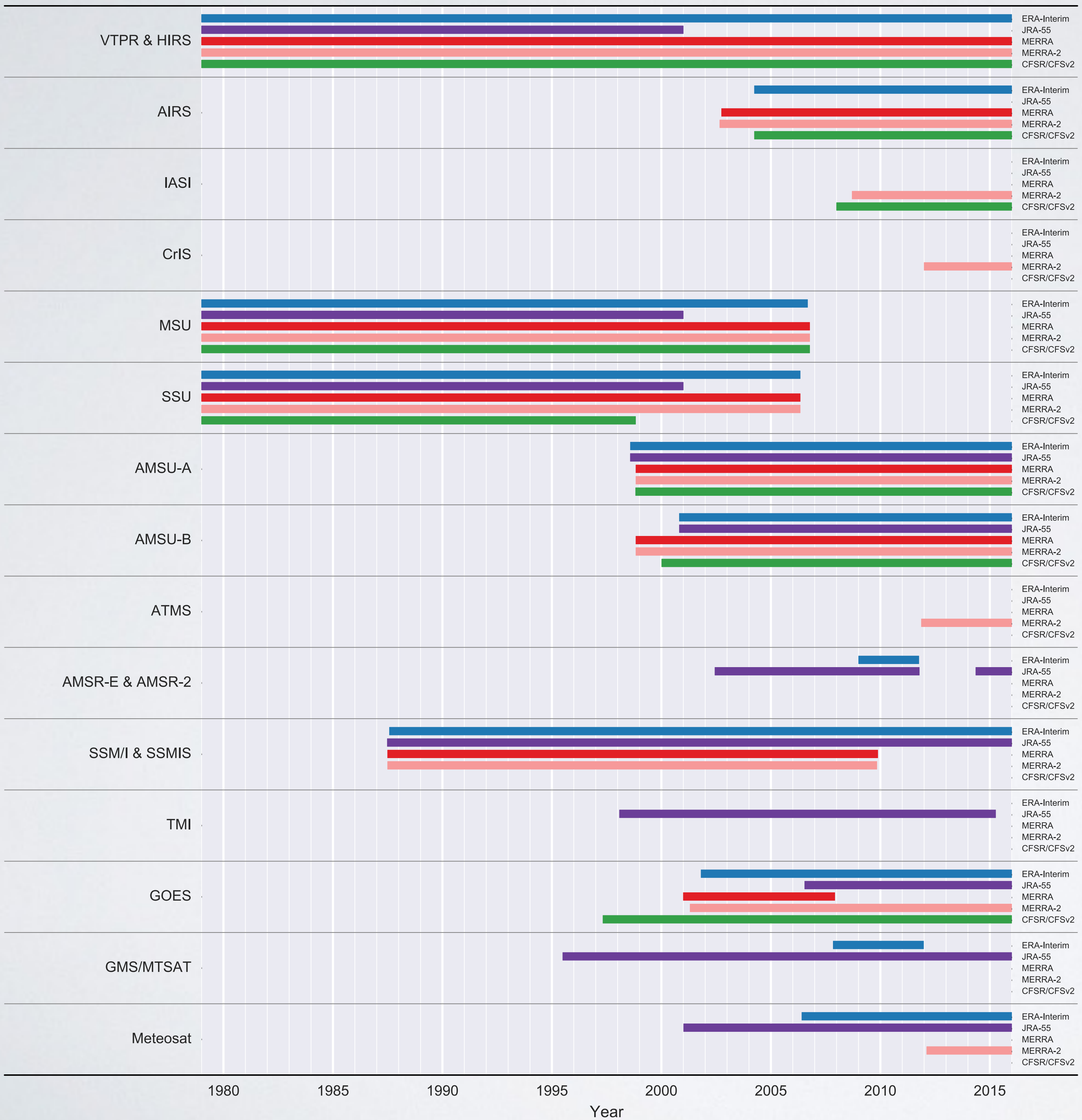
Production stream transitions

Stream transitions are a necessary part of reanalysis production, but may result in discontinuities — especially for CFSR, which has jumps in multiple variables

stratospheric water vapor, tropical clouds, upper stratospheric temperatures and winds, maybe others…



Changes in assimilated observations



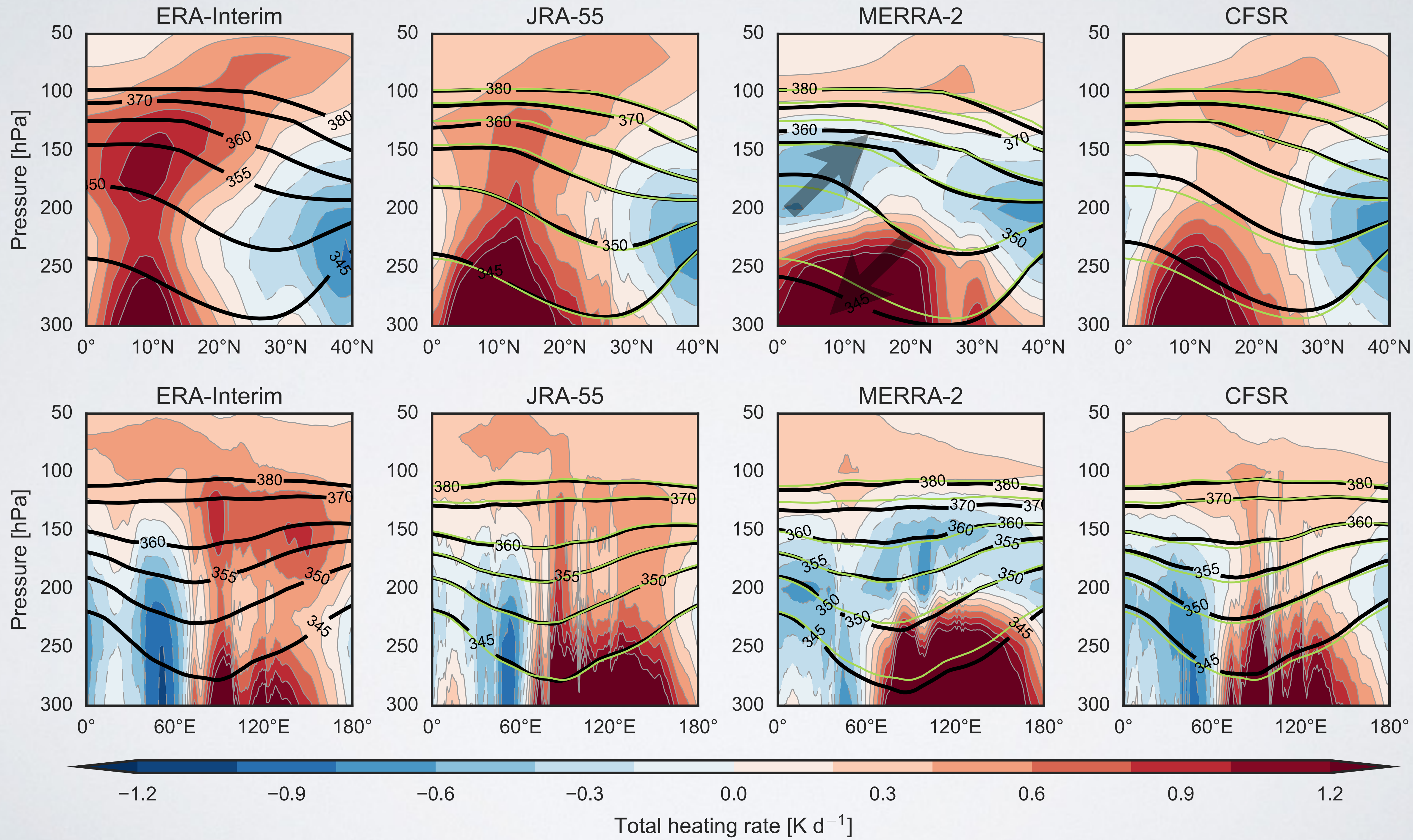
Changes in observations used in the assimilation (such as the TOVS-to-ATOVS transition in ~1998) are another potentially important source of unphysical drifts and jumps. Gradual drifts in satellite orbits or biases can also influence reanalysis quality

See our recent paper in ACP for more details:

Fujiwara et al. (2017) doi:10.5194/acp-17-1417-2017

Asian monsoon anticyclone

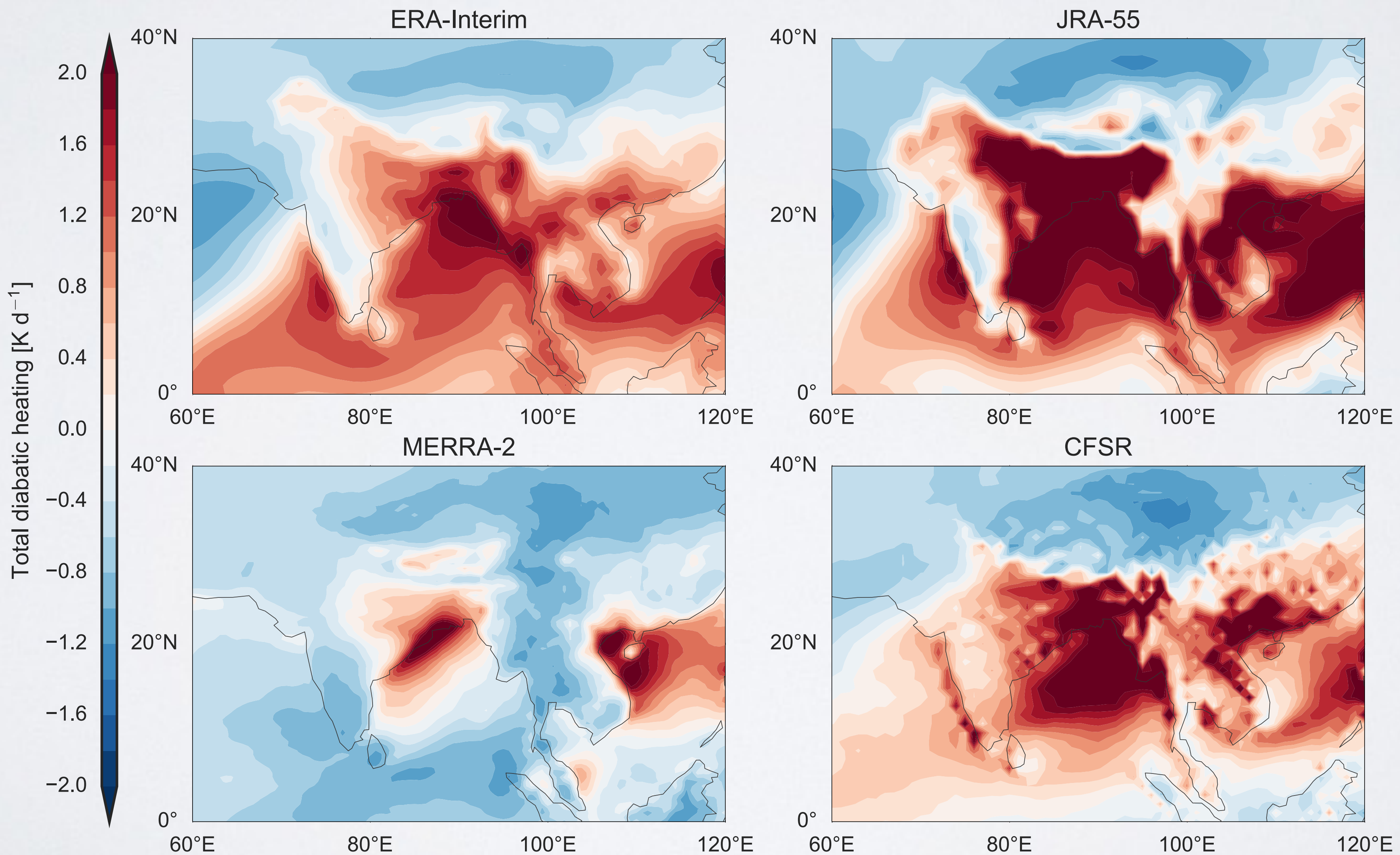
Relative biases in the horizontal and vertical distributions of diabatic heating alter thermodynamic structure in the Asian monsoon UTLS — heating pulls isentropes down; cooling pushes them up



Asian monsoon anticyclone: 200 hPa

Distributions of deep convective heating in the upper levels of the upper troposphere are again very different, with implications for convective and boundary layer sources of UTLS air

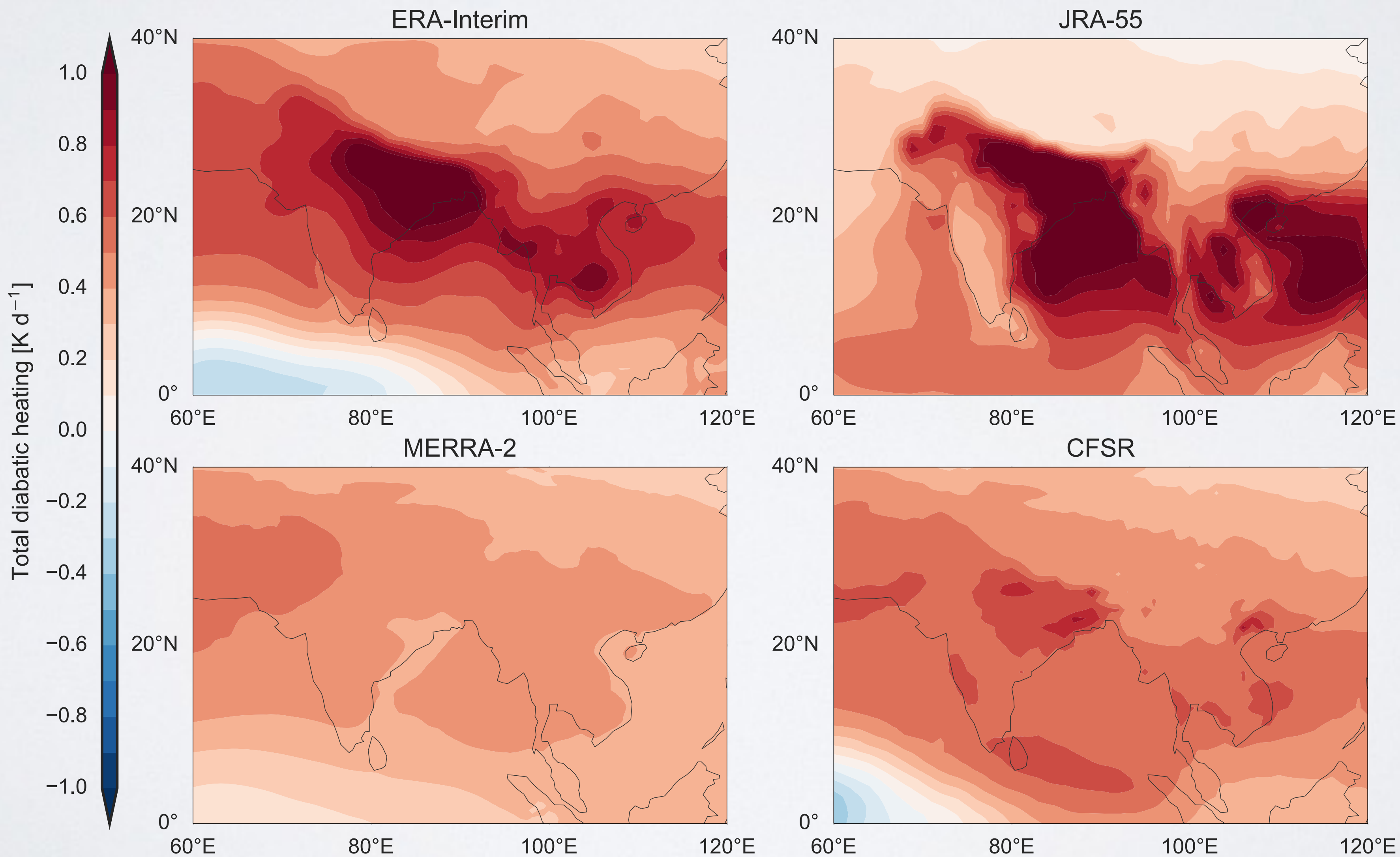
Substantial differences are evident around the Bay of Bengal, the South Slope of the Himalayas, and the Southeastern Tibetan Plateau — these differences have led to fundamentally different conclusions regarding the importance of Plateau convection to stratospheric composition



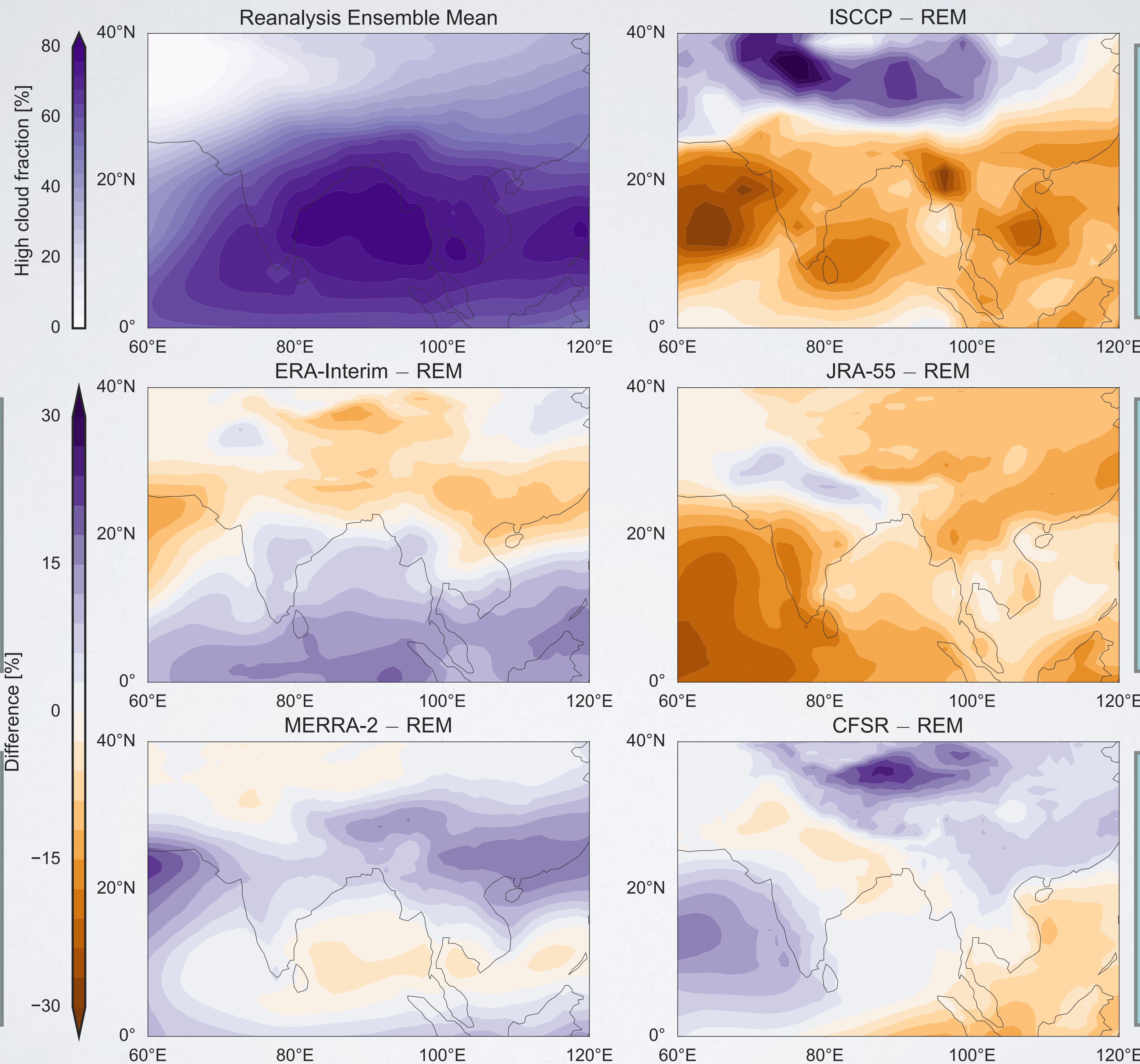
Asian monsoon anticyclone: 100 hPa

The discrepancies extend upward into the tropopause layer, with particularly stark differences over the South Slope of the Himalayas, the Bay of Bengal, and the South China Sea

The monsoon anticyclone is an important pathway into the global stratosphere. Differences in spatial distributions of radiative heating and very deep convection nearby may affect transit times, preferred pathways, convective source identification, and other aspects of transport simulations



Asian monsoon anticyclone: high clouds



ISCCP suggests that reanalyses underestimate Tibetan Plateau cloud cover

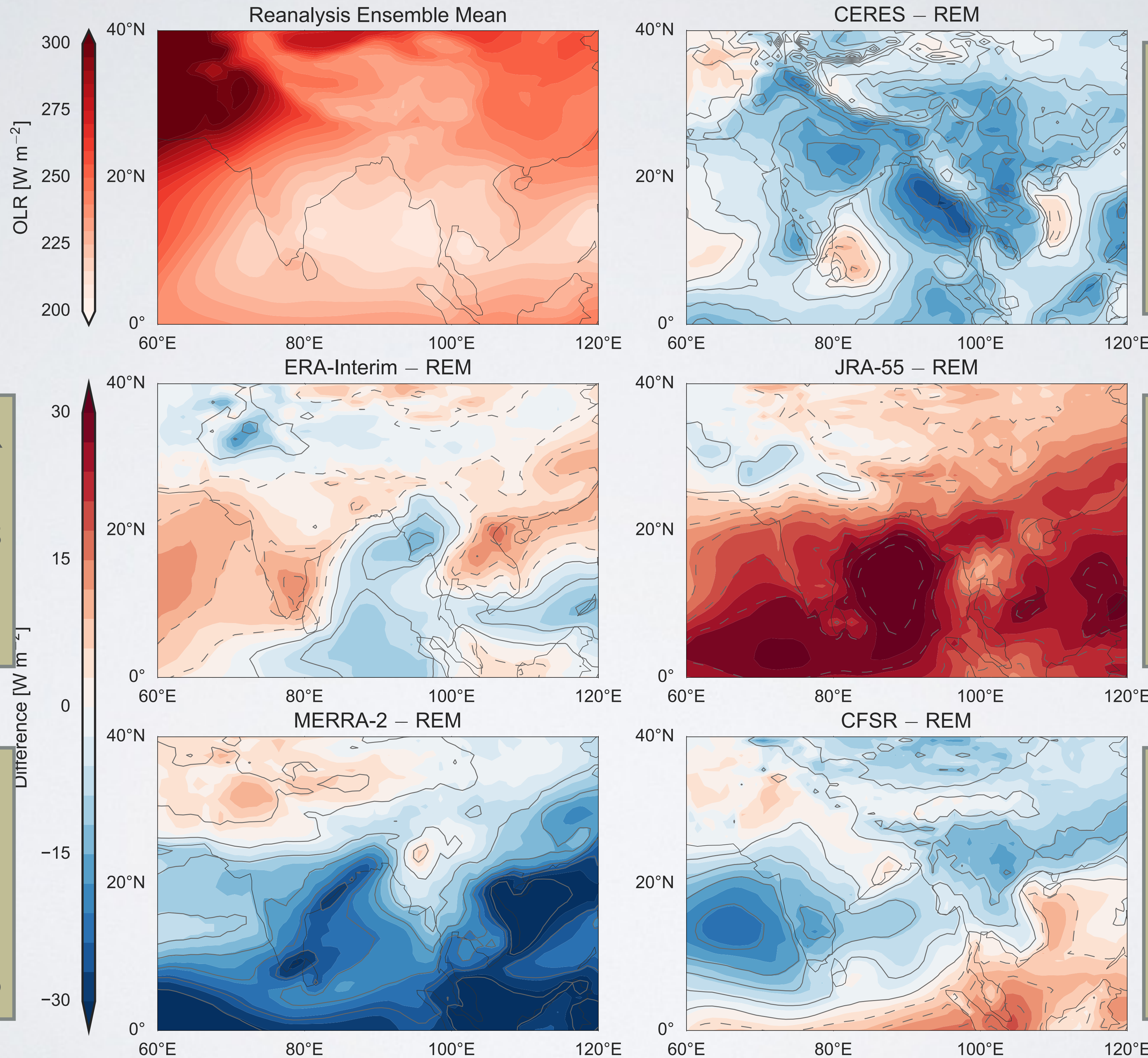
ERA-Interim puts fewer high clouds over East Asia, the Plateau and its South Slope

Strong convection along the South Slope in JRA-55, but with fewer clouds elsewhere

MERRA-2 puts more high clouds over East Asia and the Southeast Tibetan Plateau

CFSR produces more high clouds over the Plateau and East Asia, but less over India

Asian monsoon anticyclone: OLR



CERES suggests that reanalyses overestimate OLR above the monsoon region

ERA-Interim OLR is biased high in most land regions but low in most ocean regions

As in the global tropics, JRA-55 underestimates OLR and the LW CRE

Low OLR biases are widespread in MERRA-2, but differ from those implied by CERES

Biases in CFSR OLR are similar to those in high clouds but with opposite signs

Diabatic heating: summary

- There are large differences in estimates of diabatic heating among reanalyses
- These differences are not limited to any specific component of the heat budget: differences are substantial in all comparable individual components
- The sources of differences include both variables that are constrained by the data assimilation (temperature, water vapor, ozone) and variables that are not (clouds, background diffusion coefficients)
- Differences can have substantial impacts on circulation patterns in the UTLS, such as the Asian monsoon upper tropospheric anticyclone
- The largest differences in zonal mean diabatic heating are related to:
  1. the vertical location and strength of LW radiative heating in the lower stratosphere
  2. radiative and latent heating associated with tropical convection and clouds
- Transport calculations relying on reanalysis diabatic heating rates should ideally use multiple reanalyses to drive the simulations and constrain uncertainties

see also:

Wright, J. S. and S. Fueglistaler (2013): Large differences in reanalyses of diabatic heating in the tropical UTLS, *Atmos. Chem. Phys.*, 13, 9565–9576, doi:10.5194/acp-13-9565-2013

Fujiwara, M., J. S. Wright, G. L. Manney, L. J. Gray, et al. (2017): Introduction to S-RIP and overview of the reanalysis systems, Atmos. Chem. Phys., 17, 1417–1452, doi:10.5194/acp-17-1417-2017

Clouds: summary and notes

- Spatial distributions of clouds and related variables are largely consistent among reanalyses and available observations (pattern correlations consistently greater than 0.9), but this qualitative consistency masks large quantitative differences that exert substantial impacts on the TOA energy budget
- MERRA and MERRA-2 produce more and thicker clouds than other reanalyses / observations, but perform well relative to observations of OLR and LW CRE
- JRA-55 has a low bias in cloud cover relative to other reanalyses
- ERA-Interim and CFSR are quite close to the reanalysis ensemble mean in high cloud cover, but with opposing regional deviations: ERA is biased high in convective regions and low in non-convective regions, while the opposite is true for CFSR
- ERA-Interim, CFSR, and JRA-55 have high biases in OLR relative to CERES and the long-term NOAA OLR, likely due to low biases in the LW CRE
- Joint distributions of high cloud cover and related variables are broadly consistent among reanalyses, but with some interesting qualitative differences that hint at different behaviors within the tropical UT
- Interannual variability in tropical high clouds is unrealistic, with discontinuities and trends coming mainly from production stream transitions or changes in assimilated data rather than physical changes