# Tropical free-tropospheric humidity differences and their impact on the clear-sky radiation budget in global storm-resolving simulations

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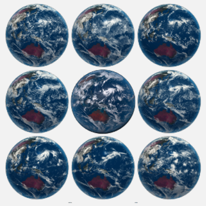
# Summary



The DYAMOND intercomparison provides the first possibility to study differences in free-tropospheric humidity across global storm-resolving models (GSRMs).

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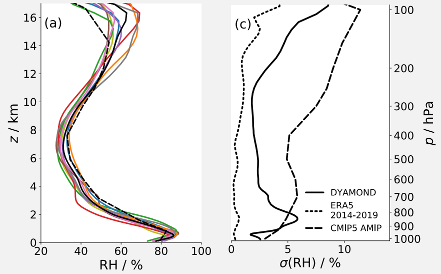


Overall, the models produce similar, C-shaped tropical mean RH profiles and agree well with the ERA5 reanalysis.

The inter-model spread in RH is approximately halved compared to GCMs. This nourishes hopes that the spread in the water vapour feedback might also be reduced in GSRMs.

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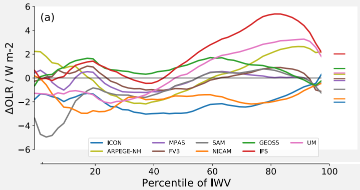


The resulting spread in clear-sky outgoing longwave radiation (OLR) is 1.2 $Wm^{-2}$ and hence not negligible.

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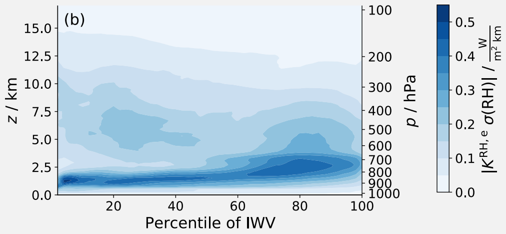


The OLR spread is mainly caused by RH differences in the lower and mid free troposphere in very dry and rather moist regimes at the transition to deep convective regions. There, a further reduction of biases would be most beneficial.

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# Motivation & Overview

Global circulation models (GCMs) differ substantially in simulated free-tropospheric RH (Figure 1). This does not only cause differences in their present-day radiation budget but also in their climate sensitivity, because the RH response - and hence the water vapour feedback - is closely related to the models' present-day RH distributions (Po-Chedley et al., 2019).

**A reduction in present-day biases in global storm-resolving models** (GSRMs; Satoh et al., 2019) **would therefore nourish hopes to reduce the uncertainty in the water vapour feedback.** With grid spacings of a few kilometers these models resolve water vapour transport with much more fidelity than GCMs, particularly because deep convection is explicitly resolved. However, other relevant processes (shallow convective and turbulent mixing, microphysics) remain poorly resolved or unresolved. Model differences in the representation of these processes can cause humidity biases.

Based on **DYAMOND, the first multi-model ensemble of GSRMs**, we address the following questions:

- How large is the inter-model spread in free-tropospheric RH in GSRMs?
- How relevant is the spread (from a present-day radiative point of view)?
- Where in the tropical atmosphere is the spread most relevant?

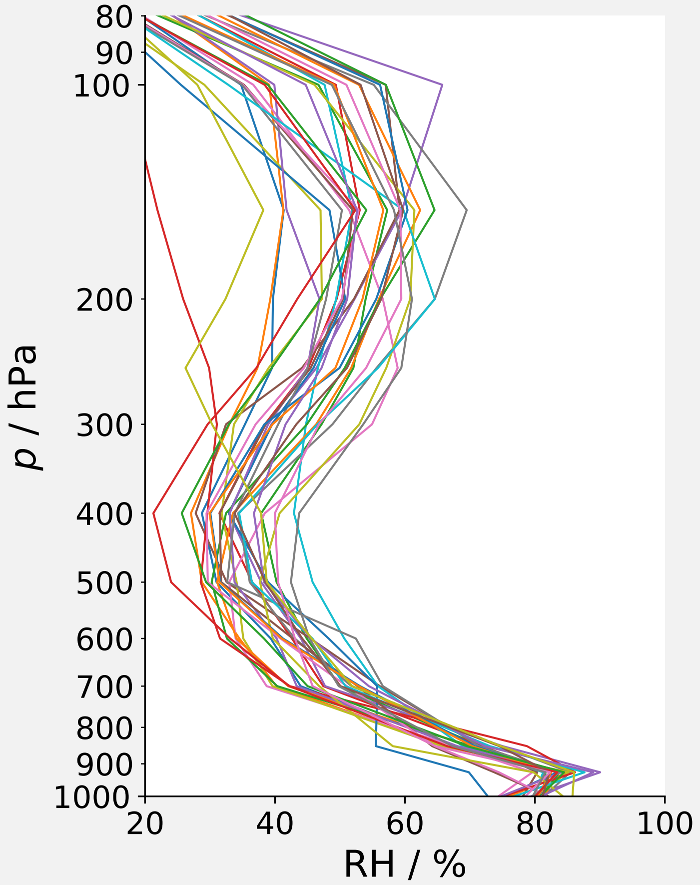


Figure 1: Tropical mean (ocean only) RH in CMIP5 AMIP models.

# DYAMOND – The first intercomparison of GSRMs

**DYAMOND** = DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (Stevens et al., 2019)

Ensemble of nine GSRMs
- Grid spacing < 5 km
- Diversity of numerical grids and parameterizations for unresolved processes

Experimental protocol:
- 40-days (1 Aug – 10 Sep 2016)
- Initial state and SST from ECMWF analysis
- Models run freely after initialization

Used for this study:
- Time period: Last 30 days (first 10 days excluded to minimize constraints by common initialization)
- Region: Tropical ocean (30° S - 30° N)

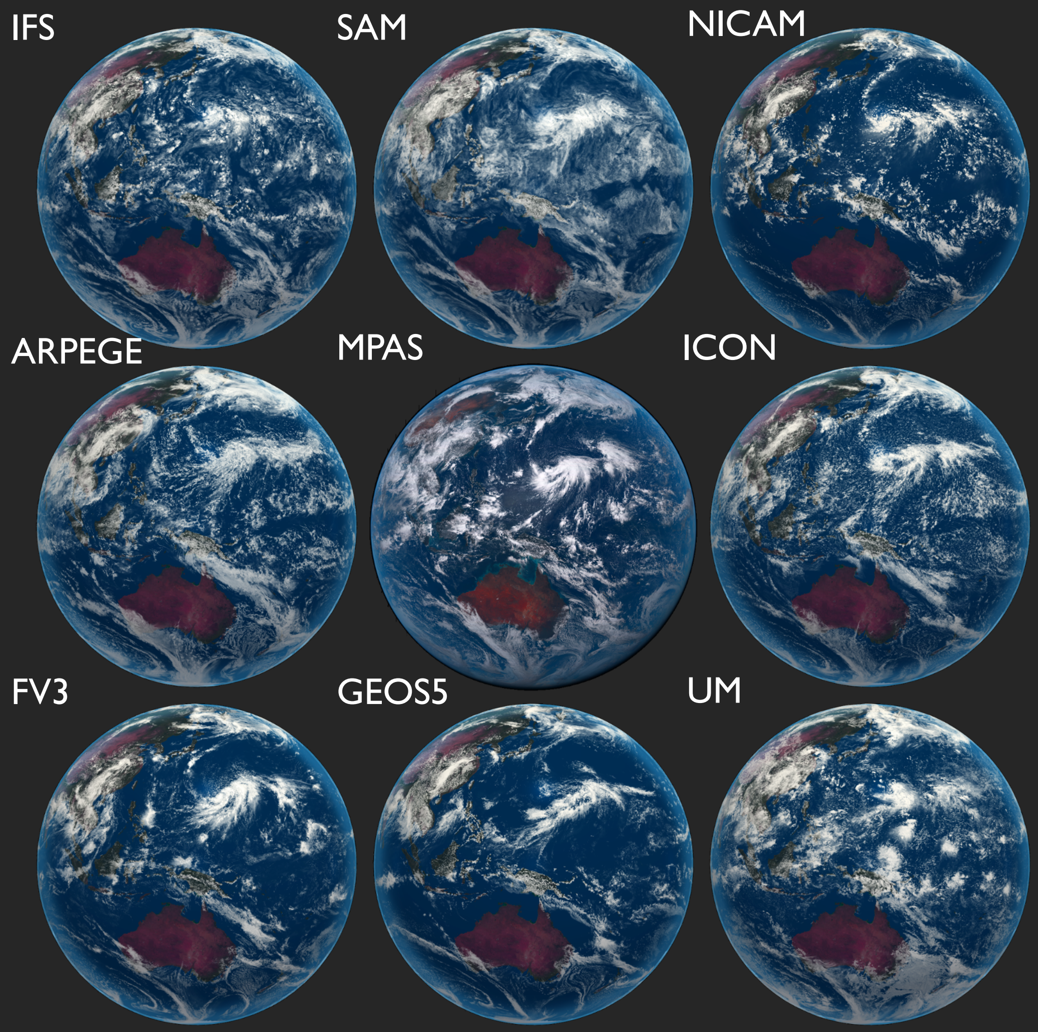


Figure courtesy: B. Stevens

# The inter-model spread in tropical mean RH is reduced in GSRMs

The DYAMOND models all produce a **similar, C-shaped tropical mean RH profile** and **agree well with the ERA5 reanalysis** (Figure 2a).

**The inter-model spread is largest in the upper troposphere and the lower free troposphere** (Figure 2c). The latter relates to a model spread in boundary layer depth.

The inter-model spread is larger than the inter-annual variability in five successive August/September periods in ERA5 (Figure 2c). This suggests that the **model differences are systematic model biases** rather than the result of a poor sampling of natural variability due to the shortness of the simulations.

The spread between DYAMOND models is about half as large as in the CMIP5 AMIP ensemble throughout the free troposphere (Figure 2c). This **indicates that the spread in GSRMs is reduced compared to GCMs.**

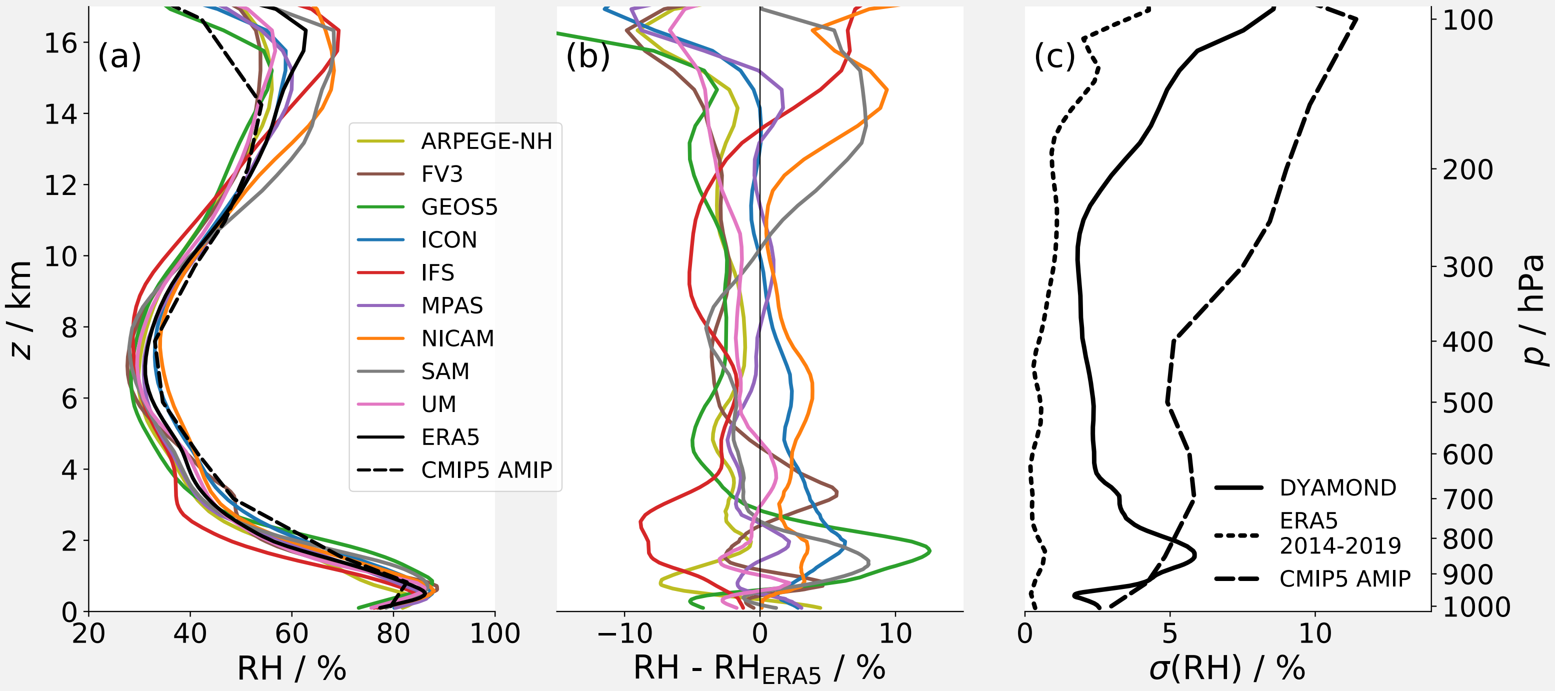


Figure 2: Tropical mean (ocean only) profiles of RH in DYAMOND models as (a) absolute values and (b) deviations from the multi-model mean. (c) Standard deviation of tropical mean RH in the DYAMOND ensemble (solid), the CMIP5 AMIP ensemble (dashed) and five successive August/September periods in ERA5 (dotted).

# Tropical regimes are depicted in moisture space

To compare different tropical moisture regimes, which are not necessarily co-located in the different models in physical space, **we compare model fields in moisture space** (Bretherton et al., 2005; Schulz and Stevens, 2018). Moisture space is spanned by ranking profiles by their integrated water vapour (IWV). **Deep convective regimes are associated with high IWV, the dry subsidence regimes with low IWV.**

Figure 3 shows different multi-model mean fields to provide some orientation in moisture space. From low to high IWV percentiles:

- Free-tropospheric RH increases
- Subsidence weakens and changes to rising motion in the highest percentiles
- Sea surface temperature (SST) increases
- All-sky outgoing longwave radiation (OLR) decreases (as high clouds become more abundant)

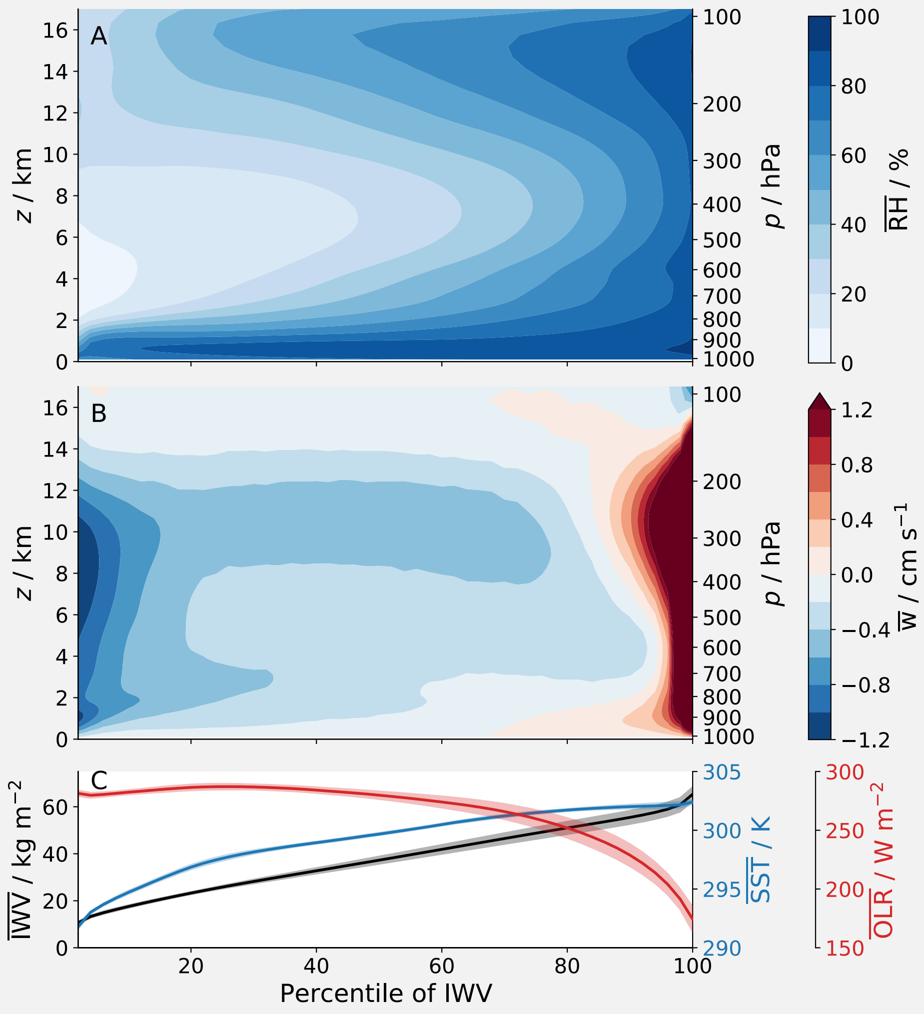


Figure 3: Multi-model mean fields in moisture space: (a) RH, (b) vertical velocity, (c) IWV, SST and all-sky OLR. Shading around the lines in (c) denotes the inter-model standard deviation.

# The mid-tropospheric RH spread is concentrated in moist tropical regimes

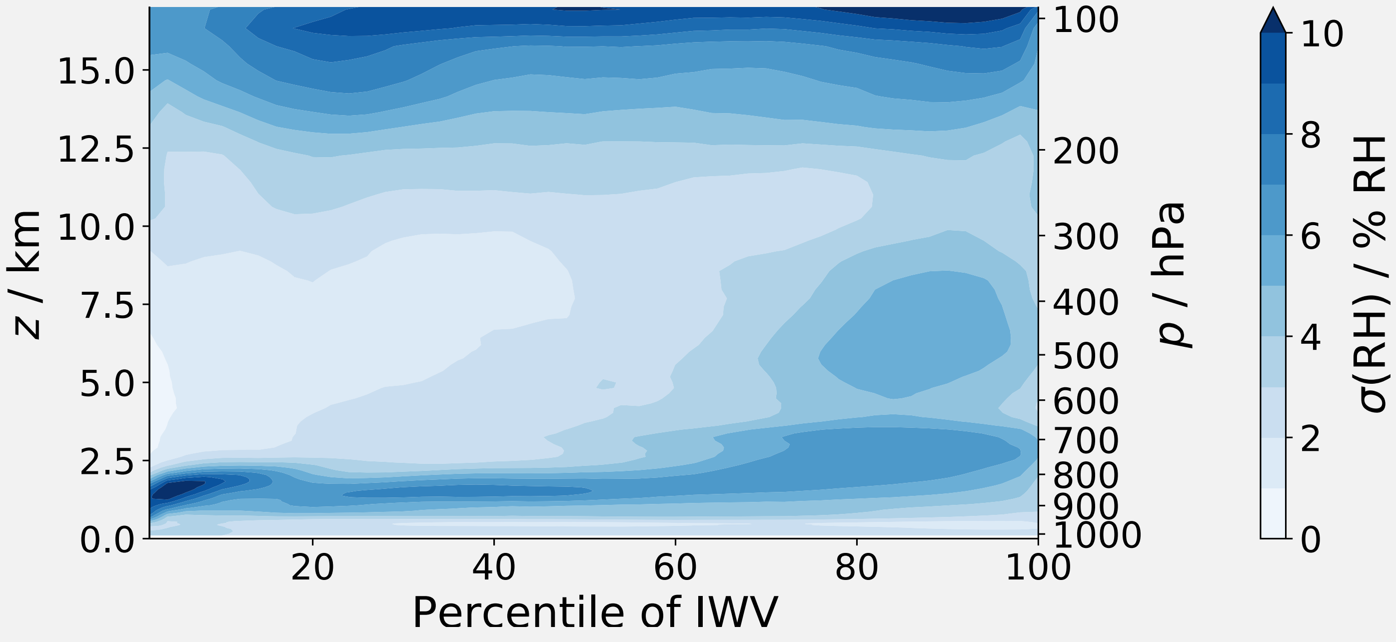


Figure 4: Inter-model standard deviation of RH in moisture space

Representing the inter-model standard deviation of RH in moisture space reveals that the large spread in the upper troposphere and around the top of the boundary layer prevails throughout the tropics (Figure 4). In the mid troposphere **the largest spread is concentrated in moist regimes around the 80th-90th IWV percentile** in proximity to deep convection. The large differences there are likely related to model differences in the representation of deep convection and/or microphysical processes.

# The resulting spread in clear-sky OLR is considerable (1.2 $Wm^{-2}$)

To assess the relevance of the RH differences we translate them into **differences in clear-sky outgoing longwave radiation (OLR)** using a radiative transfer model.

**The standard deviation in tropical mean clear-sky OLR is about 1.2 $Wm^{-2}$** (Figure 5). This is small compared to cloud radiative effects, but also a third of the estimated radiative forcing due to a $CO_2$ doubling.

Therefore, **a further reduction of humidity biases is needed to better constrain the clear-sky radiation budget**. As a first step in this direction, we identify the regions of the tropical atmosphere, in which a reduction would be most beneficial (see next slide).

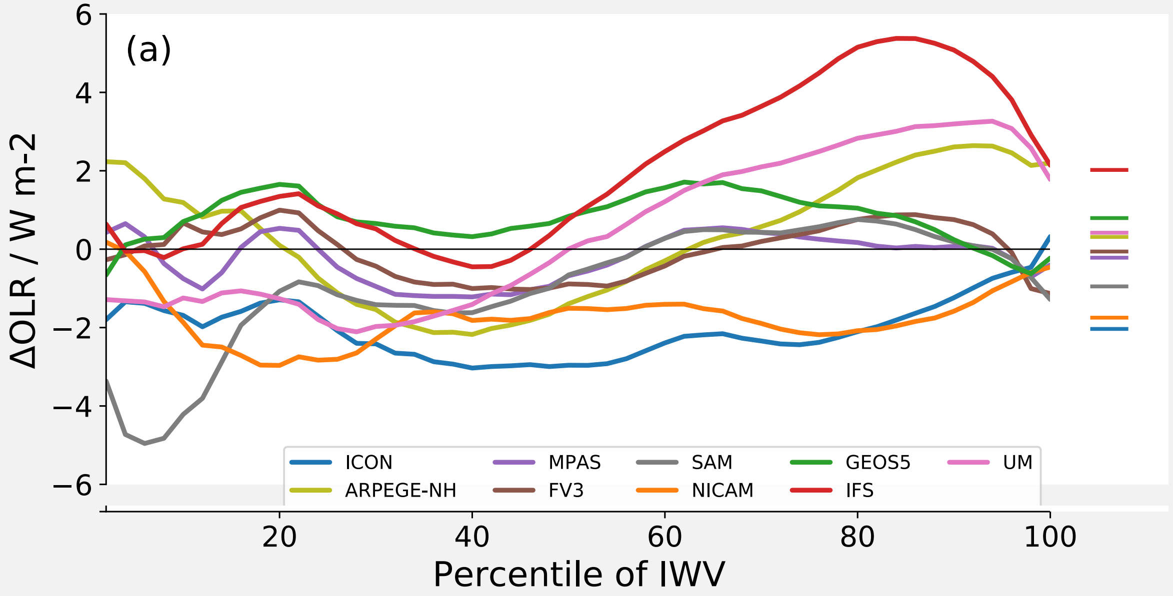


Figure 5: Clear-sky OLR of all DYAMOND models in moisture space plotted as deviation from the ERA5 OLR. Tropical mean values are indicated by the horizontal bars on the right.

# The OLR spread is mainly caused by RH differences in the lower and mid free troposphere

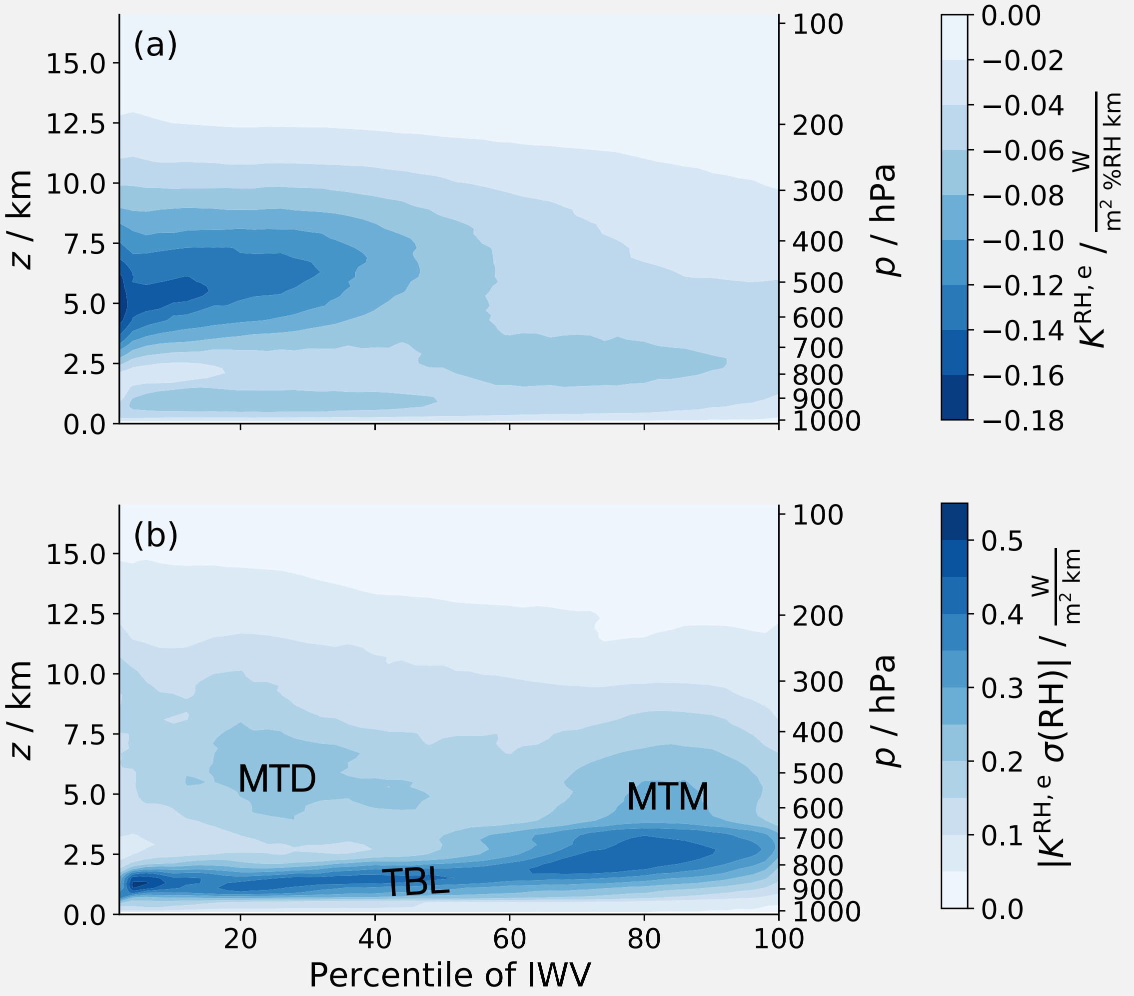


Figure 6: (a) RH response kernel $K^{\mathrm{RH}}$ showing the sensitivity of clear-sky OLR to a 1% change in RH in a 1km thick layer under constant temperature, (b) inter-model standard deviation $\sigma$(RH) weighted with $K^{\mathrm{RH}}$.

The **radiative kernel $\mathbf{K}^{\mathbf{RH}}$** (Figure 6a) provides the **sensitivity of OLR to a given perturbation in RH**. This sensitivity maximizes in the mid troposphere of the driest regimes.

To determine the impact of humidity differences on clear-sky OLR at a given point in moisture space, the inter-model standard deviation $\sigma$(RH) (Figure 4) is weighted with $K^{\mathrm{RH}}$ (Figure 6b). Based on this we identify **three regions in which a further reduction of humidity differences would be most beneficial:**

- **The mid troposphere of dry regimes (MTD)**
- **The mid troposphere of moist regimes (MTM)**
- **The top of the boundary layer (TBL)**

The **large inter-model differences in the upper troposphere are not relevant** because of the small OLR sensitivity at these altitudes.