The dynamics of ice clouds in the TTL as inferred from the isotopic composition of water vapor

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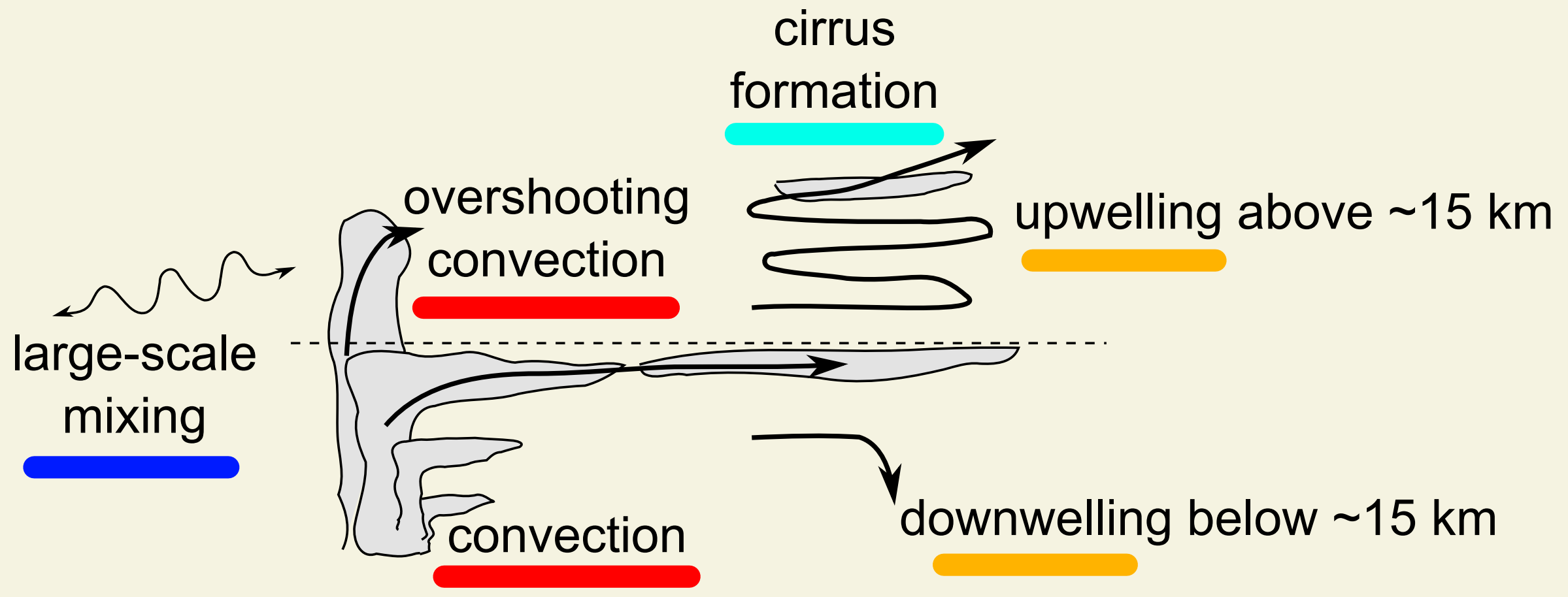
Diagnosing controls on water vapor in the TTL region

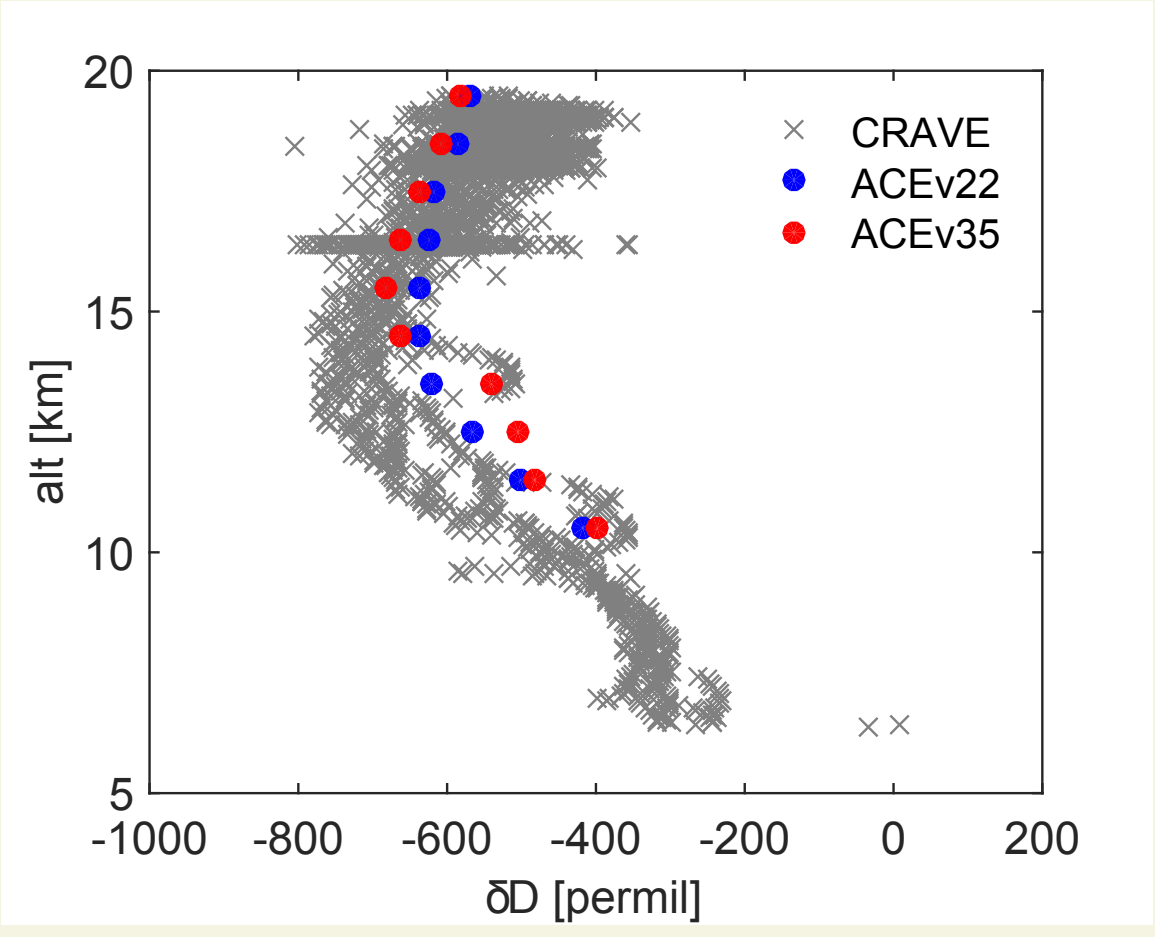
We use the isotopic composition of water to quantify the role played by convective vs large-scale processes in the water budget of the tropical tropopause layer (TTL). Those processes are of importance for the climate system: TTL water sources drive **TTL cirrus formation**, which has disproportionate radiative impact, and may affect **stratospheric dryness**. Lack of understanding hampers projections of possible effects of future climate change. By fitting the results of a simple model to isotopic observations, we show that **overshooting convection is likely the dominant source of water in the TTL**, in the 15-17 km range at least, with moistening rates 2 to 20 times higher than those from uplift or large-scale isentropic mixing.

Processes controlling TTL moisture



Added value of water isotopic composition

Isotopic composition allows diagnosis because it is altered by condensation: ice is isotopically heavier than the vapor it comes from. Under the combined effect of fractionation and mixing, air masses acquire a unique isotopic signature that integrates the history of water phase transformations since their last contact with the oceans.

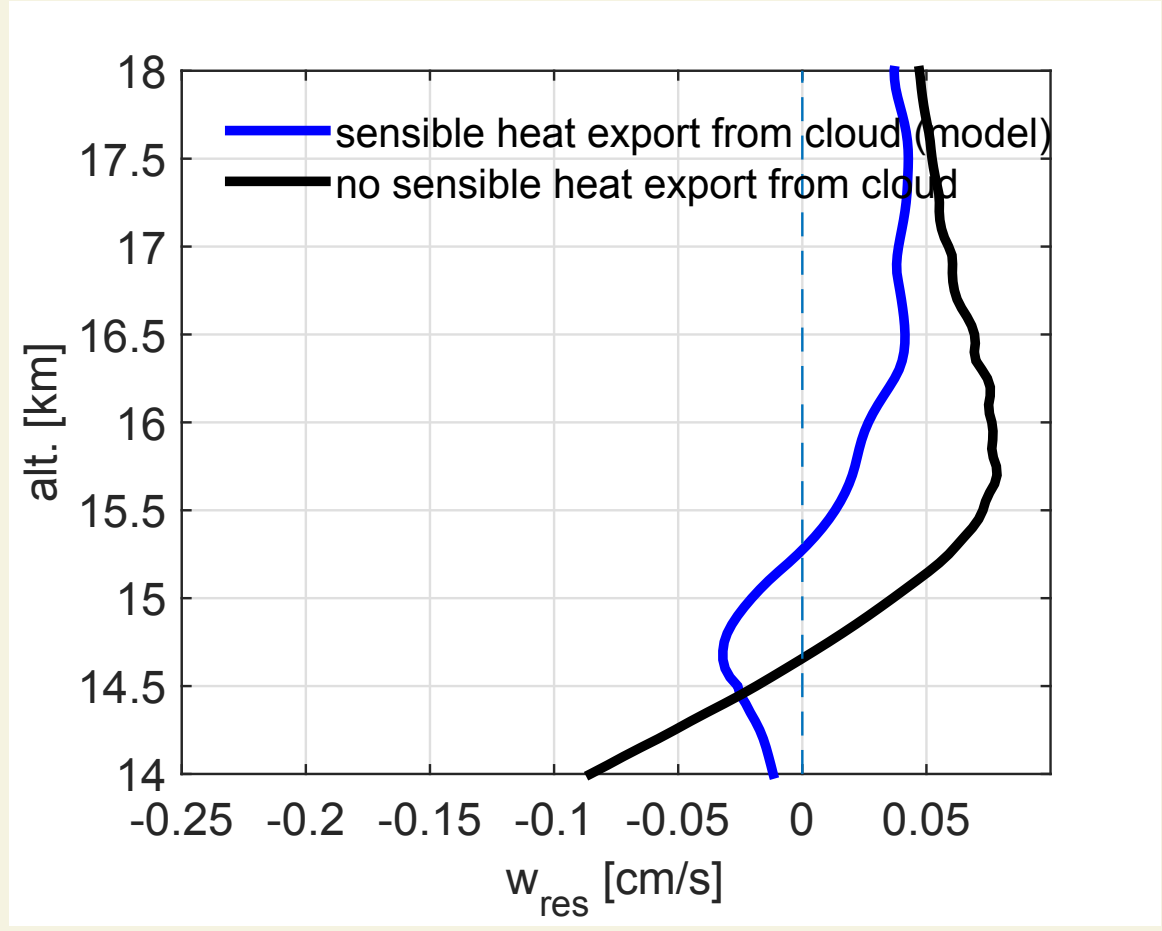


Isotopic composition of vapor observed by ACE-FTS (tropical occultations, Feb. 2004 to Aug. 2009) and by the Harvard ICOS Isotope Instrument during CR-AVE (Costa-Rica, Jan. to Feb. 2007)

Questions to answer

- What are the separate contributions of uplift, mixing and convective injection to TTL moistening rates?
- What fraction of water in in-situ cirrus originates in convection vs. large-scale uplift?
- How much ice is sublimating in the TTL at a given moment?

Convection's role in energy budget can alter inferred vertical velocities



Overshooting convection carries a **deficit of sensible heat in the TTL**. The export of that heat deficit with detrainment **partially offsets radiative heating**. For undilute convection, the difference is significant.

To interpret isotopic measurements, we construct a simple model that balances budgets of water and dry static energy and assume unmixed convection (no entrainment). The vertical velocity w_{res} in our model is much smaller than a pure radiatively-driven value (e.g. Folkins et al, 2006).

Simple model of environmental isotopic profile in tropics

Water vapor isotopic ratio R_{v}

$$\underbrace{w_{\mathrm{res}}\frac{\partial R_{\mathrm{v}}}{\partial z}} = -\left(\underbrace{(\alpha_{\mathrm{i}}-1)\frac{c}{r_{\mathrm{v}}}}+\underbrace{D\left(\frac{r_{\mathrm{vc}}}{r_{\mathrm{v}}}+\frac{r_{\mathrm{ic}}}{r_{\mathrm{v}}}\right)}+\underbrace{K\frac{r_{\mathrm{vex}}}{r_{\mathrm{v}}}}\right)R_{\mathrm{v}}+\underbrace{D\left(\frac{r_{\mathrm{vc}}}{r_{\mathrm{v}}}R_{\mathrm{vc}}+\frac{r_{\mathrm{ic}}}{r_{\mathrm{v}}}R_{\mathrm{ic}}\right)}+\underbrace{K\frac{r_{\mathrm{vex}}}{r_{\mathrm{v}}}R_{\mathrm{vex}}}$$

Vertical speed w_{res} (outside clouds)

$$w_{\mathrm{res}}\frac{\partial s}{\partial z}+\frac{1}{\rho}\left(\frac{\partial \rho w_0}{\partial z}-\frac{\partial \rho w_{\mathrm{res}}}{\partial z}\right)(s_{\mathrm{c}}-s)-Q_{\mathrm{rad}}=0$$

Detrainment rate D

$$D=\frac{1}{\rho}\left(\frac{\partial \rho w_0}{\partial z}-\frac{\partial \rho w_{\mathrm{res}}}{\partial z}\right)$$

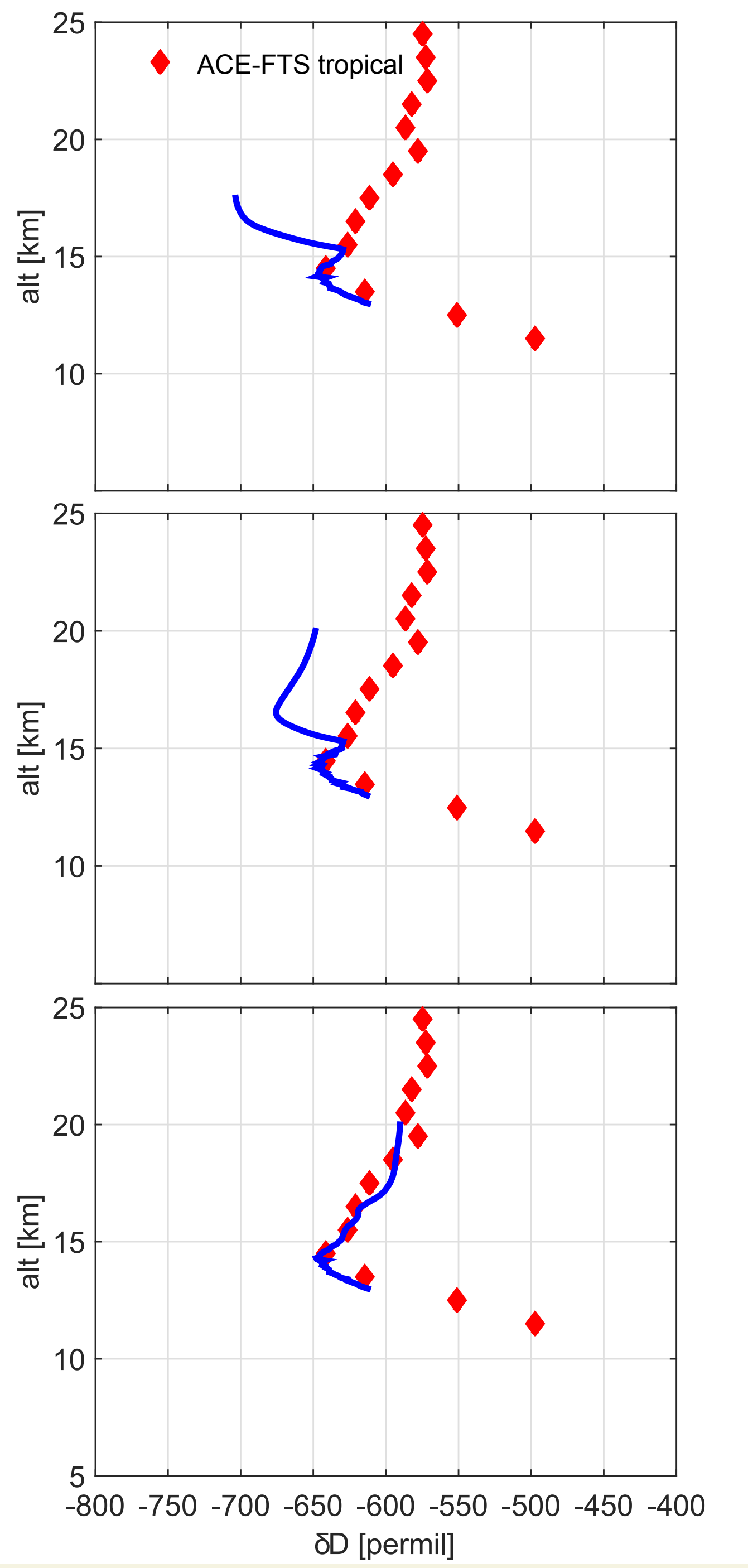
Rate of condensation c

$$c=-w_{\mathrm{res}}\frac{\partial r_{\mathrm{v}}}{\partial z}+D\left(r_{\mathrm{vc}}+r_{\mathrm{ic}}-r_{\mathrm{v}}\right)+K\left(r_{\mathrm{vex}}-r_{\mathrm{v}}\right)$$

Sources of data

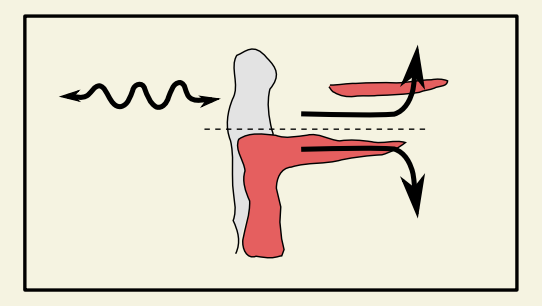
ERA-Interim (r_{v}, r_{vex}, s, Q_{rad}), Mote et al, 1998 (K), ACE-FTS (R_{vex}), Bolot et al, 2013 (r_{vc}, R_{vc})

Deuterium-enriched air source is required. Has to come from convection.



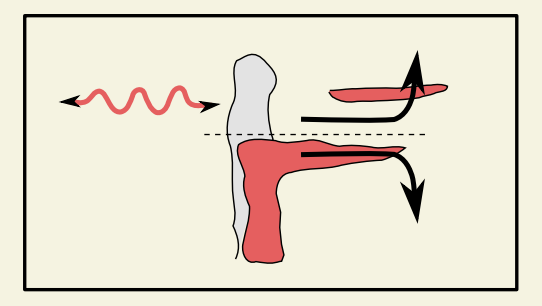
Gradual ascent + dehydration only

Deuterium would be progressively distilled out of the air. Water vapor cannot be set solely by cold-trapping along upwelling tropical trajectories. **A source of deuterium-enriched air is needed.**



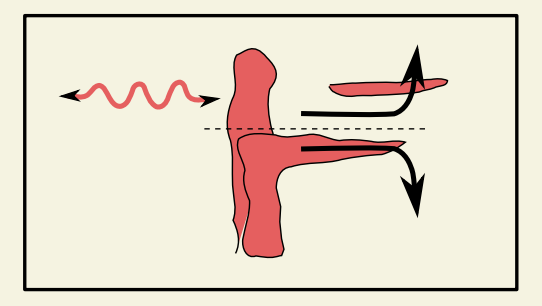
... + large-scale mixing

Extra-tropical air is somewhat enriched since it has been affected by methane oxidation. It is however **not rich enough nor is large-scale mixing intense enough to explain observations.**

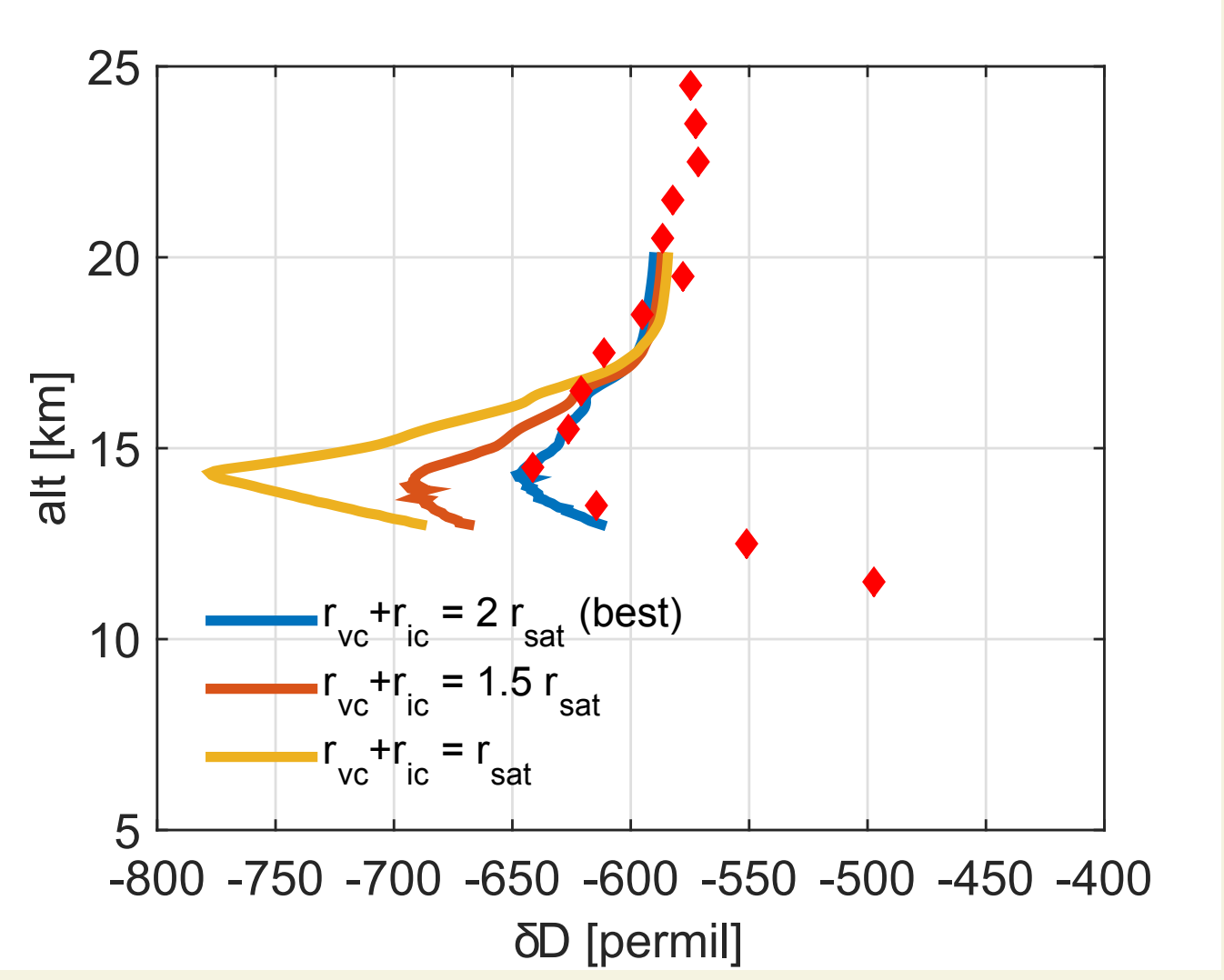


... + convective mixing

The only feasible explanation is that the **source of deuterium-enriched air has to come from convection.** The **enrichment reflects the bulk composition over vapor and ice** of the moisture detrained in the environment (ice being richer than vapor in the cloud).



Isotopic composition is sensitive to the magnitude of the moisture recycled

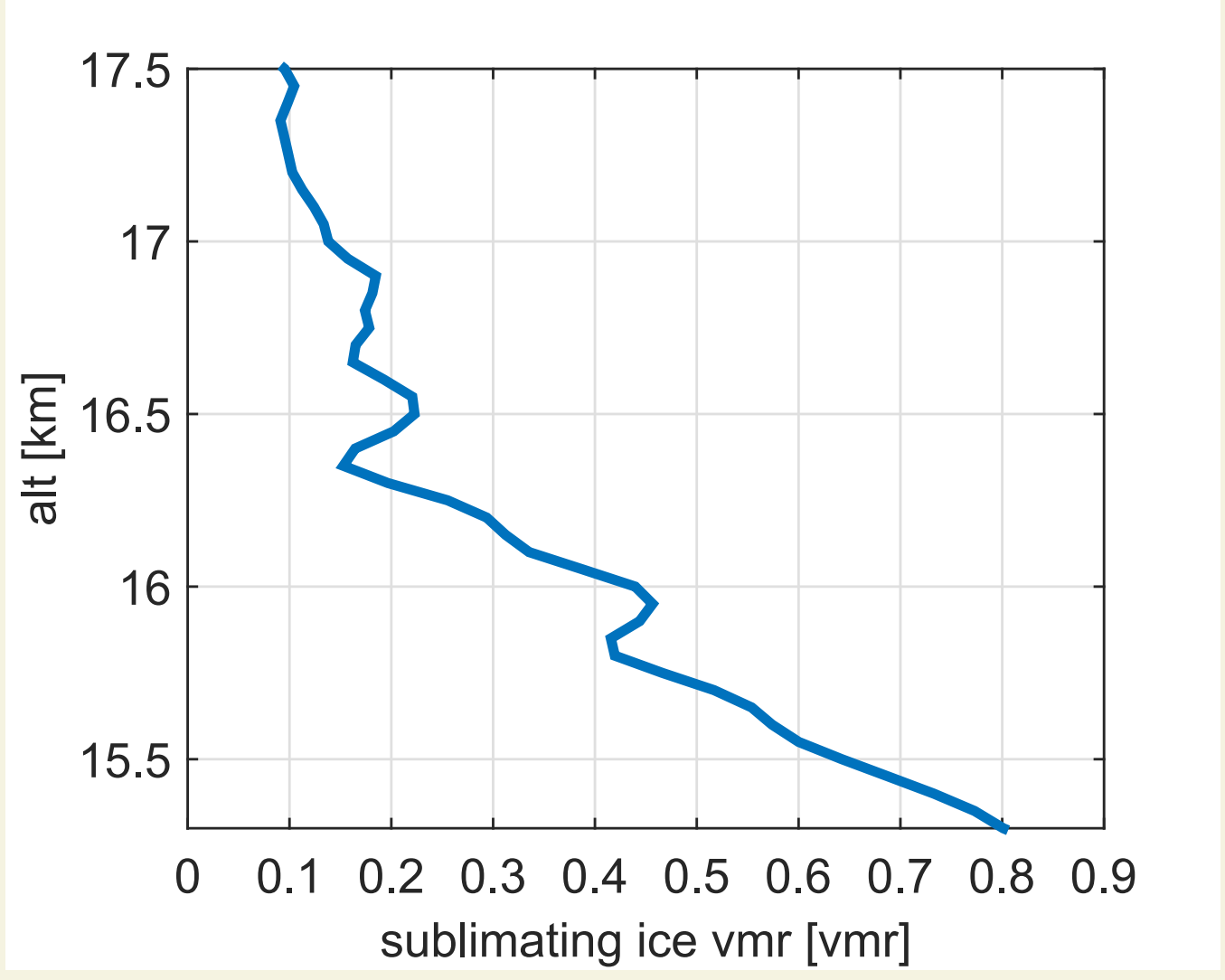


The more moisture is injected by convection, the more must redeposit as ice, forming cirrus clouds in the TTL.

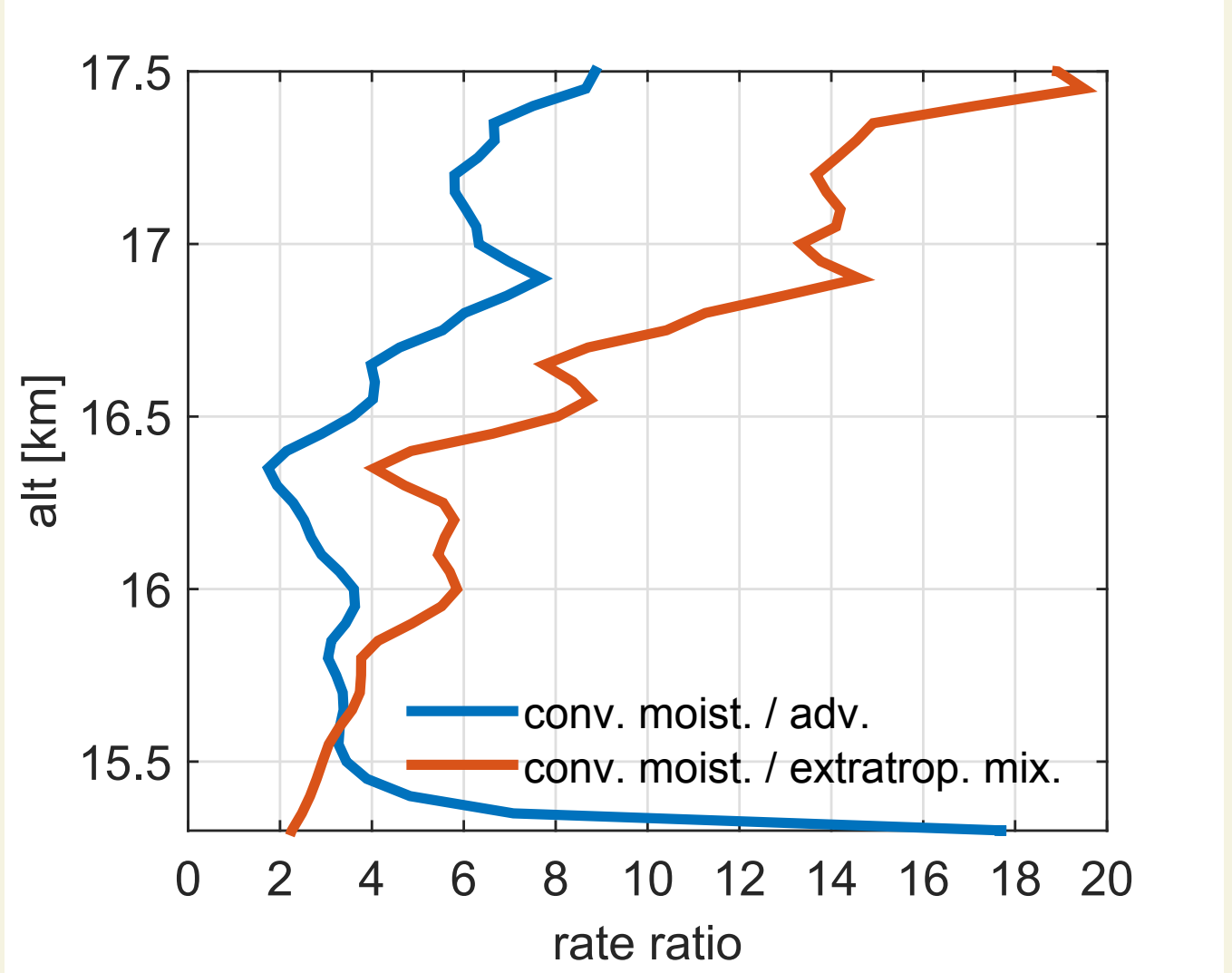
We find that the moisture convectively injected (over vapor r_{vc} and ice r_{ic}) is well quantified by the relationship: $r_{\mathrm{vc}} + r_{\mathrm{ic}} = 2\ r_{\mathrm{sat}}$.

The turnover of δD reflects the bulk composition of detrained moisture, increasingly dominated by ice as overshooting depth increases.

Our model allows estimation of the ice water content of convective cirrus that eventually sublimates. We compute the rate of sublimation of convective ice $D\ r_{\mathrm{ic}}$. With the assumption of a sublimation timescale of 1 day, this translates to an ultimately-sublimating convective ice load equivalent to 0.1-0.7 ppm. This estimate is comparable to observational ice loads from CALIPSO and Aura/MLS (Fleury et al, 2011).



Convection provides several times more moisture than uplift or isentropic mixing



The ratio of moistening by convection to moistening by uplift or large-scale mixing is consistently higher than 2 and increases with altitude. **Most of the moisture provision for cirrus cloud formation comes from convection.** Neglecting or mis-representing overshoots could result in dramatically underestimating cloudiness.

Conclusion and follow-up work

- Convection is the only source of deuterium-rich air that can produce observed isotopic profiles in the TTL.
- Convection seems to provide most of the moisture for cirrus cloud formation, at least in the 15-17 km range, followed by uplift and large-scale mixing.
- Conclusions on convective sources are somewhat dependent on cloud properties. Even if the mean isotopic profile were well known, in-situ campaigns are still needed to determine isotopic properties of cloud ice.
- Vertical velocities and detrainment rates in the TTL may be different than previously assumed. To resolve this, we need to understand the mixing properties of convection. The most logical tracers for this purpose are non-condensing short-lived species.