Dehydration in the tropical tropopause layer of a cloud-resolving model

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Introduction

What determines the water vapor content of stratospheric air?

- Water vapor enters stratosphere mainly through tropical tropopause layer (TTL)
- Coldest temperatures occur in the TTL ⇨ dehydration by condensation and precipitation
- What processes set the temperature structure of the TTL?
- What processes control the dehydration?
- Mainly two proposed **dehydration scenarios:**

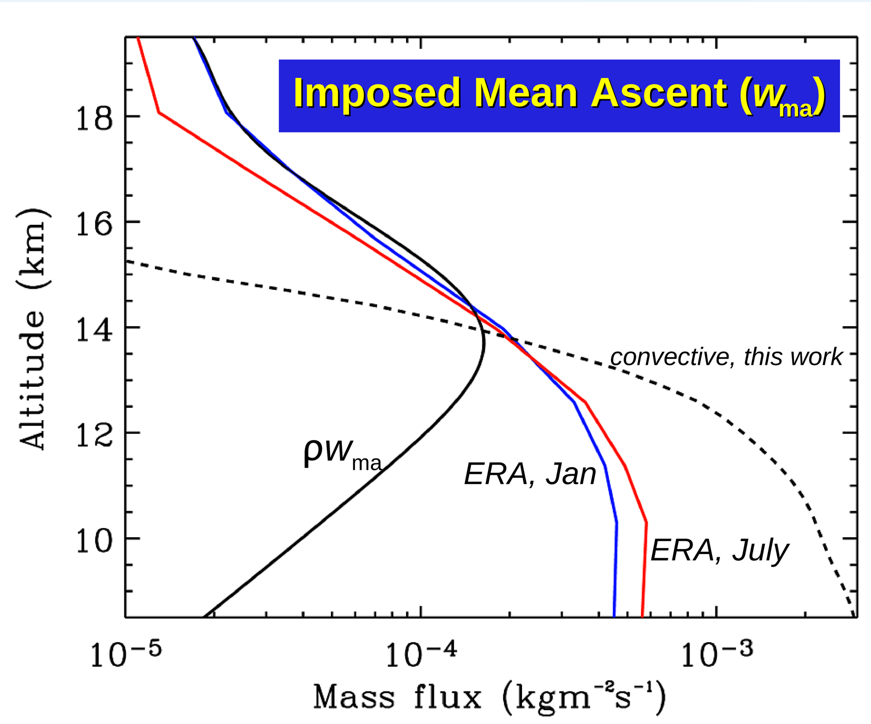
(1) slow large-scale ascent within the upward branch of the Brewer-Dobson circulation:
- large-scale dynamical cooling
- final stage of dehydration in thin cirrus clouds near the cold point (CP)
- can be altered through tropical waves (Kelvin, Rossby, Gravity)
- microphysical details of ice formation and actual path into stratosphere matter
- e.g. Holton & Gettelman (2001), Jensen & Pfister (2004)

(2) overshooting convection:
- strong local cooling through turbulent detrainment
- dehydration through ice formation within local temperature minima and subsequent precipitation
- can be altered by combining it with scenario (1)
- crucial aspects: detrainment sufficiently strong, ice formation and fall out sufficiently fast
- e.g. Sherwood & Dessler (2000)

Current Approach:
- study dehydration in the TTL within a three-dimensional cloud-resolving model (CRM) in statistical equilibrium, with imposed, horizontally uniform, slow ascent

Model & Setup

Three-dimensional cloud-resolving model (Large-Eddy Model, LEM, of UK Met Office):
- anelastic with fully interactive radiation scheme
- complex bulk microphysics: prognostic variables for mass mixing ratios of liquid water, rain, ice, snow, graupel, and number concentration of ice (q_l, q_r, q_i, q_s, q_g, and n_i)
- doubly periodic (96 km x 96 km, 2 km horizontal resolution)
- 30 km deep, rigid lid, 90 levels, 300 m vertical resolution in TTL, relaxation layer in top 5 km
- initial conditions: SST = 300 K (fixed), q_v (surface) = 17 g/kg, q_v (stratosphere) = 1.6 µg/g
- imposed mean ascent (w_{ma}, see Figure below) ⇨ control run
- 'Kelvin wave' experiment: multiply w_{ma} by $1 + A \sin^2(2\pi\, t/\tau_e) \sin(2\pi\, t/\tau)$, where τ – wave period, τ_e - envelope period, A - amplitude



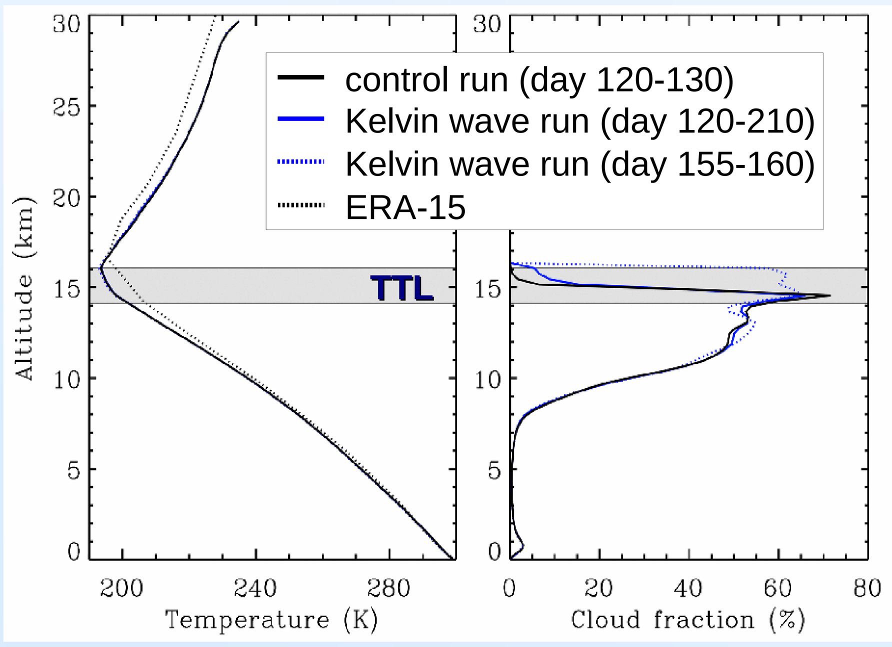
Imposed, horizontally uniform, vertical mass flux representative of the upward branch of the Brewer-Dobson circulation (black full line). Residual vertical mass flux averaged over 20 S - 20 N, 1979 – 1993 from ECMWF reanalysis data (ERA-15) for January (blue) and July (red). Dashed line shows horizontally and in time averaged convective mass flux in statistical equilibrium of present CRM study.

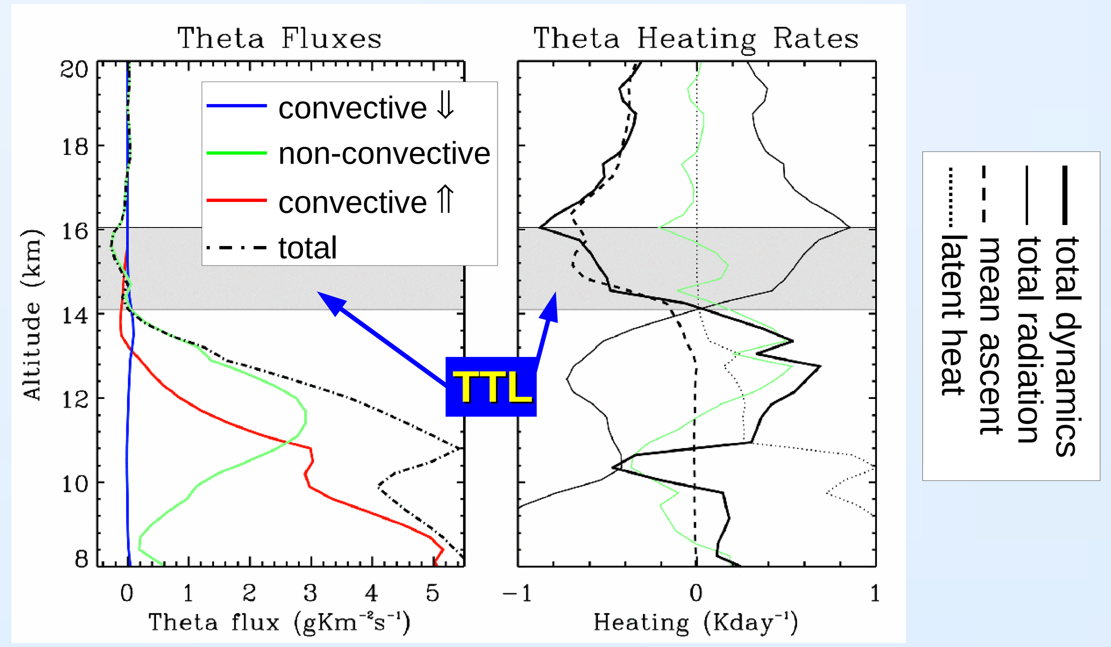
- Mass conservation: $\partial_x u + \partial_y v + \rho^{-1} \partial_z(\rho w') = 0$
- But: $D_t q = 0$ (without sources and sinks), where $D_t = \partial_t + u\,\partial_x + v\,\partial_y + (w' + w_{ma})\partial_z$

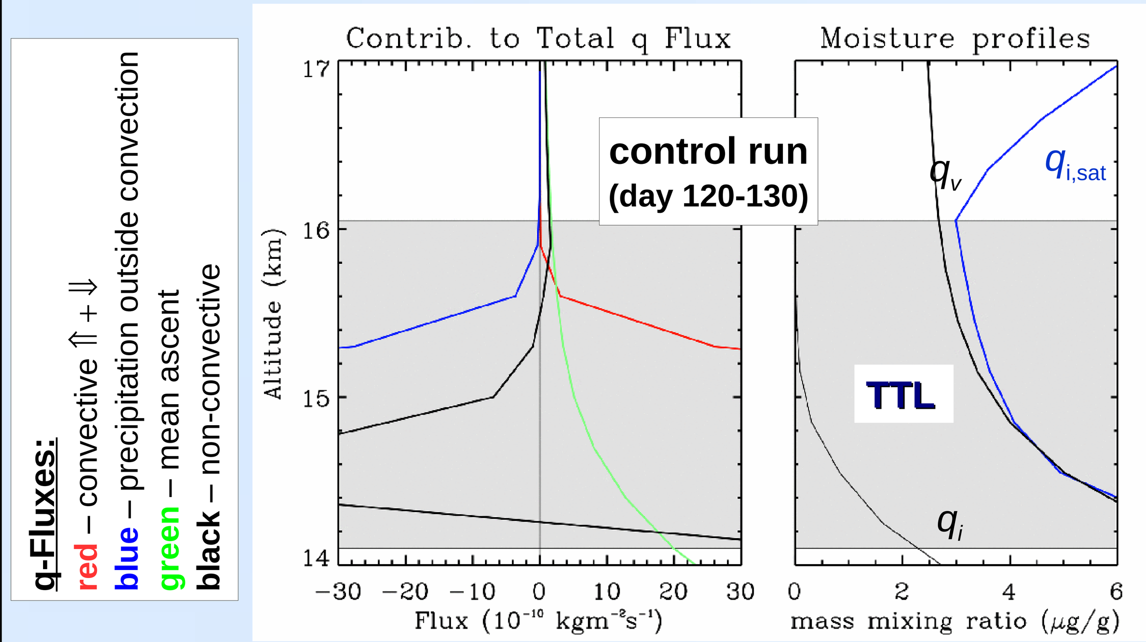
Equilibrium Statistics

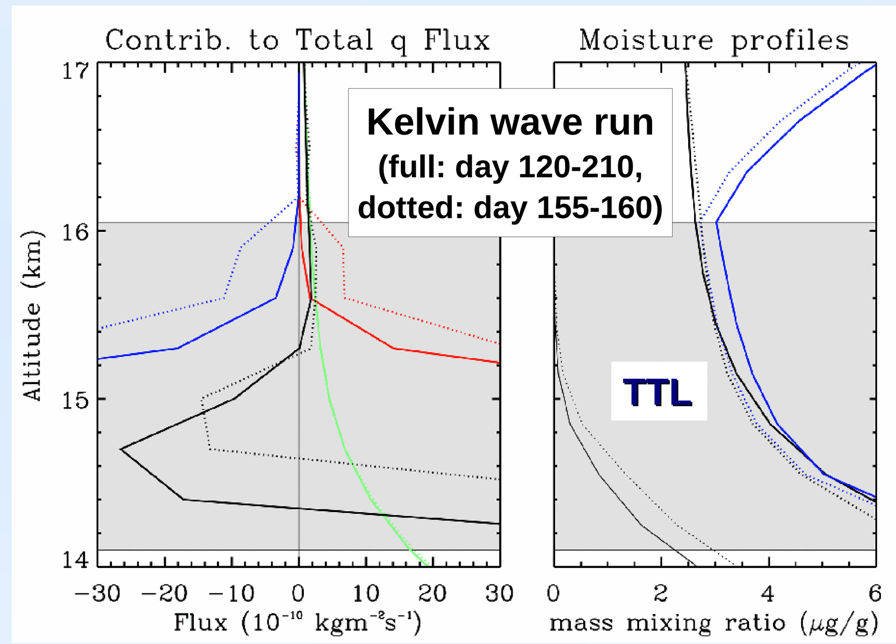
- all profiles are horizontal and temporal averages

potential temperature fluxes and heating rates for control run only (day 120-130); results of Kelvin wave experiment look very similar

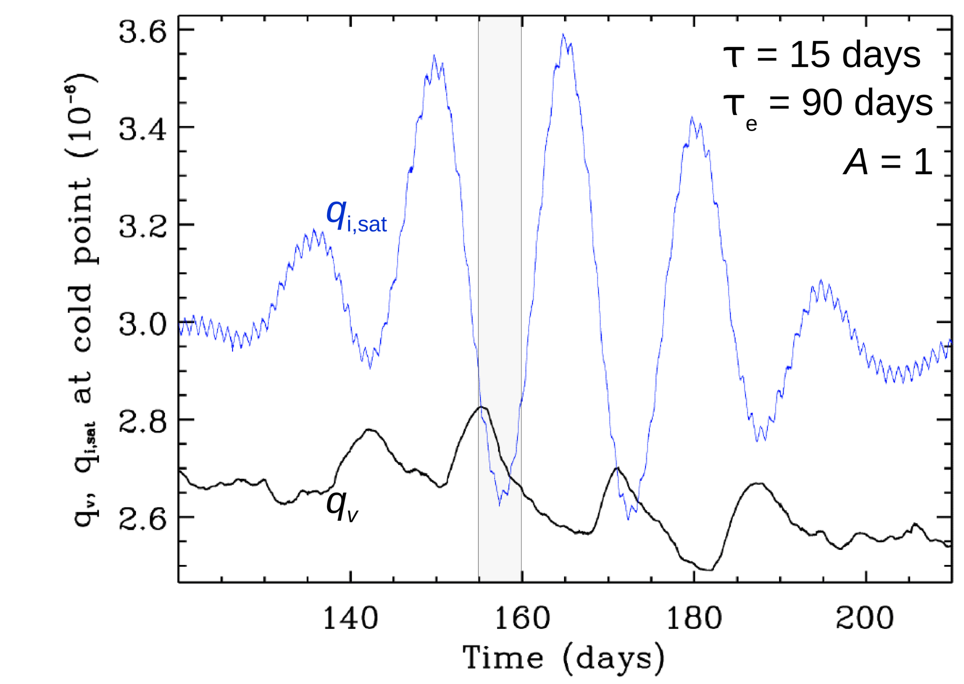


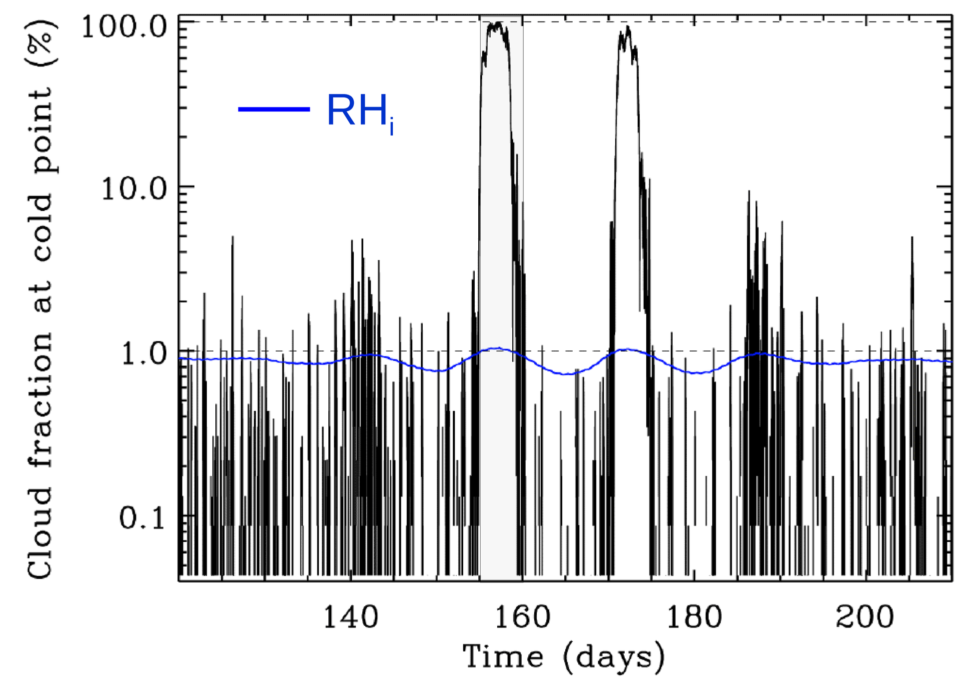






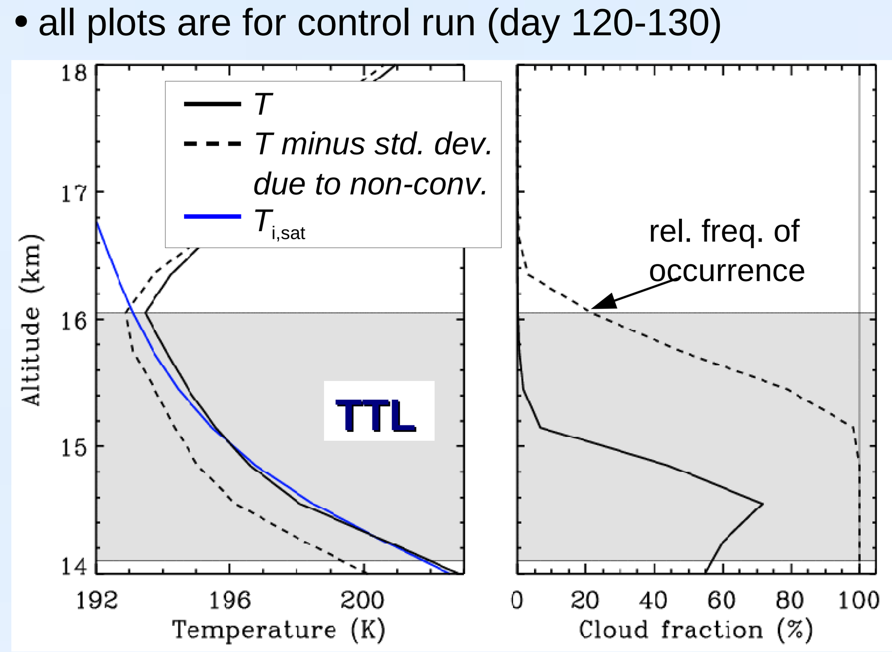
'Kelvin wave' experiment – temporal evolution at CP



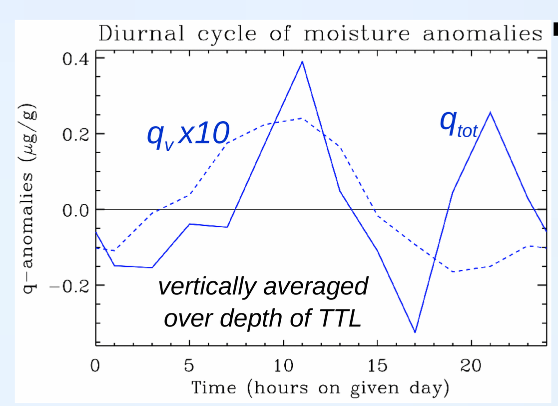


Buoyancy Waves & Diurnal Cycle

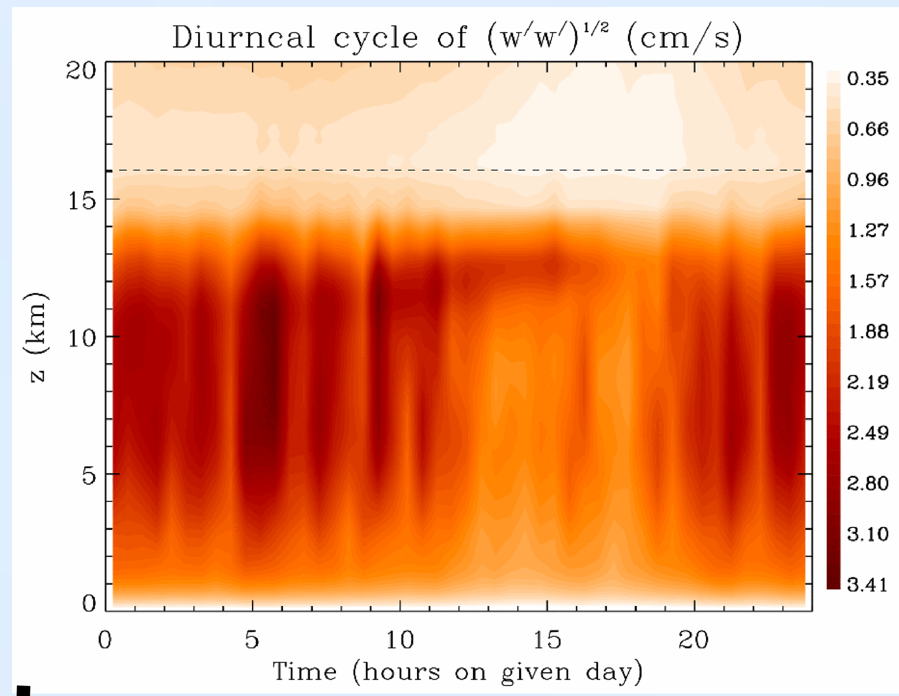
- all plots are for control run (day 120-130)



temperature perturbations of order standard deviation due to non-convective events (i.e. representative of buoyancy waves) are sufficiently strong to cause local supersaturation and thus cloud formation and potential dehydration



strong convective overshoots during night-time hydrate(!) TTL, whereas dehydration predominantly occurs during day-time (within temperature minima of buoyancy waves)



diurnal cycle in strong convective events with more convective plumes overshooting deeply into TTL during night-time

Conclusions

- transport of mass and moisture across CP dominated by slow ascent (cf. Küpper et al. 2004)
- dynamical heating rate in TTL dominated by slow ascent (in contrast to Kuang & Bretherton 2004)
- air above 15 km subsaturated with respect to ice in control run
- final stage of dehydration in convectively generated buoyancy waves
- convection tends to hydrate rather than dehydrate TTL in our simulations
- Kelvin-wave like perturbations lead to further dehydration

References

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