Idealized reconstructions of water vapor equilibrium profiles in the TTL

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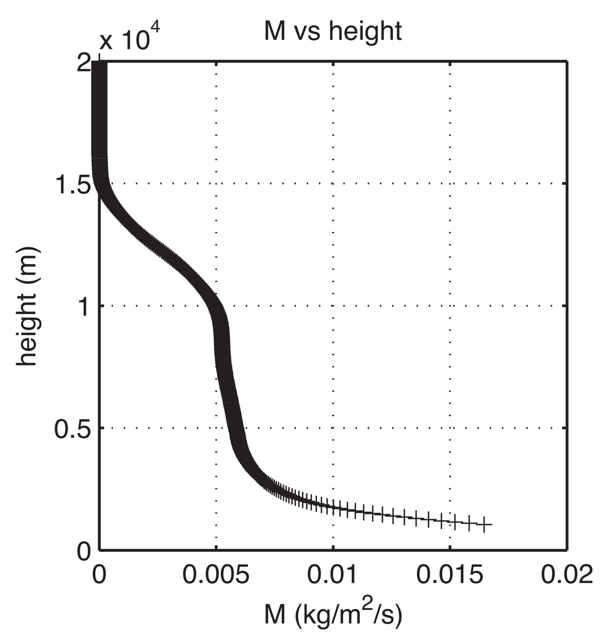
Introduction

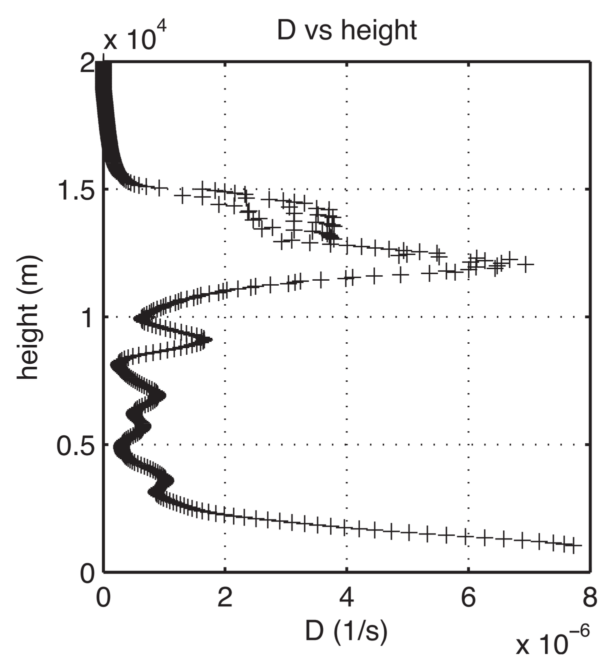
The role of overshooting deep convection in carrying water to the tropopause transition layer (the TTL, a transition region between the convective tropics and the Brewer-Dobson circulation) is an outstanding question in atmospheric science. One proposed tracer of the convective detrainment moisture flux is the isotopic composition of water vapor. We have constructed a self-consistent one-dimensional model to test that proposal and determine what we can learn from the physics of overshooting convection from mean environmental profiles of δD.

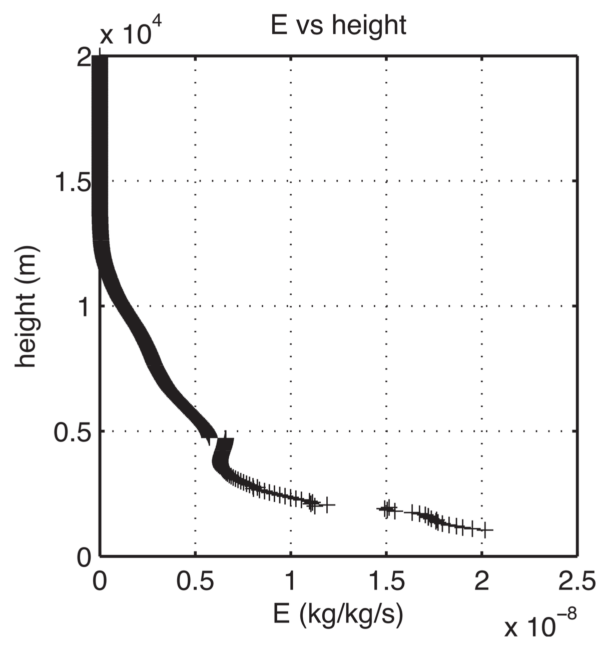
Model formulation

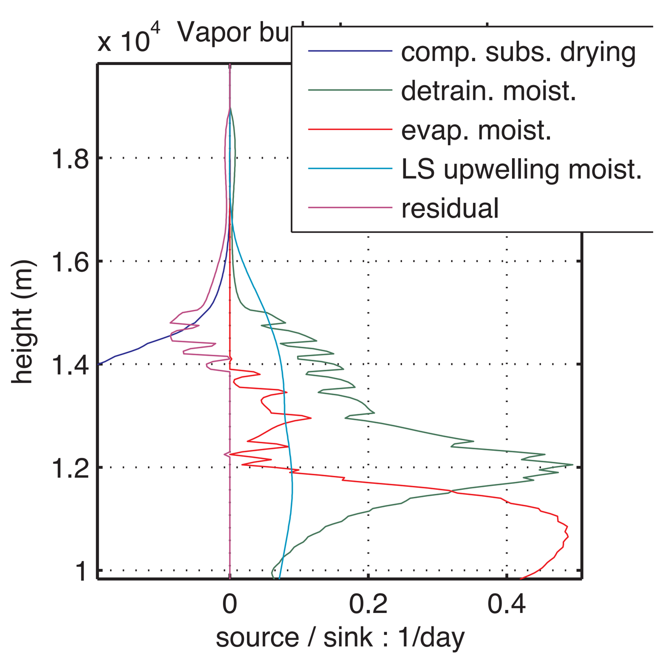
The model is a self-contained one-dimensional diabatic model for the tropics that can simulate both convection in the free troposphere and the transition region from troposphere to stratosphere, where large-scale radiative upwelling occurs. We keep the number of ad-hoc parameters as low as possible.

The model assumes a conceptual separation between two distinct regions, the small-scale convective cloud processes and the surrounding environment which is subject to large-scale upwelling or downwelling. The environment feels convection through three processes: compensating subsidence, the detrainment of saturated vapor, and the large-scale re-evaporation of precipitation. Re-evaporation of condensate can occur both within outflows and externally as precipitation falls through the environment.









Basic equations

The large scale budgets for **heat** ($s=C_pT_0+gz$) and **moisture** (q) are as follows if one only considers convective-type closures of the energy budget :

$$\frac{\partial \bar{s}}{\partial t} + \overline{\nabla \cdot s\mathbf{V}} + \frac{\partial}{\partial p}\overline{s w} = Q_R + L\,(C-E) - \frac{\partial}{\partial p}\overline{s' w'}$$

$$= Q_R - M_C \frac{\partial \bar{s}}{\partial p} + D\,(s_{cld} - \bar{s}) - L \cdot E$$

$$\frac{\partial \bar{q}}{\partial t} + \overline{\nabla \cdot q\mathbf{V}} + \frac{\partial}{\partial p}\overline{q w} = (E-C) - \frac{\partial}{\partial p}\overline{q' w'}$$

$$= -M_C \frac{\partial \bar{q}}{\partial p} + D\,(q_{cld} - \bar{q}) + E$$

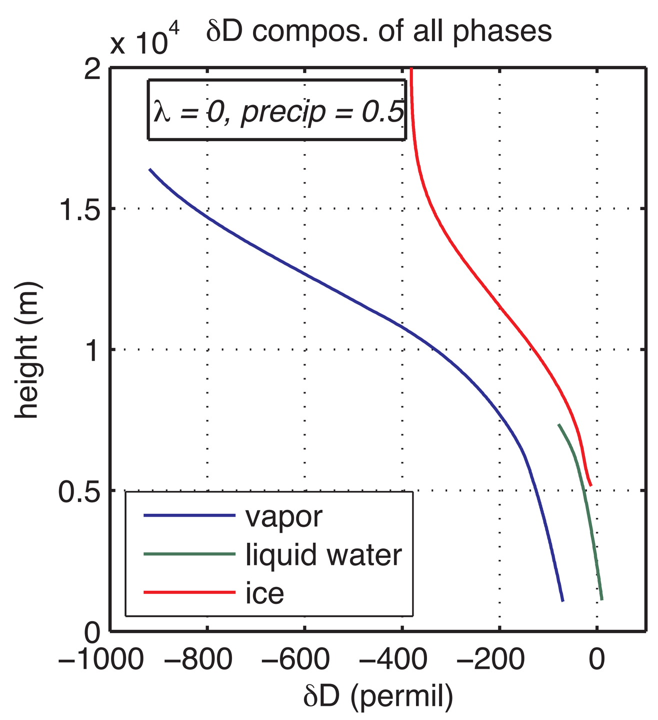
where overbar denotes averaging over a large-scale horizontal area.

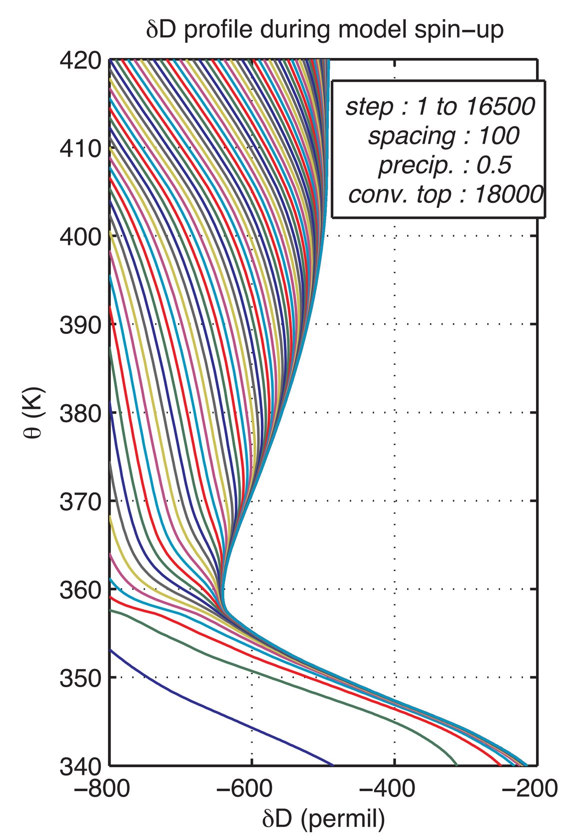
Q_R is the **radiative heating**, M_C is the **convective mass-flux** within the area of interest, D is **convective detrainment**, and E refers to **large-scale net evaporation in the environment**. Some refinements have been introduced to take into account the transition from liquid-water to ice thermodynamics with altitude, and the virtual temperature effect.

The **left-hand side of the above equations, as well as radiative heating rate**, are recomputed as tropical and multi-annual averages from ERA-INTERIM archive, with some simplifications. They **constitute the large-scale resolved forcings on the budgets of heat and moisture**.

With the large-scale forcings known, the above equations constitute a **solvable system for the convective mass flux M_C and net evaporation E**. In order to relate convective detrainment D to convective mass flux M_C, we need to prescribe convective entrainment. We use a **spectral representation of convection (multi-plume ensemble)** and each convective element has a fractional entrainment rate that makes the detrainment level consistent with buoyancy dilution. Such an approach is customary among modelers.

By pre-constraining the constitutive equations with the above assumptions, we can solve the problem in matrix form, and we **reconstruct the profiles of M_C, E and D**. Thus, we have an **equivalent mass-flux representation of all non-radiative diabatic processes** in the system.





Isotopic reconstructions

We **integrate the time-dependent budget for HDO in the environment that corresponds to the budget equation for moisture** previously considered. This approach puts a stringent constraint on the HDO budget by forcing its consistency with the moisture budget derived from ERA-INTERIM reanalysis. We initialize [HDO] to standard Rayleigh profile and integrate the equation until we see convergence of environmental δD.

Parameterization of the detrainment term $[HDO]_{cld}$ is central in the model : as overshooting convective outflows warm, ice with them evaporates to drive the outflows toward saturation. **Condensate in detrained outflows is as calculated within the full convective parameterization**. At lower levels, a fixed fraction of detrained vapor is assumed to come from convective re-evaporation.

The large-scale evaporation term is computed according to the cloud condensate composition at the level where condensate escapes the convective system and in-situ condensation is determined by the residual when the vapor budget is closed, and assumed to occur via Rayleigh fractionation.

We find that isotopic reconstructions provide useful insights on the budget of water by constraining the detrainment term $D(q_{cld}-q)$ in the moisture budget. In the TTL in particular, **knowledge of q_{cld} is an important information** to put in convective parameterizations : q_{cld} depends on how much convective ice gets injected in the environment, thus no simple theory applies to parameterize it. **We find that a suitable parameterization is given by $q_{cld} = \alpha\, q_{sat}(T)$, including in the TTL, and best agreement with measurements is found when α=1.4 in the TTL**.

We also find that the **isotopic composition of ice depends on the precipitation rate in convective towers**. We adjust precipitation so that convective ice composition is in the range -200 to -400 permil, according to recent TC4 measurements on ice phase.

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