Mock Walker circulations and the tropical tropopause layer

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Background

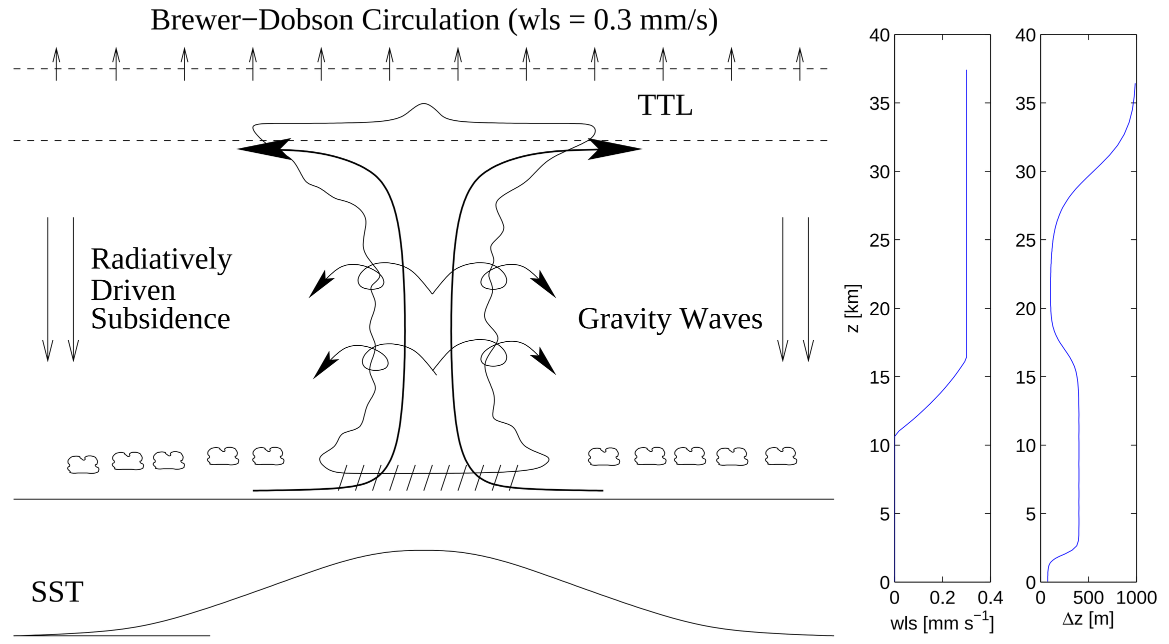
The tropical tropopause layer (TTL) is the transitional layer between the troposphere and the stratosphere over the tropics. Much of the mass entering the stratosphere passes through the TTL, so that the TTL plays an important role in determining the stratospheric water content which, in turn, affects the radiative balance and ozone chemistry in the stratosphere. Küpper et al (2004) and Kuang & Bretherton (2004) explored the role of convection in the TTL in cloud resolving model (CRM) simulations of radiative-convective equilibrium over a uniform sea surface temperature (SST) and reached differing conclusions.

Objective

To evaluate the role of convection in the TTL using simulations of a mock Walker circulation in a CRM.

Simulation Setup

Two-dimensional simulations in a periodic domain without rotation over a sinusoidally-varying SST provide an idealization of large-scale equatorial circulations in the tropics with convection centered over the warm SSTs (Grabowski et al 2000, Bretherton et al. 2006). For the study of the TTL, large-scale ascent (wls below at right) above 250 hPa is included to account for the effect of the Brewer-Dobson circulation.



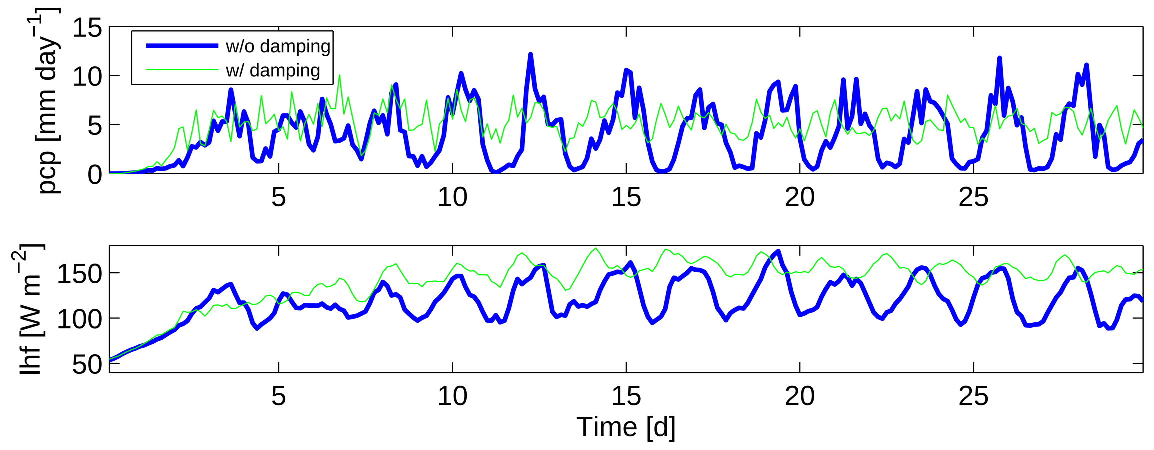
Domain: $L_x \times L_z$ = 4096 × 38 km, with Δx=2km and Δz=75–400m below a damping layer from 26–38km. SST(x) = 299.15K - 2K sin($2\pi x/L_x$). Simulations are run for 200 days, and averages/frequency distributions are computed from days 100 to 200.

Model Description

We use the System for Atmospheric Modeling (SAM), version 6.4 (Khairoutdinov & Randall 2003, also used in MMF), an anelastic model with bulk microphysics and prognostic equations for liquid–ice static energy $s_{li} = C_pT + gz - L_c(q_c + q_r) - L_s(q_i + q_s + q_g)$, total water (vapor+cloud) and precipitating water. Phases of non-precipitating and precipitating water are diagnosed from temperature. Longwave and shortwave radiative fluxes and heating are computed using the CCM3 radiation scheme.

Damping the quasi-two day oscillation

Periodicity in the x-direction allows convectively-generated gravity waves to interact resonantly on an approximately two day timescale as seen in the domain-averaged precipitation and latent heat flux timeseries. See also Grabowski et al (2000).

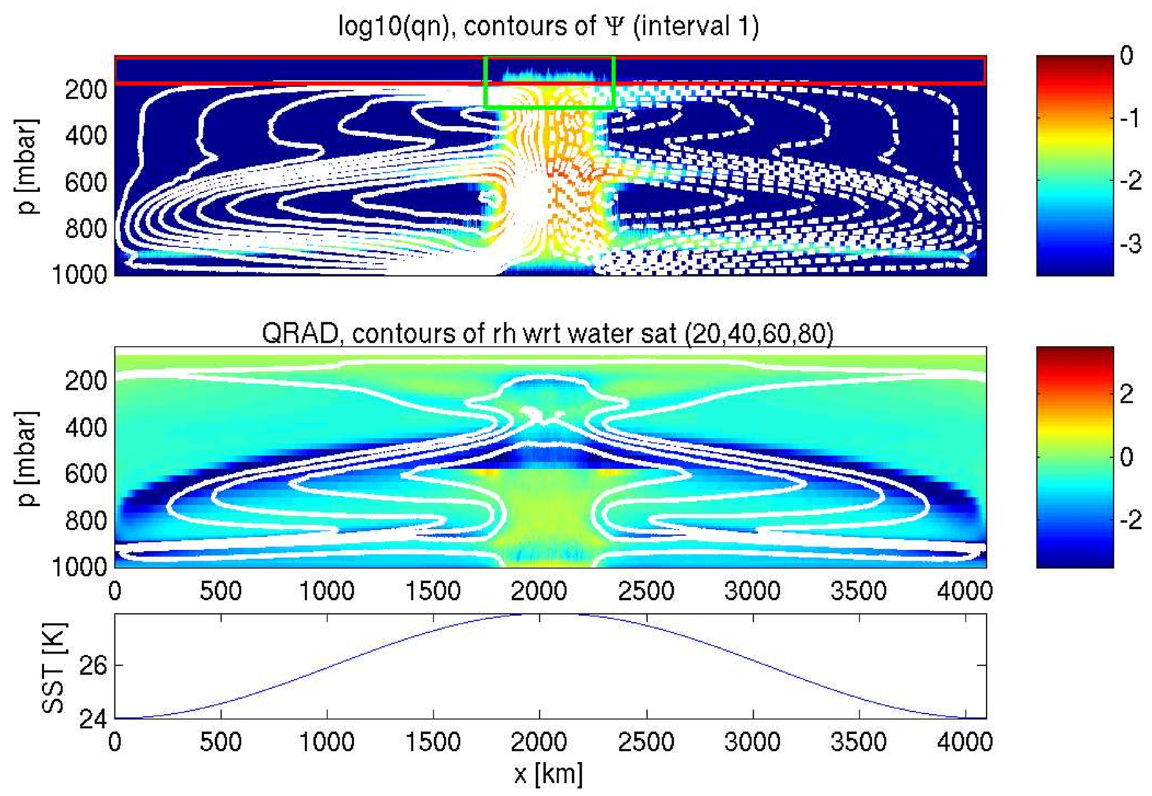


The impact of the resonant gravity waves on processes in the TTL is lessened by damping the velocity and temperature anomalies at the edges of the domain to their local mean value (accumulated with a ten day averaging timescale). The damping timescale is four hours at the edges of the domain and increases away from the edges of the domain as $1/\cos(\pi x/L_x)^8$ and also increases in the boundary layer, so that the damping has negligible impact near the surface and in the convecting region.

The rest of the figures depict time-averaged values and frequency distributions from the run with gravity wave damping at the edges of the domain.

Time-averaged Circulation

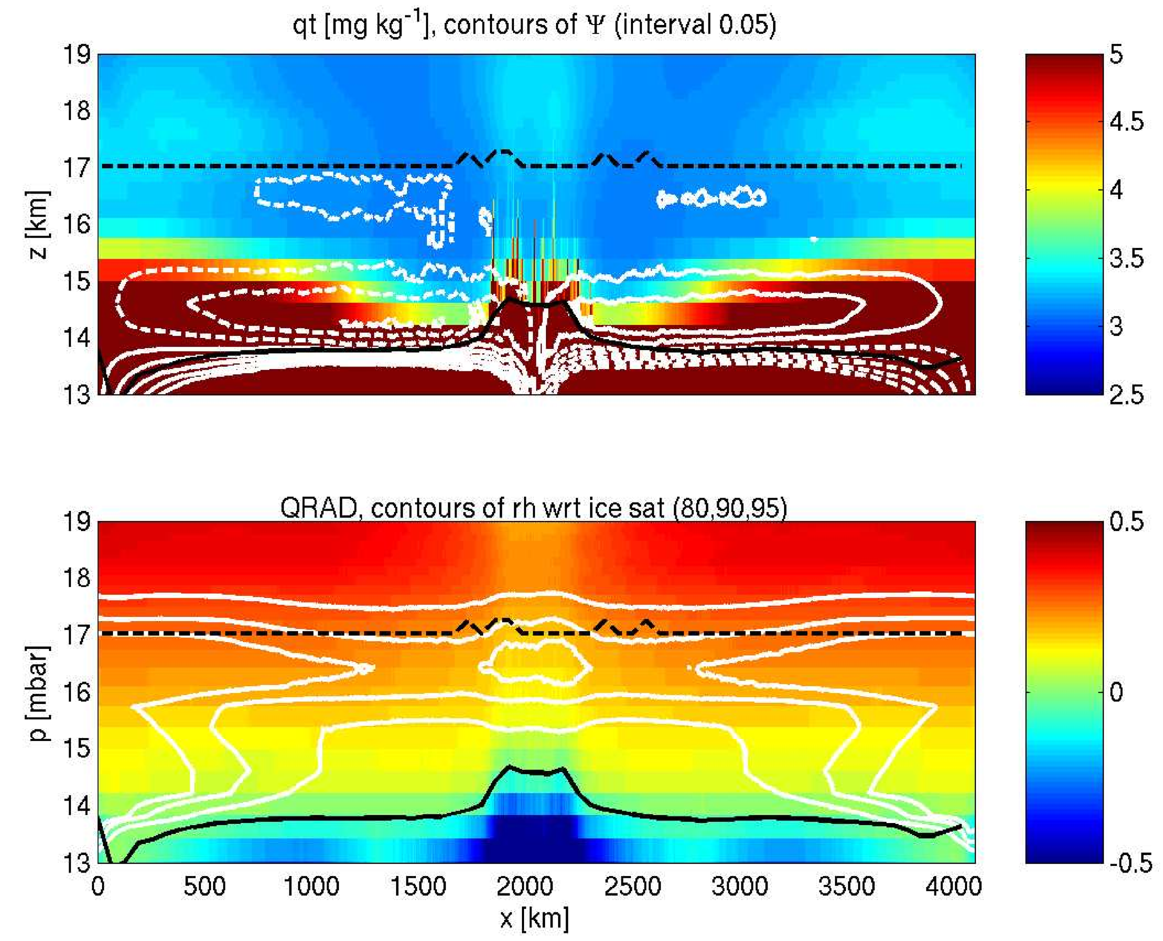
Contours of a time-averaged mass streamfunction Ψ indicate ascent is concentrated in the convective region over the warmest SSTs. Detrainment occurs in the upper troposphere and also in the mid-troposphere around the freezing level. Subsidence in the upper troposphere is distributed throughout the non-convective region but is concentrated at the edges of the domain in the lower troposphere.



The radiative cooling is strongest at the top edge of the mid-tropospheric detrainment layer and at the top of the boundary layer at the edge of the domain.

Reverse Circulation in the TTL

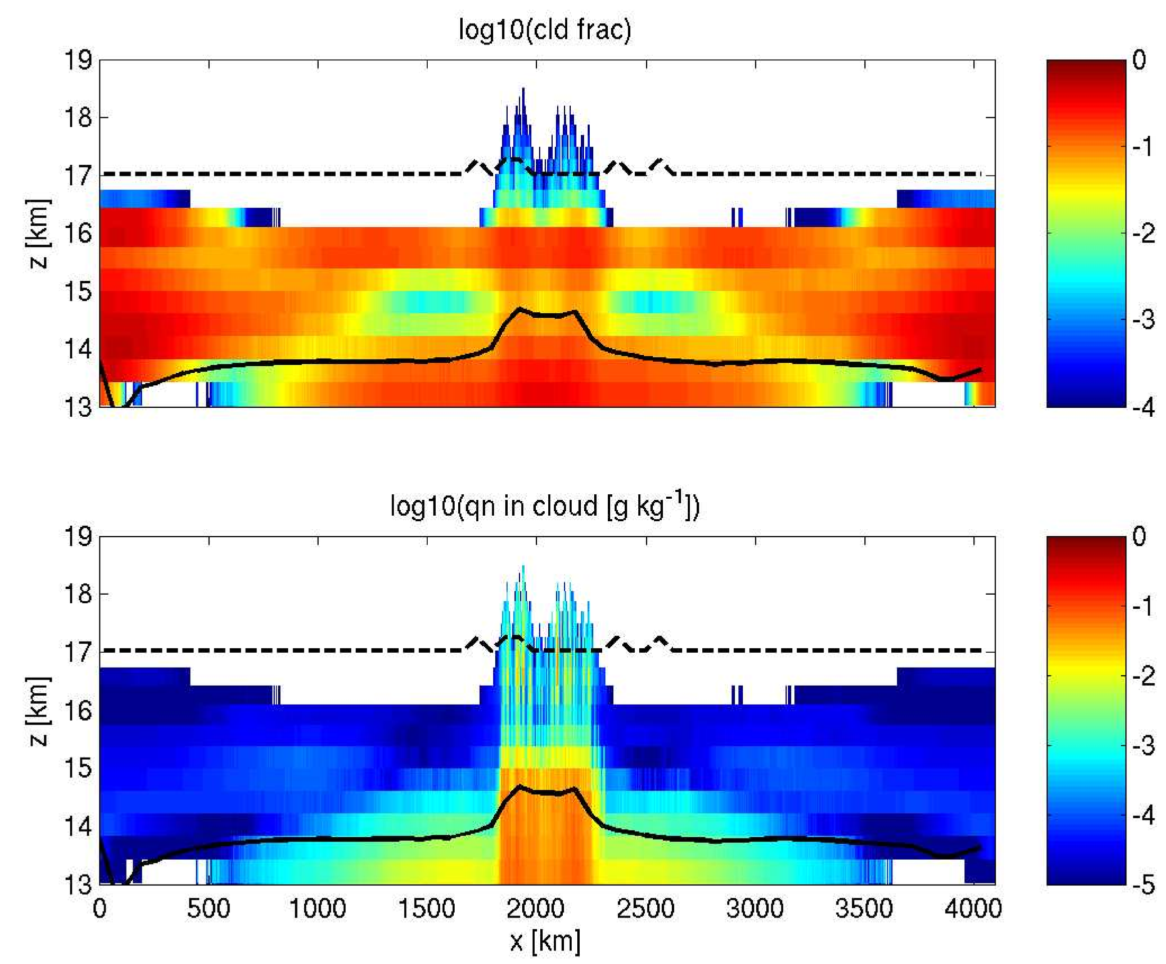
Contours of the mass streamfunction Ψ in the TTL (red box in time-averaged circulation plot) indicate the presence of a reverse circulation in the TTL as suggested by Sherwood & Dessler (2001). This circulation appears to be driven by a reduction in radiative heating over the convective region and affects the distribution of water vapor and cloud in the TTL.



The dashed and solid black lines indicate the heights of the cold point and the level of zero full sky radiative heating, respectively. These heights were computed from time-averaged and 64km block-averaged fields.

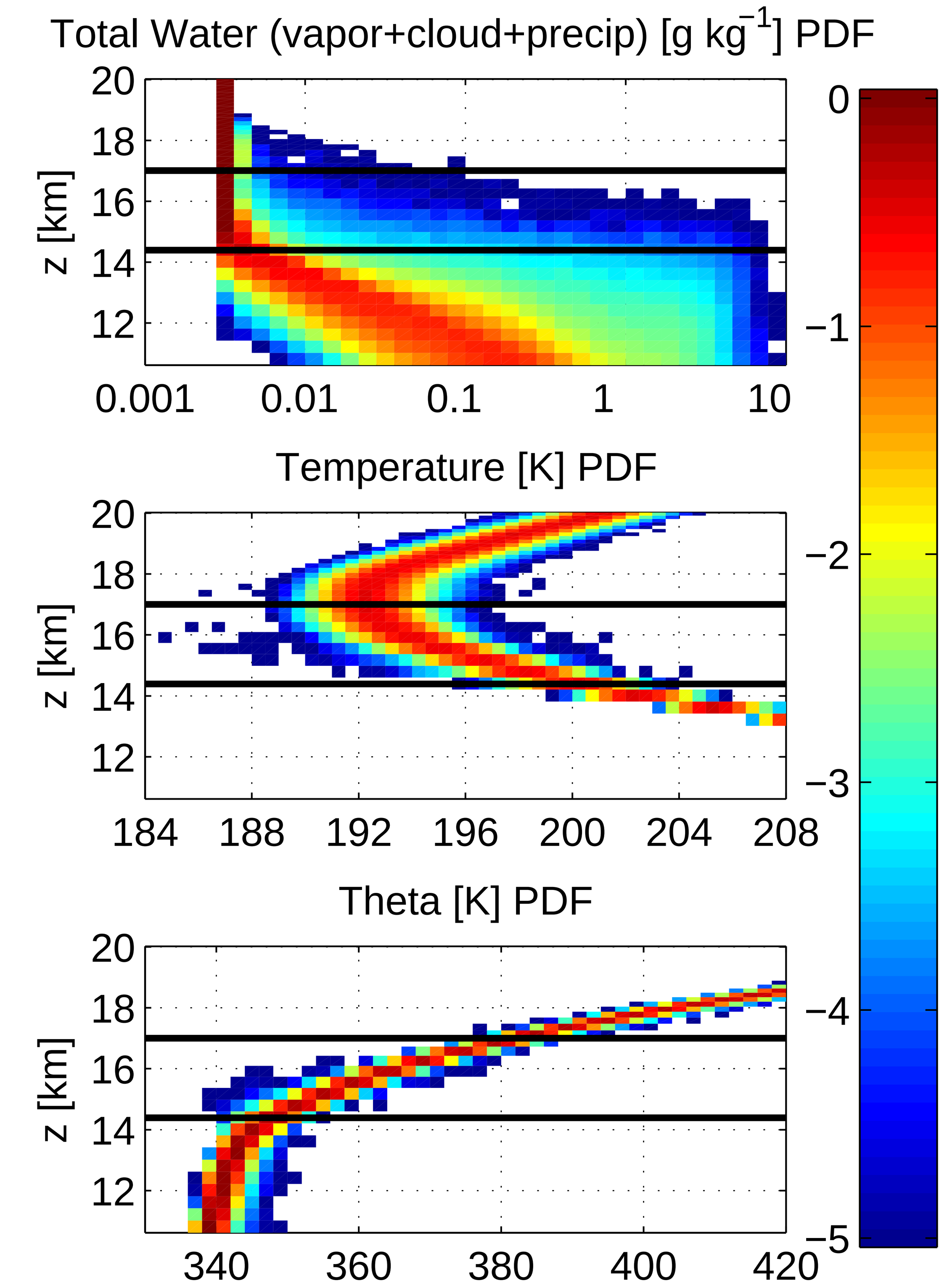
Presence of cloud at the cold point

Time-averaged cloud fraction and in-cloud cloud condensate amount indicate that convection does reach and overshoot the cold point tropopause, but that this occurs infrequently. The overshoots appear to affect the height of the tropopause at a few locations around the convective region but do not change it substantially as compared to the rest of the domain.



Frequency distributions in the TTL

In the TTL over the convective region (green box in time-averaged circulation plot), frequency distributions computed from instantaneous values at individual grid boxes show that convective plumes with large condensate amounts penetrate to near the cold point. However, smaller variability in θ and lower condensate levels at the cold point suggest that overshooting plumes mix strongly as they approach the cold point.



Conclusions

- Convection in a mock Walker circulation reaches the cold point tropopause (CPT).
- CPT height is affected by overshooting but changes little from non-convective region.
- The simulated TTL is affected by a mean secondary circulation forced by reduced radiative heating above convective cirrus anvils.

References

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