Trajectory and Microphysical Modeling of H_2O and Clouds in the Tropical Tropopause Layer

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Introduction

Stratospheric humidity is mainly controlled by the freeze-drying of tropospheric air as it ascends across the tropical cold-point tropopause (Fig. 1a). The details of the Tropical Tropopause Layer (TTL) dehydration mechanism, including the roles of deep convection, waves and cloud microphysical processes (Fig. 1b), are not well understood. The goal of this research is to better understand the processes that control H_2O and cirrus clouds in the TTL.

★ How well do our trajectory and cloud microphysical models simulate the observed H_2O and cloud fields in the TTL?

★ What are the impacts of convection, subgrid-scale waves, and cloud microphysics on TTL humidity and cirrus cloud abundance?

★ How sensitive are the simulated results to the radiative heating rates (which determine the vertical motions of parcels along their diabatic trajectories)?

(a) (b)

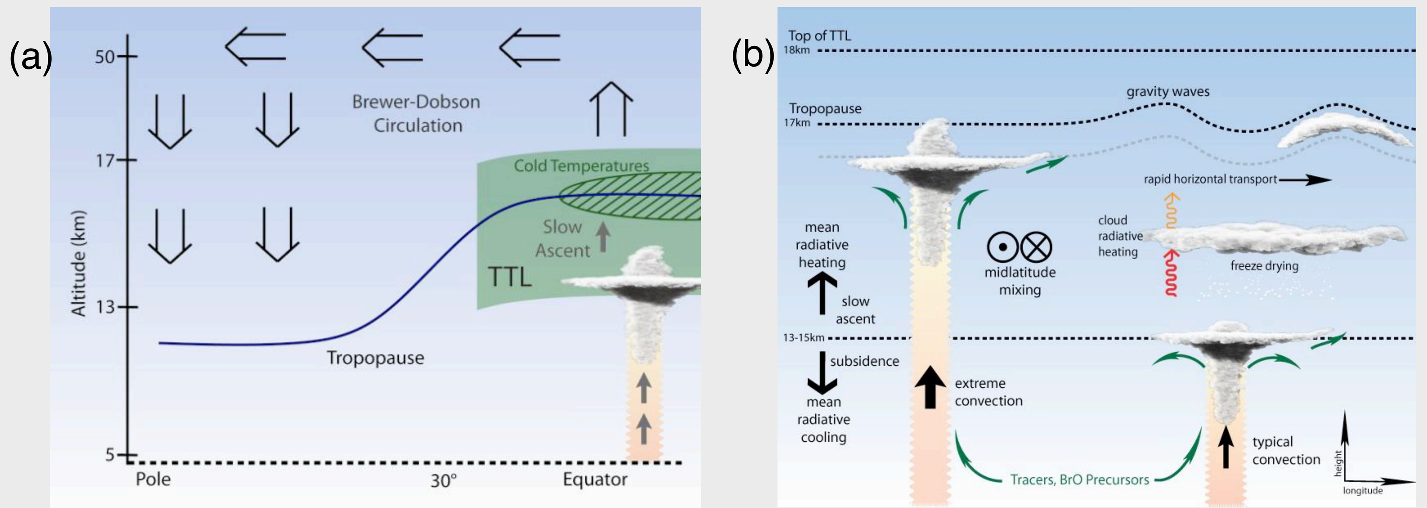


Fig. 1: (a) Schematic of the zonal mean cross-section of the TTL where air is dehydrated ("freeze-dried") as it ascends through the cold-point tropopause. (b) Longitude-height cross-section of the TTL and the many processes that influence TTL humidity and clouds.

Conclusions

•Waves dehydrate (by 0.5 ppmv), whereas convection and microphysics moisten (by 0.6 and 0.7 ppmv, respectively) the 100 hPa level (Fig. 10, Table 1).

•Waves and convection both increase the tropical mean cloud occurrence by ~25% near the 100 hPa (~16.5 km) level (Fig. 9). More than half of the cloud occurrence at and above the cold point is wave driven, while in situ formation of clouds downstream of convection dominates cloud occurrence below ~100 hPa.

• TTL humidity and clouds are sensitive to variations in the radiative heating rates. Temporal variability of the heating rates dehydrate the 100 hPa level and increase cloud occurrence frequencies throughout the TTL (not shown).

•Heterogeneous nucleation and convective ice injection have relatively minor impacts on TTL humidity and cloud frequency (not shown).

Table 1: Effects of waves, convection, and microphysics on the tropical mean 100 hPa H_2O mixing ratio and cloud occurrence frequency in the mid to upper TTL (16 - 18 km). Percent change relative to the base simulation are shown in parenthesis.

	H_2O, ppmv	cloud occurrence, %
waves (sub-grid scale)	–0.46 (–19%)	+3.6 (+29%)
convection	+0.56 (+23%)	+3.2 (+26%)
microphysics	+0.71 (+29%)	N/A

Ueyama *et al.* (2015, *JGR*, in review)

Methodology

Trajectory Model

1. Calculate 60-day backward (diabatic) trajectories on 1 Feb 2007 every 2° latitude x 2° longitude in the tropics (20°S - 20°N) from the 372 K potential temperature (~100 hPa) level.

•Heating rates (vertical motions) from offline radiative transfer calculations (*Yang et al.*, 2010) and ERA-interim wind and temperature fields

•ERA-Interim temperatures and winds with enhanced wave-driven variability [*Kim and Alexander,* 2014] (Fig. 4)

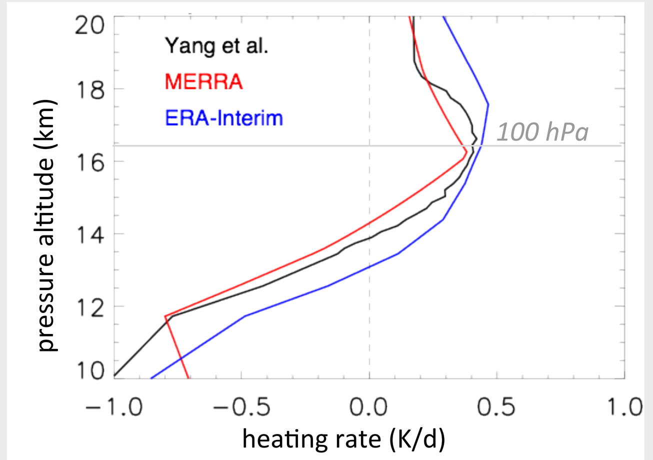


Fig. 2 (top): Vertical profiles of tropical (20°S-20°N) mean radiative heating rate in boreal winter (DJF 2006-07) based on (black) *Yang et al.* [2010], (red) MERRA and (blue) ERA-Interim reanalysis data.

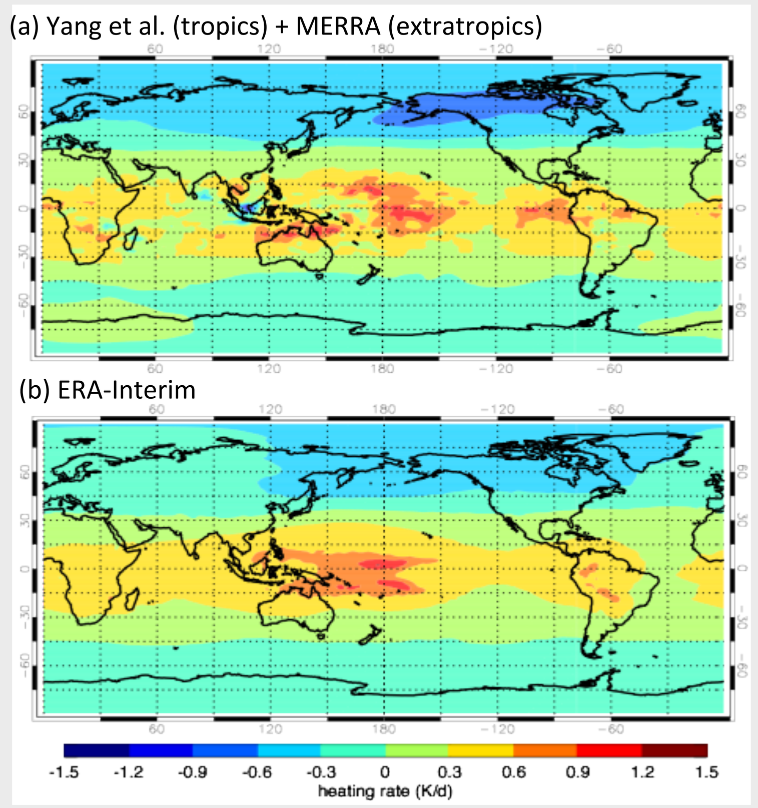
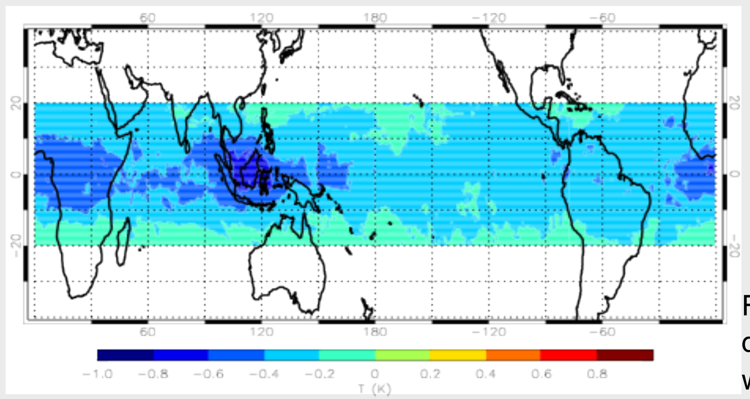


Fig. 3 (right): Boreal winter (DJF 2006-07) radiative heating rates at ~100 hPa level: (a) Yang et al. + MERRA, (b) ERA-Interim.



• *Yang et al.* [2010] heating rates in the TTL are generally weaker and exhibit larger spatial variability than those of ERA-Interim.

• Waves lower the cold-point temperature throughout the tropics (mean –0.25 K) with largest impact over Indonesia (–0.84 K).

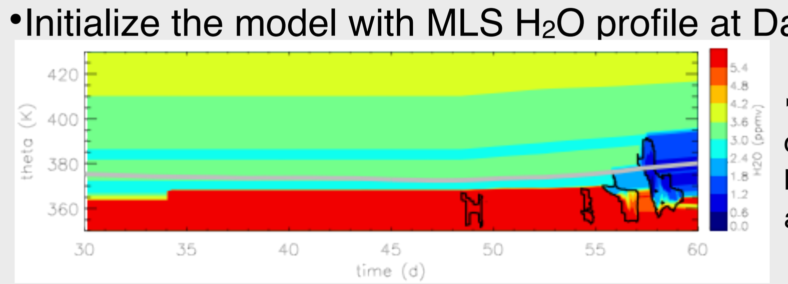
Fig. 4 (left): Tropical cold-point temperature difference due to waves [*Kim and Alexander,* 2014] in boreal winter (DJF 2006-07).

Cloud Microphysical Model

✦ Time-dependent, one-dimensional (vertical) model that tracks the growth, sedimentation, sublimation of individual ice crystals

• Simulate ice clouds and H2O along parcel trajectories

•Initialize the model with MLS H_2O profile at Day –60



• H_2O profile is influenced by clouds (black contours) and convection (saturated at lower levels, red) along the parcel trajectory (parcel altitude in gray line).

Fig. 5: A sample time-height "curtain" of H_2O mixing ratio of a given parcel trajectory.

✦ Convection scheme

Trace trajectories through geostationary satellite convective cloud-top height fields, and saturate the column up to the cloud-top altitude

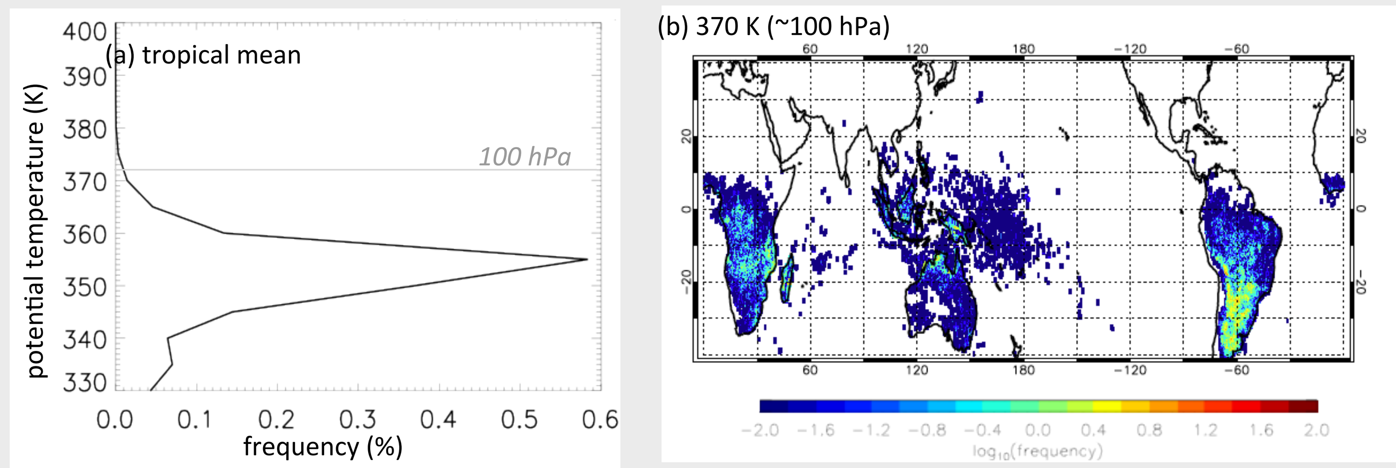


Fig. 6: Convective cloud-top height distribution in boreal winter (DJF 2006-07): (a) tropical (20°S-20°N) mean profile, (b) spatial distribution of convective clouds with tops reaching the 370 K level.

Results

Model *vs.* Observations

- The simulated 100 hPa H_2O field agrees reasonably well with MLS observations (r = 0.54, RMSE = 0.5 ppmv), but is ~20% too dry.
- Spatial distribution of cloud occurrence frequencies in the mid to upper TTL is well correlated with that of CALIPSO

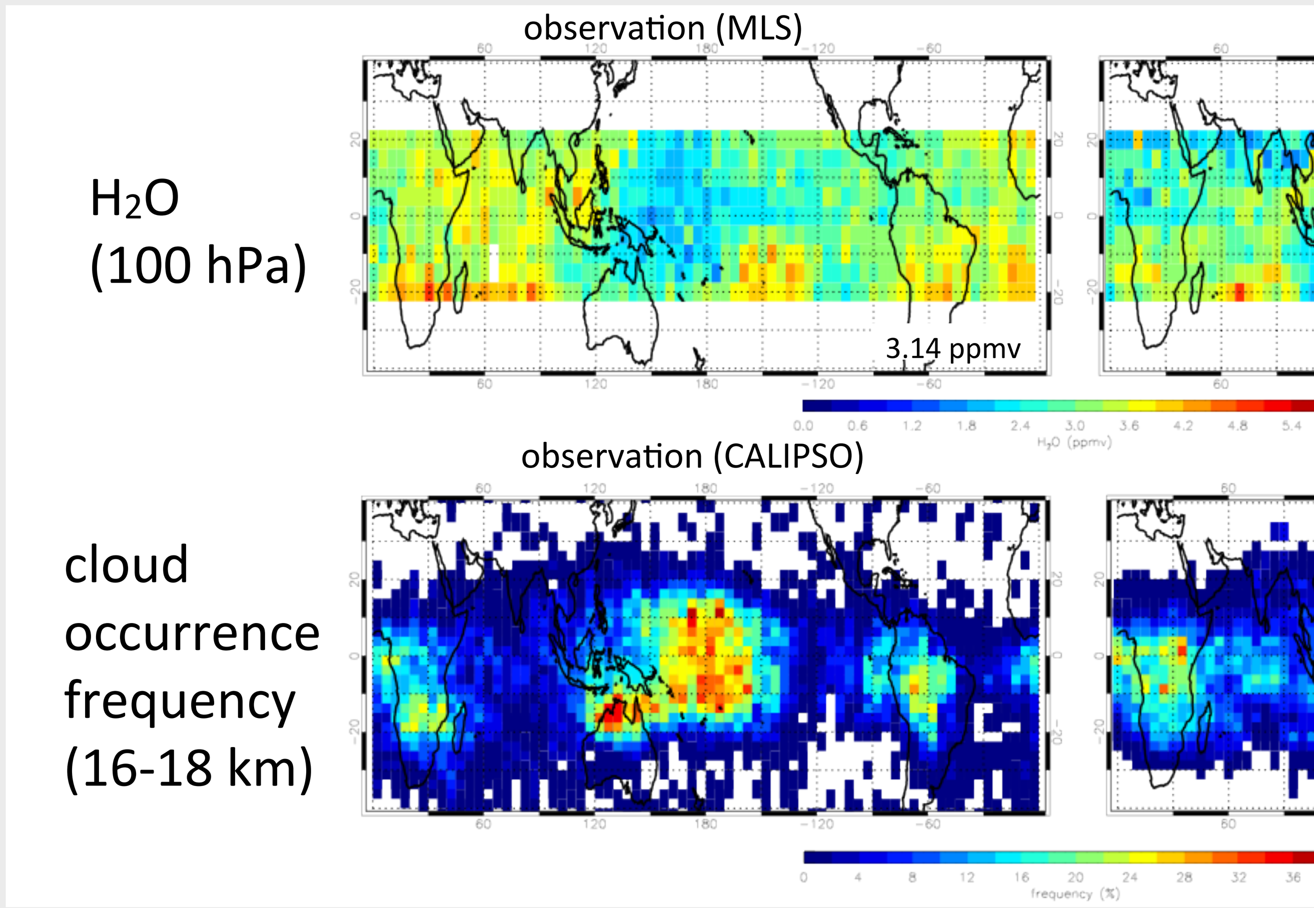


Fig. 7: (top) The 100 hPa H_2O mixing ratios on 1 Feb 2007 of the centered 7-day mean MLS observation and model. (bottom) Cloud occurrence frequencies in the mid to upper TTL (16-18 km) during Dec 2006 - Jan 2007 based on CALIPSO observation and model data.

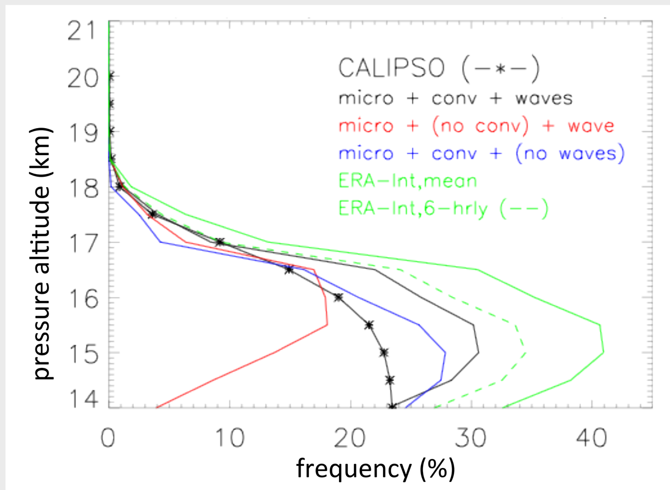


Fig. 8: Vertical profiles of tropical (20°S-20°N) mean cloud occurrence frequency in boreal winter (DJ 2006-07) based on CALIOP and model.

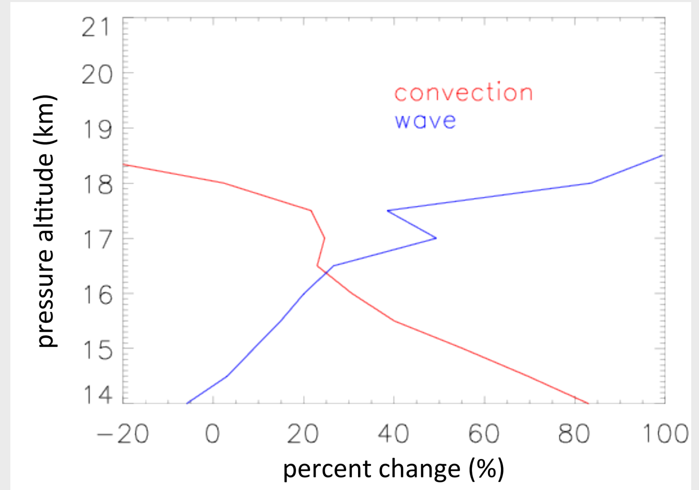


Fig. 9: Vertical profiles of the fractional change in the tropical (20°S-20°N) mean cloud occurrence frequency due to convection and waves.

• Cloud frequencies in the simulation with microphysics, convection, and waves agree well with those of CALIPSO at and above the cold point (~17 km): 8.4% vs. 9.2% at 17 km.

•Waves and convection increase cloud occurrence equally by ~25% near the 100 hPa (~16.5 km) level.

• Cloud occurrence at and above the cold point is mainly wave driven, while clouds in the lower TTL are primarily in situ clouds that form downstream of convection.

Sensitivity Tests

- Waves dehydrate (by 0.46 ppmv), whereas convection and microphysics moisten (by 0.56 and 0.71 ppmv, respectively)
- Waves and convection both increase cloud occurrence in the mid to upper TTL.

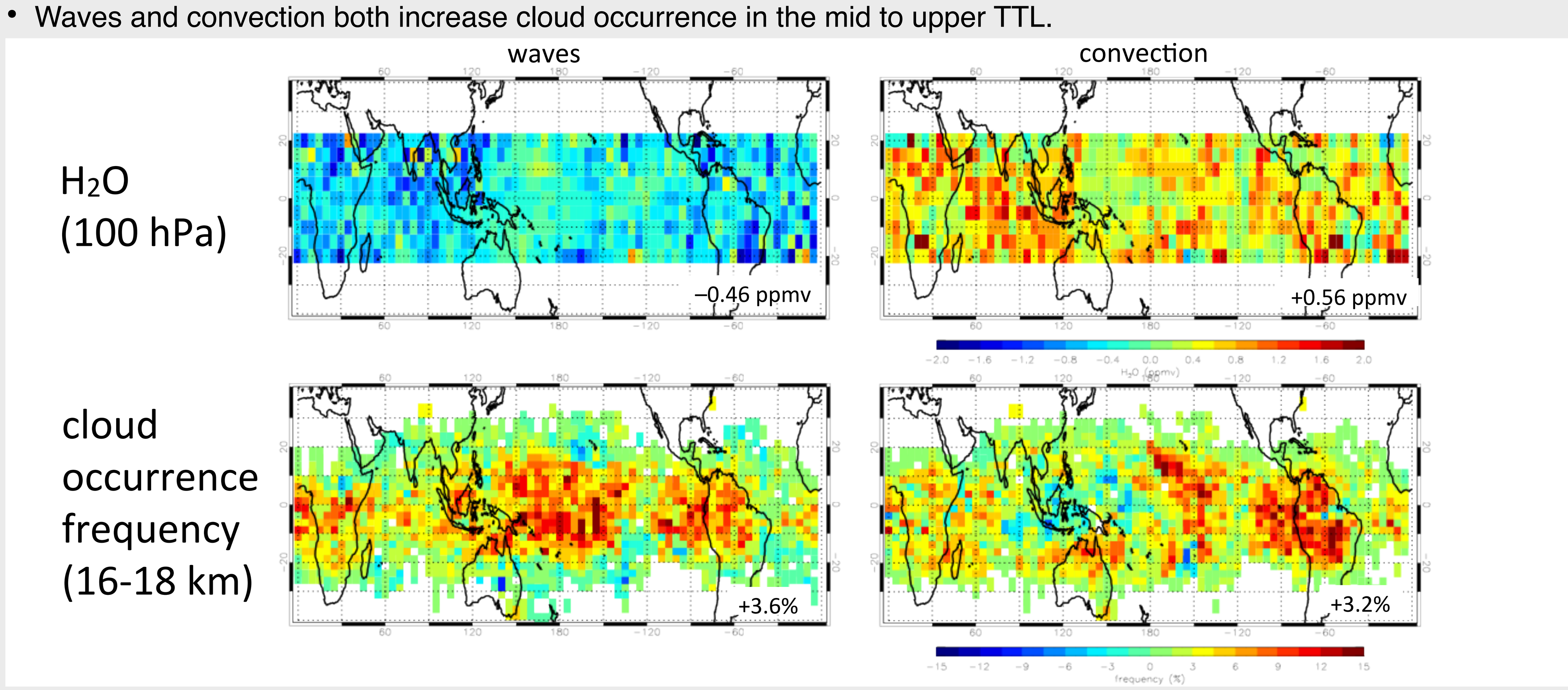


Fig. 10: The impacts of (left) waves, (middle) convection, and (right) microphysics on the (top) 100 hPa H_2O field and (bottom) cloud occurrence frequency in the mid to upper TTL.