Moisture-Radiative Cooling Instability

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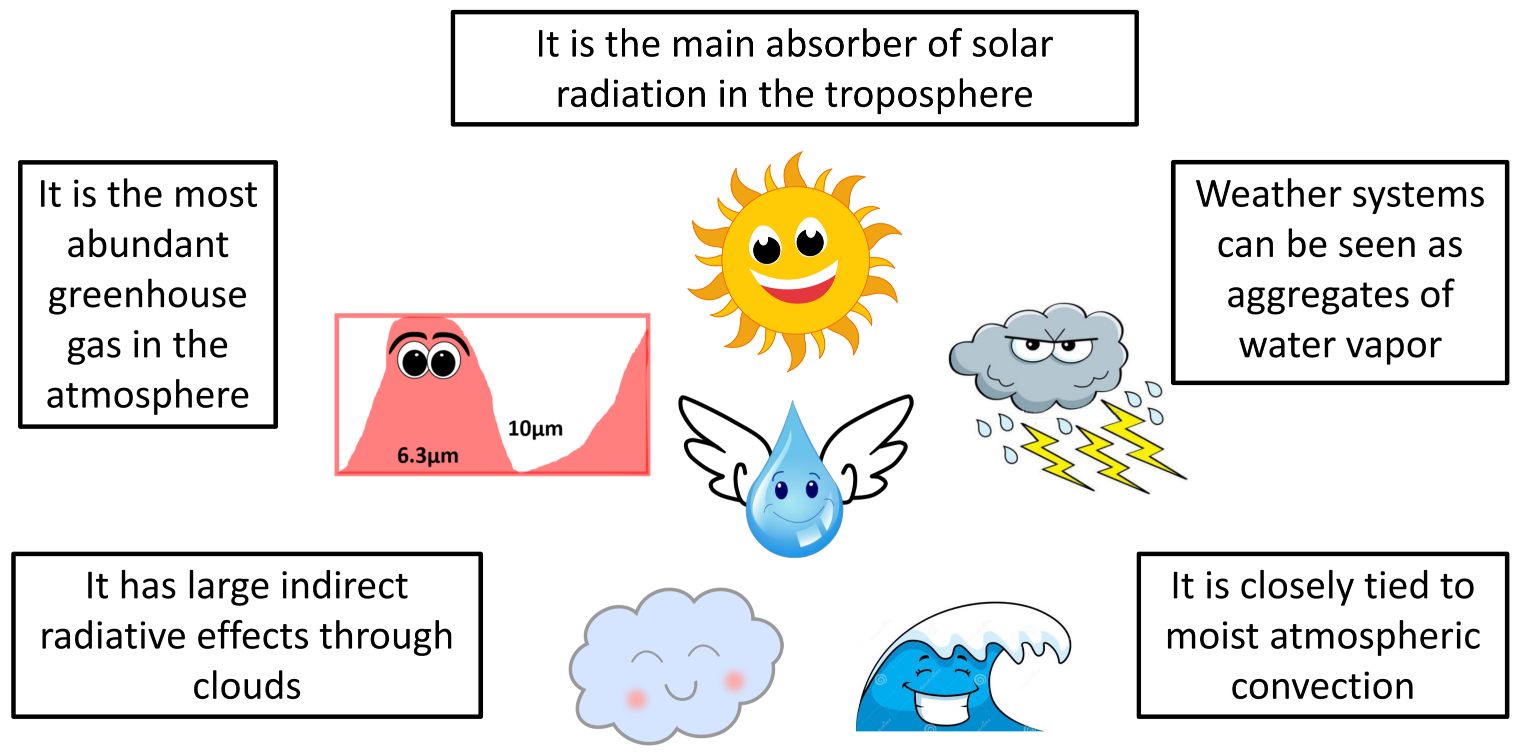
1. Motivation

Why is water vapor important?



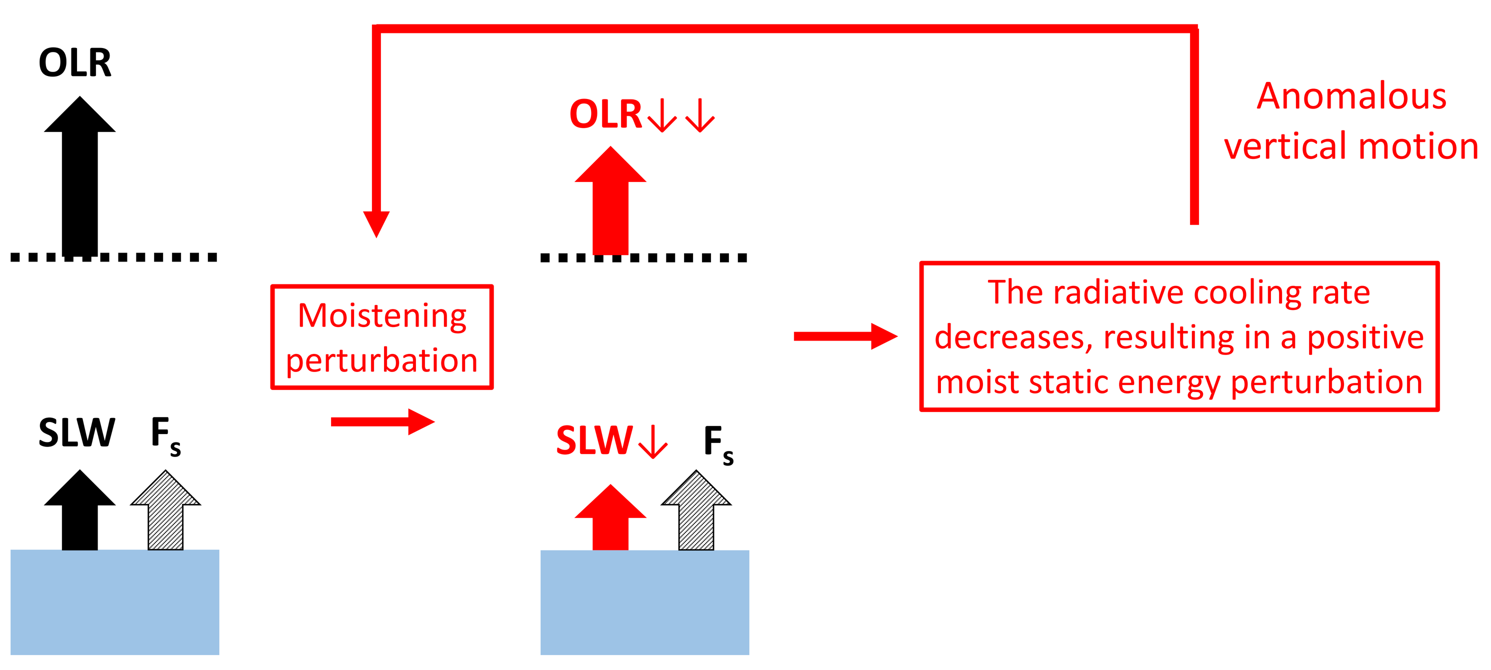
Unanswered questions

1) How much of the observed **variability** of water vapor is **internal vs external**?

2) How do the **physical mechanisms** leading to the **clustering of water vapor** in nature compare to those of convective self-aggregation in models?

3) How do the atmospheric **radiative cooling** and **column water vapor** co-vary?

2. Mechanism



Radiative-convective equilibrium at fixed surface temperature:

Atmospheric radiative cooling ($\widehat{Q}$)

= Outgoing Longwave radiation (**OLR**)
– Surface longwave flux (**SLW**)

= Surface enthalpy flux (**F_s**)

Moisture-radiative cooling instability
= Growth of small water vapor perturbation through effect on total atmospheric radiative cooling

The mechanism relies on:
- Temperature close to constant (e.g. weak temperature gradients in Tropics)
- No damping by lateral transport

The linear instability mechanism operates when the **total radiative cooling decreases with column water**; its partial growth rate (in 1/second) is:

$$-\frac{1}{L_v}\frac{\partial \widehat{Q}}{\partial \widehat{r}}$$

LATENT HEAT OF VAPORIZATION OF WATER VAPOR → L_v; ← RADIATIVE COOLING ($\widehat{Q}$); ← COL. WATER VAPOR ($\widehat{r}$)

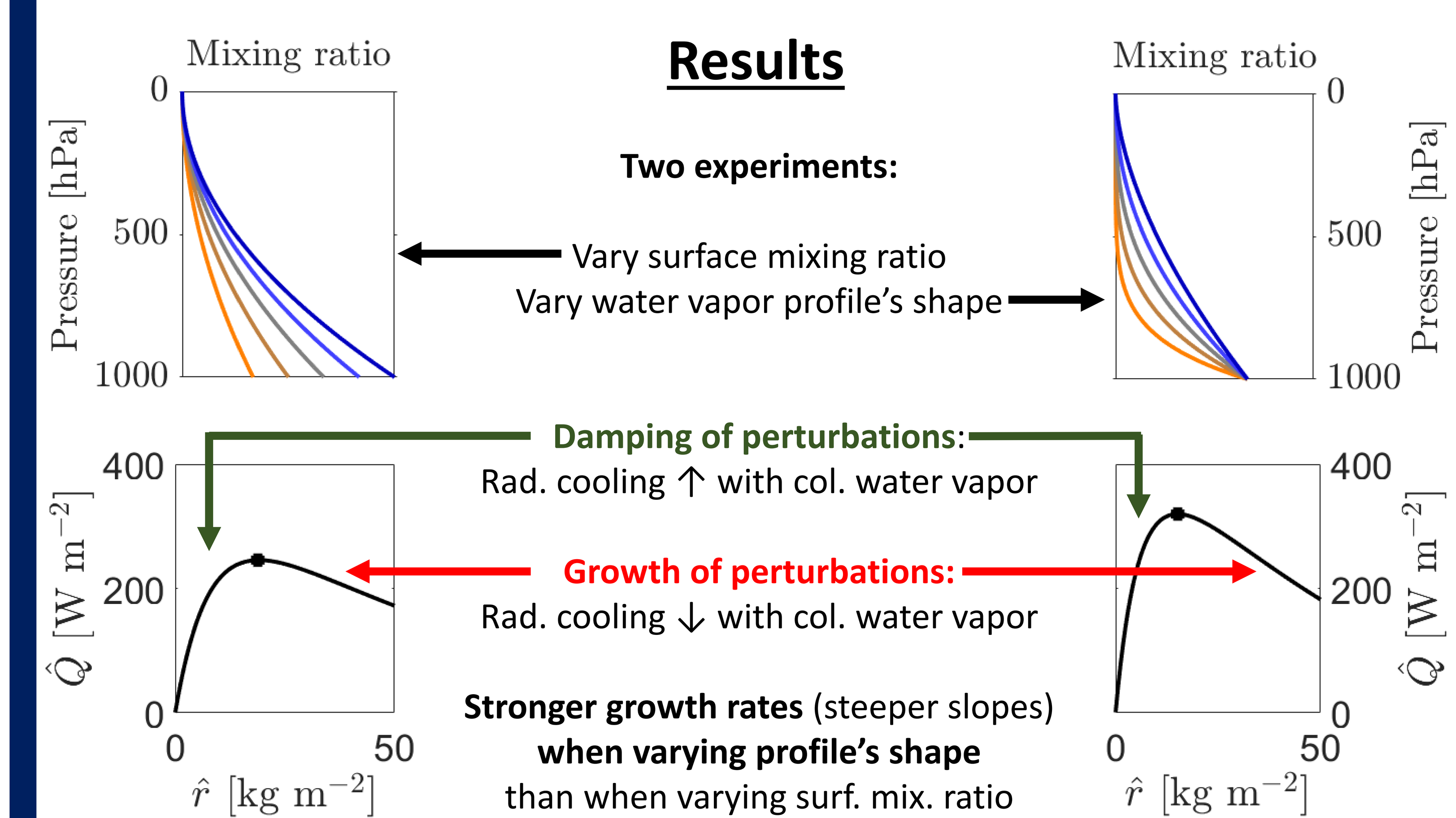
3. Gray-radiation theory

Method

Question: How do the total atmospheric radiative cooling and column water vapor co-vary in a simple gray-radiative analytical model of the atmosphere?

- 1D, plane-parallel atmosphere and 2-stream Schwarzschild equations for radiative fluxes.
- Only absorbing gas is water vapor, with two average absorption coefficients of 0.1 and $0.01\mathrm{m^2kg^{-1}}$ for longwave and shortwave radiation.
- Fixed temperature profile is moist adiabatic with surface value of 300K.
- Prescribed vertical structure of water vapor perturbations.

Results



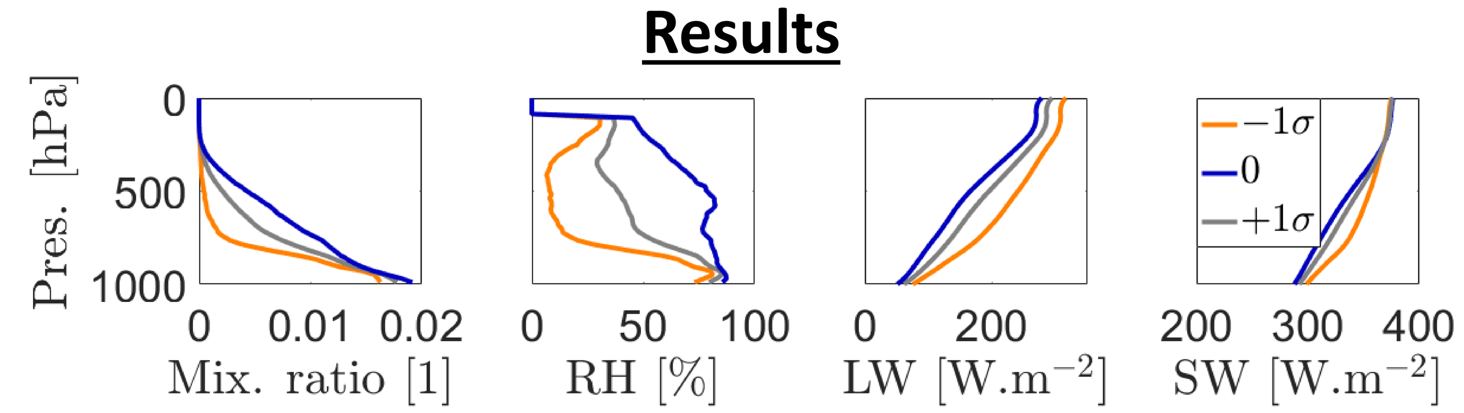
4. Observed variability

Method

Question: How do clear-sky radiative fluxes and column water vapor co-vary in nature?

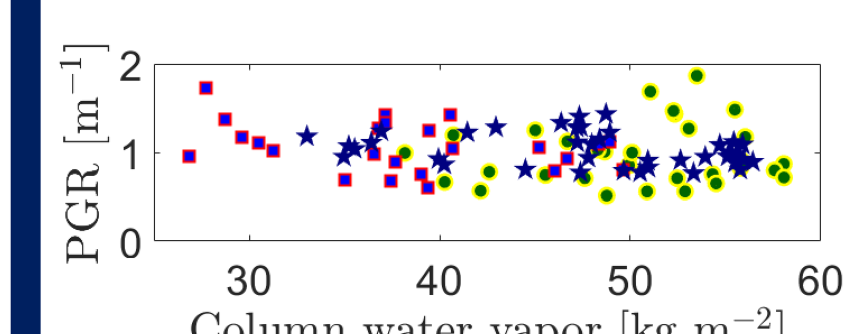
- Retrieve 20 years of bi-daily soundings for 12 tropical stations in Jan/Apr/Jul/Oct.
- For a given station and month: Average all temperature profiles.
- Average all relative humidity profiles (0), moistest (+1σ) and driest RH profiles (-1σ).
- Feed the profiles to a radiative transfer model (RRTMG) → radiative fluxes.

Results



Case study of Chuuk Lagoon (Micronesia): Water vapor variability is:
- Small near the surface,
- Largest in the mid to upper troposphere.

⇒ **Atmospheric cooling ↓ with col. water vapor**, leading to partial growth rates ≈ 1/month.



All 12 Tropical stations are potentially unstable, with positive growth rates:

Mean growth rate : 1.0/month
Standard deviation: 0.3/month

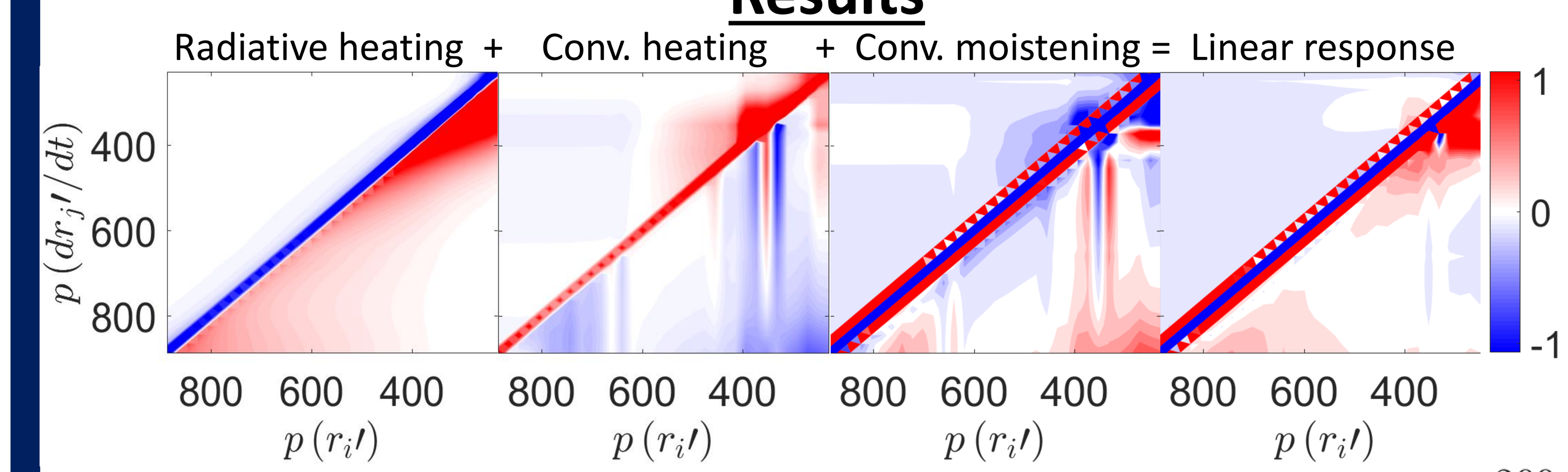
5. Vertical structure

Method

Question: How do water vapor profiles evolve for short times under the sole influence of convection and clear-sky radiation?

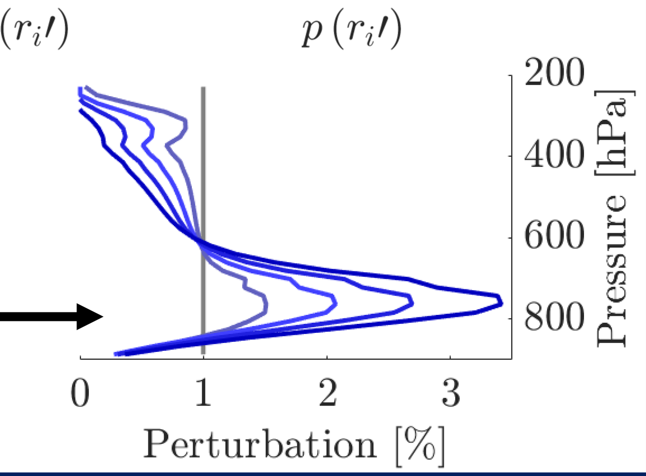
- Run radiative-convective model tested against observations (MITSCM) to equilibrium.
- Introduce small water vapor perturbation r_j' at level (j).
- Run the model for 1 time-step in weak temperature gradient mode and measure the water vapor tendency dr_i'/dt at every level (i) → Linear response matrix M_{ij}.

Results



- The linear response has **unstable vertical modes above** surface temperatures of **300K**.
- It **shifts** water vapor **perturbations downwards**.

Example for a high surface temperature of 310K →
Uniform 1% perturbation at day 0 linearly grows to more than 3% in the lower troposphere in 4 days!



6. Conclusion: Observational needs

Summary

1. Instability condition: **Atmospheric radiative cooling ↓ with column water vapor**.
2. Observed tropical **moisture variability largest in mid-troposphere** ⇒ condition satisfied.
3. **Radiation & convection** combined **↑ perturbations for SST>300K** and shift them down.

Observational needs

Bulk energetics: Bi-daily surface radiative & turbulent fluxes for Tropical weather stations.
→ Network of **ground-based passive sensors** (e.g. IR spectrometers and MW radiometers), aiming at developing a worldwide product with systematic error covariance matrices.

Moist thermodynamics: Convective and radiative heating profiles in Tropical troposphere.
→ If possible, **ground-based** network of **high-resolution active remote sensors** (e.g. Temperature, Water Vapor Raman LIDARs, and Water Vapor Differential Absorption LIDAR).
→ Improve **retrieval algorithms** for passive remote sensing of **temp & water vapor profiles**.

Key references

1. K.A. Emanuel, A. A. Wing, and E. M. Vincent (2014), **Radiative-convective instability**, *J. Adv. Model. Earth Syst.*, 6, 75–90, doi:10.1002/2013MS000270.
2. C.E. Holloway, et al. (2016), **Observing convective aggregation**, *Surveys in Geophysics*.
3. T.D. Robinson, and D. C. Catling (2012), **An analytic radiative-convective model for planetary atmospheres**, *Astrophys. J.*, 757(1), 104, doi:10.1088/0004-637X/757/1/104.
4. A.A. Wing,, and K. A. Emanuel (2014), **Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations**, *J. Adv. Model. Earth Syst.*, 6, 59–74, doi:10.1002/2013MS000269.