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A model for the large-scale advection, condensation and diffusion of water vapor

1. Motivation

Why is water vapor important?

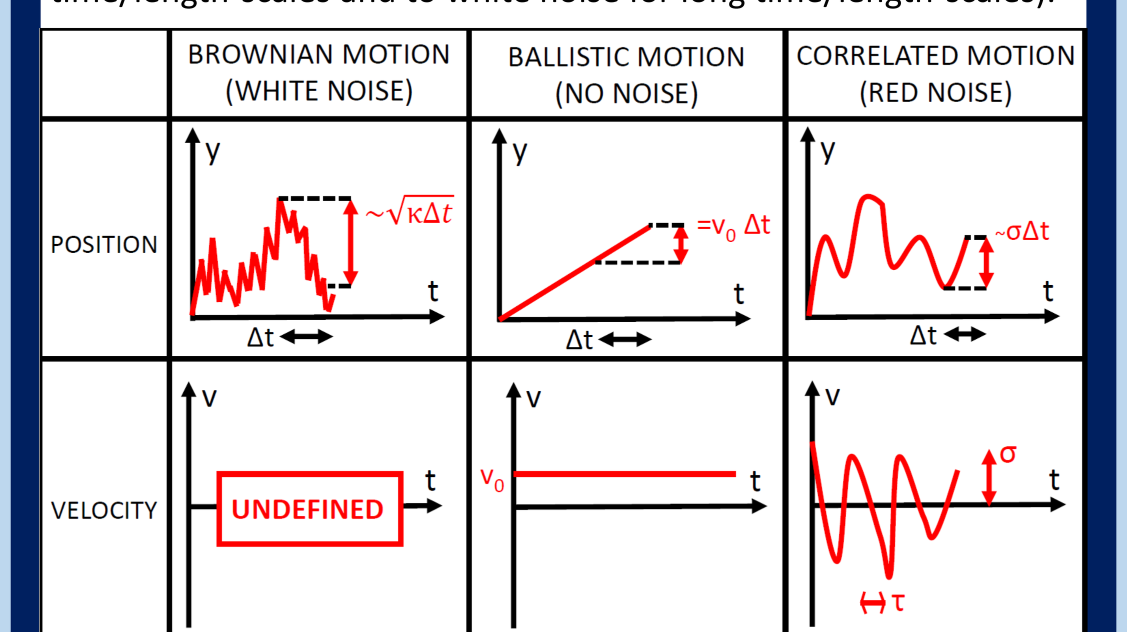
- It is the main greenhouse gas in the atmosphere.
- It also has indirect radiative effects through clouds.
- It is closely tied to moist atmospheric convection in the Tropics.
- It has effect on atmospheric dynamics.
- Weather systems can be seen as aggregates of water vapor.

What is an advection-condensation model?

A model that only takes into account:

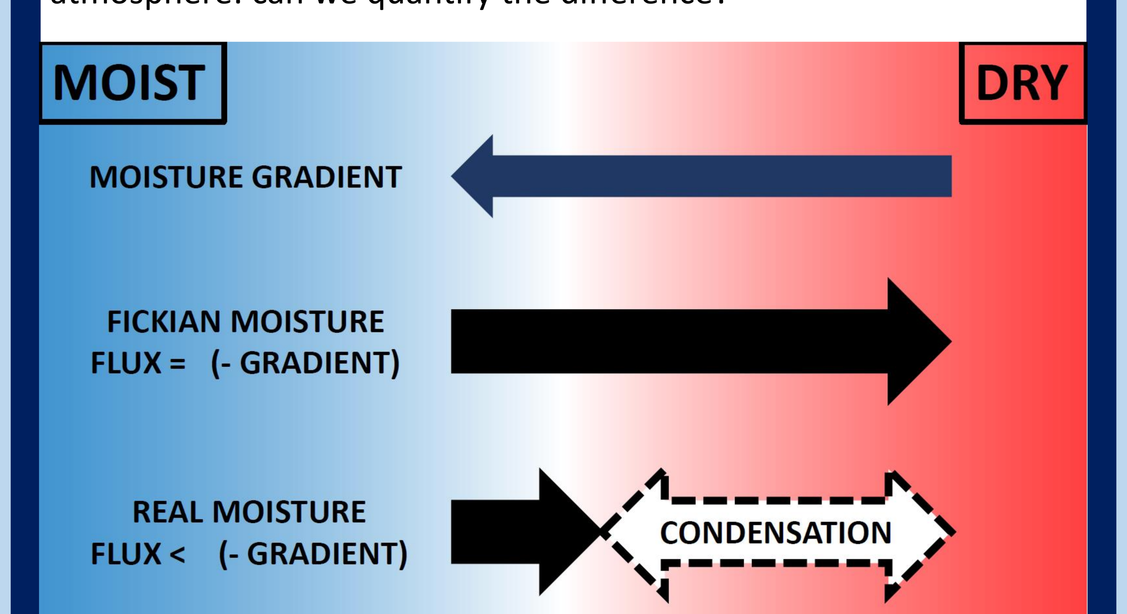
1) **The condensation of water vapor, without resolving the microphysical details of condensation itself.** The model relies on $q^*(p,T)$, a quantity called the saturation specific humidity, that only depends on pressure and temperature. When the specific humidity (concentration) q of water vapor exceeds its saturation value $q^*(p,T)$, the water vapor condenses to bring q back to q^*.

2) **The advection (transport) of water vapor by the wind velocity field, which is a parameter of the model.** The wind can be obtained from observations, reanalysis data, but can also be parametrized in very simple ways to make the model analytically solvable. Progress has been made by modeling the displacement of air parcels as white noise, in which case the velocity is undefined. Here, we make progress by using red noise, which is more physical and general (red noise is equivalent to ballistic motion for short time/length-scales and to white noise for long time/length-scales).



How does this model help us understand large-scale moisture fluxes?

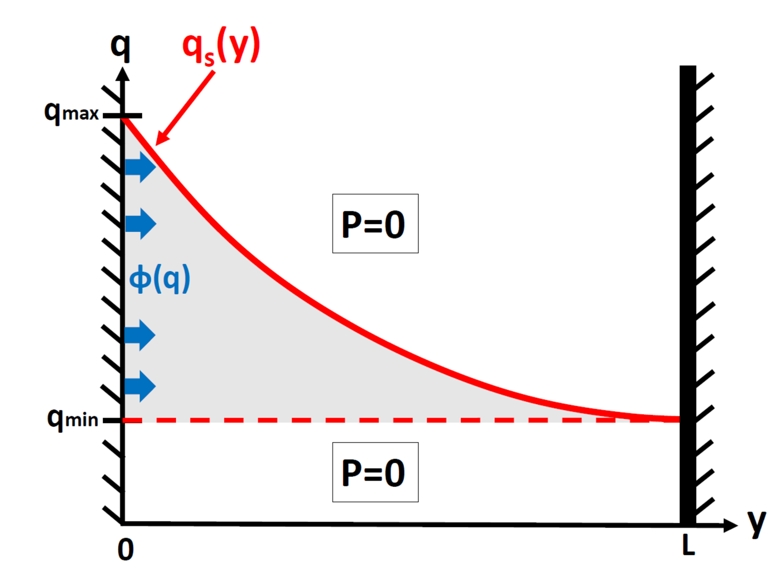
Fick's law tells us that the flux of a passive scalar is proportional to the large-scale gradient and in opposite direction, BUT this is not true for water vapor, which condenses and rains out of the atmosphere: can we quantify the difference?



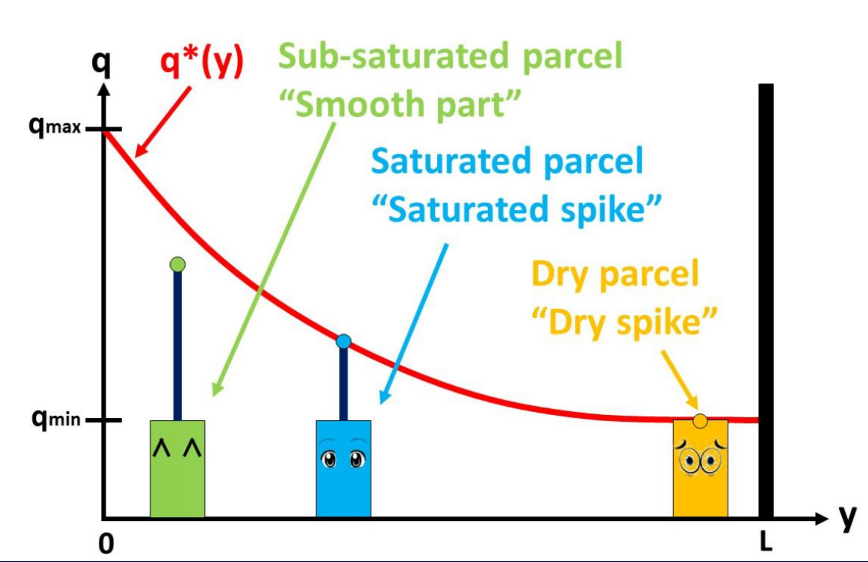
2. Model setup

What are the 3 simple rules of the game in this model?

1. Each parcel moves randomly (but smoothly) between the Tropics (y=0) and the Poles (y=L).
2. Every time a parcel comes back to the Tropics, it is remoistened following a prescribed distribution of water vapor $\phi(q)$.
3. Every time a parcel's moisture exceeds the prescribed large-scale saturation value $q^*(y)$, its moisture condenses back to q.

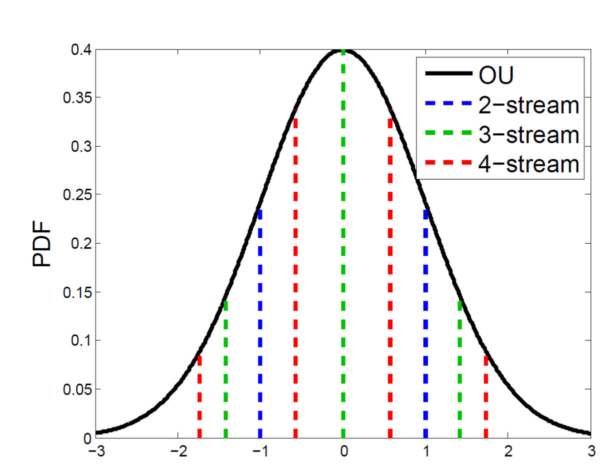


Since the model is stochastic, you can think of each air parcel individually. The physics are obtained by looking at the statistical properties of the ensemble (throw a million independent parcels in the domain and look at the mean moisture, moisture flux, etc.). The distribution of moisture has three parts:



3. Two-stream model

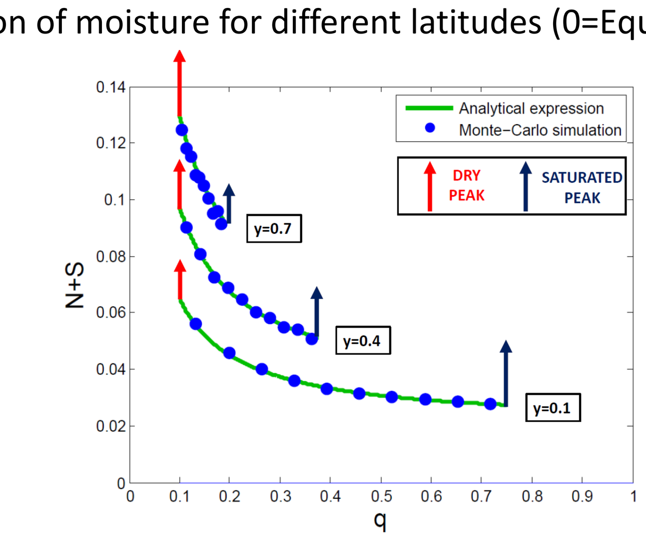
The red noise model is (probably) impossible to solve analytically in an insightful way. We discretize the problem to make it simpler: Instead of taking into account the full Gaussian distribution of velocities, we only consider 2/3/4…. velocities that "mimic" the Gaussian distribution, which is called the 2/3/4-stream model.



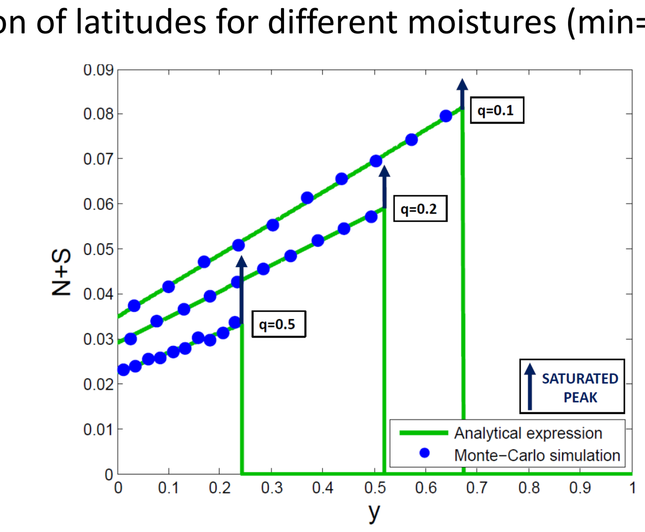
4. Results

What is the distribution of moisture in the 2-stream model?

Distribution of moisture for different latitudes (0=Equator, 1=Pole):

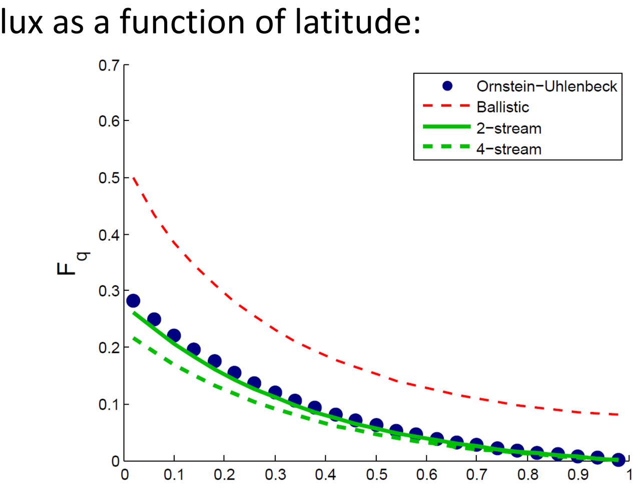


Distribution of latitudes for different moistures (min=0.1, max=1):

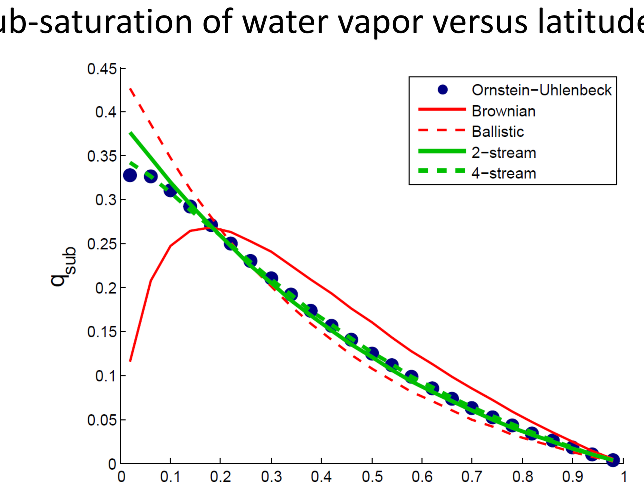


How do the 2/4-stream models compare to the red noise simul.?

Moisture flux as a function of latitude:



Average sub-saturation of water vapor versus latitude:



What does the 2-stream model teach us?

- It gives us analytical solutions for all the statistical properties.
- It tells us how much the moisture flux deviates from Fick's law:

$$\underbrace{F_q}_{\text{Moisture flux}} = -\underbrace{\kappa}_{\text{Diffusivity of the random motion}}\Big(\underbrace{\boxed{\frac{d\langle q\rangle}{dy}}}_{\text{Fick's law}}\ \underbrace{\boxed{-W\left|\frac{dq^*}{dy}\right|}}_{\text{Add. term}}\Big)$$

Large-scale gradient: $\frac{d\langle q\rangle}{dy}$

Amount of parcels that have condensed: W

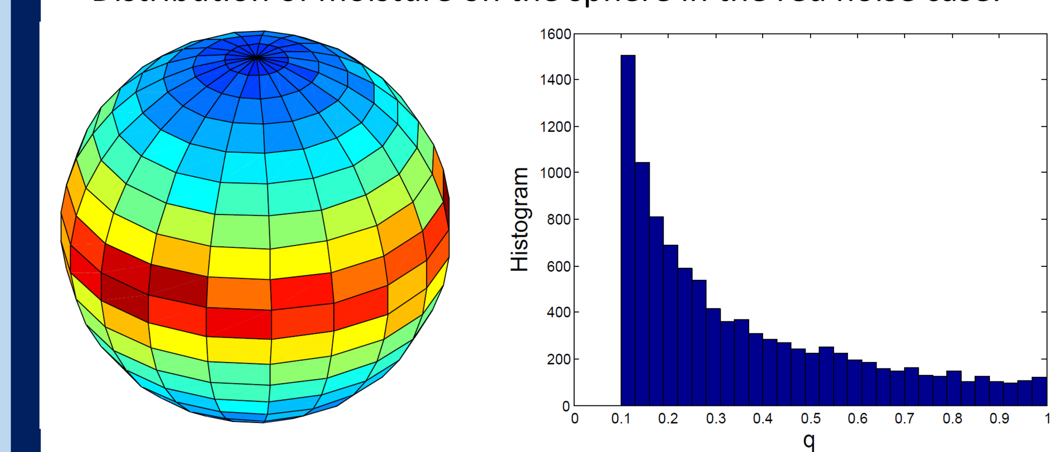
Slope of sat. moisture profile: $\left|\frac{dq^*}{dy}\right|$

5. Future work

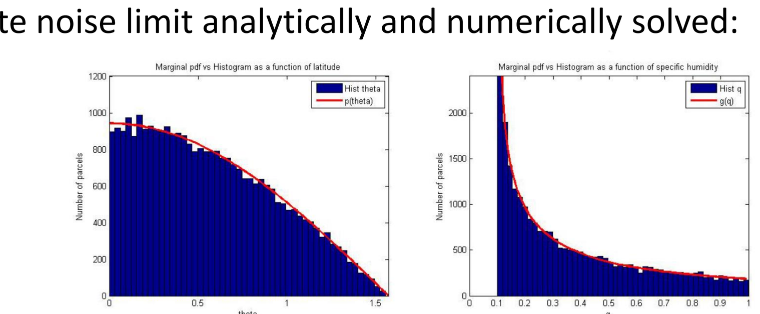
Generalization of the model to a sphere:

Goals:
- Better understand turbulence and large-scale condensation in a thin planetary atmosphere
- Compare the model to meteorological data

Preliminary results:
- Distribution of moisture on the sphere in the red noise case:



- White noise limit analytically and numerically solved:



6. Key references

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7. Acknowledgments

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