LO and Behold Convectively Coupled Kelvin Waves

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Thanks to:

Ming Cai for suggesting I apply LO to atmospheric moist convection

Kerry Emanuel for helping to formulate LO

Alexey Fedorov for giving me the freedom to work on this

BIRS Workshop organizers for inviting me

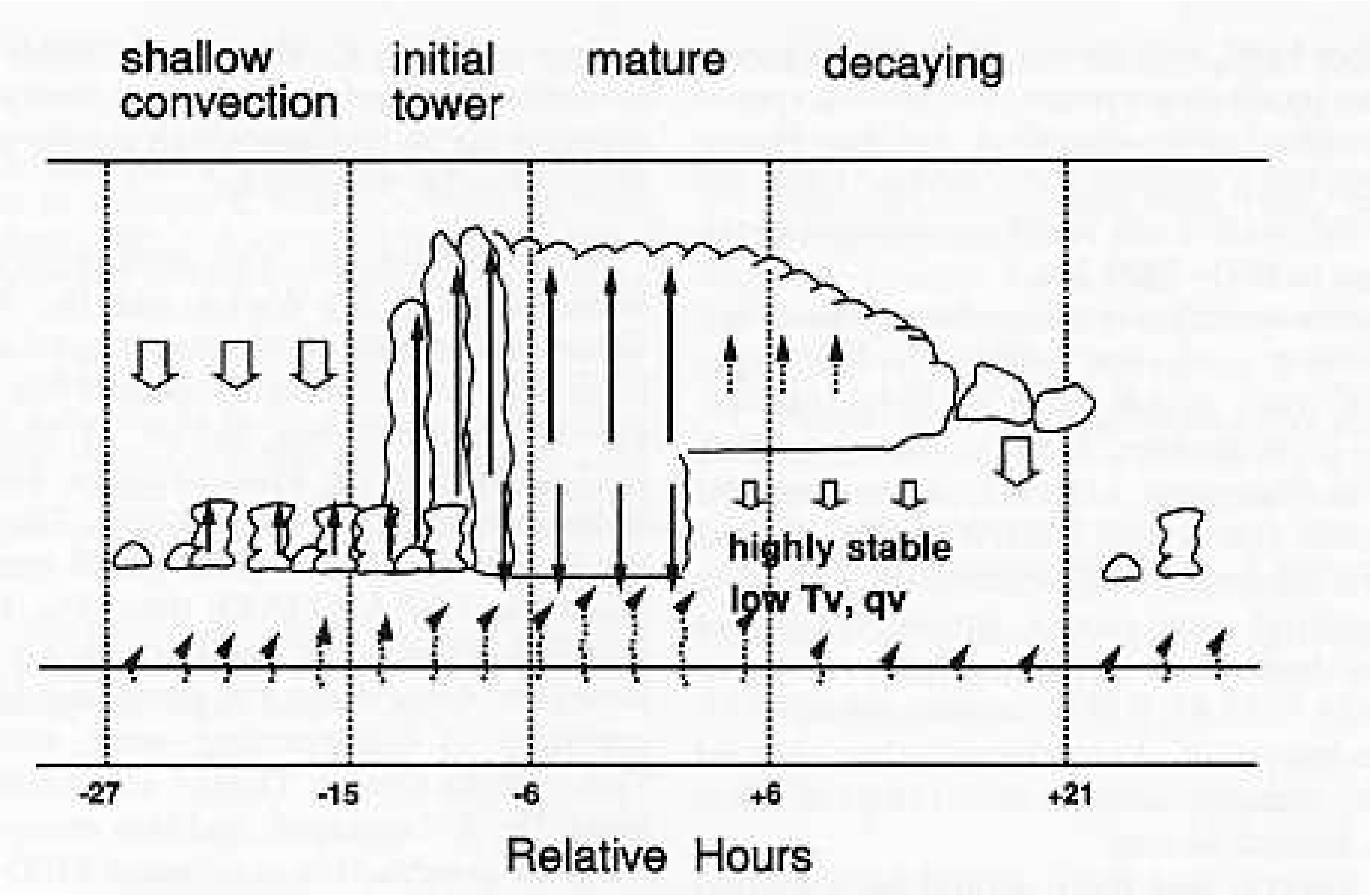
Outline

1. Moist Enthalpy Budgets of Equatorial Waves
2. Lagrangian Geophysical Fluid Modeling
3. Lagrangian Overturning
4. Single Column Experiments
5. Three Dimensional Simulations

Moist Enthalpy Budgets of Equatorial Waves

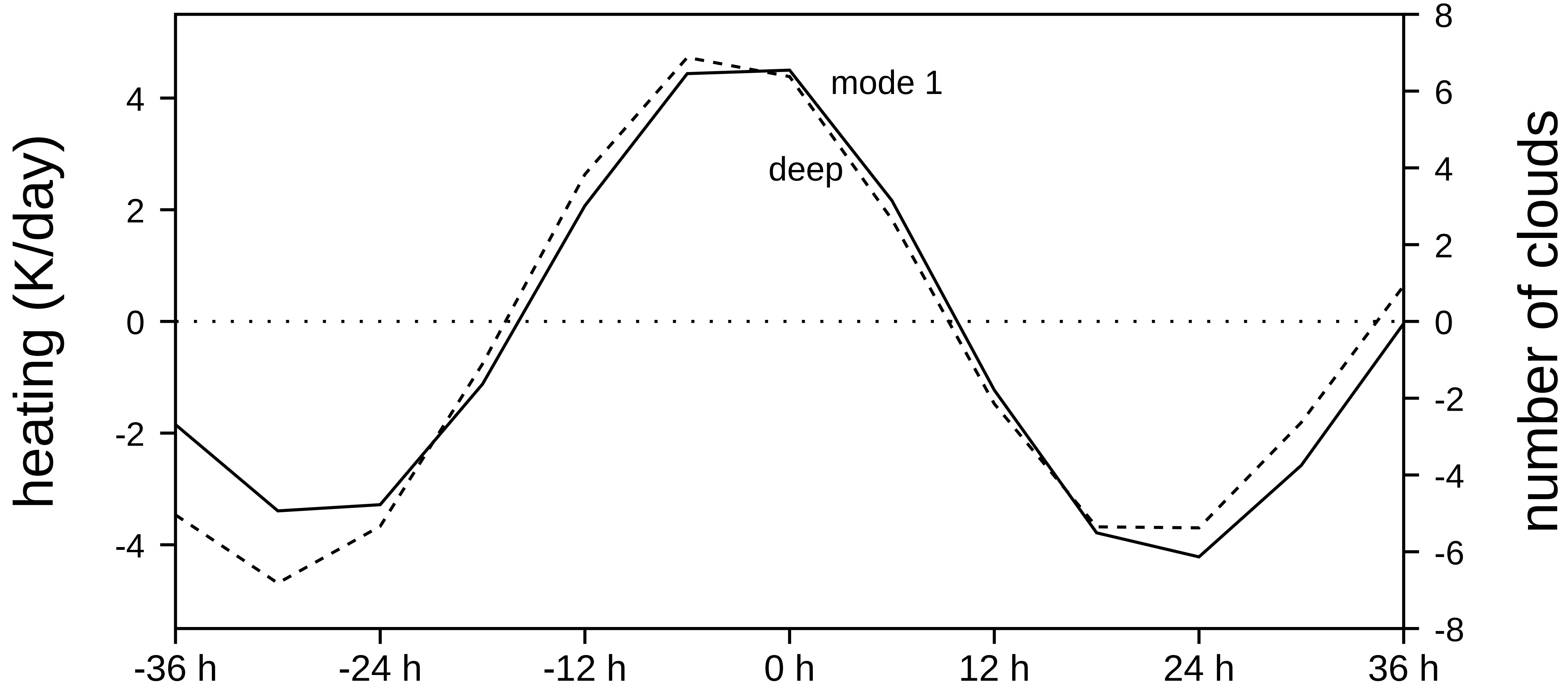
Life Cycle of Convection in 2-Day Waves

Takayabu et al. (1996)



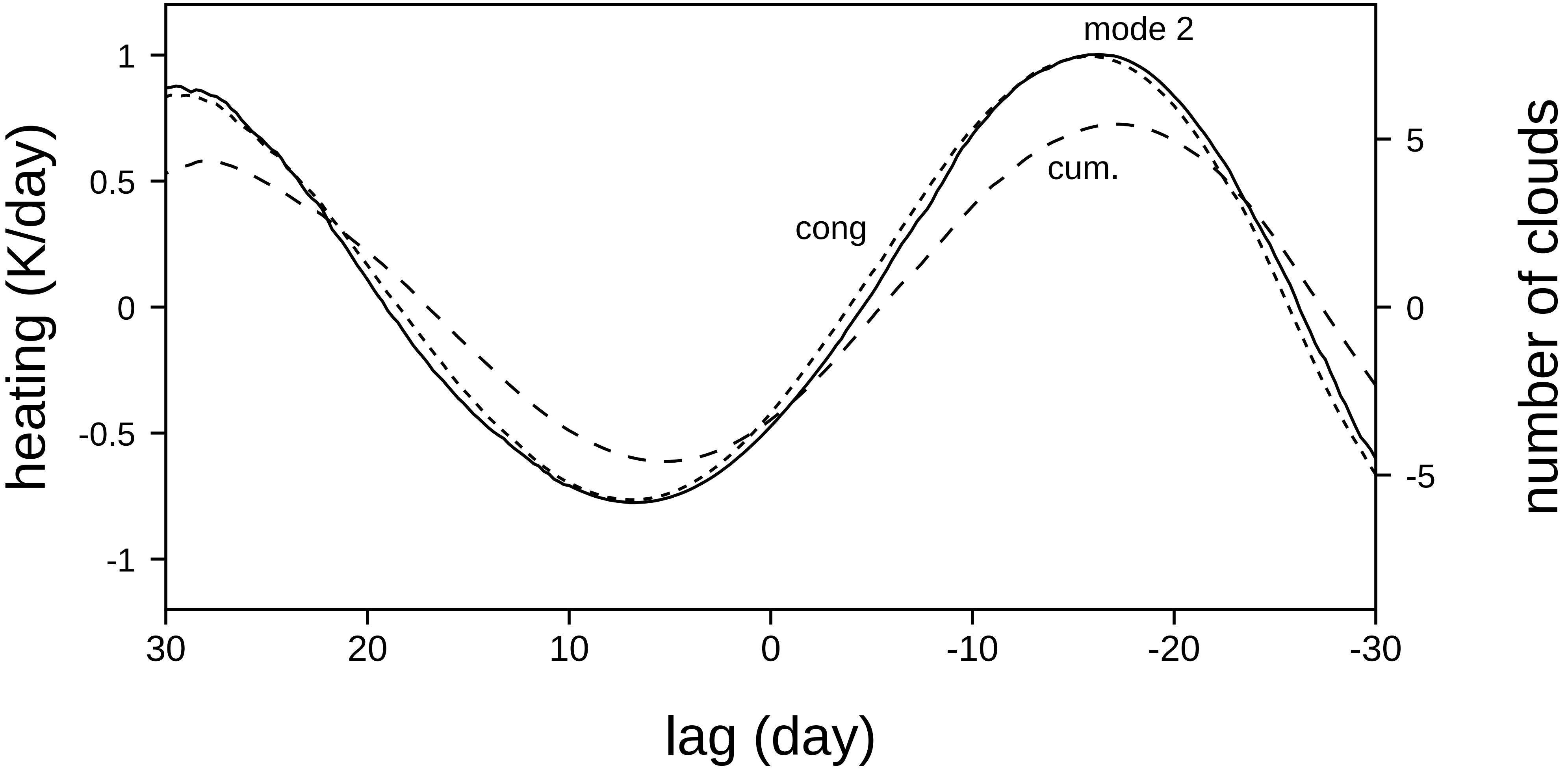
Deep Convective Cloud Count and 1st Baroclinic Mode Heating in 2-Day Waves

Johnson et al. (1999), Haertel et al. (2008)



Shallow Cumulus and Congestus Cloud Counts and 2nd Baroclinic Mode Heating in the MJO

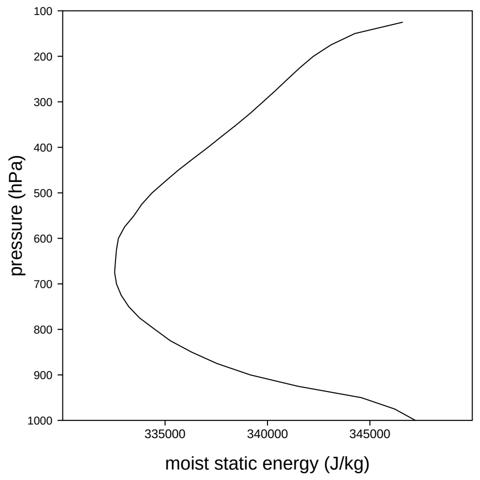
Johnson et al. (1999), Haertel et al. (2008)



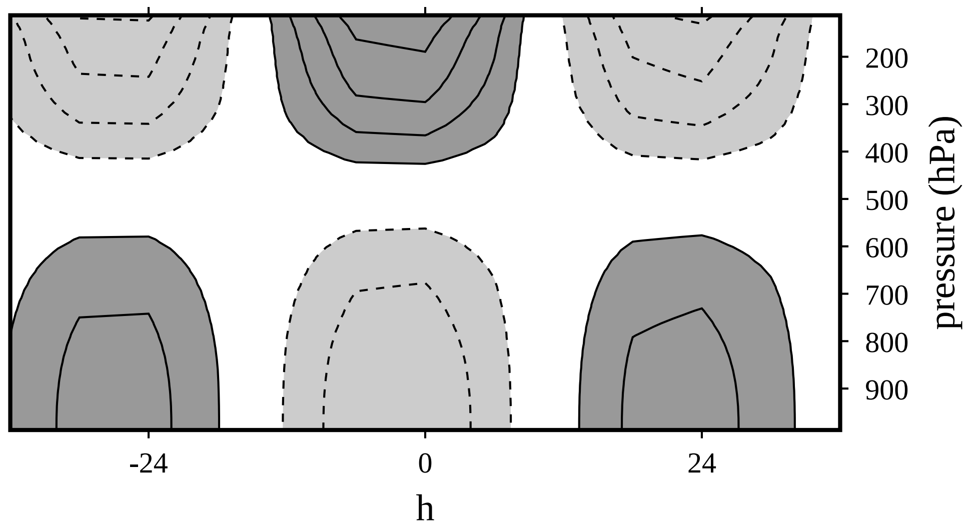
Convergence of Moist Static Energy in 2-Day Waves

Haertel et al. (2008)

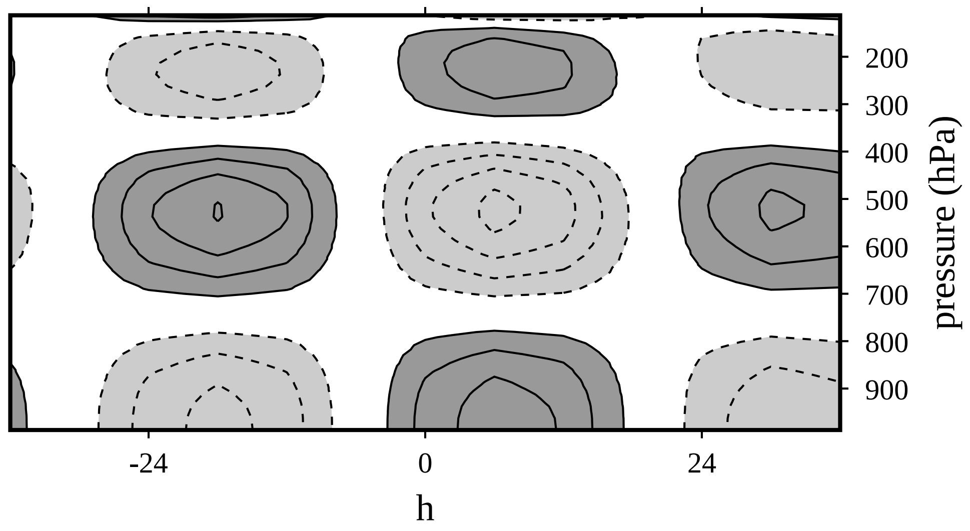
moist static energy



mode 1 divergence

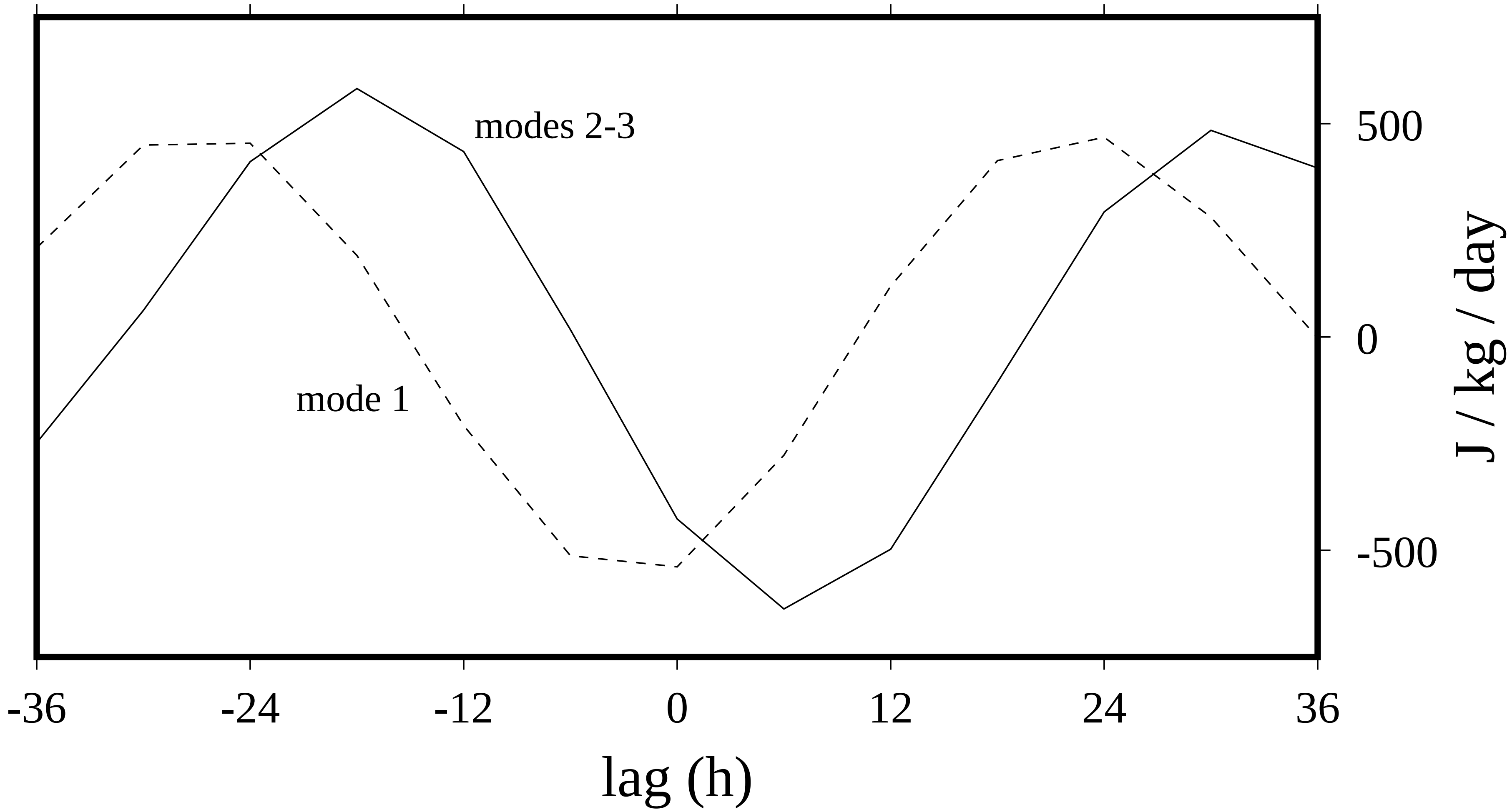


modes 2-3 divergence



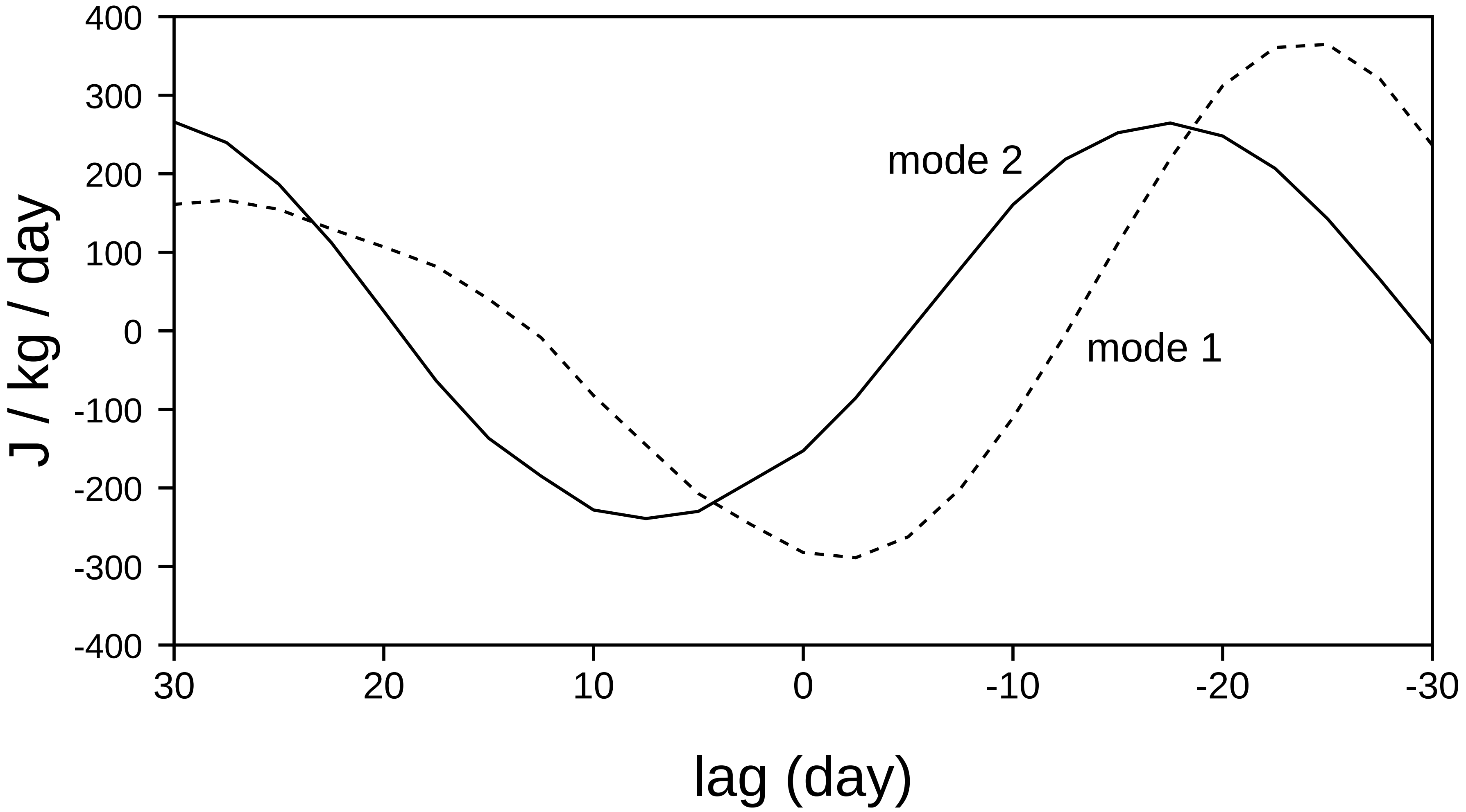
Convergence of Moist Static Energy in 2-Day Waves (cont.)

Haertel et al. (2008)



Convergence of Moist Static Energy in the MJO

Haertel et al. (2008)



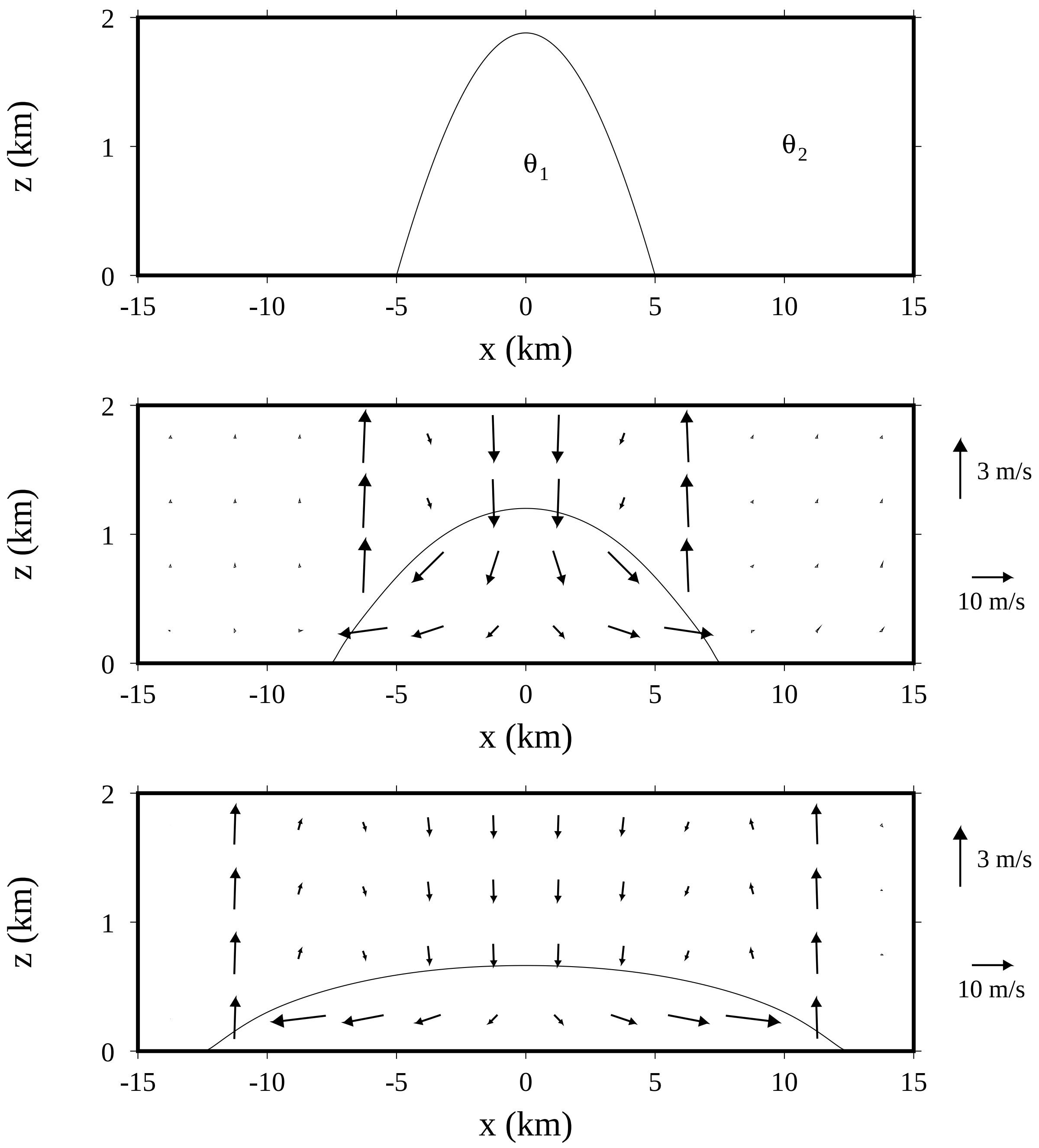
Conclusion

Horizontal circulations driven by shallow cumulus and congestus are of 1st order importance in column integrated moist enthalpy budgets for 2-day waves and the MJO

Lagrangian Geophysical Fluid Modeling

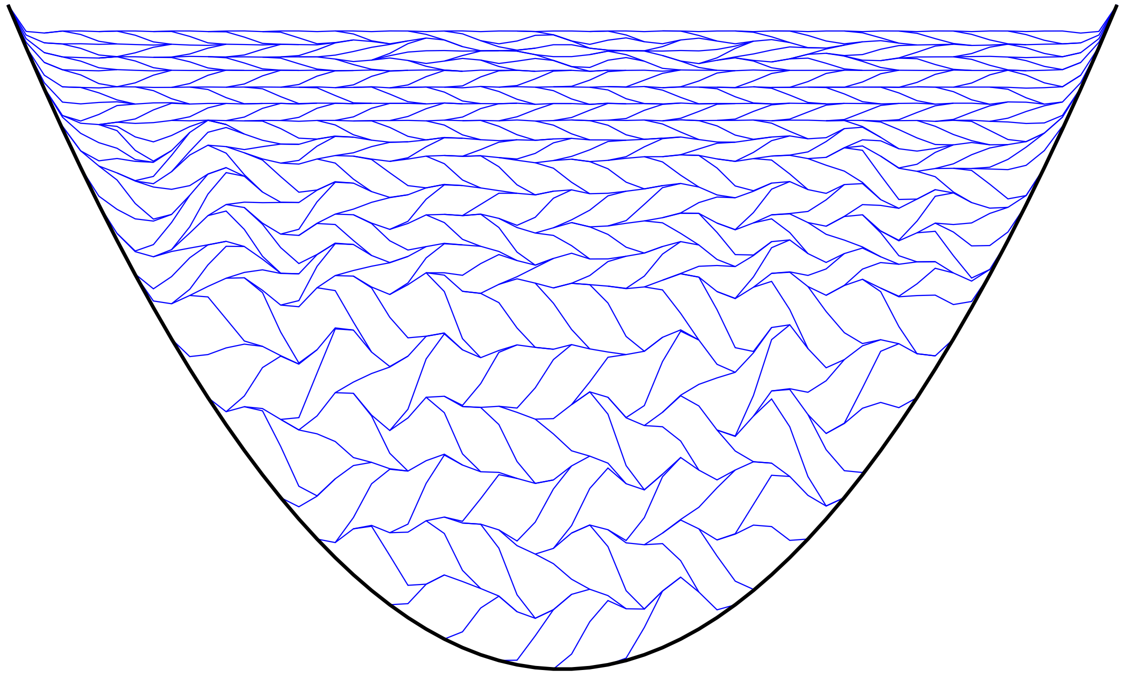
Simulations of Thunderstorm Outflows

Haertel et al. (2001)



Slippery Sacks Concept

Haertel and Randall (2002)



Equations of Motion

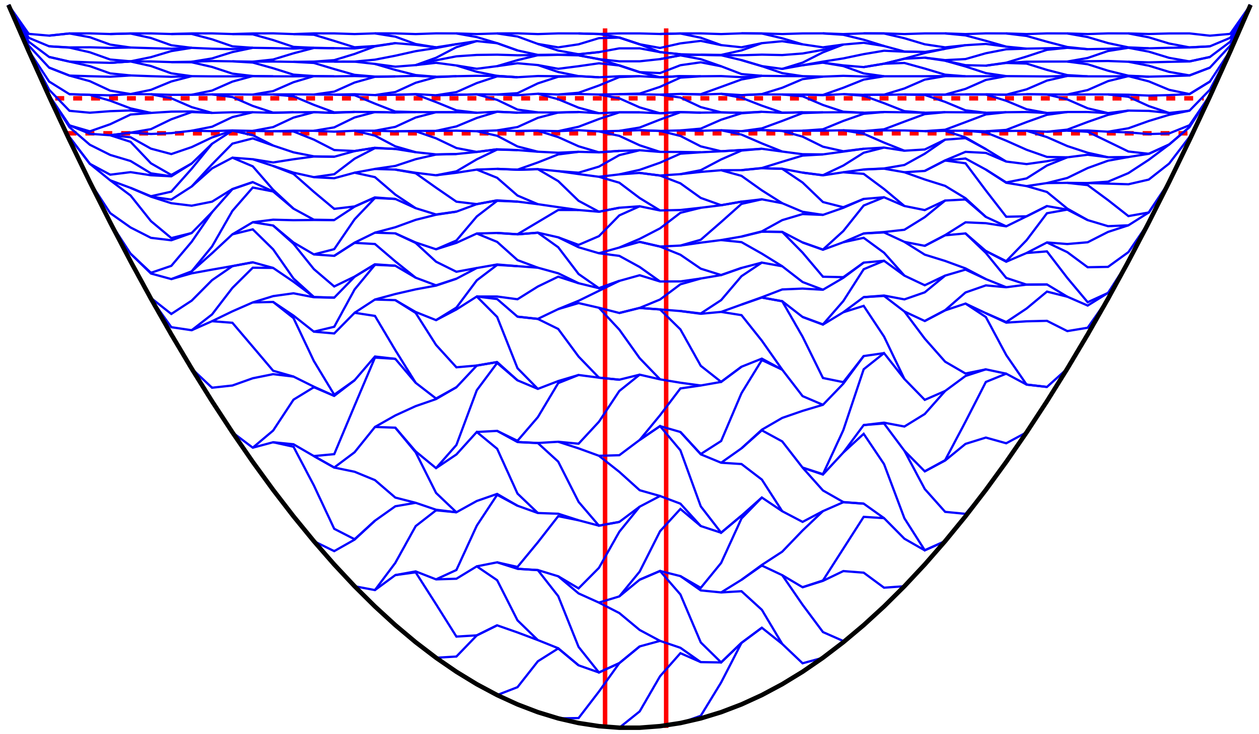
$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i$$

$$\frac{d\mathbf{v}_i}{dt} + f\ \mathbf{k} \times \mathbf{v}_i = \frac{\mathbf{F}_{p_i}}{M_i} + \mathbf{D}_{\mathbf{v}_i}$$

Pressure Force

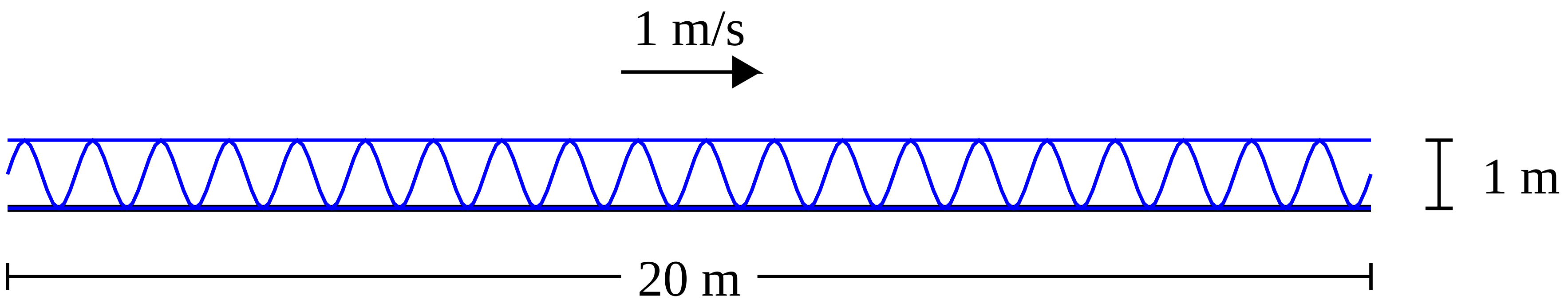
$$\mathbf{F}_{p_i} = \int_{S_i} p \, \mathbf{n} \, dA$$

Mixing Columns and Rows

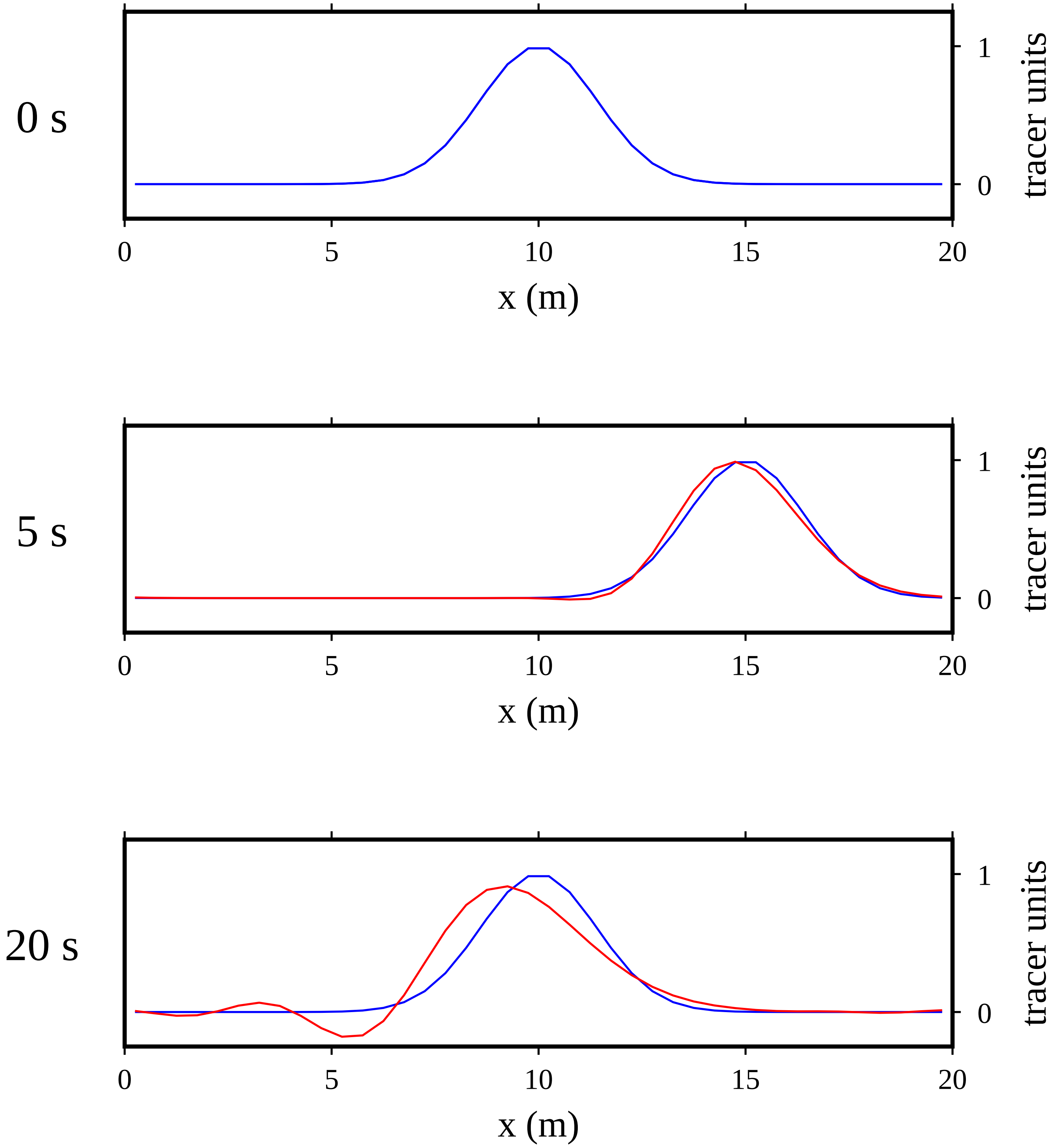


Idealized Tests

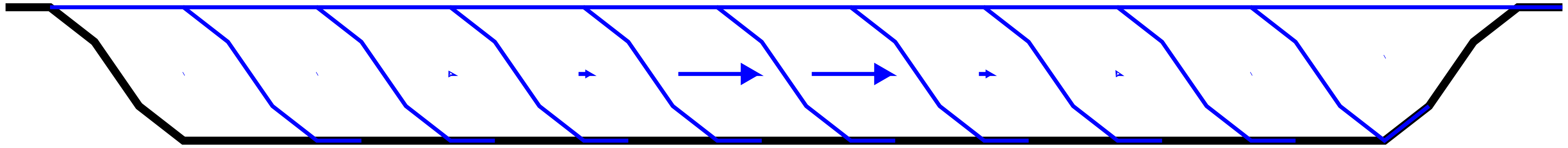
Advection



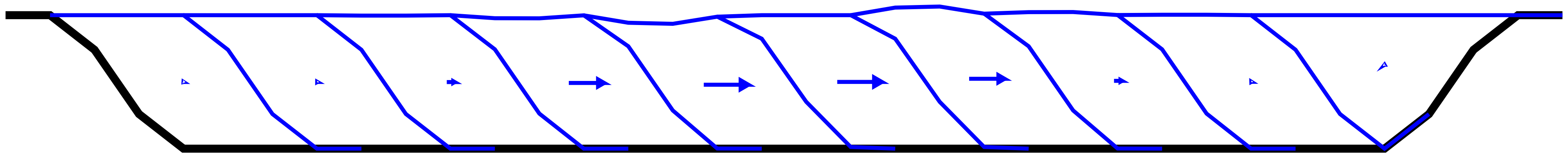
Tracer Distribution



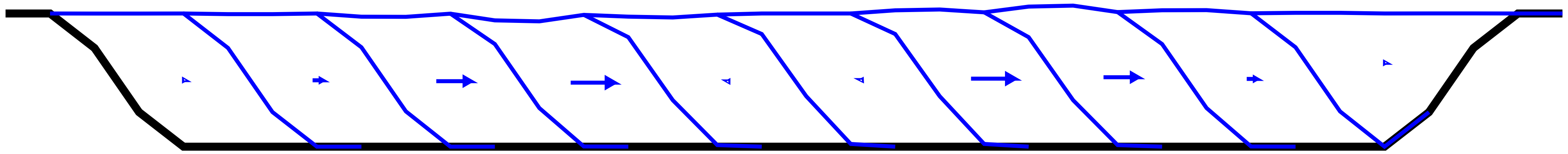
External Gravity Waves



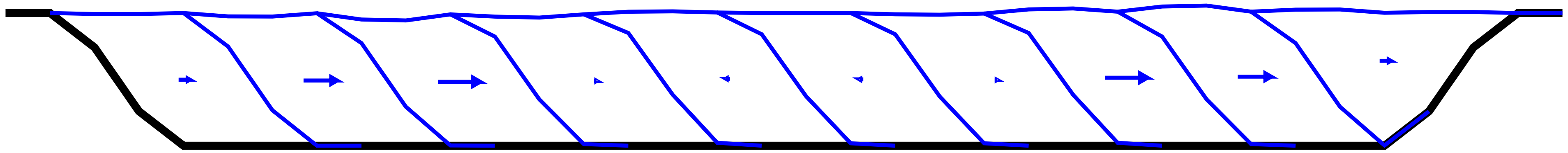
External Gravity Waves



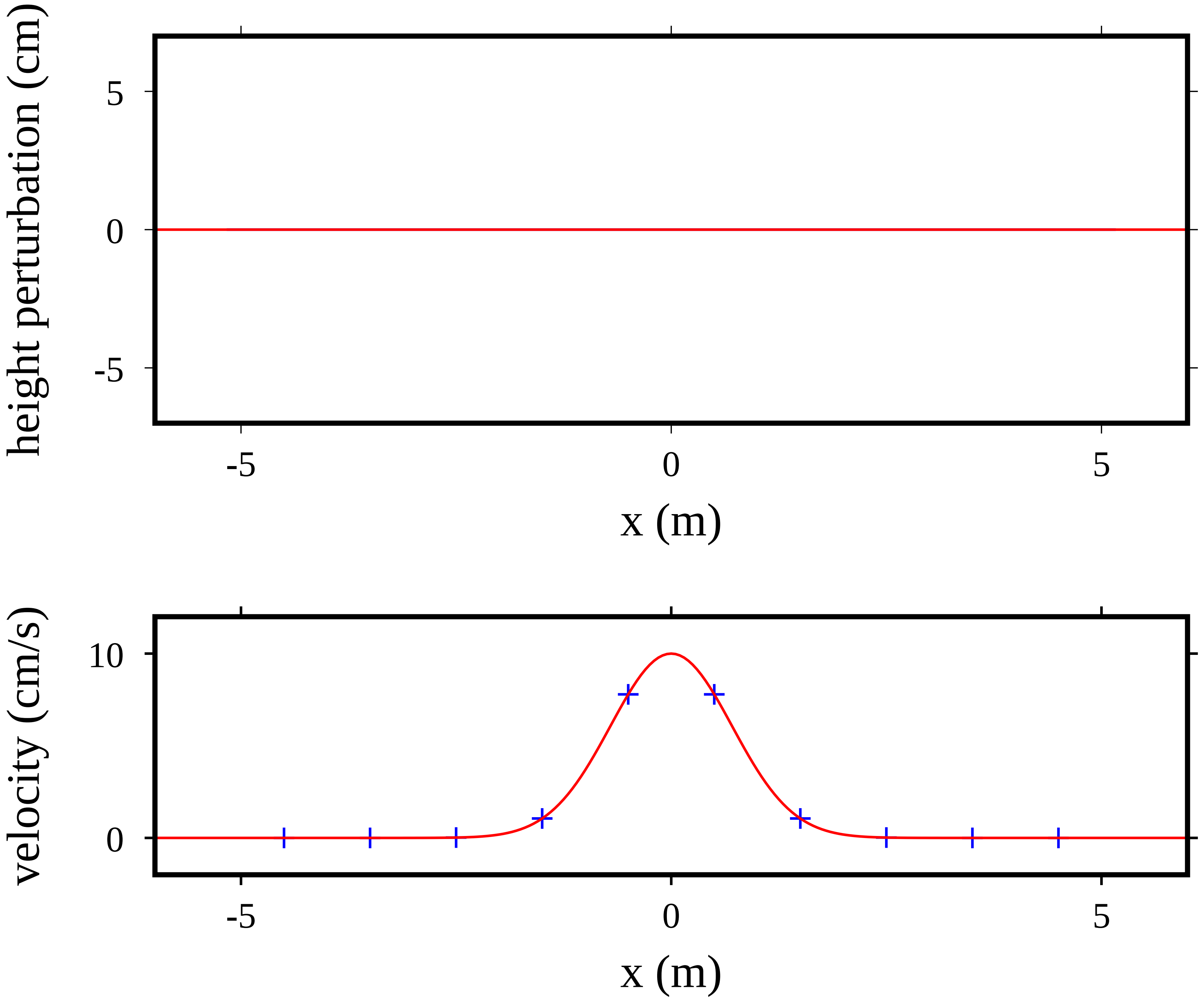
External Gravity Waves

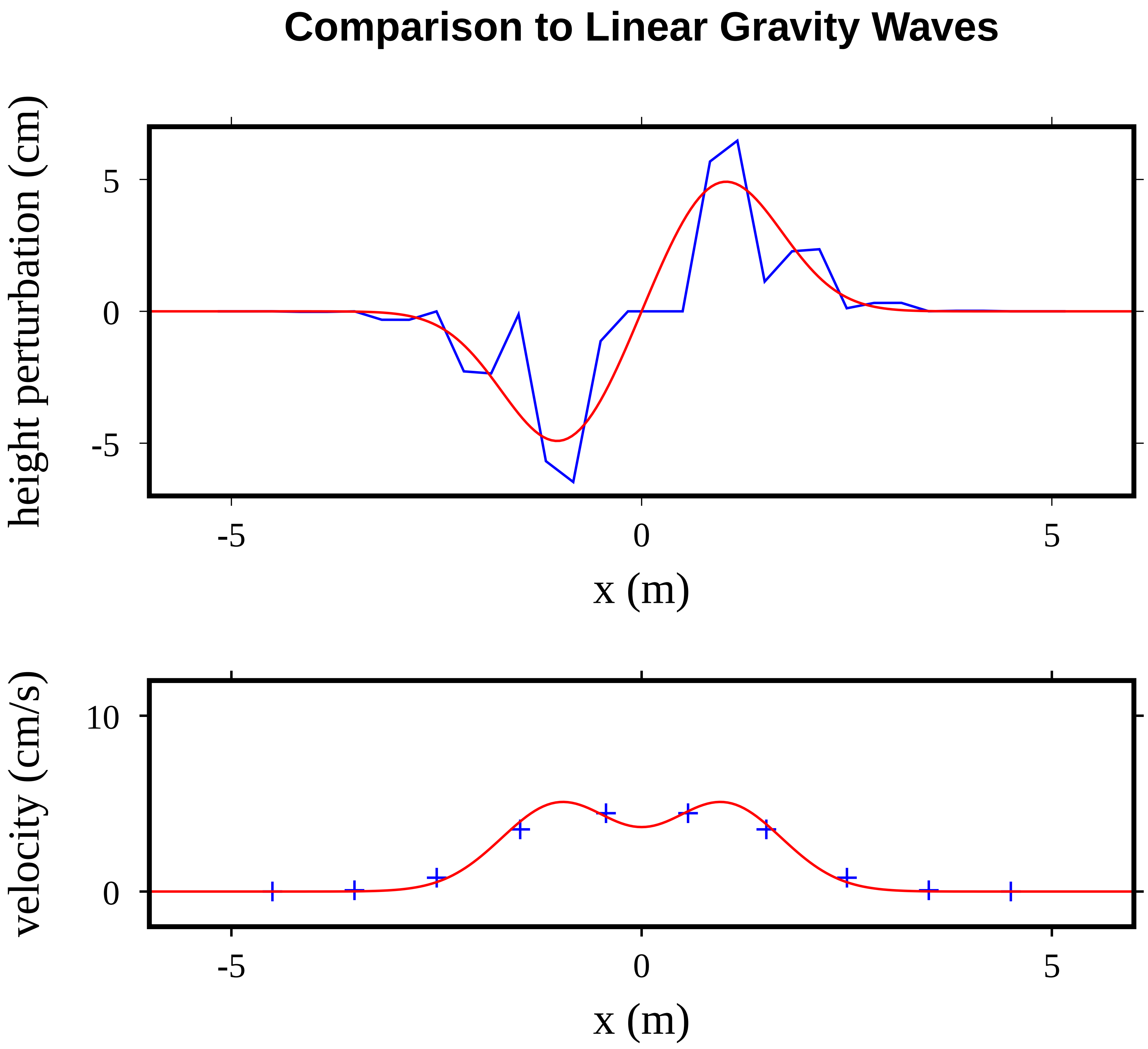


External Gravity Waves

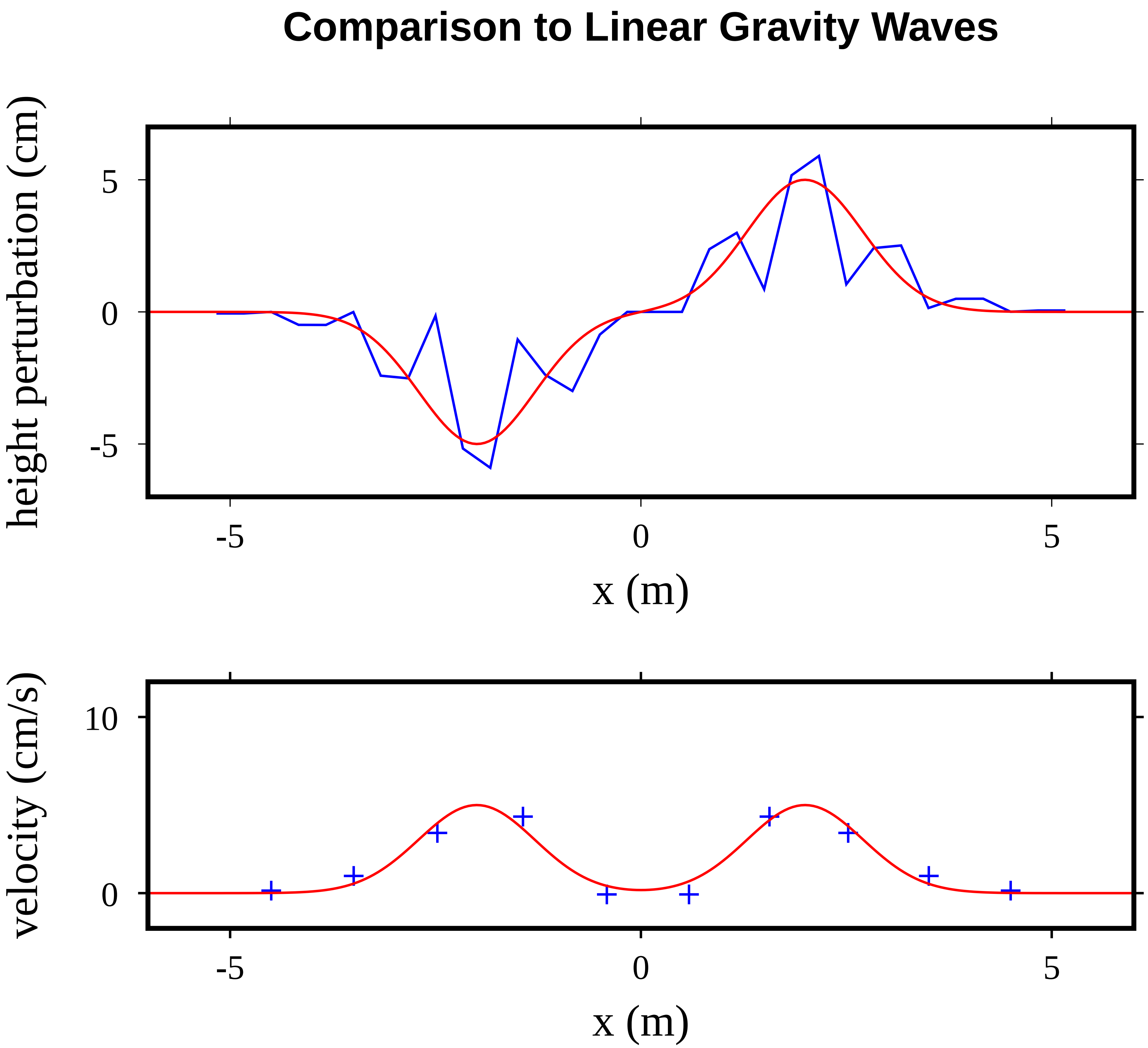


Comparison to Linear Gravity Waves

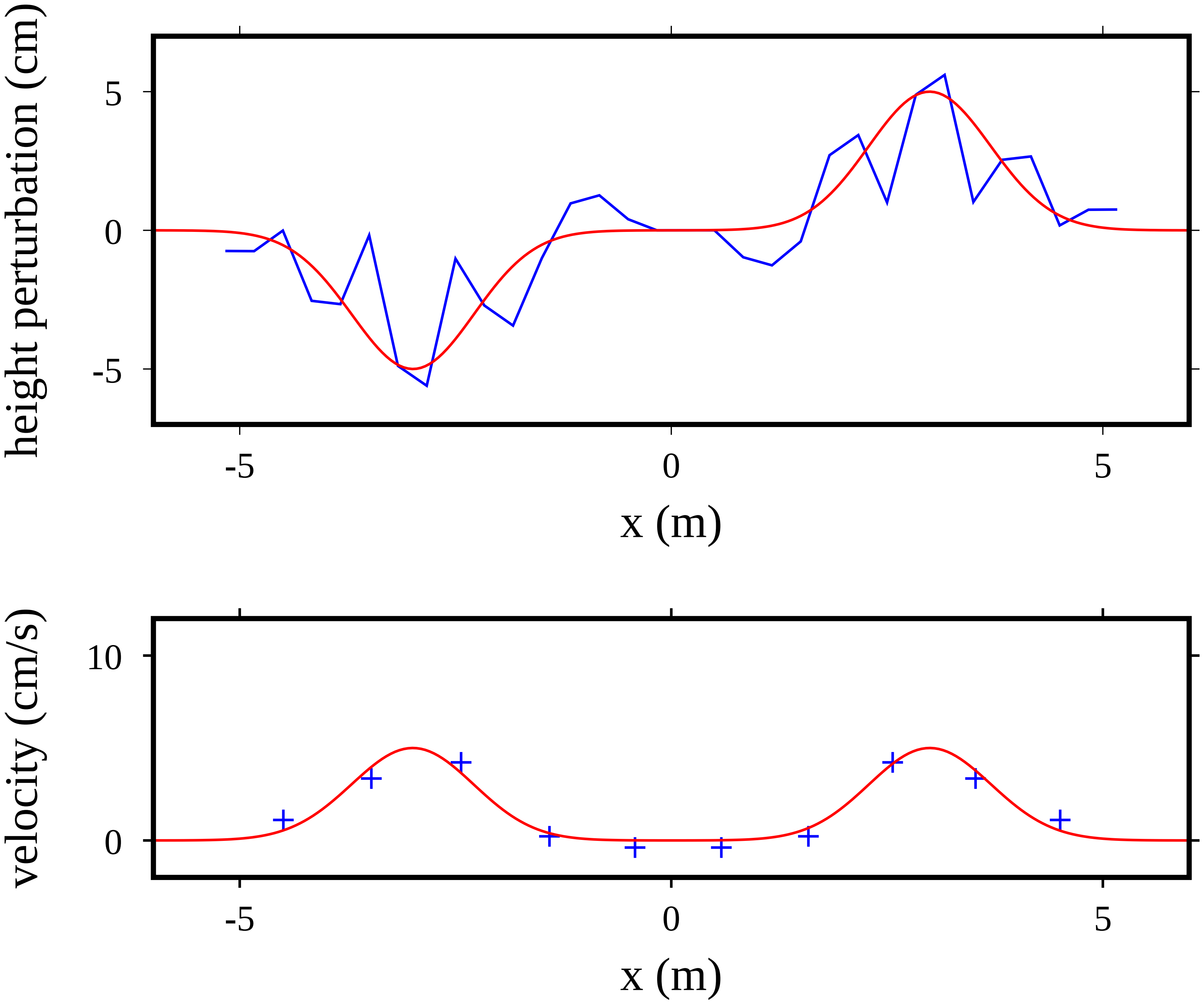


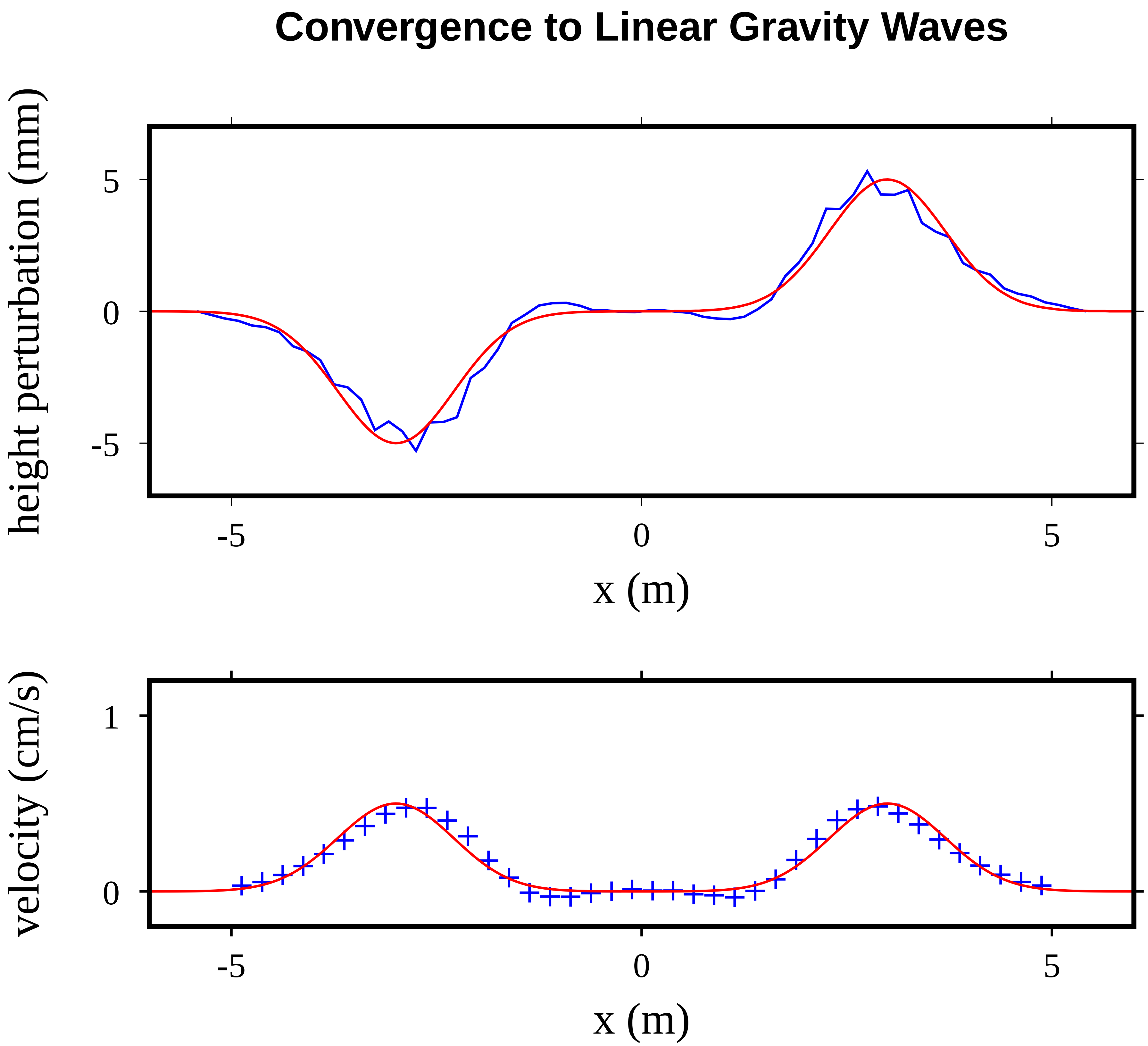


Comparison to Linear Gravity Waves


Comparison to Linear Gravity Waves
height perturbation (cm)
5
0
-5
-5
0
5
x (m)
velocity (cm/s)
10
0
-5
0
5
x (m)

Comparison to Linear Gravity Waves

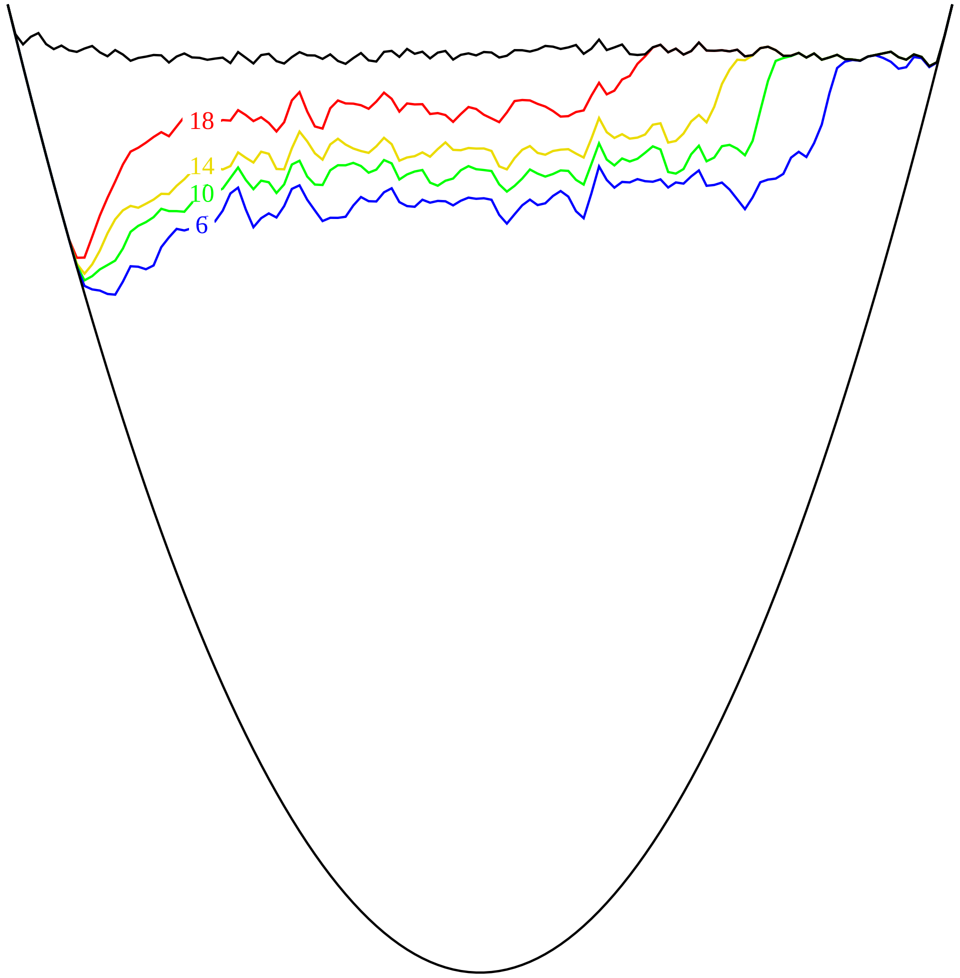



Convergence to Linear Gravity Waves
height perturbation (mm)
5
0
-5
-5
0
5
x (m)
velocity (cm/s)
1
0
-5
0
5
x (m)

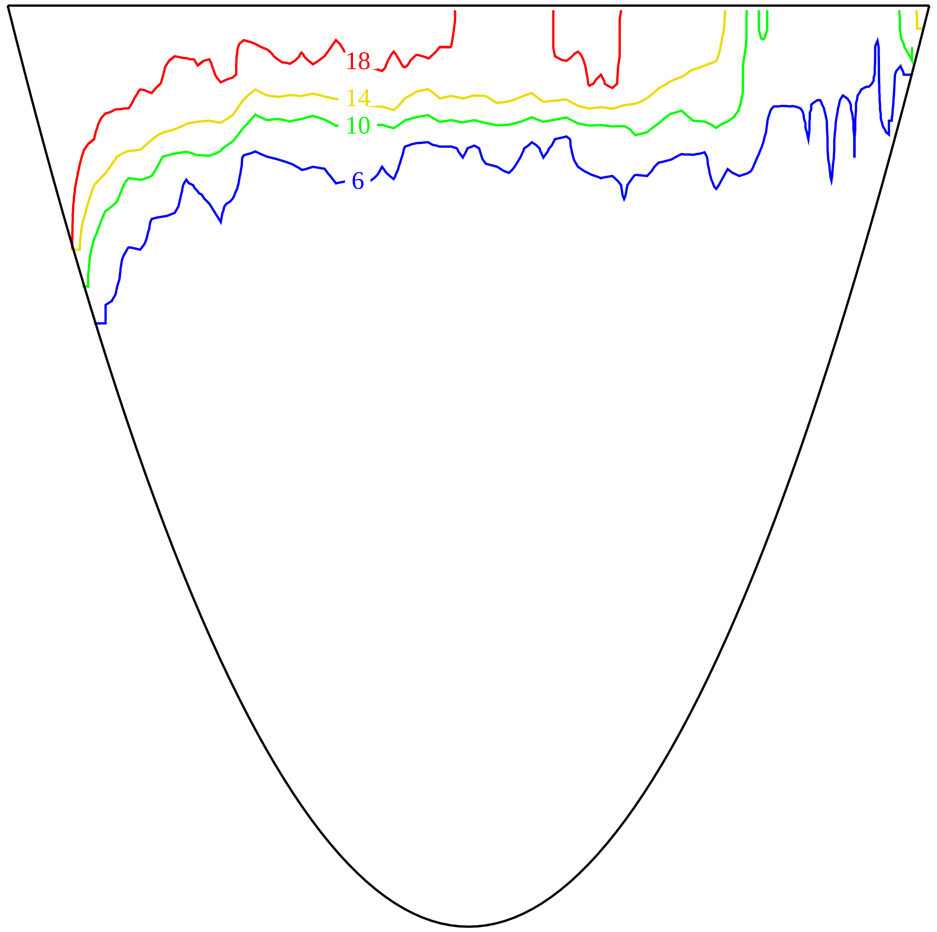
Lake Upwelling

Haertel et al. (2004)

Lagrangian Ocean Model

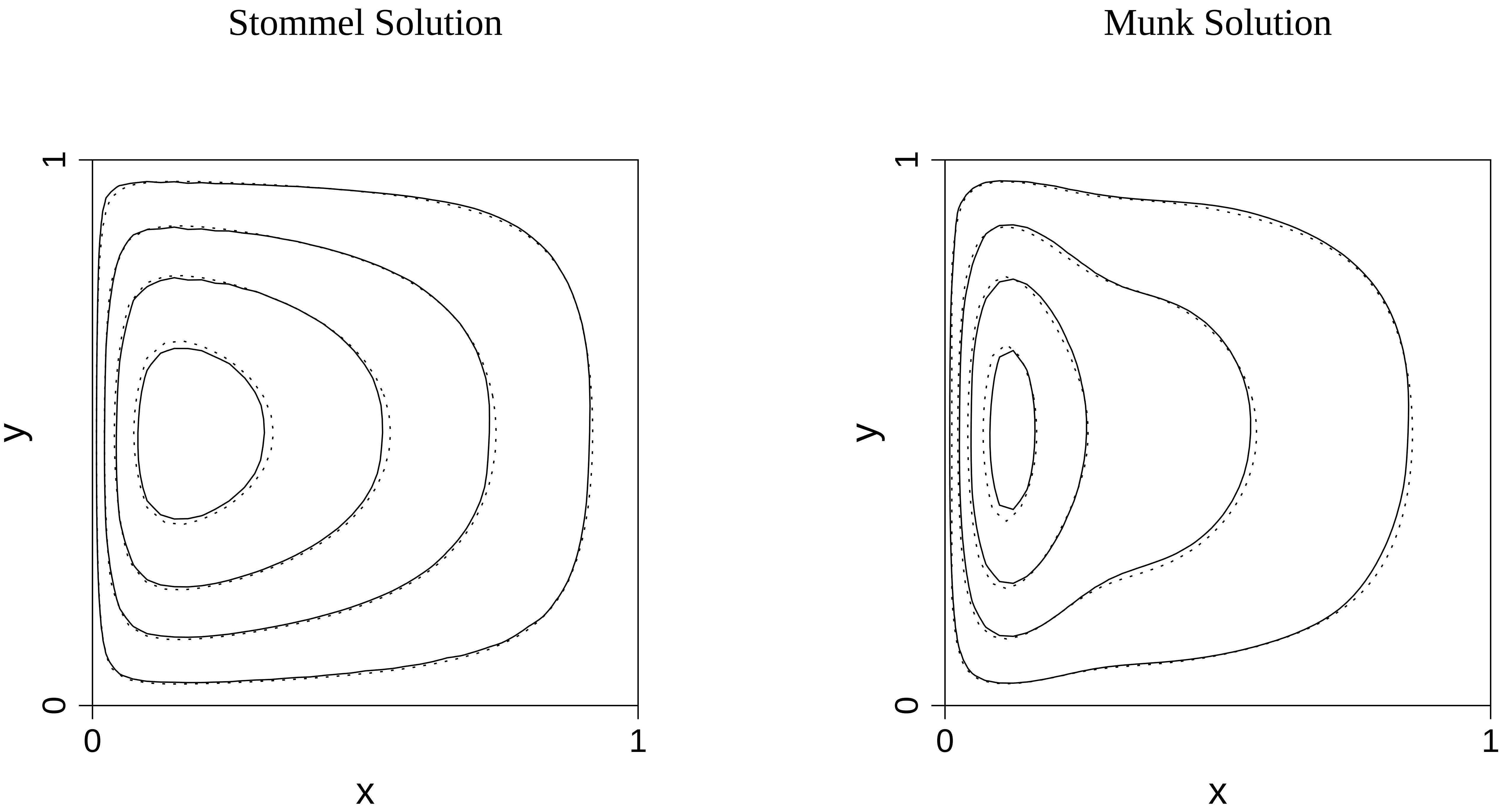


Princeton Ocean Model



Western Boundary Currents

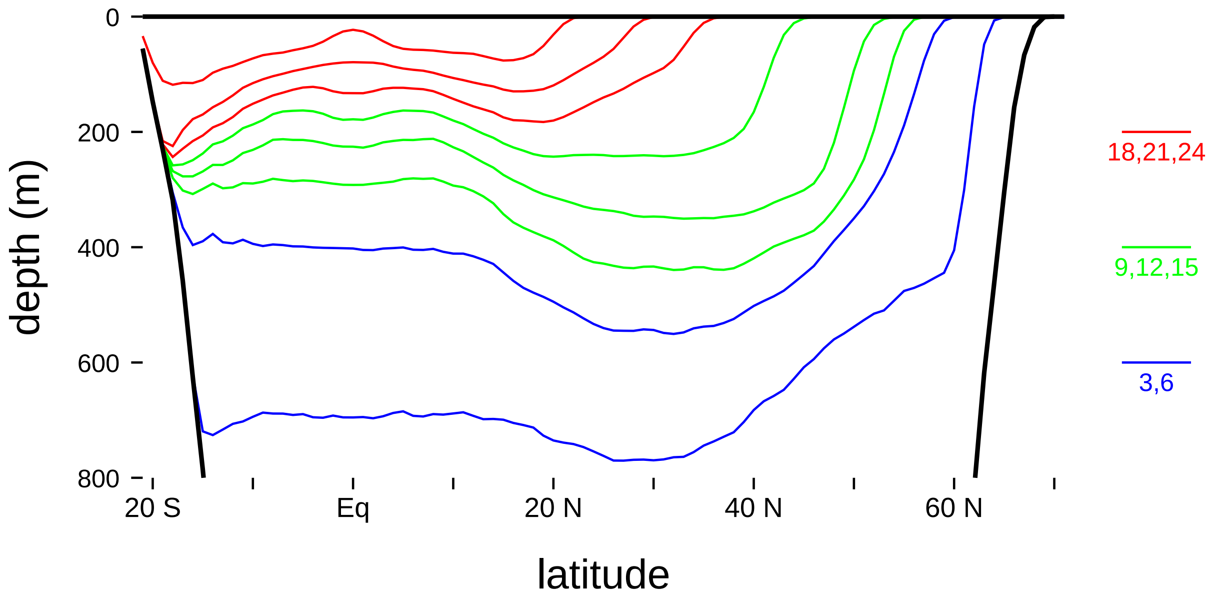
Haertel et al (2009)



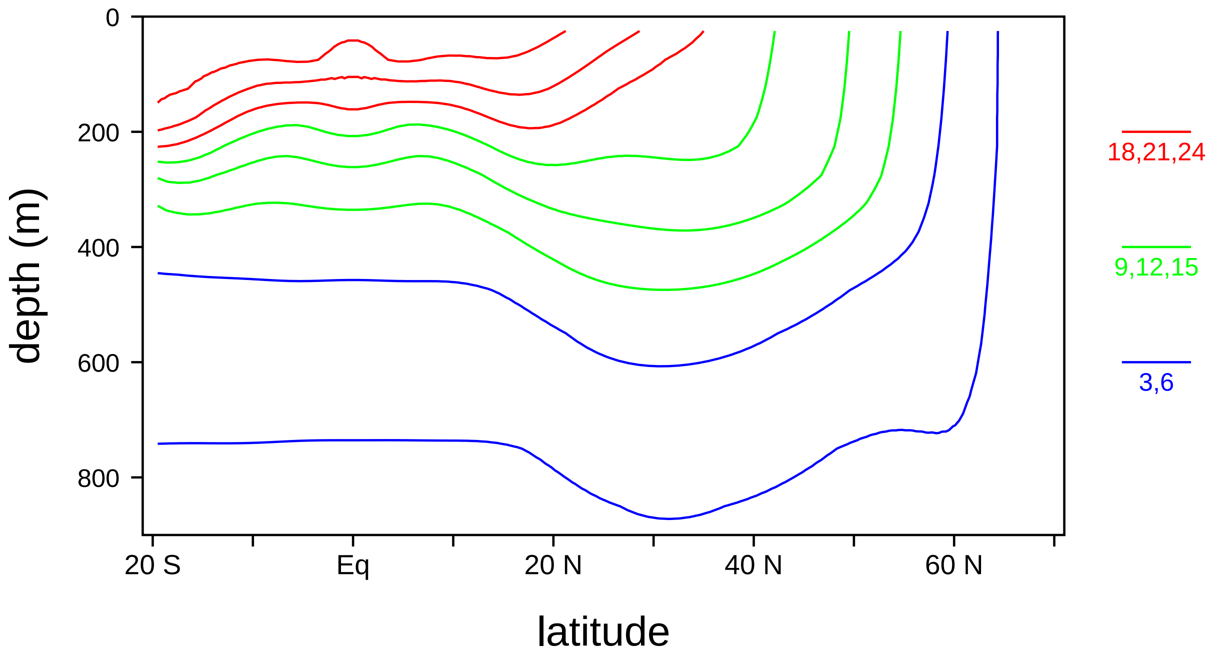
Idealized North Atlantic Ocean

Haertel et al. (2009)

Lagrangian Ocean Model



MITgcm



Lagrangian Overturning

Lagrangian Overturning as a Convective Parameterization

Consider two parcels A and B centered in the same column of a lagrangian model. Suppose A lies beneath B. If exchanging the vertical positions of A and B leads to $\theta(A) > \theta(B)$, then do so!

Details that may not be immediately obvious . . .

1. The new (potential) temperature and specific humidity of A are calculated by assuming equivalent potential temperature is conserved and excess water vapour condenses

2. In practice A and B each represent large collections of parcels

3. Parcel exchange can be done so that a single parcel can ascend or descend entire column in a single time step . . . or not

Potential Advantages of Lagrangian Overturning

1. Physically based; captures the essence of convection
2. Handles both dry and moist convection
3. Ascending and descending parcels in a given column can have different properties (e.g., up moist / down dry).
4. The existence and/or depth of convection responds to local perturbations in thermodynamics profiles
5. Descending parcels have a long memory
6. Parcel trajectories are provided at no additional computational cost
7. Few tunable parameters

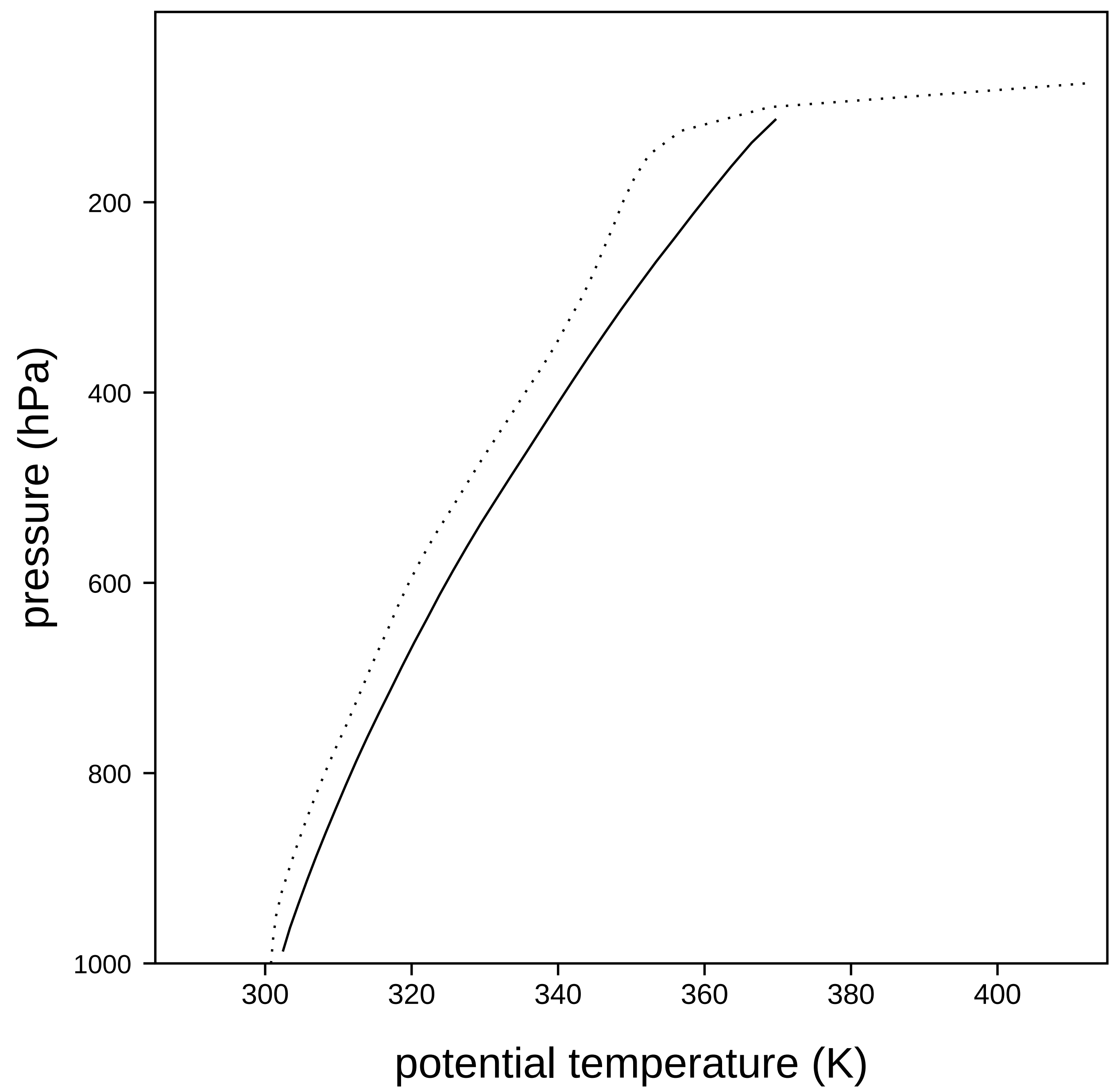
Single Column Experiments

Components of Single Column Model

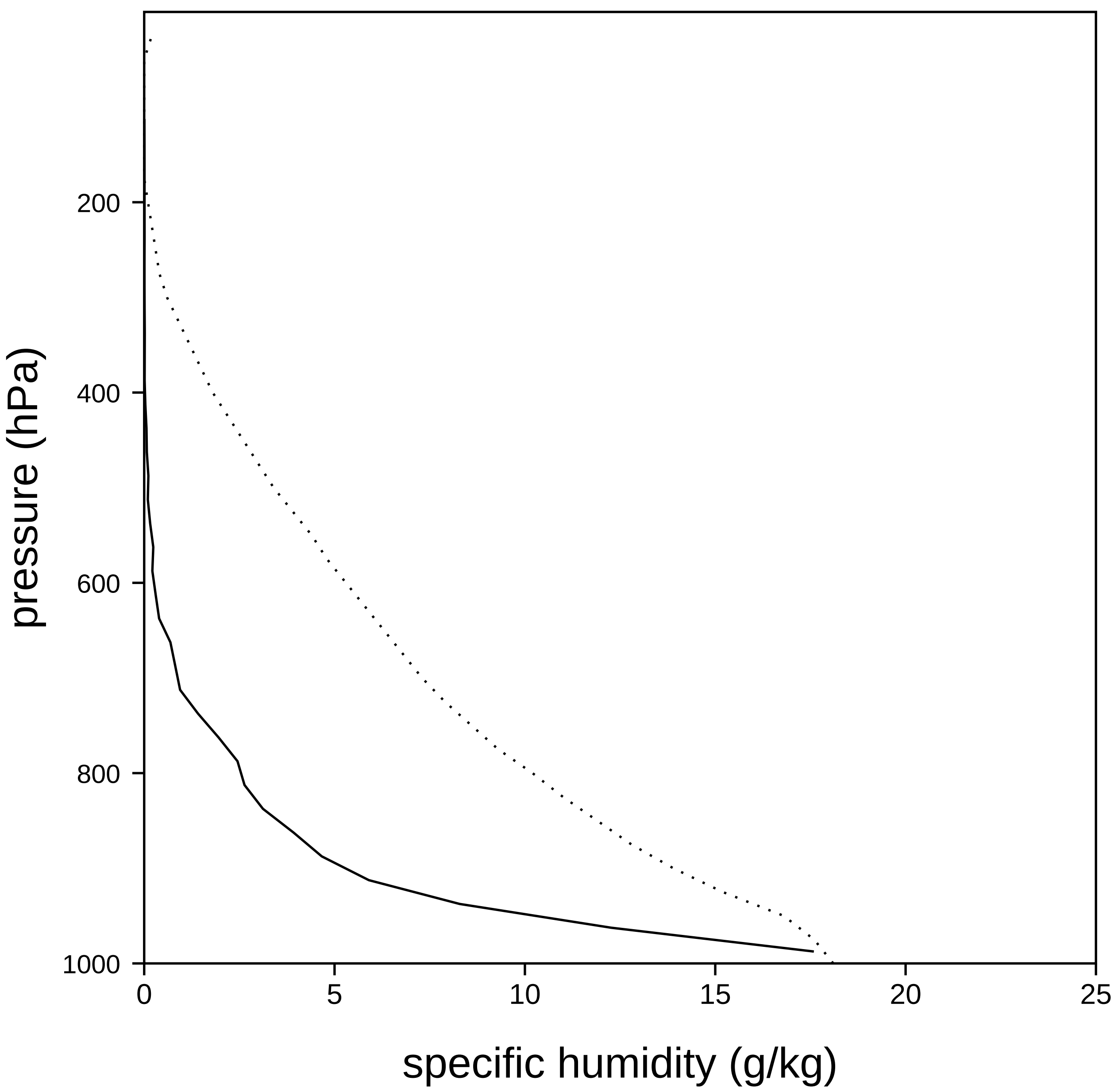
1. Surface Fluxes: Restore T, q of lowest parcel to SST, qsat(SST)
2. Radiation: 1 K/day cooling, fixed stratospheric temperature
3. Evaporation: Fixed percentage of liquid water evaporates each time step
4. Rain: Condensed water falls to next parcel down each time step
5. Convection: Lagrangian Overturning

Experiment 1: No mixing, no evaporation of rain (control)

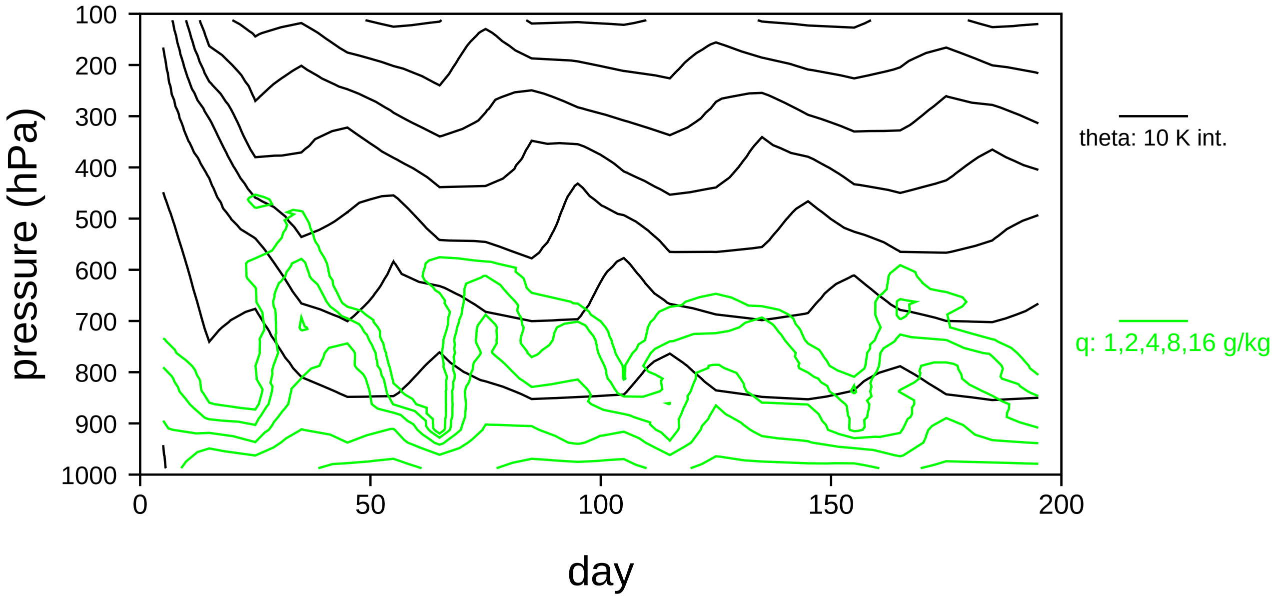
Average Potential Temperature (LO solid, COARE IFA dashed)

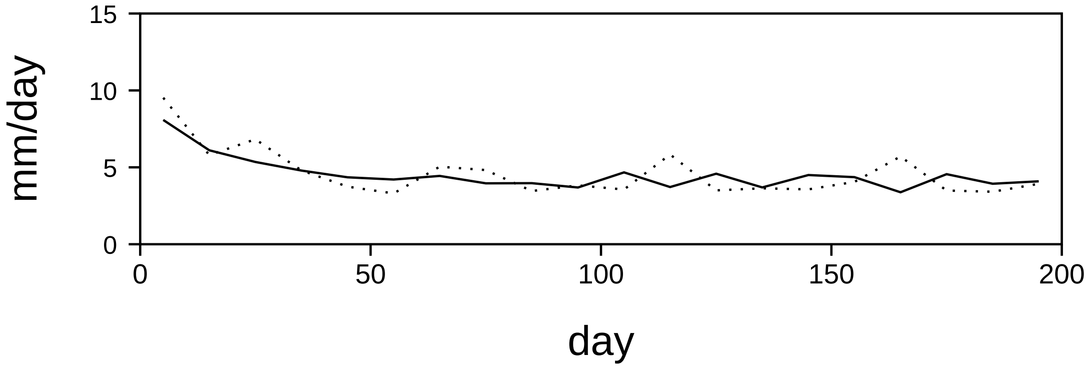


Average Specific Humidity (LO solid, COARE IFA dashed)

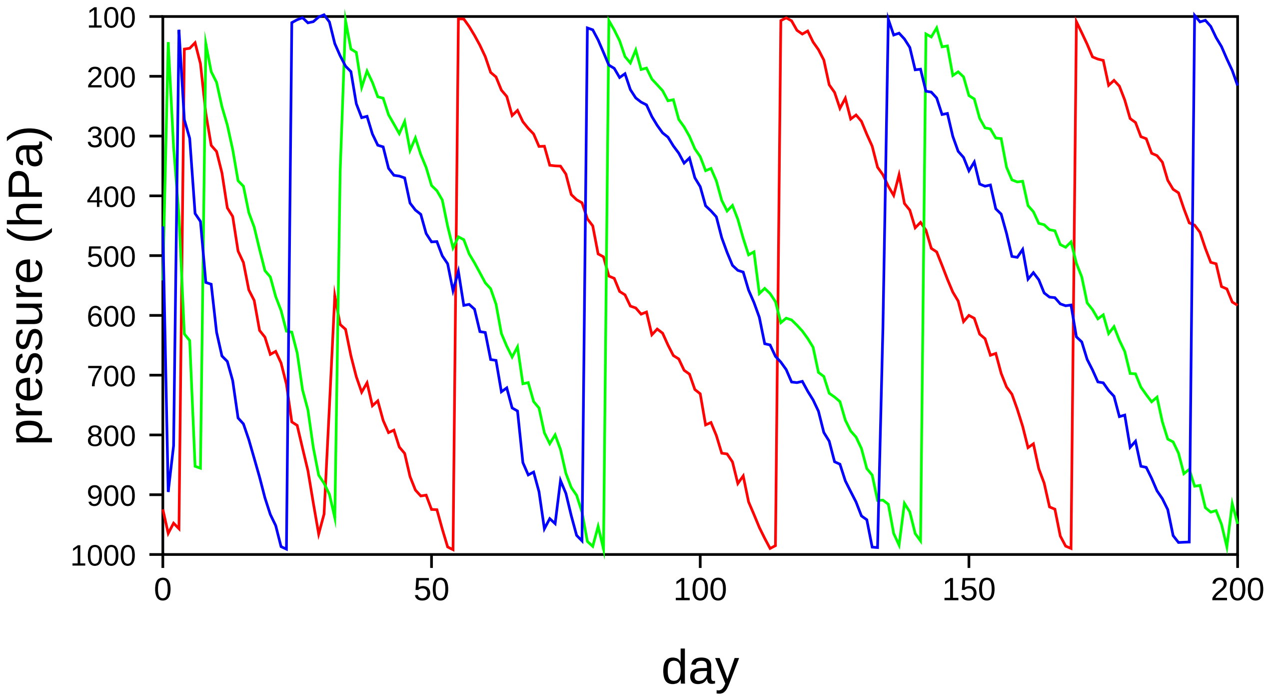


Time Pressure Series of Potential Temperature, Specific Humidiy, Rainfall, and Evaporation



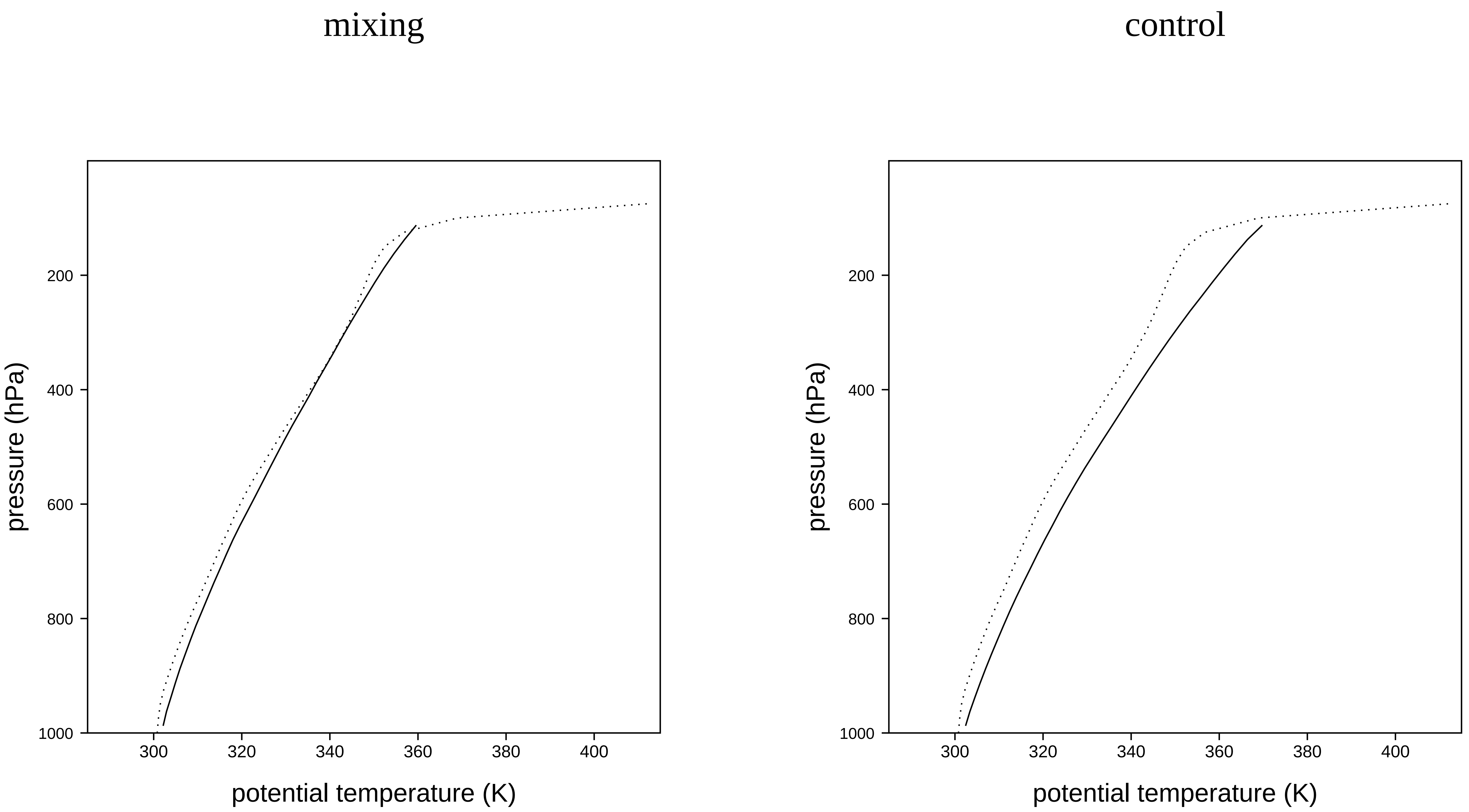


Sample Parcel Trajectories

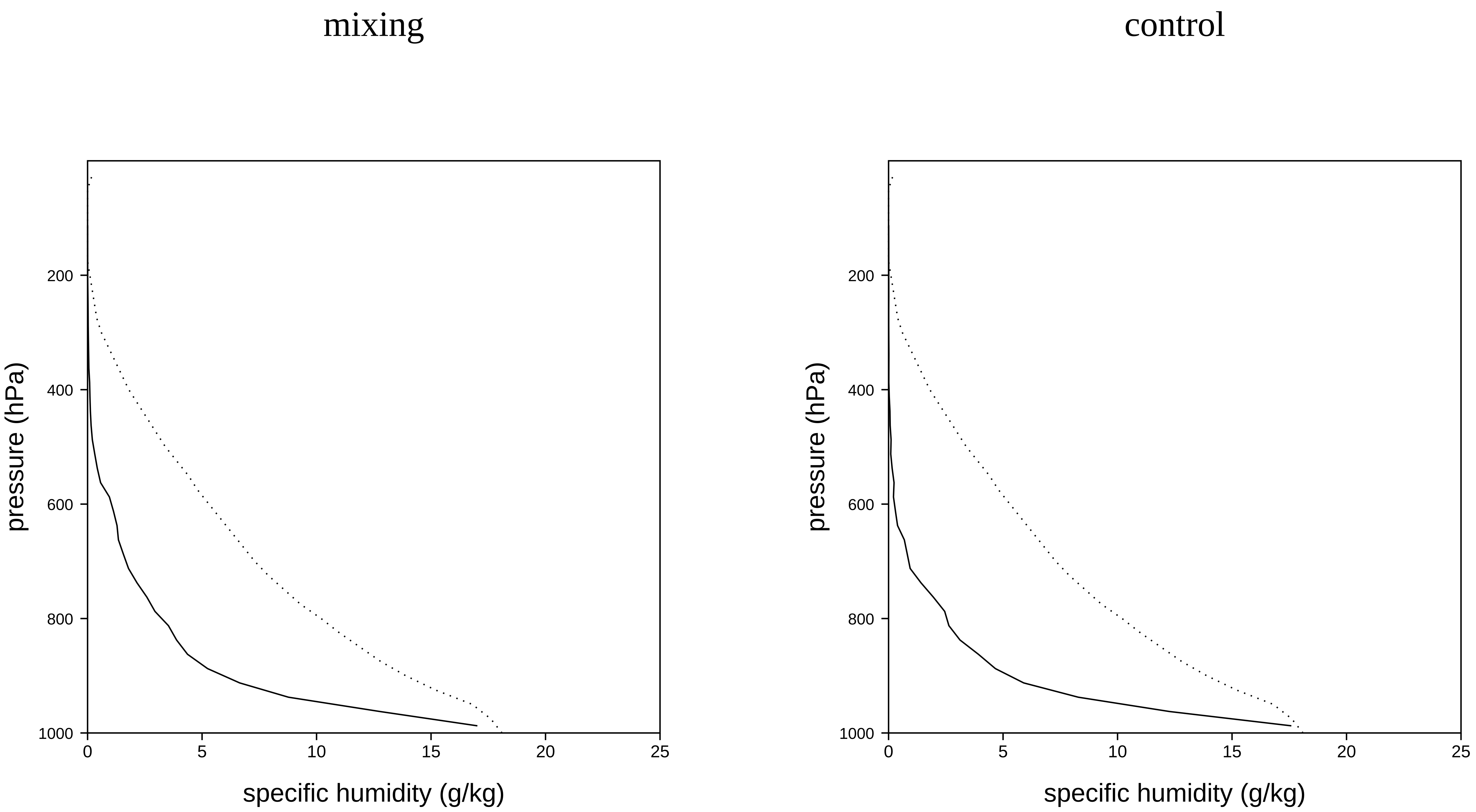


Experiment 2: Mixing, No evaporation of rain

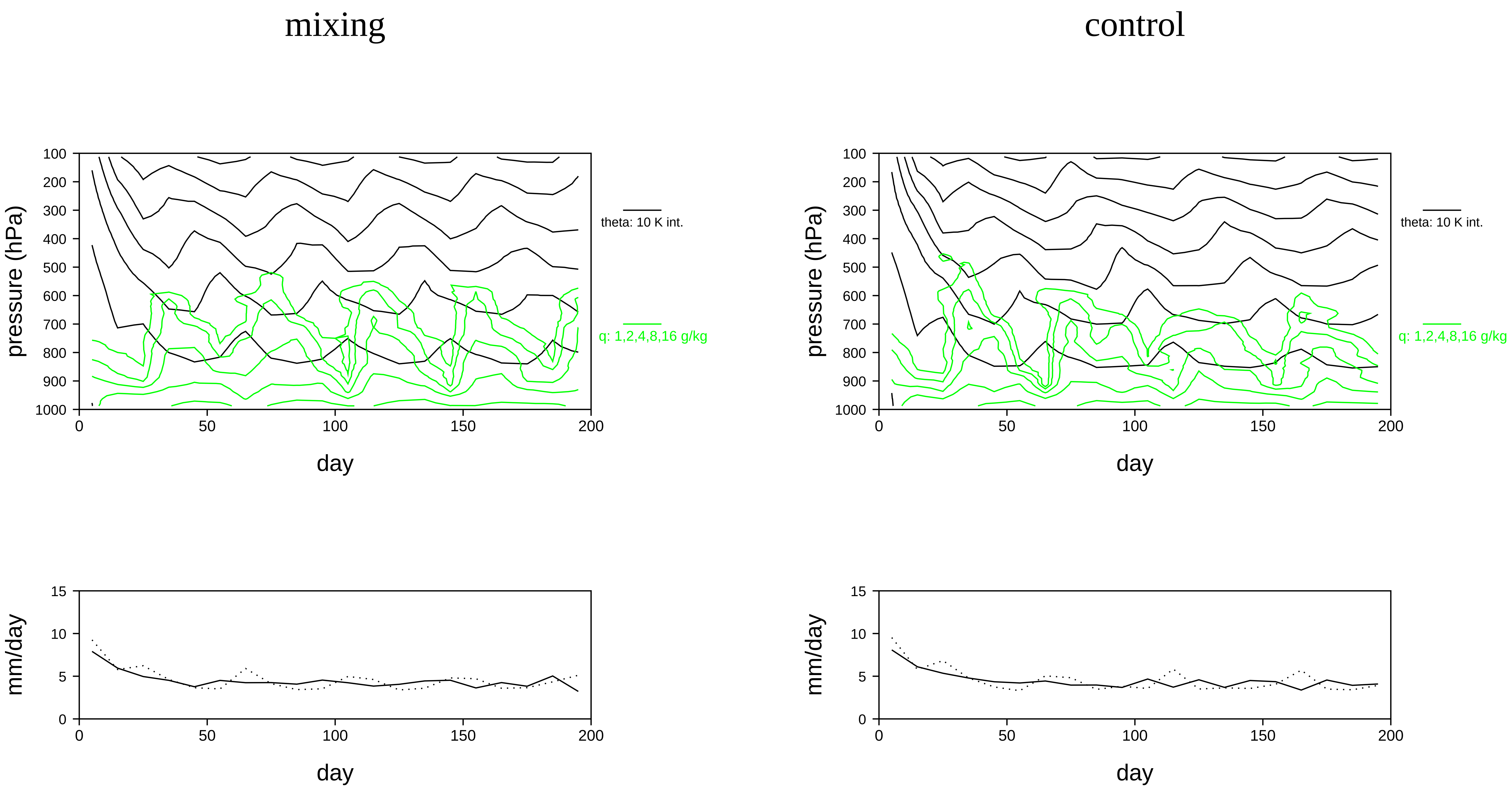
Average Potential Temperature (LO solid, COARE IFA dashed)



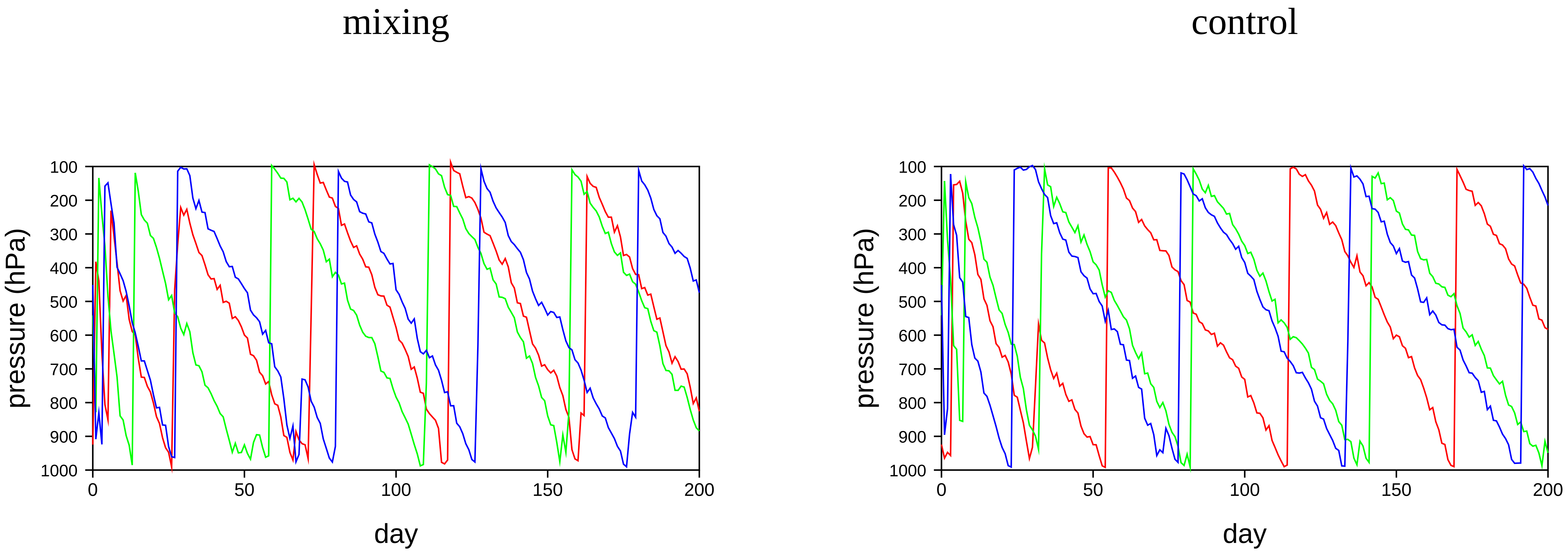
Average Specific Humidity (LO solid, COARE IFA dashed)



Time Pressure Series of Potential Temperature, Specific Humidity, Rainfall, and Evaporation

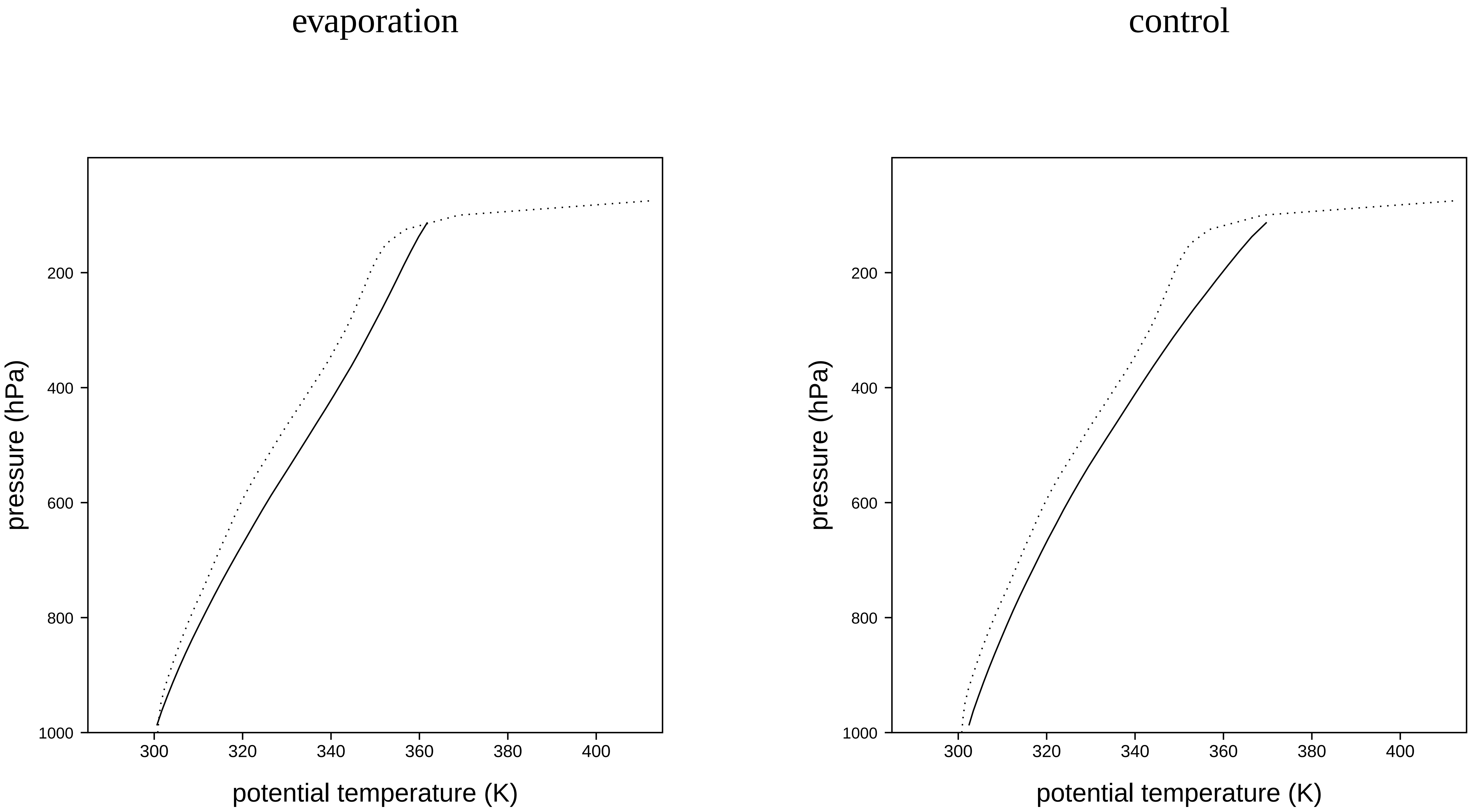


Sample Parcel Trajectories

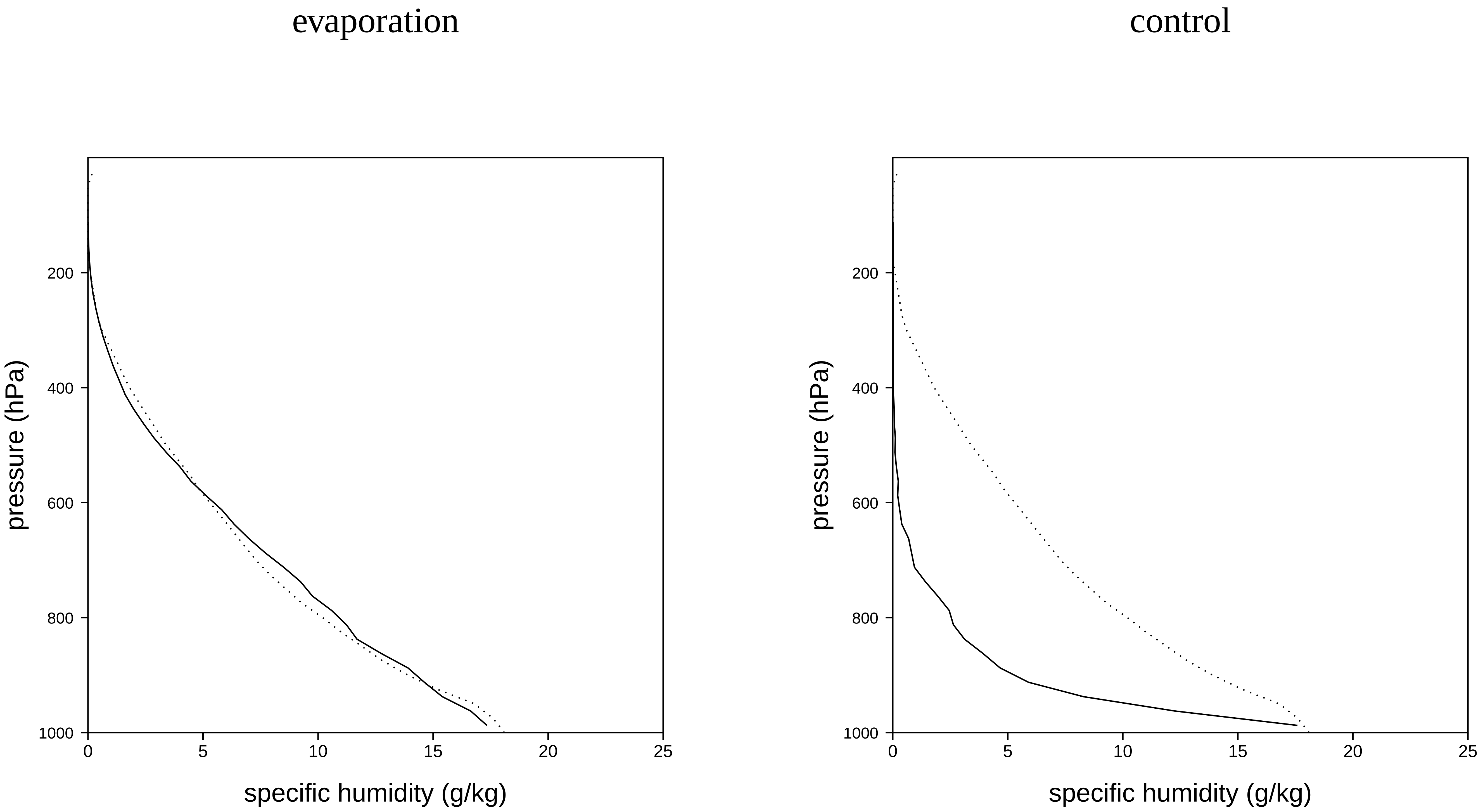


Experiment 3: Evaporation of rain, no mixing

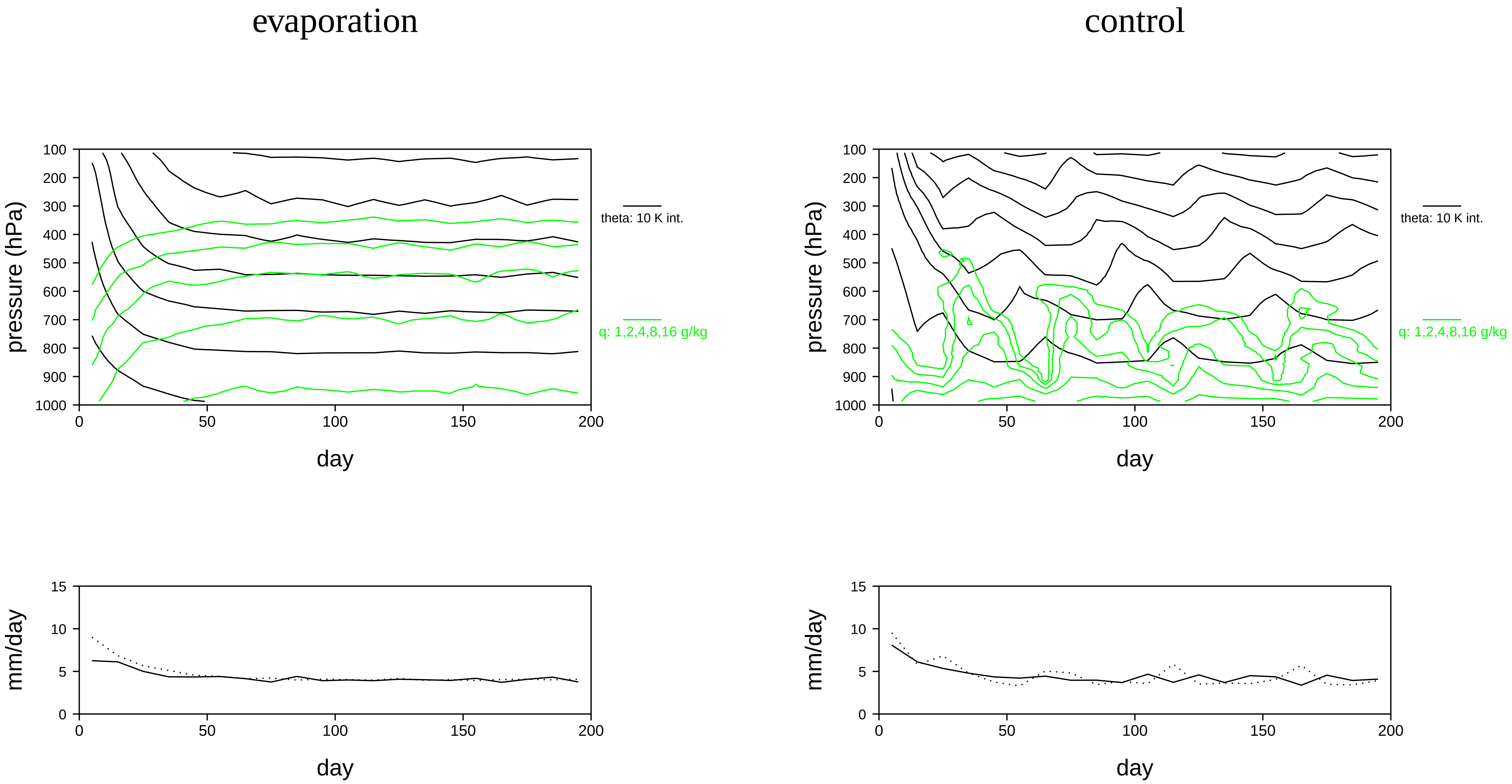
Average Potential Temperature (LO solid, COARE IFA dashed)



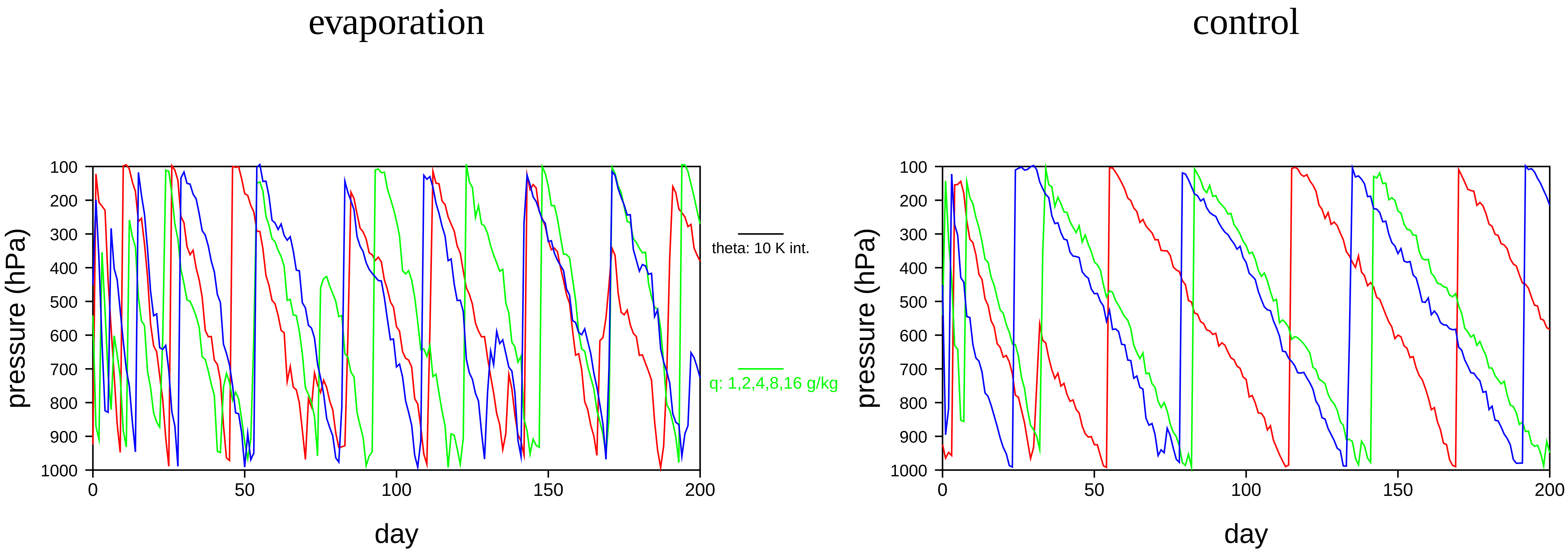
Average Specific Humidity (LO solid, COARE IFA dashed)



Time Pressure Series of Potential Temperature, Specific Humidity, Rainfall, and Evaporation



Sample Parcel Trajectories

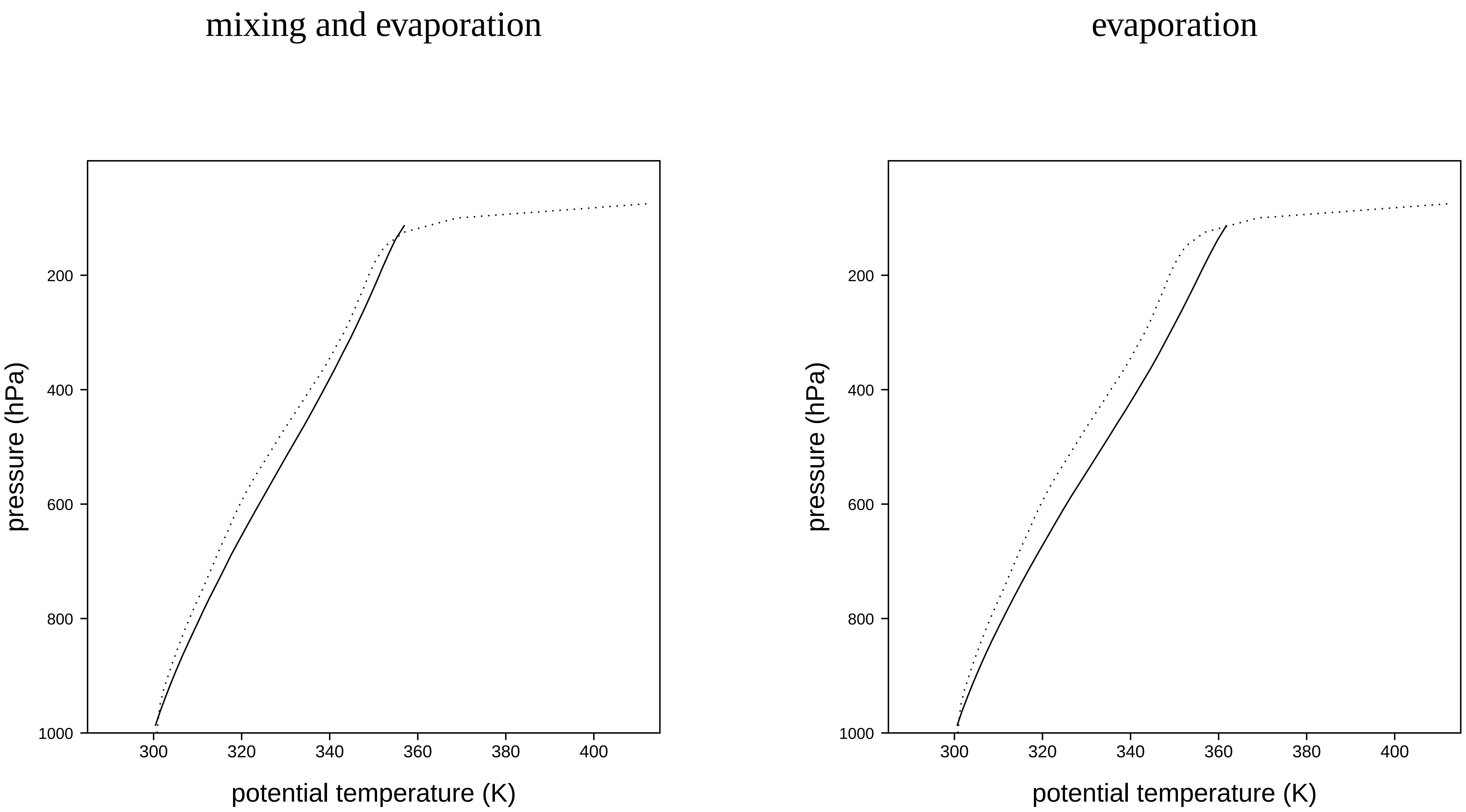


evaporation

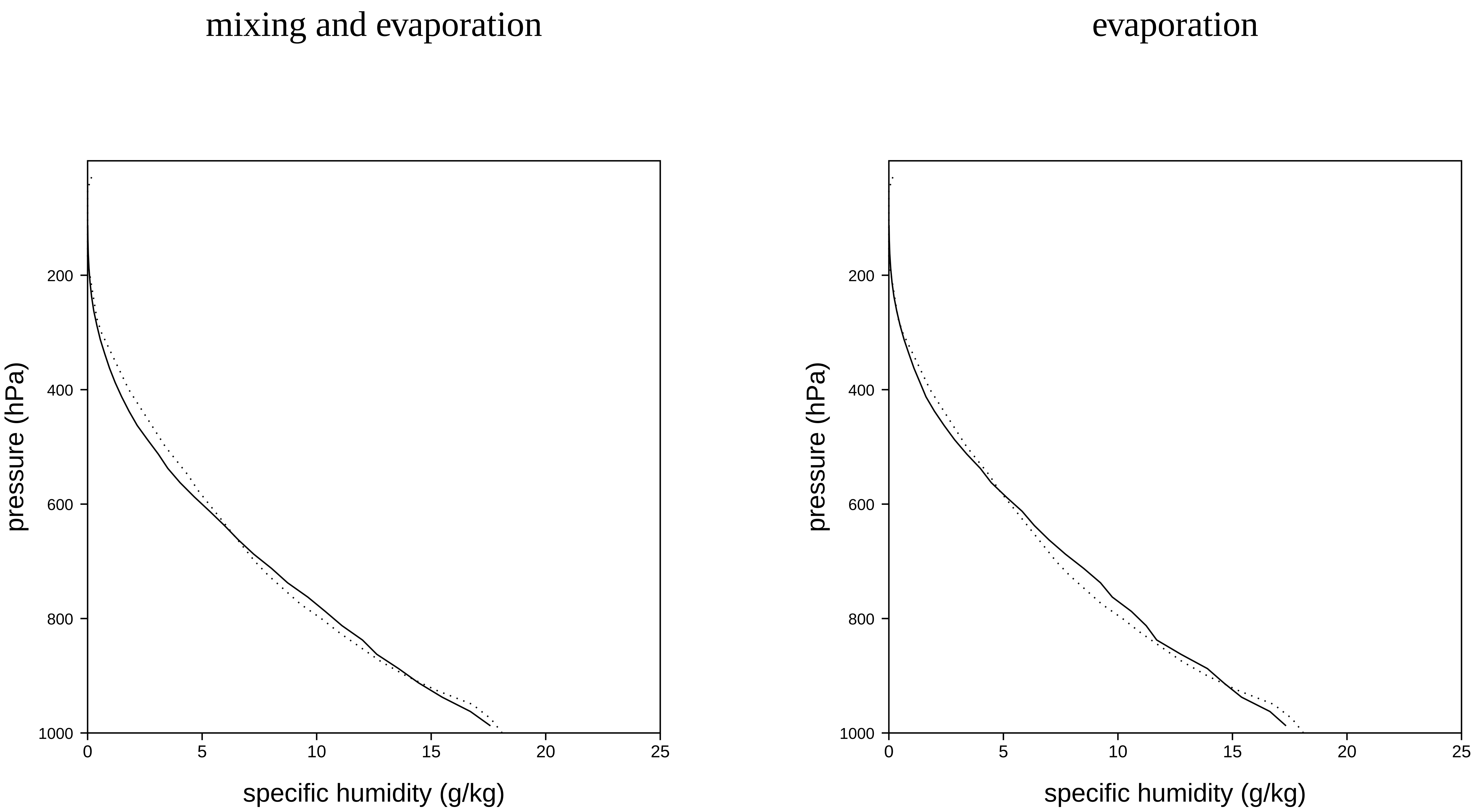
control

Experiment 4: Evaporation of rain and mixing

Average Potential Temperature (LO solid, COARE IFA dashed)



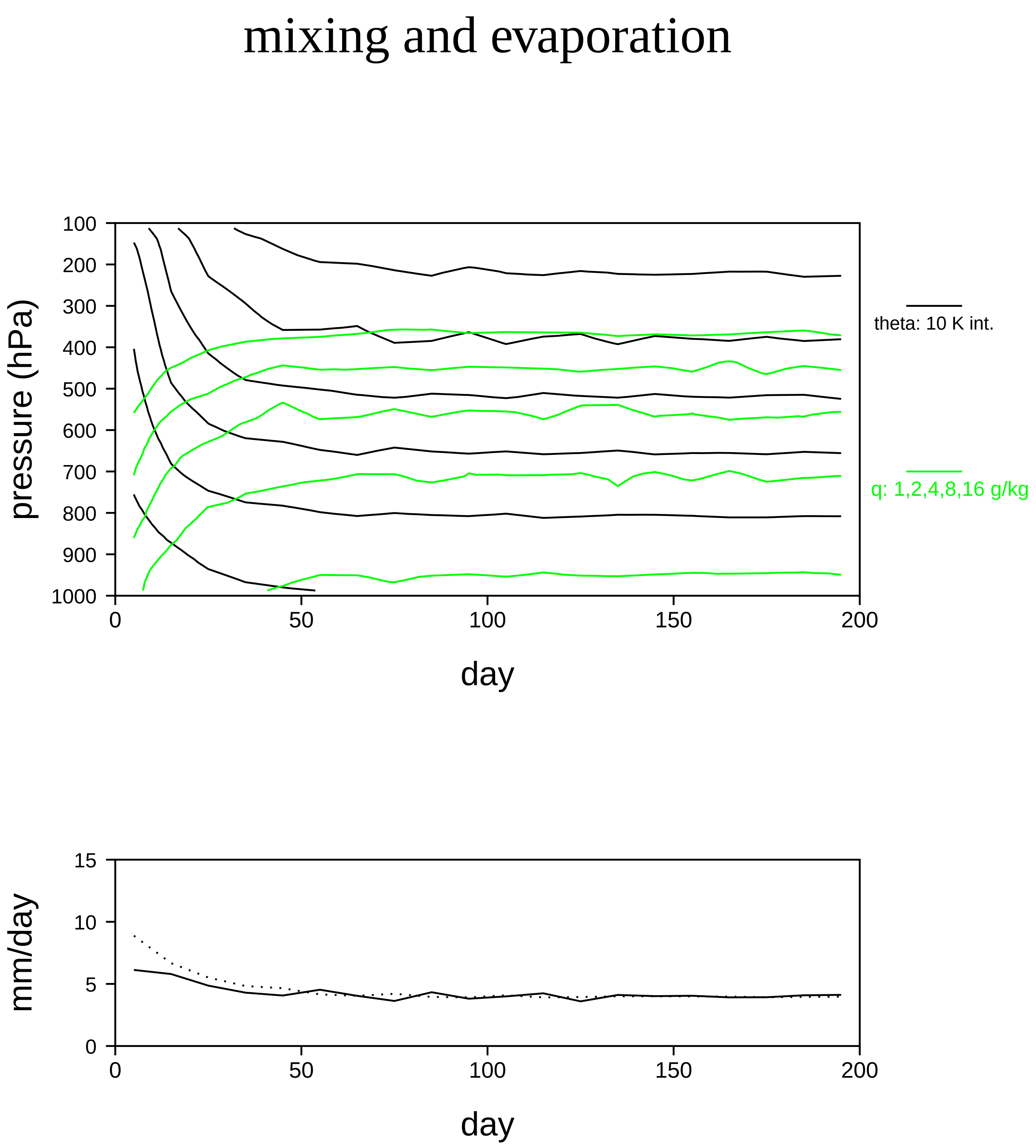
Average Specific Humidity (LO solid, COARE IFA dashed)

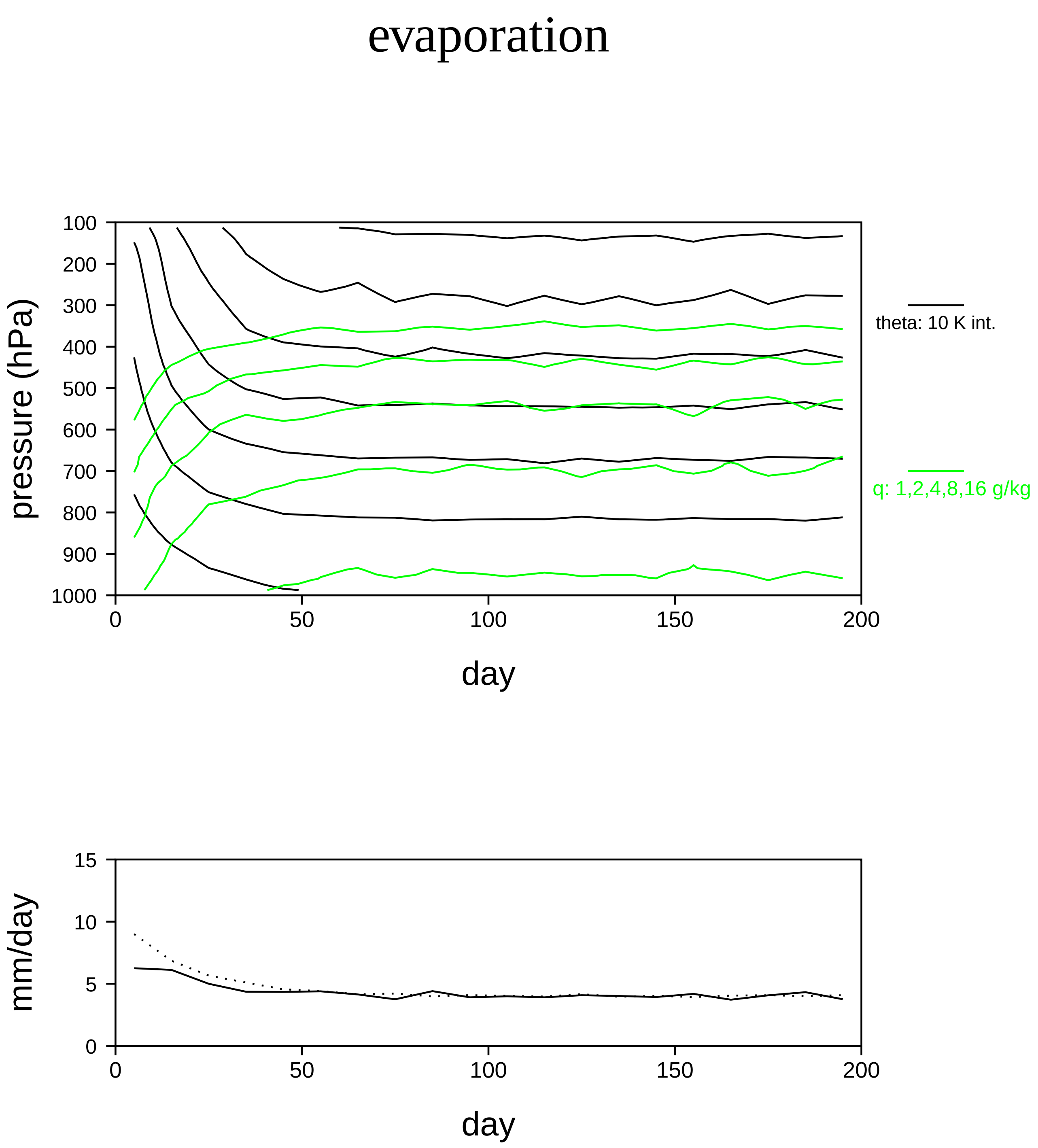


mixing and evaporation

evaporation

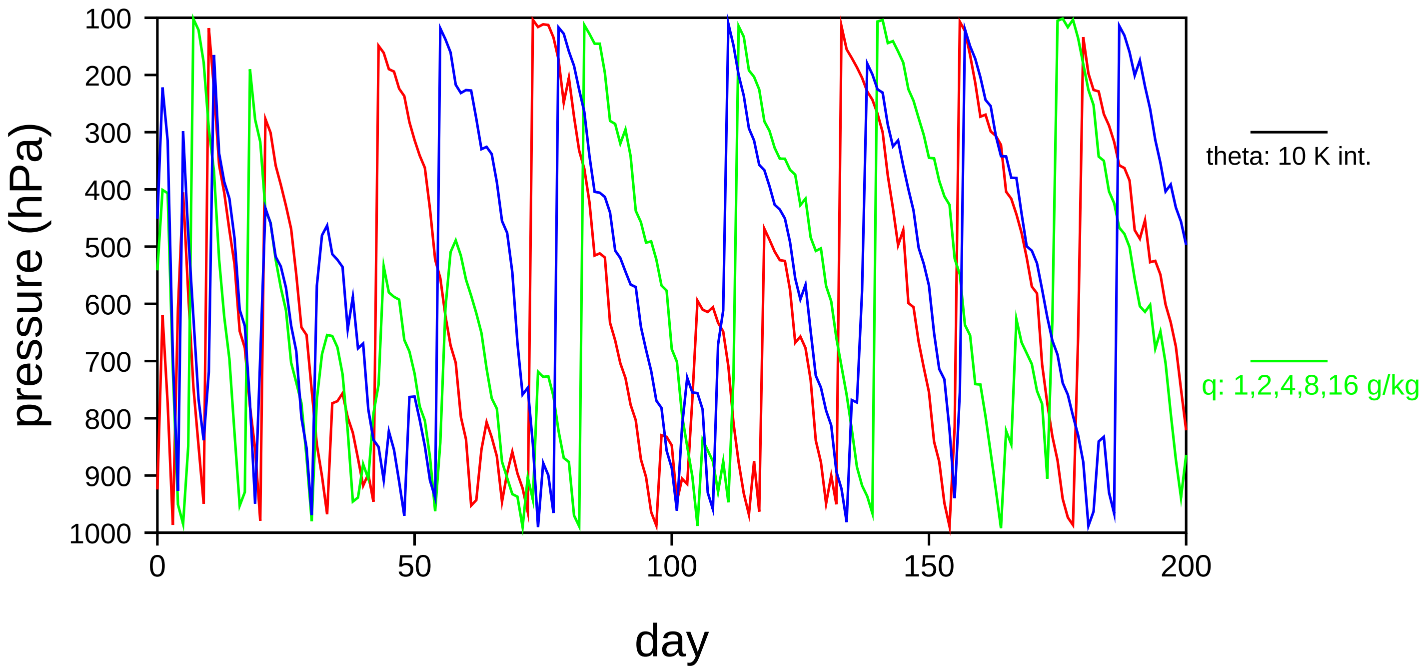
Time Pressure Series of Potential Temperature, Specific Humidity, Rainfall, and Evaporation


mixing and evaporation

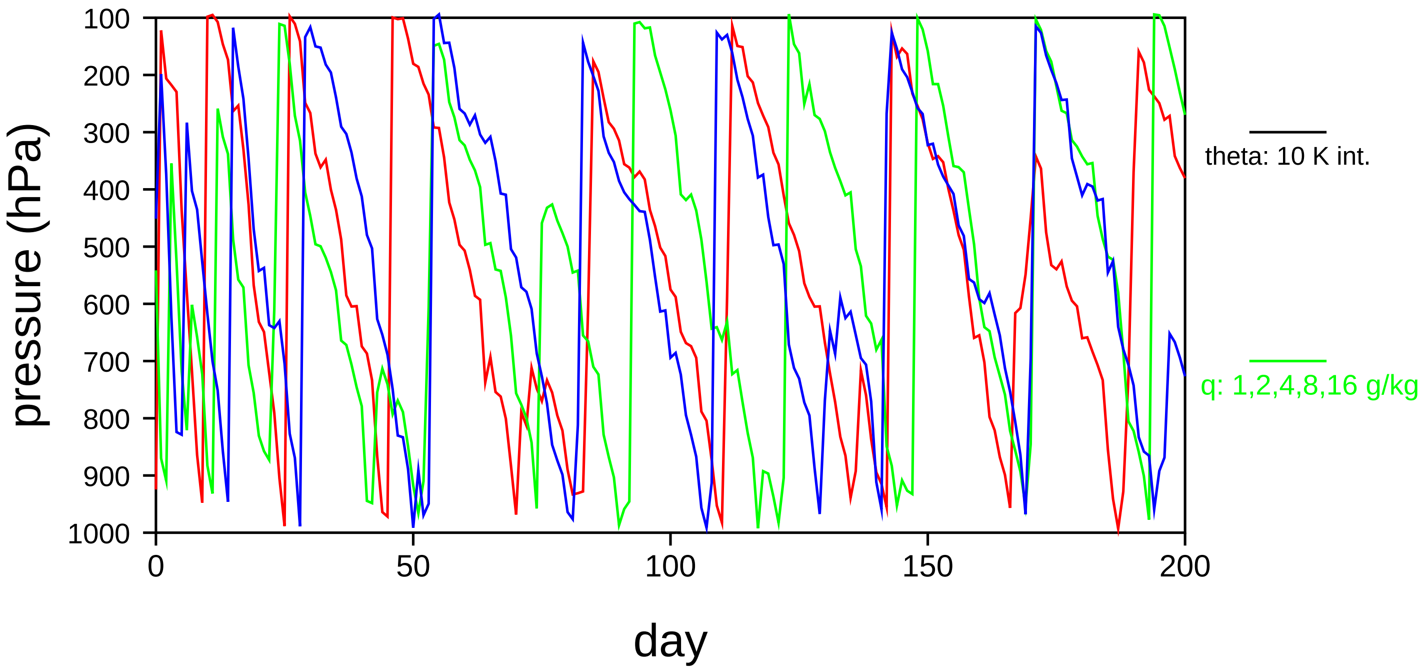

evaporation

Sample Parcel Trajectories

mixing and evaporation



evaporation



Conclusions from Single Column Experiments

1. Including evaporation of rain is critical for generating realistic moisture profiles

2. When the mid-troposphere is warm, LO produces relatively shallow convection that moistens the lower troposphere.

3. Interesting oscillation that couples descending temperature anomalies and convective morphology

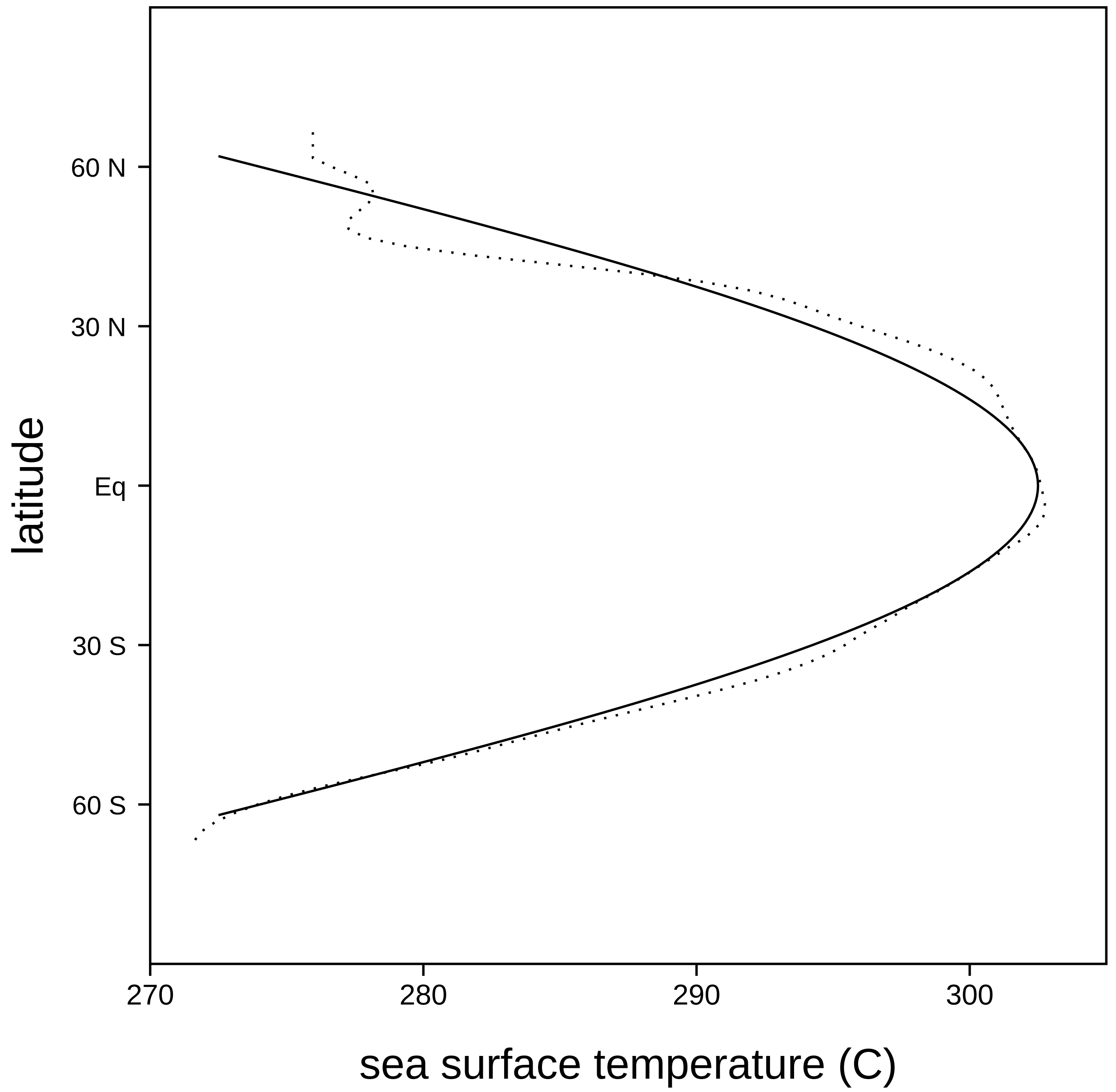
Three Dimensional Simulations

Model Charaterisitics

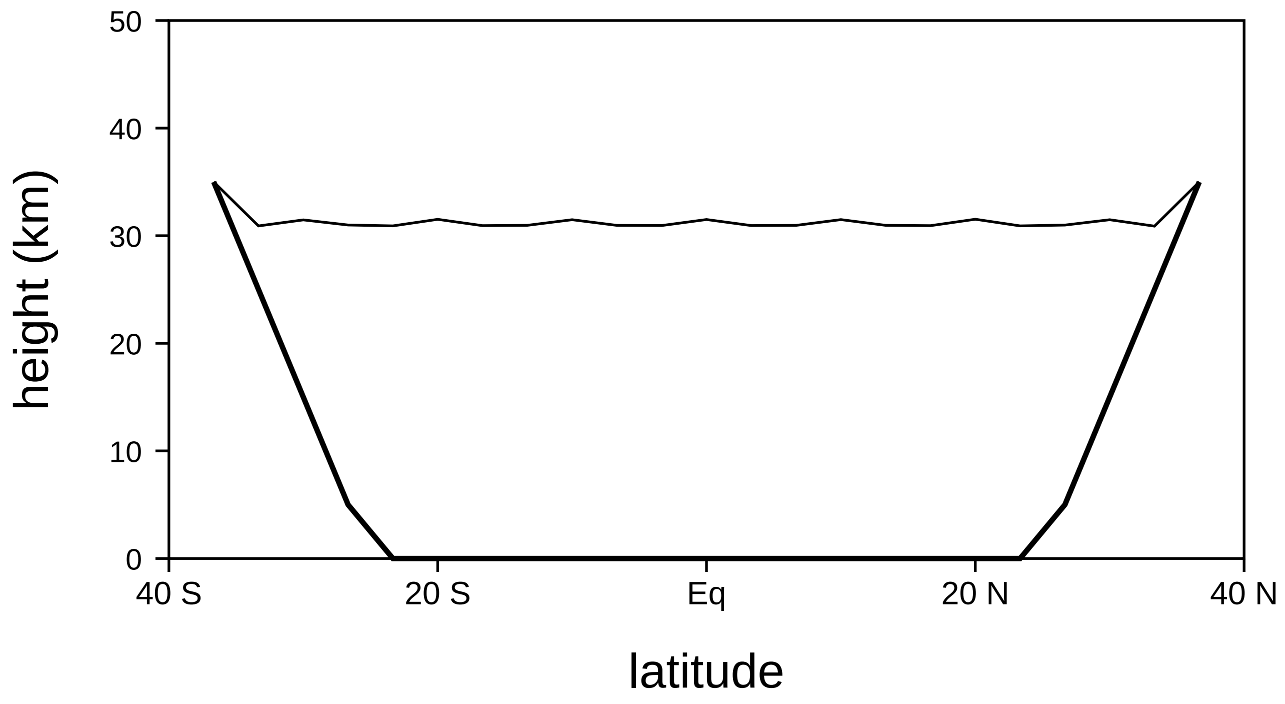
- Tropics of an Aquaplanet
- Zonally symmetric SST
- Lagrangain dynamical core
- Sloping meridional boundaries at 25-35 N/S

Sea Surface Temperature

LO model solid, Levitus 150-160 E dashed

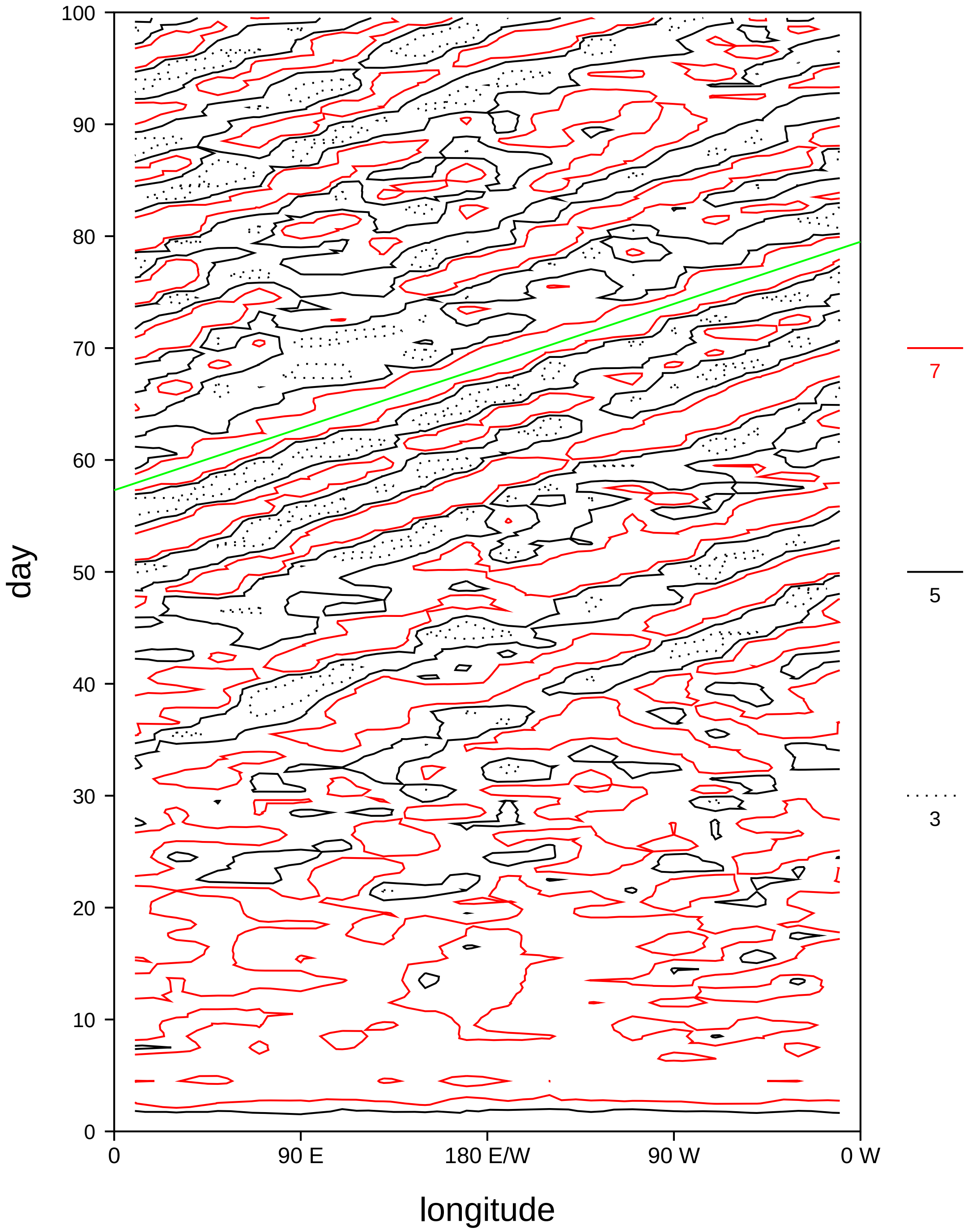


Surface Topography



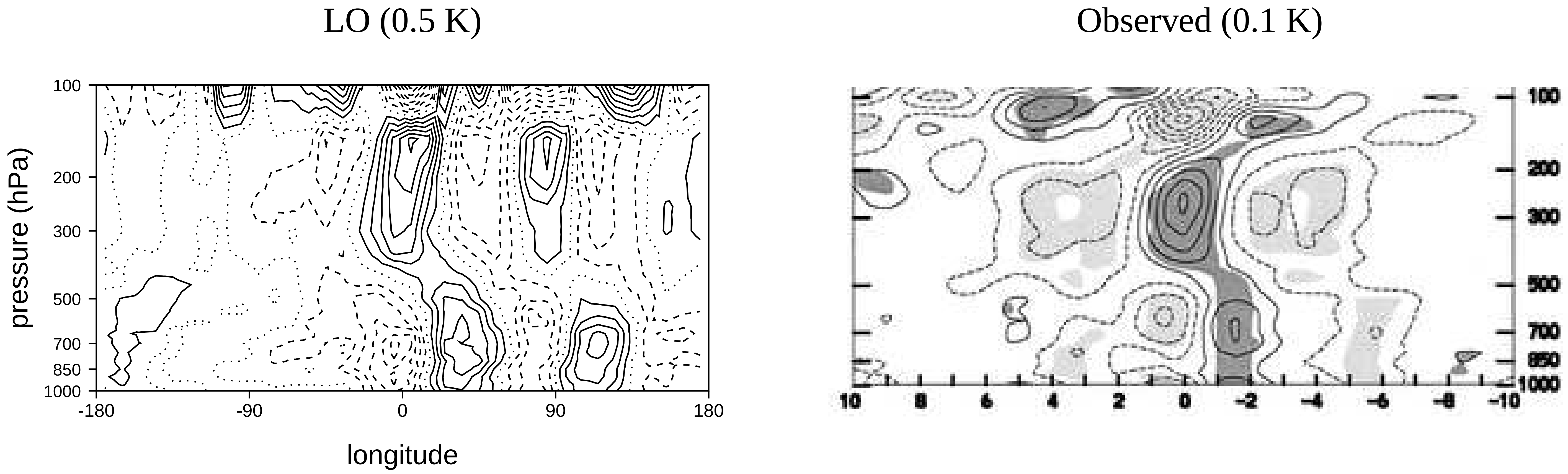
Control Run: No mixing, Evaporation of Rain

Time Longitude Series of Rainfall (mm/day, 15 S - 15 N)



Comparison of LO generated Kelvin Wave and Straub and Kiladis (2003) Composite

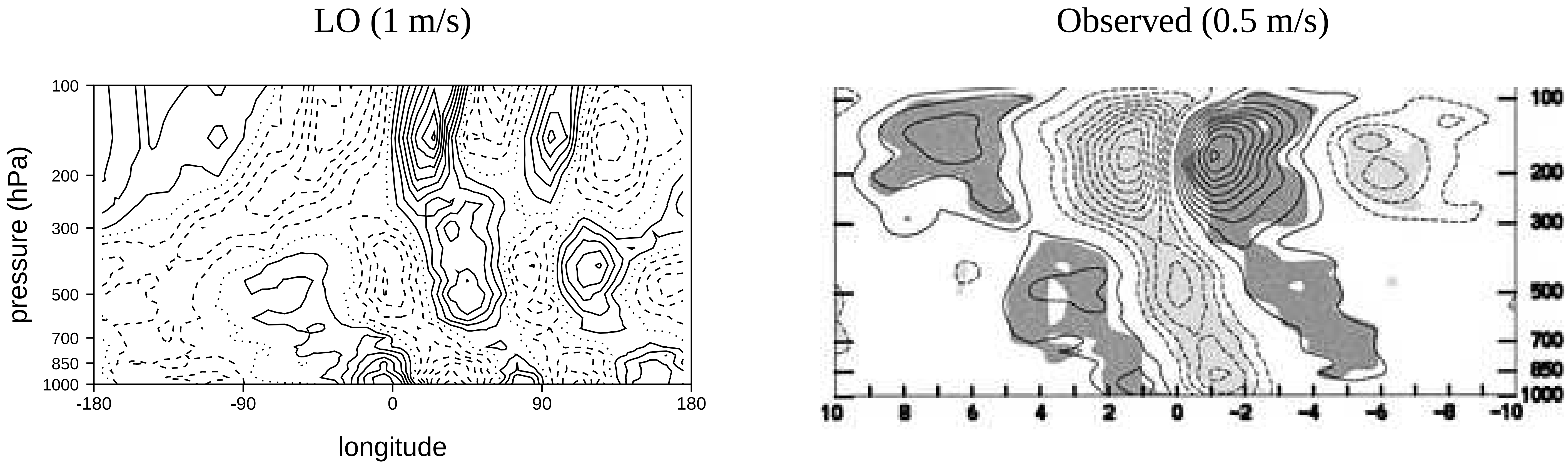
Temperature



LO (0.5 K)

Observed (0.1 K)

Zonal Wind

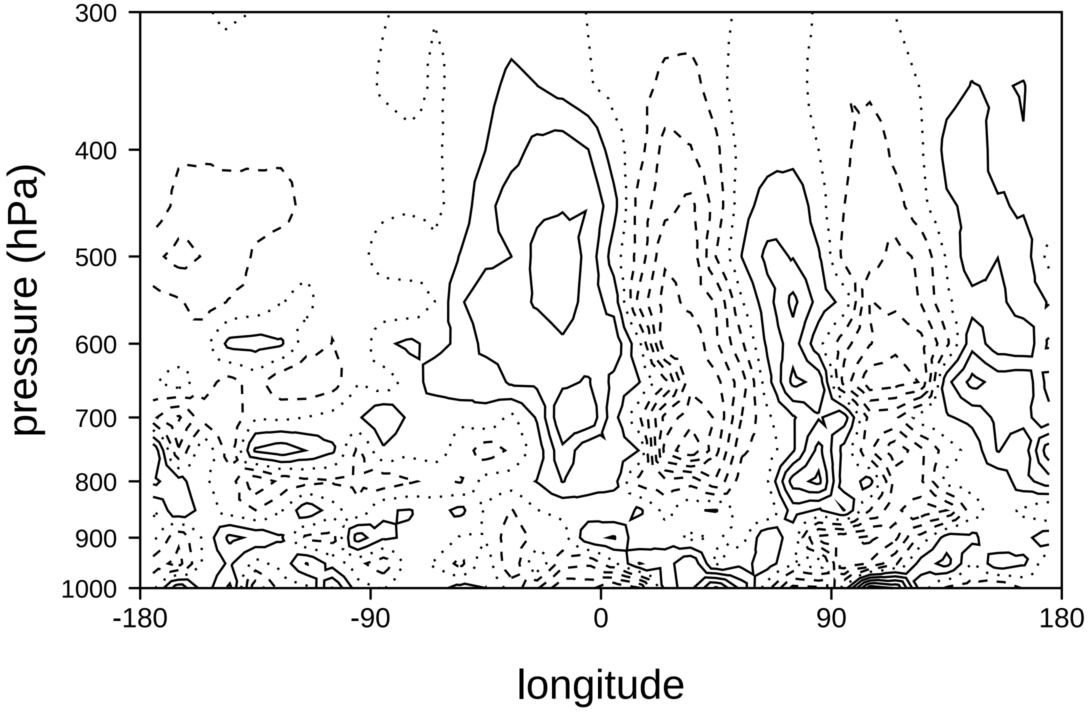


LO (1 m/s)

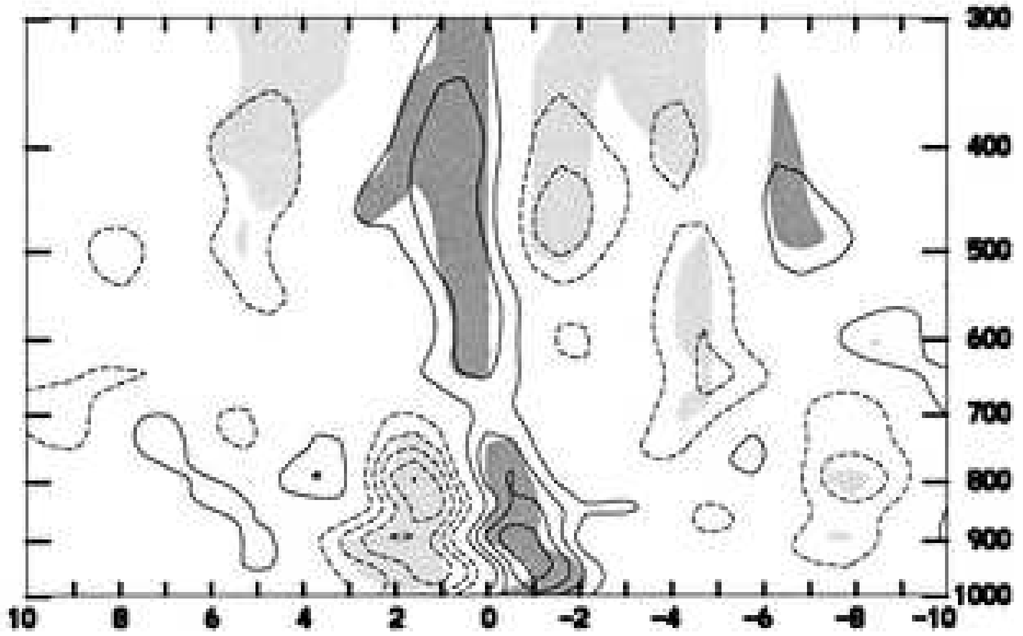
Observed (0.5 m/s)

Specific Humidity

LO (0.2 g/kg)

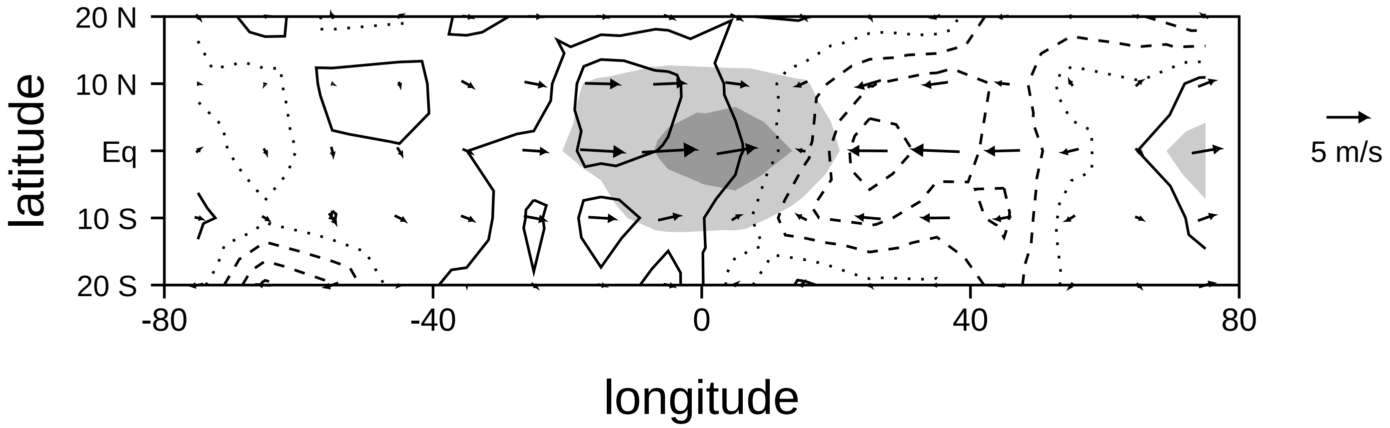


Observed (0.1 g/kg)

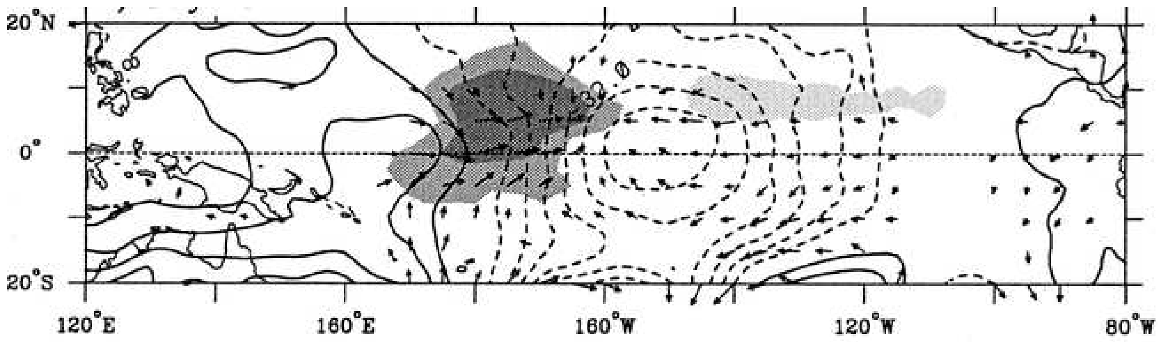


Surface pressure (height) and velocity perturbations

LO (1 hPa)

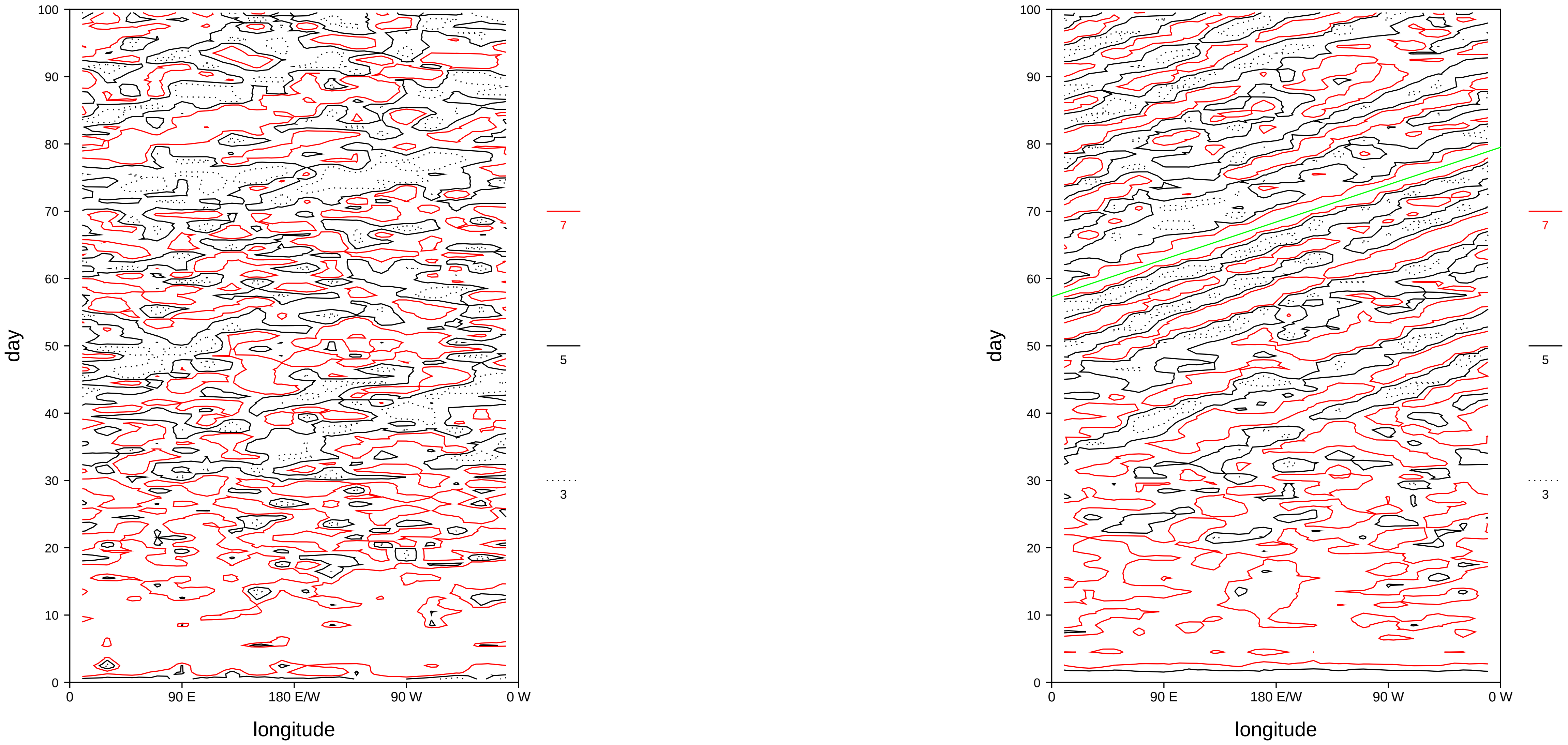


Observed (8 m)



Removing Evaporation of Rain

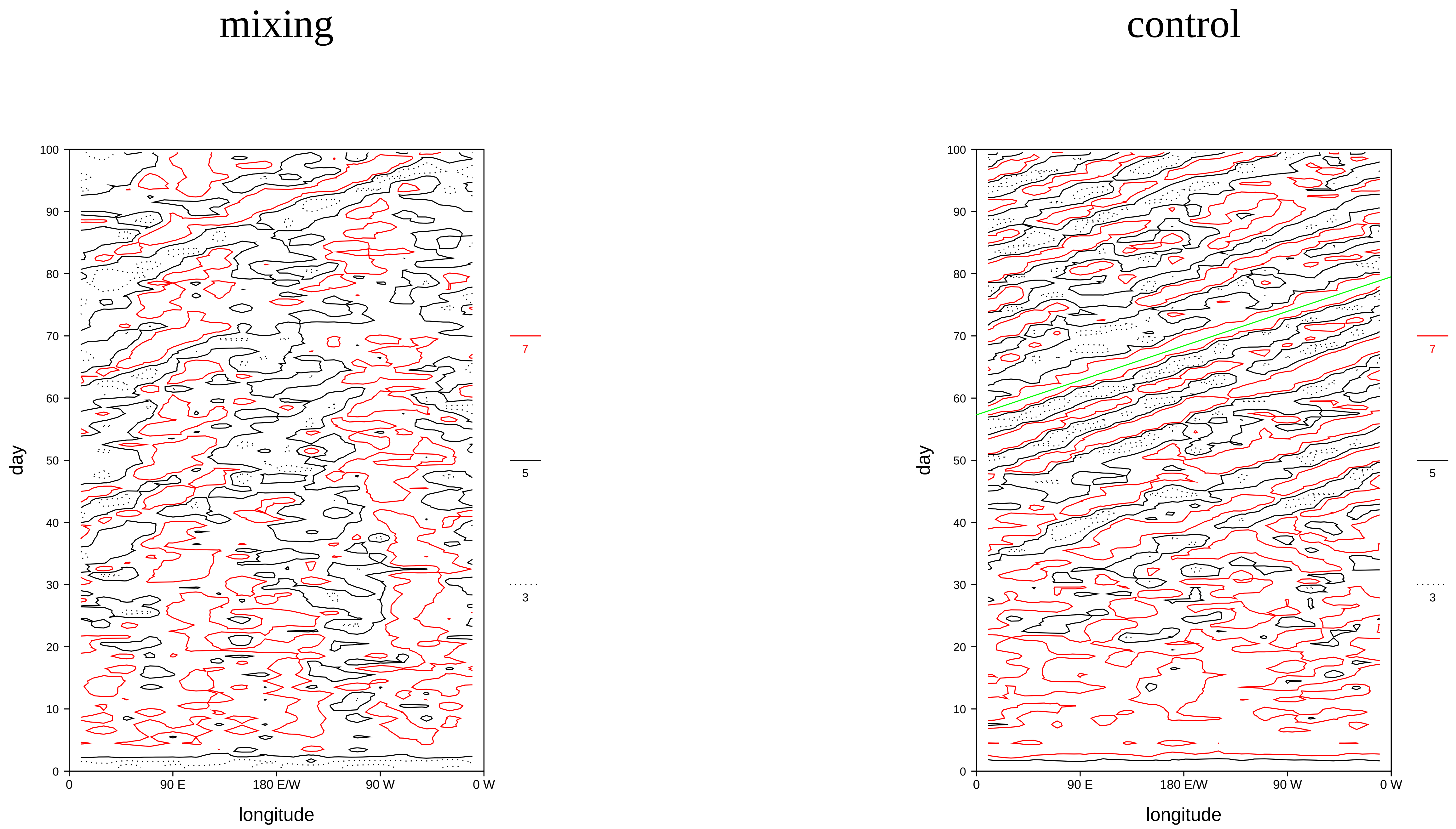
Time Longitude Series of Rainfall (mm/day, 15 S - 15 N)


no evaporation of rain

control

Including Mixing

Time Longitude Series of Rainfall (mm/day, 15 S - 15 N)

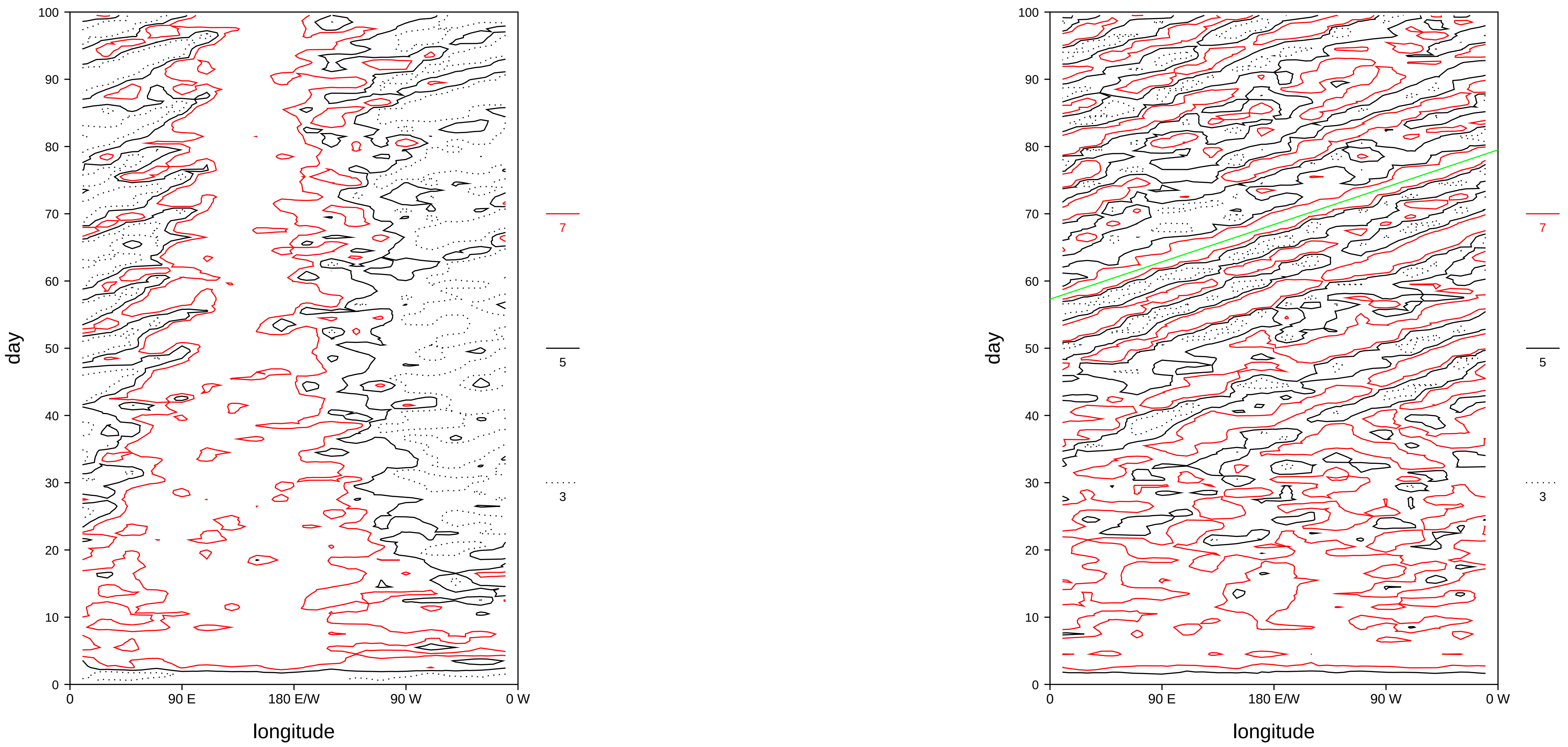


mixing

control

Including a Warm Pool

Time Longitude Series of Rainfall (mm/day, 15 S - 15 N)



warm pool

control

Preliminary Conclusions

1. Using LO with evaporation of rain generates robust convectively coupled Kelvin waves

2. These waves apparently result for a wave-convection interaction (not WISHE)

3. Including convective mixing (entrainment) reduces the frequency and longevity of Kelvin waves

Future Work

1. Mechanism of LO generated Kelvin waves
2. Other convectively coupled waves?
3. Can LO be used to produce an MJO?
4. Other applications?