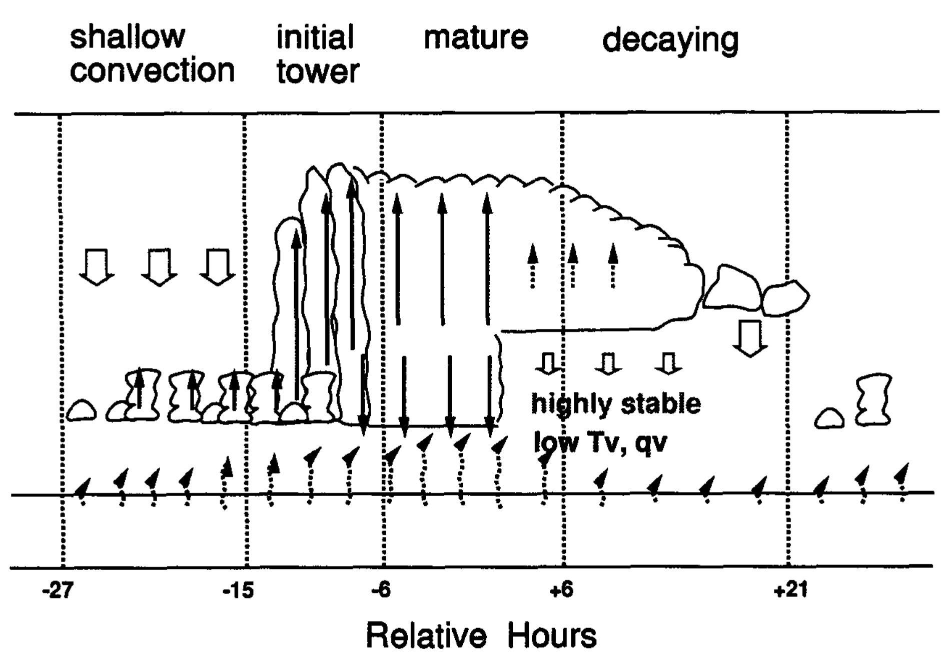
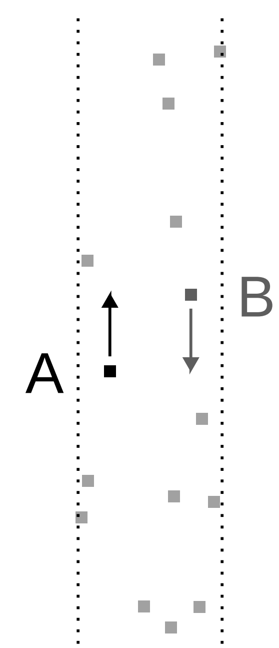
Do we need to resolve convective plumes to accurately simulate climate?

Patrick Haertel
Yale University





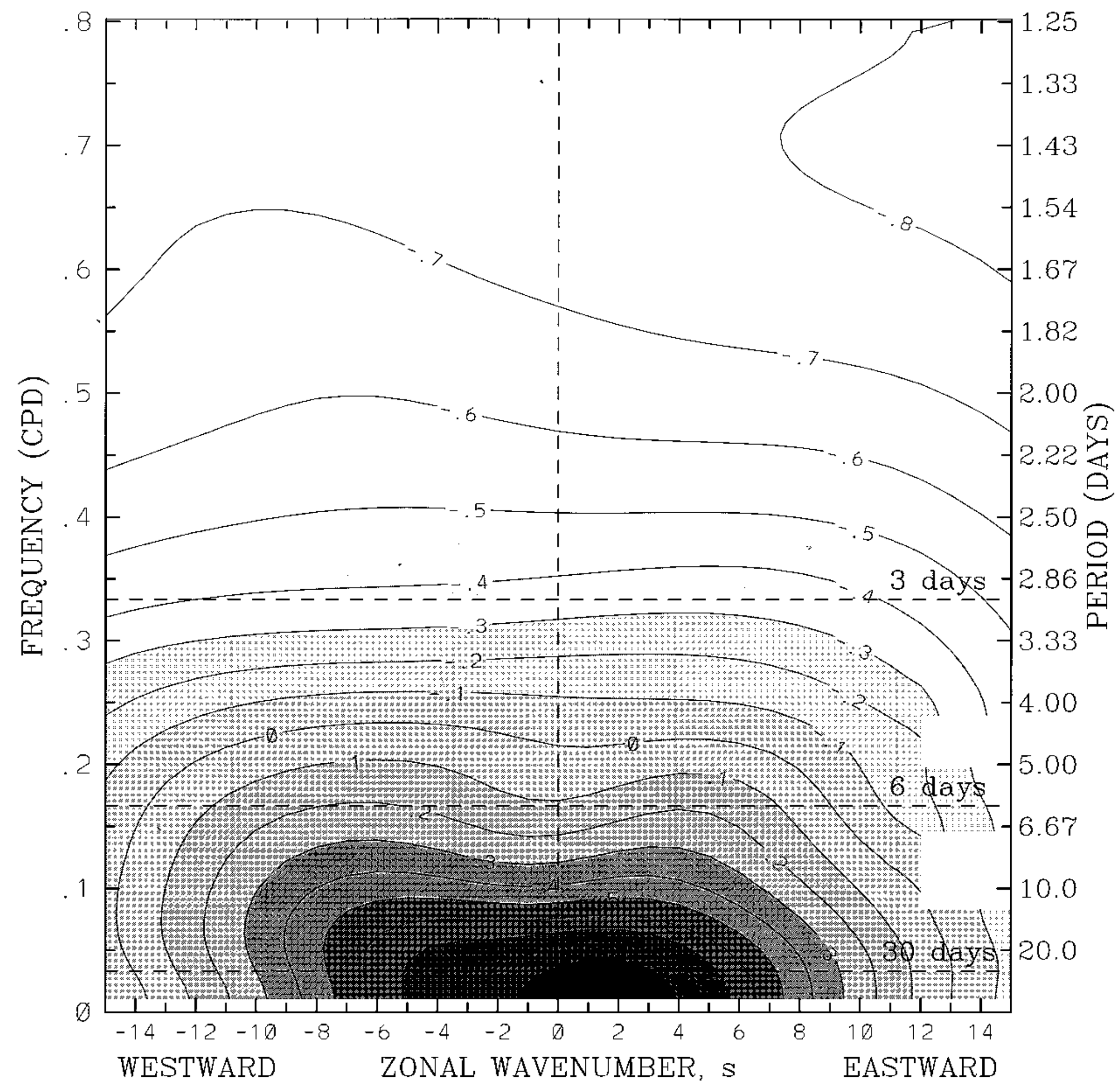
Outline

1. Background and Motivation
2. Lagrangian Numerical Method
3. Simulating Tropical Convection

Background and Motivation

Tropical Convection "Background" Spectra (15 S - 15 N)

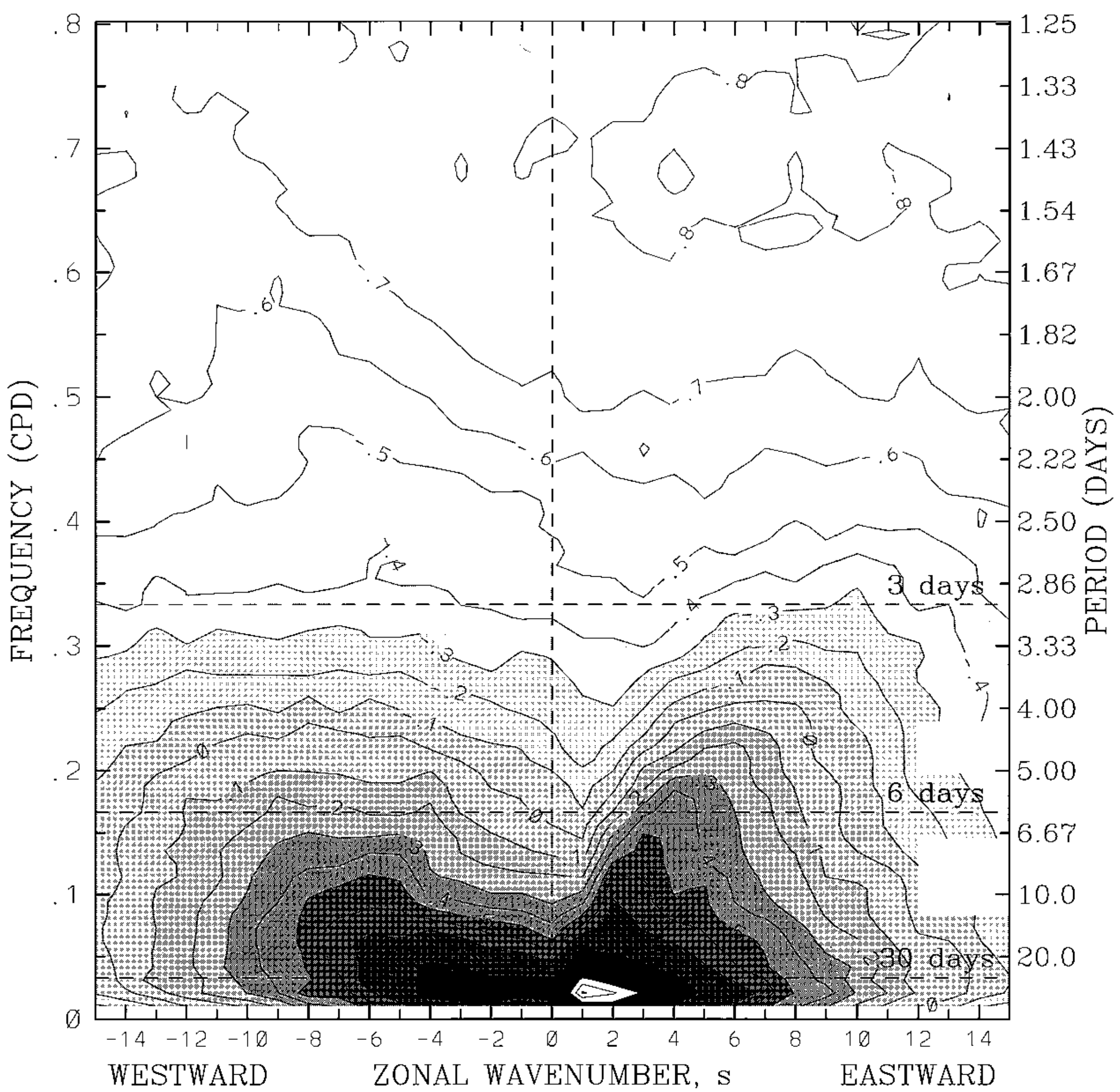
Wheeler and Kiladis (1999)



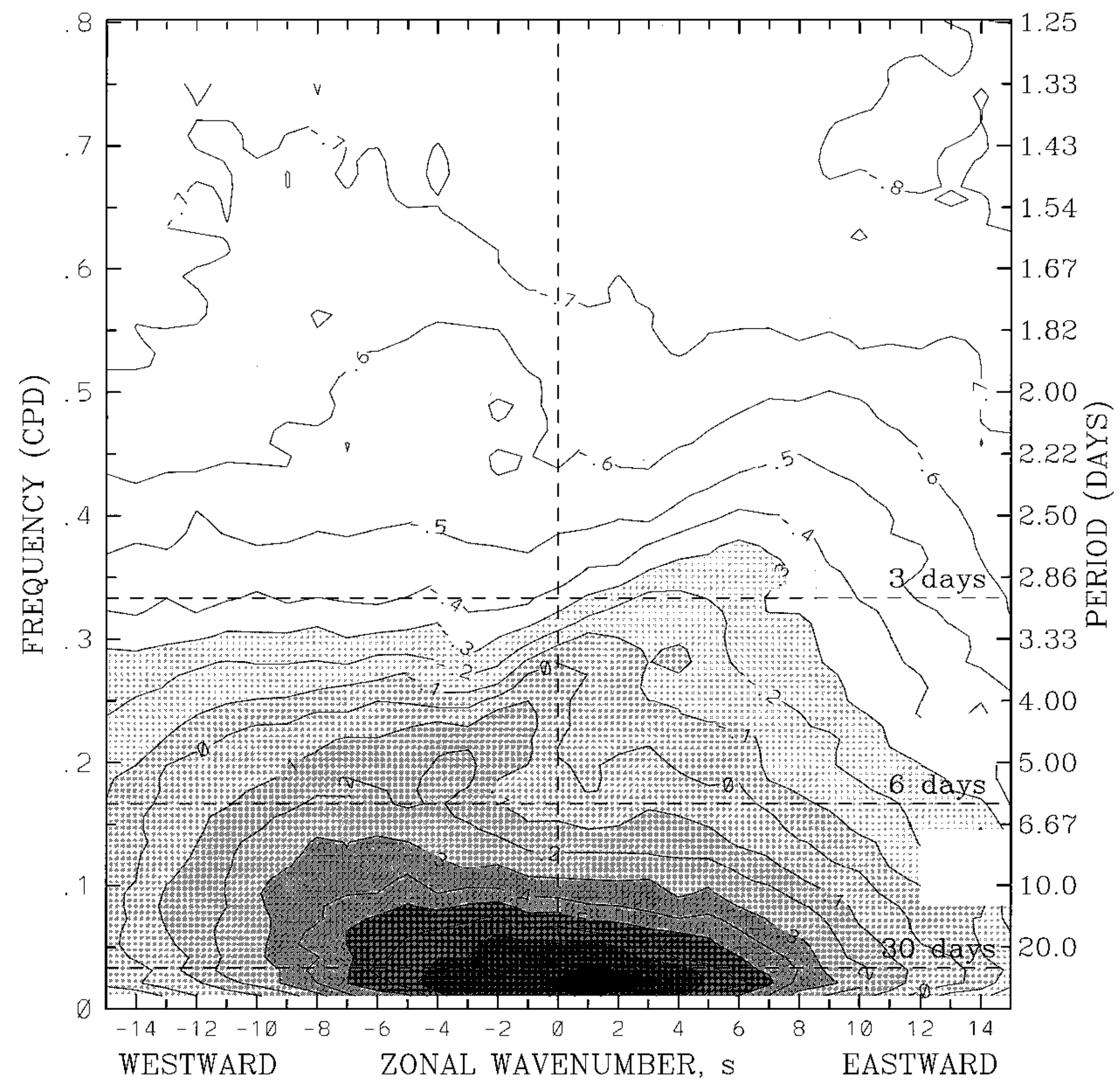
Raw Symmetric and Antisymmetric Tropical OLR Spectra

Wheeler and Kiladis (1999)

symmetric



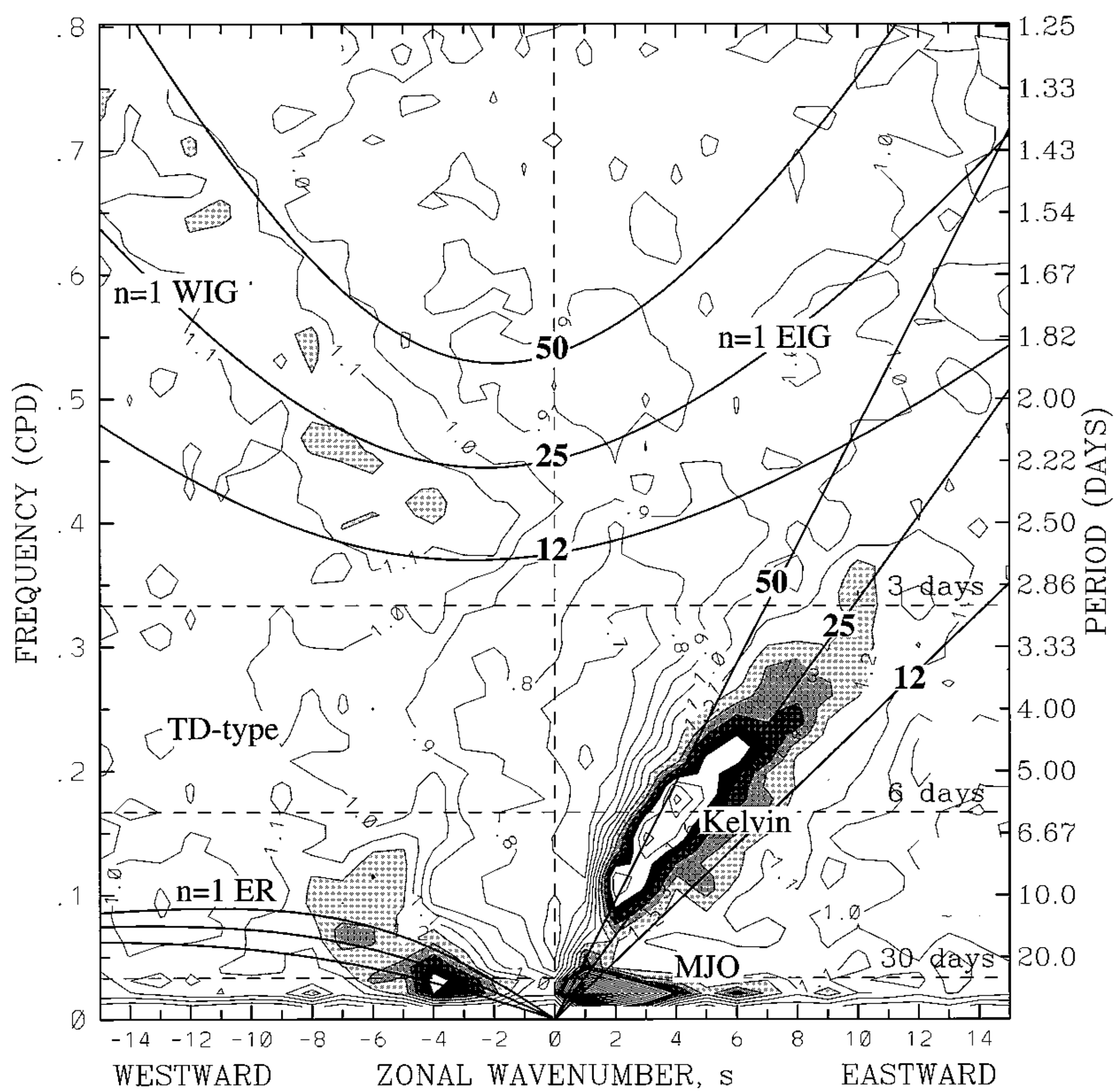
antisymmetric



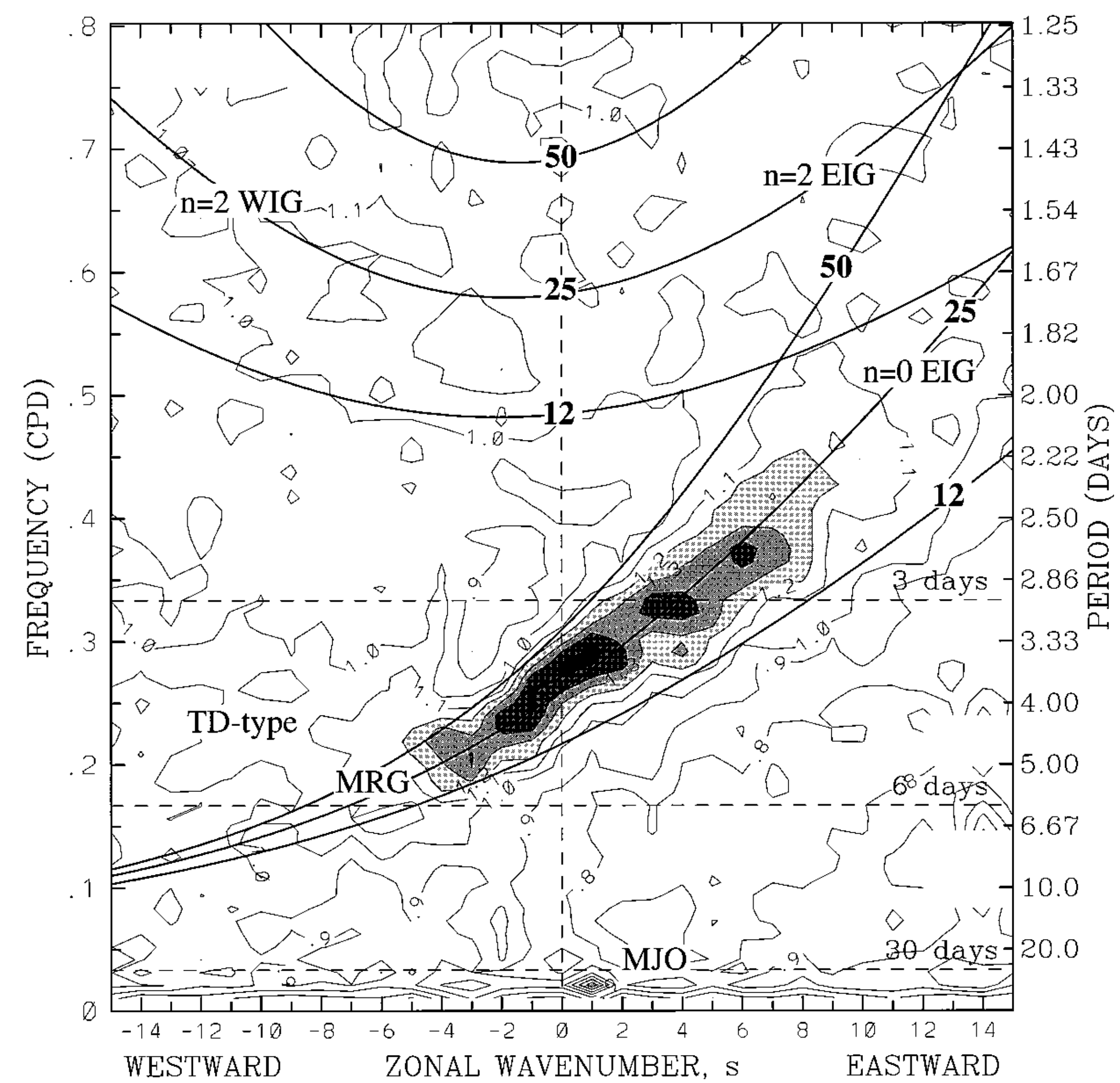
Filtered Symmetric and Antisymmetric Tropical OLR Spectra

Wheeler and Kiladis (1999)

symmetric

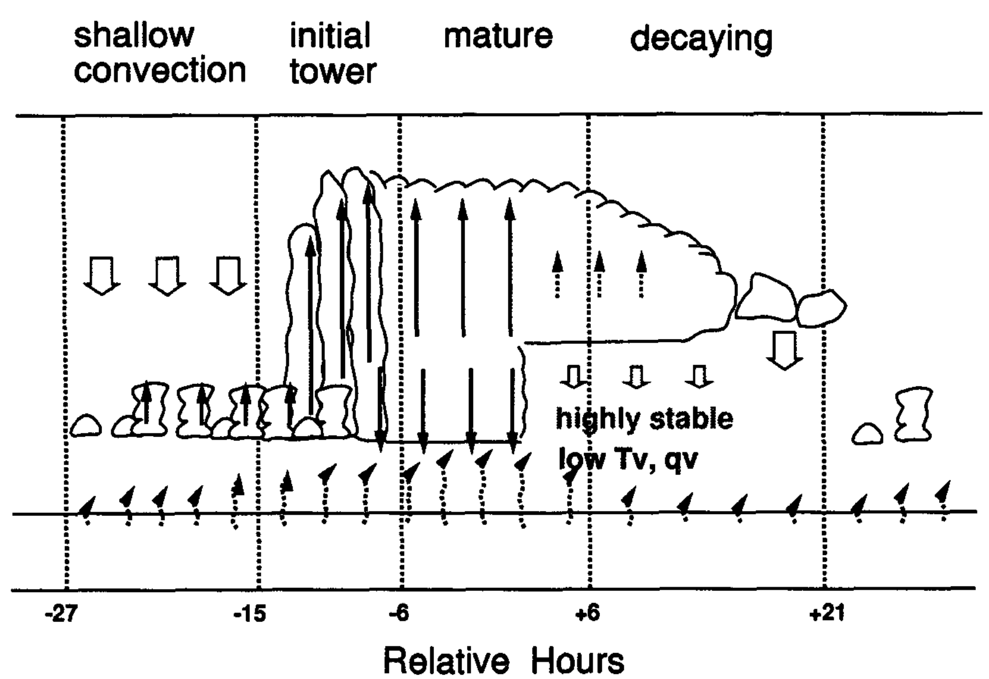


antisymmetric

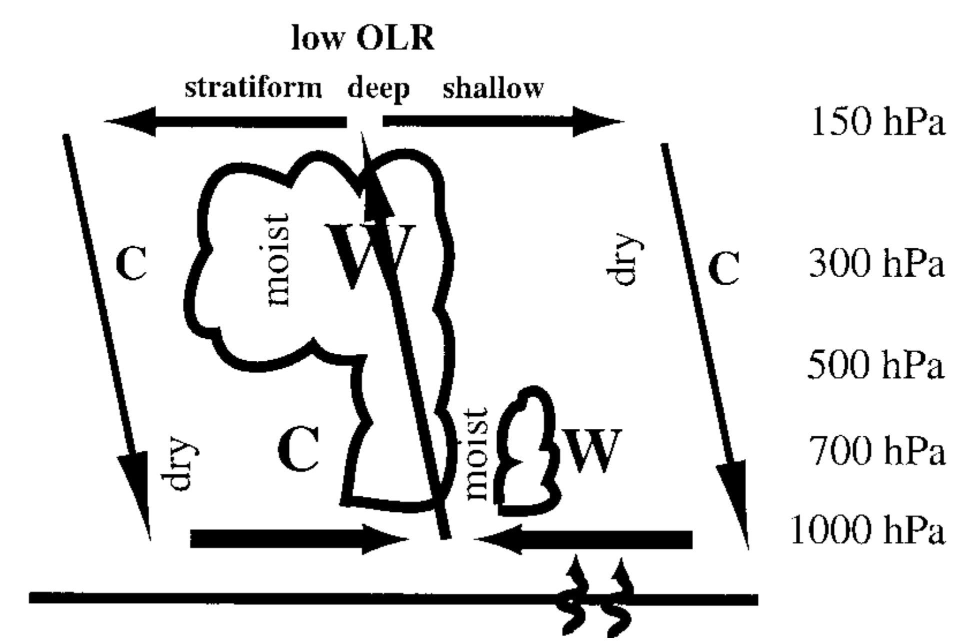


Convective Morphology

2-Day Wave (Takayabu et al 1996)

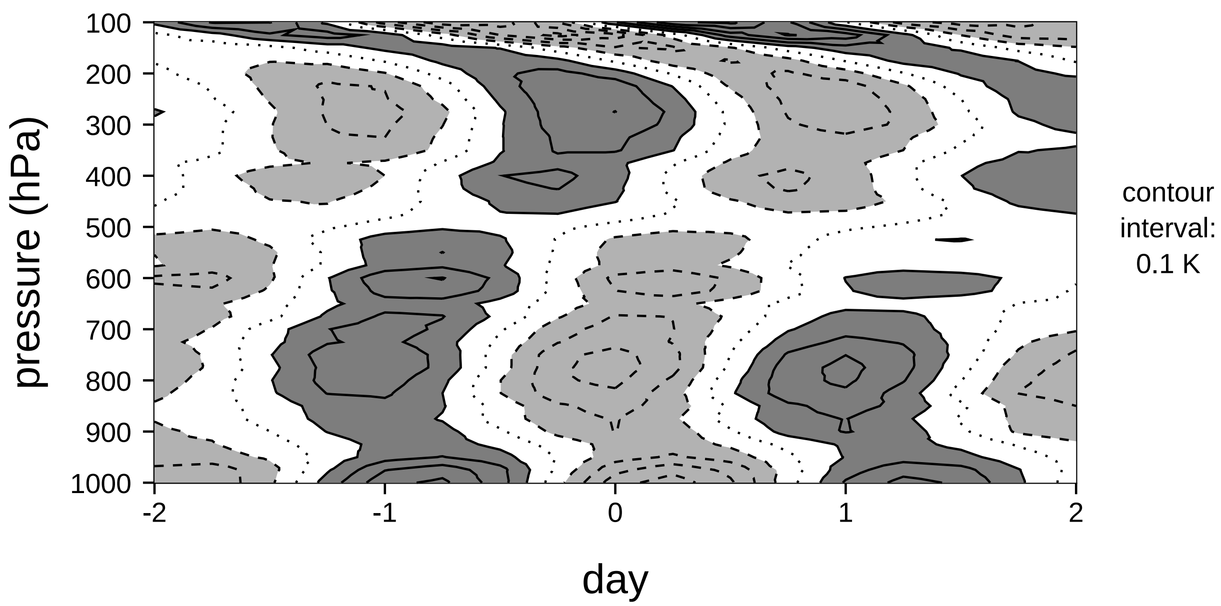


Kelvin Wave (Straub and Kiladis 2003)

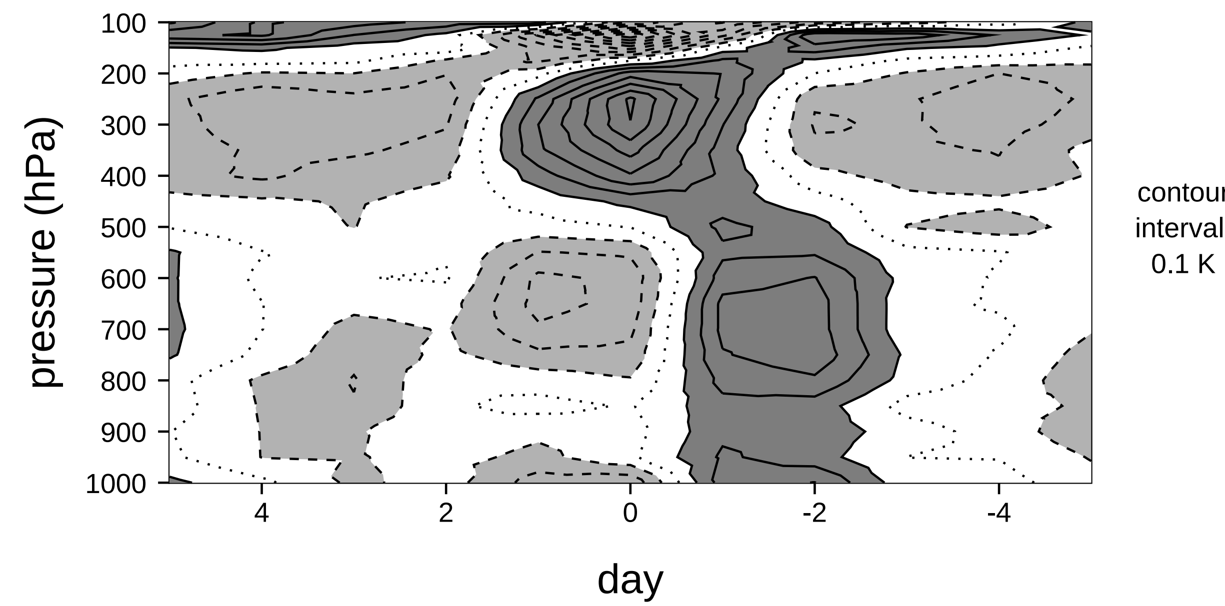


Temperature Perturbations

2-Day Wave (Haertel and Kiladis 2004)

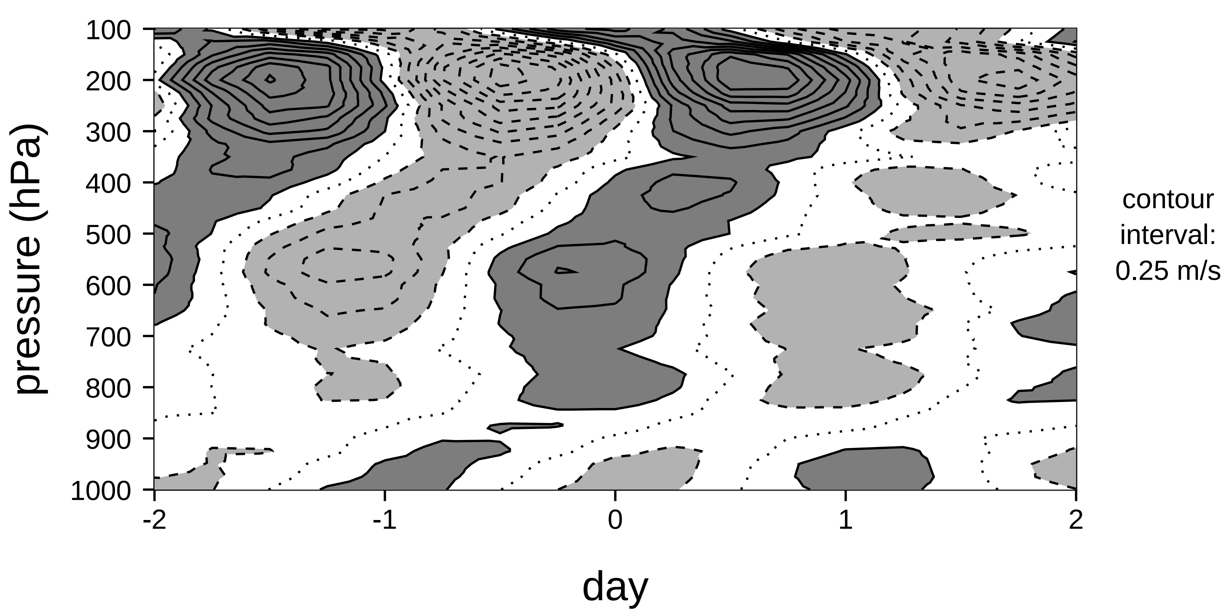


Kelvin Wave (Straub and Kiladis 2003)

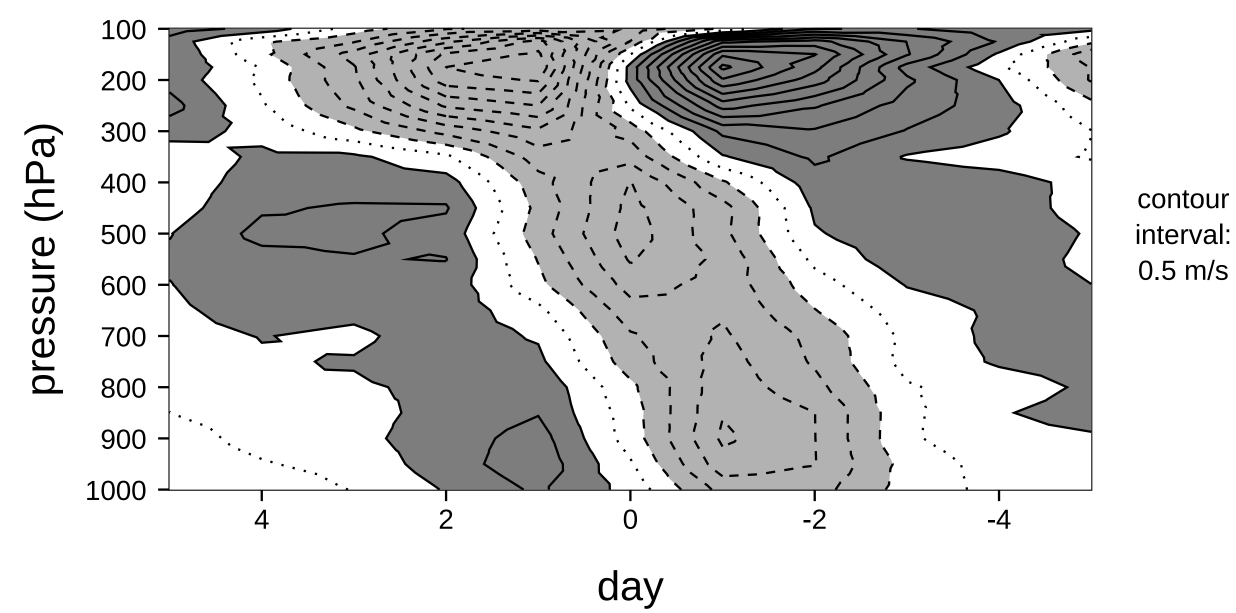


Zonal Wind Perturbations

2-Day Wave (Haertel and Kiladis 2004)



Kelvin Wave (Straub and Kiladis 2003)



Equatorial Waves in Nature

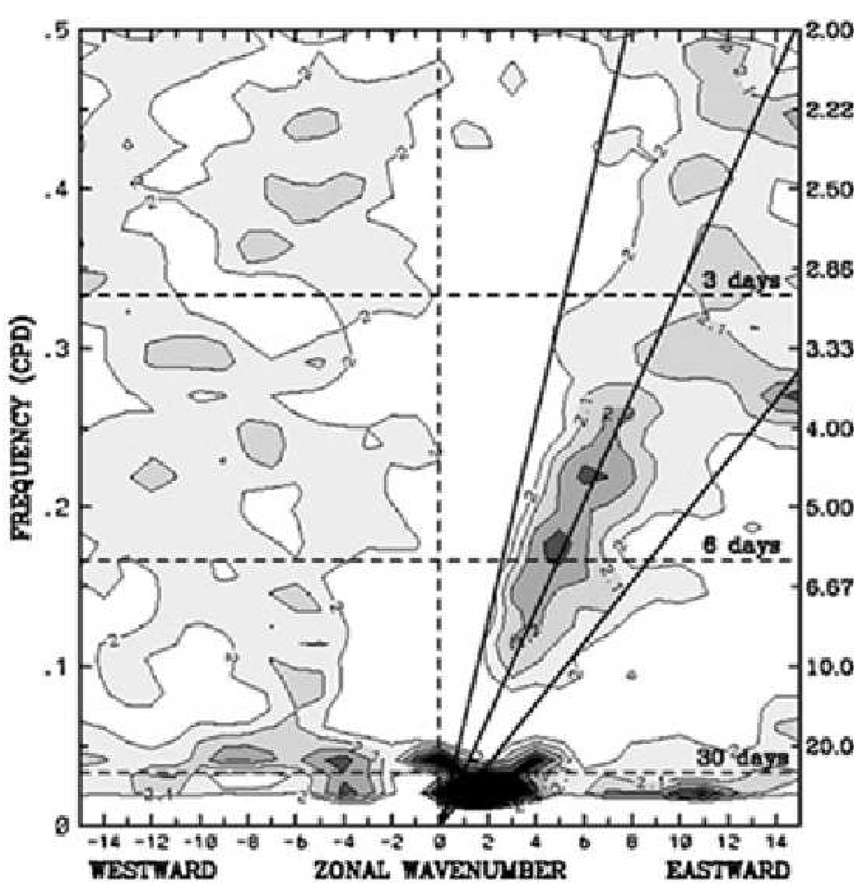
- Shallow to deep convection followed by enhanced stratiform precipitation
- Nearly out of phase lower and upper tropospheric temperature perturbations, transition to a cool lower troposphere during convection, weak temperature variations near 500 hPa
- Tilted wind perturbations with maxima near the surface, at mid-levels, and near the tropopause

Kelvin Waves in Climate Models

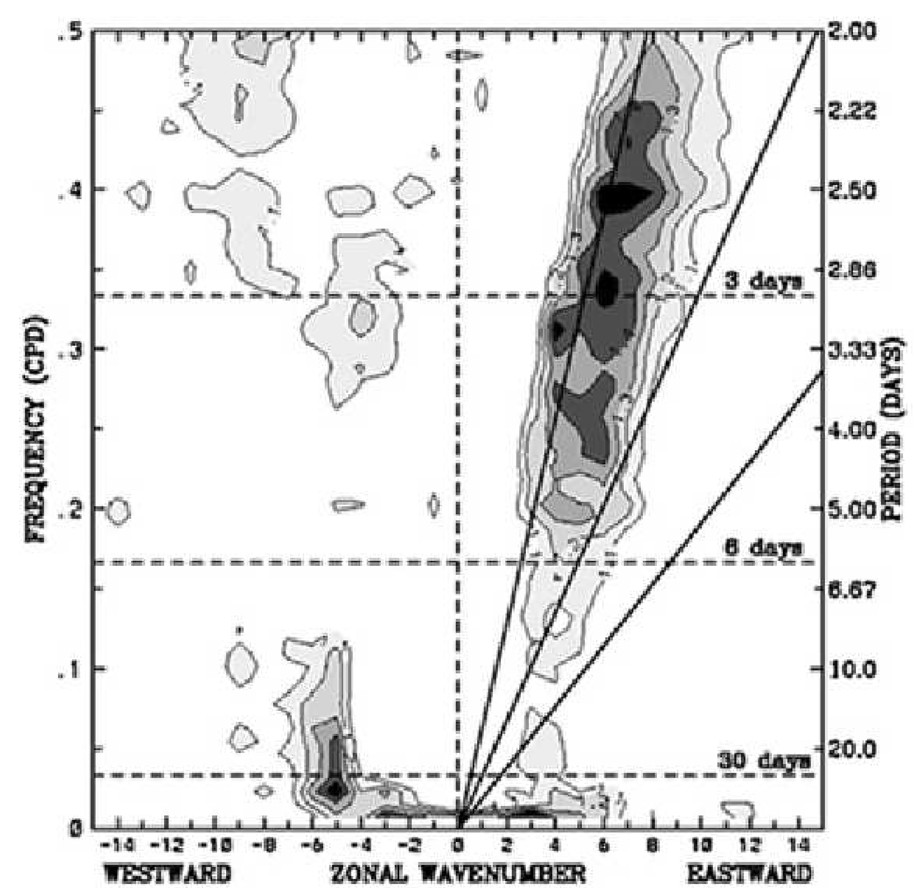
Spectral Signal

Straub et al. (2010)

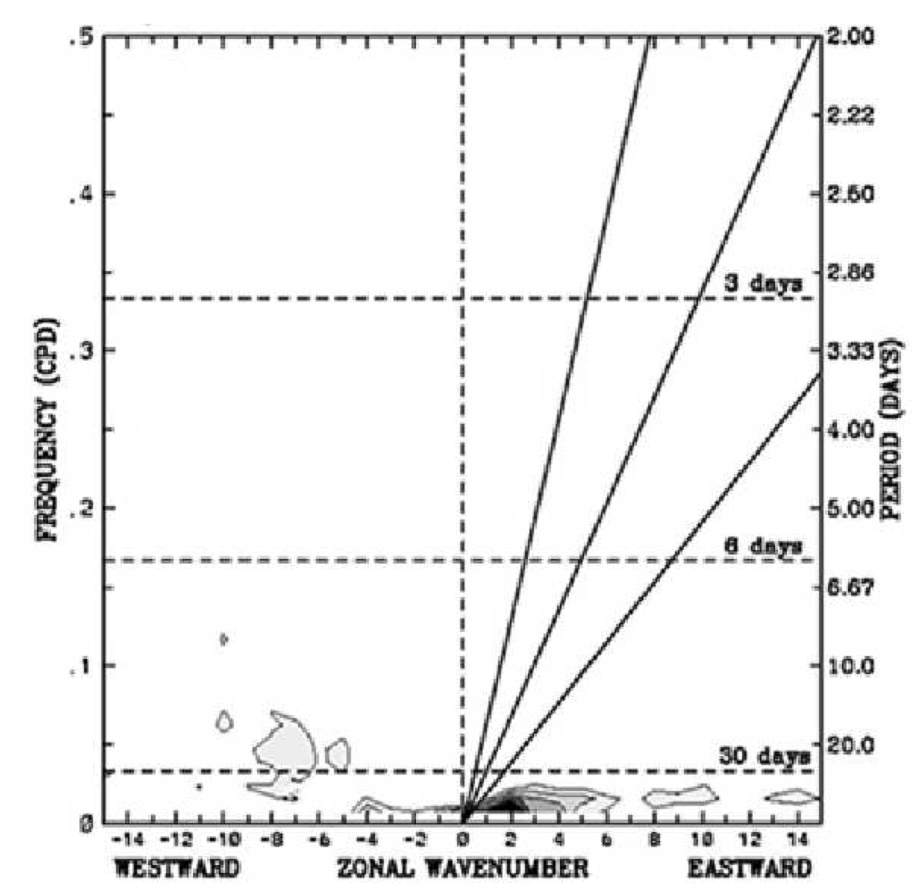
TRMM



Climate Model 1



Climate Model 2

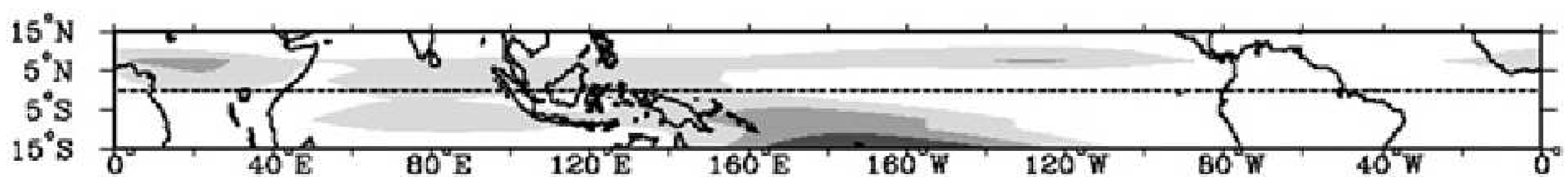


Spatial Distribution

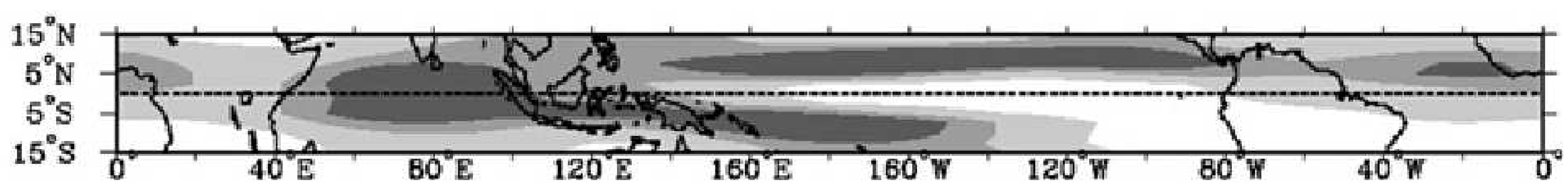
Straub et al. (2010)

TRMM

Climate Model 1



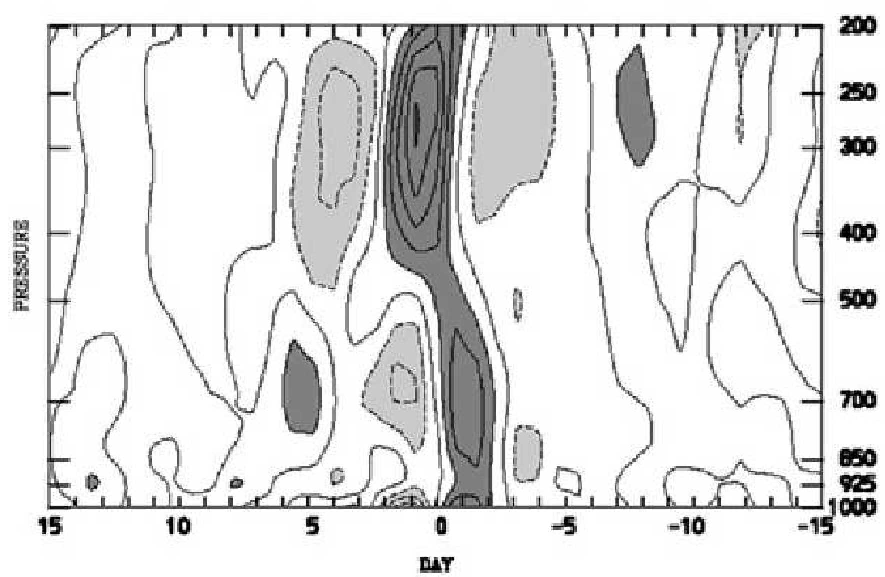
Climate Model 3



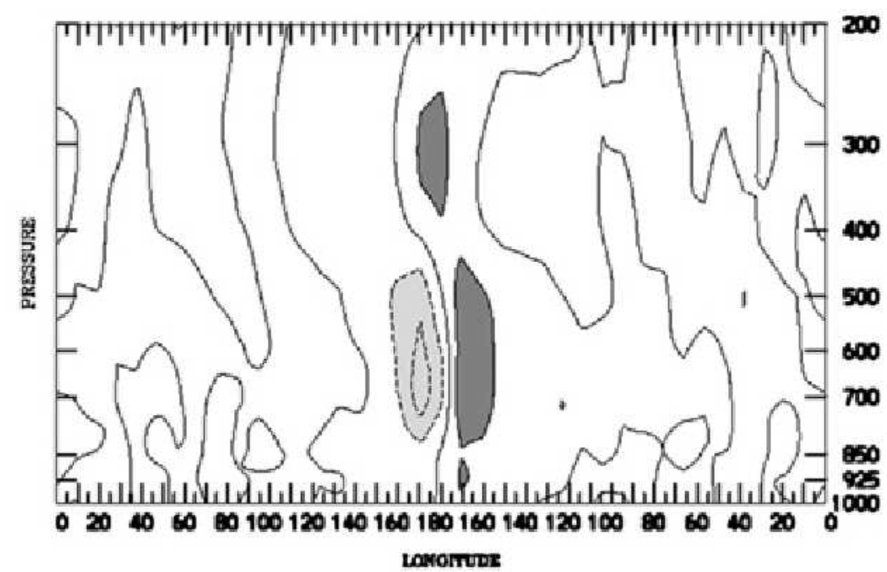
Vertical Structure of Temperature

Straub et al. (2010)

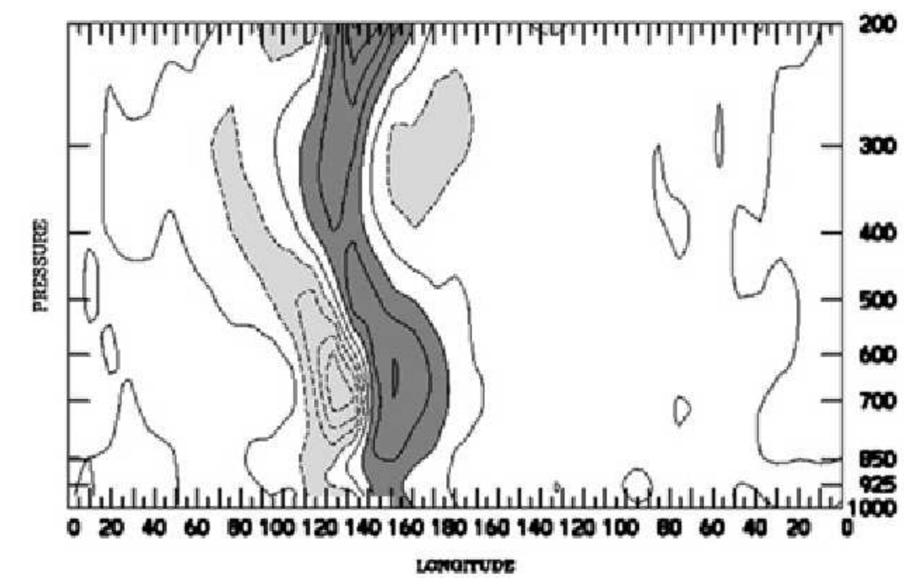
Observed



Climate Model 4



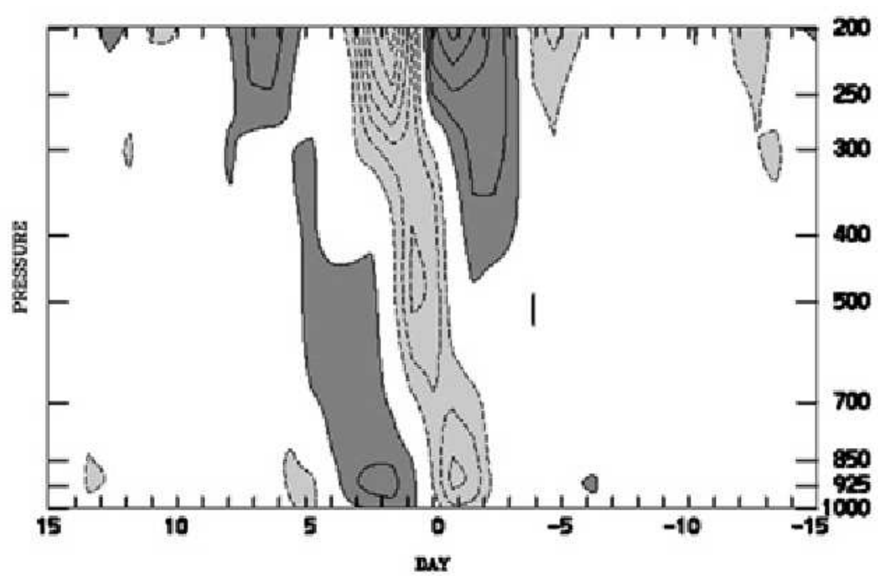
Climate Model 5



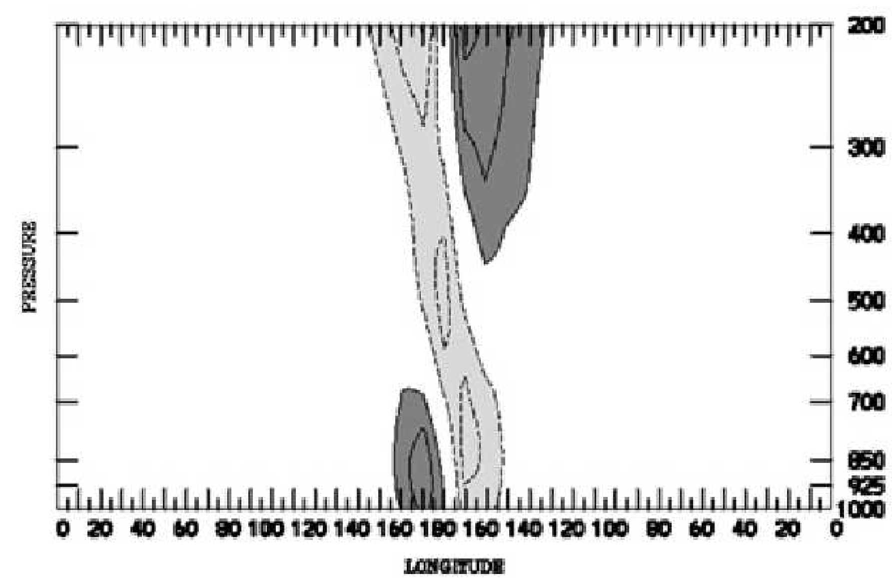
Vertical Structure of Zonal Wind

Straub et al. (2010)

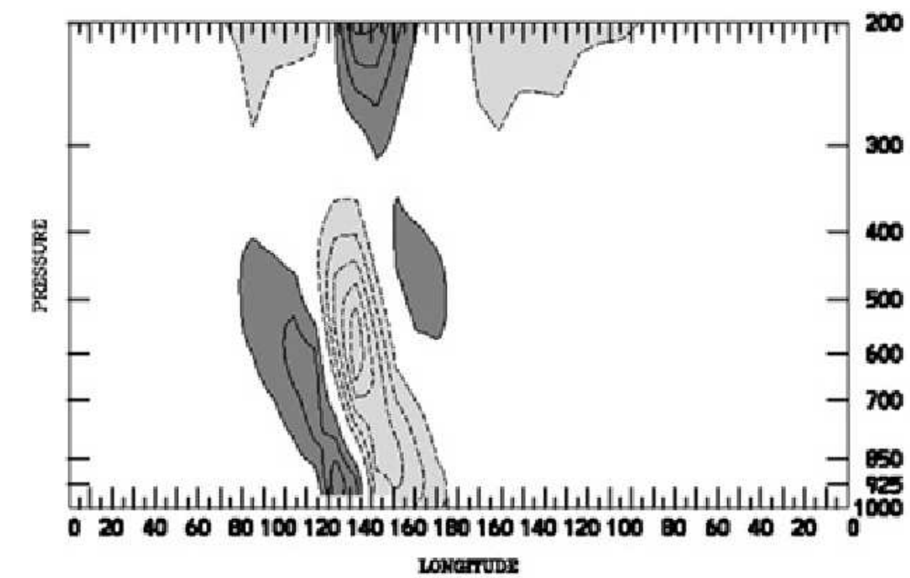
Observed



Climate Model 4



Climate Model 5



Kelvin Waves in Climate Models

Straub et al. (2010)

- Half of the models have a spectral signal in the Kelvin-wave band
- About one-quarter of the models have a reasonable spatial distribution of Kelvin-wave-filtered variance
- A few models have vertical structures that qualitatively resemble observations

Similarities for MJO and other Equatorial Waves

- Shallow to deep convection, followed by enhanced stratiform precipitation (e.g. Haertel et al. 2008)

- Tilted wind/moisture/heating perturbations (e.g. Kiladis et al. 2005)

- Poorly represented in most conventional climate models (e.g., Lin et al. 2006; Kim et al. 2009)

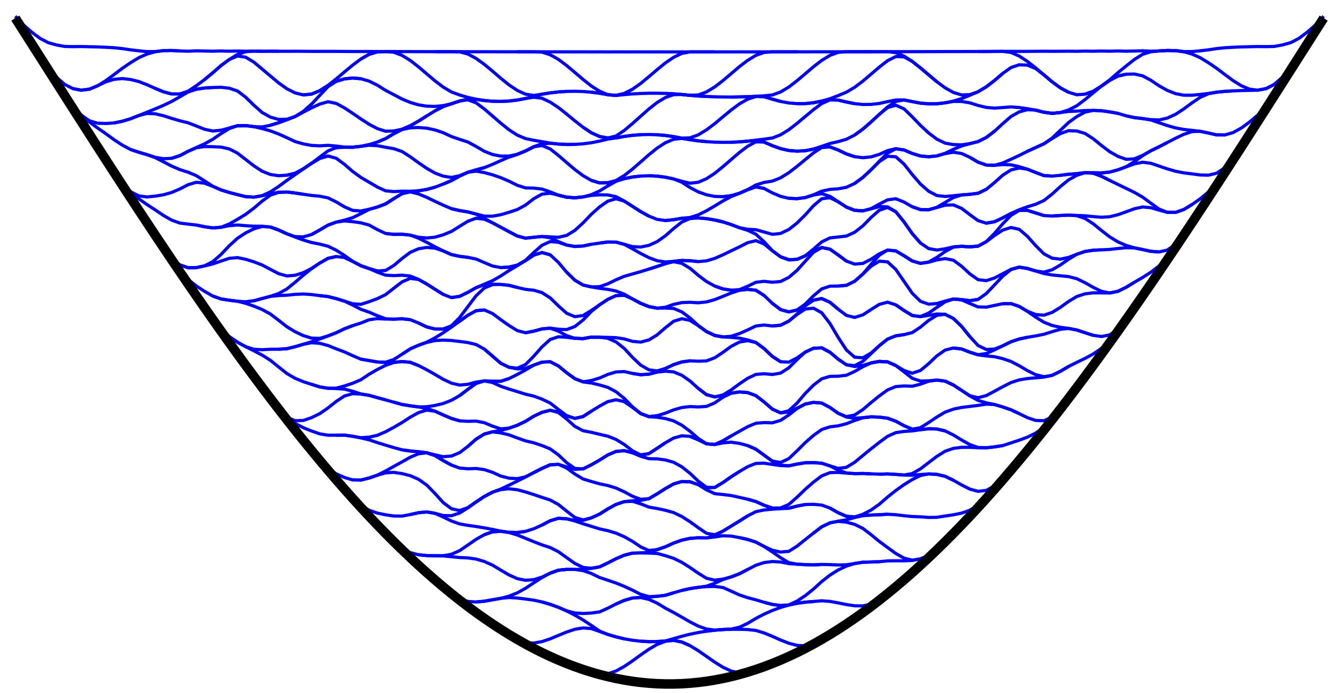
Motivation

Because conventional climate models continue to struggle to adequately represent the multi-scale organization of tropical convection, observed variations in convective morphology, and tilted vertical structures of synoptic to planetary scale waves, there is reason to explore alternative numerical methods and convective parameterizations.

Lagrangian Numerical Method

Conforming Parcel Concept

Haertel and Randall (2002)

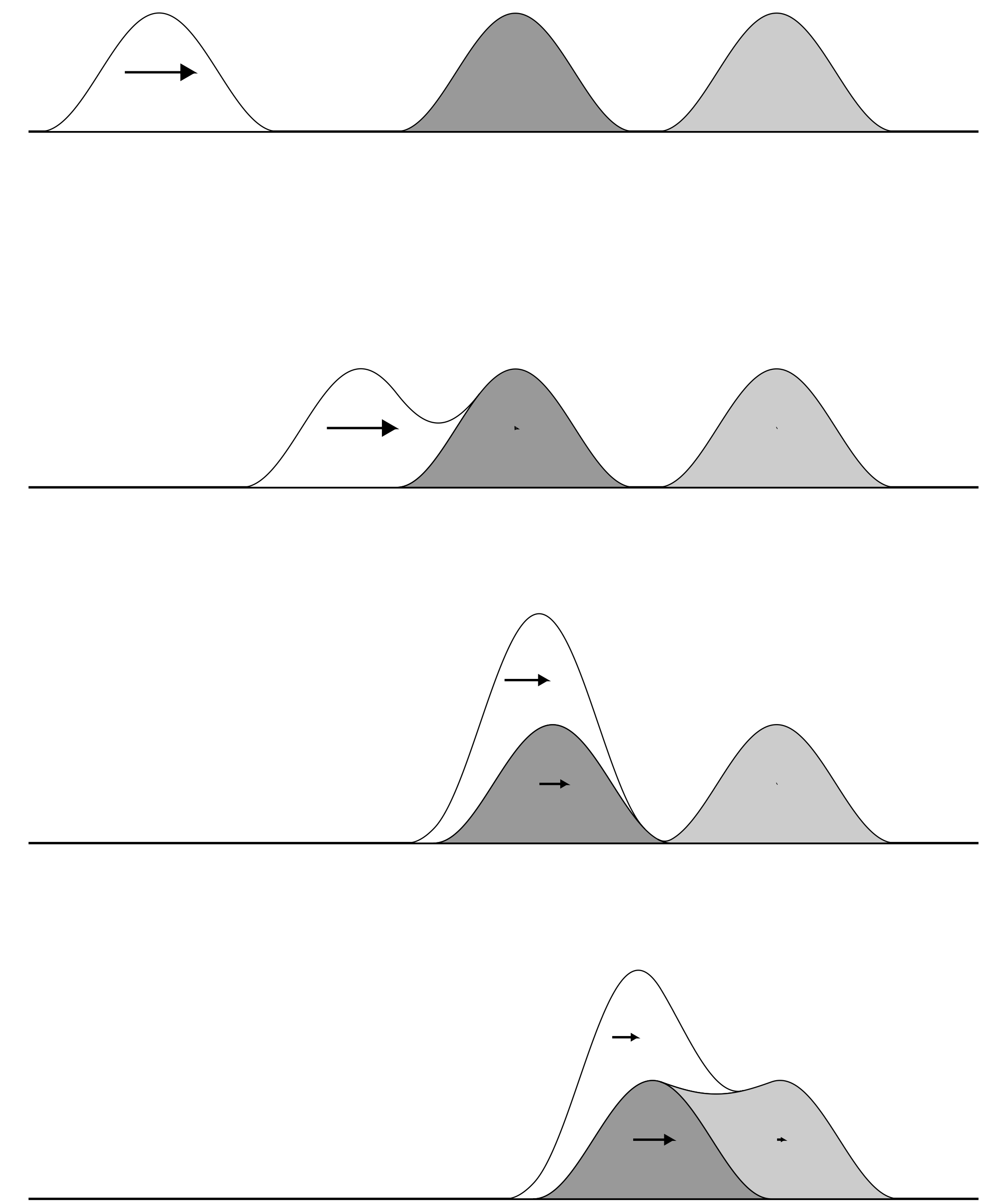


Advantages of the Lagrangian Method

1. Control over mixing
2. Trajectories for every parcel
3. Representing moist convection

Properties of Parcels

1. one vertical thickness function for all parcels
2. surfaces conform
3. uniform density (or potential temperature)
4. hydrostatic pressure
5. dense parcels slide underneath less dense parcels



Equations of Motion

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

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

Pressure Force

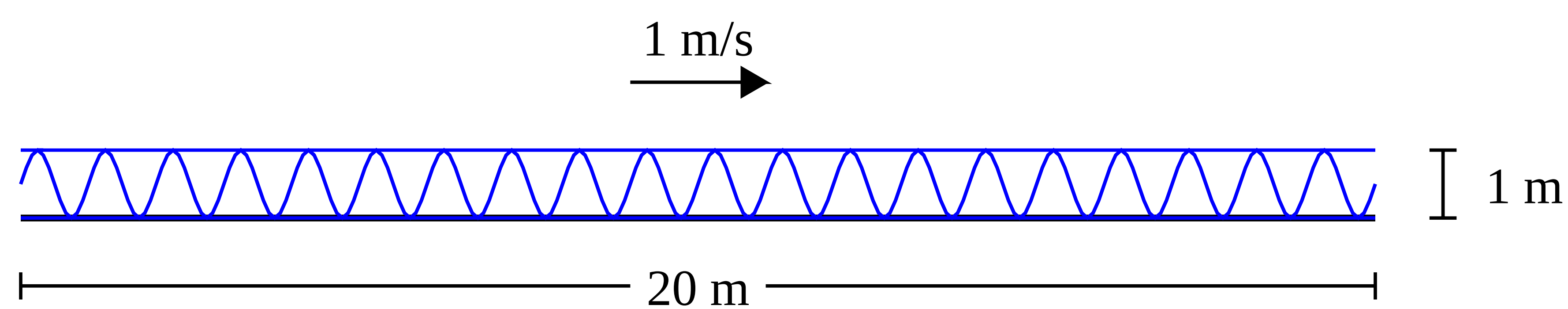
$$\mathbf{F}_{p_i} = \int_{S_i} p \, \mathbf{n} \, dA$$

Computational Efficiency

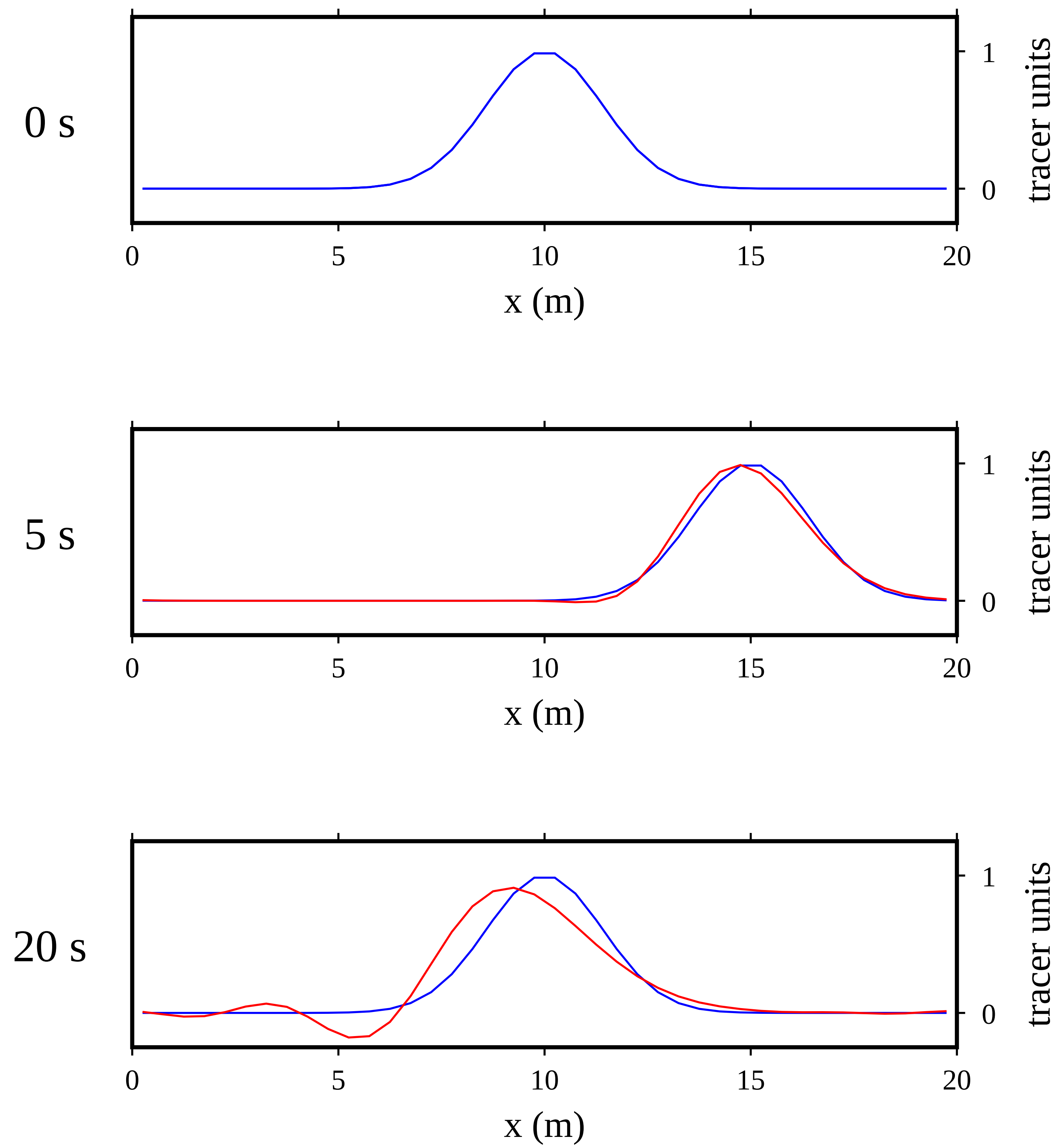
- O(n) where n is number of parcels
- Competitive with Eulerian models when optimized (Haertel et al 2004)

Idealized Tests

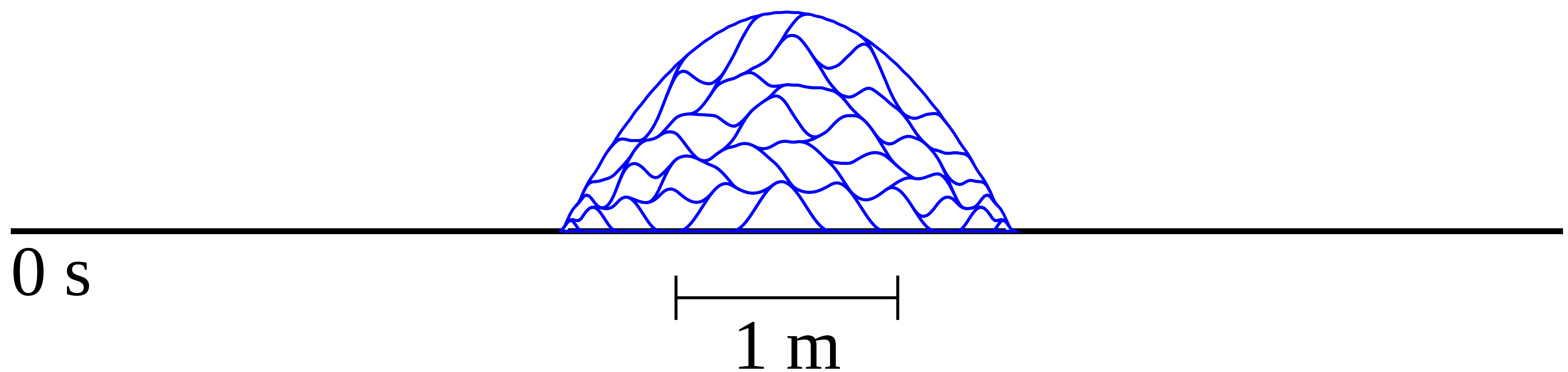
Advection

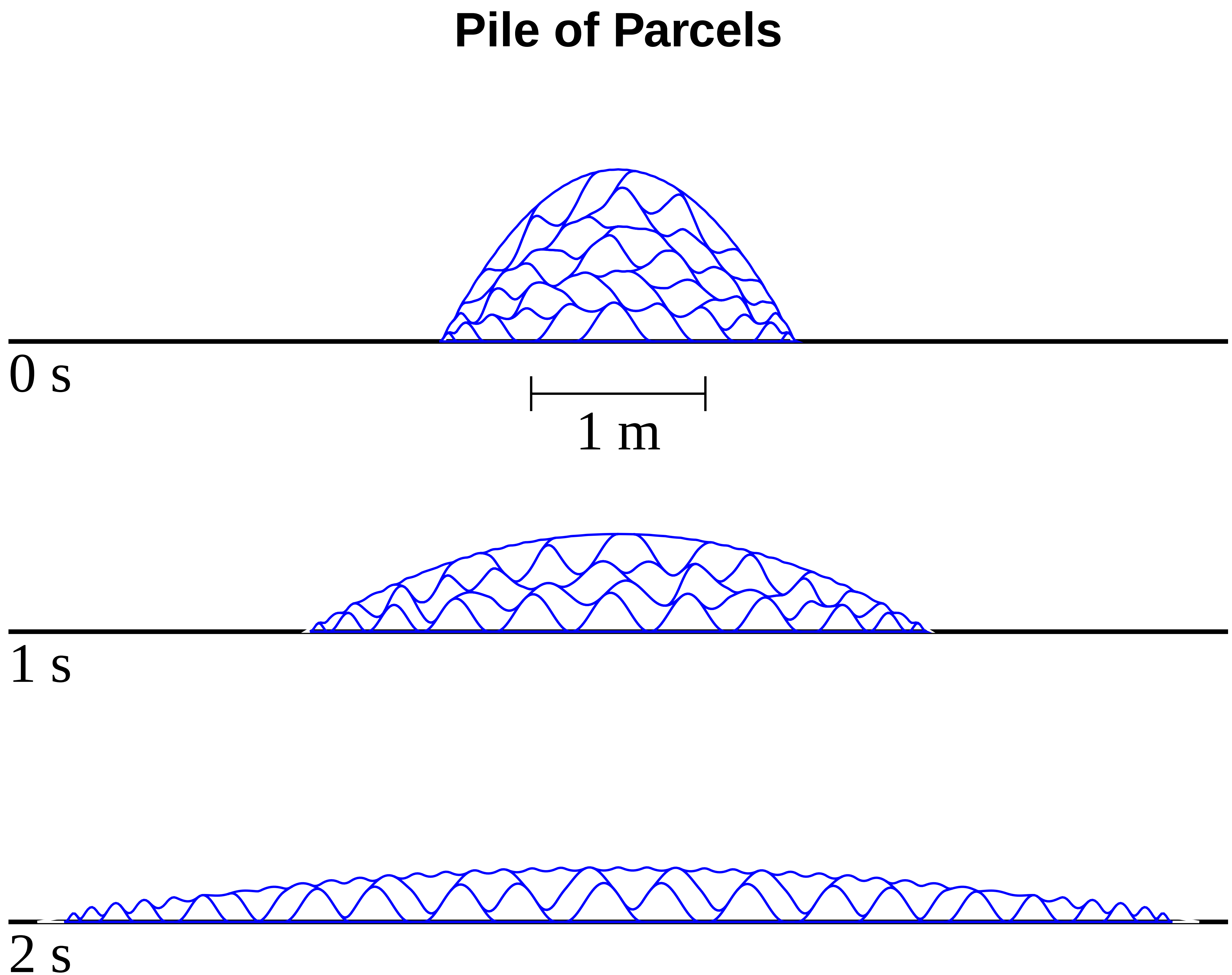


Tracer Distribution

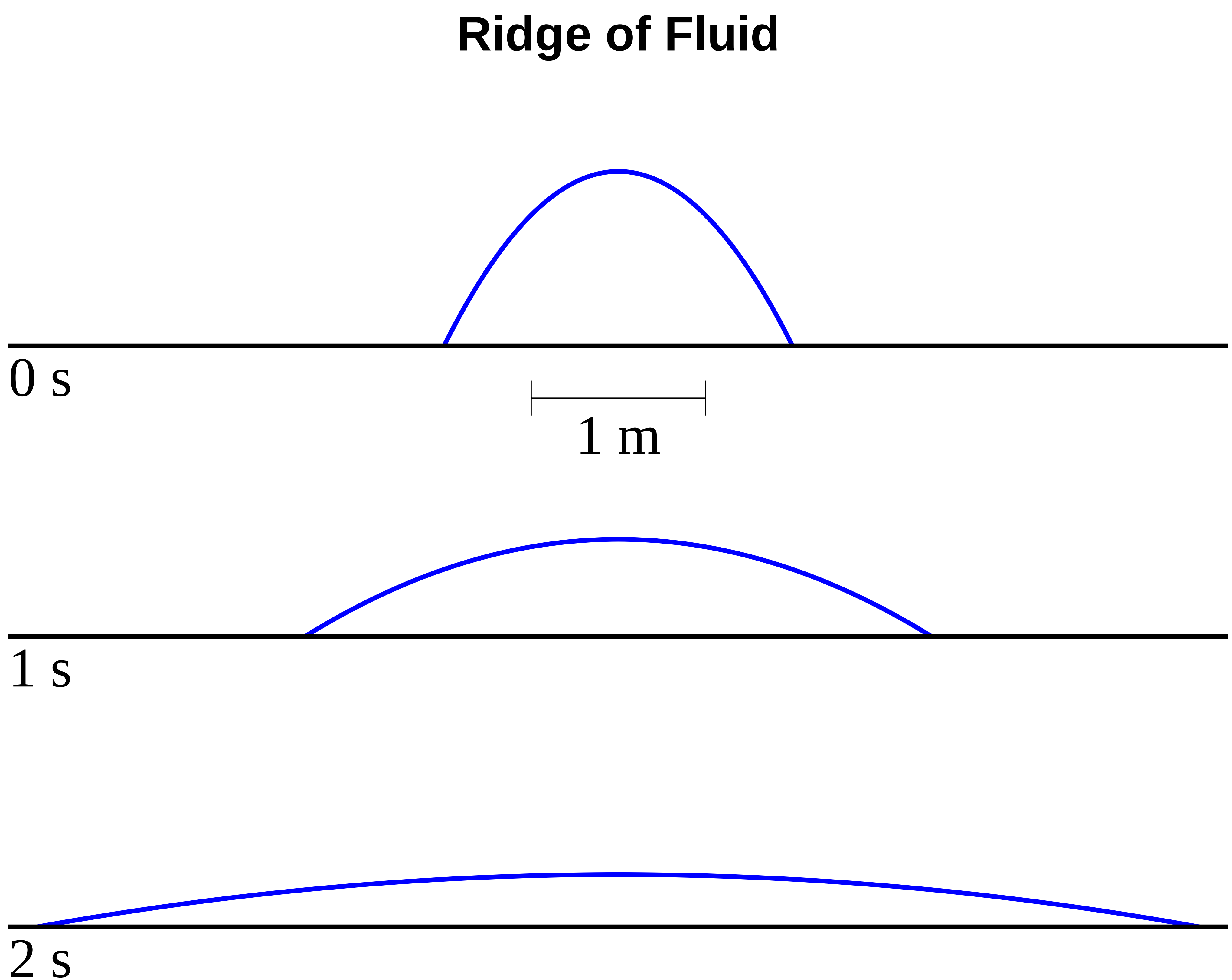


Pile of Parcels

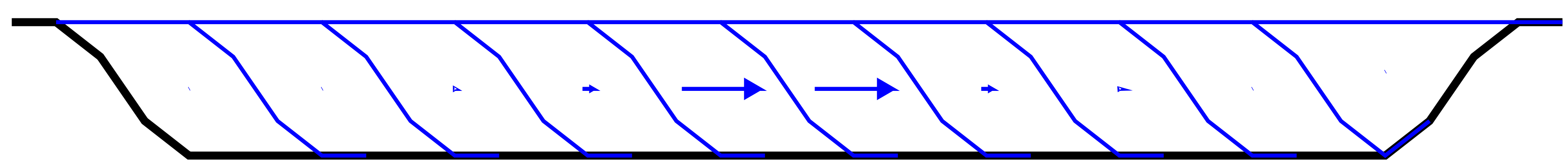




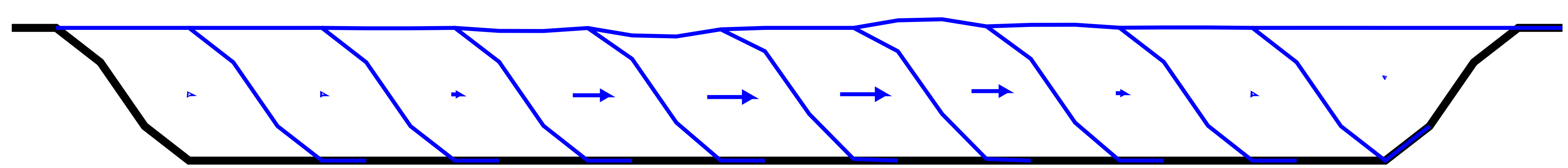
Pile of Parcels
0 s
1 m
1 s
2 s


Ridge of Fluid
0 s
1 m
1 s
2 s

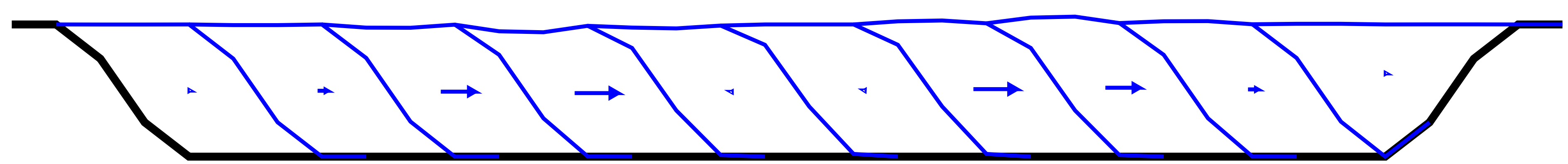
External Gravity Waves



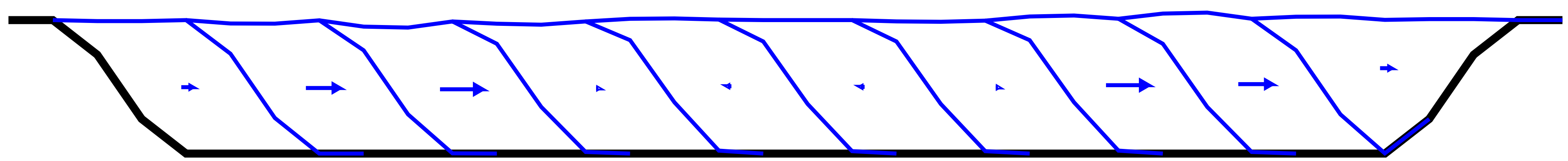
External Gravity Waves



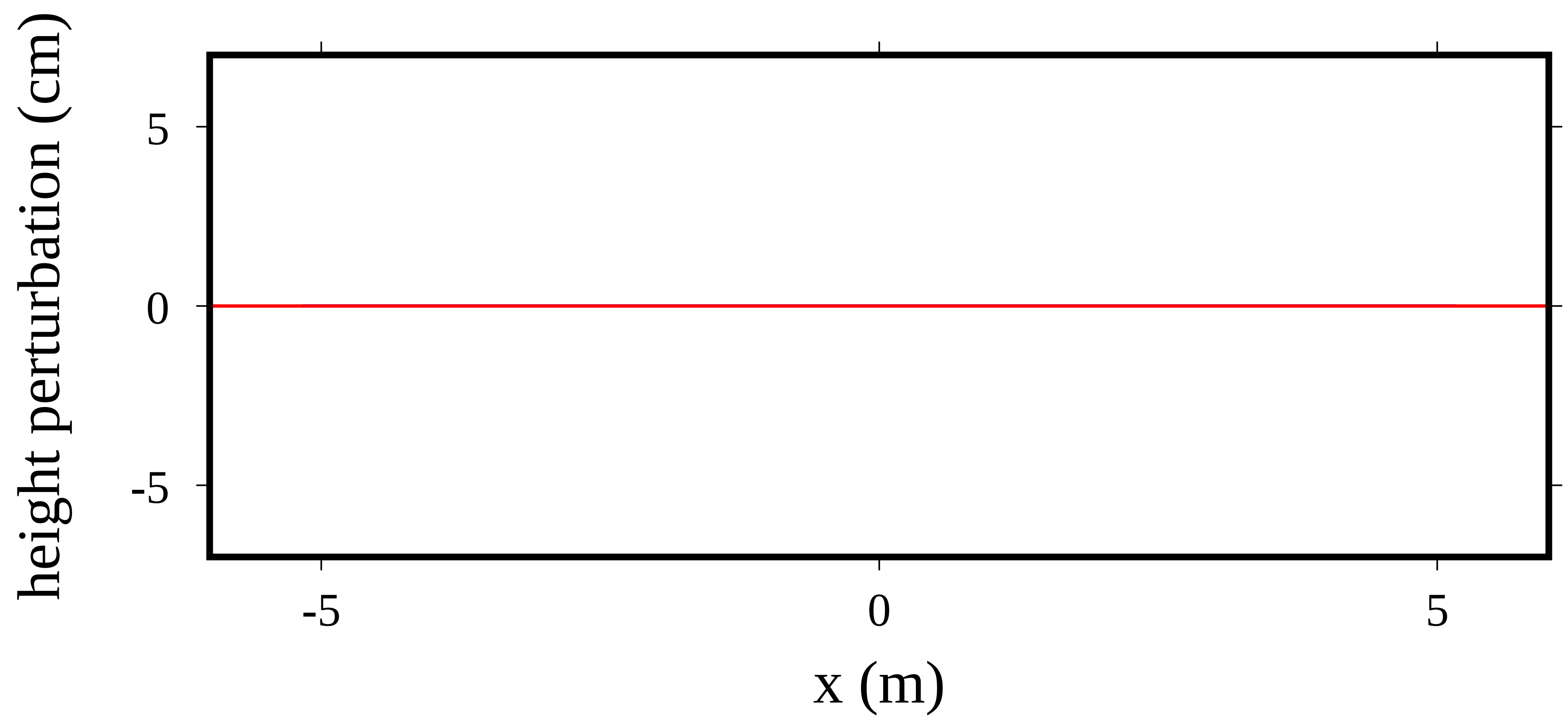
External Gravity Waves

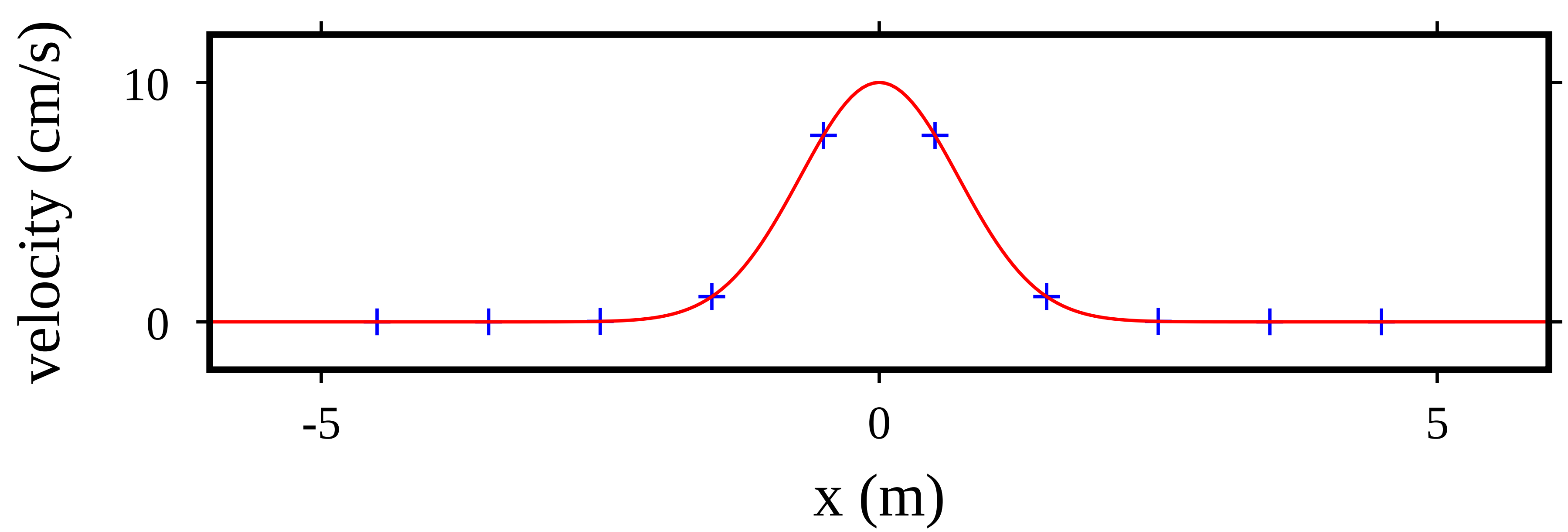


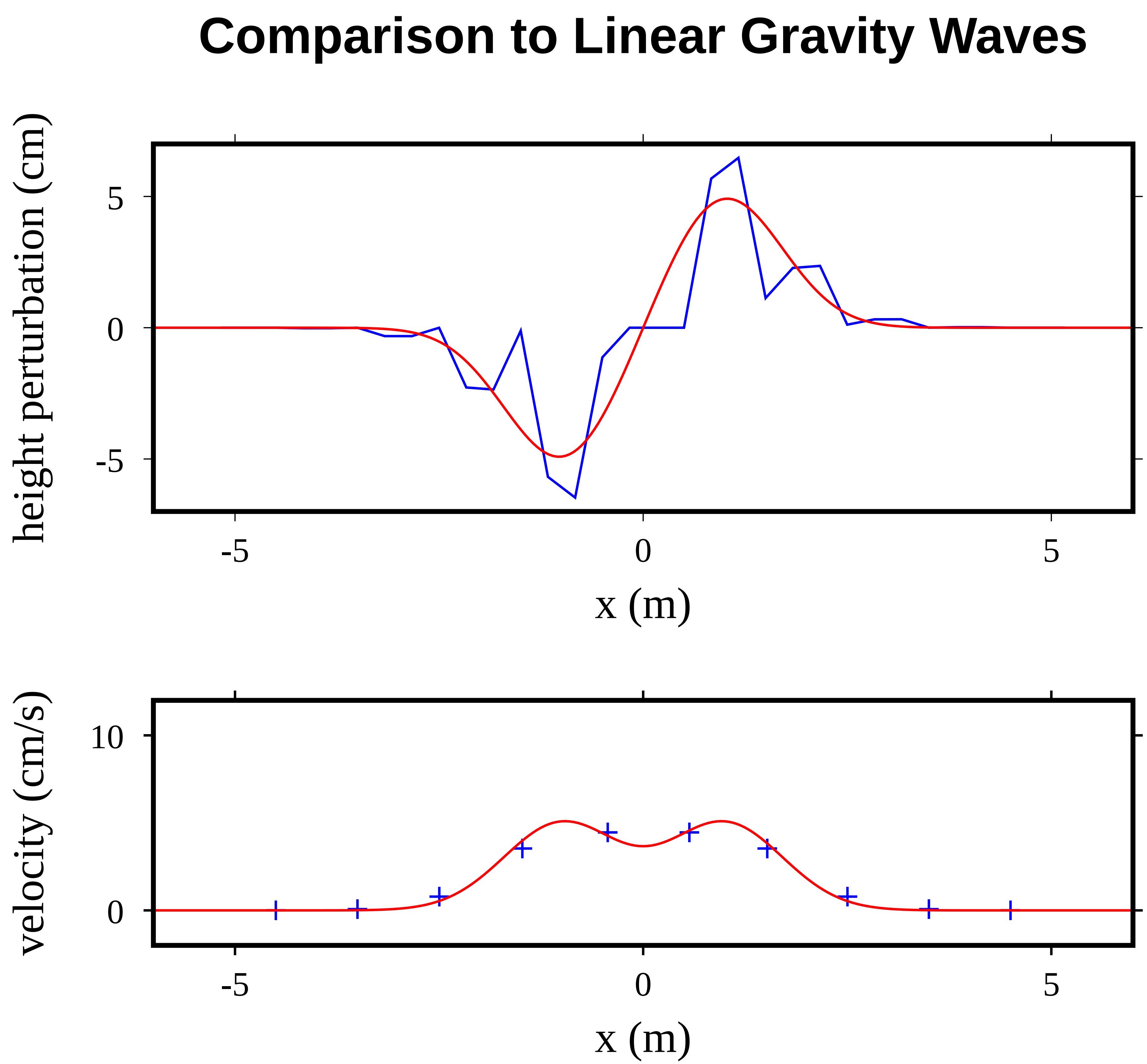
External Gravity Waves



Comparison to Linear Gravity Waves

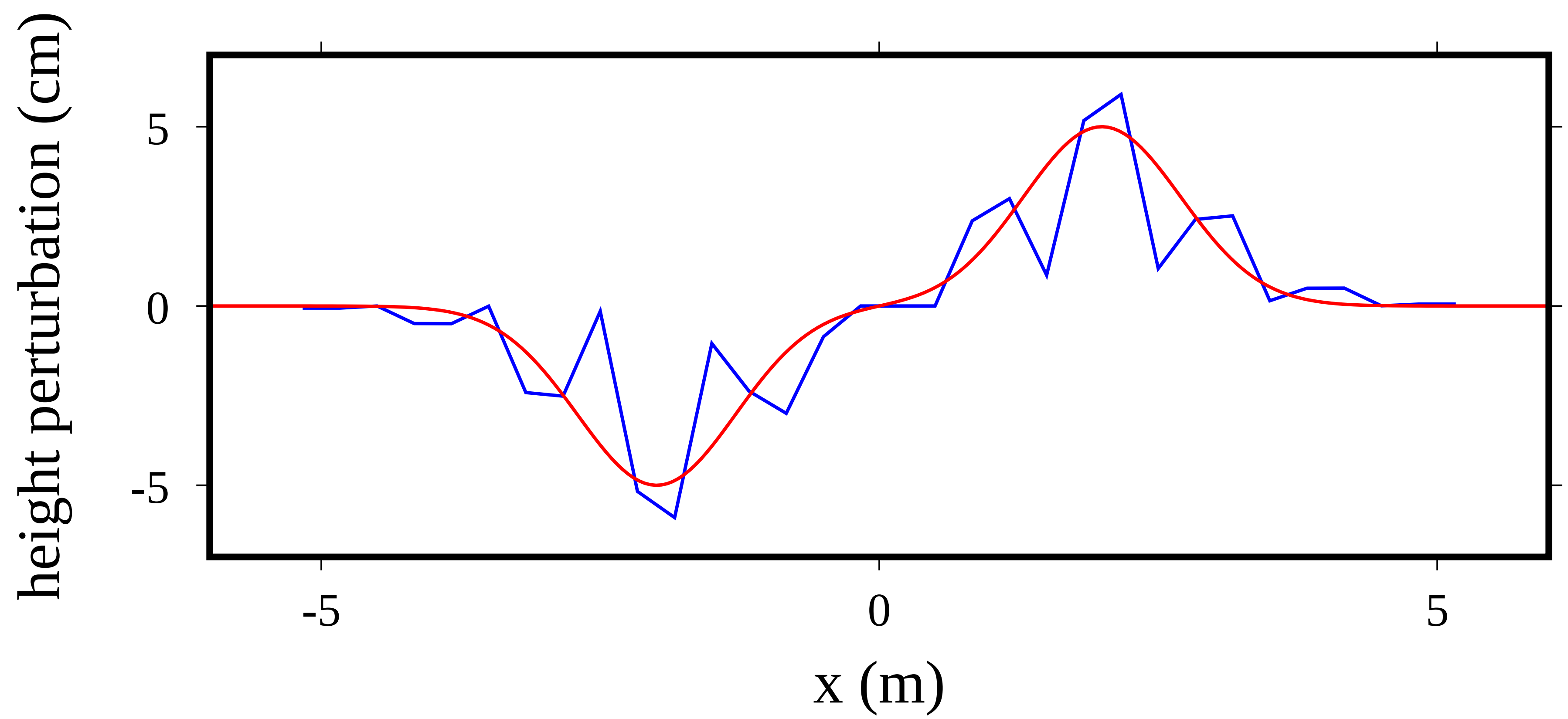


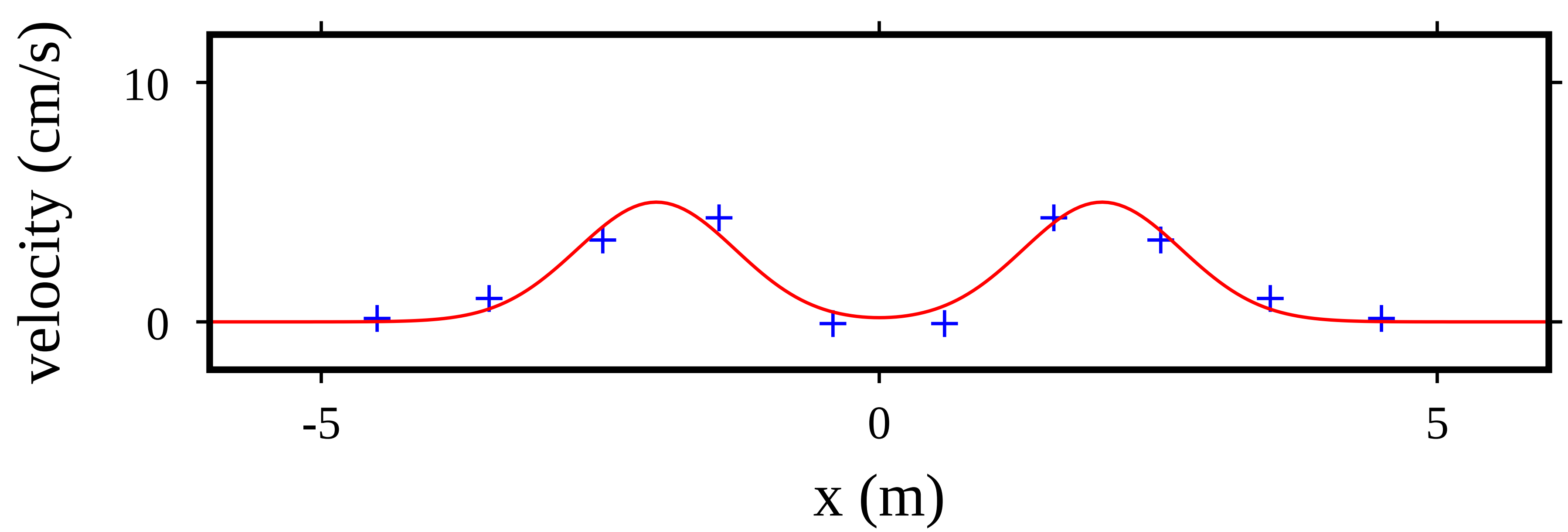


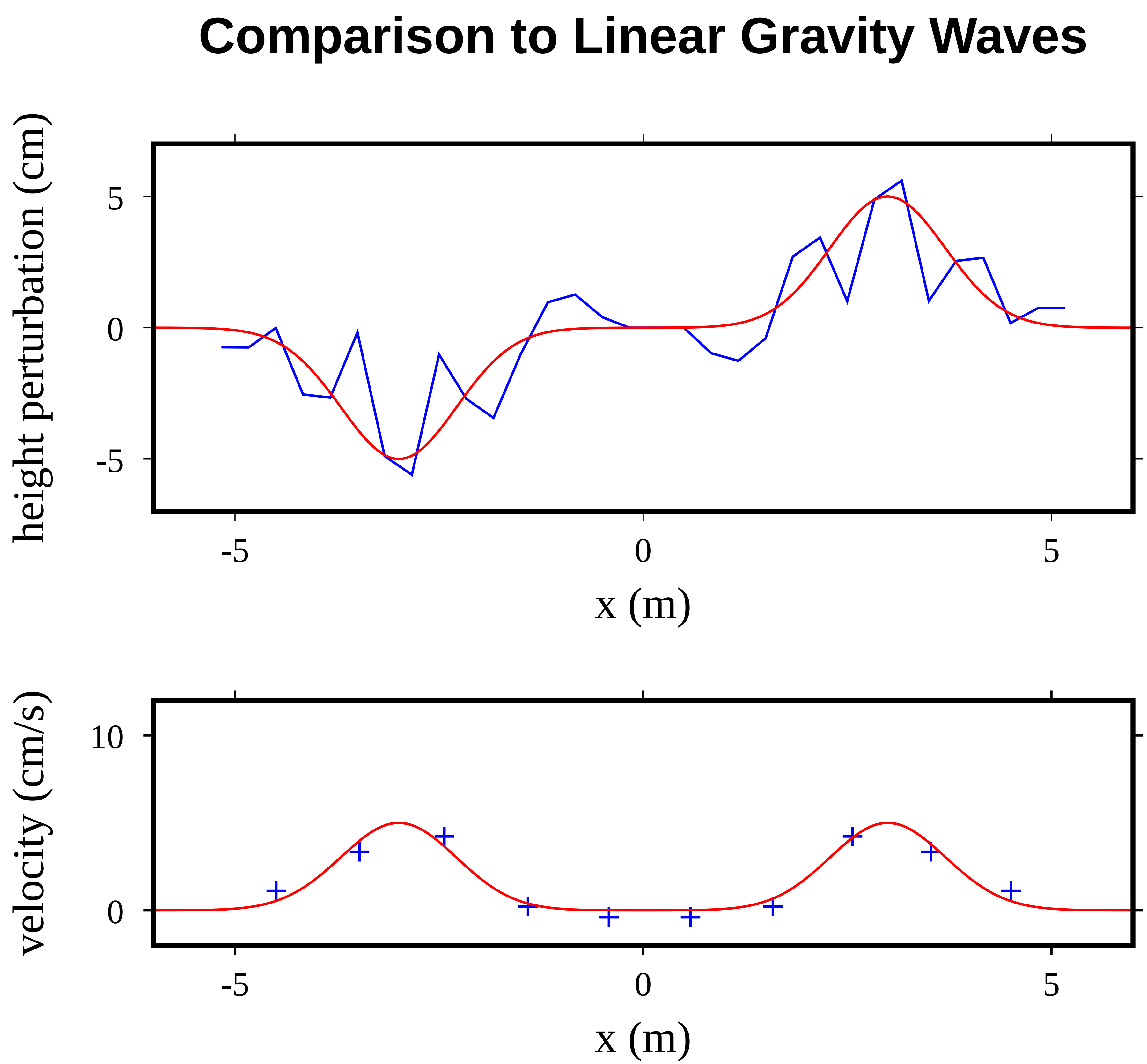


Comparison to Linear Gravity Waves
height perturbation (cm)
5
0
-5
-5
0
5
x (m)
velocity (cm/s)
10
0
-5
0
5
x (m)

Comparison to Linear Gravity Waves

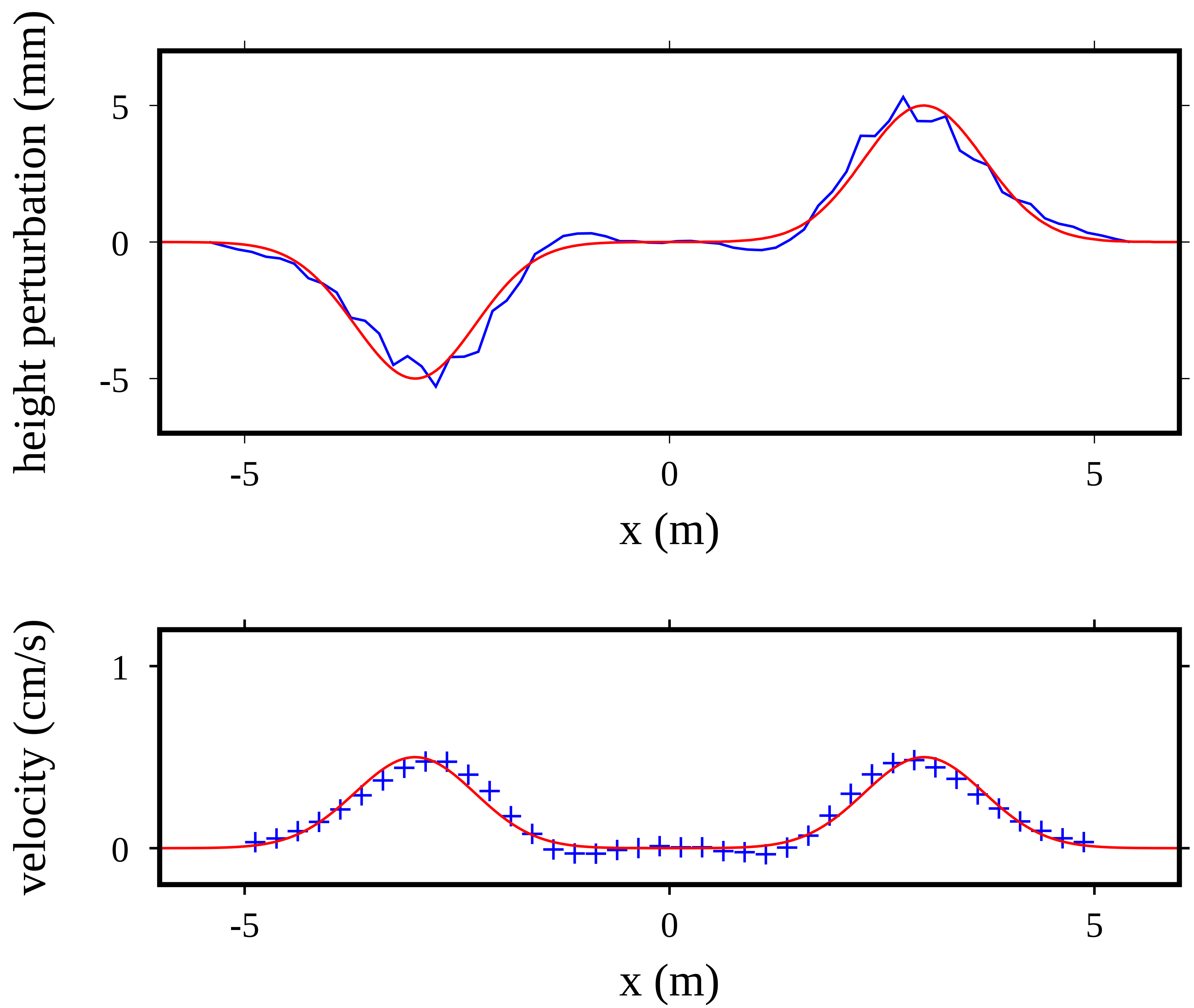


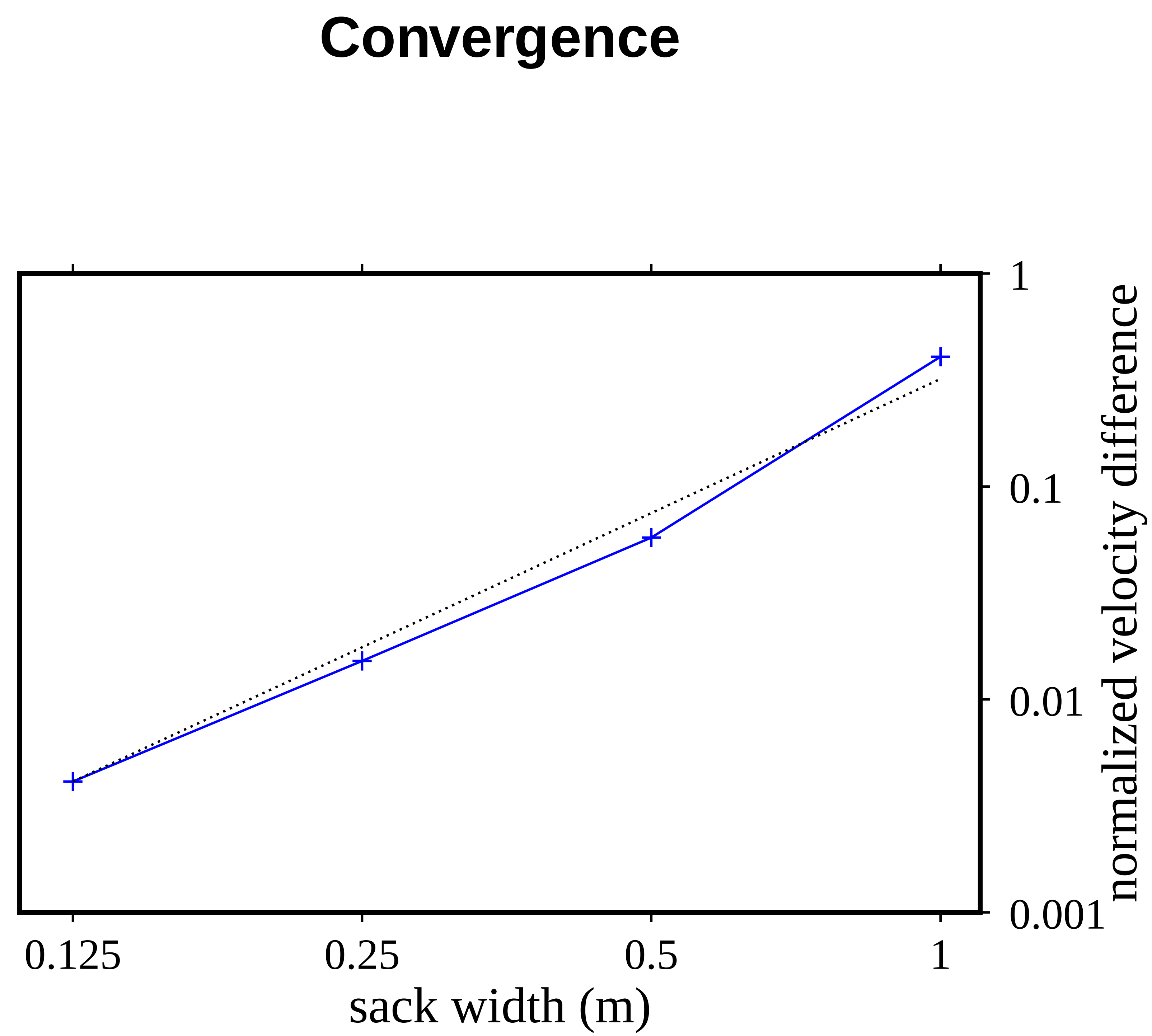




Comparison to Linear Gravity Waves
height perturbation (cm)
5
0
-5
-5
0
5
x (m)
velocity (cm/s)
10
0
-5
0
5
x (m)

Convergence to Linear Gravity Waves

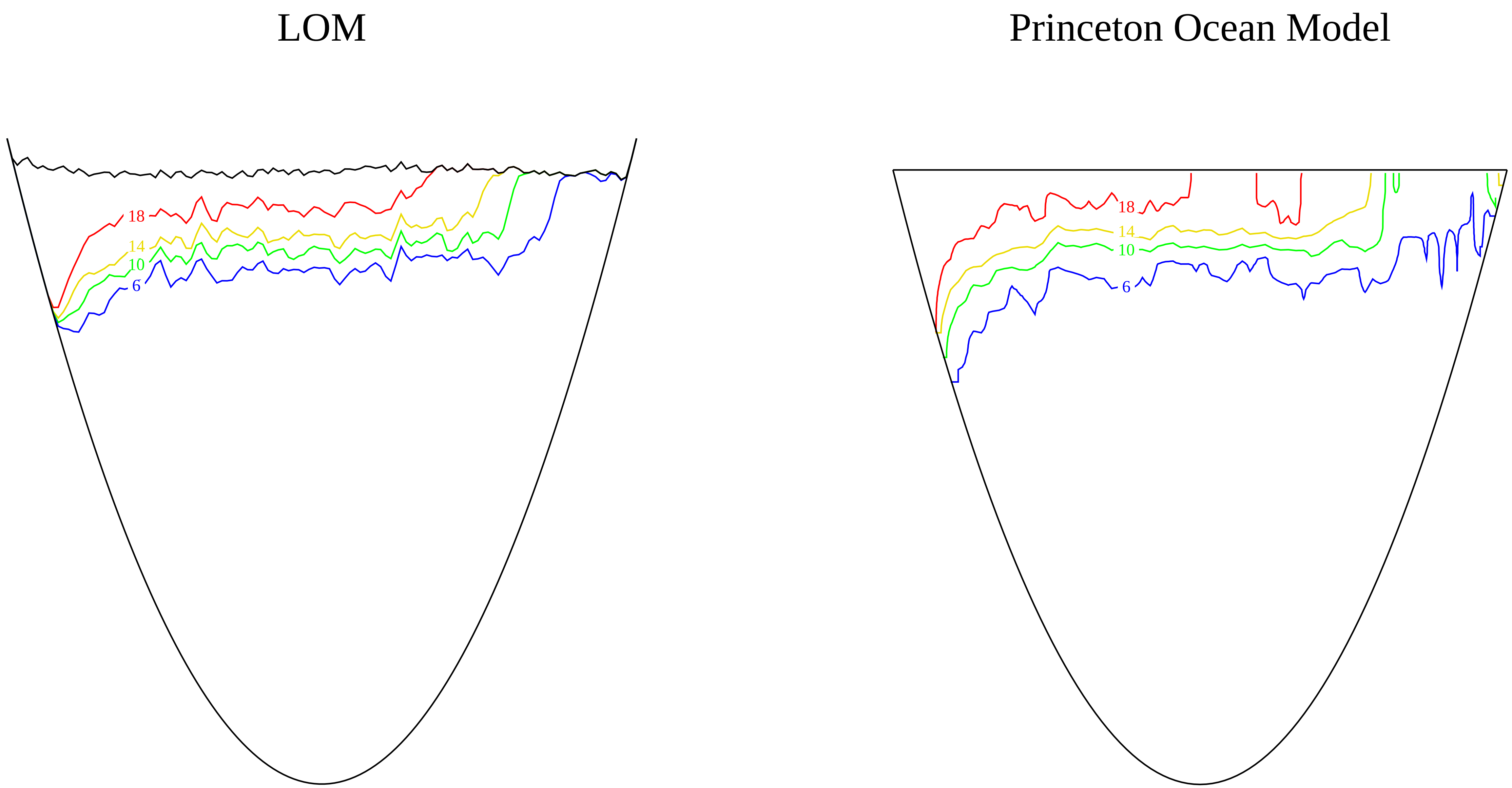



Convergence
1
0.1
0.01
0.001
normalized velocity difference
0.125
0.25
0.5
1
sack width (m)

Lake and Ocean Applications

Lake Upwelling

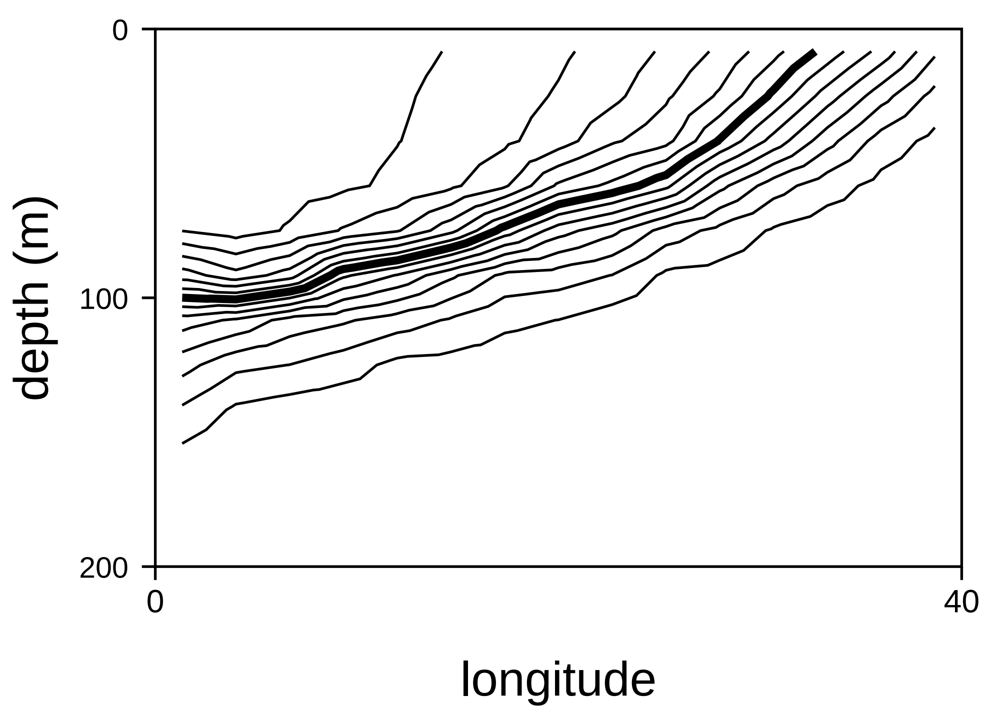
Haertel et al. (2004)



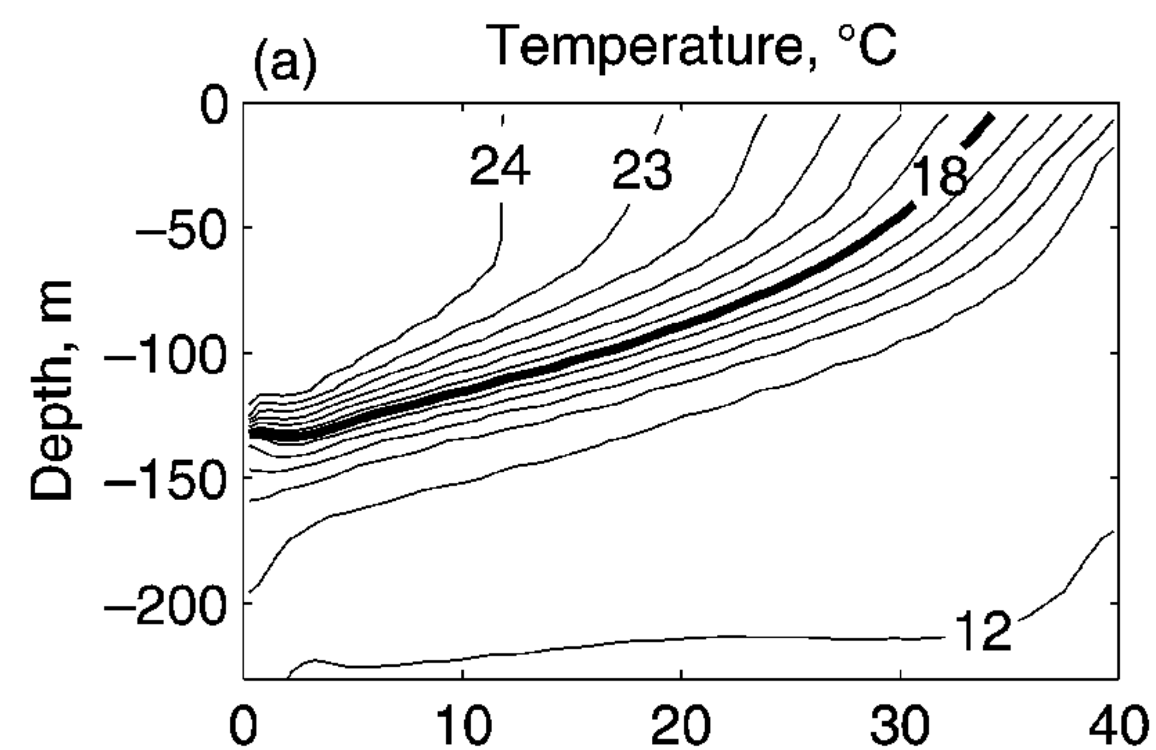
Idealized Equatorial Ocean: Thermocline

Fedorov et al. (2004)

LOM



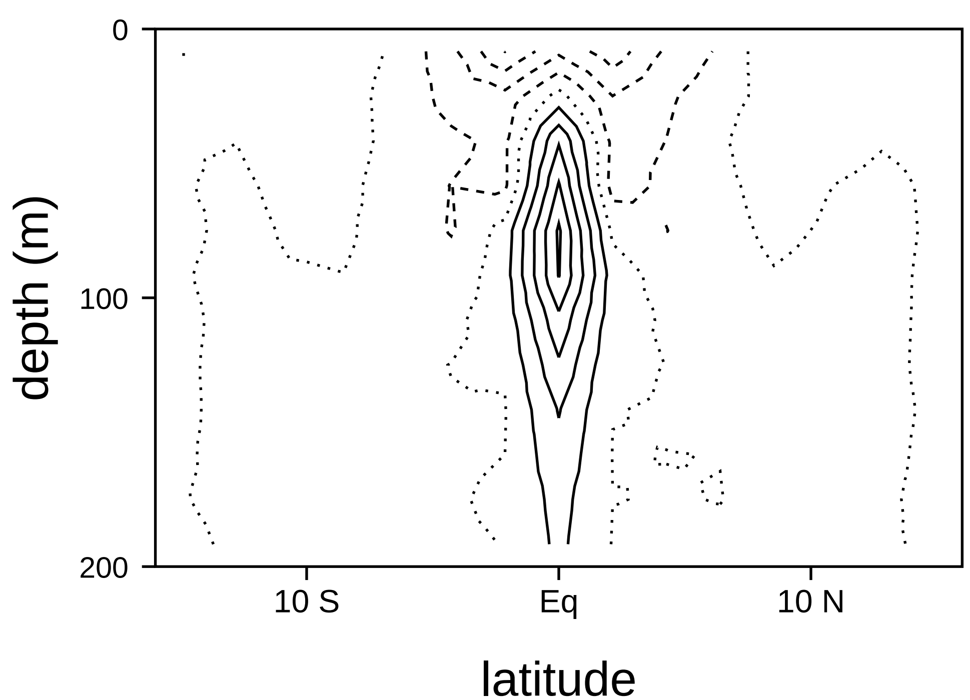
MOM4



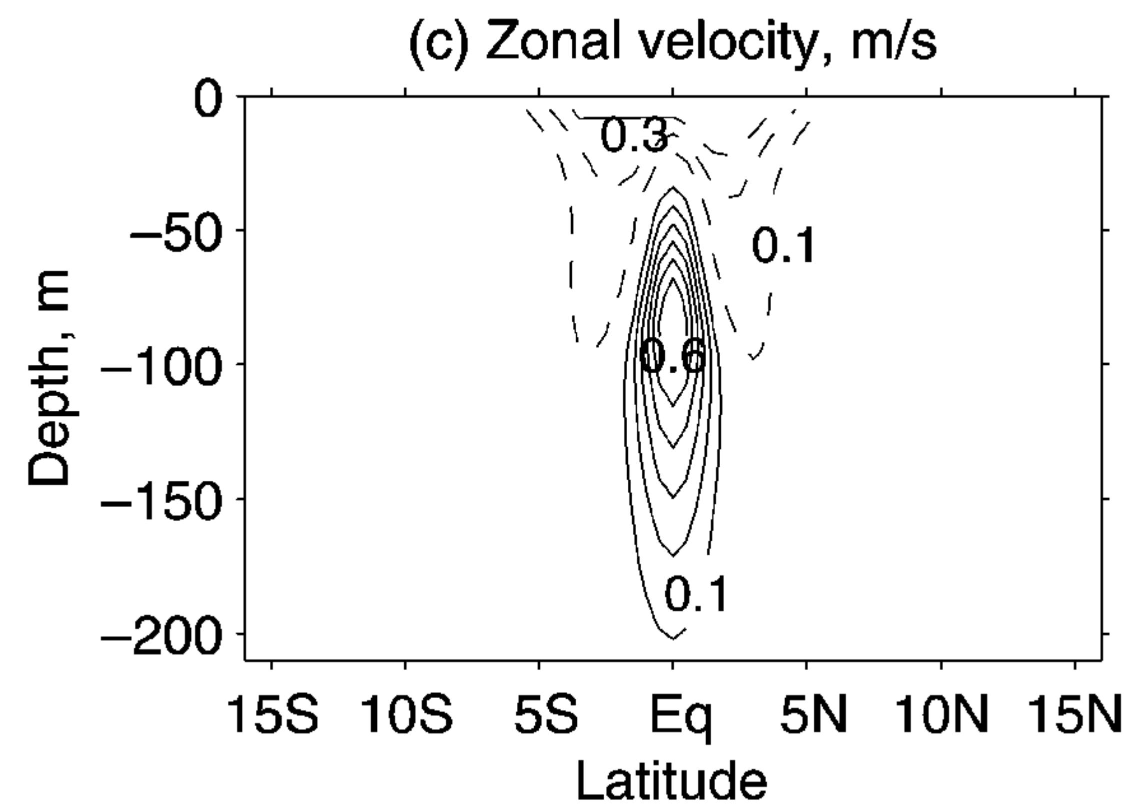
Idealized Equatorial Ocean: Equatorial Undercurrent

Fedorov et al. (2004)

LOM



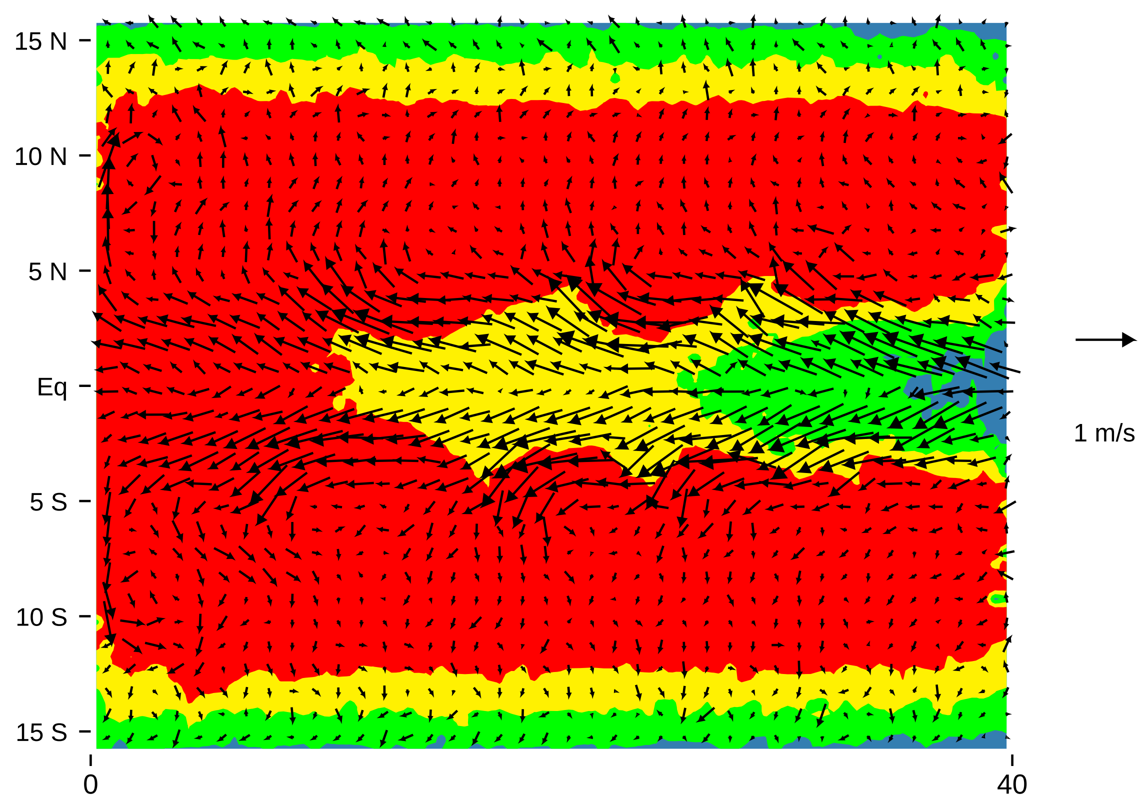
MOM4



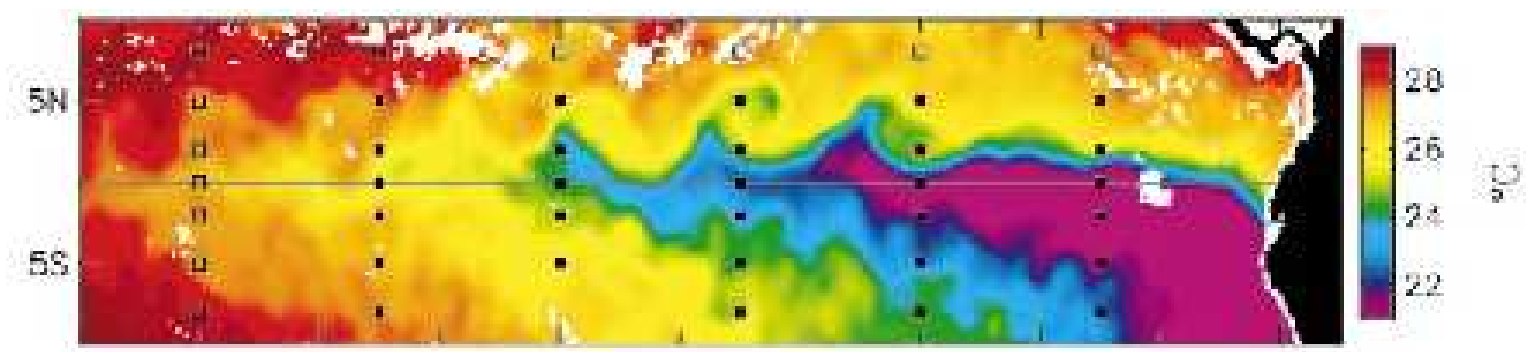
Tropical Instability Waves: Surface Temperature

Chelton et al. (2001)

LOM



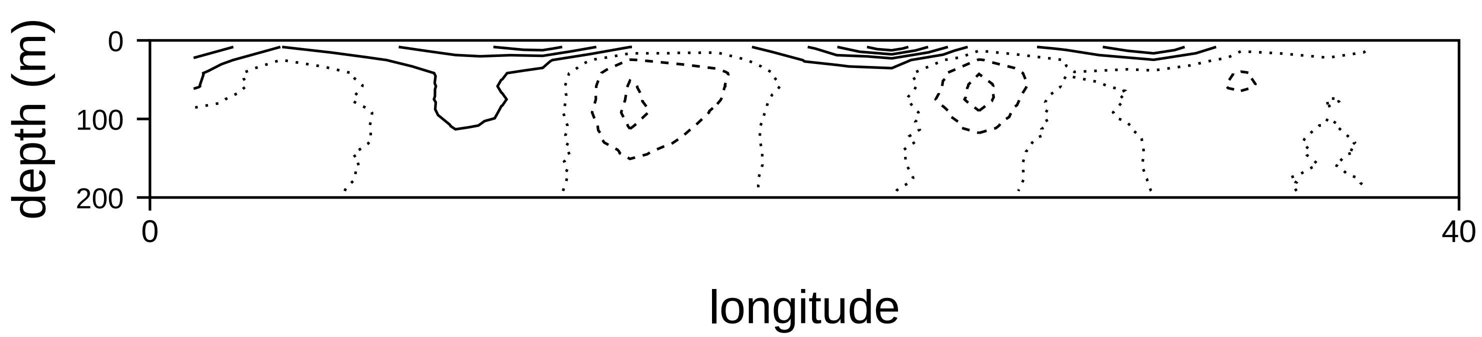
Observed



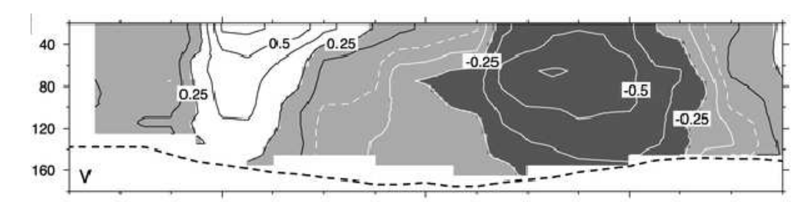
Tropical Instability Waves: Meridional Velocity

Kennen and Flament (2000)

LOM

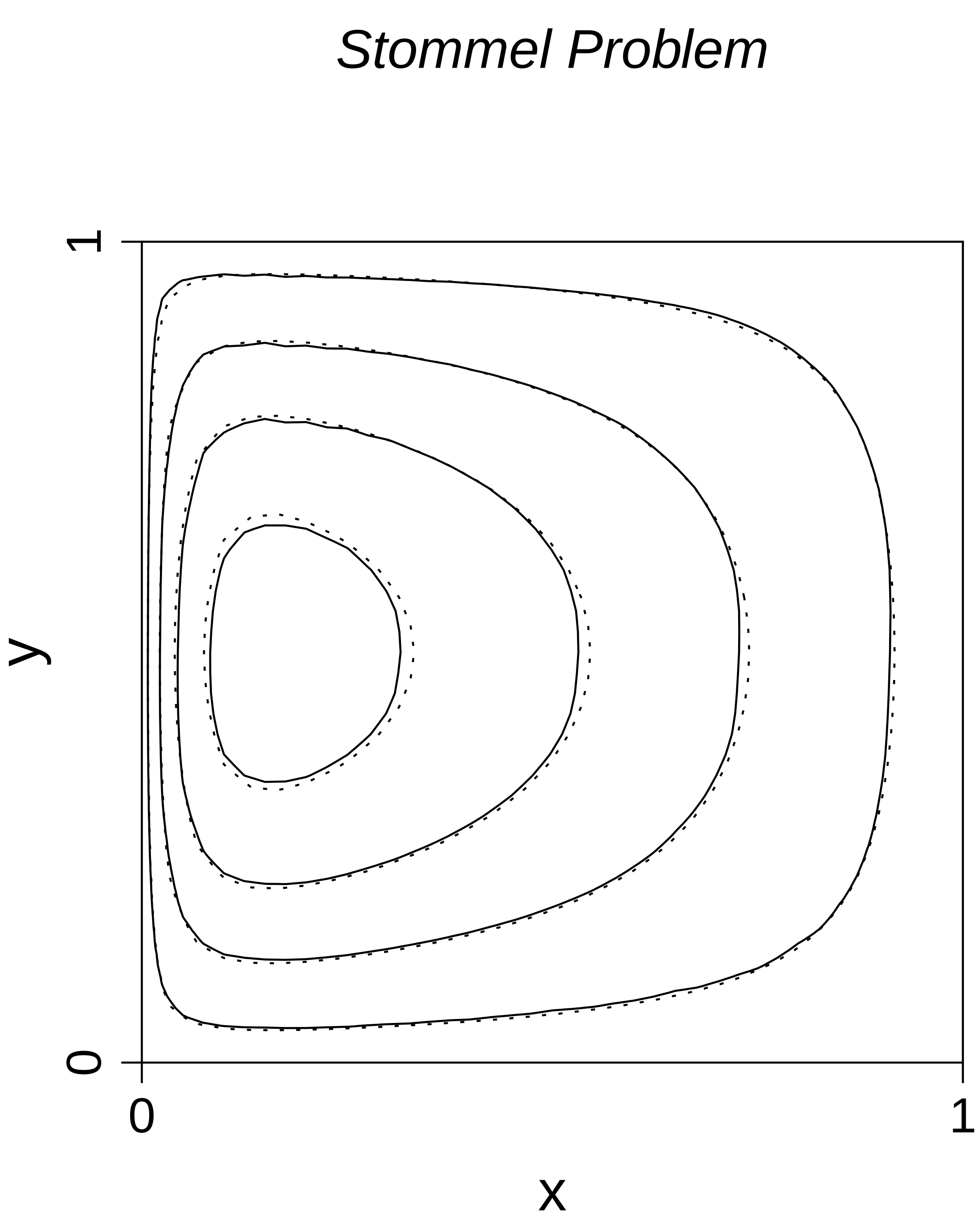


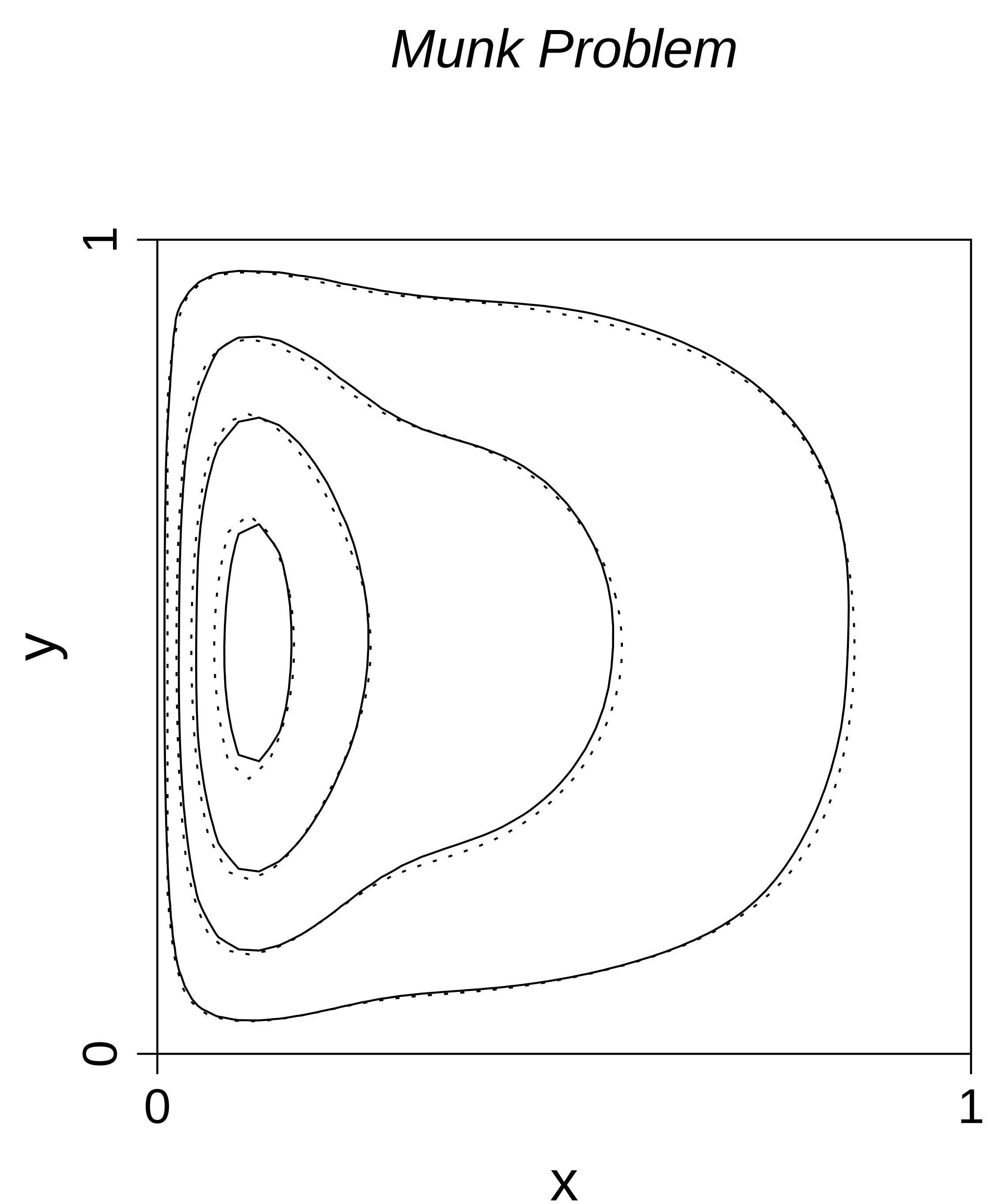
Observed



Western Boundary Currents

Haertel et al. (2009)

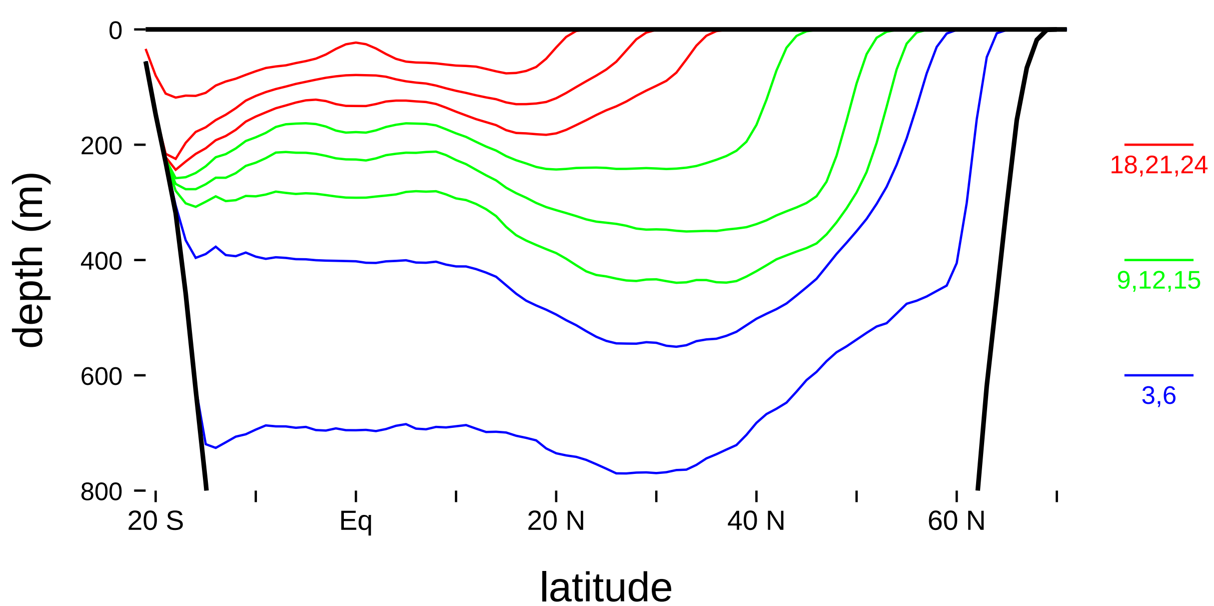




North Atlantic Thermocline

Haertel et al. (2009)

LOM



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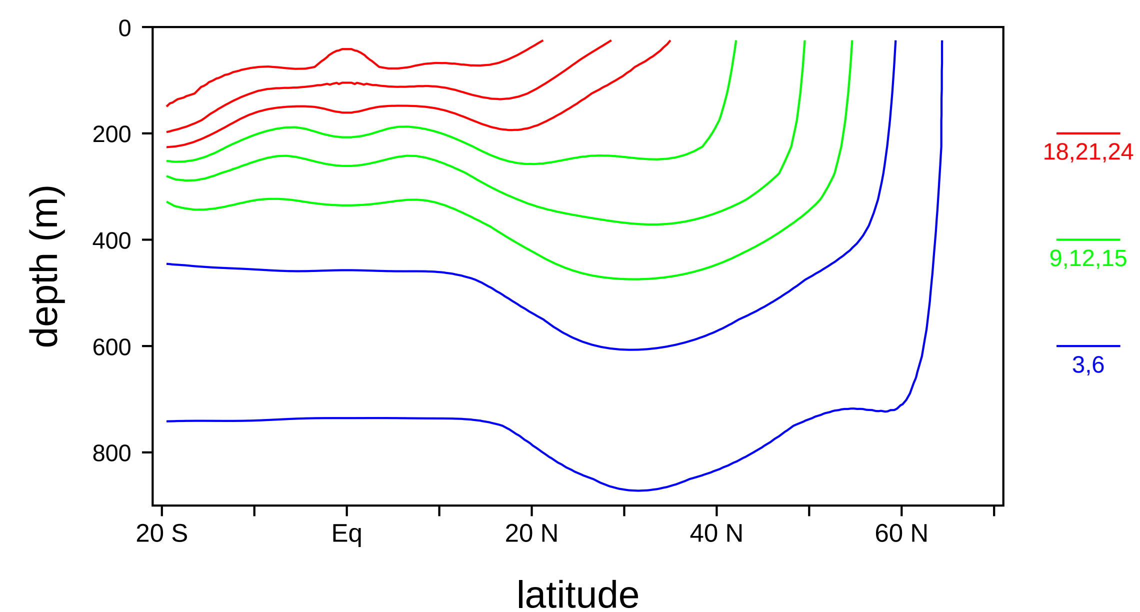
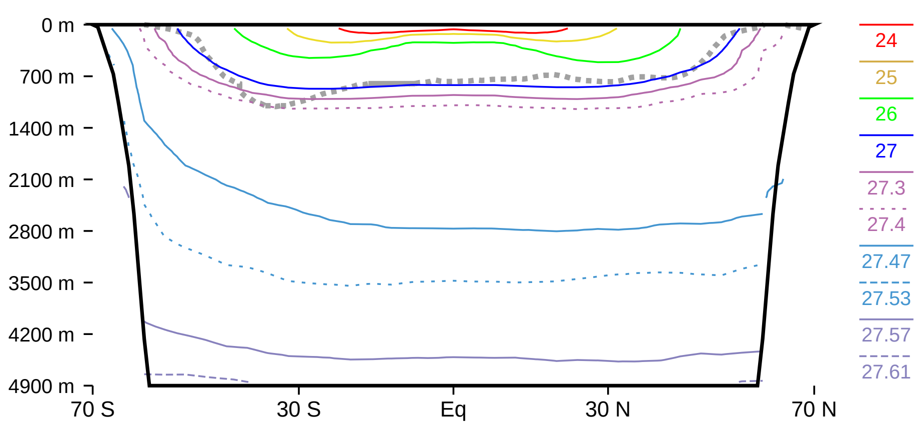


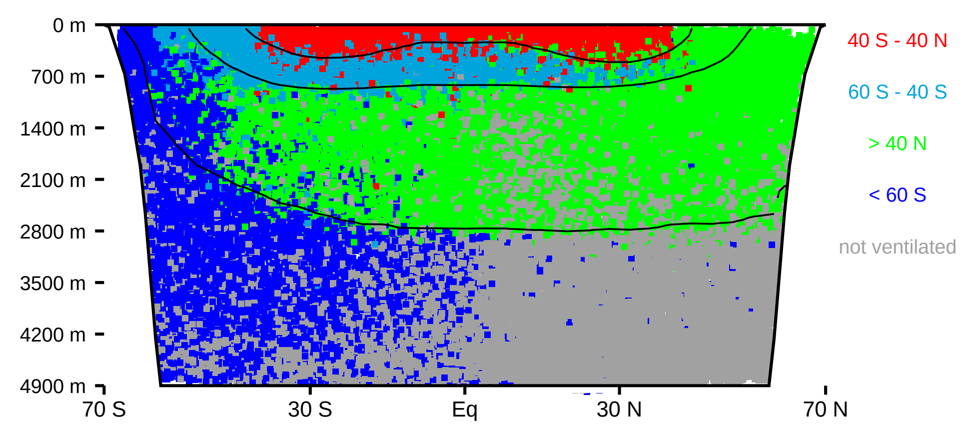
The Ventilated Ocean: Atlantic Stratification and Overturning

Haertel and Fedorov (2011)

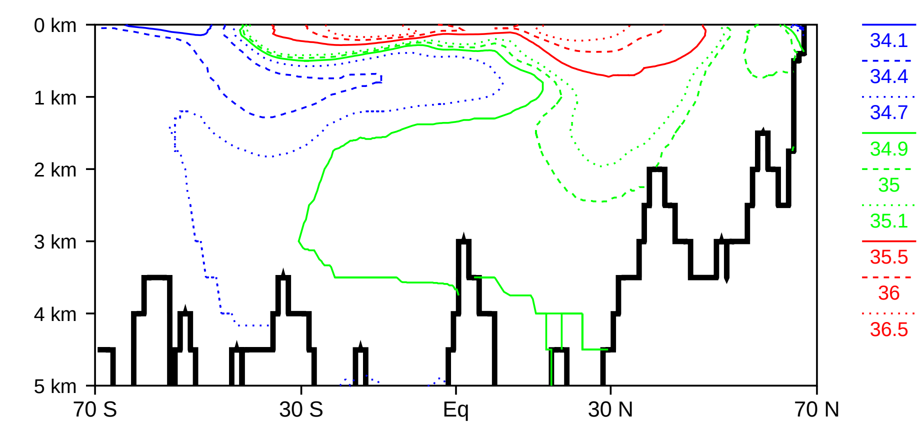
simulated density



latitude of last surface contact

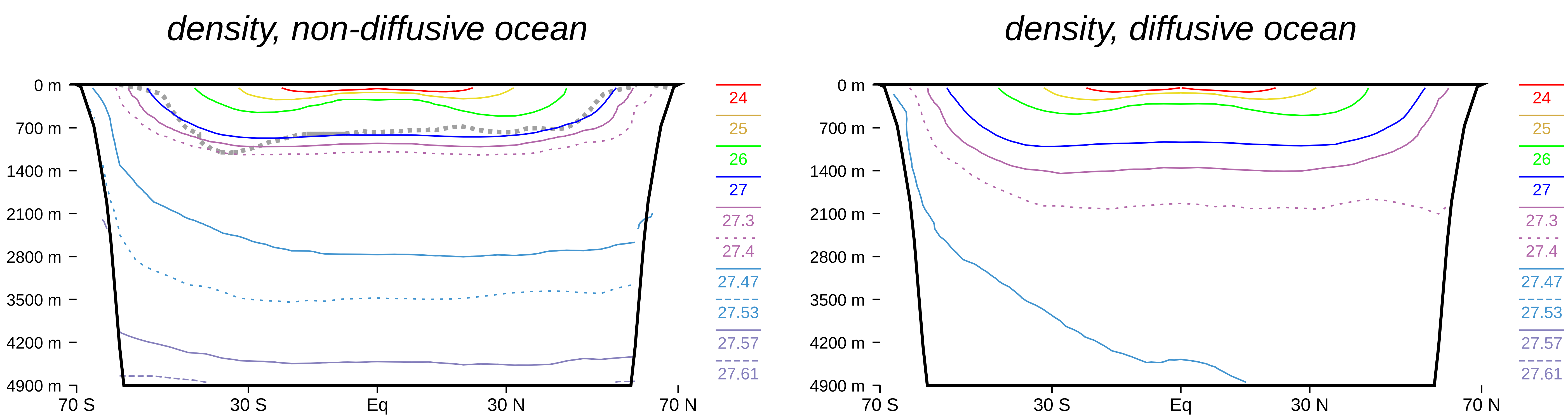


observed salinity at 30 W



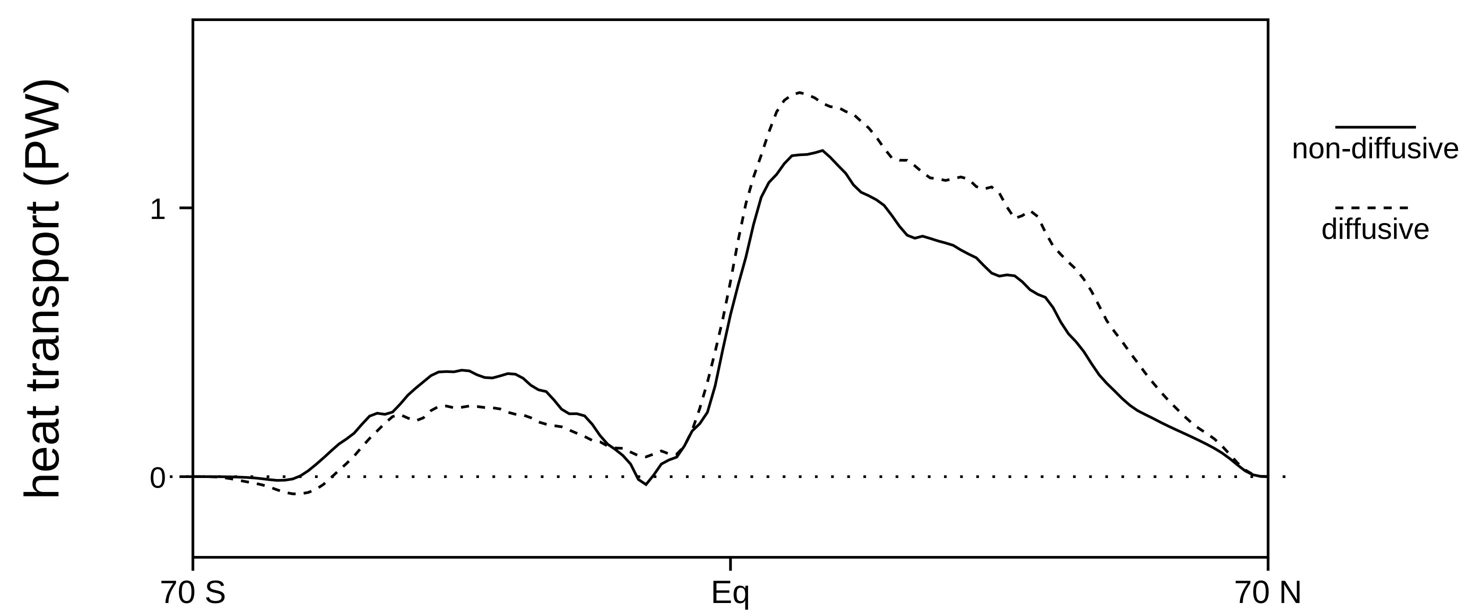
Ventilated Ocean: Effects of Mixing on Stratification

Haertel and Fedorov (2011)



Ventilated Ocean: Effects of Mixing on Heat Transport

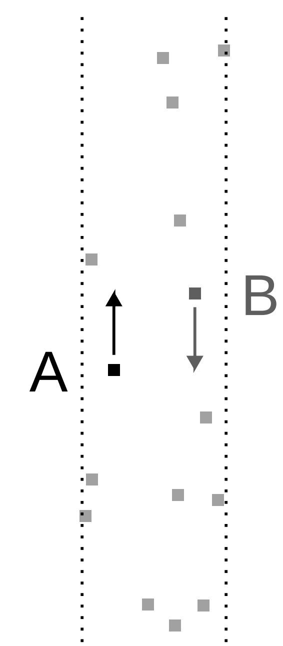
Haertel and Fedorov (2011)



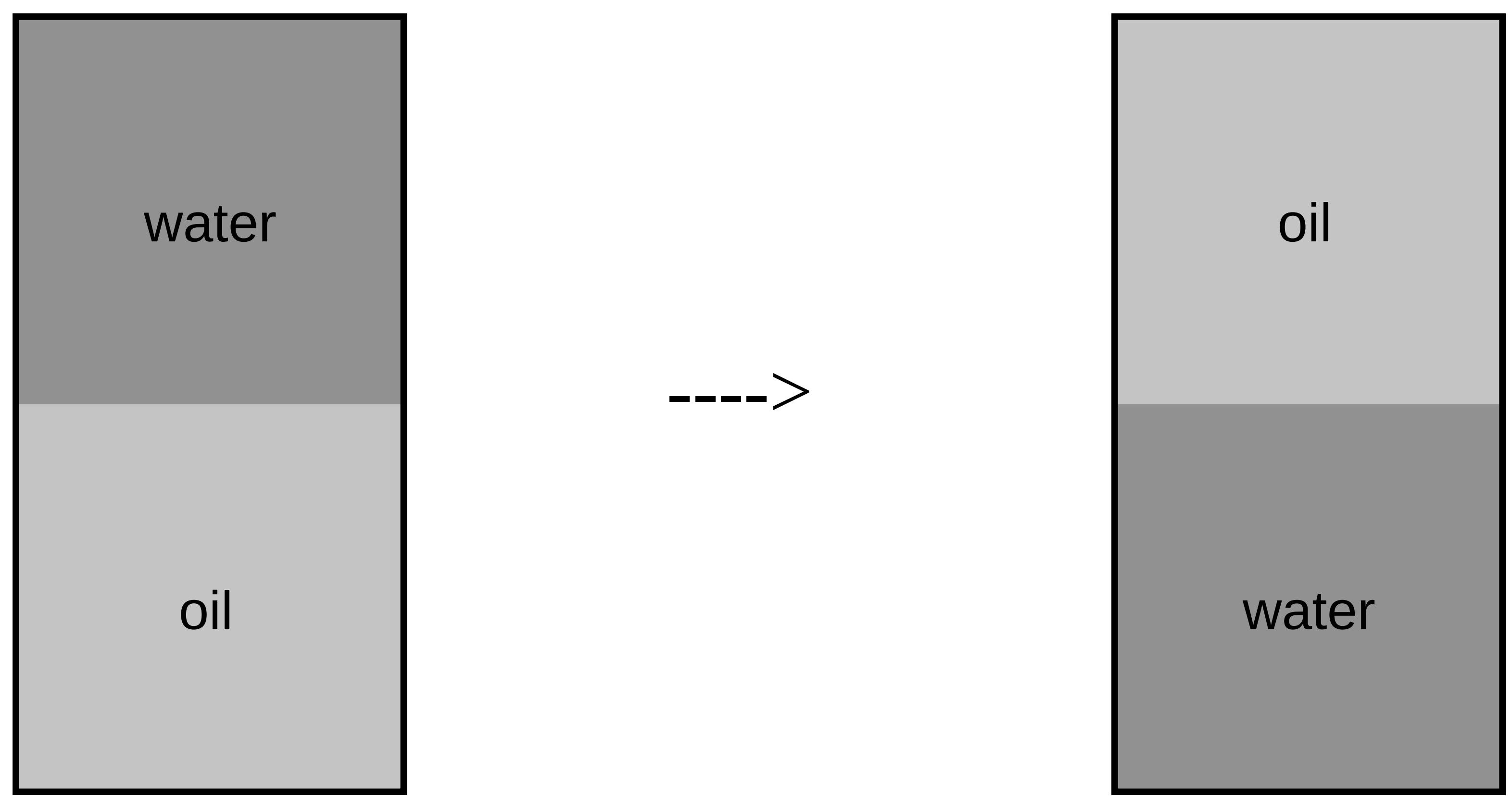
Simulating Tropical Convection

Lagrangian Overturning

Suppose two overlapping parcels A and B are centered in the same column of the model domain with A beneath B. LO exchanges the vertical positions of A and B when this leads to $\theta(A) > \theta(B)$.

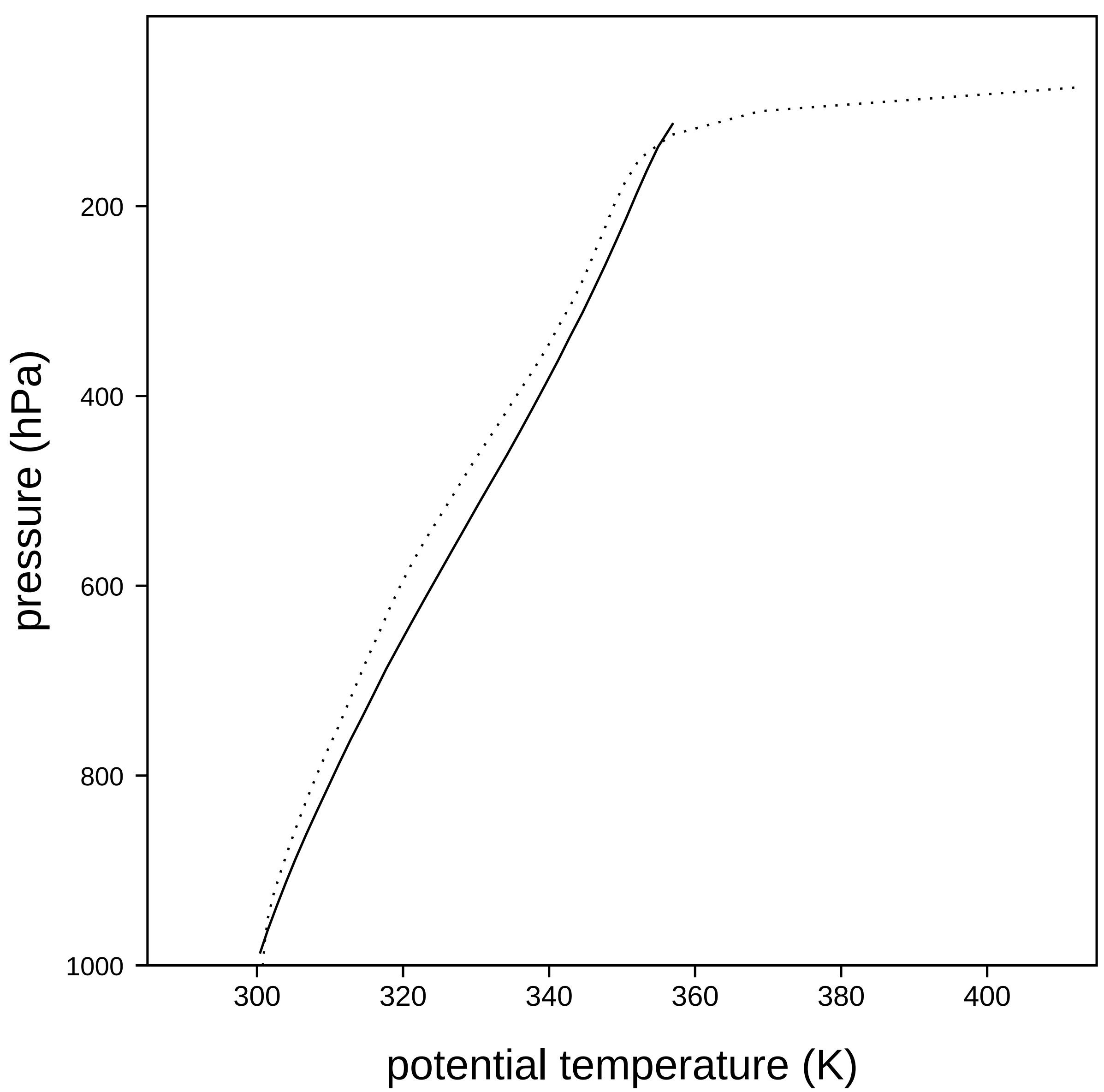


Simple Illustration of Lagrangian Overturning

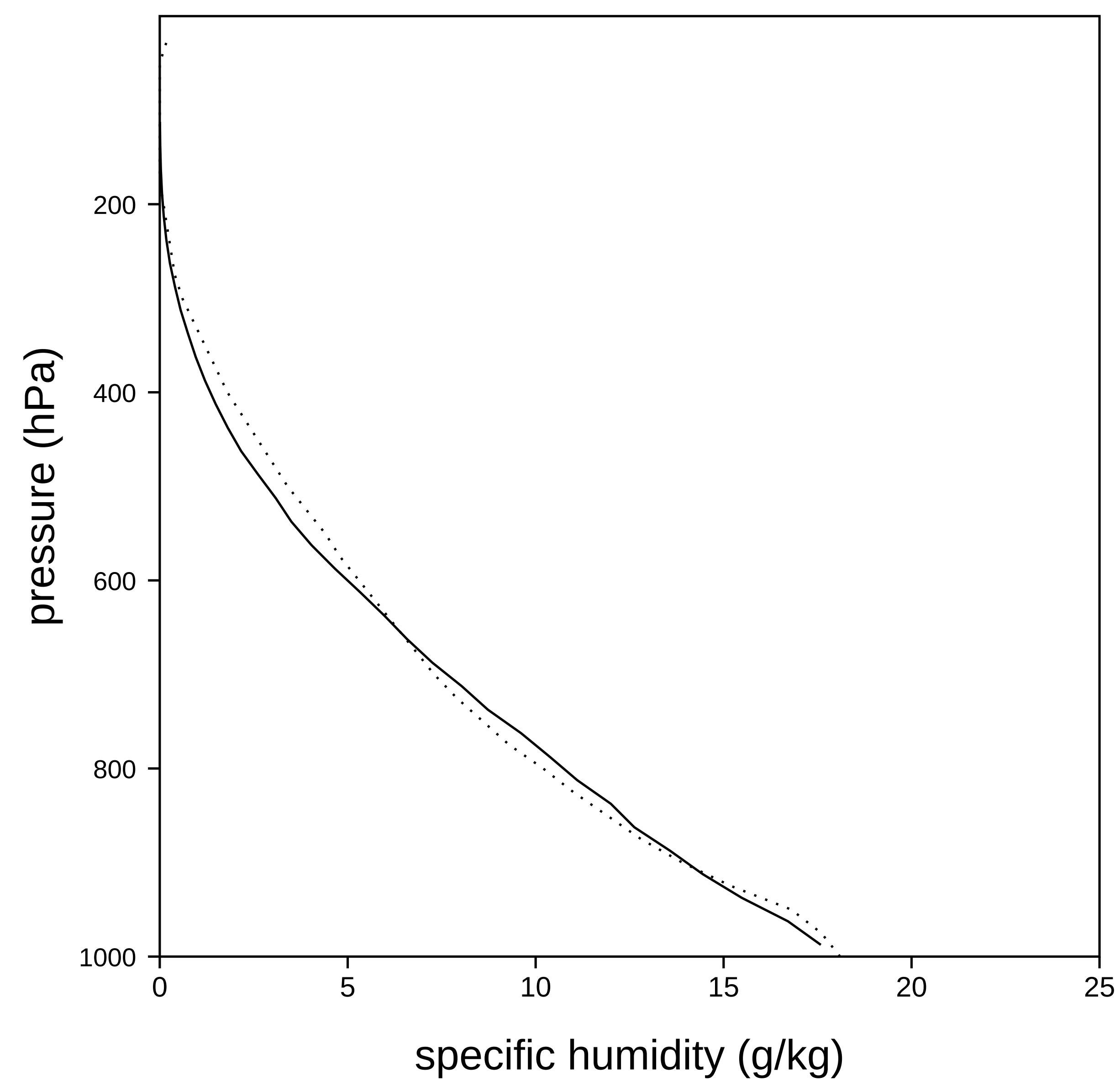


Applying Lagrangian Overturning in a Single Column Model

temperature (SCM solid, COARE dashed)



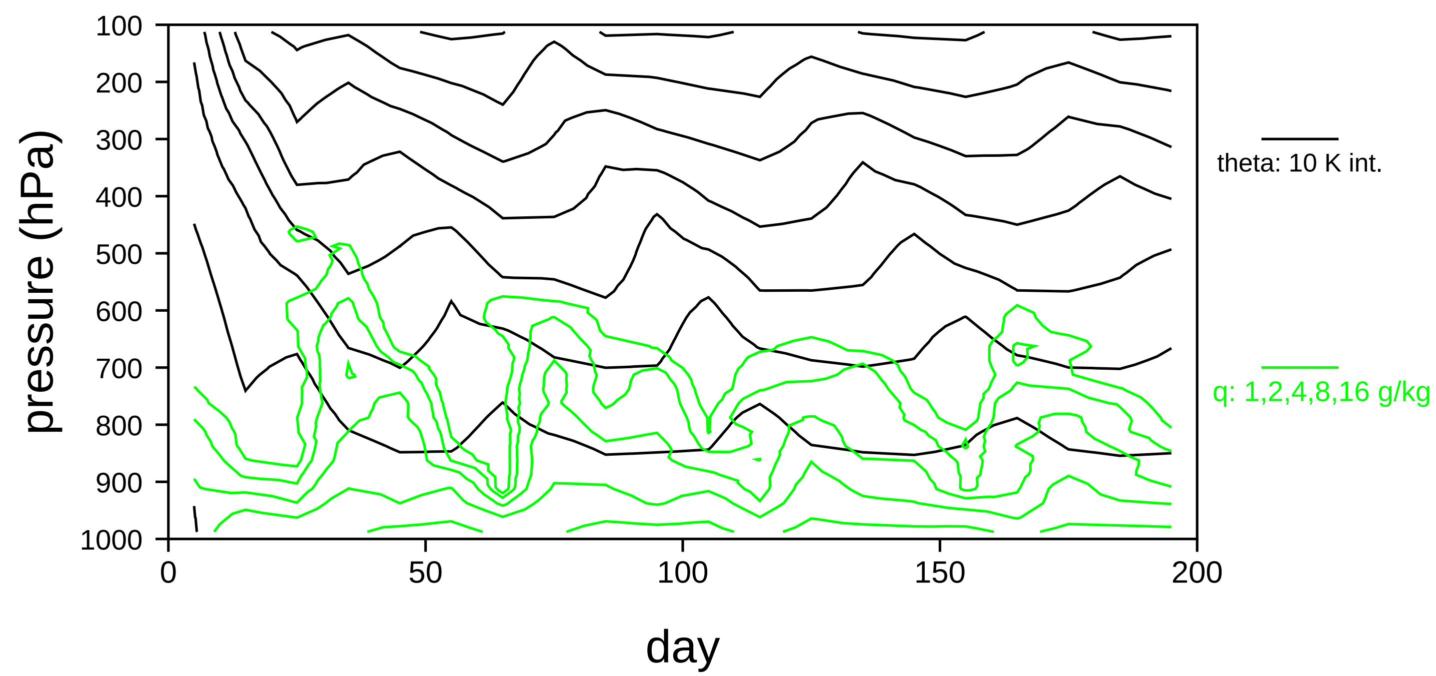
specific humidity (SCM solid, COARE dashed)



Conventional Cumulus Parameterization vs. Lagrangian Overturning (LO)

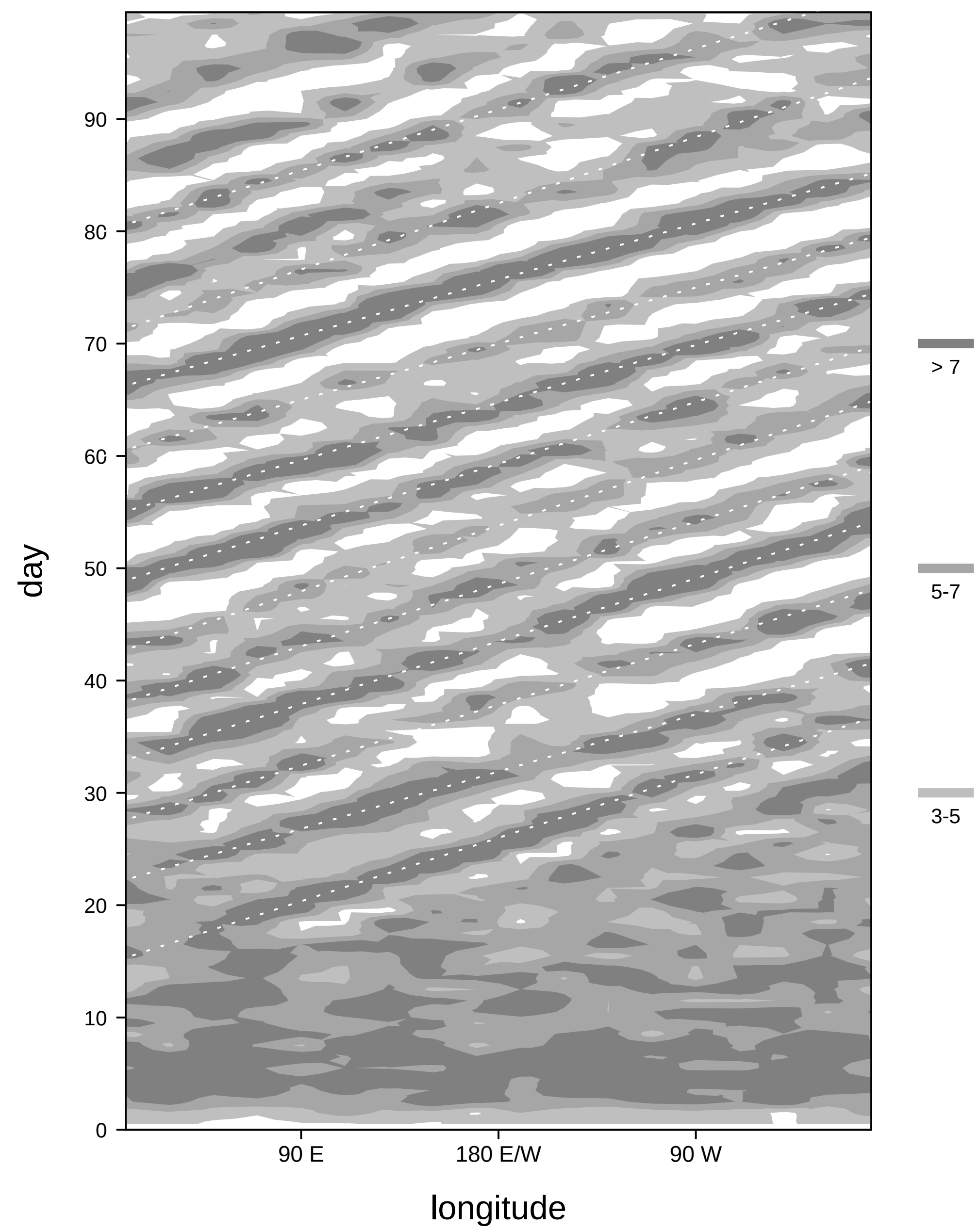
Arakawa (2003): "The majority of the existing cumulus parameterization schemes are based on the quasi-equilibrium concept, either explicitly or implicitly, through the adjustments of temperature and humidity profiles to reference profiles."

Non-steady behavior in LO single column model



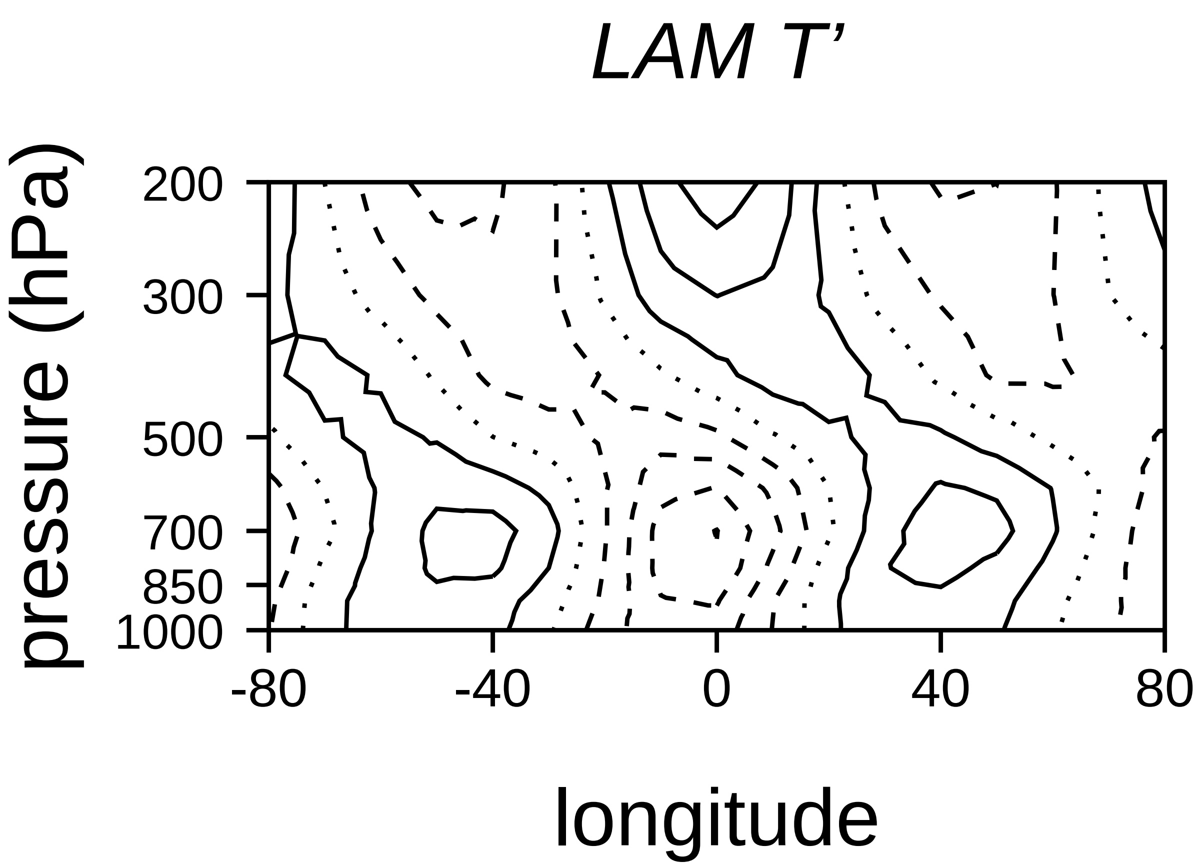
Convectively Coupled Kelvin Waves

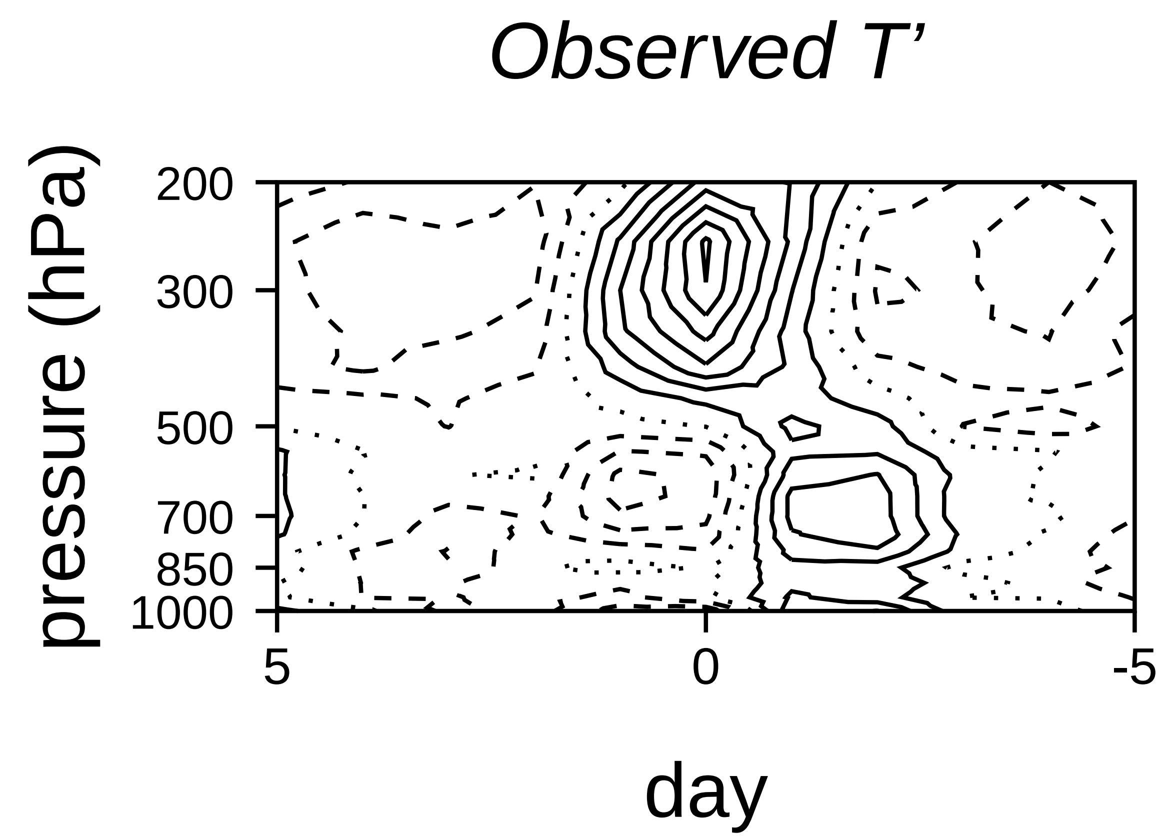
Haertel and Straub (2010)



Convectively Coupled Kelvin Waves

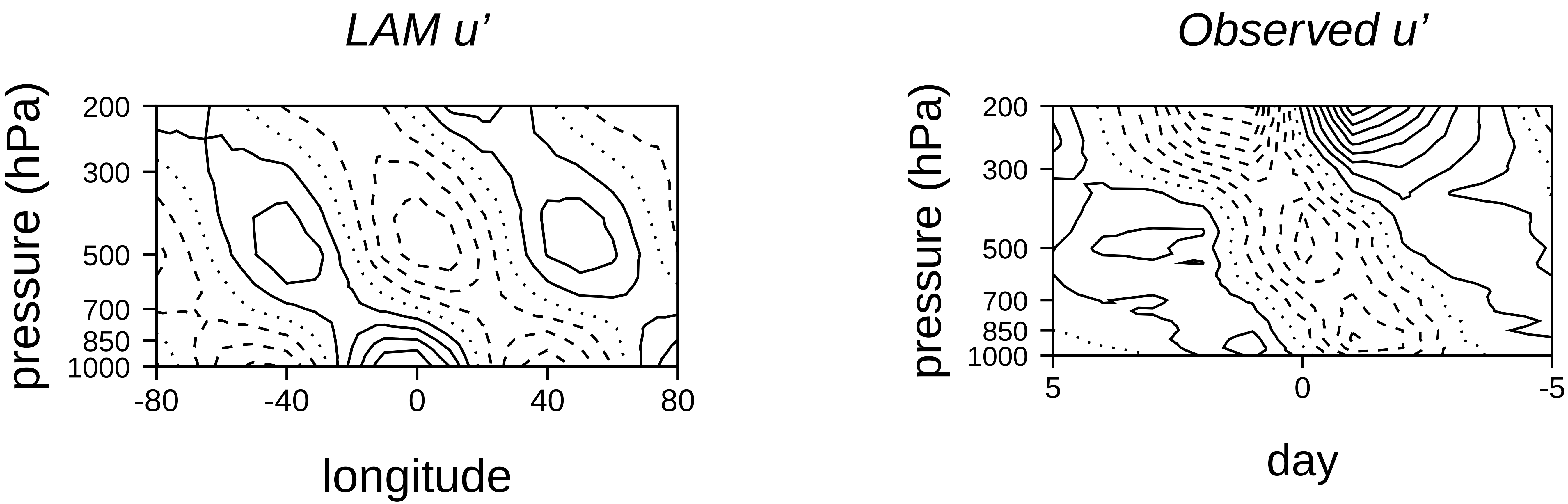
Haertel and Straub (2010)





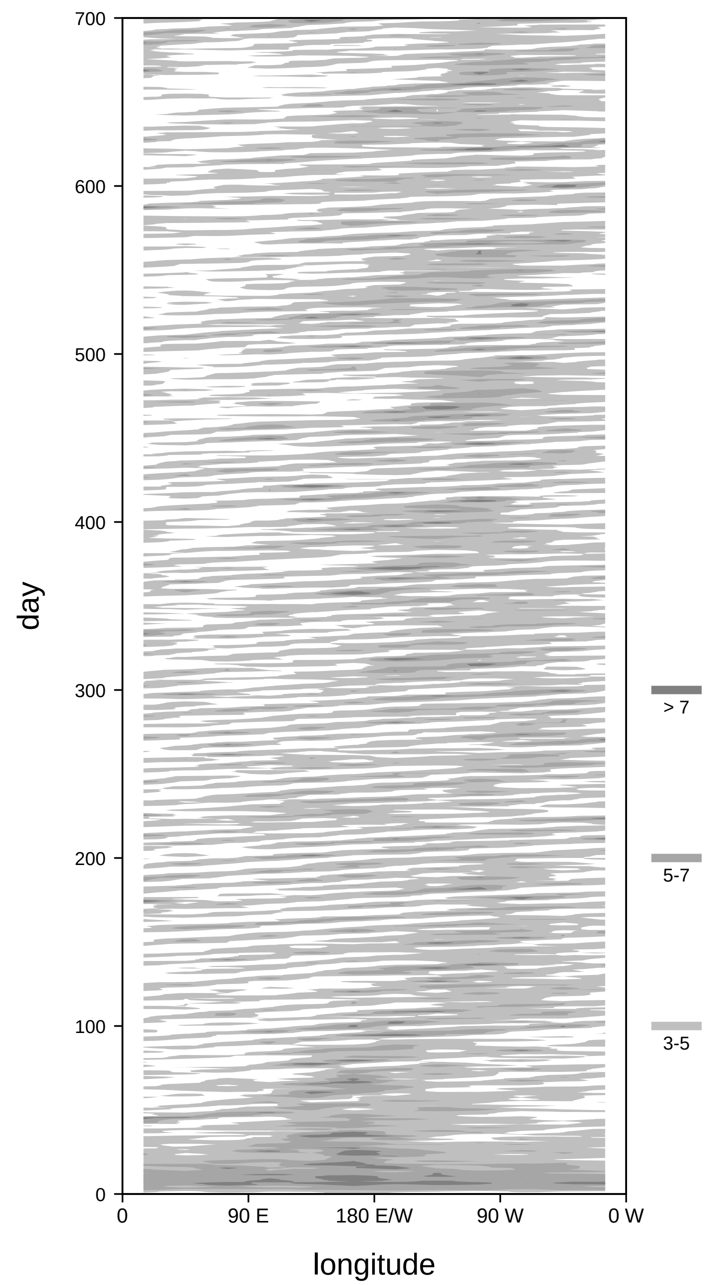
Convectively Coupled Kelvin Waves

Haertel and Straub (2010)

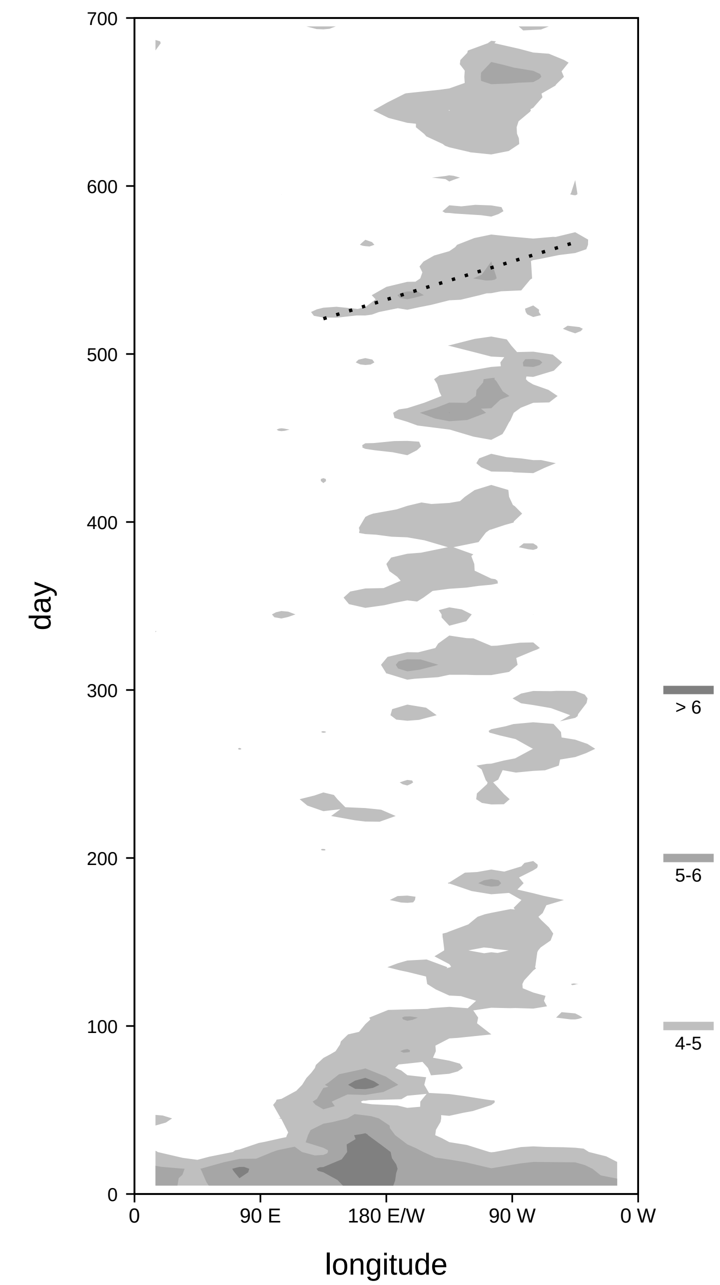


Apparent Madden Julian Oscillation

rainfall

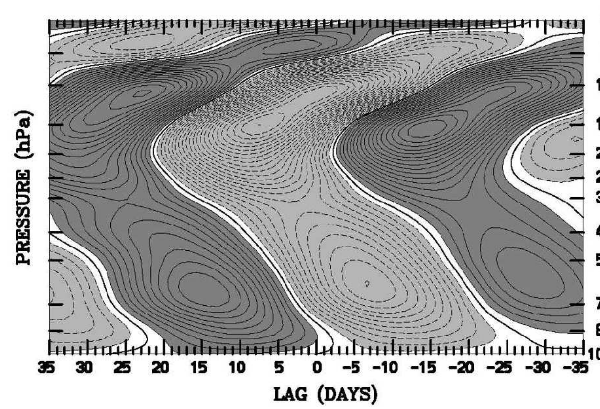


low-pass (> 10 day) rainfall

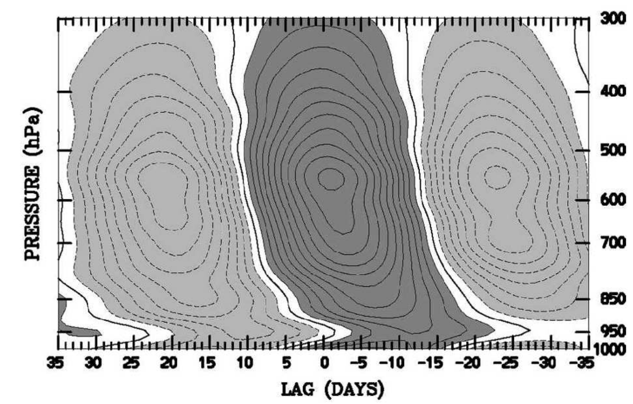


Observed and Simulated Vertical Structure of the Madden Julian Oscillation

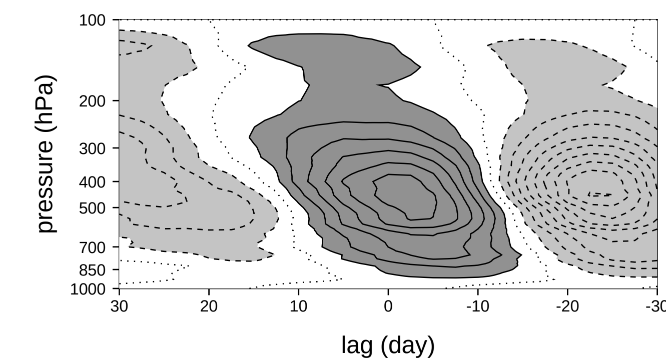
observed u (0.5 m/s)



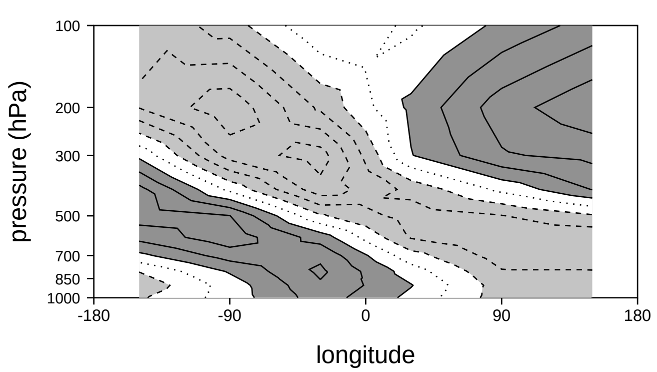
observed q (0.1 g/kg)



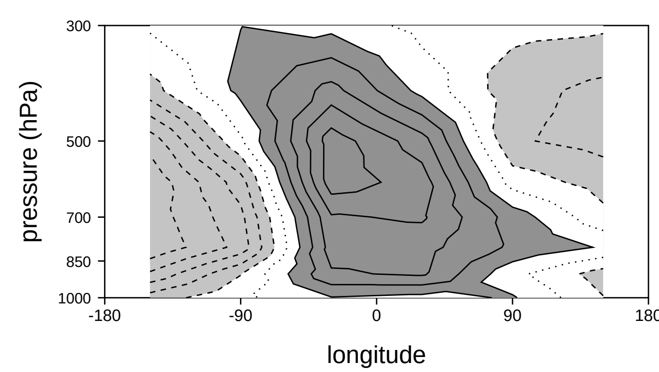
observed heating (0.5 K/day)



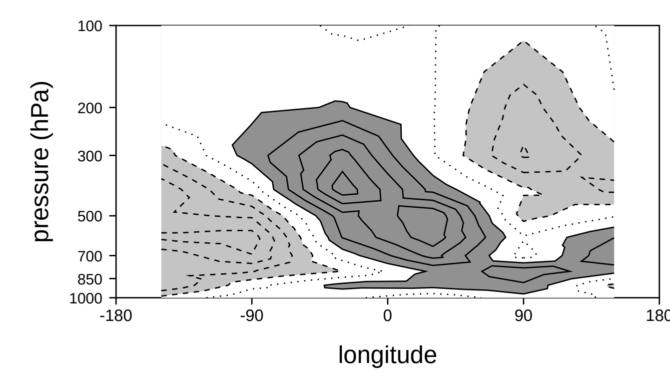
simulated u (0.5 m/s)



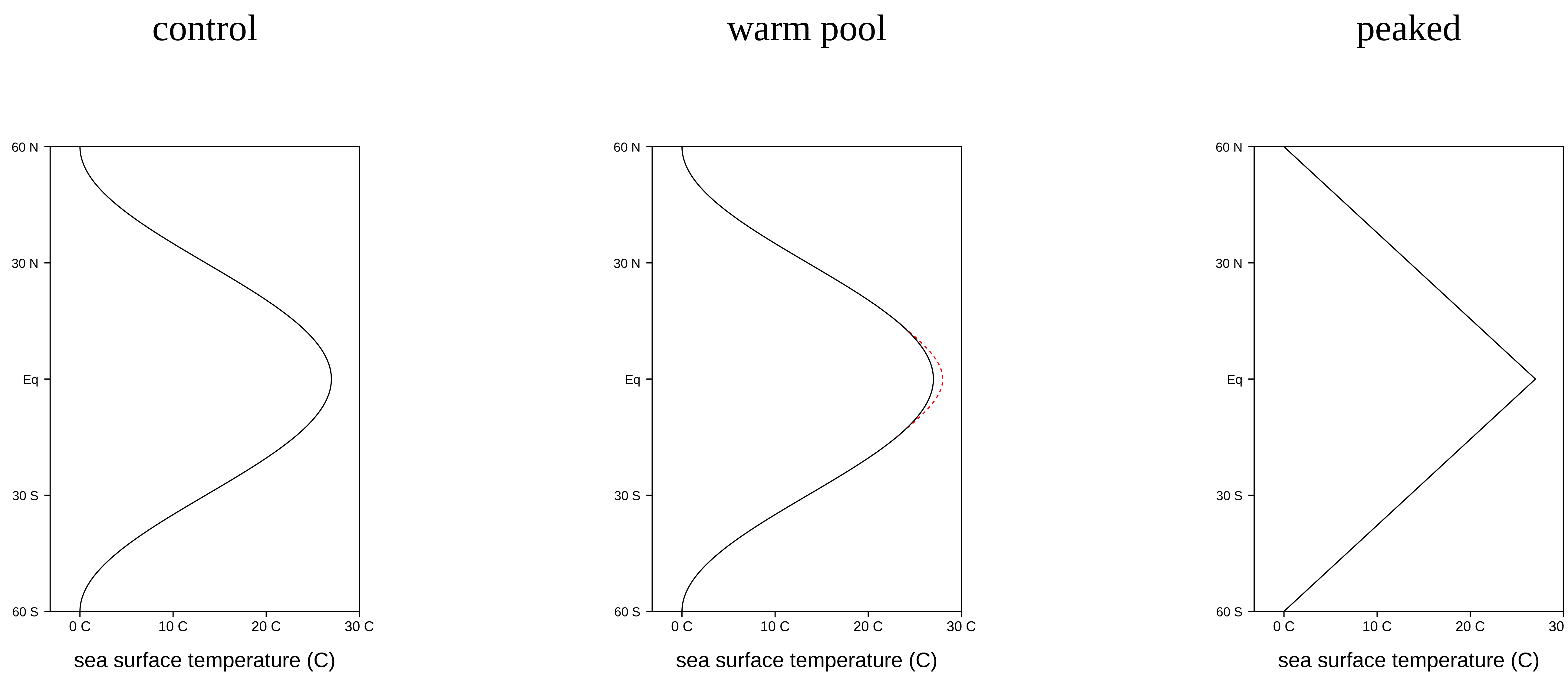
simulated q (0.1 g/kg)



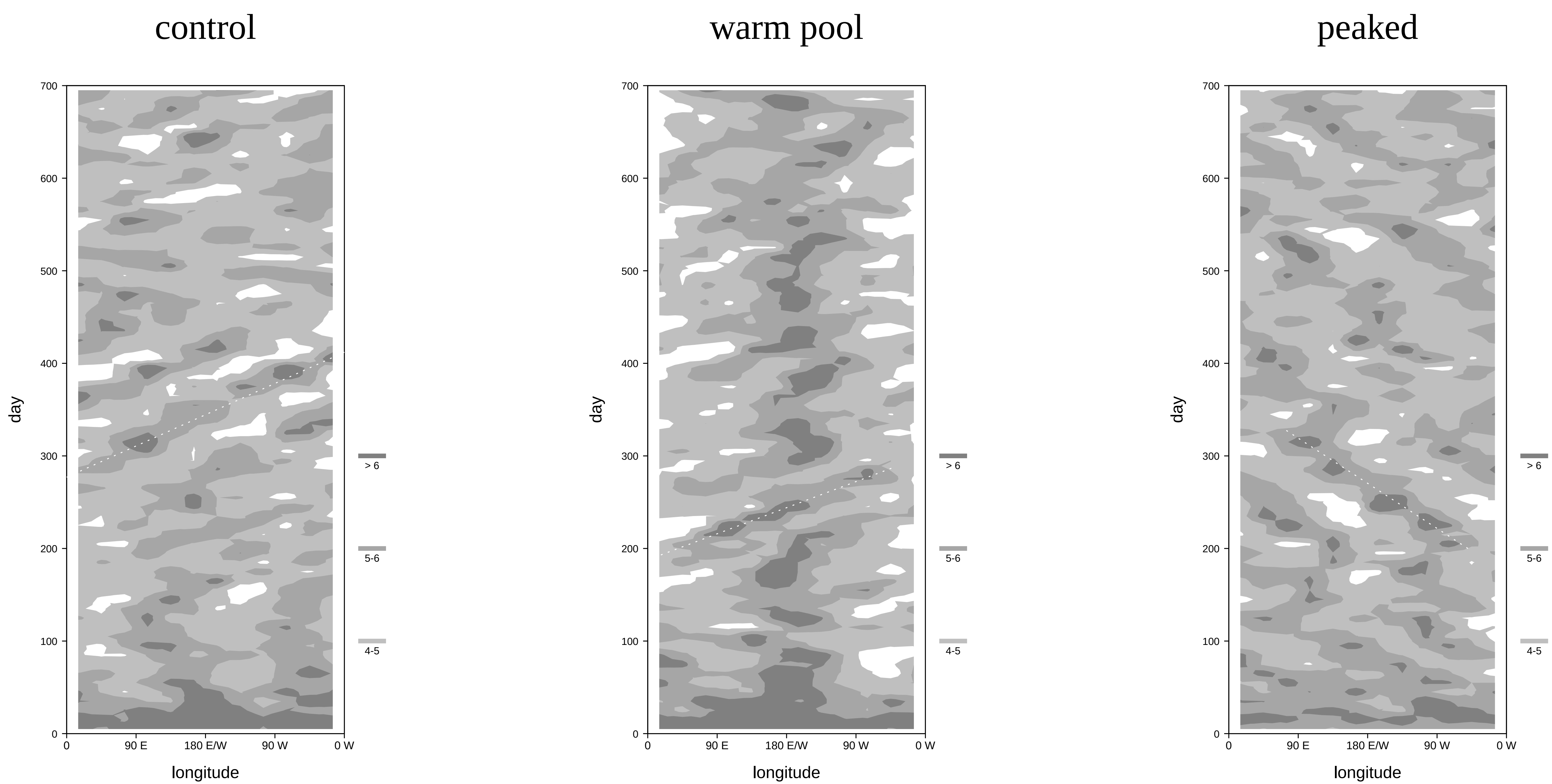
simulated heating (0.1 K/day)



Sea Surface Temperature for Preliminary Aqua Planet Experiment (APE) Runs



Filtered Rainfall for Preliminary Aqua Planet Experiment (APE) Runs



Summary

- Simulating the multi-scale structure of tropical convection continues to be a challenge for climate models. For example, in the case of AR4 climate models only half have a spectral signal of Kelvin waves, about one-quarter have realistic spatial distributions, and 2 or 3 models have qualitatively correct vertical structures.
- Over the past decade I have developed a lagrangian numerical method that simulates fluid circulations by predicting motions of parcels. This method successfully simulates a range of lake and ocean phenomena including: upwelling, boundary currents, thermocline structure, meridional overturning, tropical instability waves, equatorial undercurrents
- In recent applications to the atmosphere in an Aquaplanet setting Kelvin waves with realistic temperature and wind structures spontaneously form. The LAM also generates MJOs with realistic horizontal structure and propagation, titled wind, moisture and heating perturbations, and a convective life cycle like that seen in nature.

Questions ? ? ?

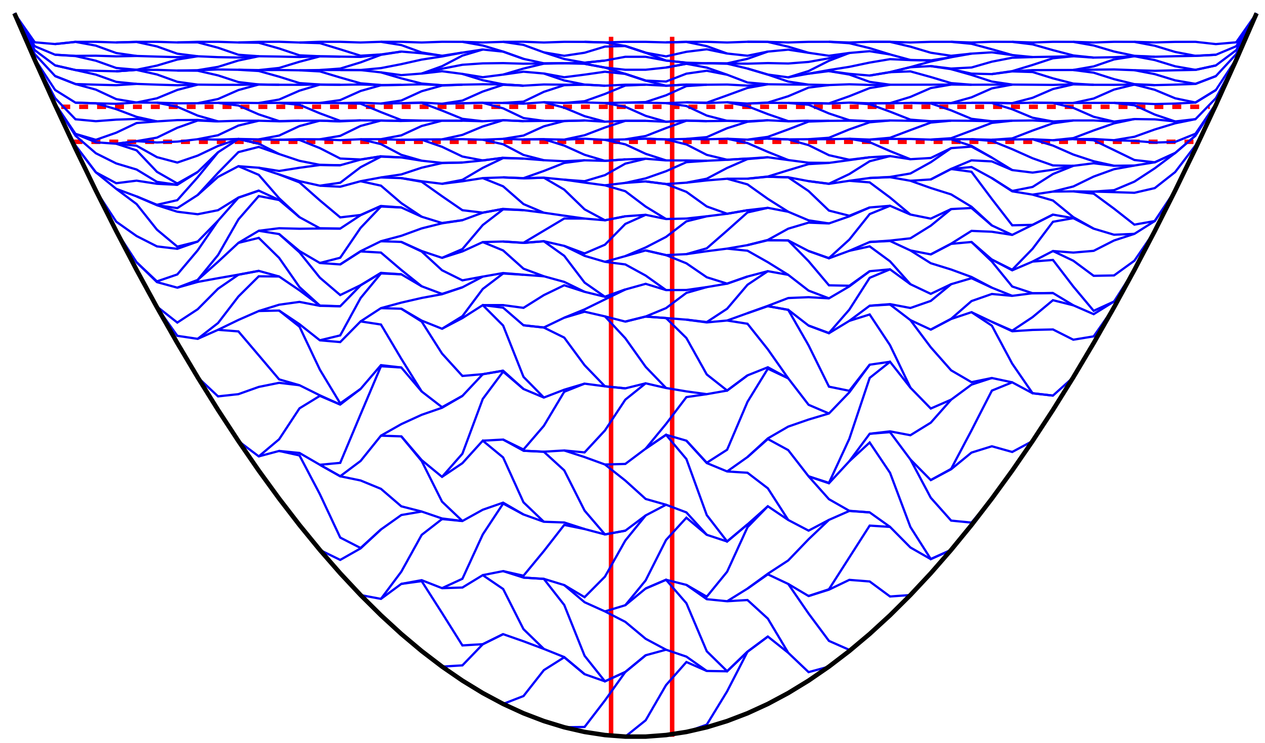
Future Work

- Studying the mechanism, shear sensitivity, and upscale transports of Kelvin waves simulated with the LAM

- Identifying the driving force behind MJO-like disturbances in the LAM, and what determines whether MJOs or Equatorial Rossby waves are favored

- Conducting the full suite of aqua planet experiments for the LAM, and examining circulations, rainfall patterns, and other kinds of tropical convective systems.

Mixing Columns and Rows



Equations of Motion

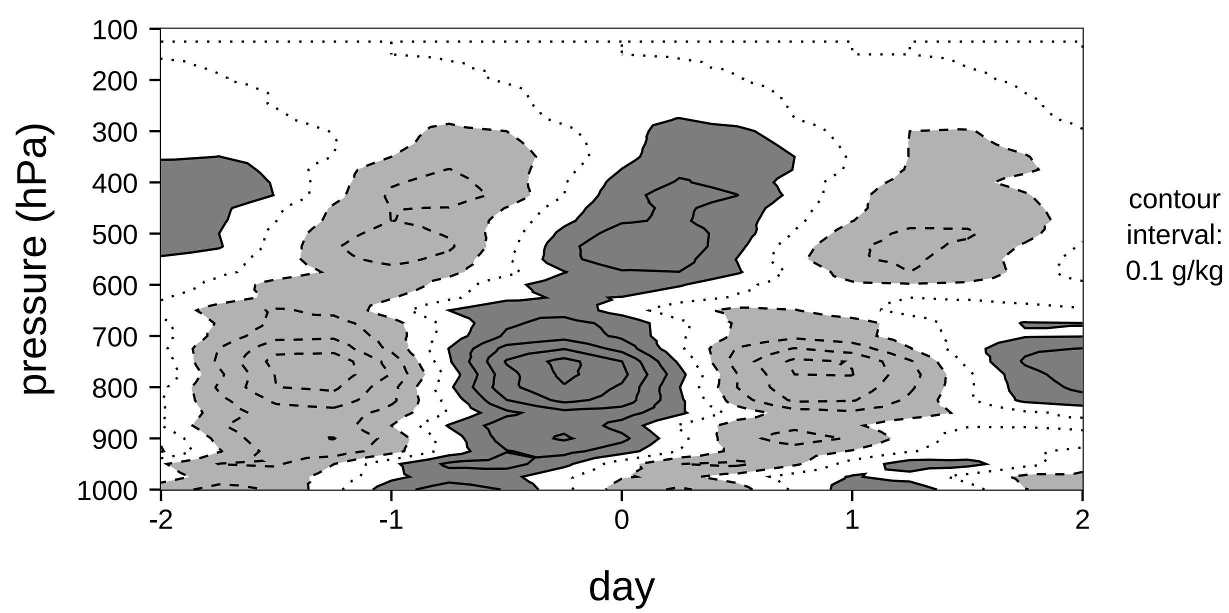
$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} + f\ \mathbf{k} \times \mathbf{v} = \mathbf{A}_p + \mathbf{A}_m$$

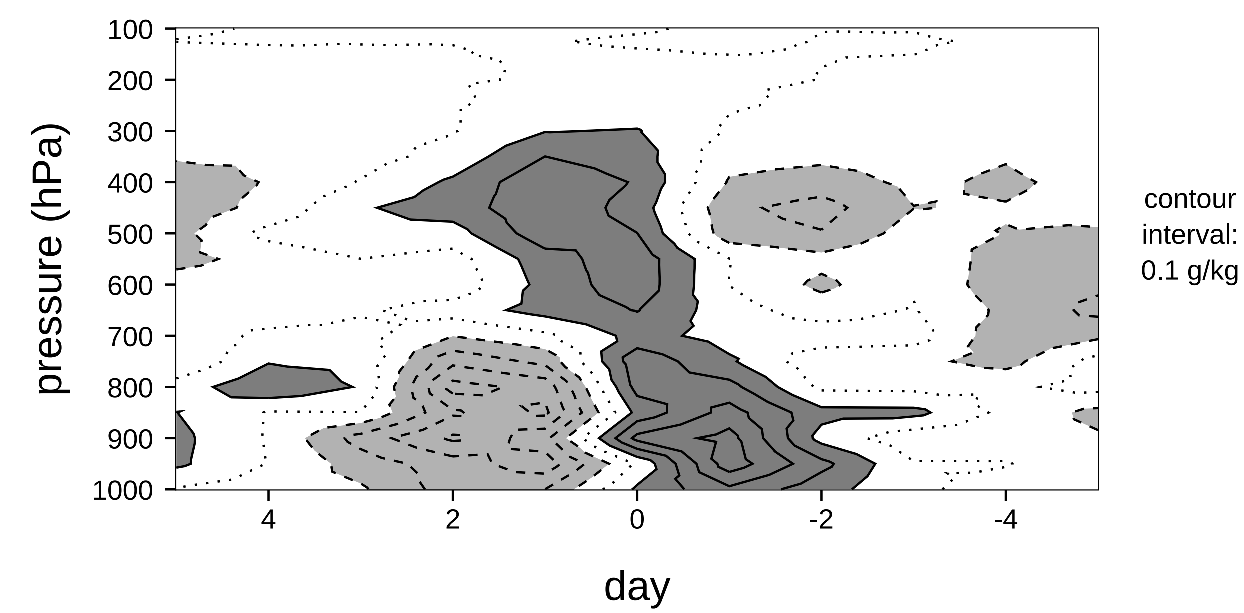
$$\mathbf{A}_p = -\frac{1}{W} \int_H \delta p \nabla M\ dA$$

Observed Moisture Perturbations

2-Day Wave (Haertel and Kiladis 2004)



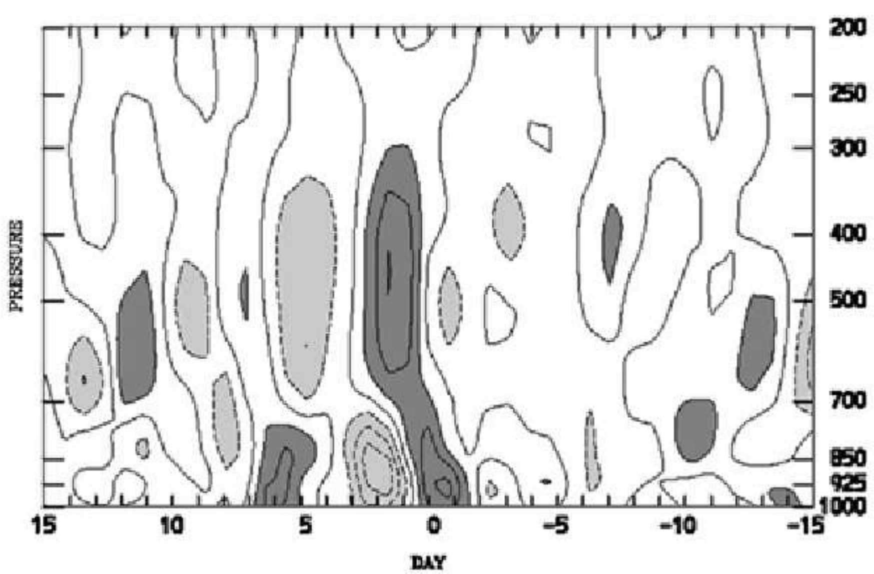
Kelvin Wave (Straub and Kiladis 2003)



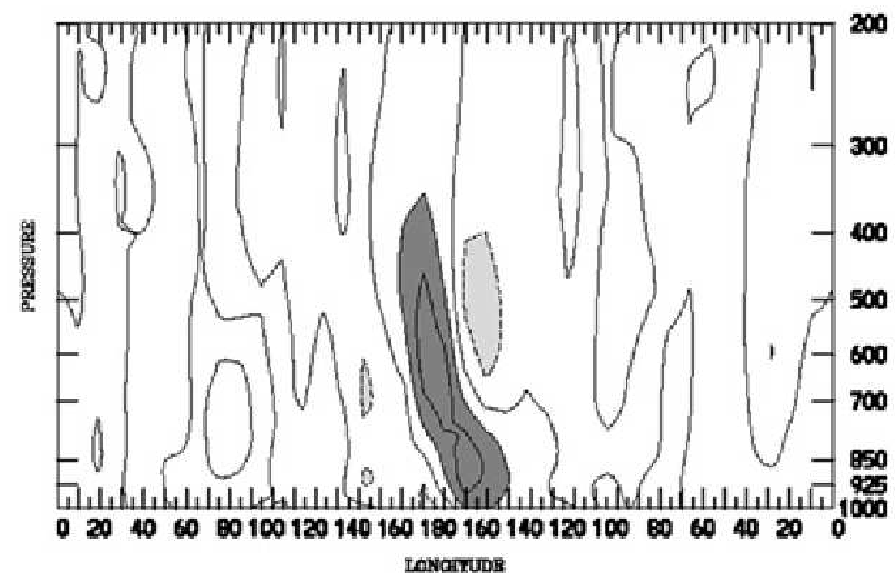
Vertical Structure of Moisture for Kelvin Waves in Climate Models

Straub et al. (2010)

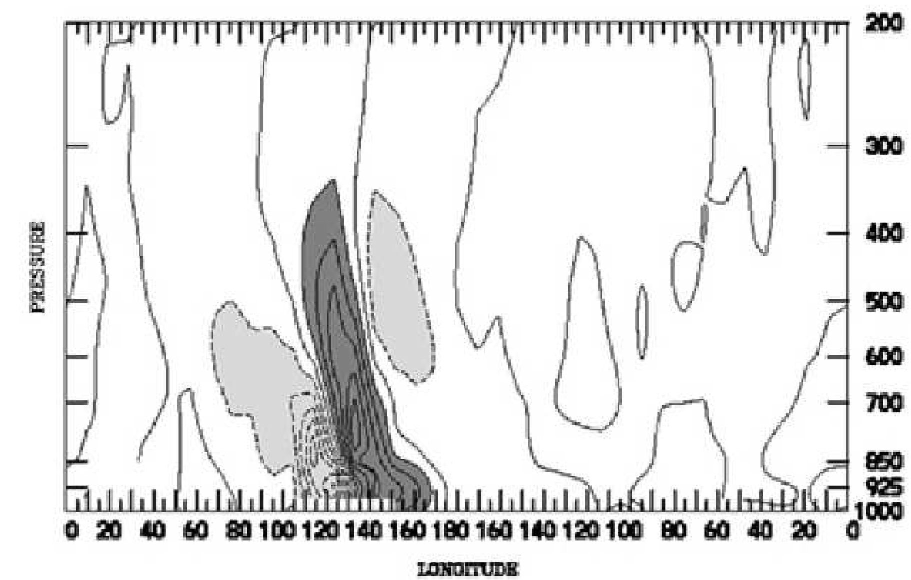
Observed



Climate Model 4

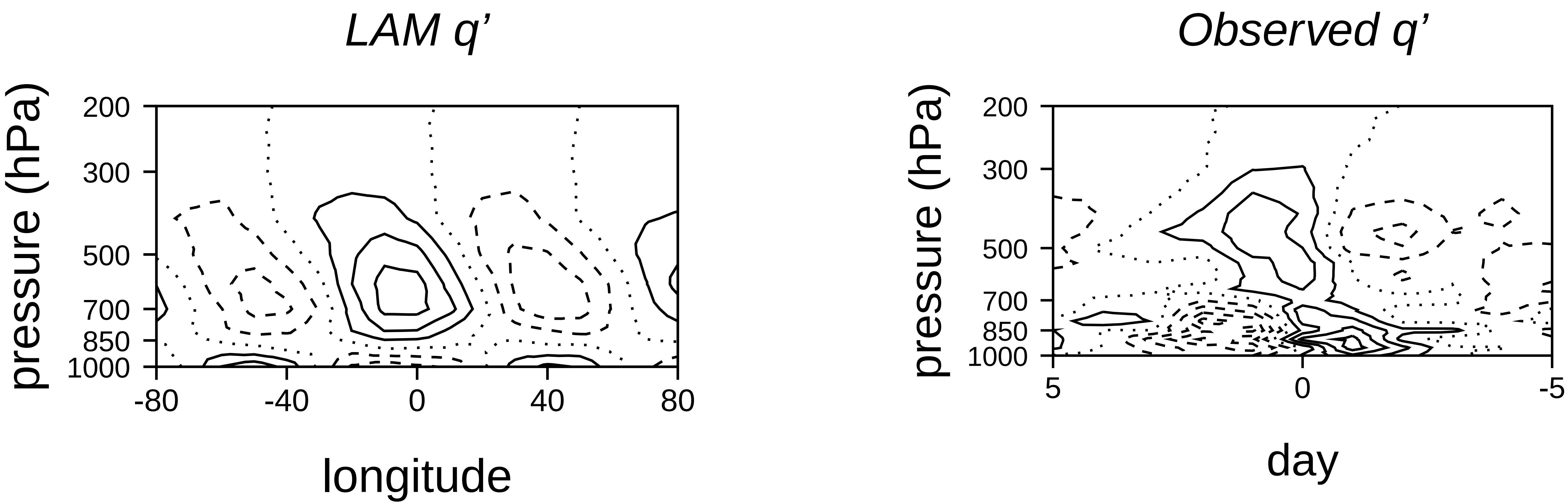


Climate Model 5



Convectively Coupled Kelvin Waves on an Aqua Planet

Haertel and Straub (2010)



Extra: Vertical Structures: EIG, MRG, ER, MJO Understanding LO through an Oil and Water Thought Experiment 2D CCGWs squall system ?