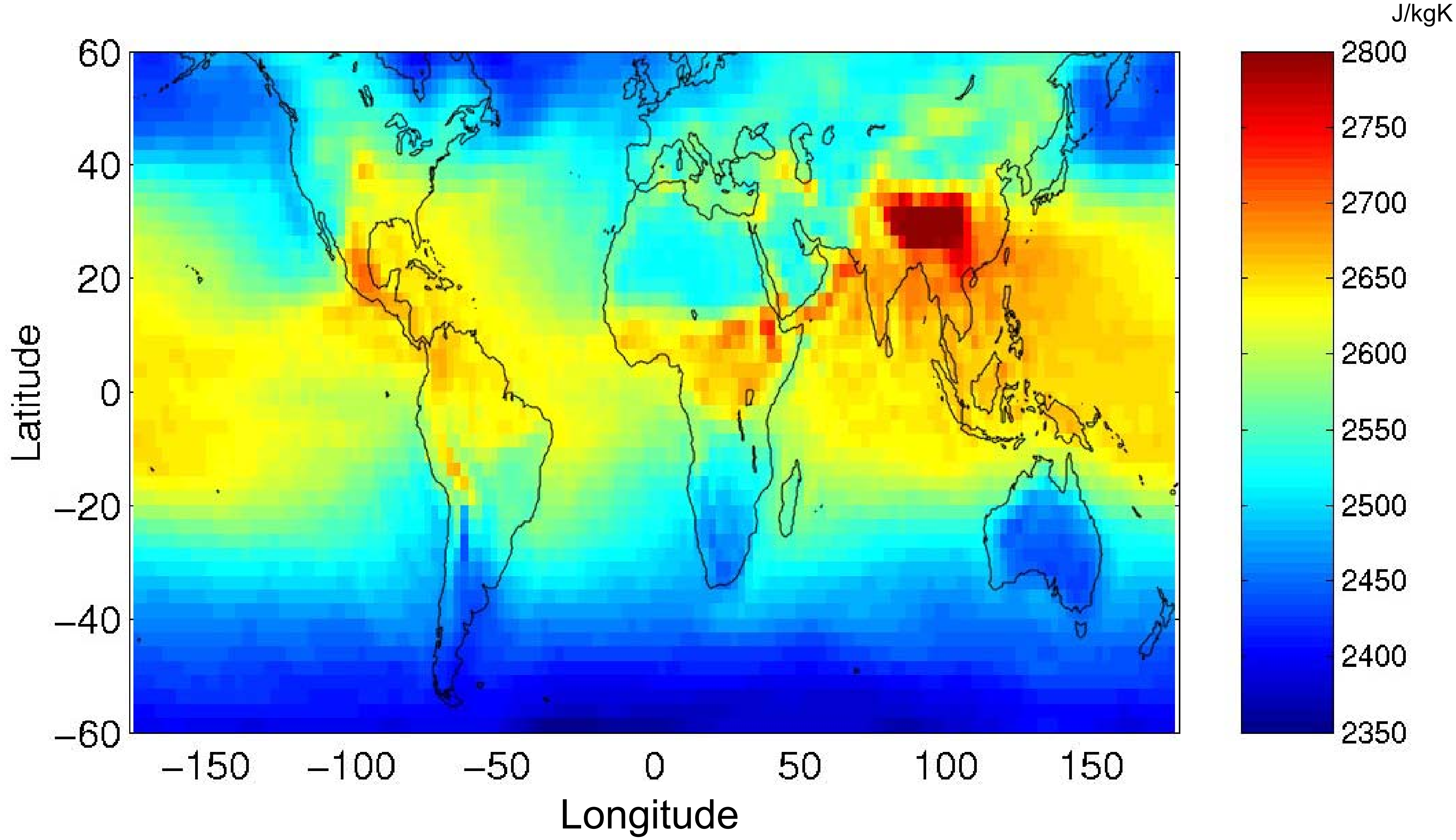
Physical Origins of the Monsoon

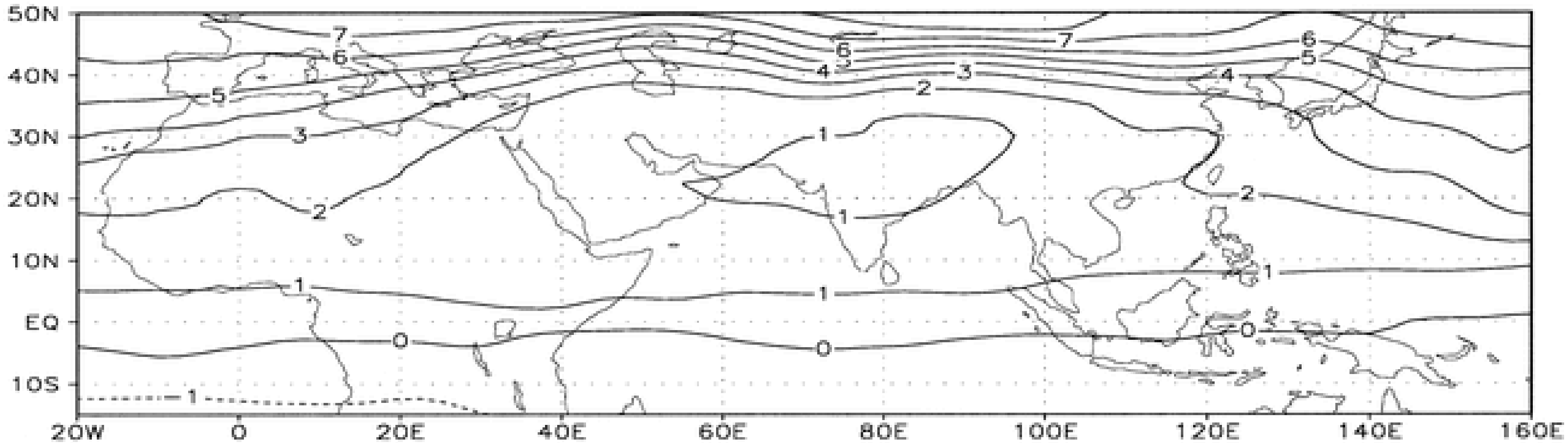
See figures on pages 24267-24270
In journal:
Molnar, and Emanuel. *Journal of Geophysical Research* 104 (1999): 24267-70.

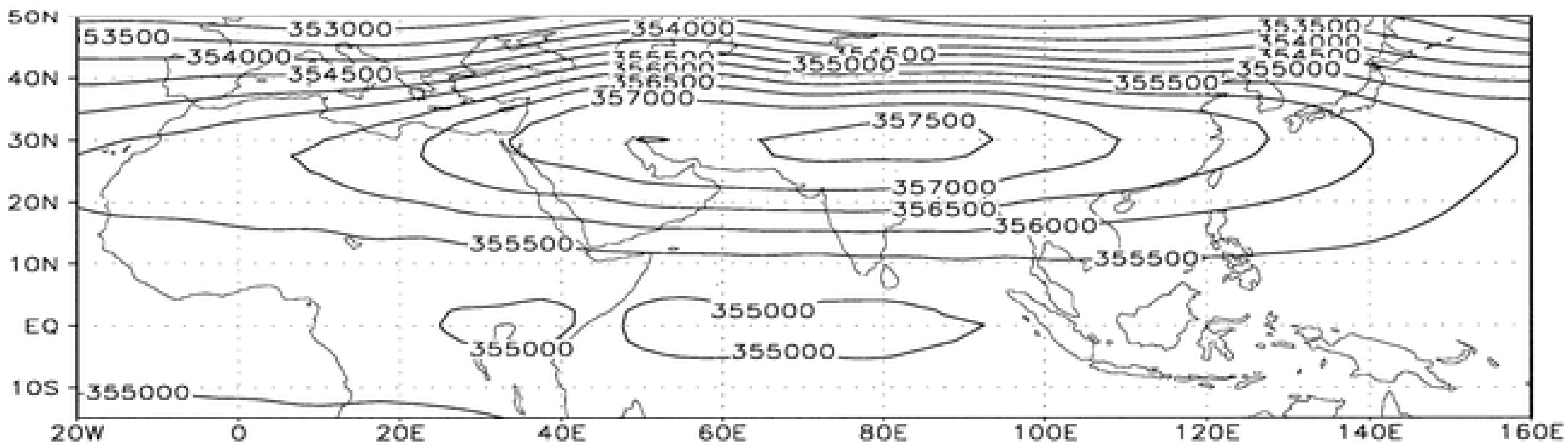
July 1 observed 1000 mb s_b



NCEP Reanalysis

PV, M, on 370K, Jul 87-90

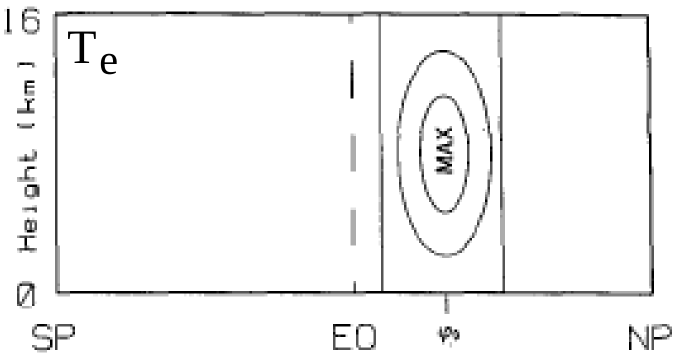


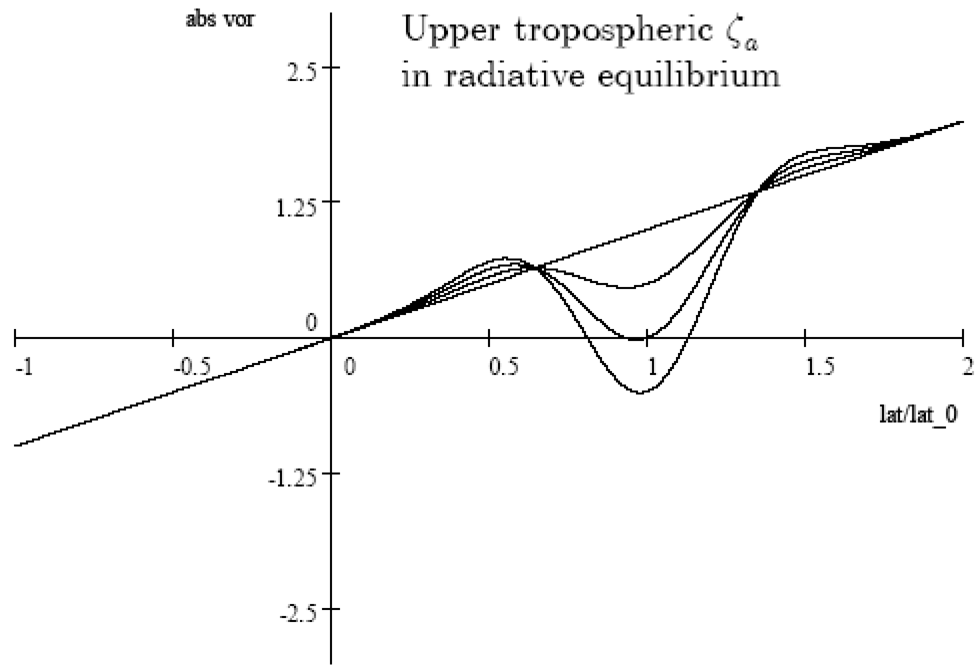


Two-D Simulations

Off-equatorial forcing in 2D

[Plumb & Hou, JAS, 1992]





Off-equatorial forcing

[Plumb & Hou, JAS, 1992]

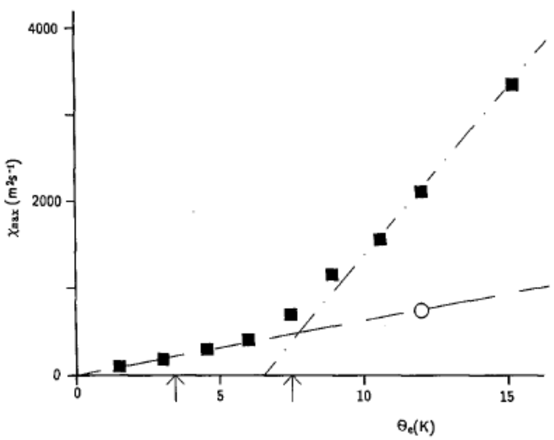
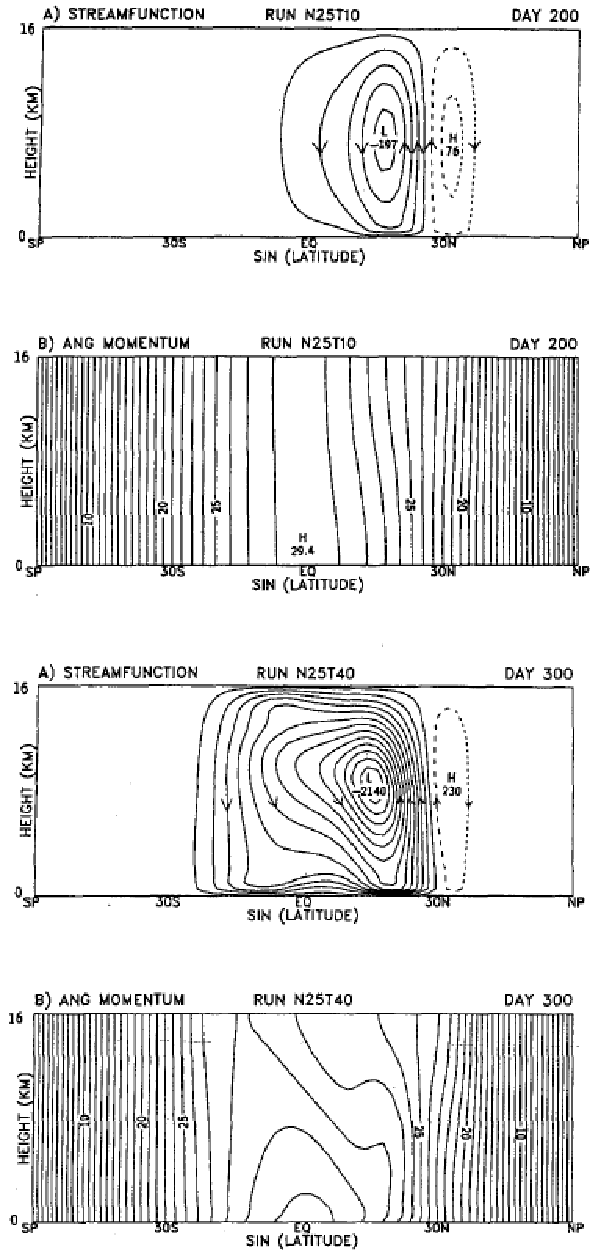
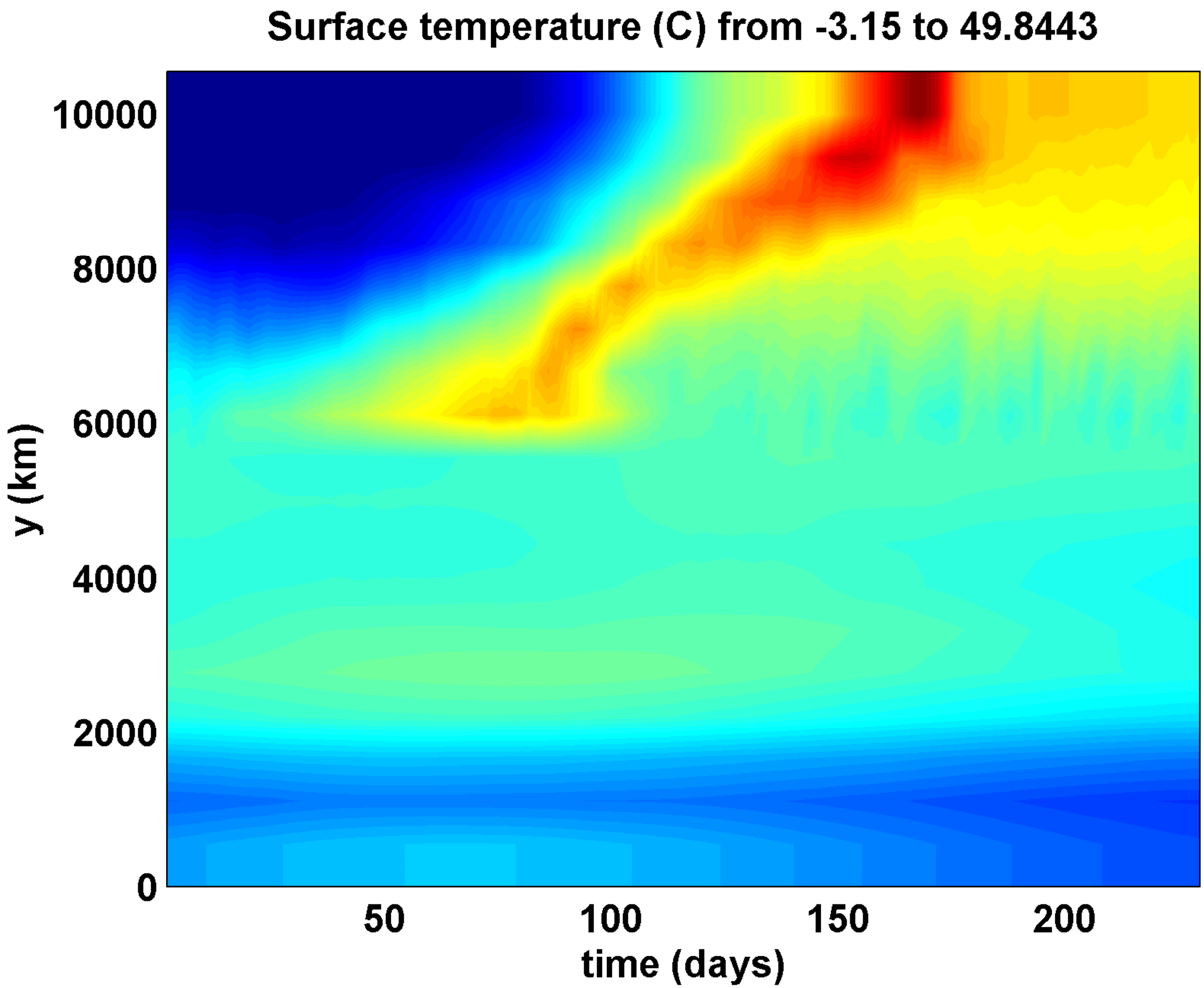


FIG. 4. Dependence of the maximum value of the steady streamfunction χ on the forcing amplitude Θ_e. The squares show points determined from results of the complete, nonlinear model. The circle shows a result from the linearized model, and the dashed line the linear dependence of χ_{max} on Θ_e. The steeper, dash–dot, line is drawn by eye and has no other significance. The two arrows show the theoretical value of Θ_e at which the TE solution becomes irregular; the left arrow is for the inviscid case, the right arrow for $\nu = 2.5\ m^2\ s^{-1}$ according to the linear model results.

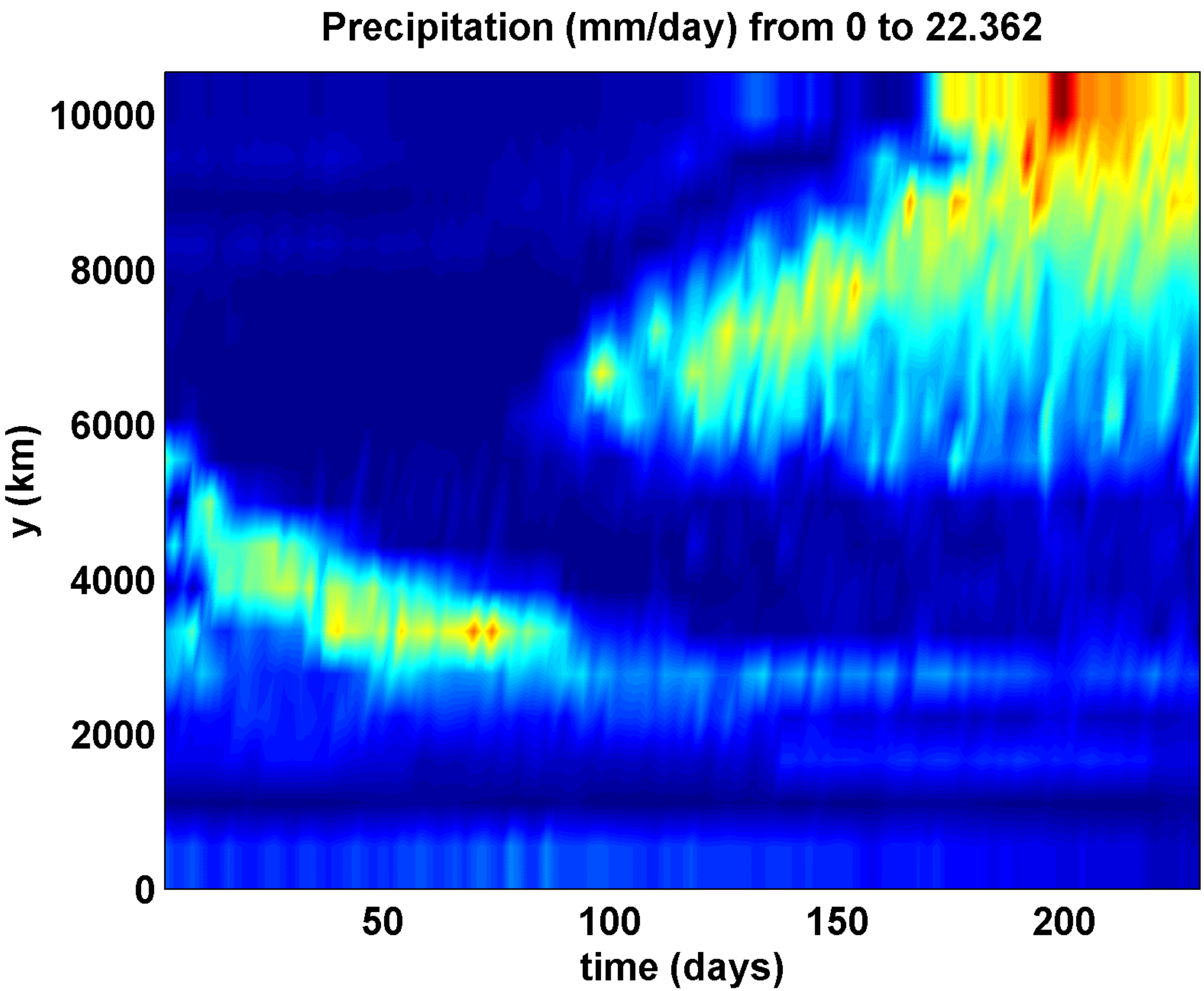


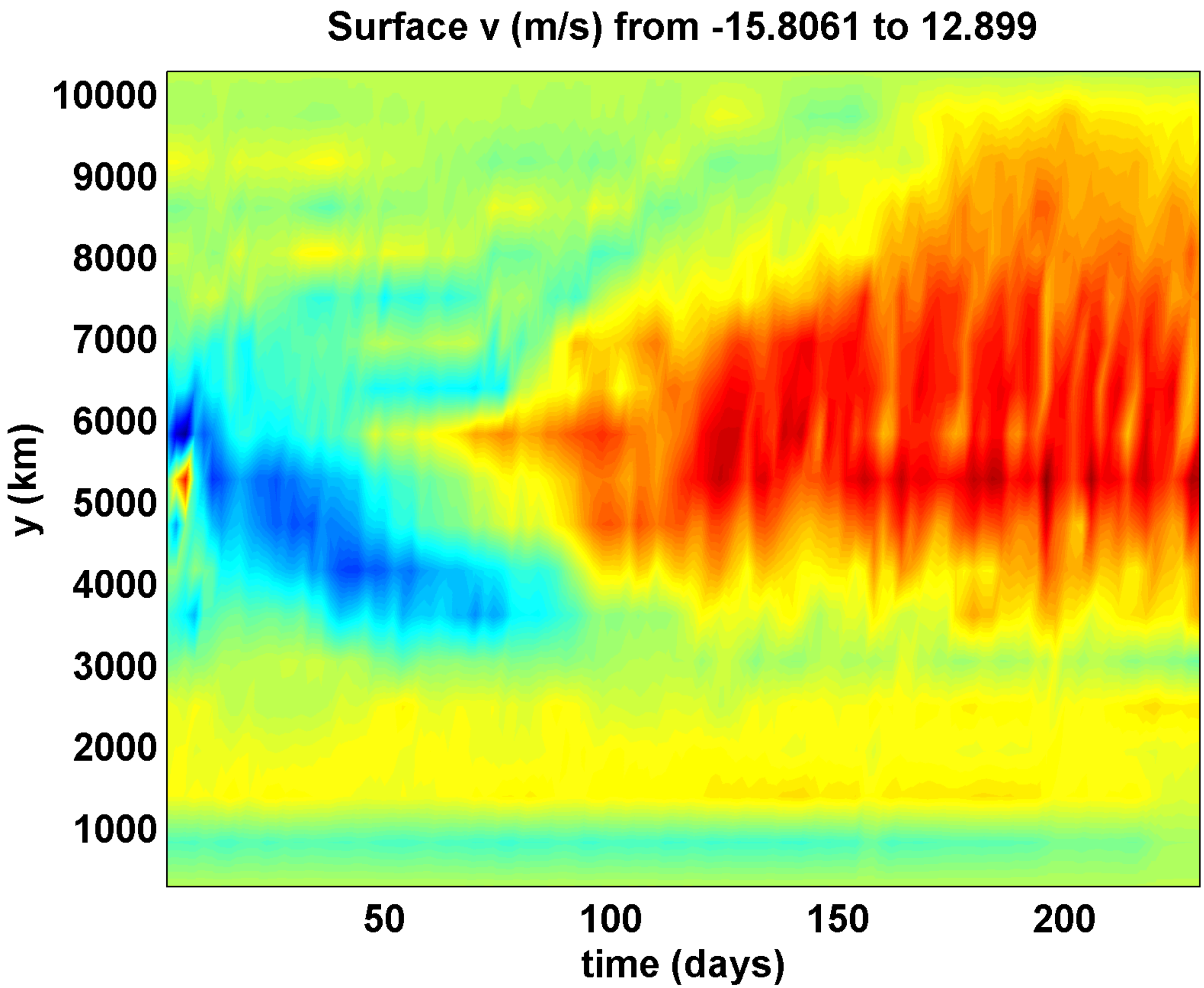
Simple PE Model

- Only 20 grid columns, N-S
- High resolution in vertical
- Convection, radiation, and cloud schemes
- Land poleward of 12 N (y=6000 km)
- Slab ocean
- Annual cycle of insolation

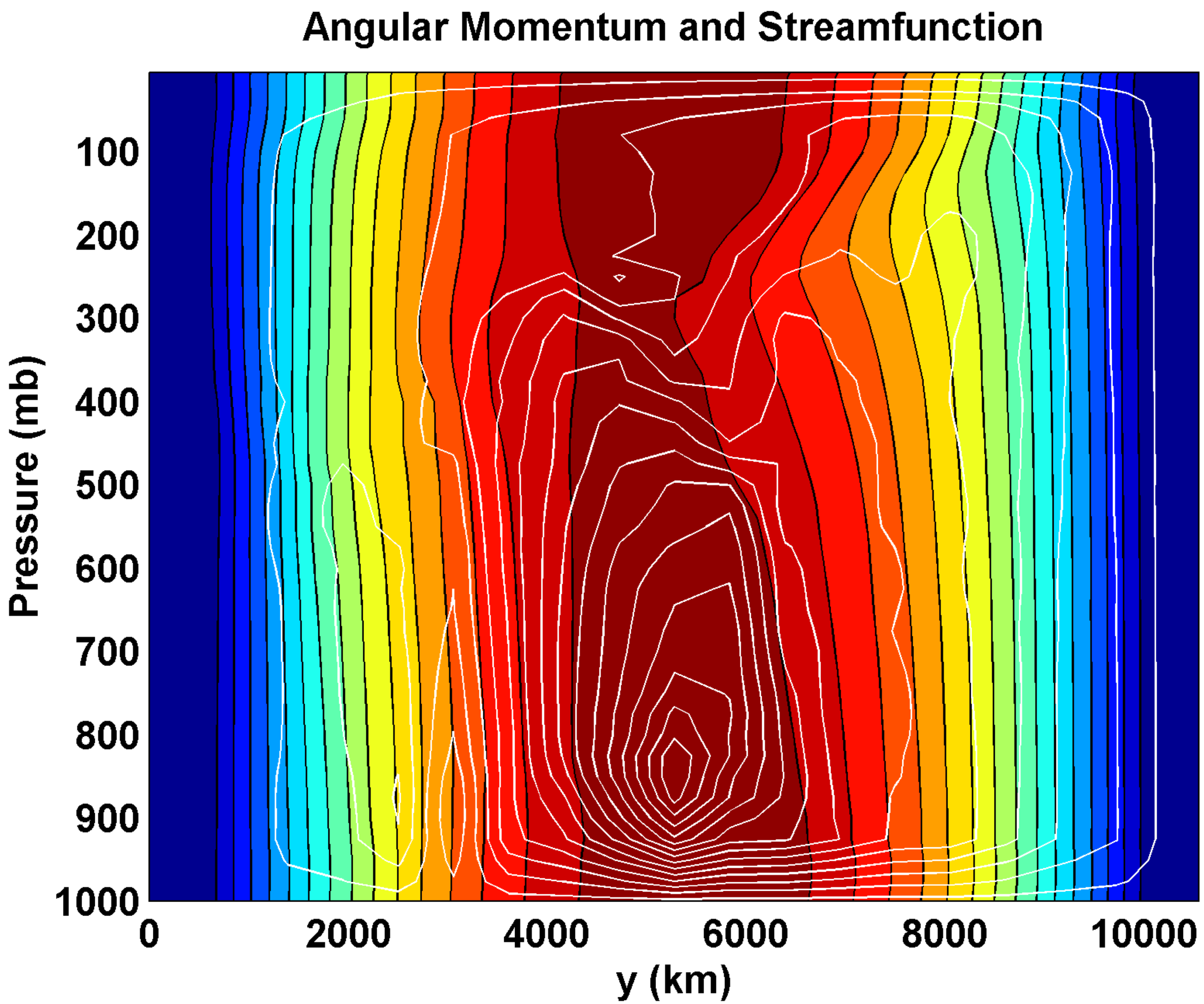


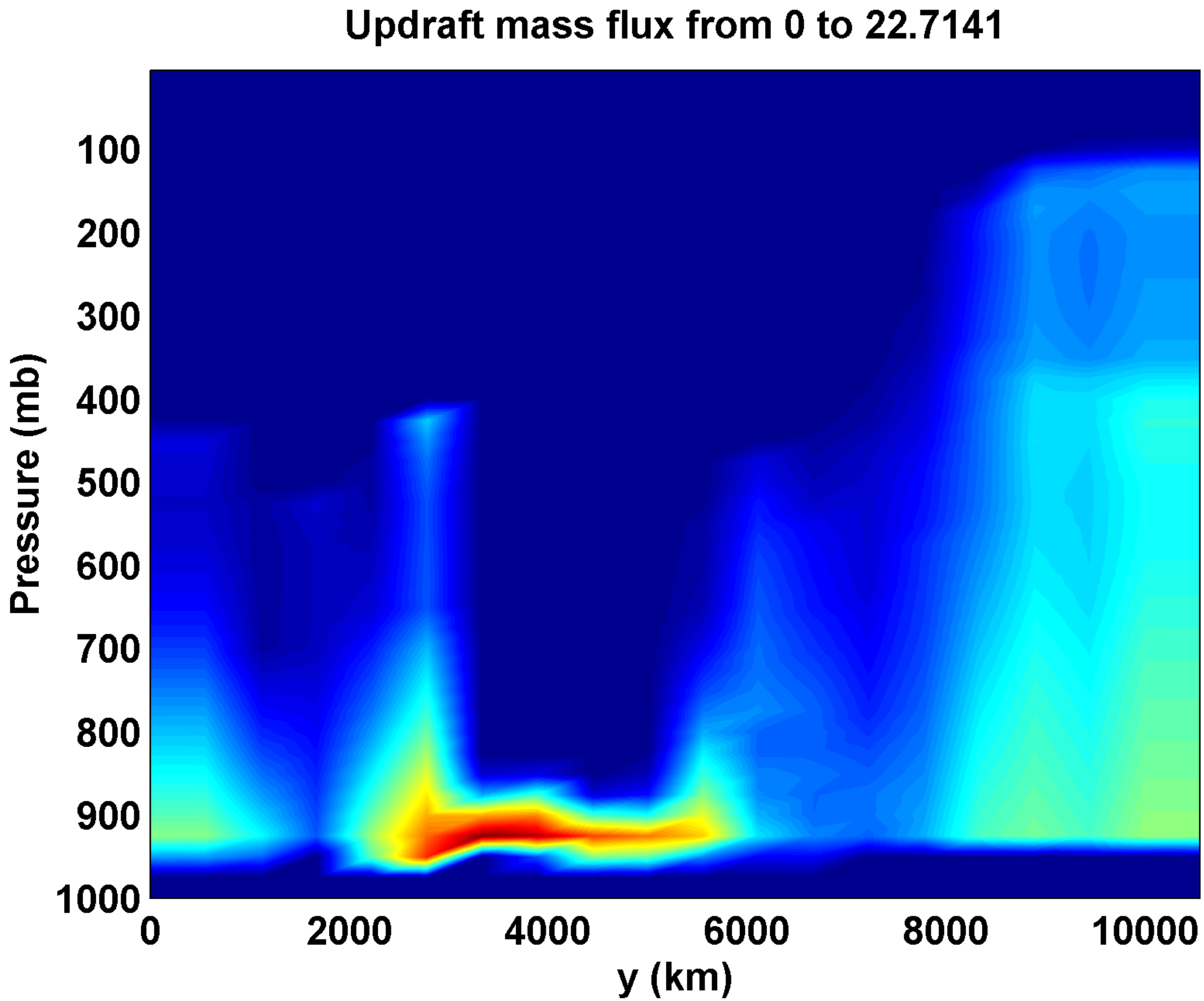
Surface temperature (C) from -3.15 to 49.8443
10000
8000
6000
4000
2000
0
y (km)
50
100
150
200
time (days)


Precipitation (mm/day) from 0 to 22.362
y (km)
0
2000
4000
6000
8000
10000
50
100
150
200
time (days)

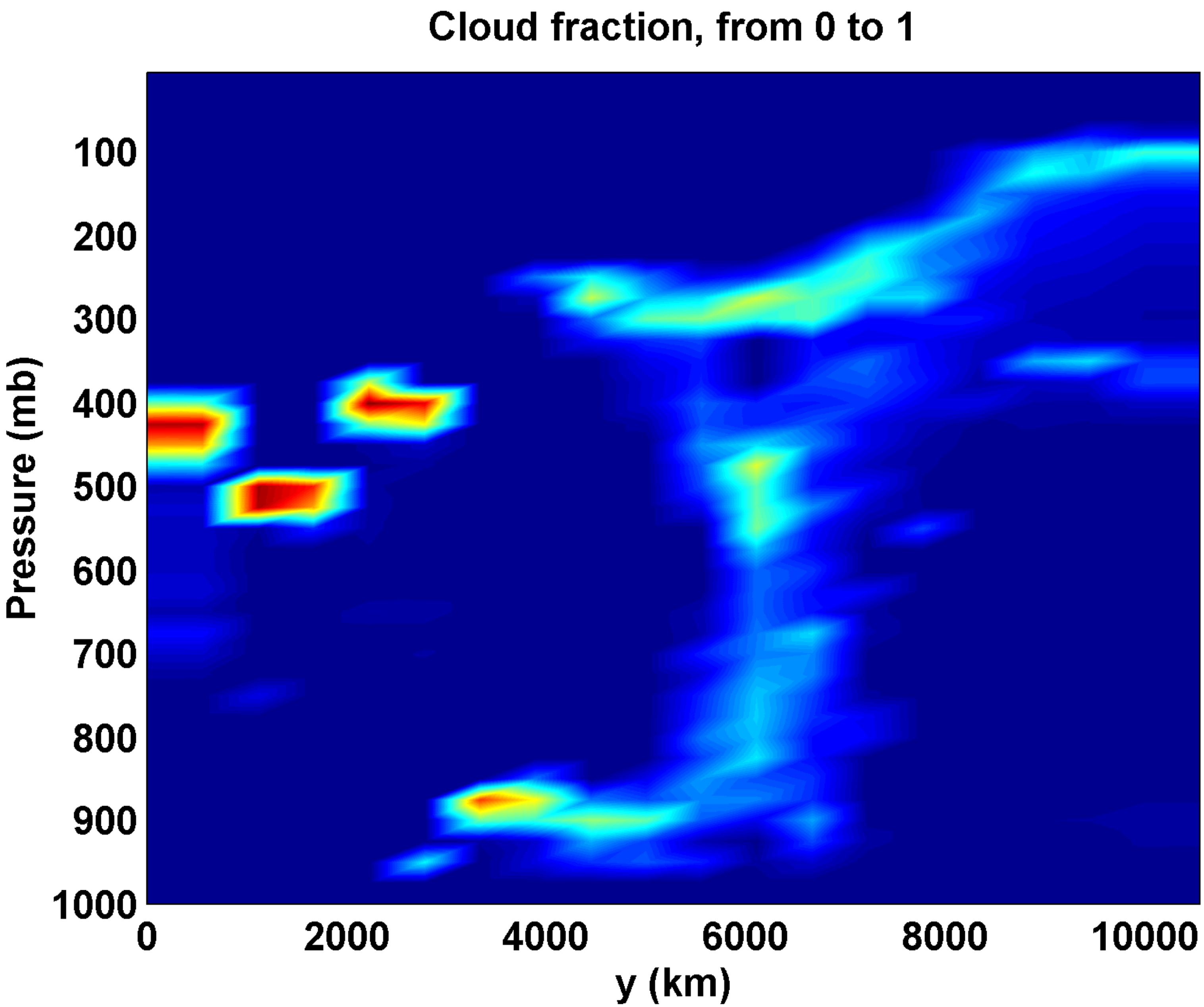


Surface v (m/s) from -15.8061 to 12.899
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
y (km)
50
100
150
200
time (days)

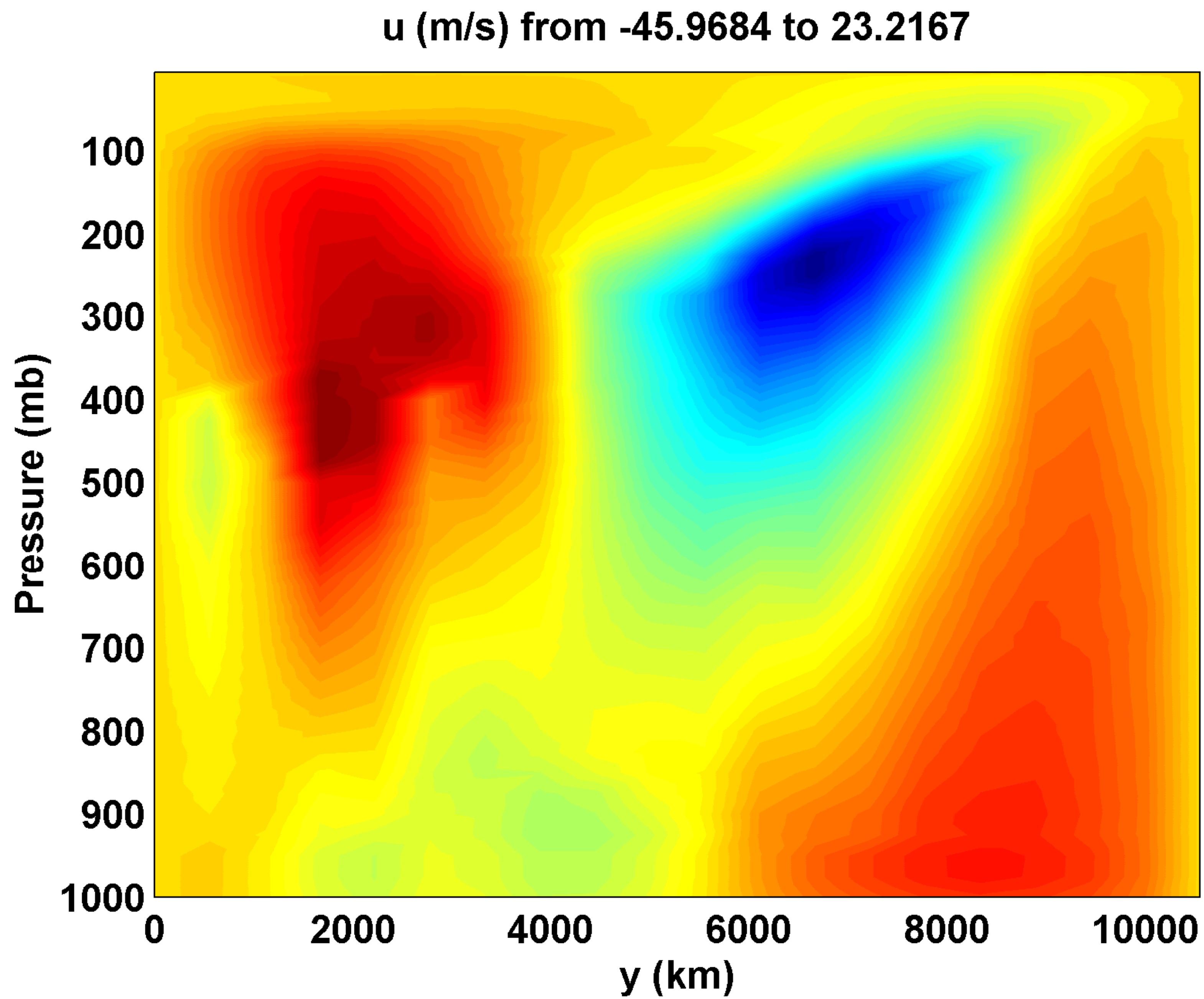

Angular Momentum and Streamfunction
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)

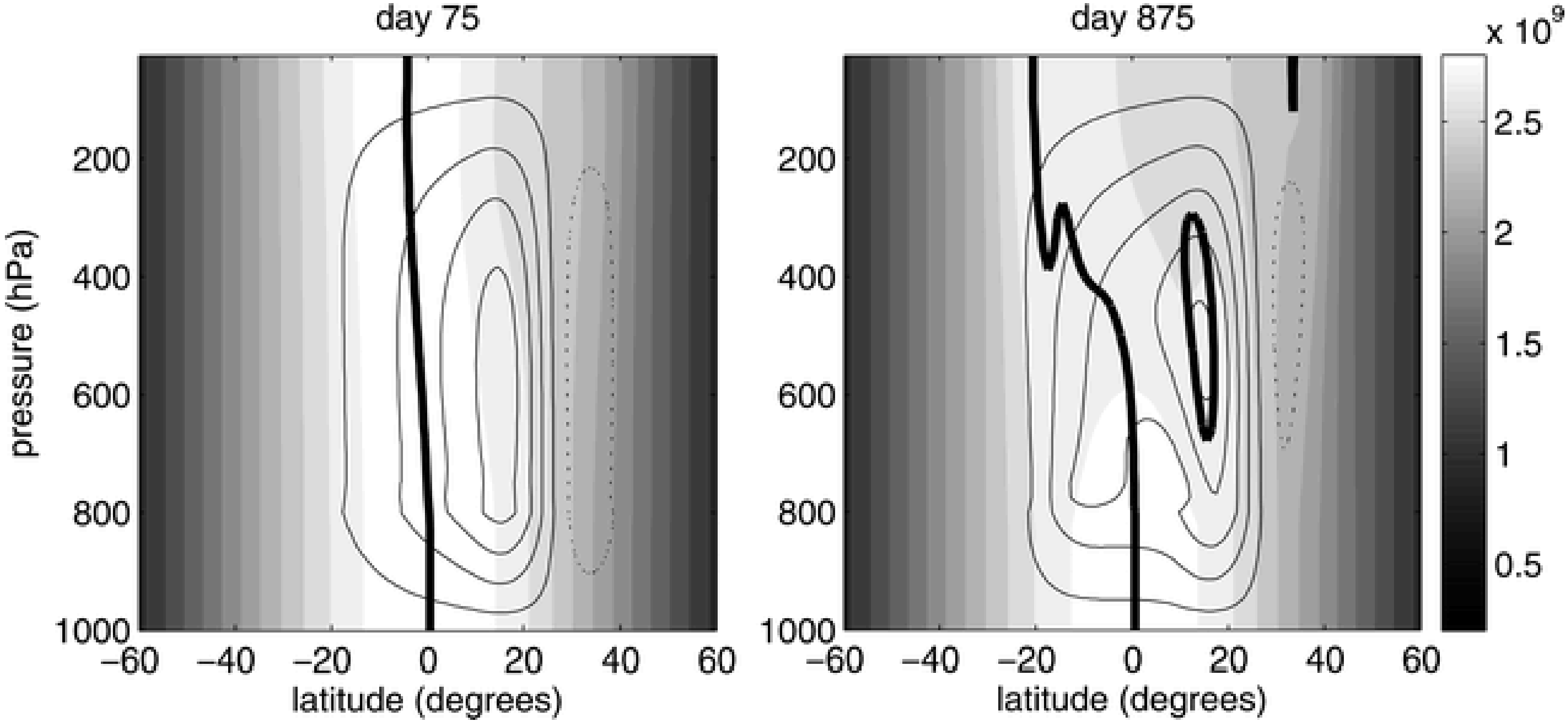


Updraft mass flux from 0 to 22.7141
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)

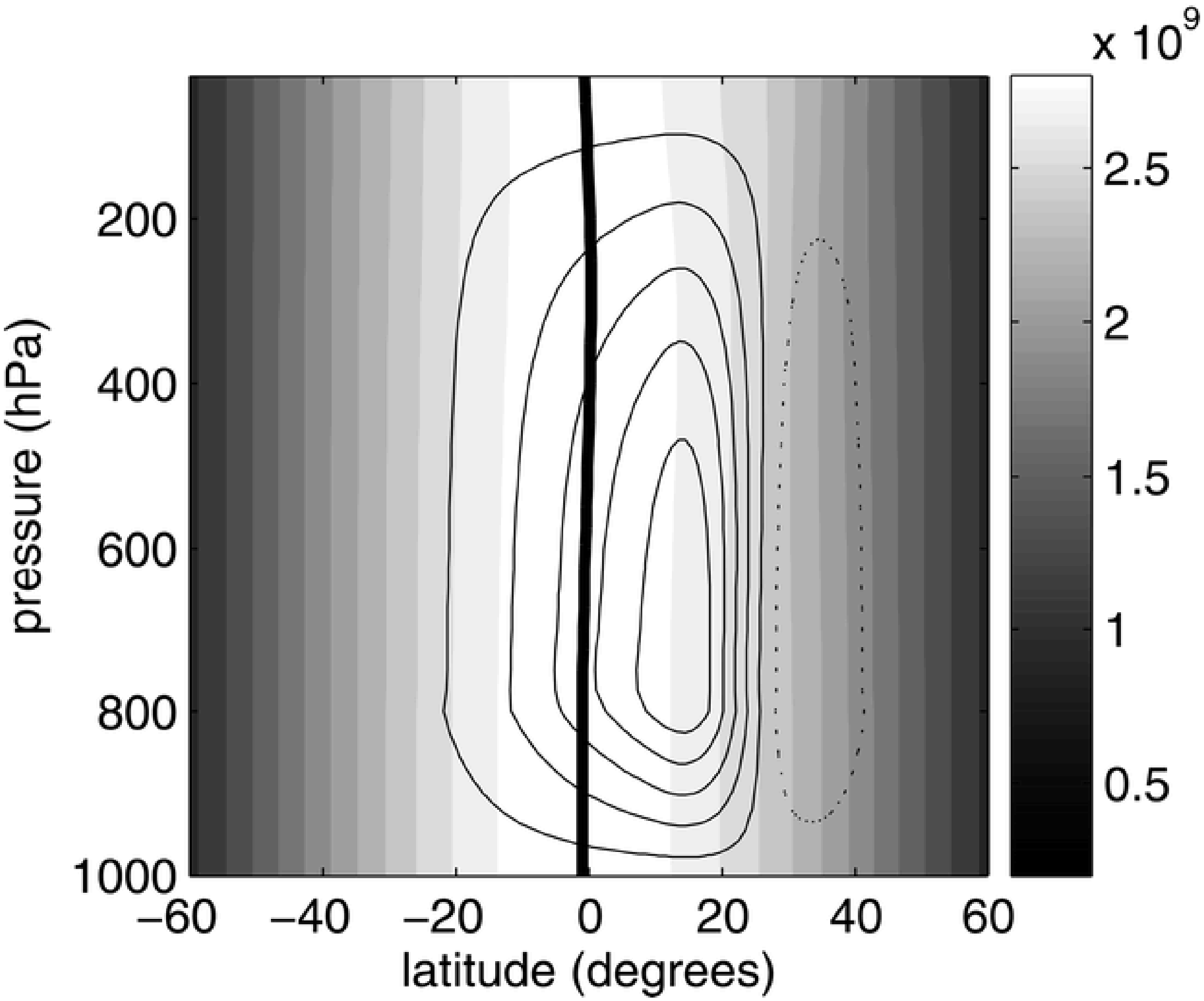


Cloud fraction, from 0 to 1
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)

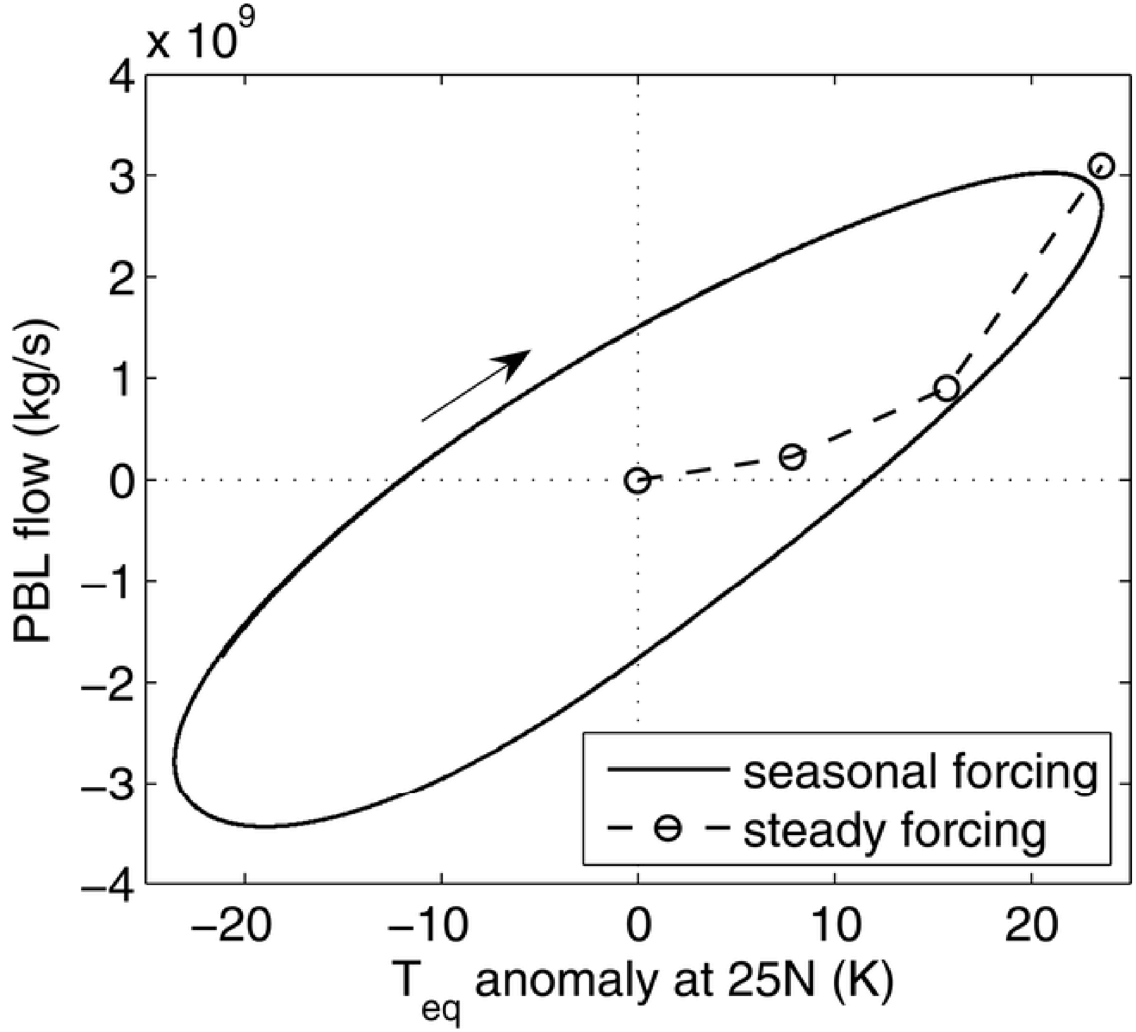

u (m/s) from -45.9684 to 23.2167
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)



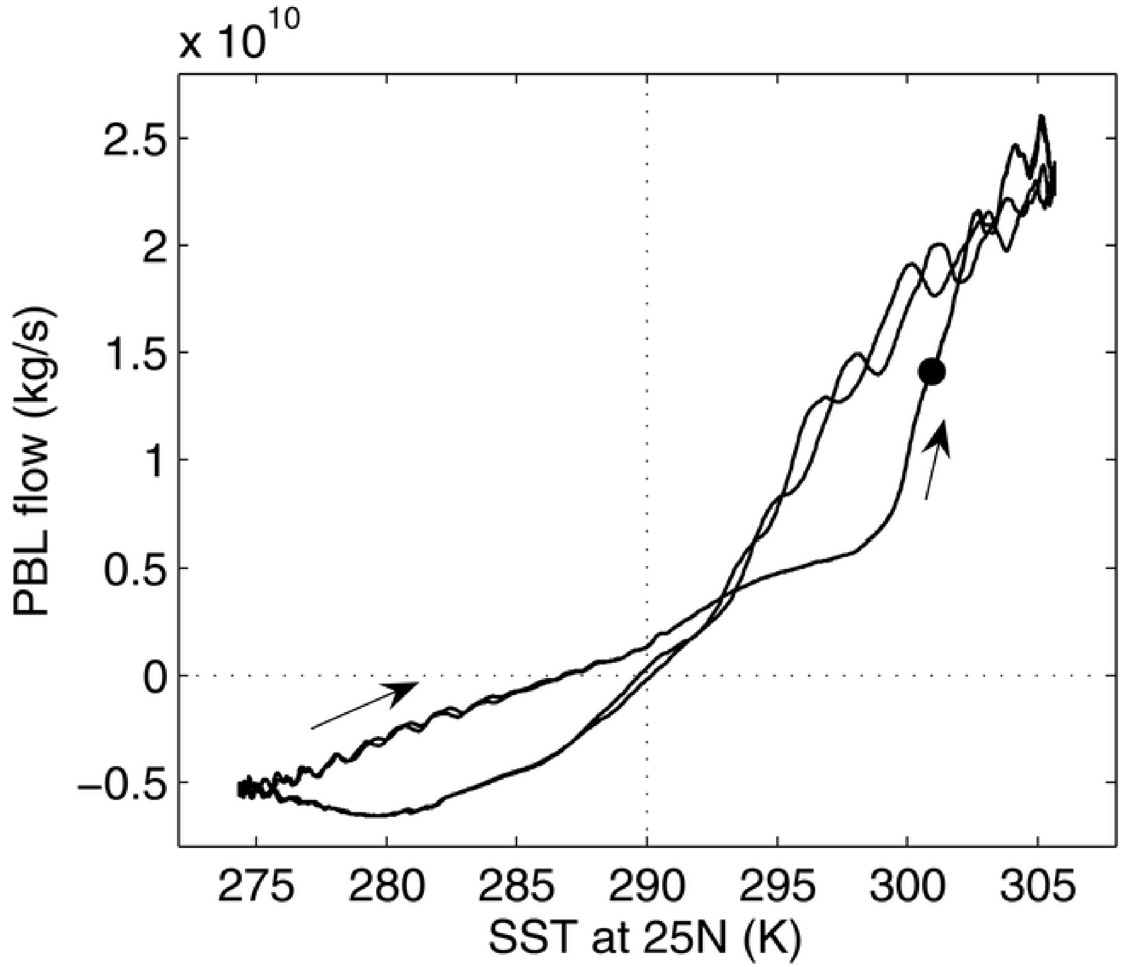
Absolute angular momentum (shading) and meridional streamfunction (thin contours) for the dry GCM with steady forcing and θ_m = 15 K (left) at the initial transient peak and (right) after the model achieved a steady state. Thick solid line is the zero absolute vorticity contour. Streamfunction contour interval is 1×10^{10} kg s^{-1}, starting at 0.5×10^{10} kg s^{-1}, with negative contours (denoting clockwise rotation) dashed. Angular momentum contour interval is 0.2×10^9 m^2 s^{-1}.



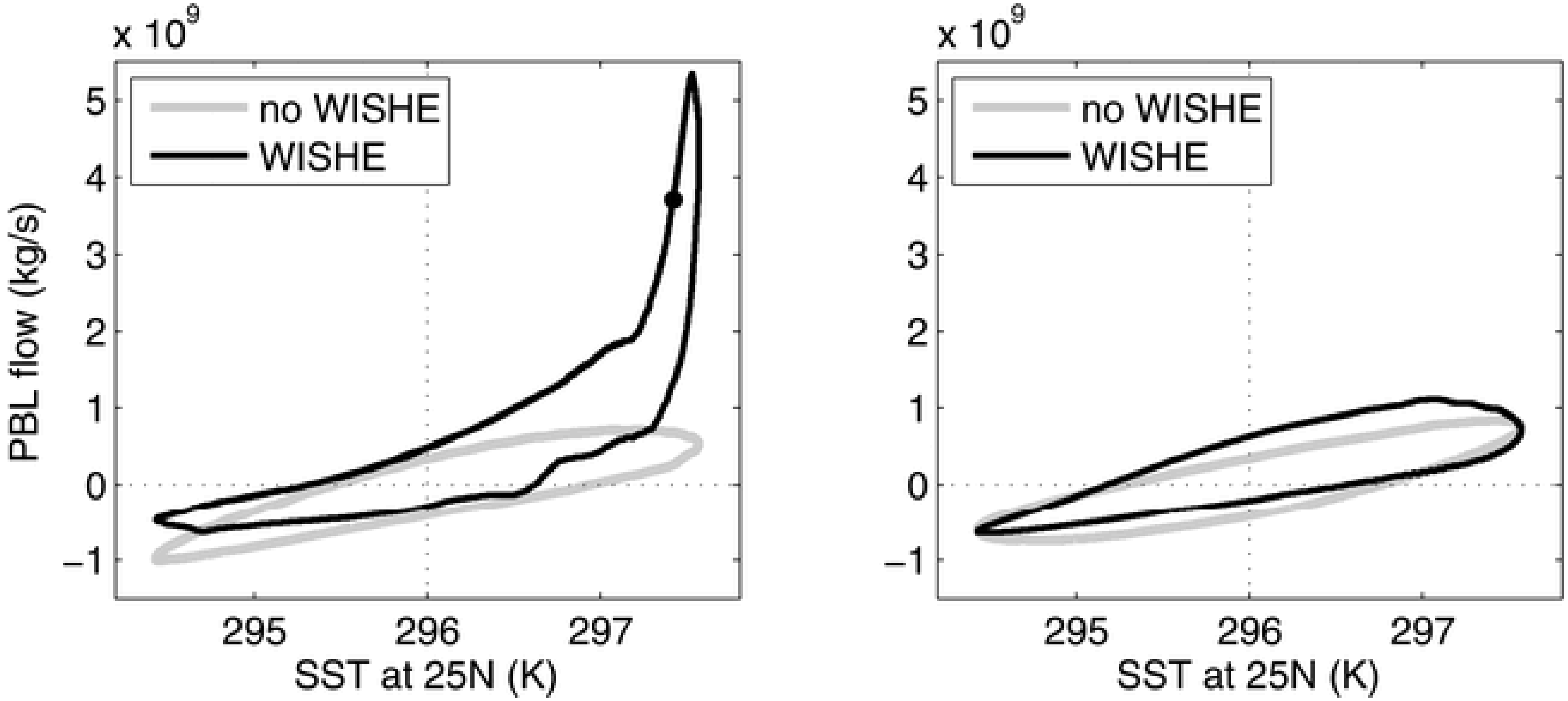
As in Fig. 2, but for the dry GCM with seasonally varying forcing, at the time of largest PBL flow.



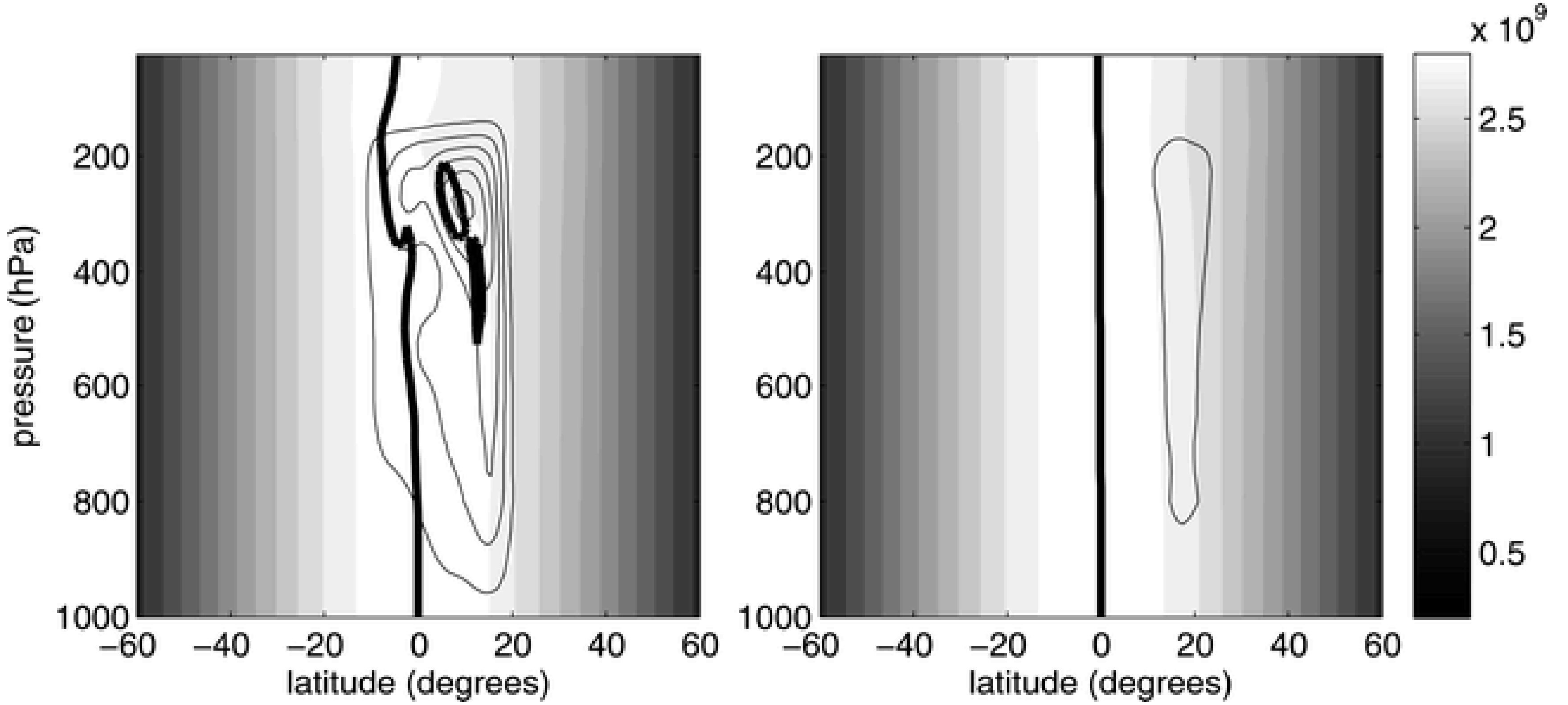
Phase diagram of the PBL flow and the spatial extremum of the equilibrium temperature anomaly for the dry GCM. Solid line is for the run with seasonally varying forcing, with time progressing in the direction of the arrow. The circles connected by the dashed line denote the equilibrated response to steady forcings.



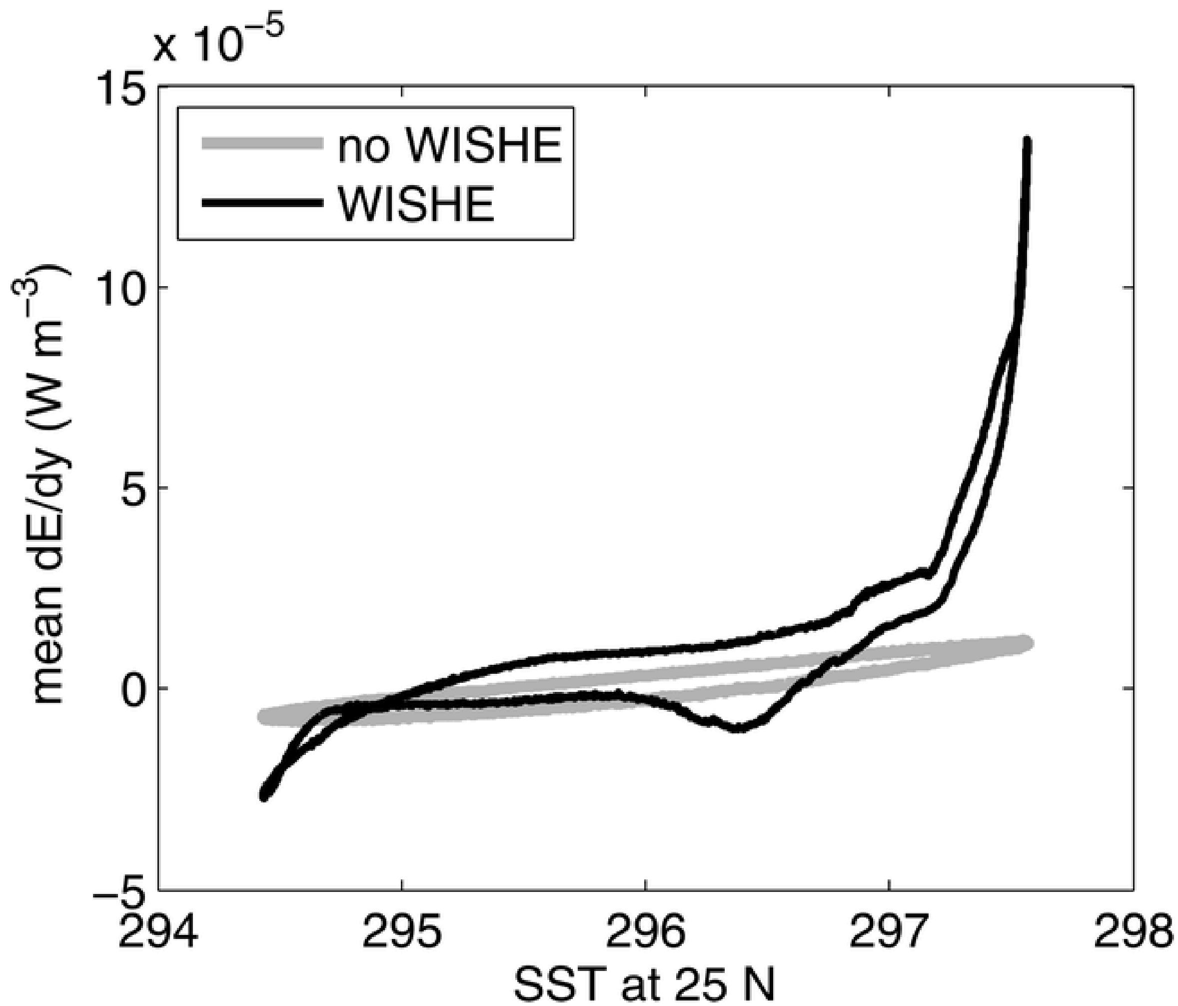
As in Fig. 4, but the phase diagram for the moist GCM with strong forcing (θ_m = 10 K) and wind-independent surface enthalpy fluxes. The dot denotes the model state for which *M* and are shown in Fig. 7.



As in Fig. 4, but the phase diagram for the moist GCM with weak forcing (θ_m = 1.0 K). Runs (left) with and (right) without nonlinear momentum advection are shown. The black and gray lines are for runs with and without WISHE, respectively. Dot in (left) denotes the time at which *M* and are shown in Fig. 9.

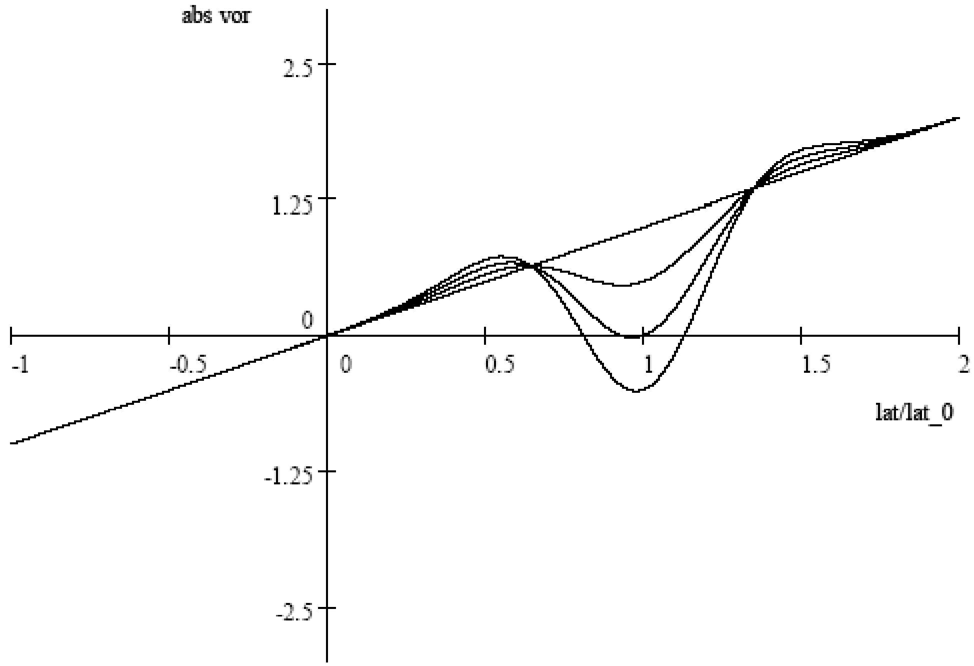


As in Fig. 7, but for the moist GCM with weak forcing (θ_m = 1.0 K), at times denoted by the dot in Fig. 8. Runs (left) with and (right) without WISHE are shown (both included nonlinear momentum advection).



Phase diagram, for the moist GCM with weak forcing (θ_m = 1.0 K), of the meridional mean meridional gradient of surface enthalpy fluxes, with the mean taken between the enthalpy flux peak and 10°N, plotted against the SST at 25°N. The black and gray lines are for runs with and without WISHE, respectively, both with nonlinear momentum advection.

Does the $\zeta_a = 0$ criterion have any relevance under 3D dynamics?



Model runs (*Nikki Prive*)

MIT model   64S – 64N; 4 degree resolution

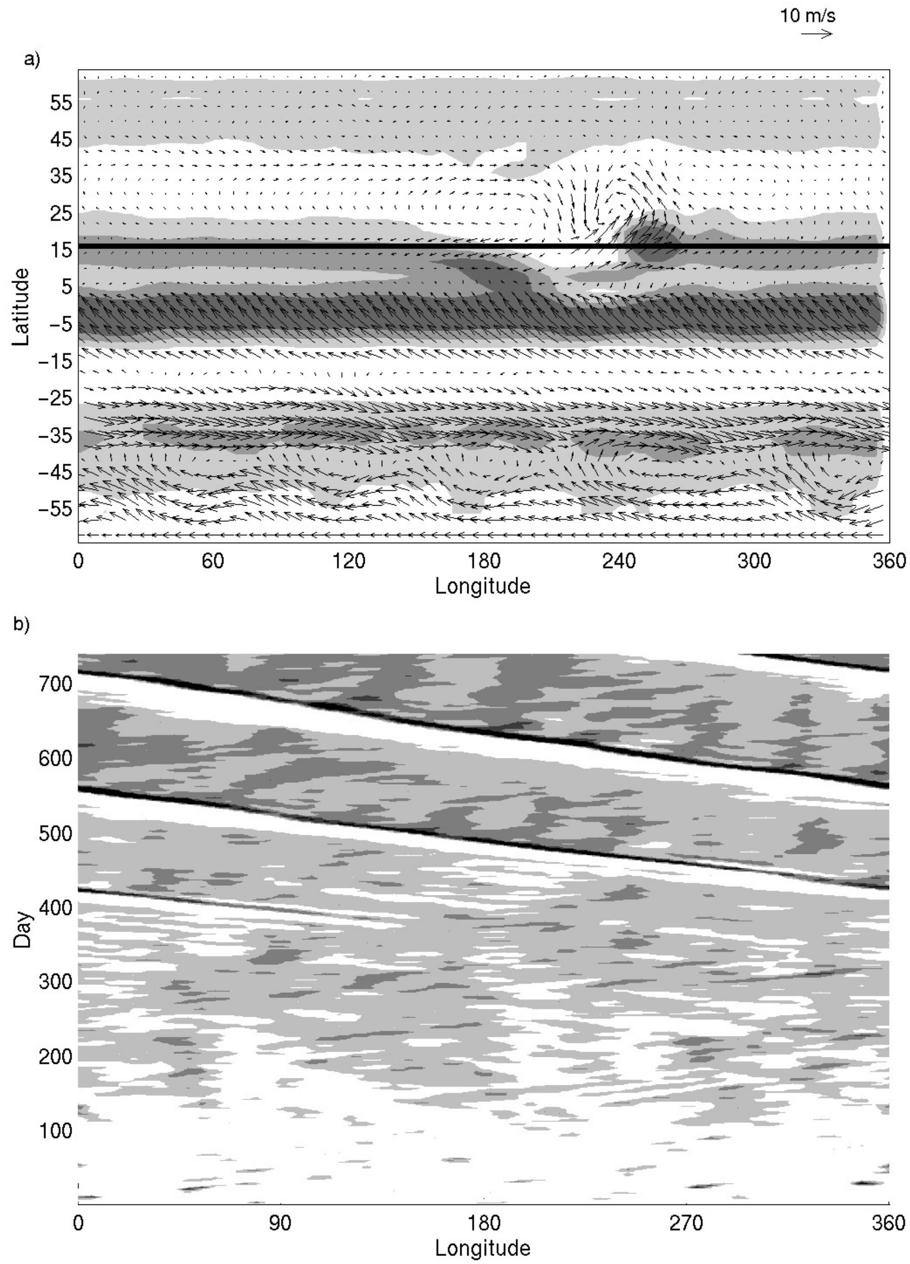
Moist model with simple lower boundary conditions

Ocean: specified SST

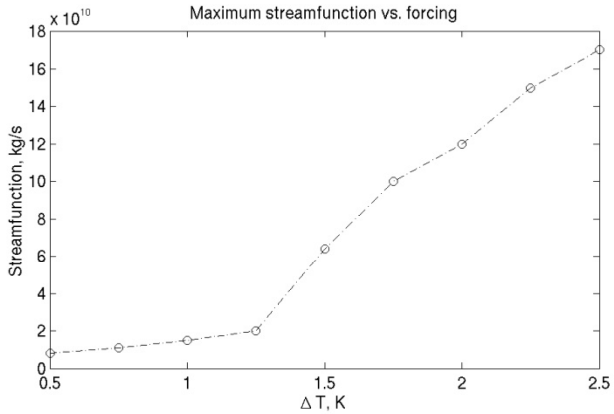
Land: specified total surface heat flux, bucket hydrology

Moist convection parameterization (Emanuel)

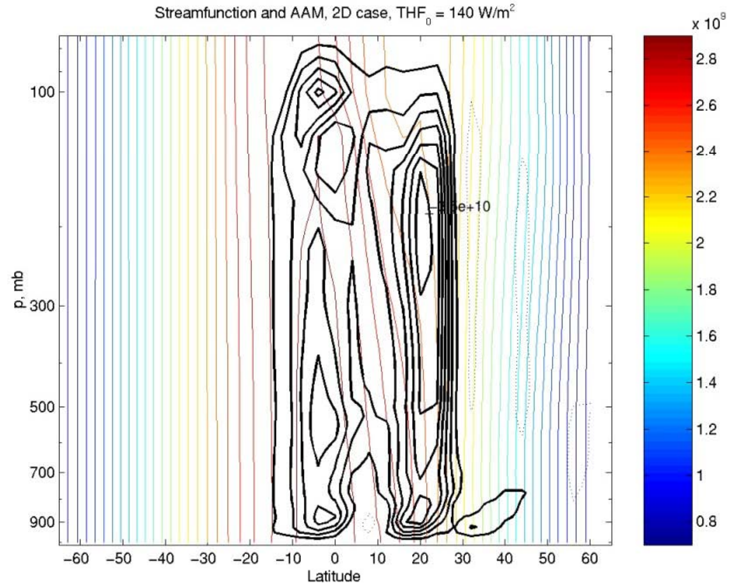
"Radiation": Newtonian relaxation to 200K

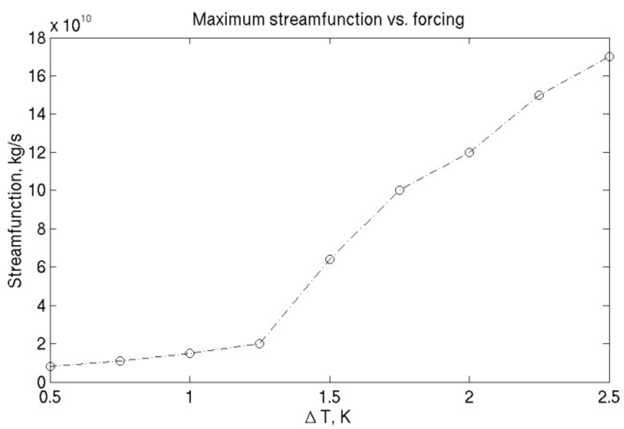


Courtesy of Nikki Prive. Used with permission.

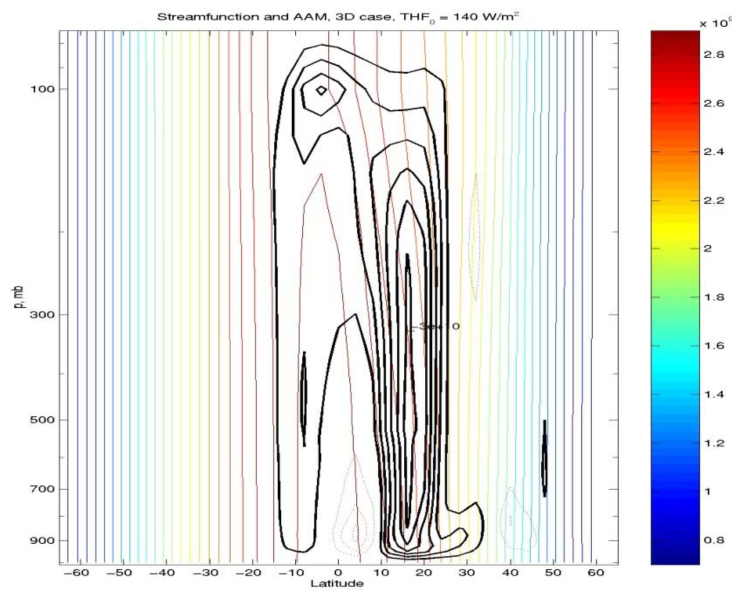

Maximum streamfunction vs. forcing
x 10^10
Streamfunction, kg/s
Δ T, K

2D


Streamfunction and AAM, 2D case, THF0 = 140 W/m2
p, mb
Latitude
x 10^9


Maximum streamfunction vs. forcing
x 10^10
Streamfunction, kg/s
Δ T, K

3D


Streamfunction and AAM, 3D case, THF0 = 140 W/m2
p, mb
Latitude
x 10^9

3) Cross-equatorial flow: does three-dimensionality matter?

Cross-equatorial flow *[Pauluis, JAS, 2004]*

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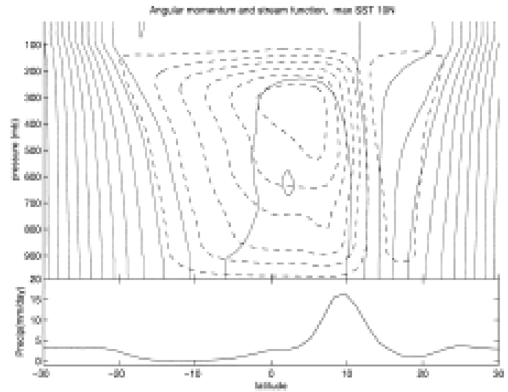

Fig. 7. Same as in Fig. 3 but for an ML depth of 100 hPa, and a maximum SST at 10°N.

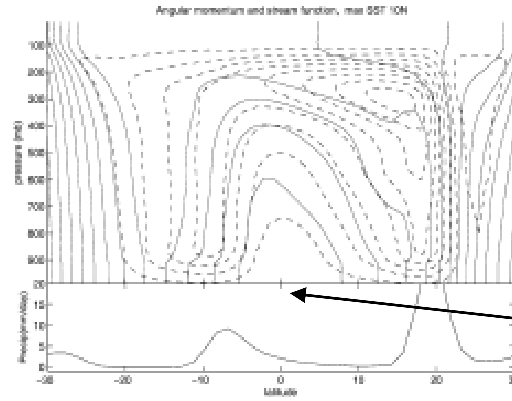

Fig. 8. Same as in Fig. 3 but for an ML depth of 100 hPa, and a maximum SST at 20°N.

Strong SST gradient across equator

Weak SST gradient across equator

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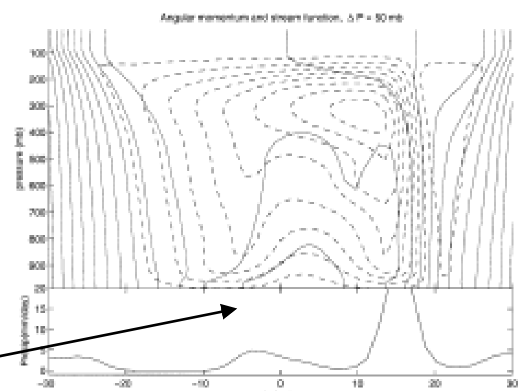


Fig. 3. (top) Angular momentum (solid line) and streamfunction (dashed line) for an ML depth of 50 hPa. Contour interval is 2% of the angular momentum of the solid-body rotation at the equator and 4×10^{11} kg s^{-1} for the streamfunction. (bottom) Precipitation (mm day^{-1}). Only the regions between 30°S and 30°N are shown.

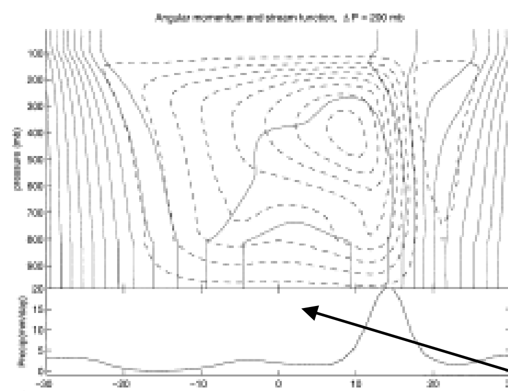
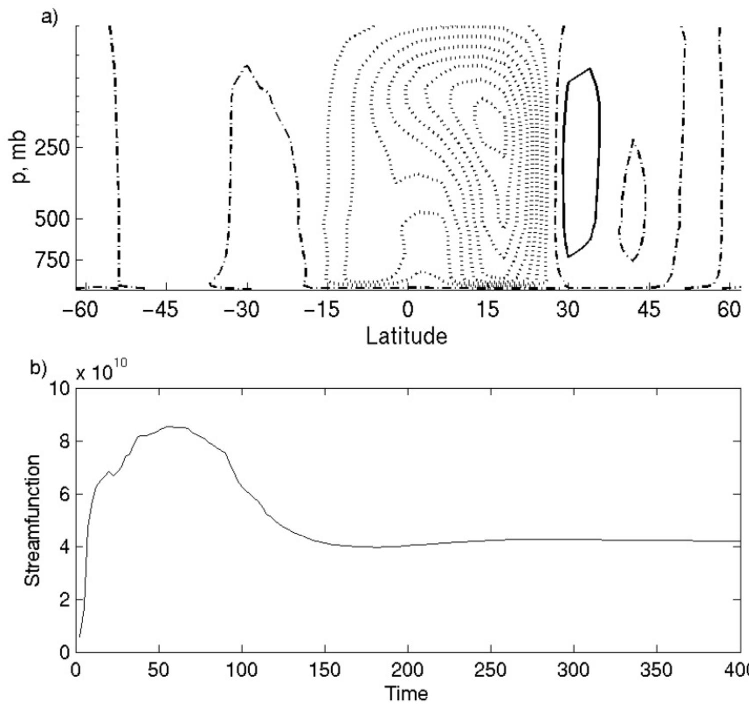


Fig. 5. Same as in Fig. 3 but for an ML depth of 200 hPa.

Shallow boundary layer

Deep boundary layer

3D



2D

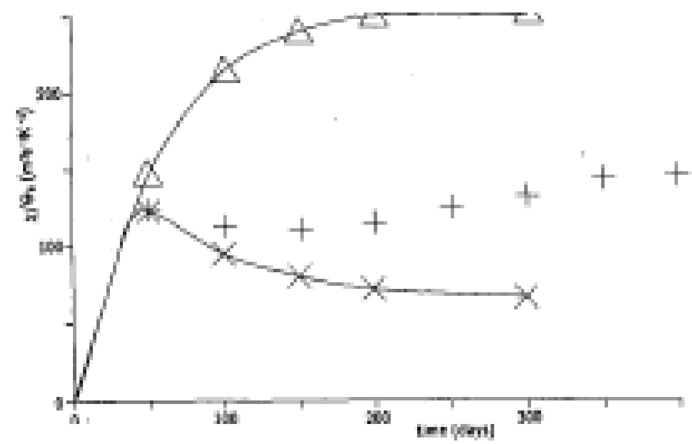
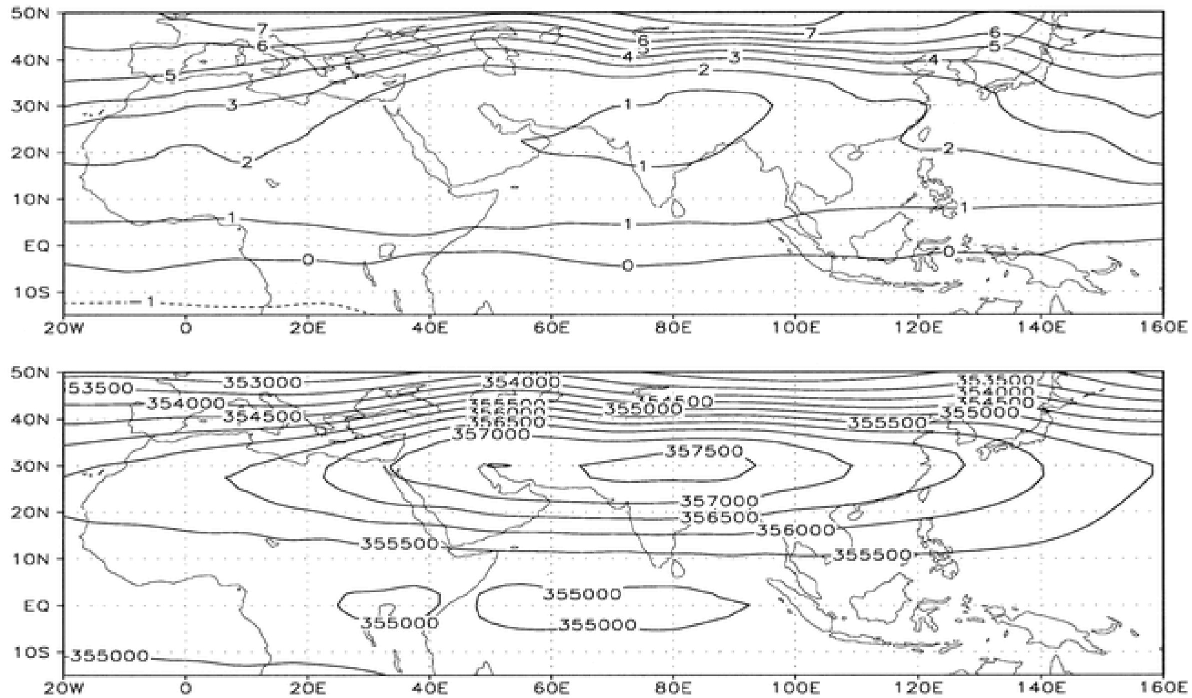
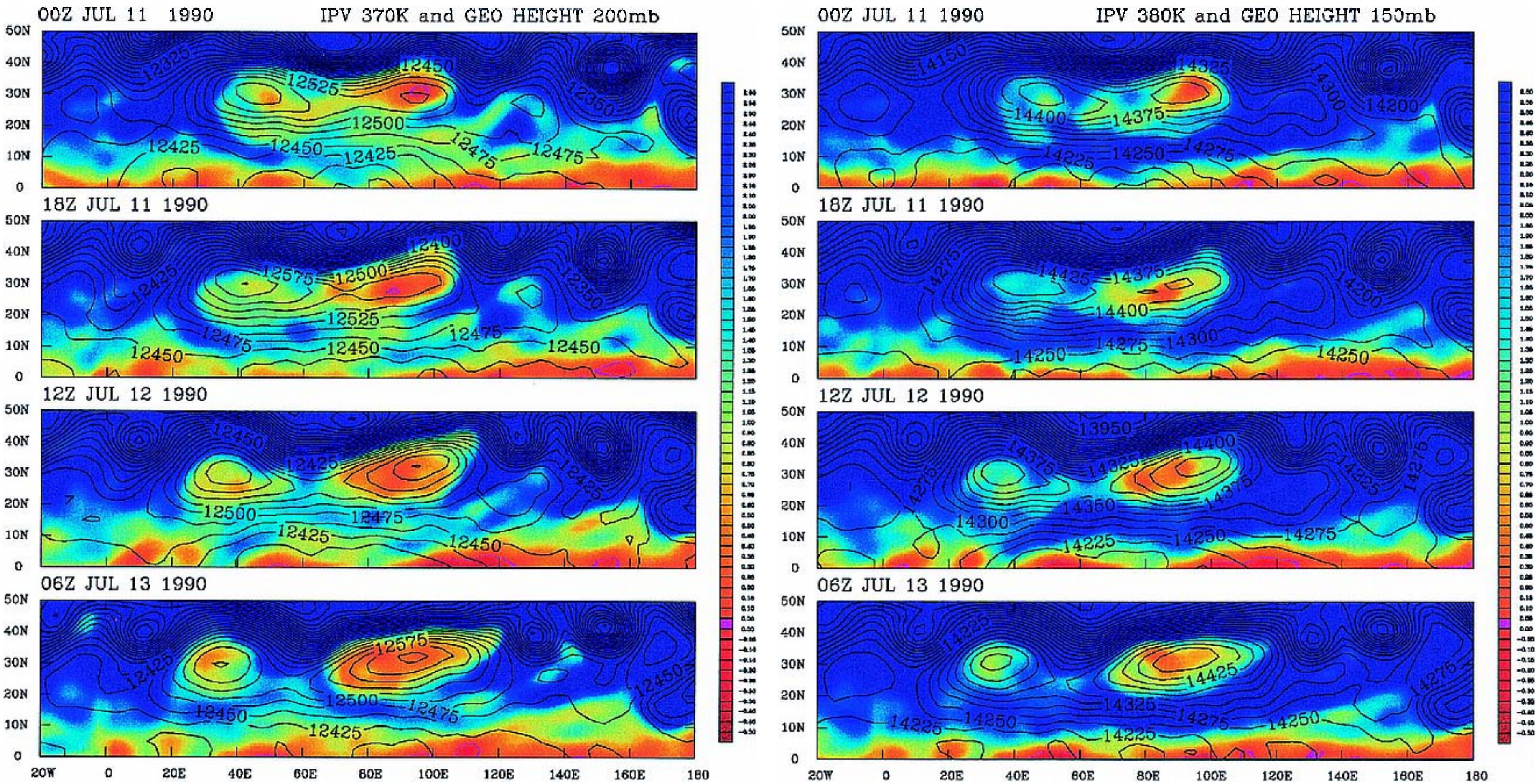


FIG. 6. Development of the circulation with time. Plot shows the streamfunction, χ_{max} scaled by θ_v, as a function of time. Cases (values of θ_v) are: (×) 3.0 K, (+) 7.5 K, (Δ) 12.1 K.


50N
40N
30N
20N
10N
EQ
10S
20W
0
20E
40E
60E
80E
100E
120E
140E
160E
7
6
5
4
3
2
1
0
-1
353000
353500
354000
354500
355000
355500
356000
356500
357000
357500

Upper tropospheric PV on θ = 370/380K and Z on 200/150hPa

[Hsu & Plumb 1999]

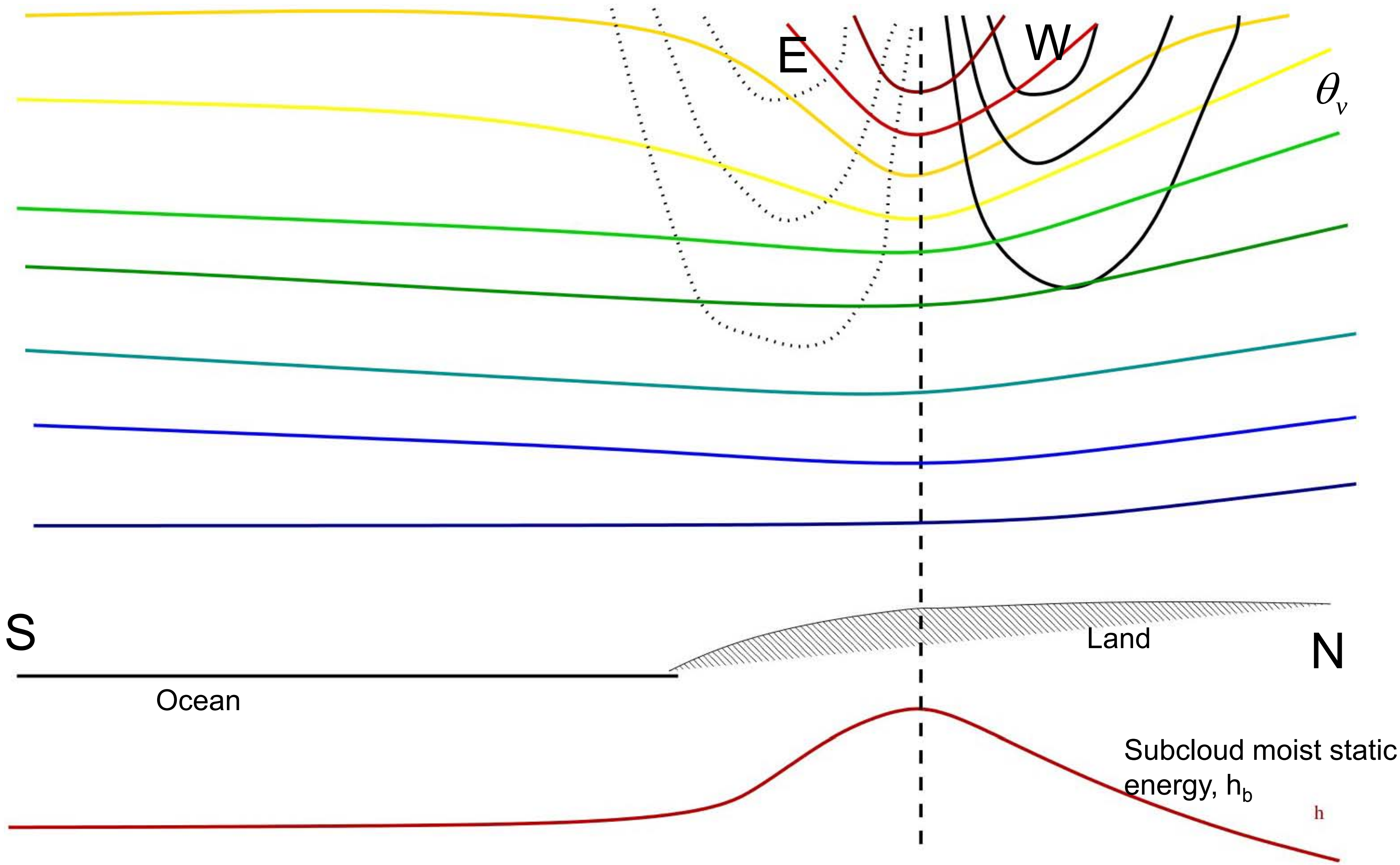


Theories of Monsoon Location

- Plumb and Hou (1992), Emanuel (1995), Zheng (1998)
  – Explained axisymmetric circulation induced by local subtropical forcing
- Rodwell and Hoskins (1995)
  – Rossby waves induce subsidence to the west of the monsoon,creatin g east-west asymmetry
- Xie and Saiki (1999)
  – Hydrological feedbacks limit inland progression of the monsoon
- Chou, Neelin, and Su (2001)

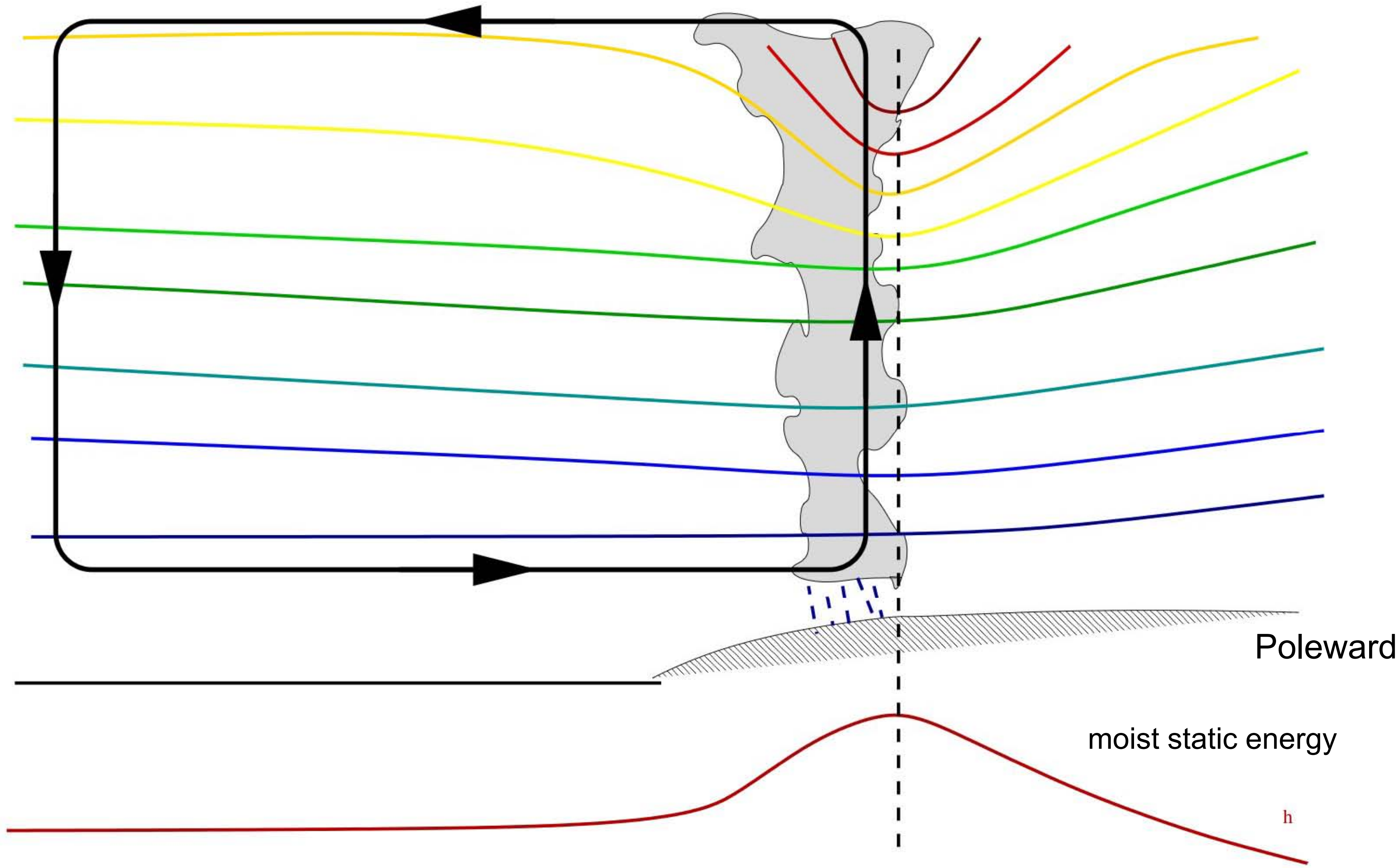
  Advection of low moist static energy air, hydrological feedbacks, and Rodwell-Hoskins effect all limit poleward extent of the monsoon

Impact of local h_b maximum over land



Courtesy of Nikki Prive. Used with permission.

Resulting meridional circulation and precipitation

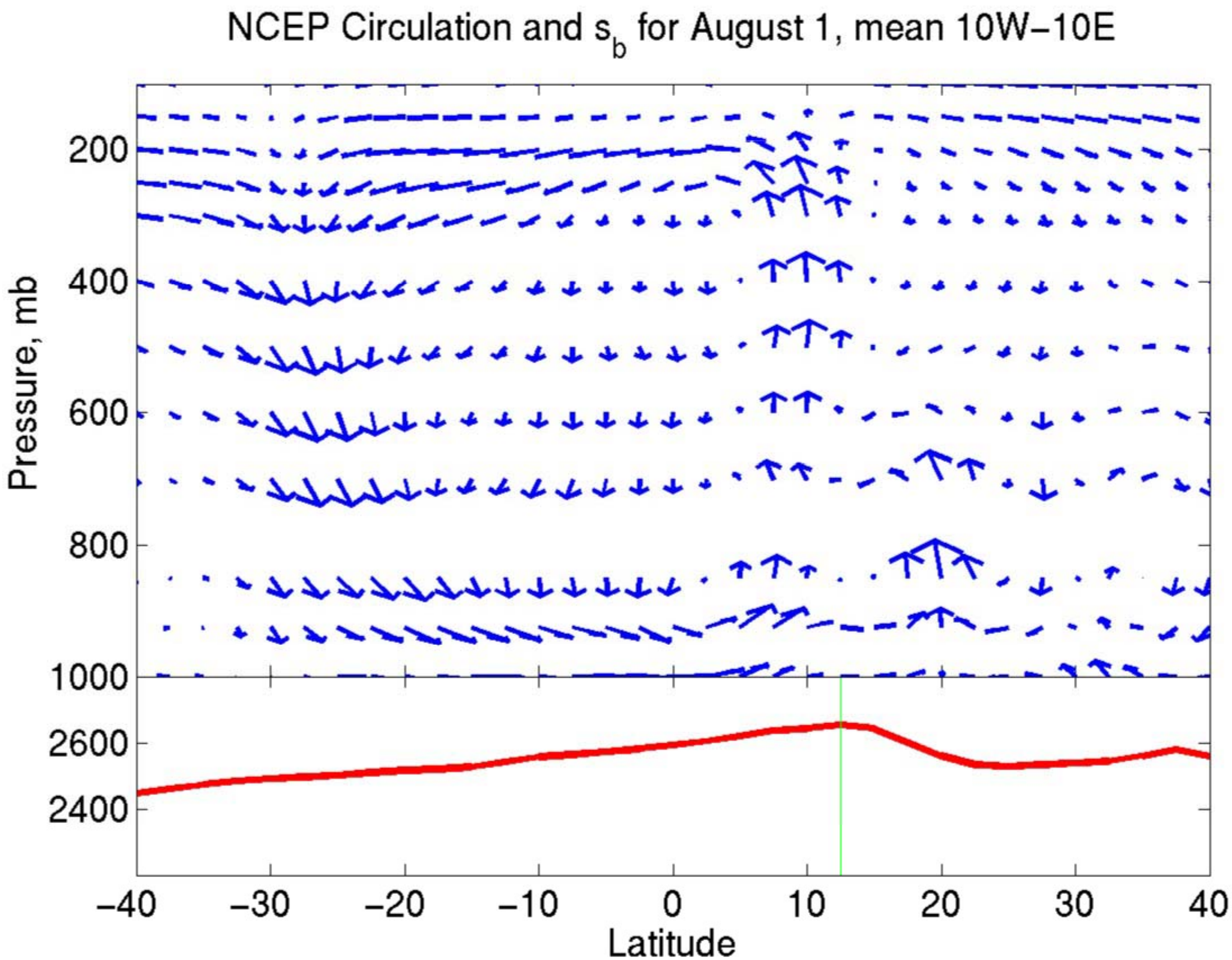


Factors that affect s_b

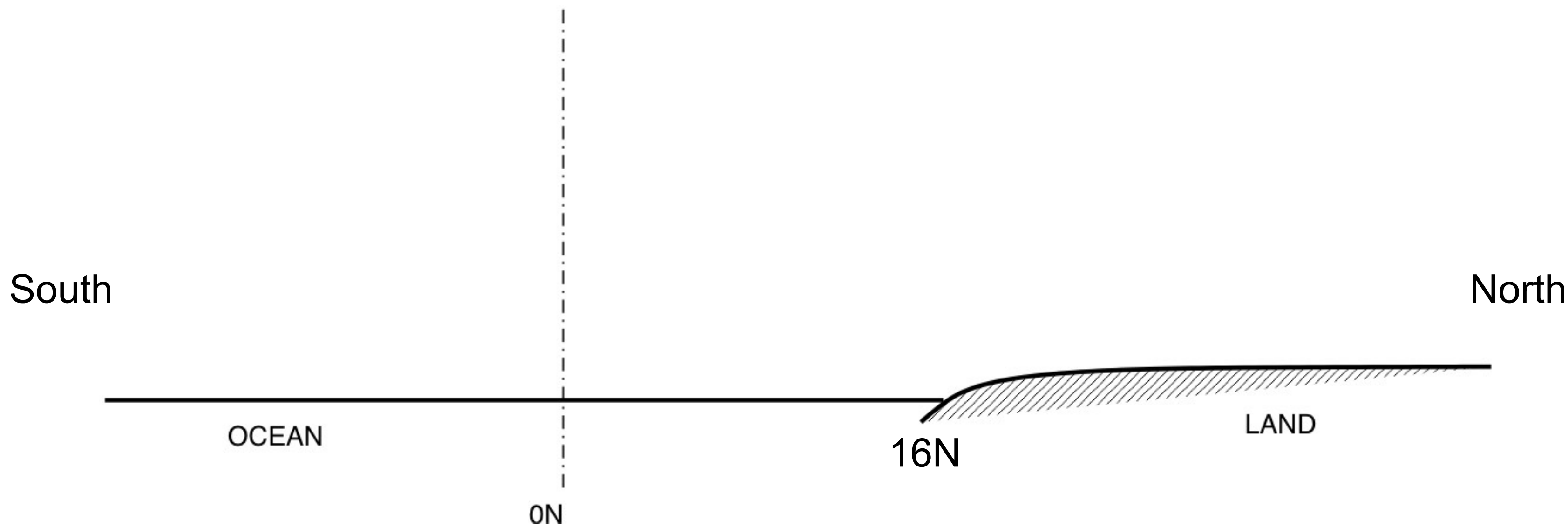
- Surface heat fluxes
- Evaporation of precipitation in convective downdrafts
- Radiative cooling
- Entrainment at the top of the subcloud layer
- Advection by large-scale flow

Circulation may have a strong impact on the subcloud s_b distribution through these feedbacks.

Observed circulation and subcloud s_b



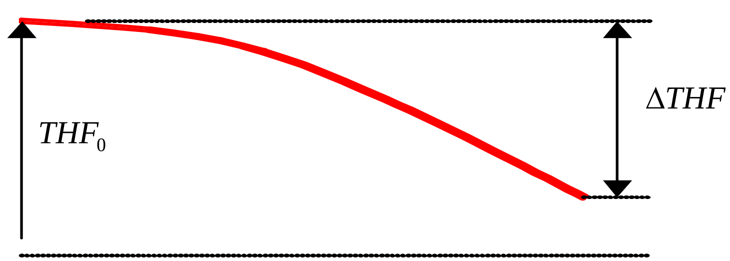
Model Setup



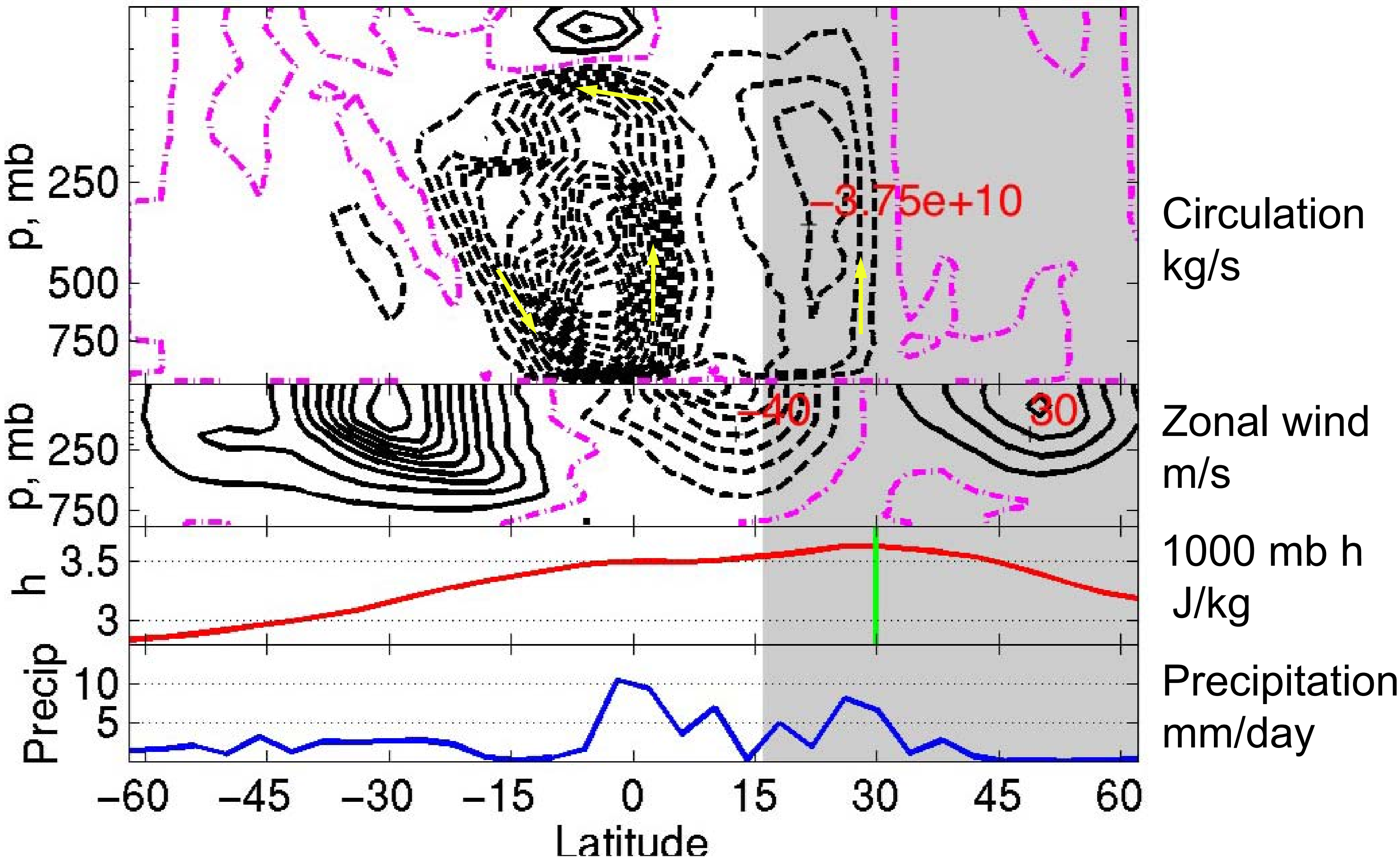
Over land, the surface forcing is determined by

$$THF(\phi) = LHF(T_S) + SHF(T_S)$$

$$THF(\phi) = THF_0 - \Delta THF \sin^2(\phi - \phi_0)$$

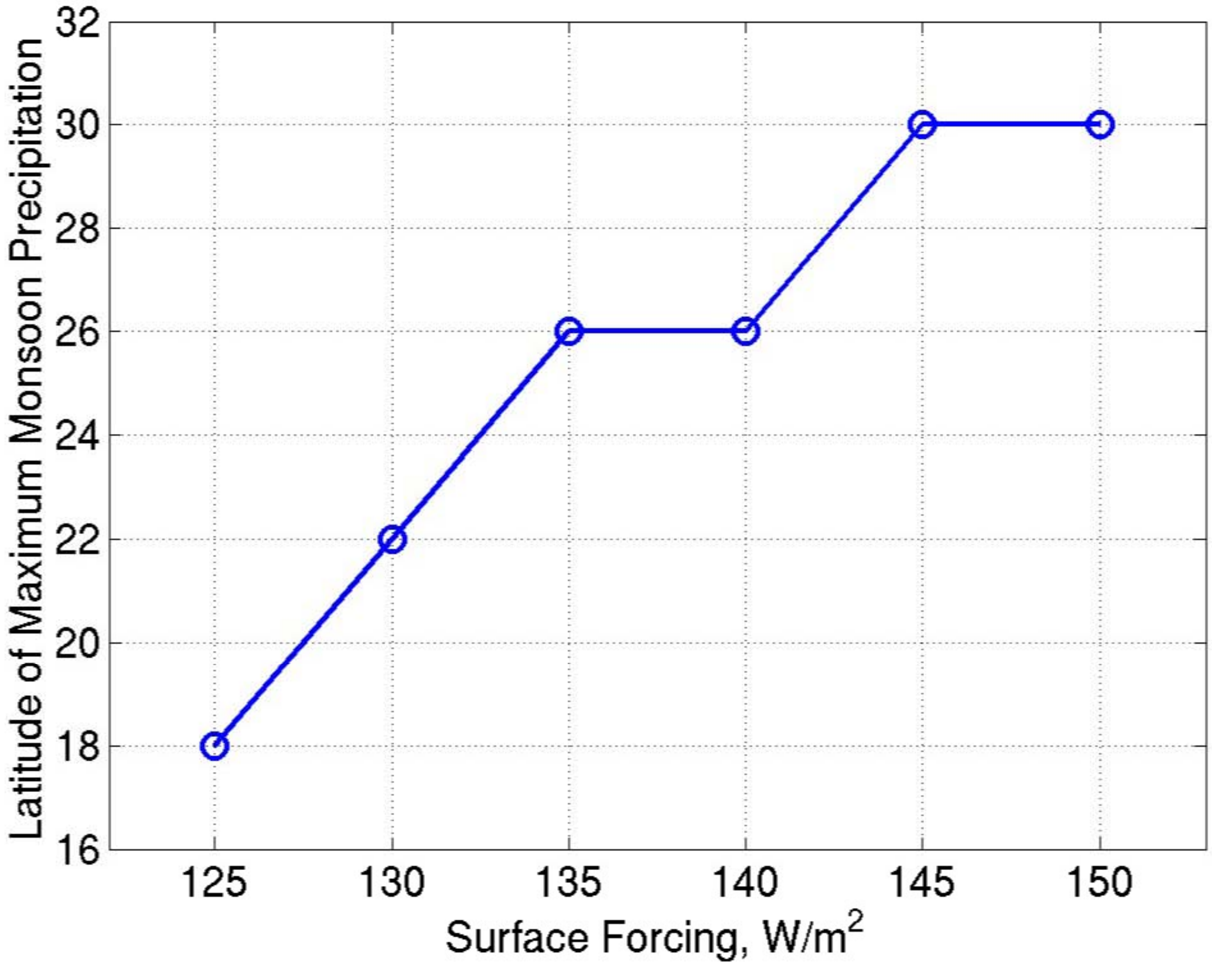


2D Monsoon



p, mb
250
500
750
-3.75e+10
p, mb
250
750
-40
30
h
3.5
3
Precip
10
5
−60 −45 −30 −15 0 15 30 45 60
Latitude
Circulation kg/s
Zonal wind m/s
1000 mb h J/kg
Precipitation mm/day

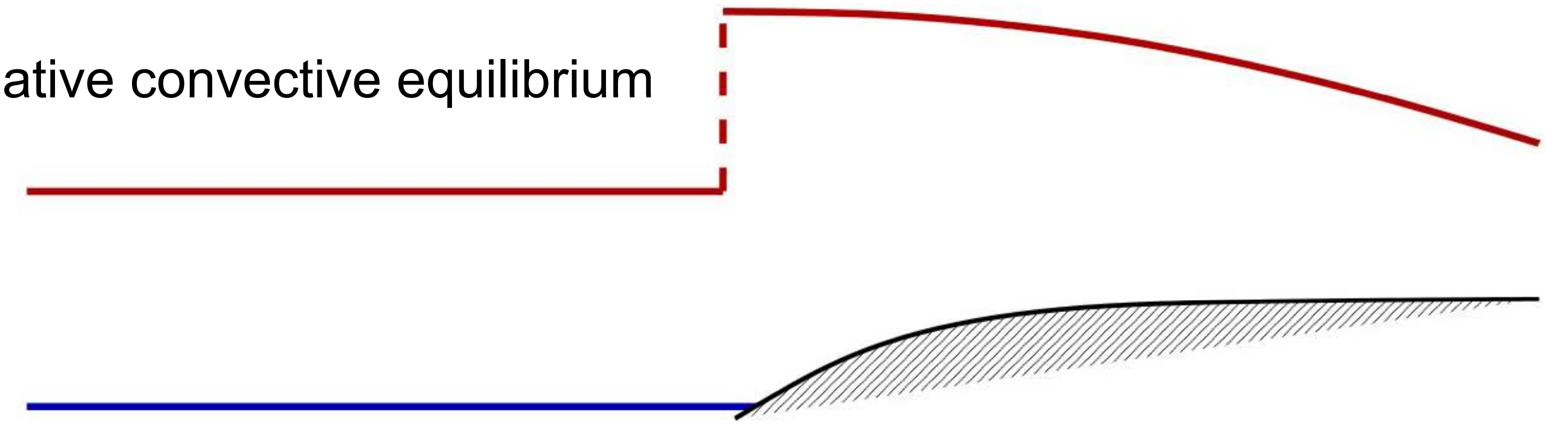
Monsoon Latitude



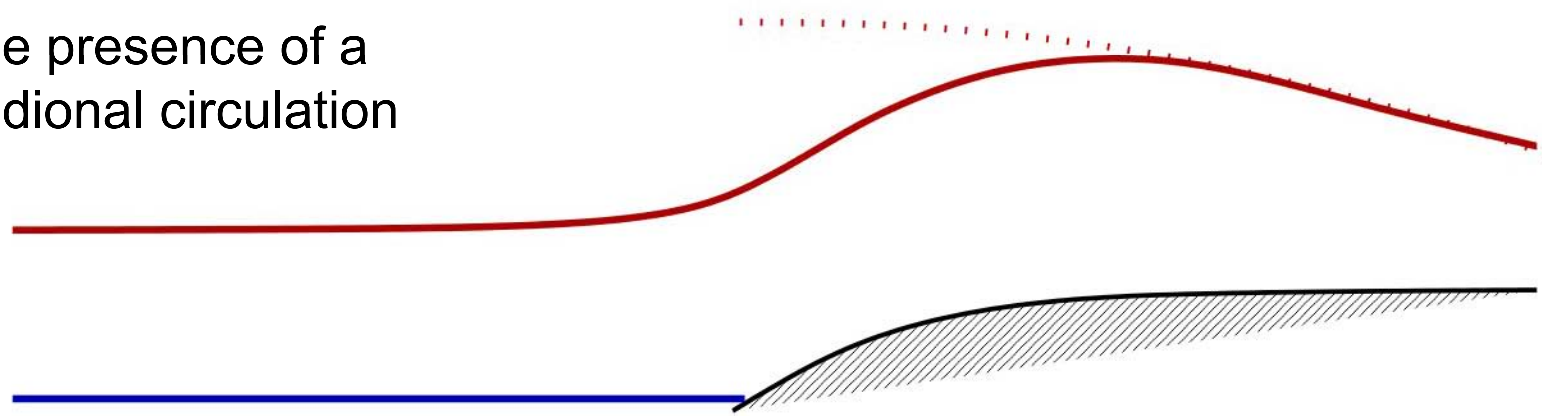
Courtesy of Nikki Prive. Used with permission.

Impact of flow on h_b

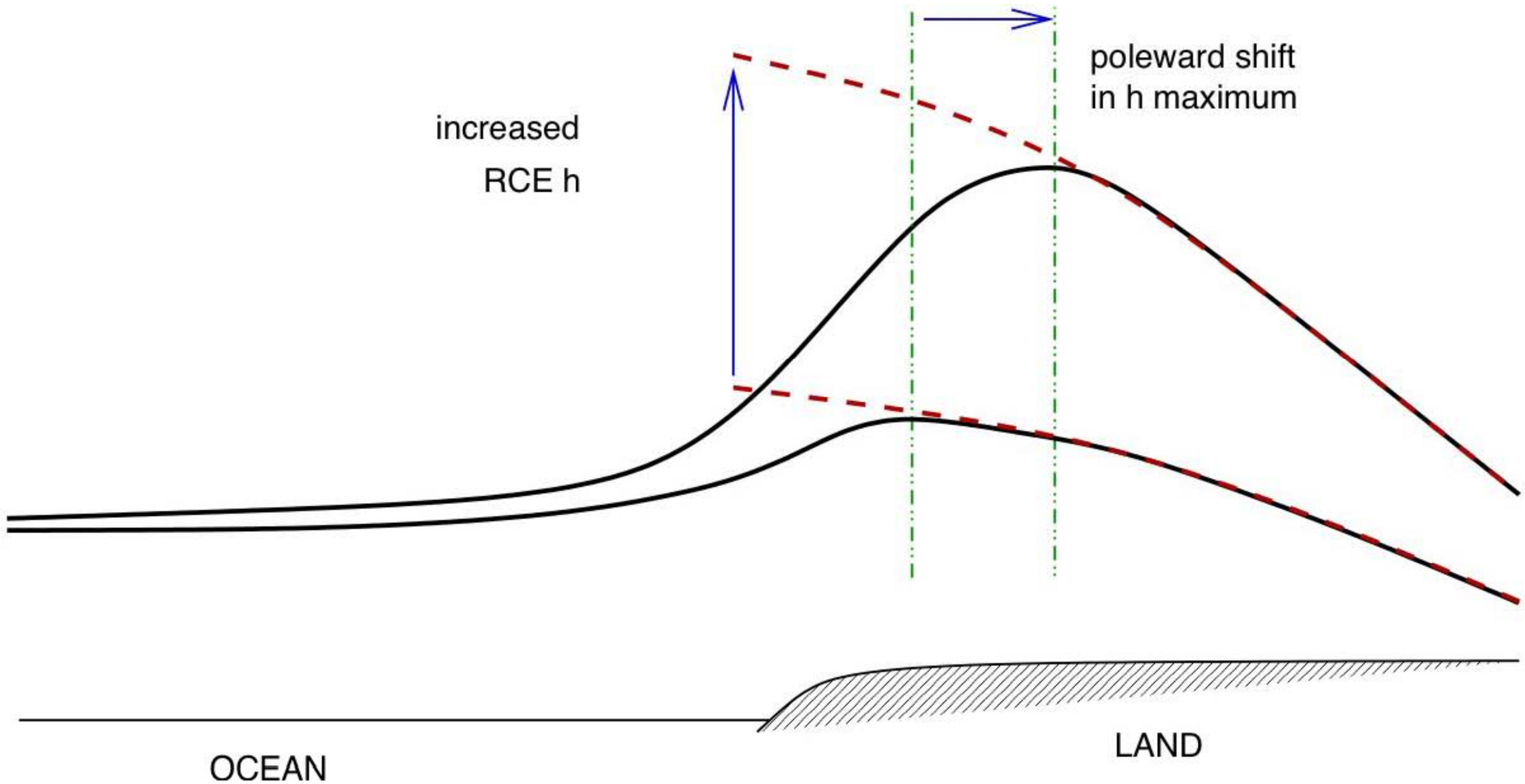
Radiative convective equilibrium



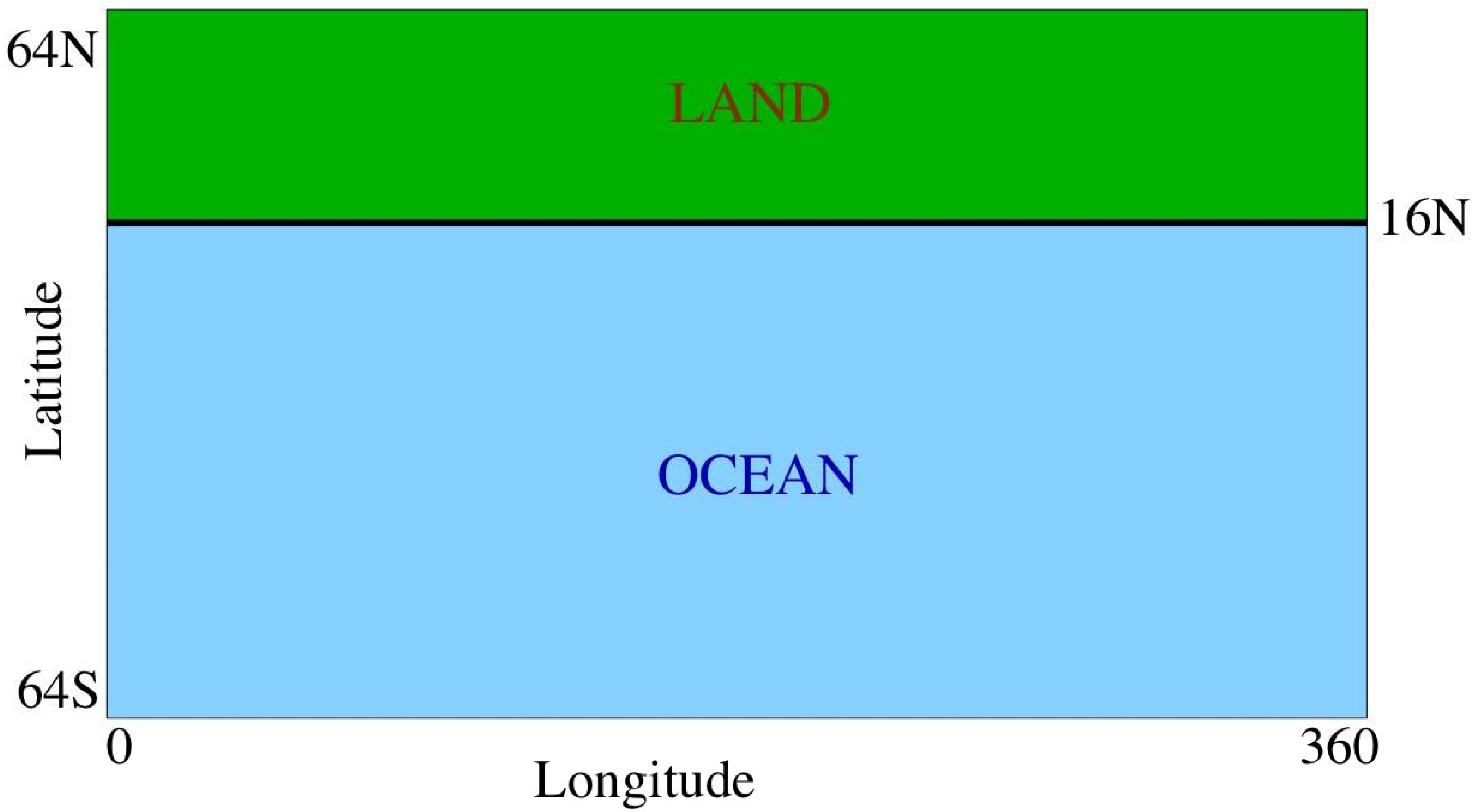
In the presence of a
meridional circulation



So what is going on with h_b?

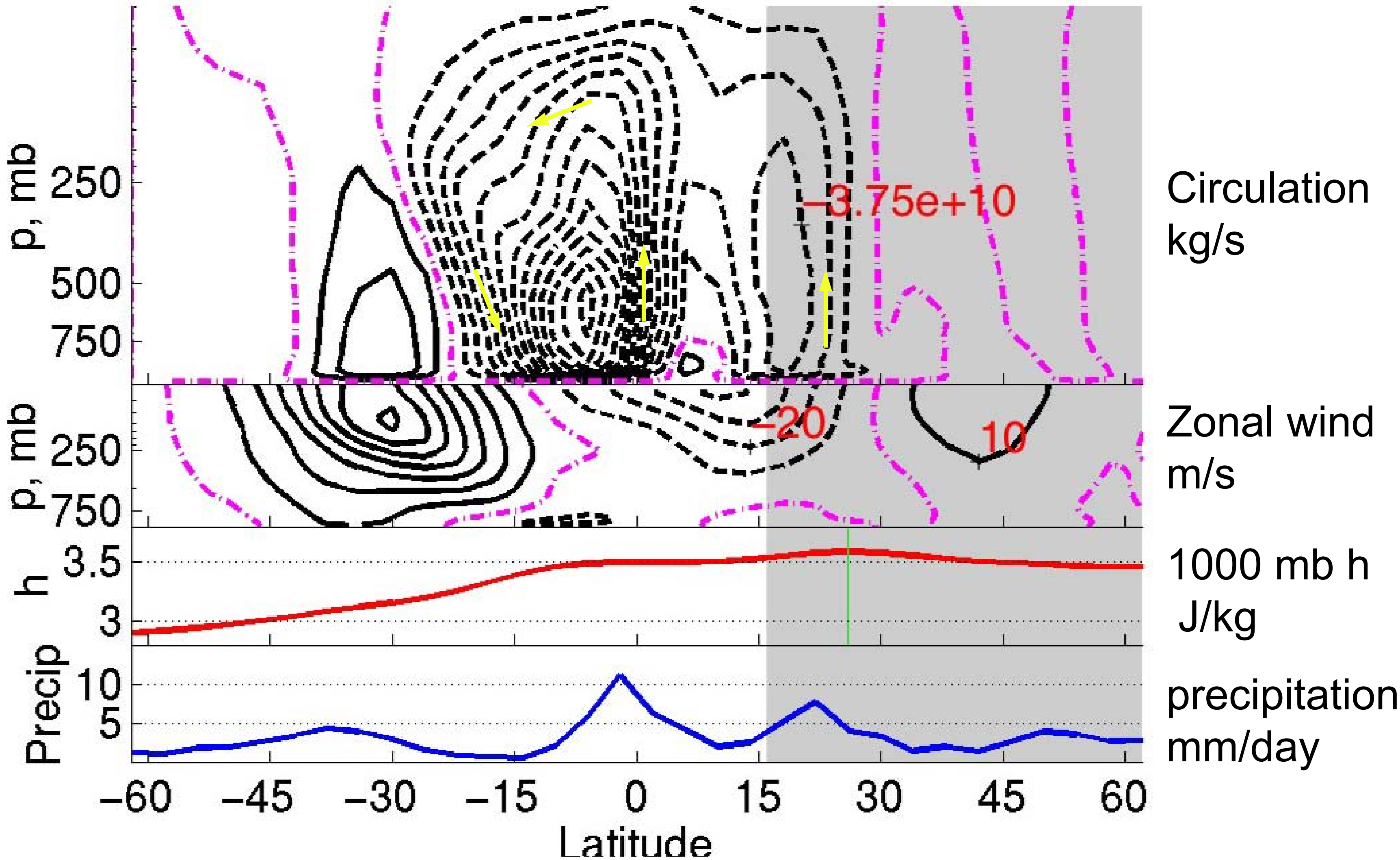


Expand to 3D

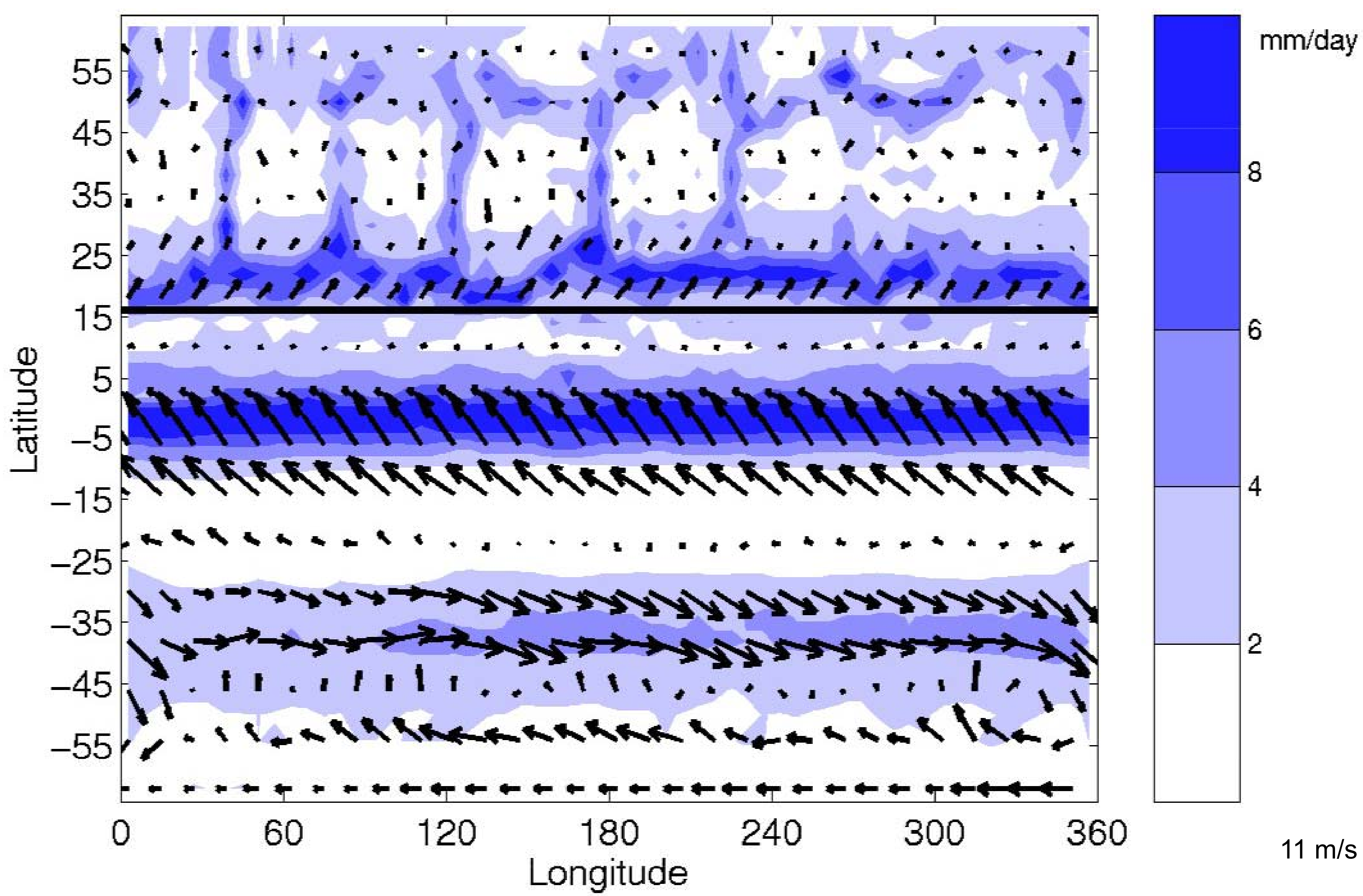


Courtesy of Nikki Prive. Used with permission.

3D Monsoon

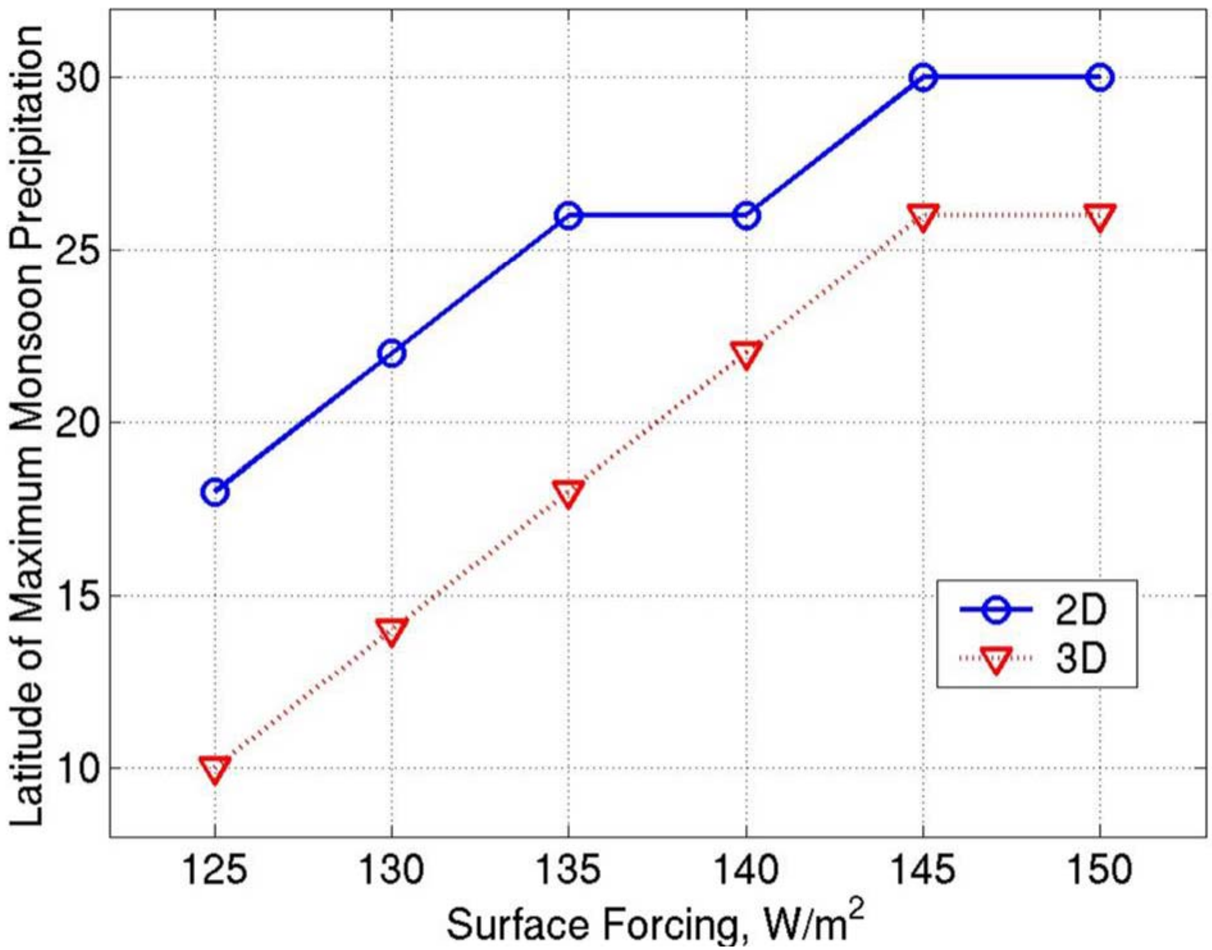

p, mb
250
500
750
-3.75e+10
Circulation kg/s
p, mb
250
750
-20
10
Zonal wind m/s
h
3.5
3
1000 mb h J/kg
Precip
10
5
precipitation mm/day
-60 -45 -30 -15 0 15 30 45 60
Latitude

1000 mb winds and precipitation

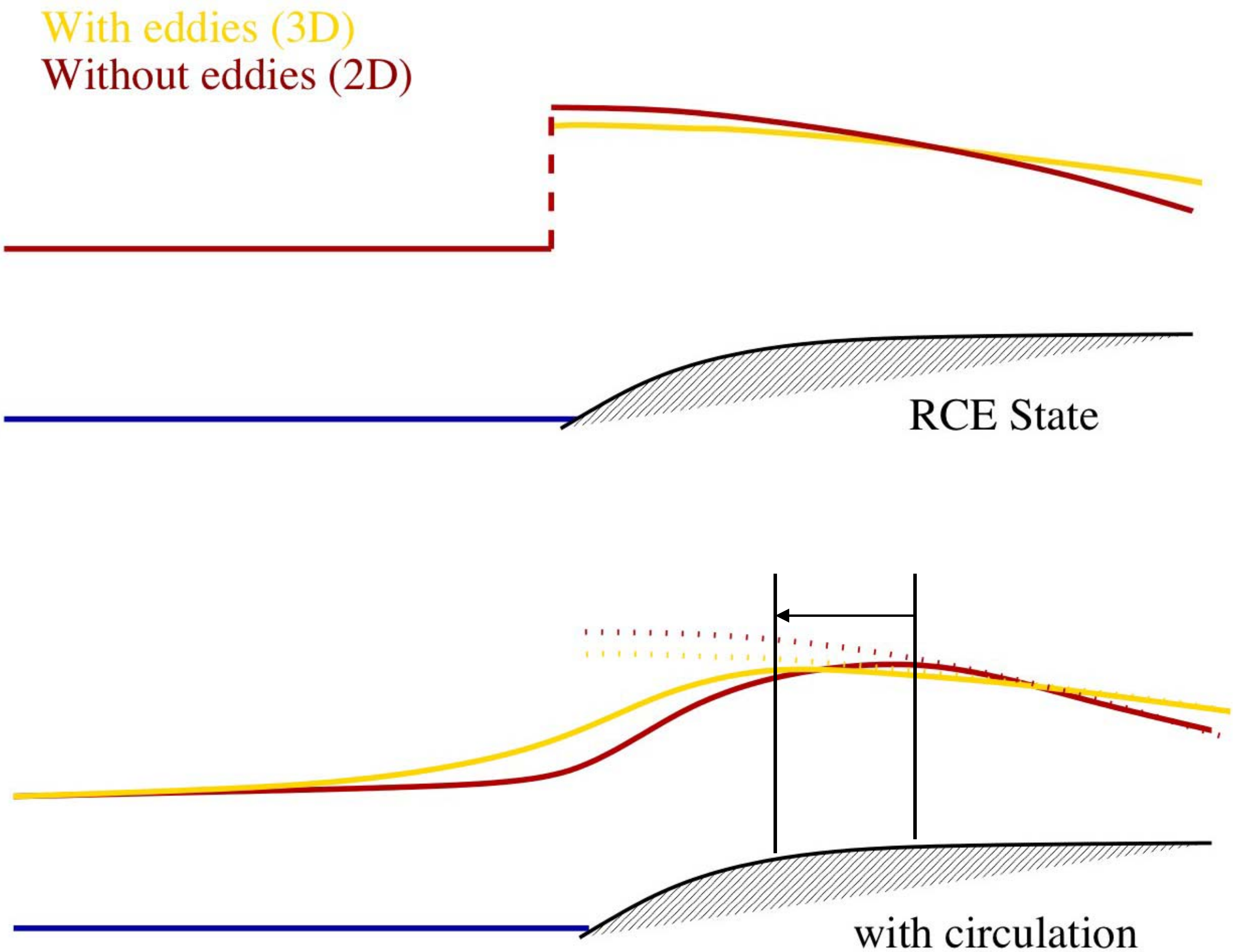


Courtesy of Nikki Prive. Used with permission.

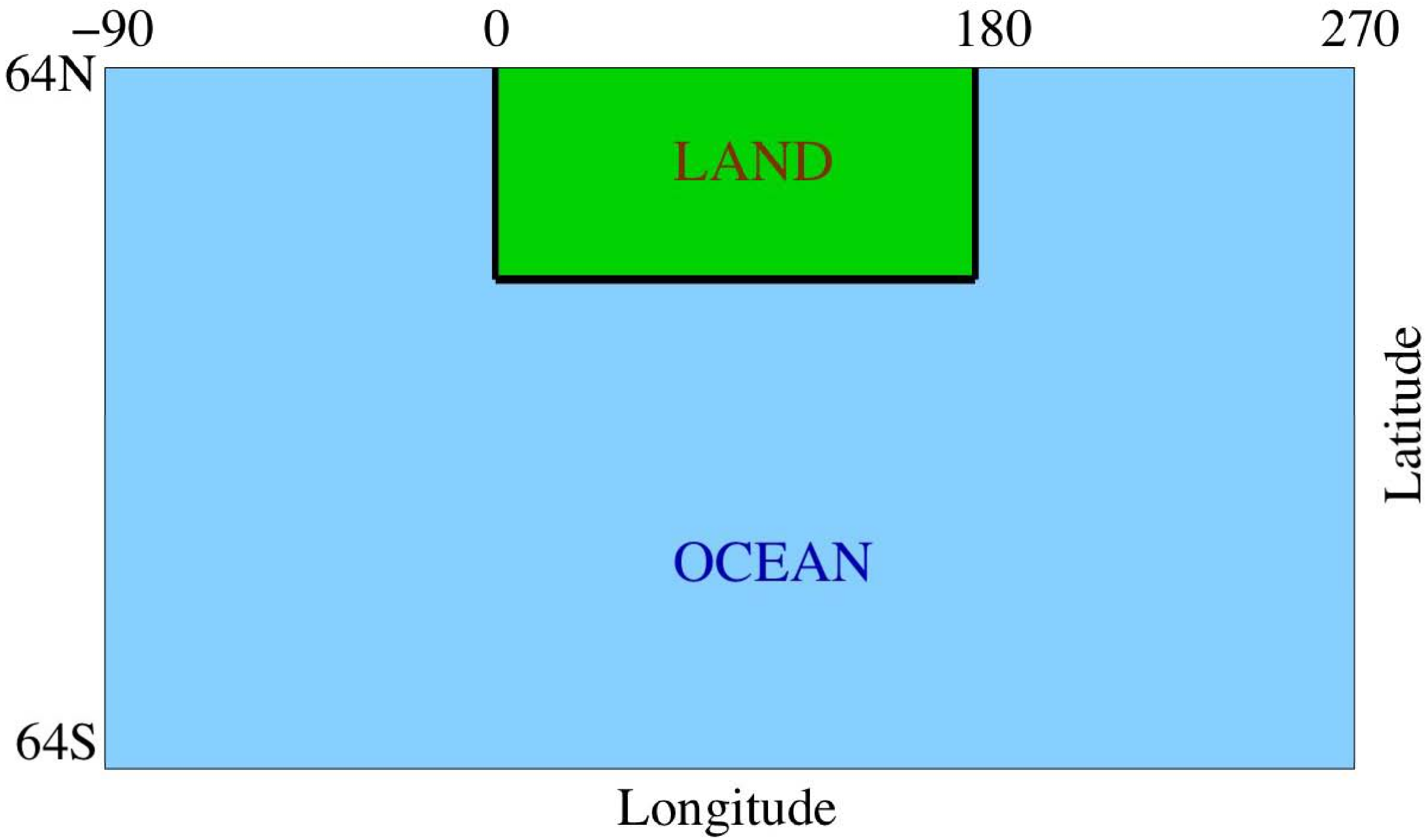
Monsoon Latitude: 2D vs 3D



Impact of eddies on subcloud h

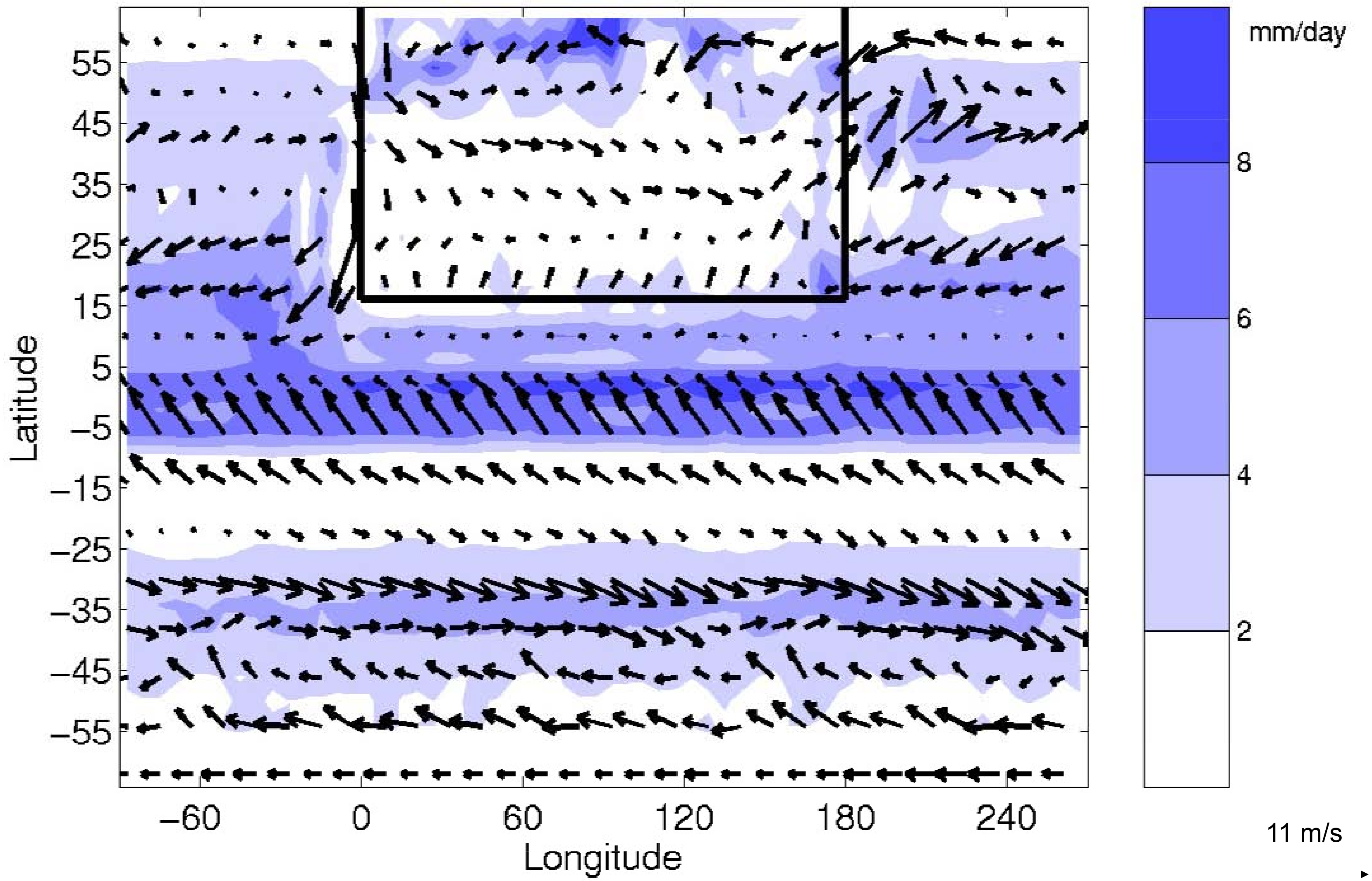


Introduce continental asymmetry



Courtesy of Nikki Prive. Used with permission.

What happened to the monsoon?



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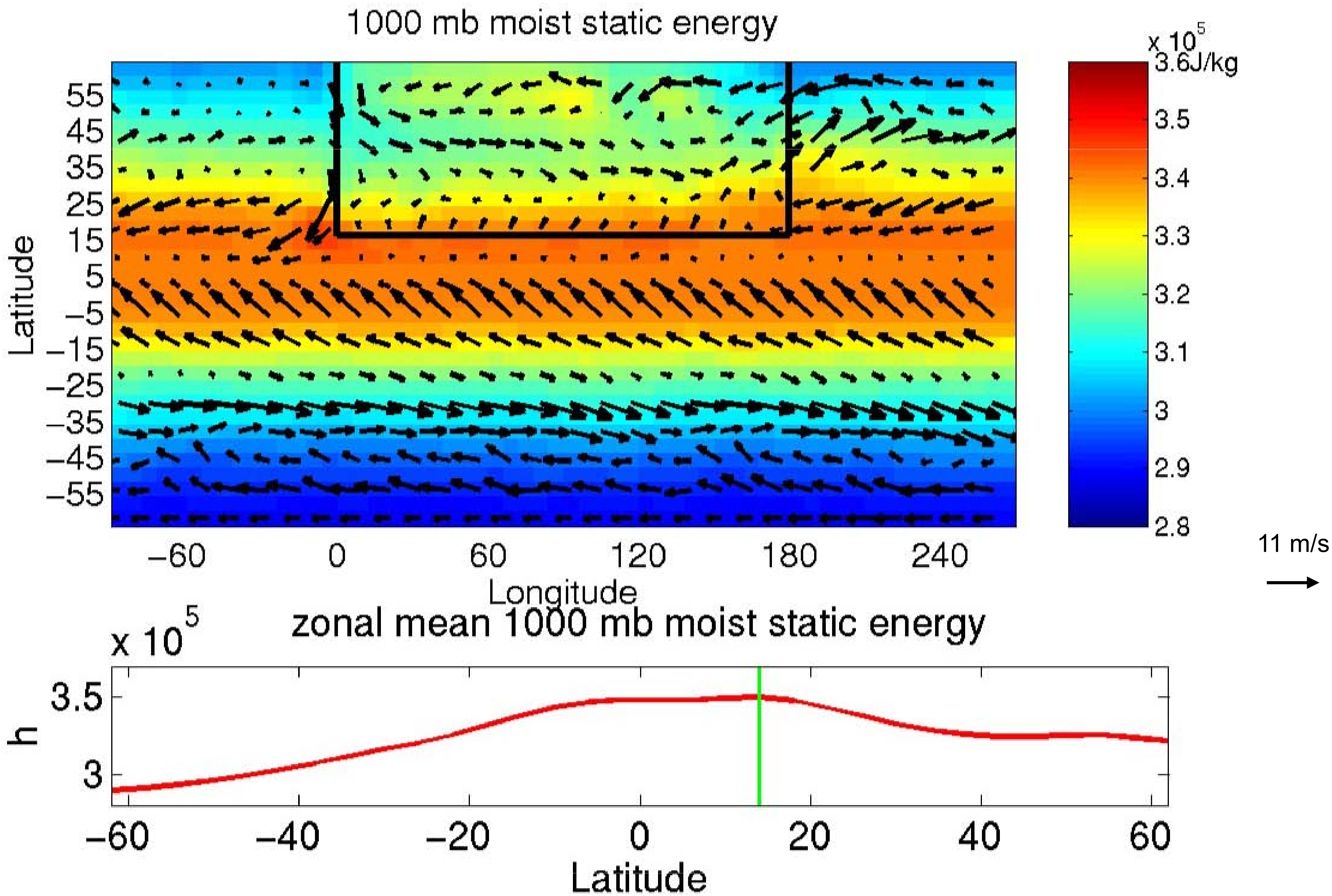
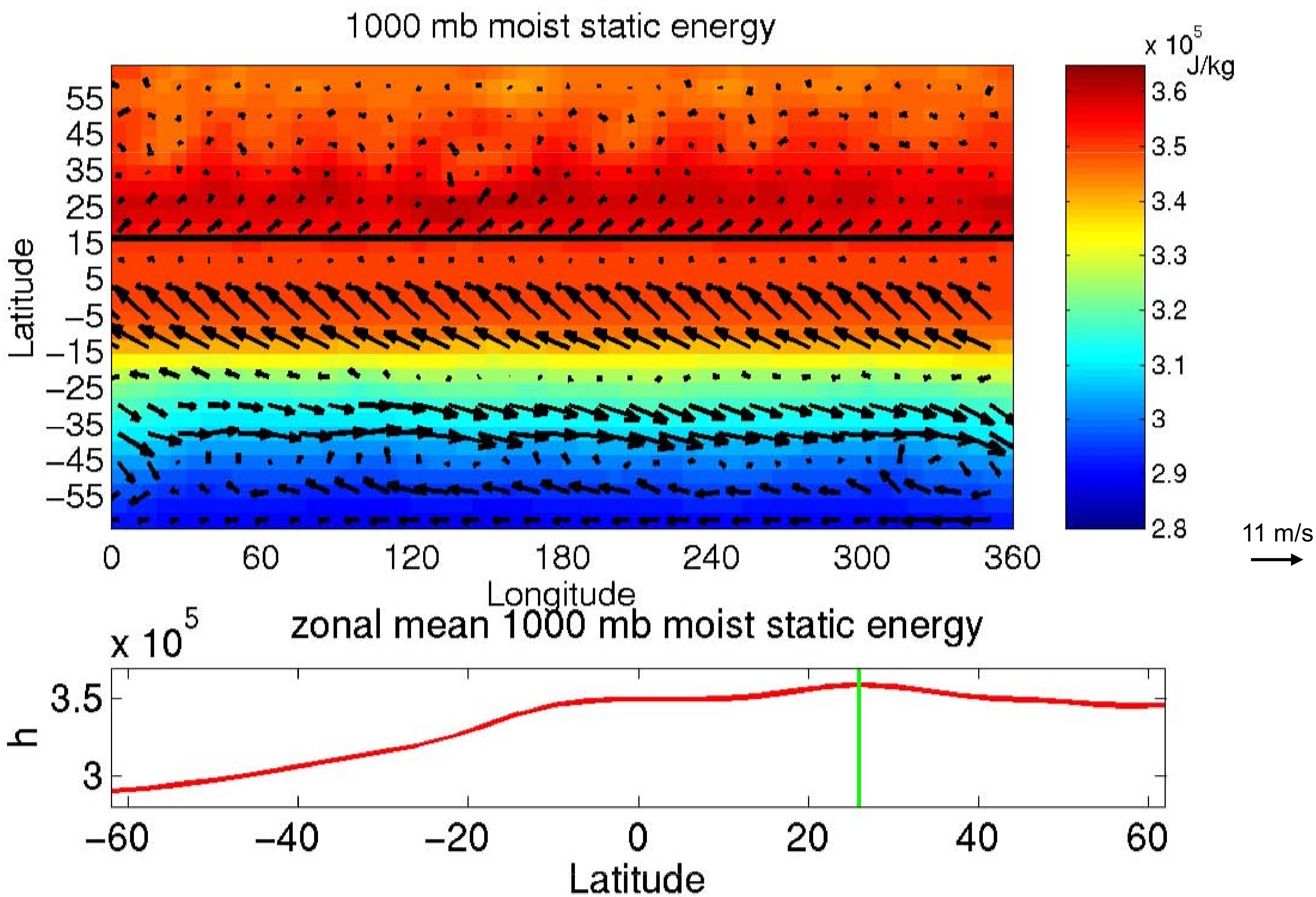
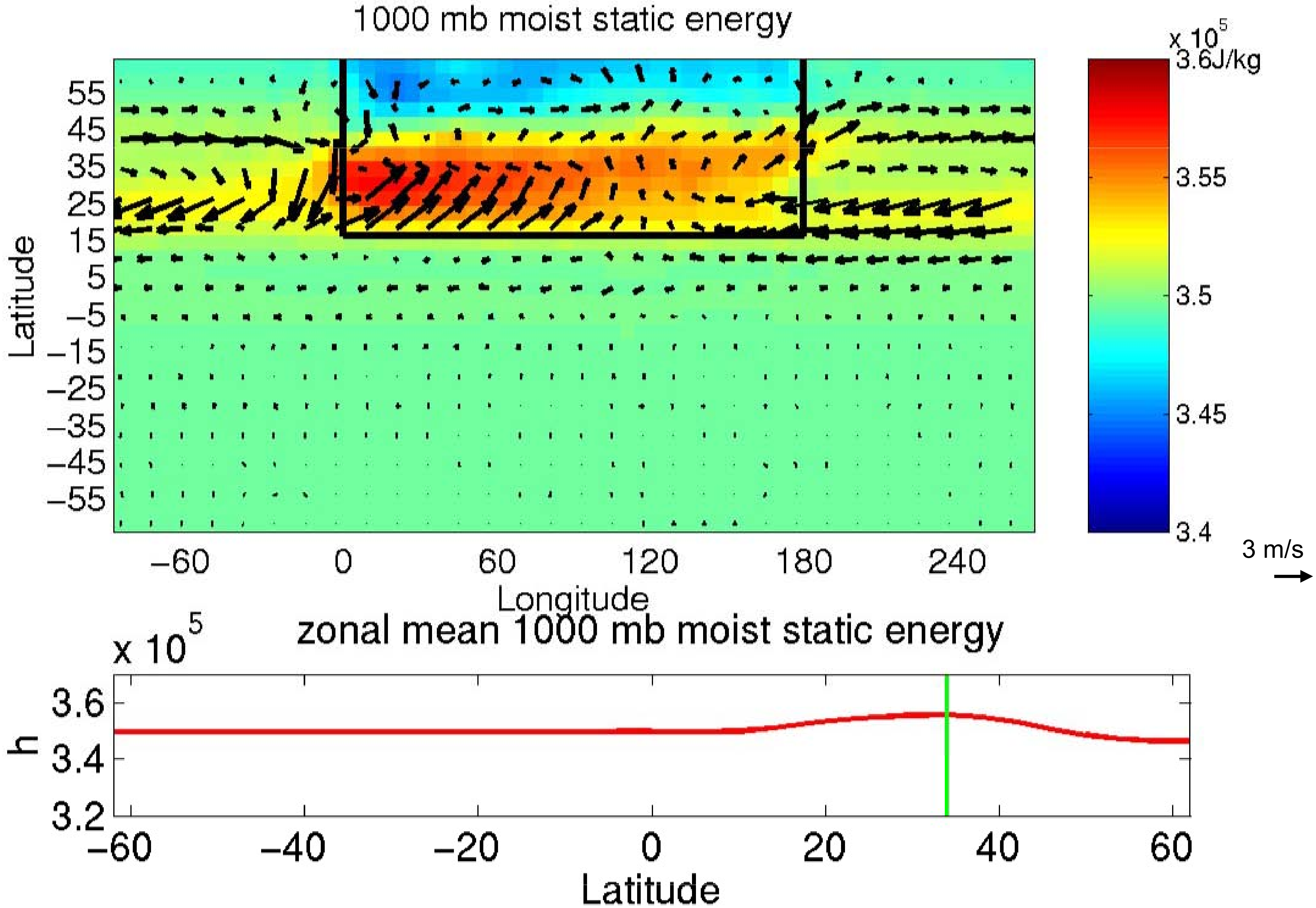
Impact of advection of low h_b air



Comparison h_b distribution



Subcloud h_b with warm ocean



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Remove the source of low h_b…