Why is there ascent on the cold side of equator?

Meridional pressure gradient above the PBL:

$$\frac{\partial \varphi}{\partial y} = -\mathbf{V} \bullet \nabla v - 2\Omega \sin\theta\, u$$

$$\cong -\frac{1}{2}\frac{\partial v^2}{\partial y} - 2\Omega \sin\theta\, u$$

Hydrostatic:

$$\varphi_{PBL} = \varphi - R\frac{\Delta p_{pbl}}{p}\left(T_v\right)_{pbl}$$

$$\rightarrow \quad \frac{\partial \varphi_{pbl}}{\partial y} = \frac{\partial \varphi}{\partial y} - R\frac{\Delta p_{pbl}}{p}\left(\frac{\partial T_v}{\partial y}\right)_{pbl}$$

$$= -\frac{1}{2}\frac{\partial v^2}{\partial y} - 2\Omega \sin\theta\, u - R\frac{\Delta p_{pbl}}{p}\left(\frac{\partial T_v}{\partial y}\right)_{pbl}$$

PBL momentum:

$$V \bullet \nabla v - F_v = -\left(\frac{\partial \varphi}{\partial y}\right)_{pbl} - 2\Omega \sin\theta\, u_{pbl}$$

$$\rightarrow \frac{1}{2}\left(\frac{\partial v^2}{\partial y}\right)_{pbl} - F_v \cong \frac{1}{2}\left(\frac{\partial v^2}{\partial y}\right) + R\frac{\Delta p_{pbl}}{p}\left(\frac{\partial T_v}{\partial y}\right)_{pbl} + 2\Omega \sin\theta\left(u - u_{pbl}\right)$$

$$F_v \cong -C_D \frac{|\mathbf{V}|}{h} v$$

F_v dominant when $h <\sim C_D \Delta y$

$$\left(C_D \simeq 10^{-3}\right)$$

Thin, frictionally dominated PBL:

$$C_D \frac{|\mathbf{V}|}{h} v \cong R \frac{\Delta p_{pbl}}{p} \left(\frac{\partial T_v}{\partial y} \right)_{pbl} + 2\Omega \sin\theta (u)$$

u constrained by angular momentum conservation:

$$u_{min} = \frac{\Omega a}{\cos\theta} \left[\sin^2\theta - \sin^2\theta_0 \right],$$

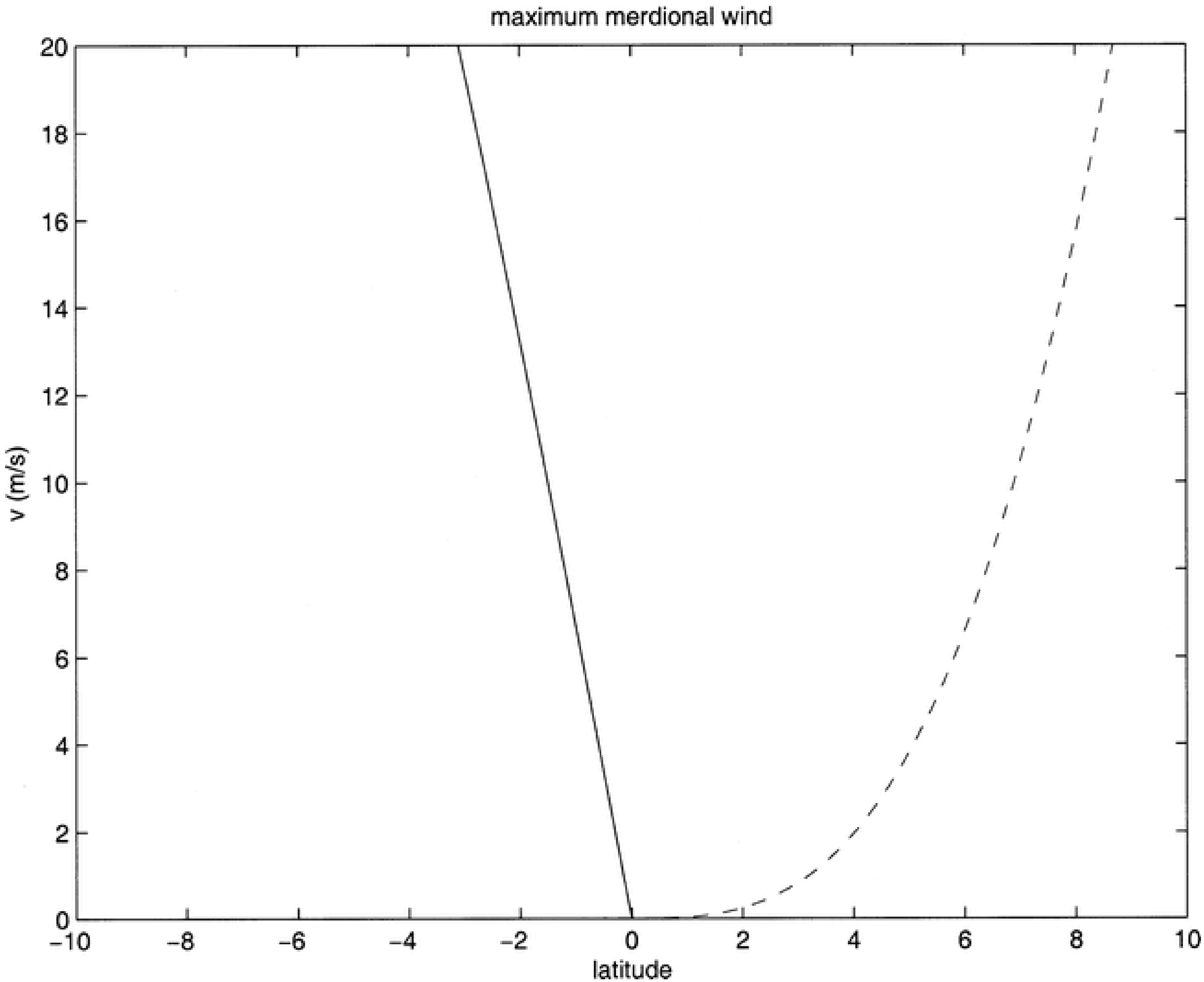
$$u_{max} = \frac{\Omega a}{\cos\theta} \sin^2\theta$$

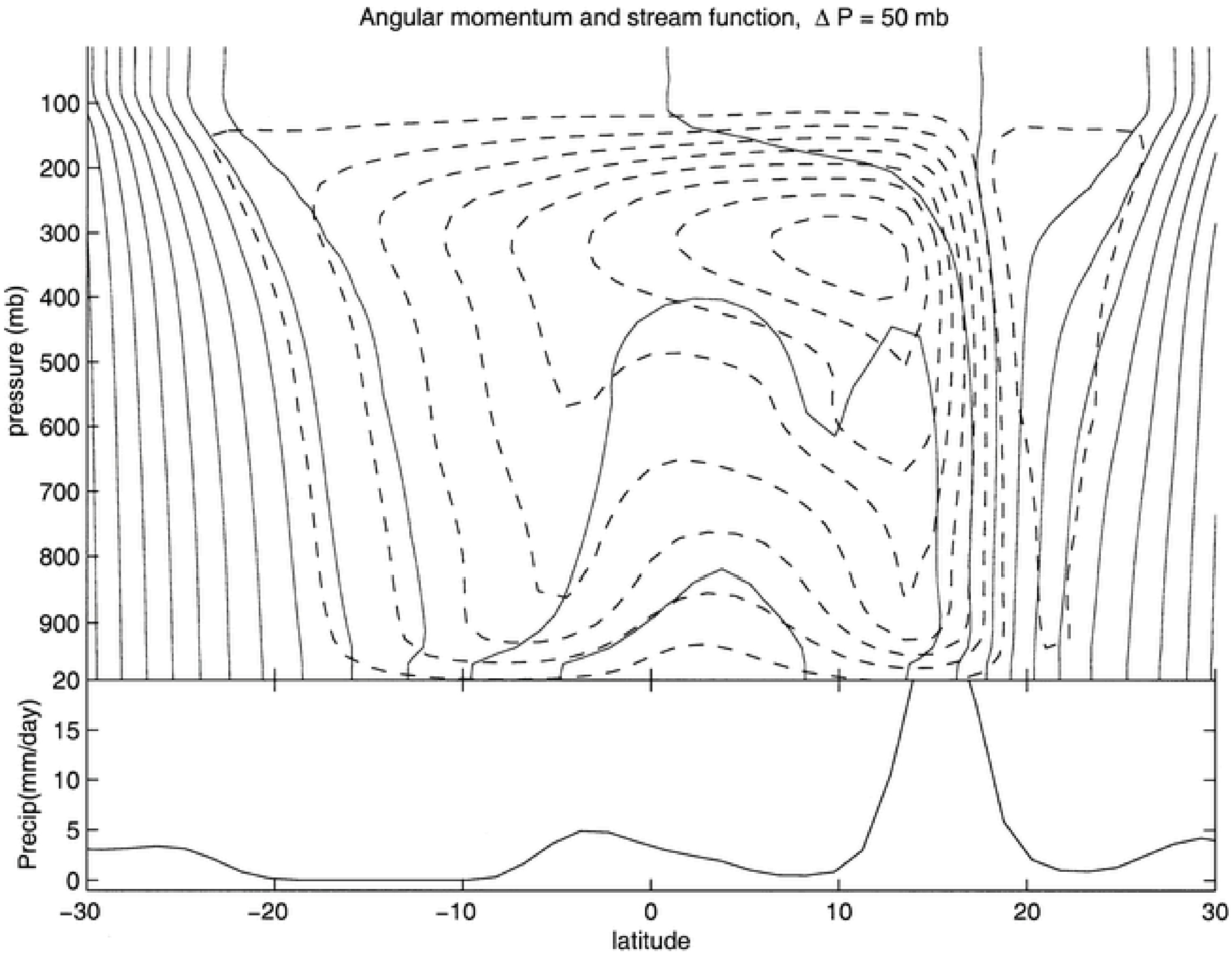
Cold side of equator:

$$C_D \frac{|\mathbf{V}|}{h} v \cong R \frac{\Delta p_{pbl}}{p} \left(\frac{\partial T_v}{\partial y} \right)_{pbl} + 2\Omega^2 a \tan\theta \left[\sin^2\theta - \sin^2\theta_0 \right]$$

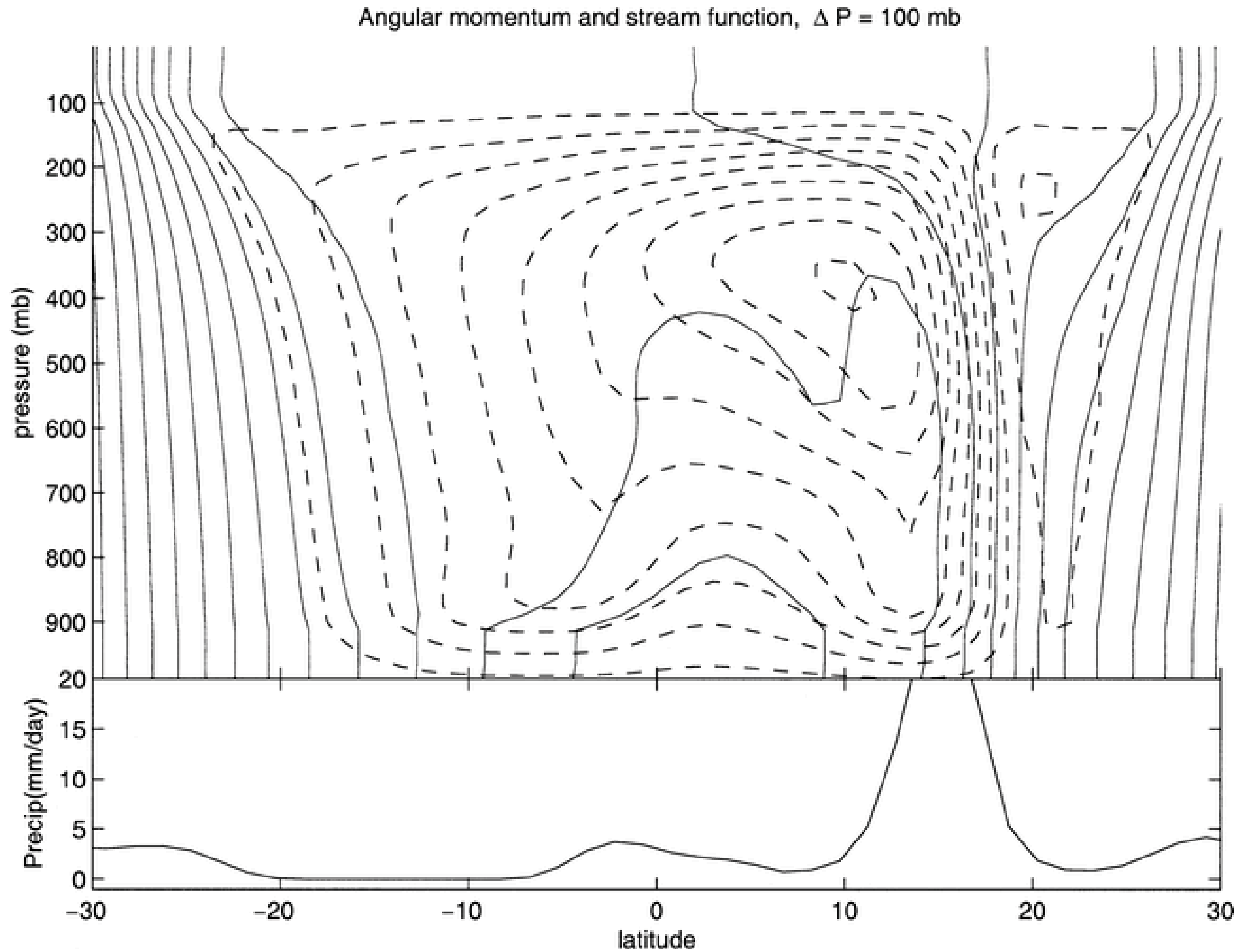
Warm side of equator:

$$C_D \frac{|\mathbf{V}|}{h} v \cong R \frac{\Delta p_{pbl}}{p} \left(\frac{\partial T_v}{\partial y} \right)_{pbl} + 2\Omega^2 a \tan\theta \sin^2\theta$$

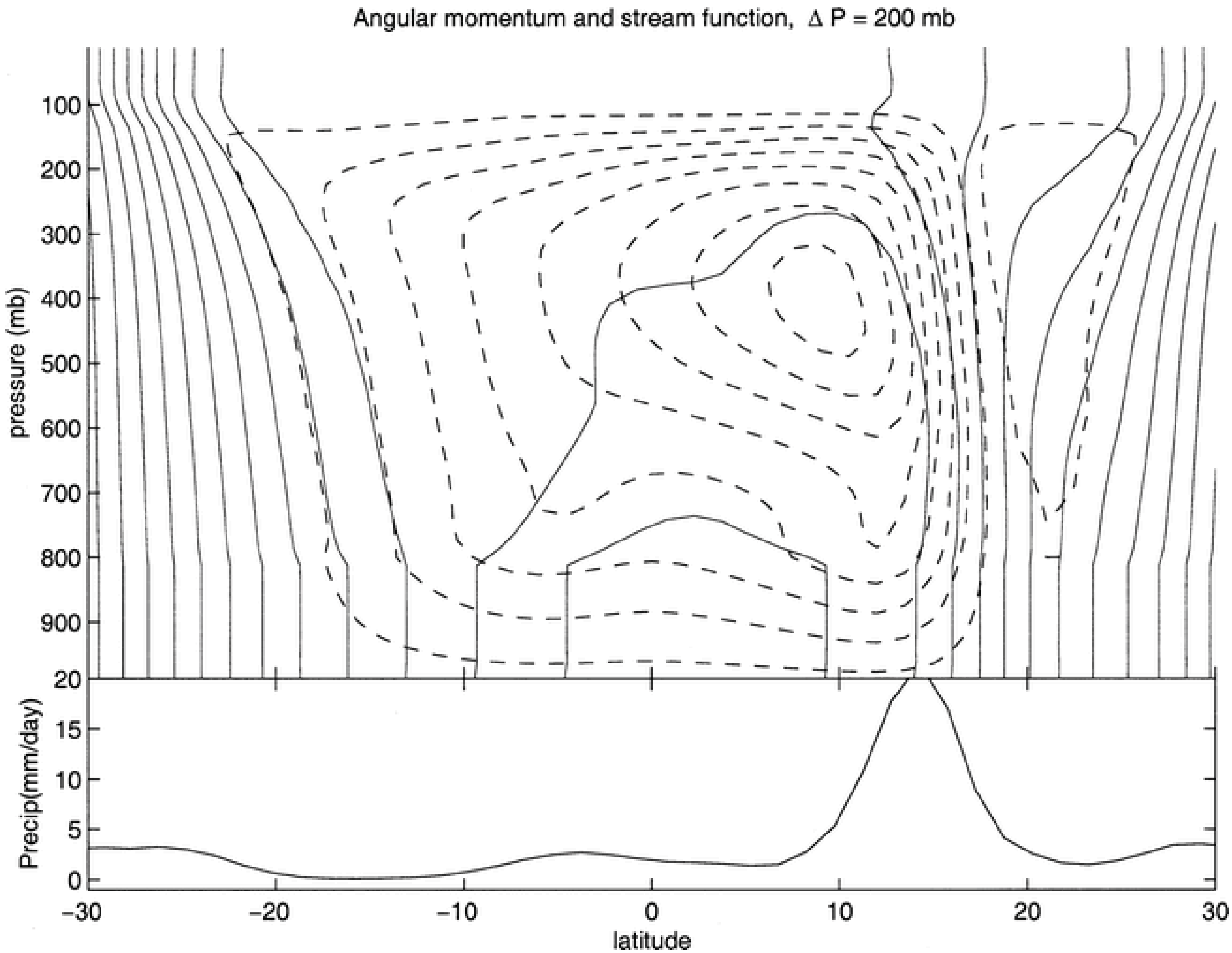

maximum merdional wind
v (m/s)
latitude
20
18
16
14
12
10
8
6
4
2
0
−10
−8
−6
−4
−2
0
2
4
6
8
10



$$\Delta p_{pbl} = 50\ mb$$

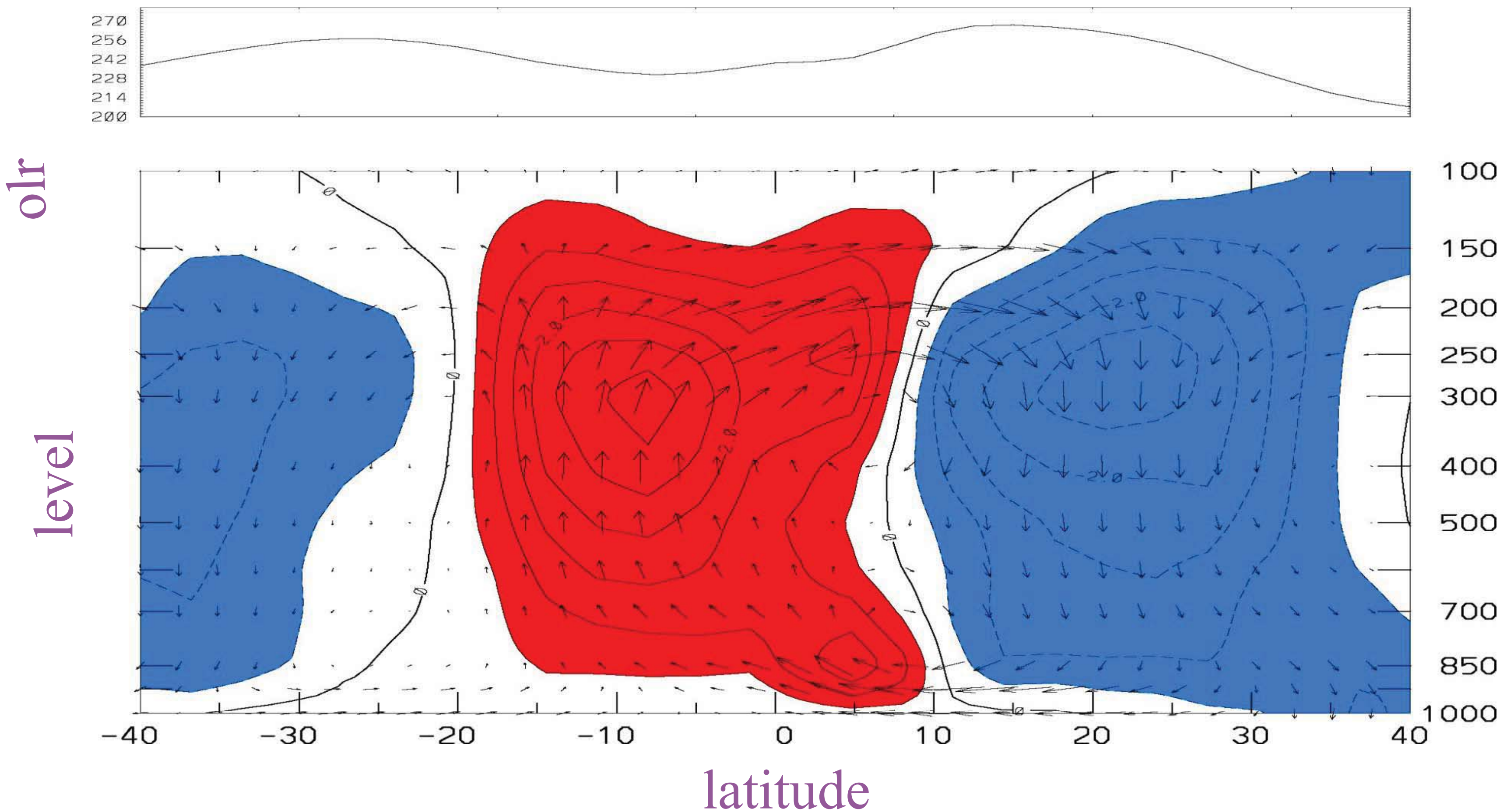


$$\Delta p_{pbl} = 100\ mb$$



$$\Delta p_{pbl} = 200\ mb$$

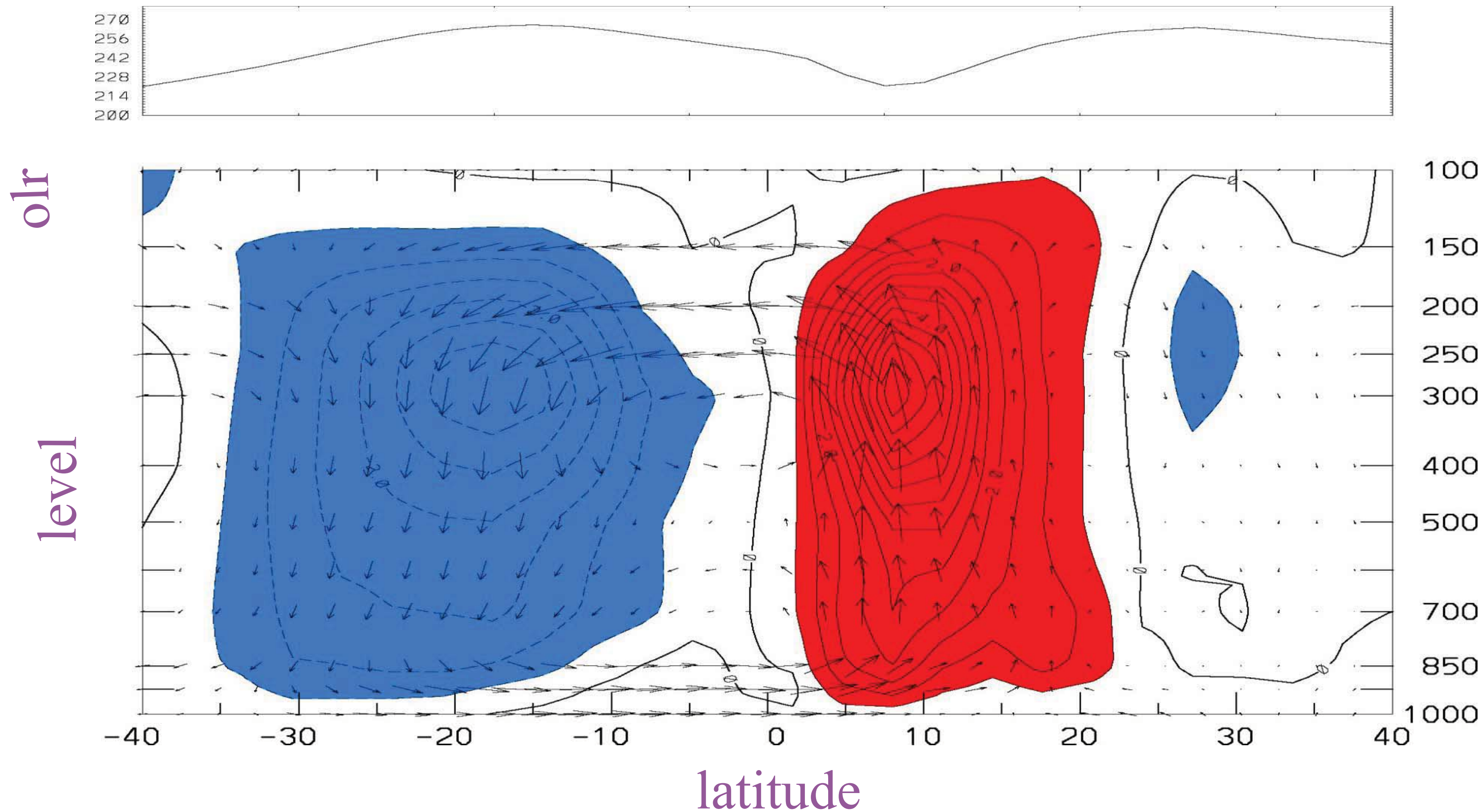
January Zonal Mean OLR, Vertical and Meridional Wind, 1979-1993 from ECMWF



Contour interval 1 mm s^{-1}

Shading Red Positive (Upward)

July Zonal Mean OLR, Vertical and Meridional Wind, 1979-1993 from ECMWF

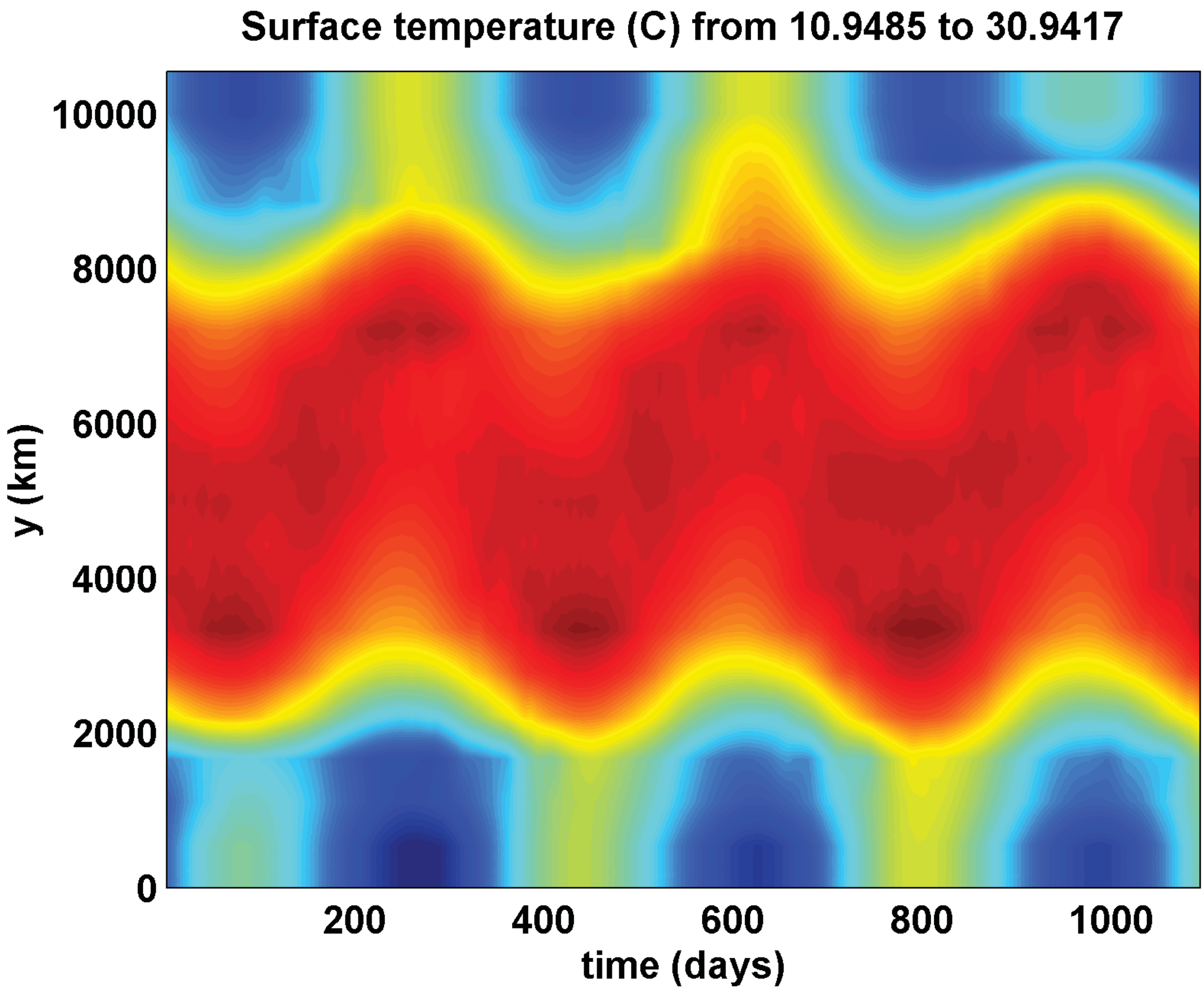


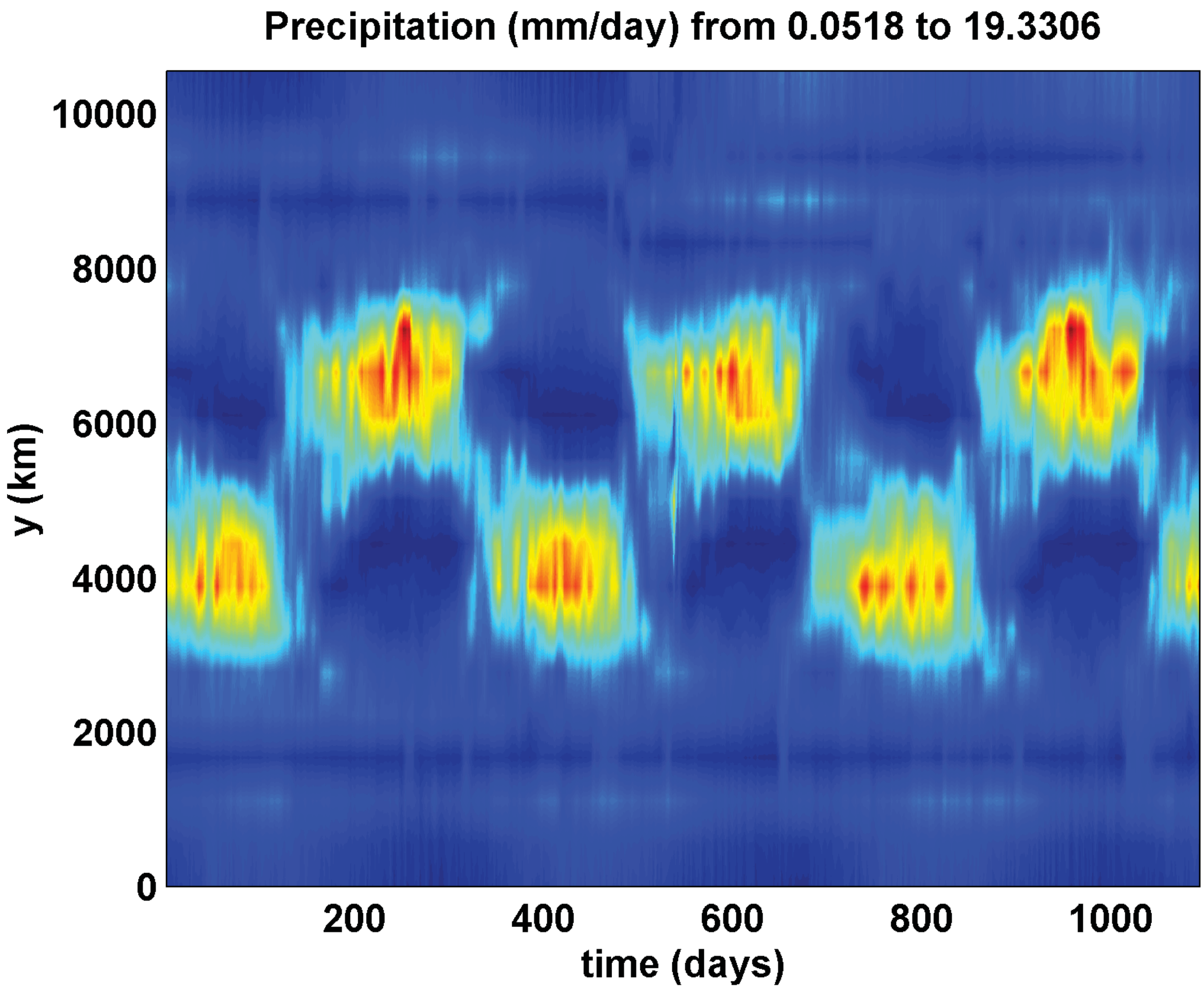
Contour interval 1 mm s^{-1}

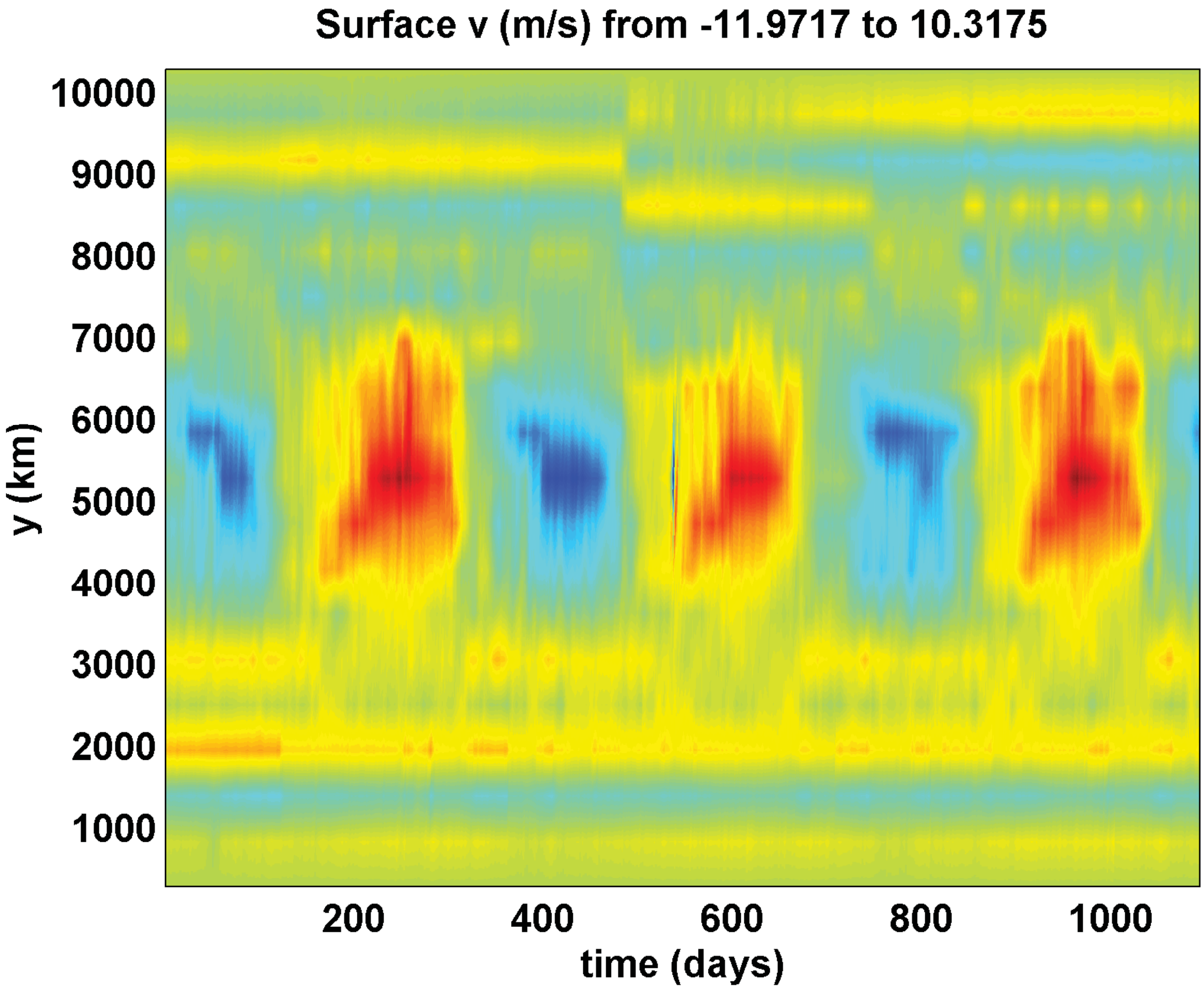
Shading Red Positive (Upward)

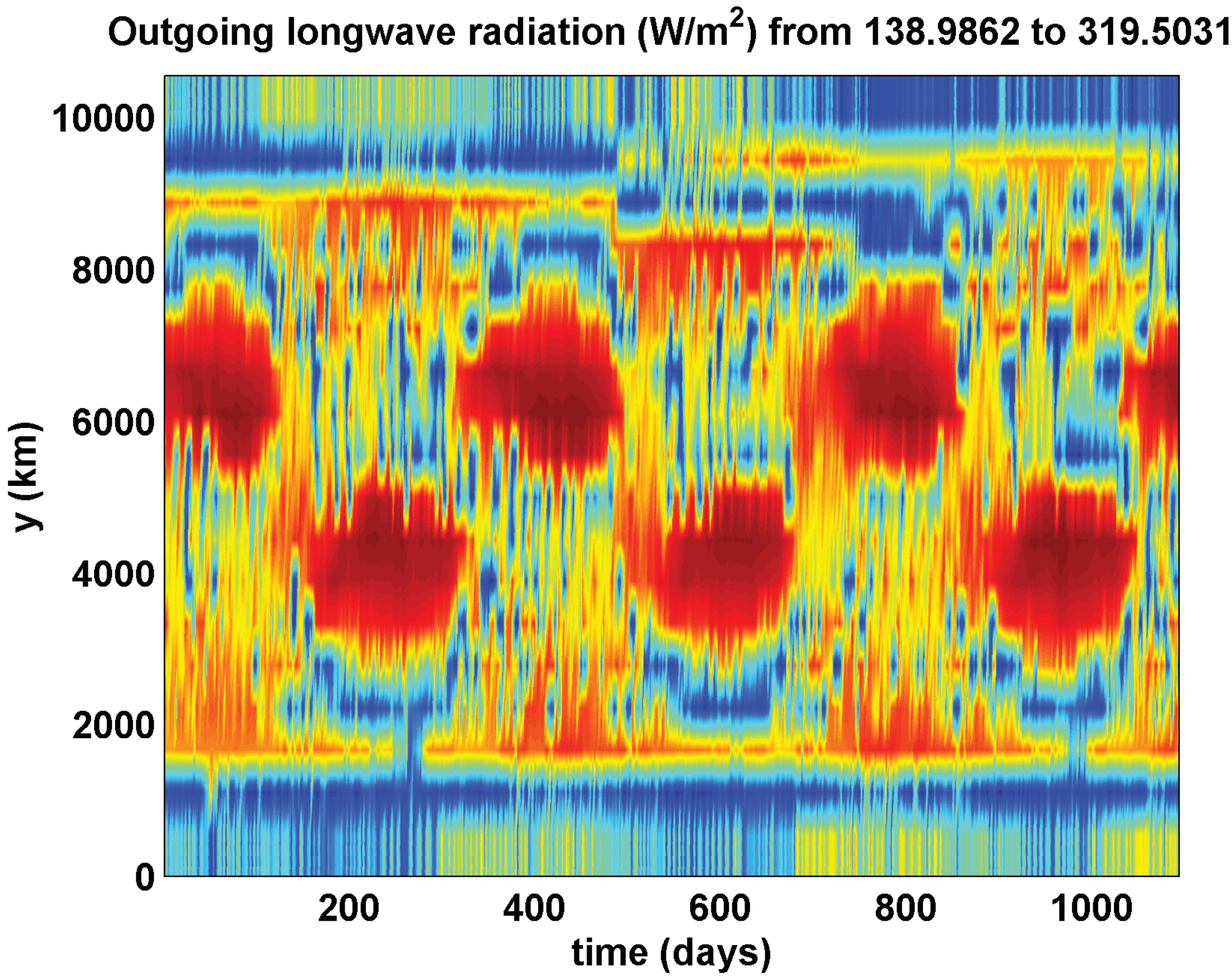
Two-D primitive equation model

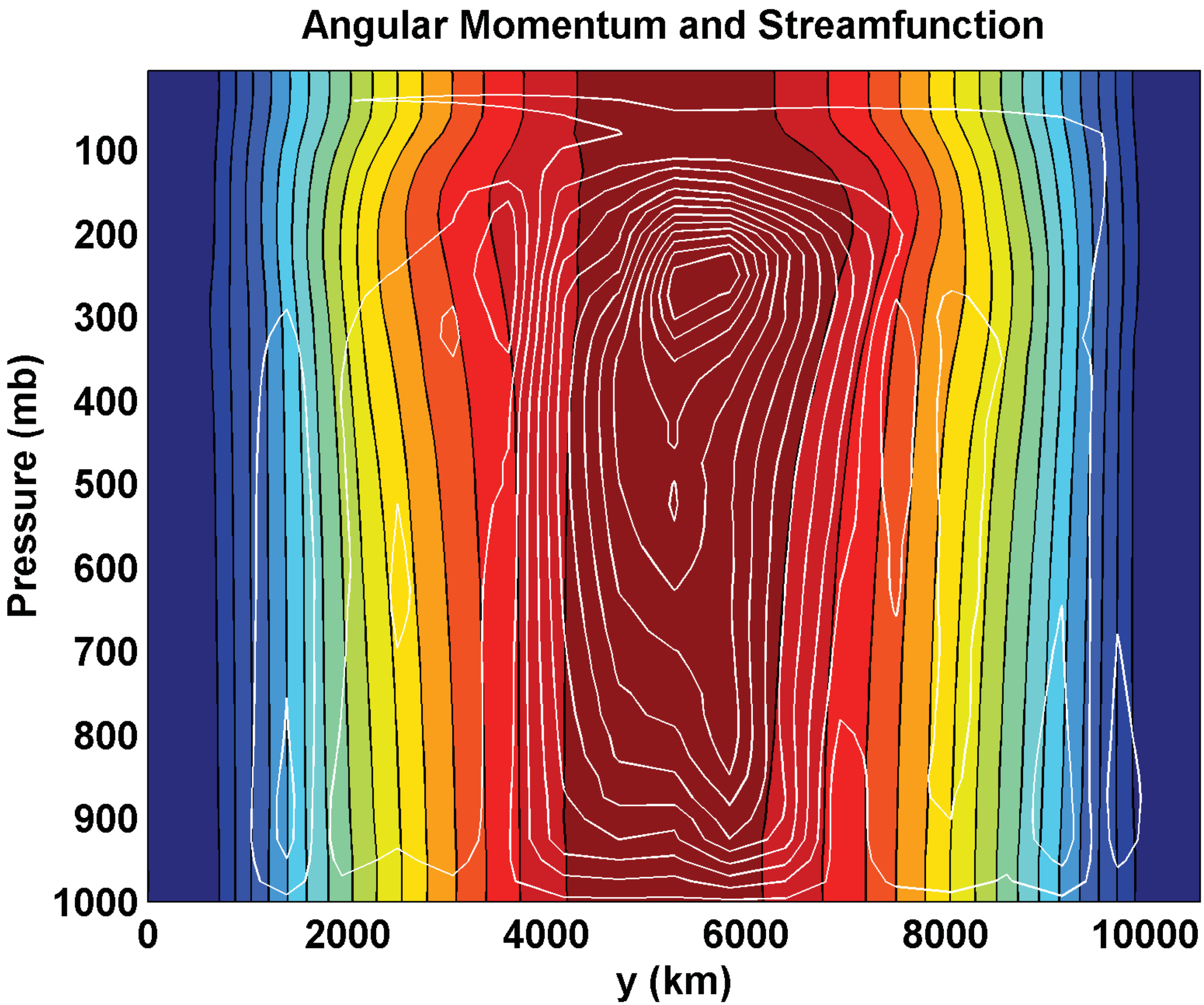
- Parameterizations of
  - convection
  - fractional cloudiness
  - radiation
  - surface fluxes
- Ocean mixed layer energy budget
- Model forced by annual cycle of solar radiation
- Available for class projects

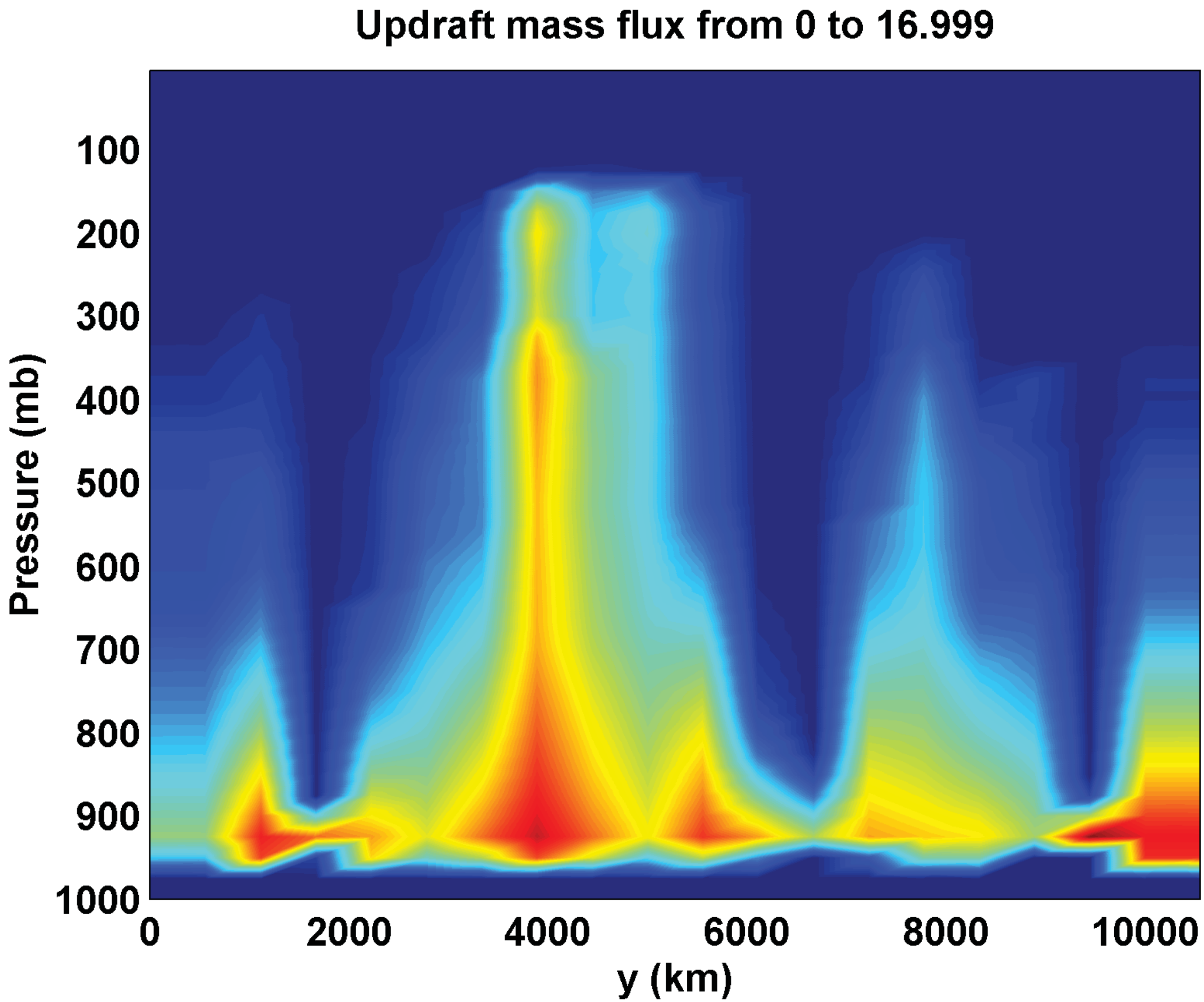

Surface temperature (C) from 10.9485 to 30.9417
10000
8000
6000
4000
2000
0
y (km)
200
400
600
800
1000
time (days)

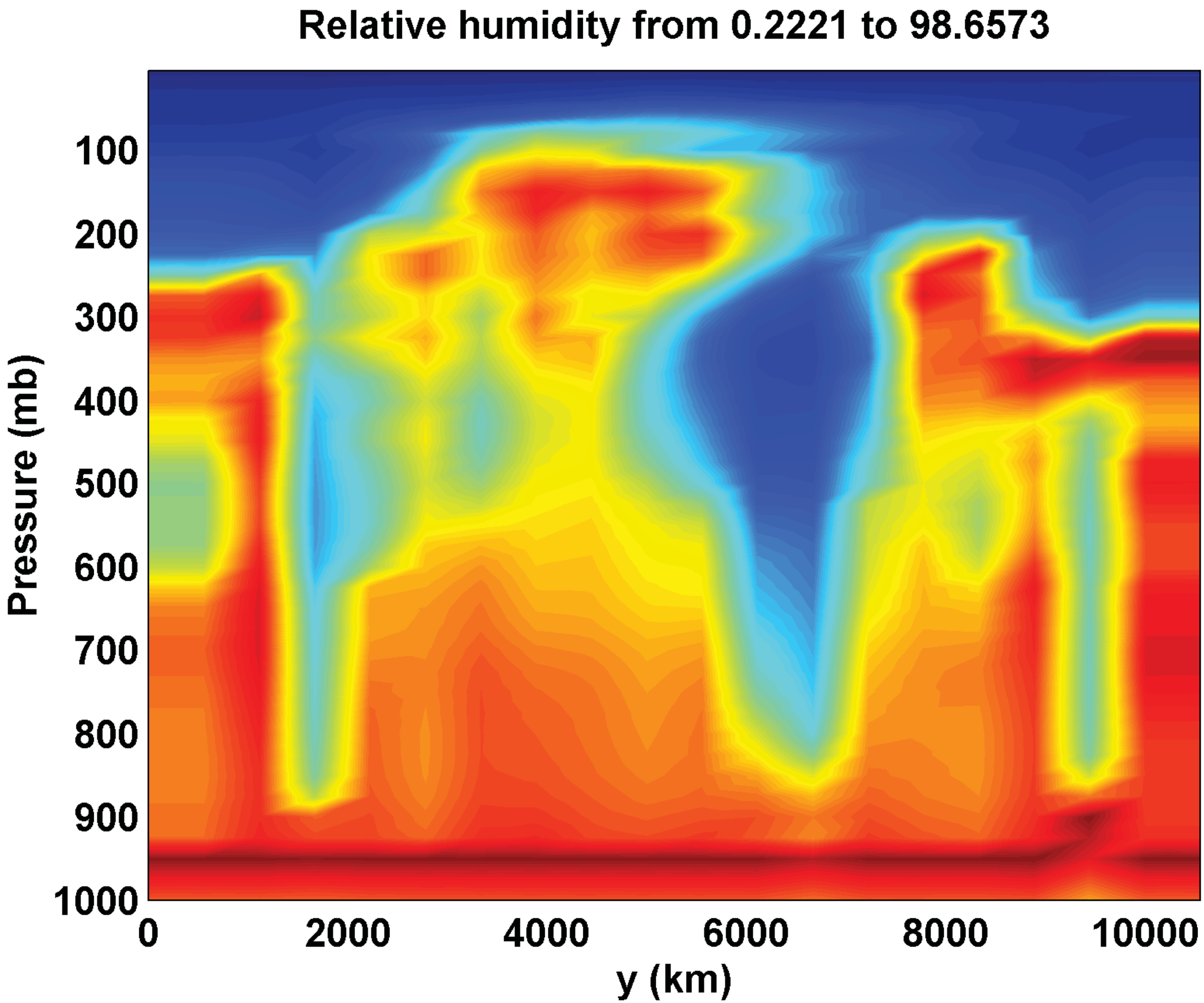

Precipitation (mm/day) from 0.0518 to 19.3306
10000
8000
6000
4000
2000
0
y (km)
200
400
600
800
1000
time (days)


Surface v (m/s) from -11.9717 to 10.3175
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
y (km)
200
400
600
800
1000
time (days)


Outgoing longwave radiation (W/m2) from 138.9862 to 319.5031
y (km)
10000
8000
6000
4000
2000
0
200
400
600
800
1000
time (days)


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


Updraft mass flux from 0 to 16.999
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)


Relative humidity from 0.2221 to 98.6573
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
y (km)

The ideal Hadley circulation...

- Conserves angular momentum m in upper branch

$$\bar{v}\partial_y \bar{m} \approx 0$$

Since $\partial_y \bar{m} \propto f + \bar{\zeta}$, this implies

$$(f + \bar{\zeta})\bar{v} = f(1 - \mathrm{Ro})\bar{v} \approx 0$$

with *local Rossby number* $\mathrm{Ro} = -\bar{\zeta}/f \to 1$

- Is energetically closed (no heat export)

- Responds *directly* to variations in thermal driving

- Result: $\phi_h \sim (H_t' \Delta_h')^{1/2}, \qquad \Psi_{\max} \sim (H_t' \Delta_h')^{5/2}$

(Schneider 1977; Schneider & Lindzen 1976, 1977; Held & Hou 1980)

Ideal Hadley circulation theory...

- Is intuitively appealing (direct reponse to thermal driving)

- Appears to account for extent of circulation in Earth's atmosphere

But does it account for variations in Hadley circulation as climate varies?

12.811 Tropical Meteorology
Spring 2011