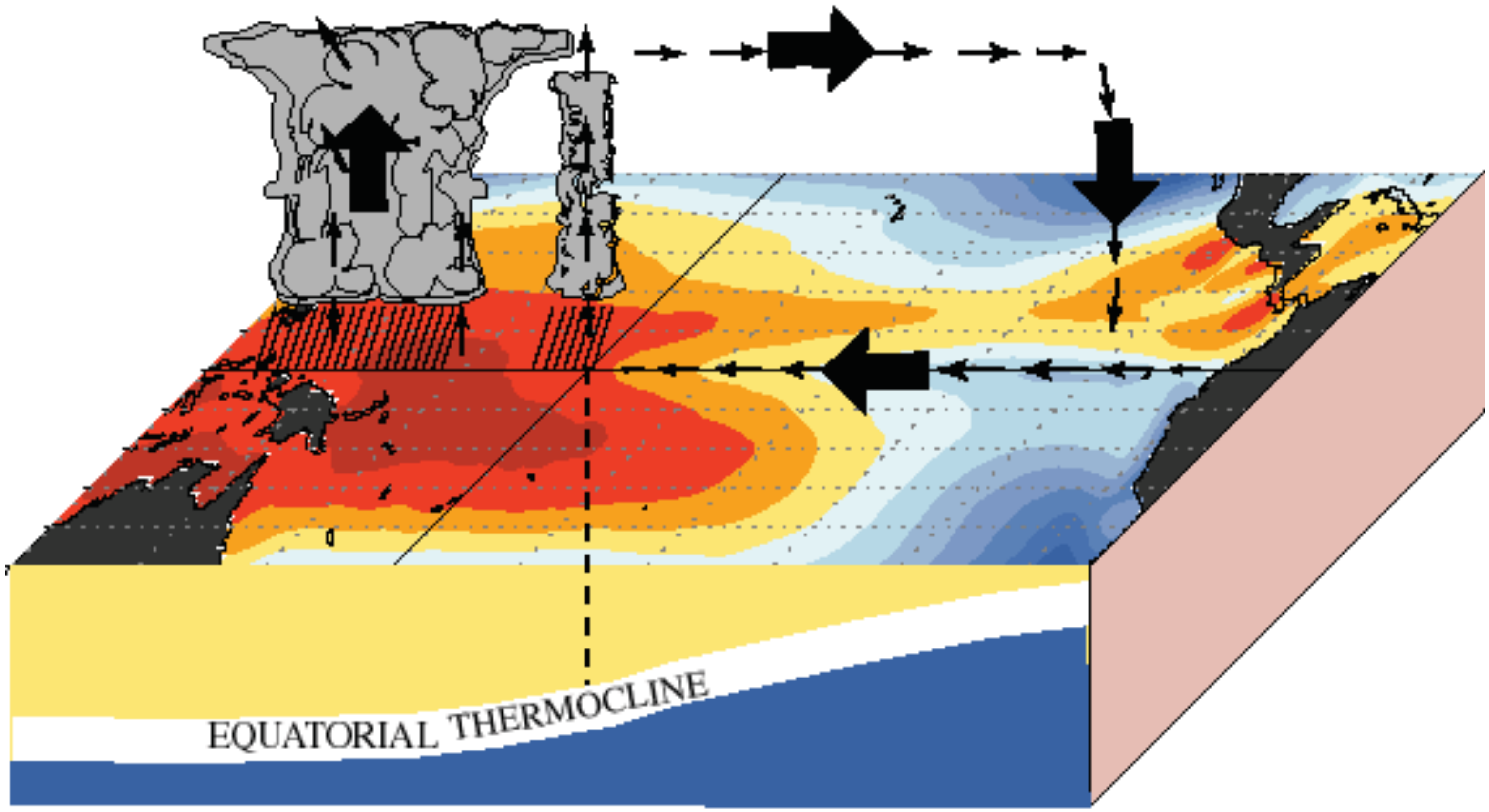
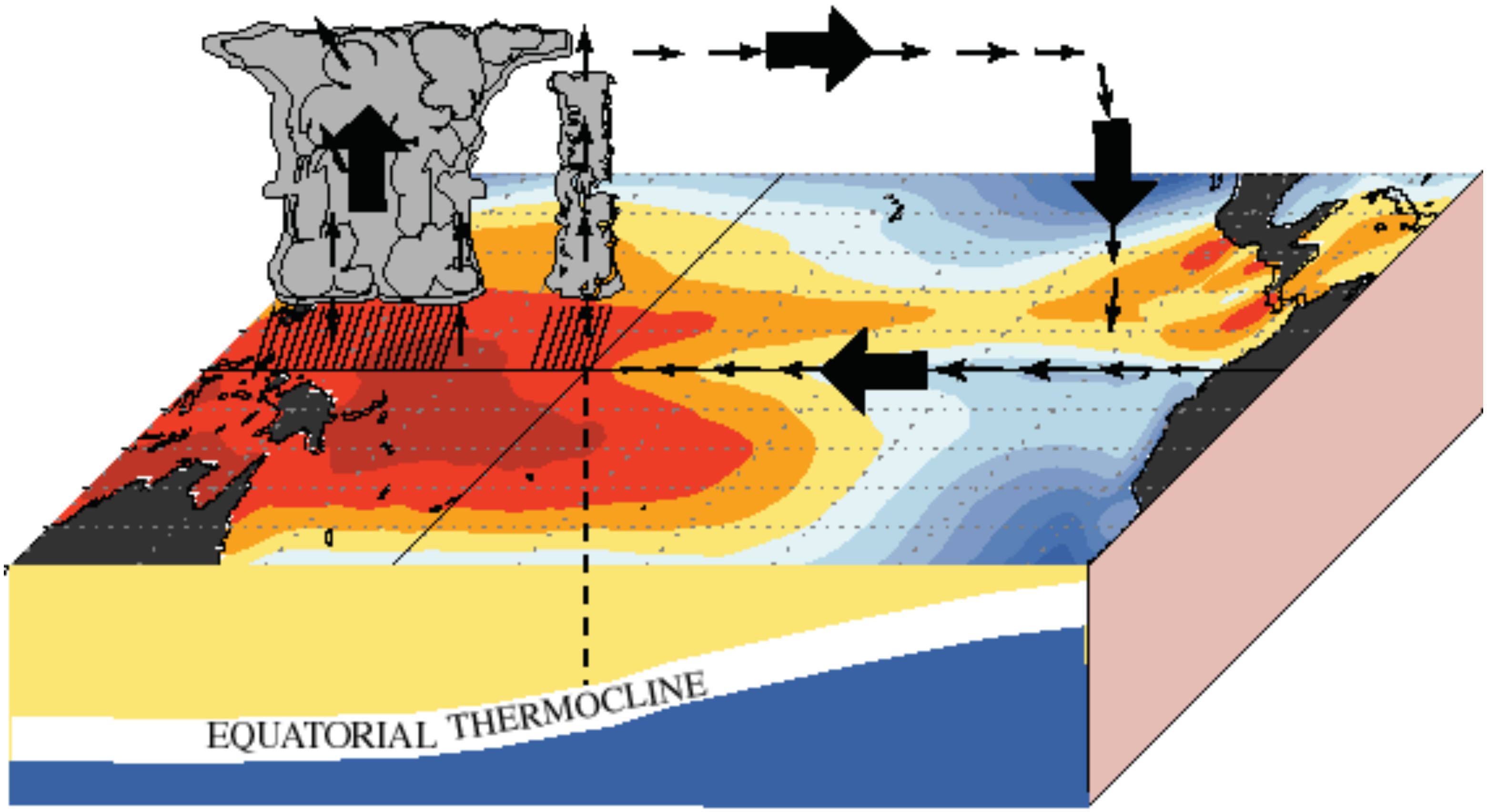
The Walker Circulation

December - February Normal Conditions



December - February Normal Conditions

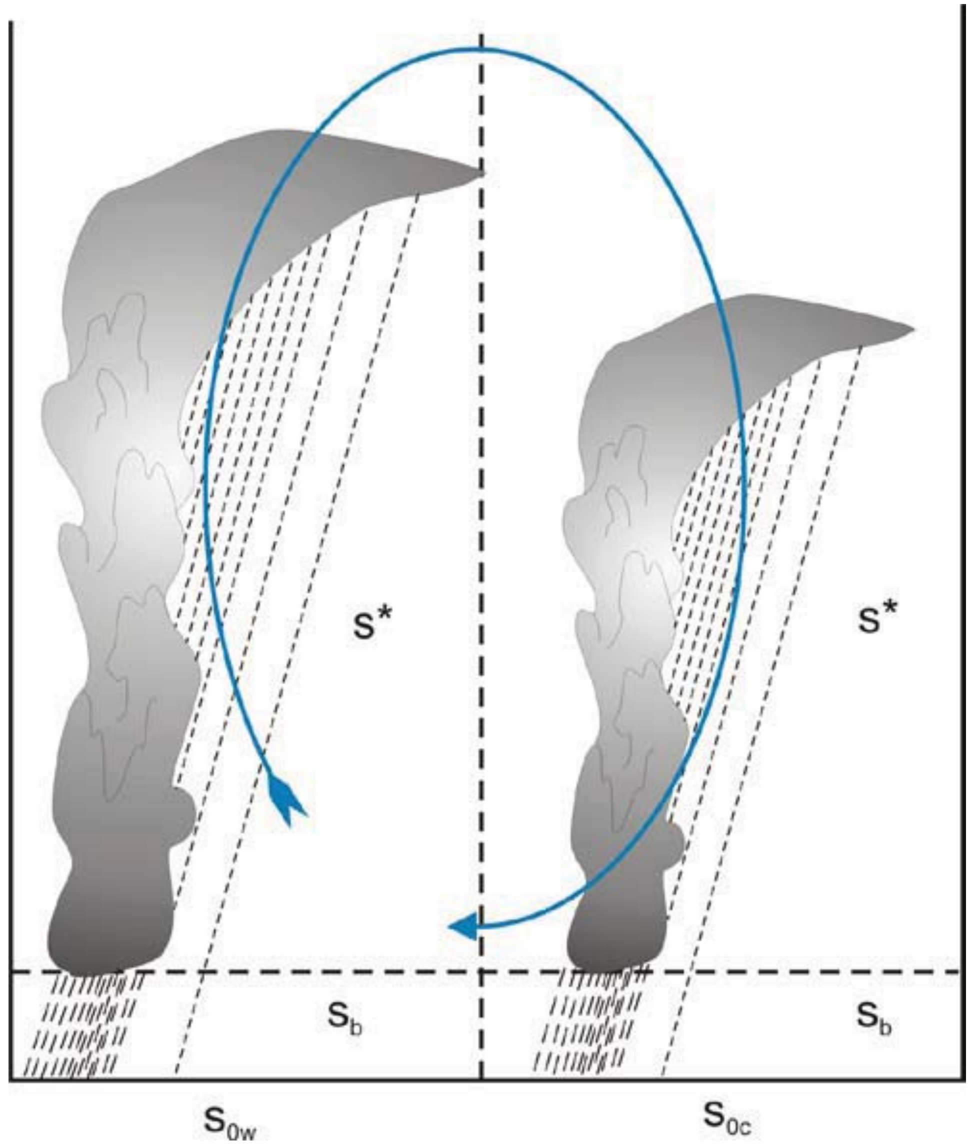


Two-Box Model

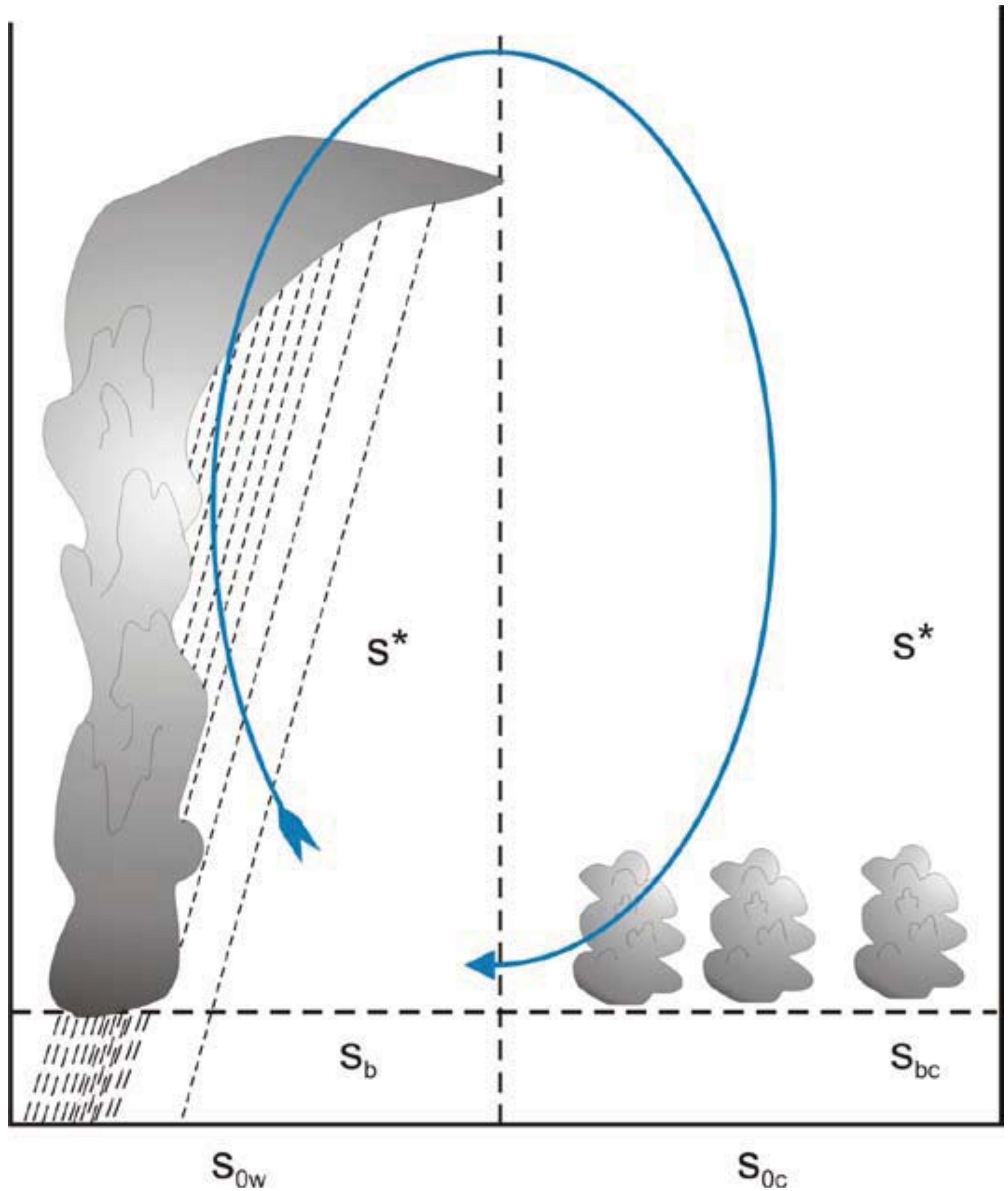
Key Assumptions:

- BL entropy quasi-equilibrium
- Convective neutrality
  - $s^* = s_b$ where deep convection is occurring
- WTG: weak temperature gradient
  - s^* horizontally homogeneous in free troposphere

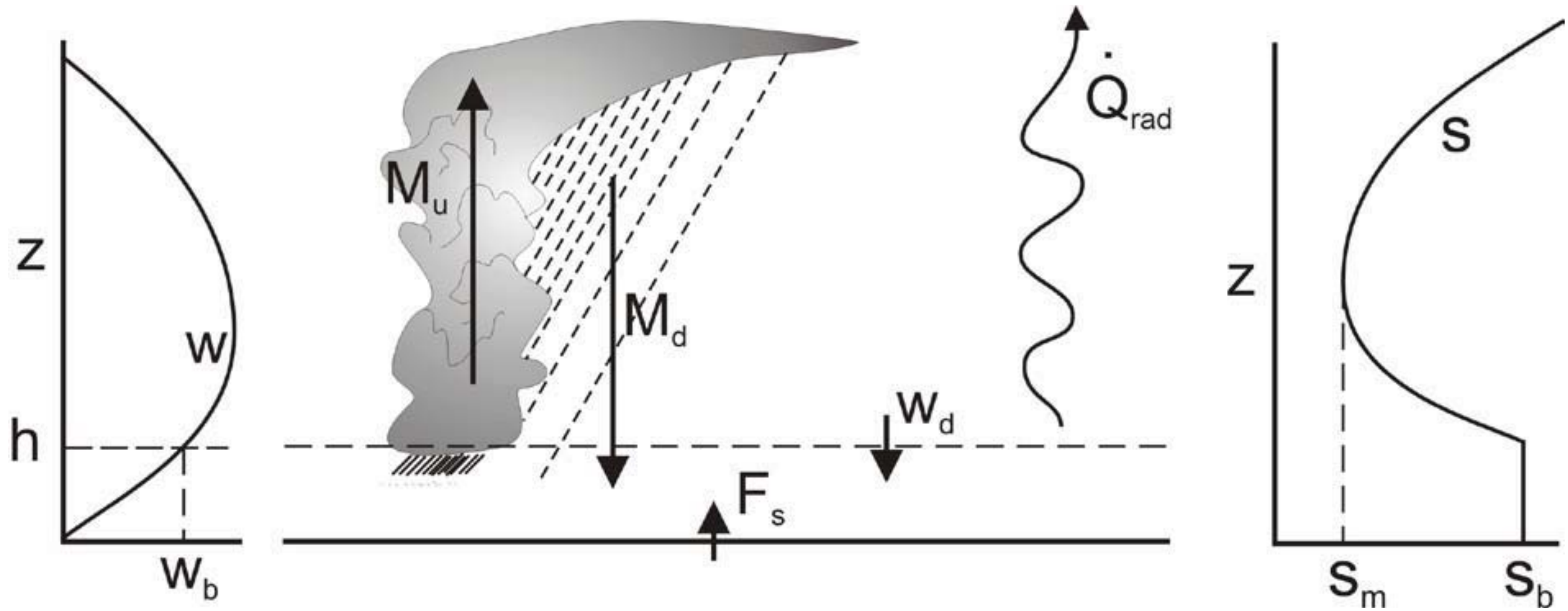
Two-Box Model:



Weak circulation: Deep convection in both boxes



Strong circulation: Deep convection only in warm box



$$h\frac{\partial s_b}{\partial t} \approx 0 = F_s - \left(M_d + \left(1-\sigma\right)w_d\right)\left(s_b - s_m\right)$$

Mass:

$$M_u - M_d - \left(1-\sigma\right)w_d = w_b$$

$$\rightarrow M_u = w_b + \frac{F_s}{s_b - s_m} \qquad (1)$$

Free troposphere heat balance:

$$\left(M_u - M_d - w\right)\mathbf{S} = \dot{Q}_{cool},$$

$$\mathbf{S} \equiv c_p \frac{T}{\theta}\frac{\partial \theta}{\partial z}$$

Convective downdraft:

$$M_d = \left(1 - \varepsilon_p\right)M_u$$

$$\rightarrow \boxed{\varepsilon_p M_u = w + \dot{Q}_{cool} / \mathbf{S}} \qquad (2)$$

Combine (1) and (2)

$$Let \quad w_b = \gamma w$$

$$w = \frac{1}{1-\gamma\varepsilon_p}\left[\frac{\varepsilon_p F_s}{s_b - s_m} - \frac{\dot{Q}_{cool}}{\mathbf{S}}\right],$$

$$M_u = \frac{1}{1-\gamma\varepsilon_p}\left[\frac{F_s}{s_b - s_m} - \frac{\gamma\dot{Q}_{cool}}{\mathbf{S}}\right]$$

Note that $M_u > w$

Begin with:

$$w = \frac{1}{1-\gamma\varepsilon_p}\left[\frac{\varepsilon_p F_s}{s_b - s_m} - \frac{\dot{Q}_{cool}}{\mathbf{S}}\right],$$

$$M_u = \frac{1}{1-\gamma\varepsilon_p}\left[\frac{F_s}{s_b - s_m} - \frac{\gamma\dot{Q}_{cool}}{\mathbf{S}}\right]$$

Mass Continuity:

$$w_w = -w_c$$

For convenience:

$$C_D\,|\mathbf{V}| = constant$$

$$\frac{\dot{Q}_{cool}}{\mathbf{S}} \equiv R = constant$$

$$s_b - s_m \equiv \Delta s = constant$$

Scale variables:

$$w \rightarrow \frac{R}{1-\gamma\varepsilon_p} w,$$

$$M_u \rightarrow \frac{R\gamma}{1-\gamma\varepsilon_p} M,$$

$$s \rightarrow \frac{R\Delta s}{C_D |\mathbf{V}| \varepsilon_p} s,$$

$$\alpha \equiv \frac{1}{\gamma \varepsilon_p}$$

Nondimensional equations:

$$w = s_0 - s - 1,$$

$$M = \alpha\left(s_0 - s\right) - 1$$

Requirement that $w_w = -w_c$ **:**

$$s = \frac{1}{2}\left(s_{0w} + s_{0c}\right) - 1,$$

$$w_w = -w_c = \frac{1}{2}\left(s_{0w} - s_{0c}\right),$$

$$M_w = \alpha - 1 + \frac{\alpha}{2}\left(s_{0w} - s_{0c}\right),$$

$$M_c = \alpha - 1 - \frac{\alpha}{2}\left(s_{0w} - s_{0c}\right).$$

Convection ceases when $M_c < 0$:

$$s_{0w} - s_{0c} > \frac{2(\alpha - 1)}{\alpha}$$

Balance in cold box when $M_c = 0$:

(Dimensional): $w_c = -R$ (free atmosphere)

$$-\gamma w_c = \frac{C_D |\mathbf{V}|}{\Delta s}\left(s_{0c} - s_c\right)$$ (boundary layer)

Nondimensional solutions for cold box:

$$w_c\left(=-w_w\right)=-\frac{\alpha-1}{\alpha},$$

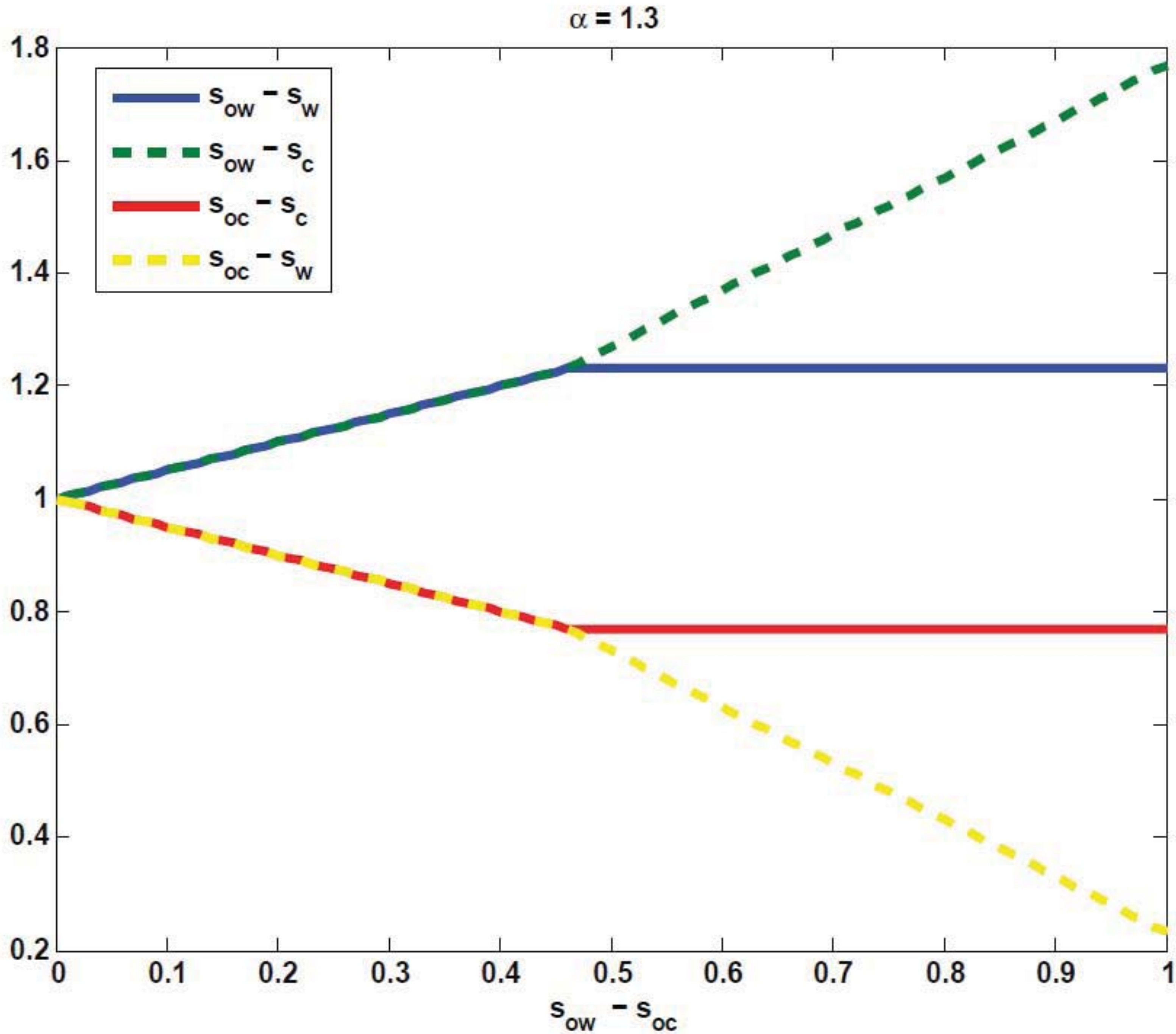
$$s_c=s_{0c}-1/\alpha.$$

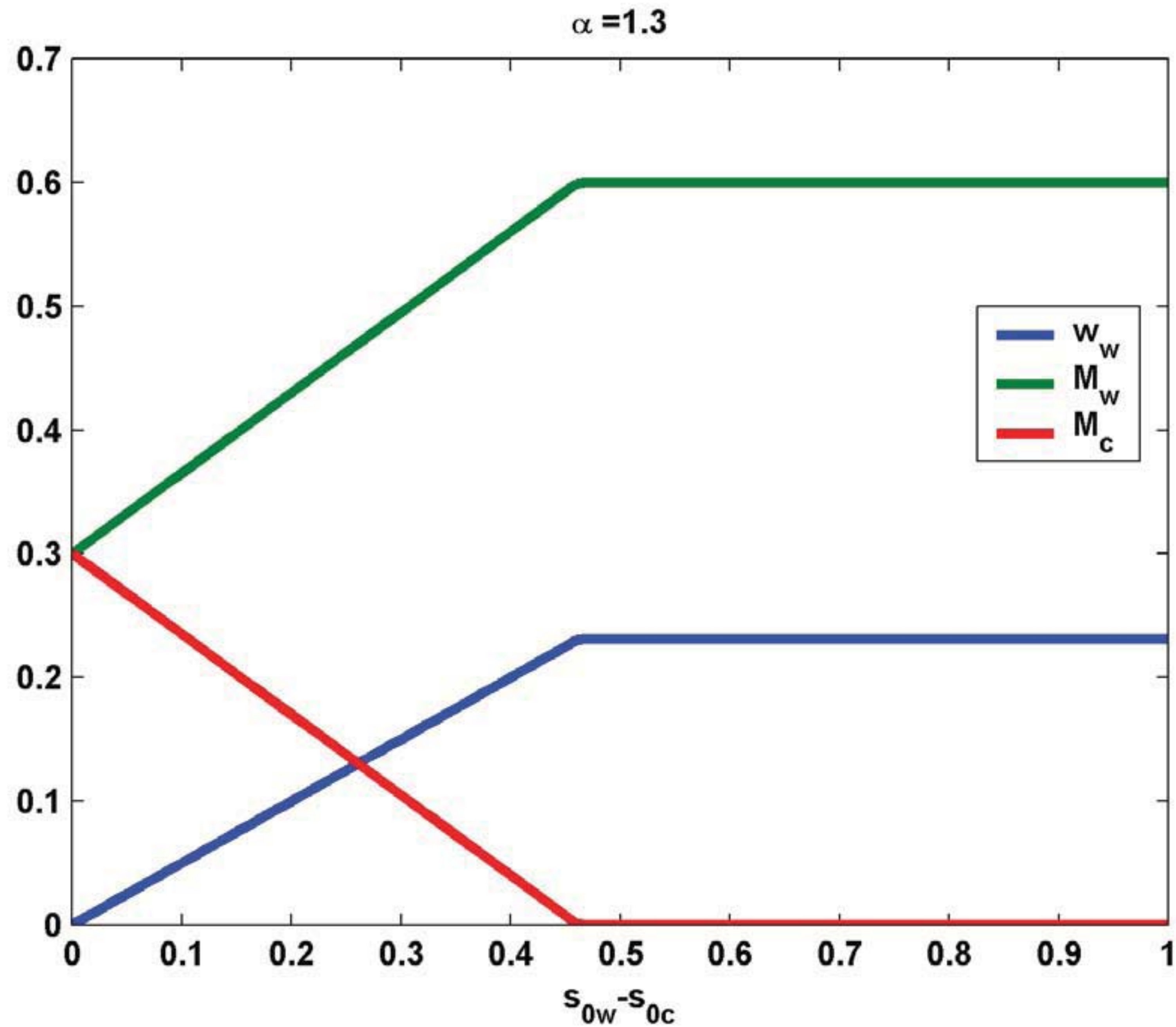
Nondimensional solutions for warm box:

$$w_w=s_{0w}-s_w-1=1-1/\alpha$$

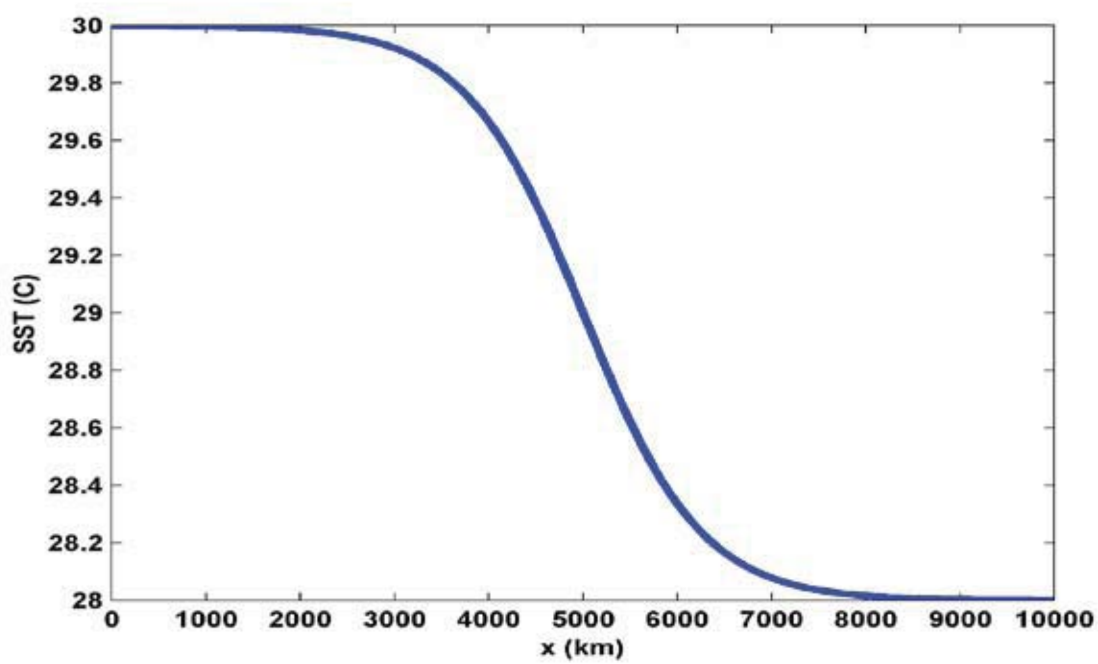
$$\rightarrow s_w=s_{0w}+\frac{1}{\alpha}-2$$

$$M_w=\alpha\left(s_{0w}-s_w\right)-1=2\left(\alpha-1\right).$$

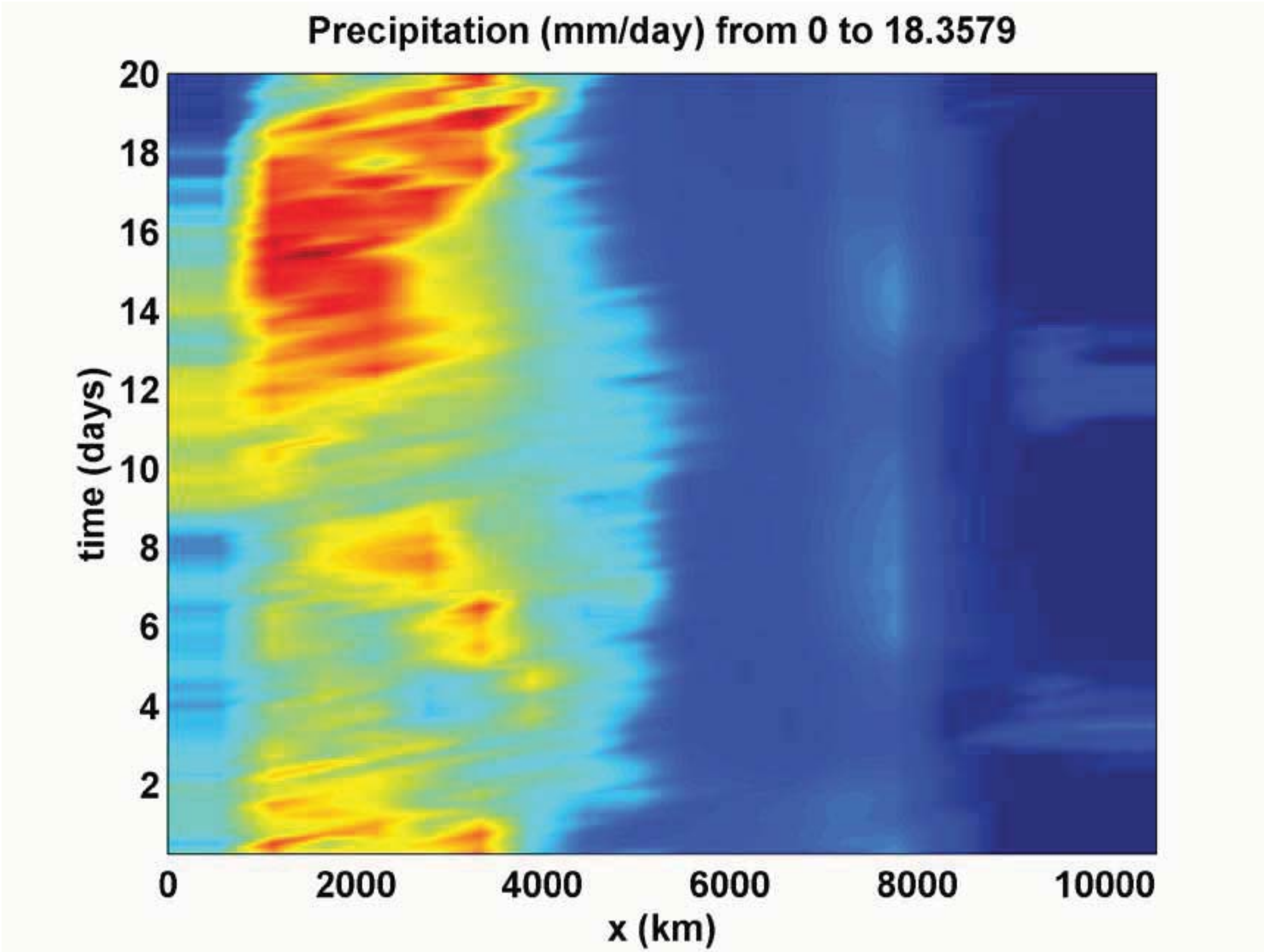

α = 1.3
s_ow - s_w
s_ow - s_c
s_oc - s_c
s_oc - s_w
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
s_ow - s_oc

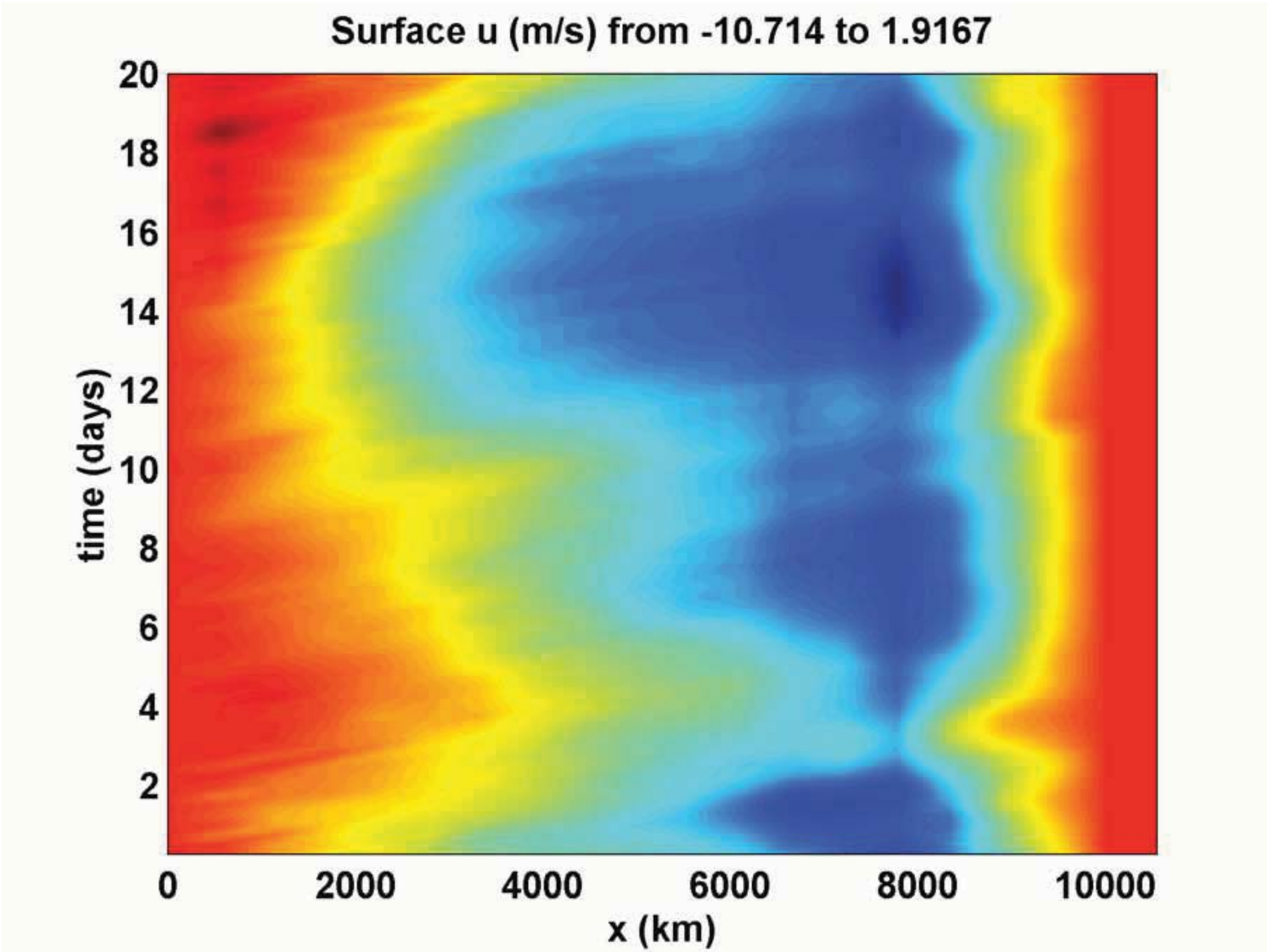

α =1.3
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
w_w
M_w
M_c
s_{0w}-s_{0c}

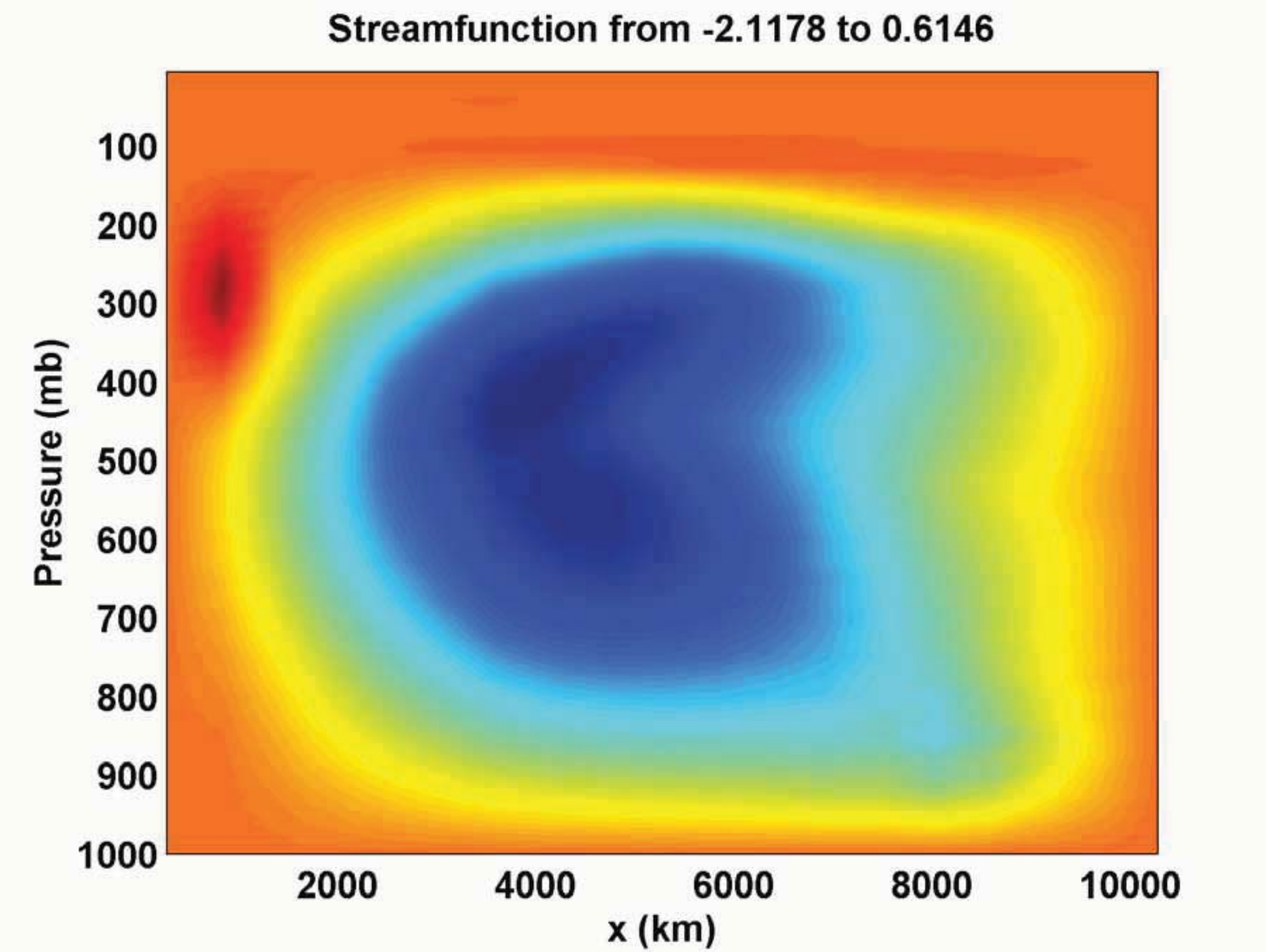
Simulations with 2-D model using 20 columns spanning 100 degrees of longitude

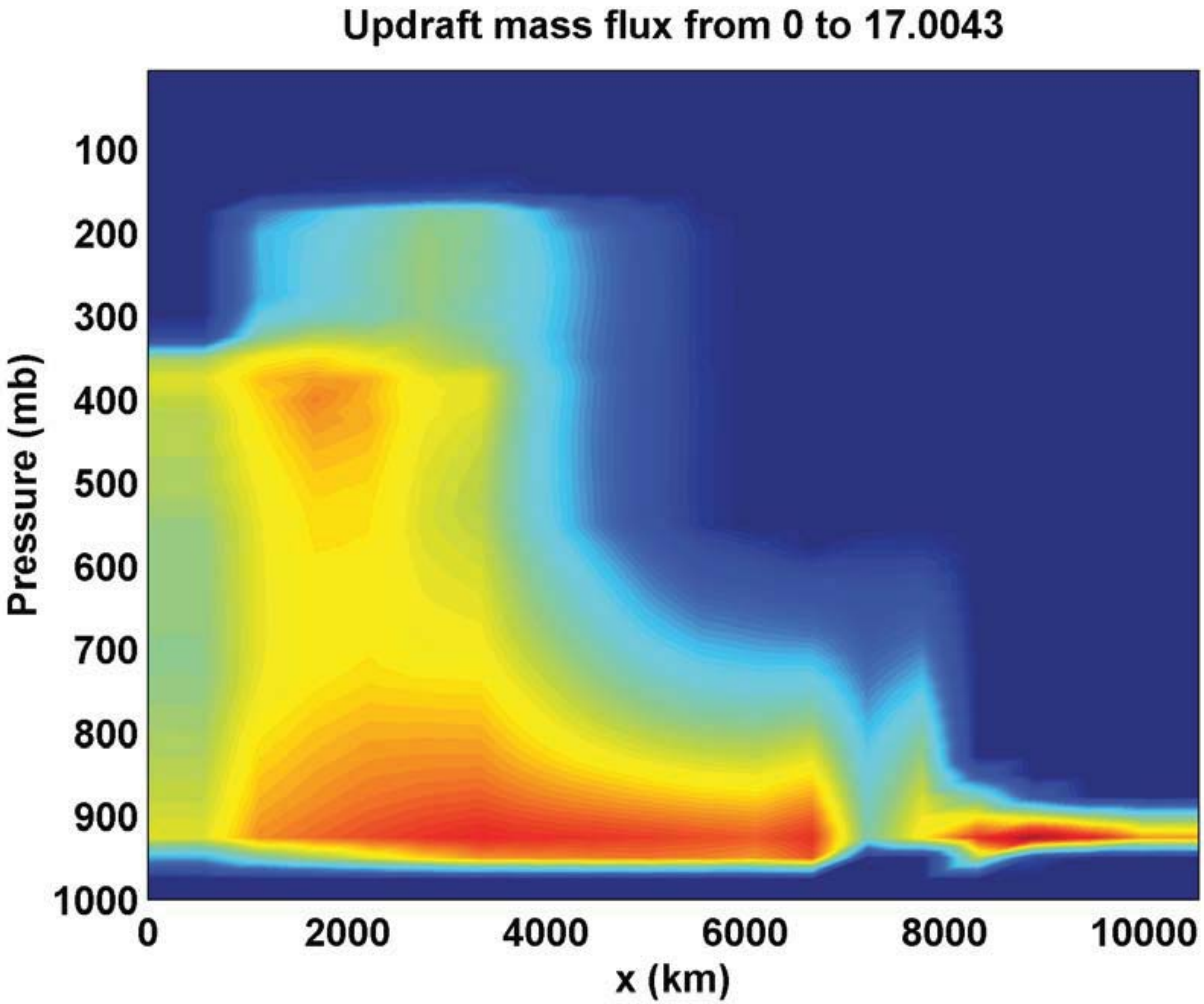


$$\Delta SST = 2^o\,C$$

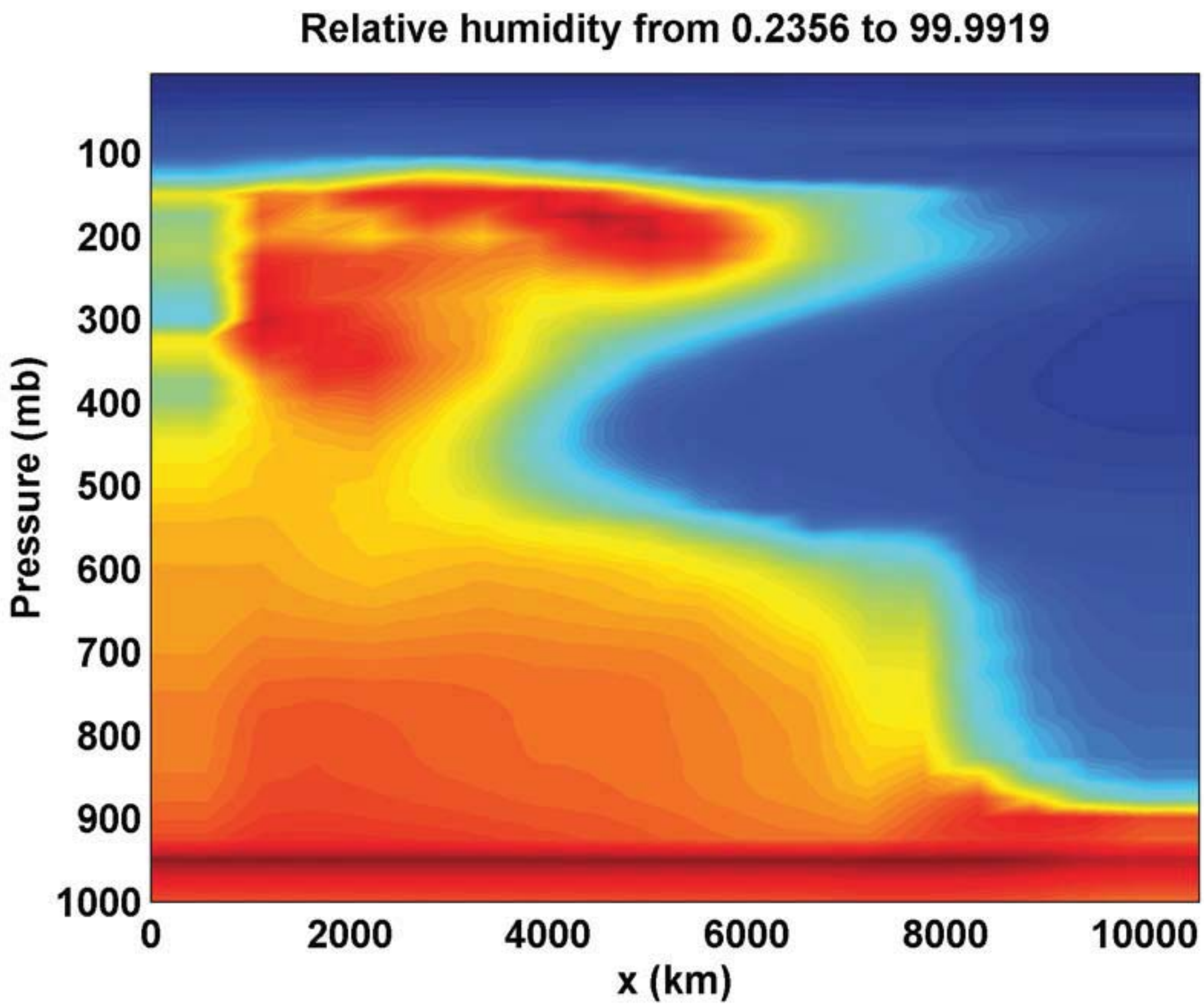


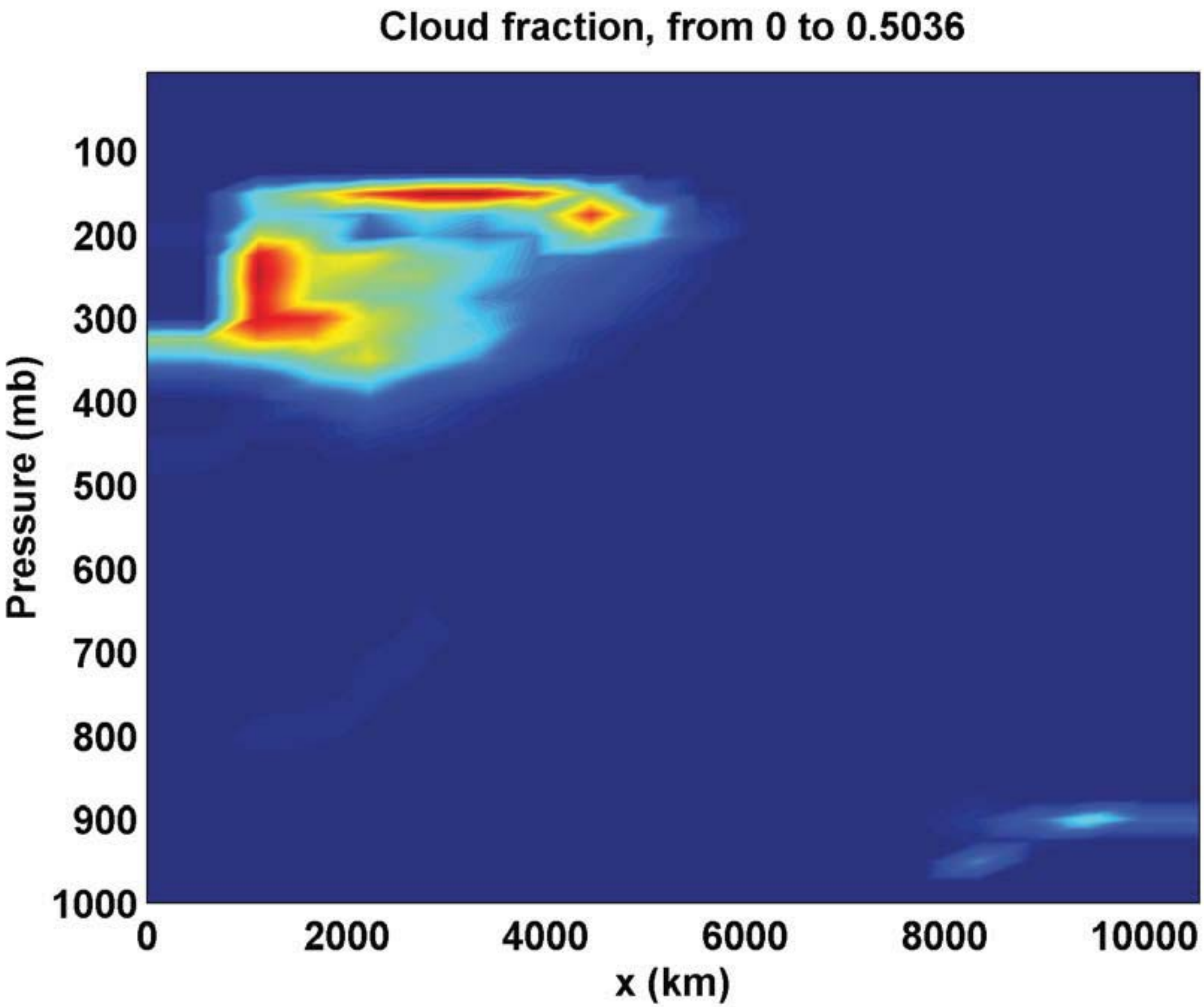

Surface u (m/s) from -10.714 to 1.9167
time (days)
20
18
16
14
12
10
8
6
4
2
0
2000
4000
6000
8000
10000
x (km)


Streamfunction from -2.1178 to 0.6146
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
2000
4000
6000
8000
10000
x (km)

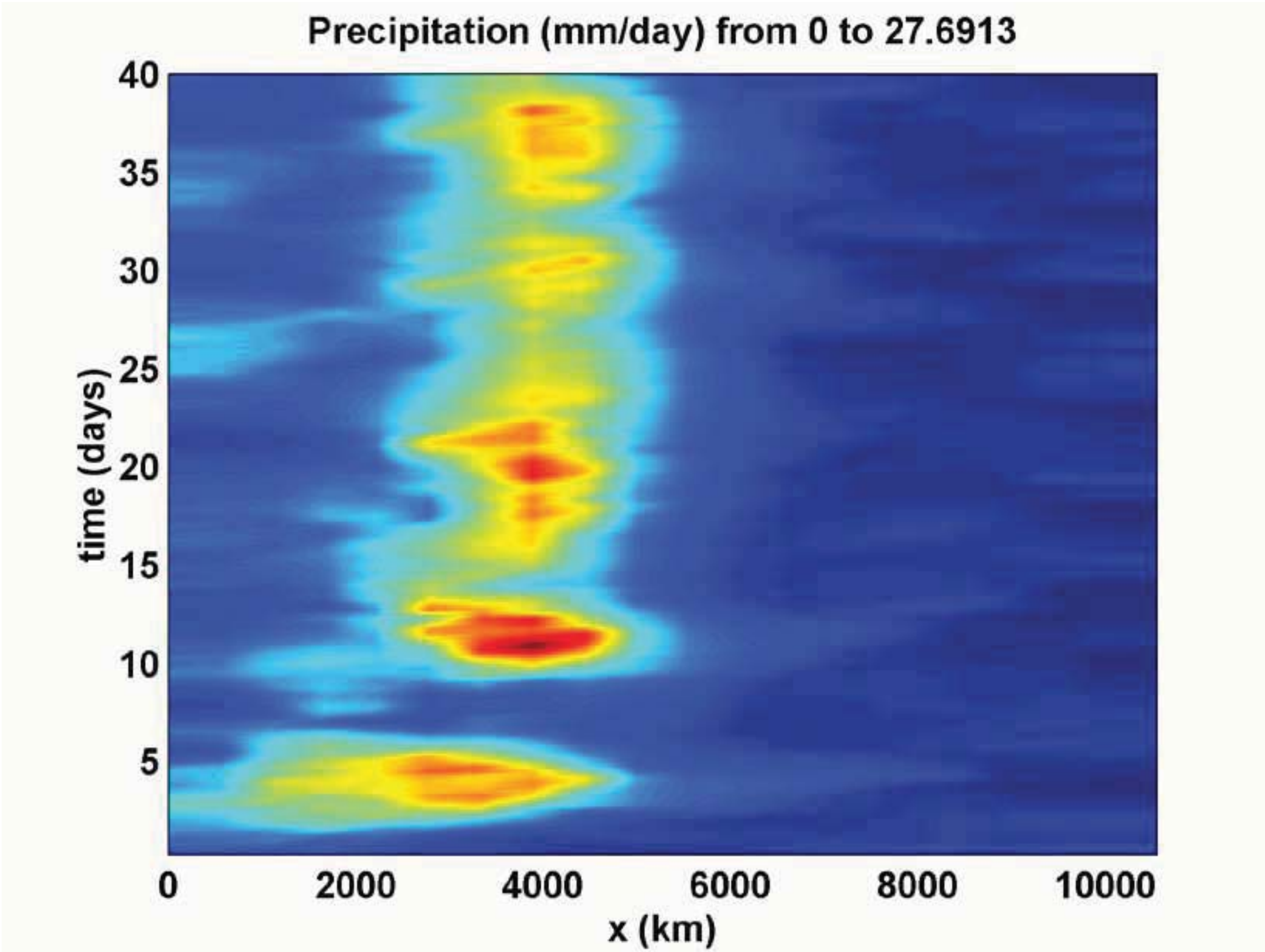


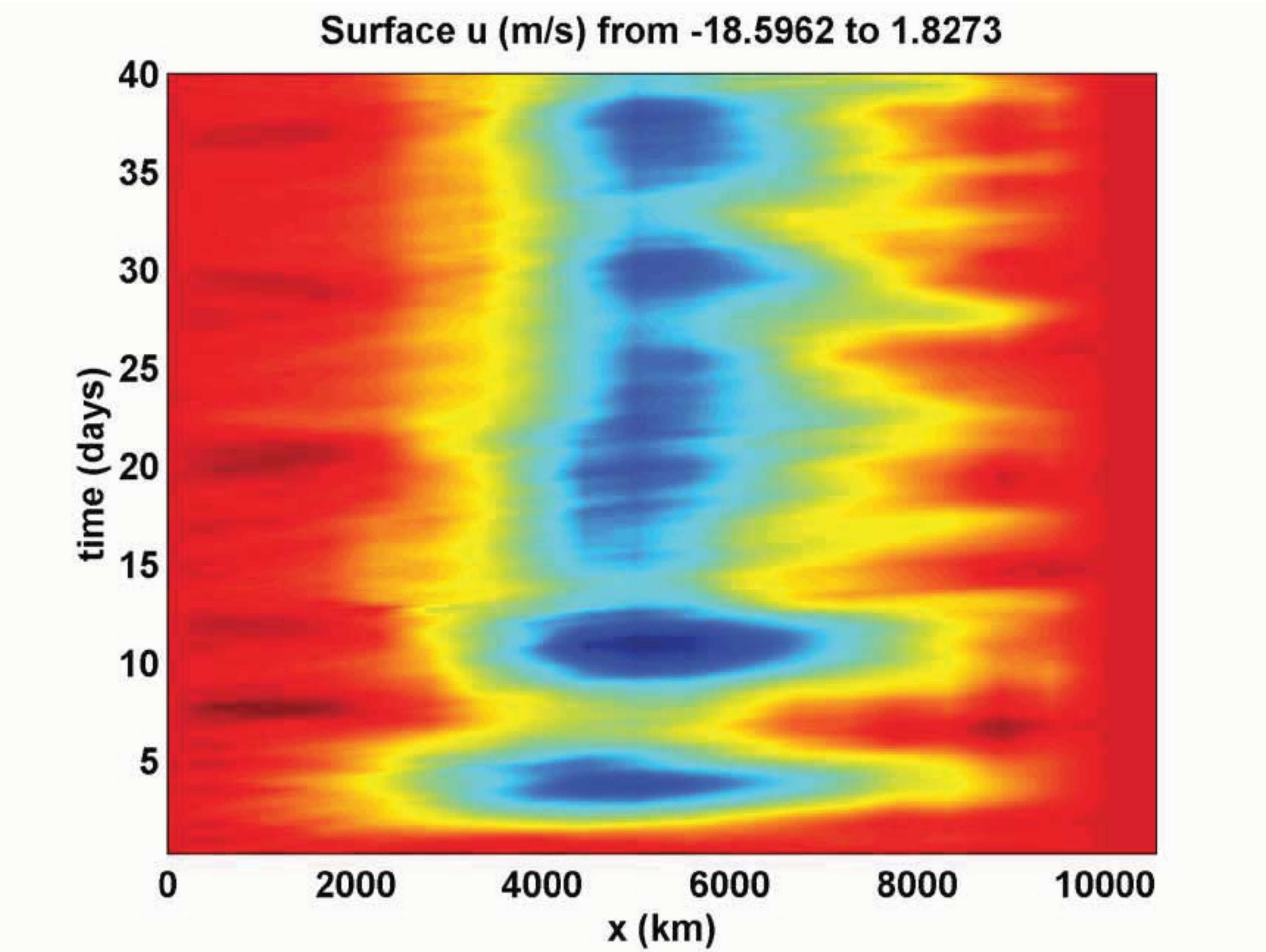
Updraft mass flux from 0 to 17.0043
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)

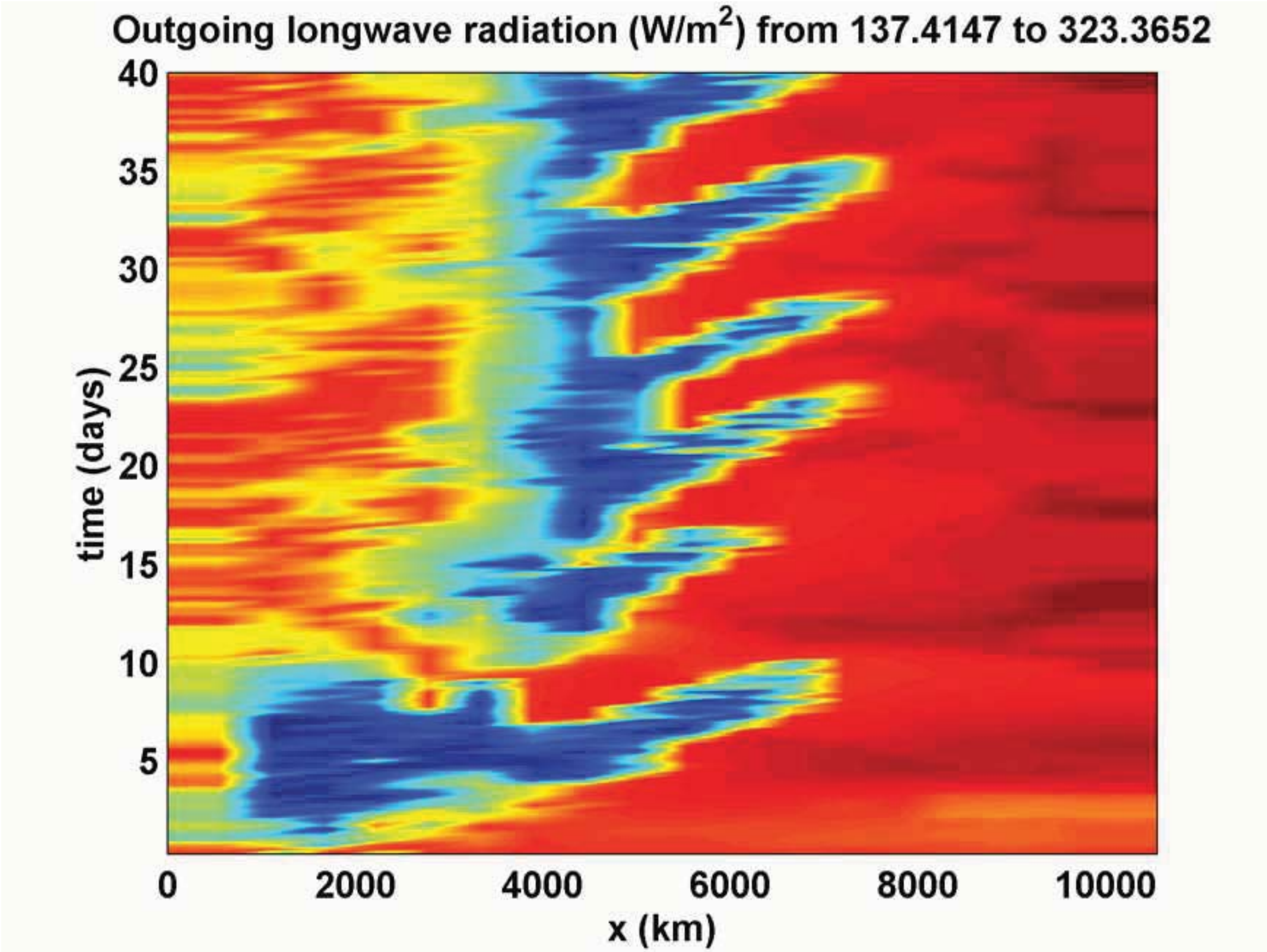

Relative humidity from 0.2356 to 99.9919
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)

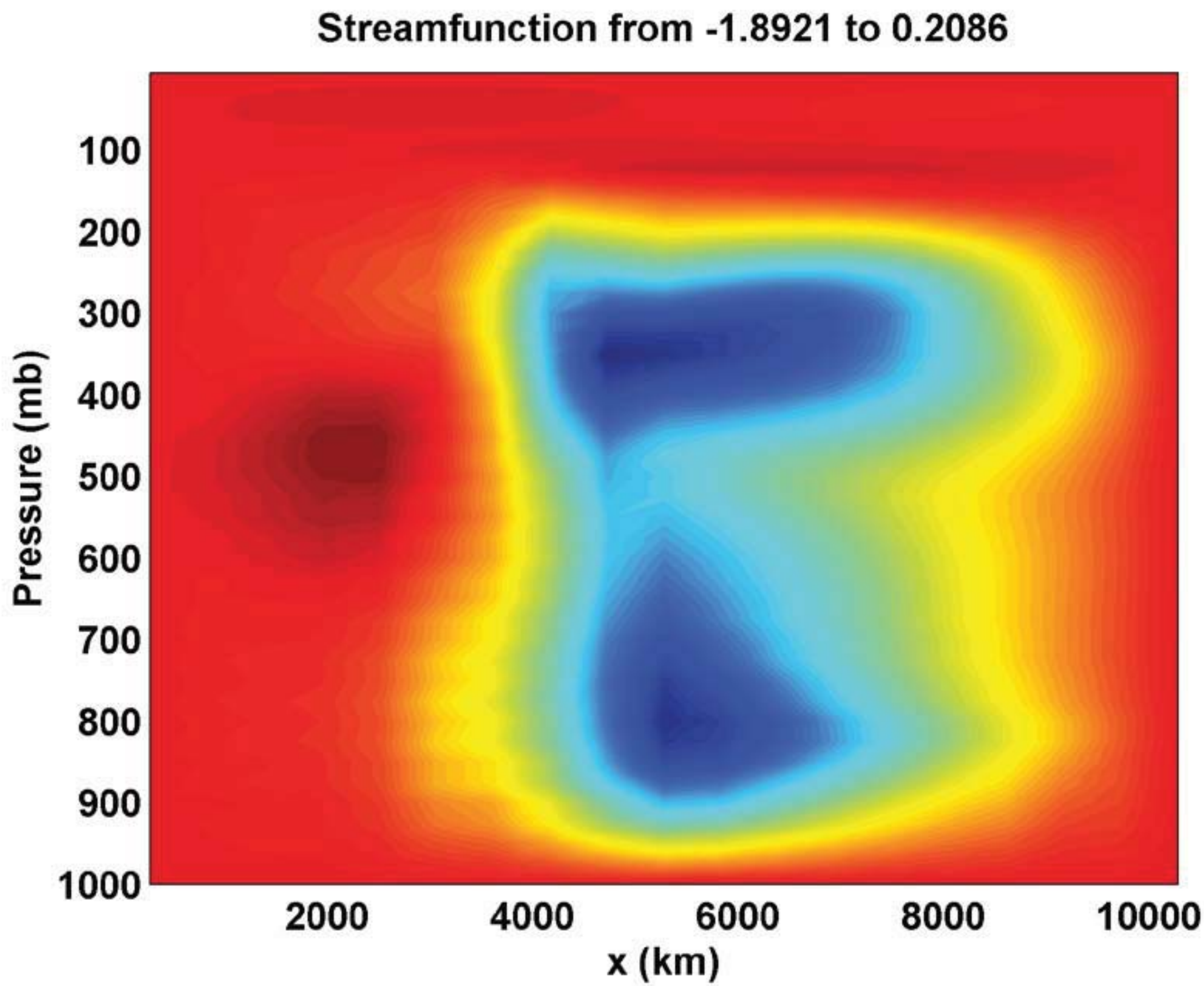

Cloud fraction, from 0 to 0.5036
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)

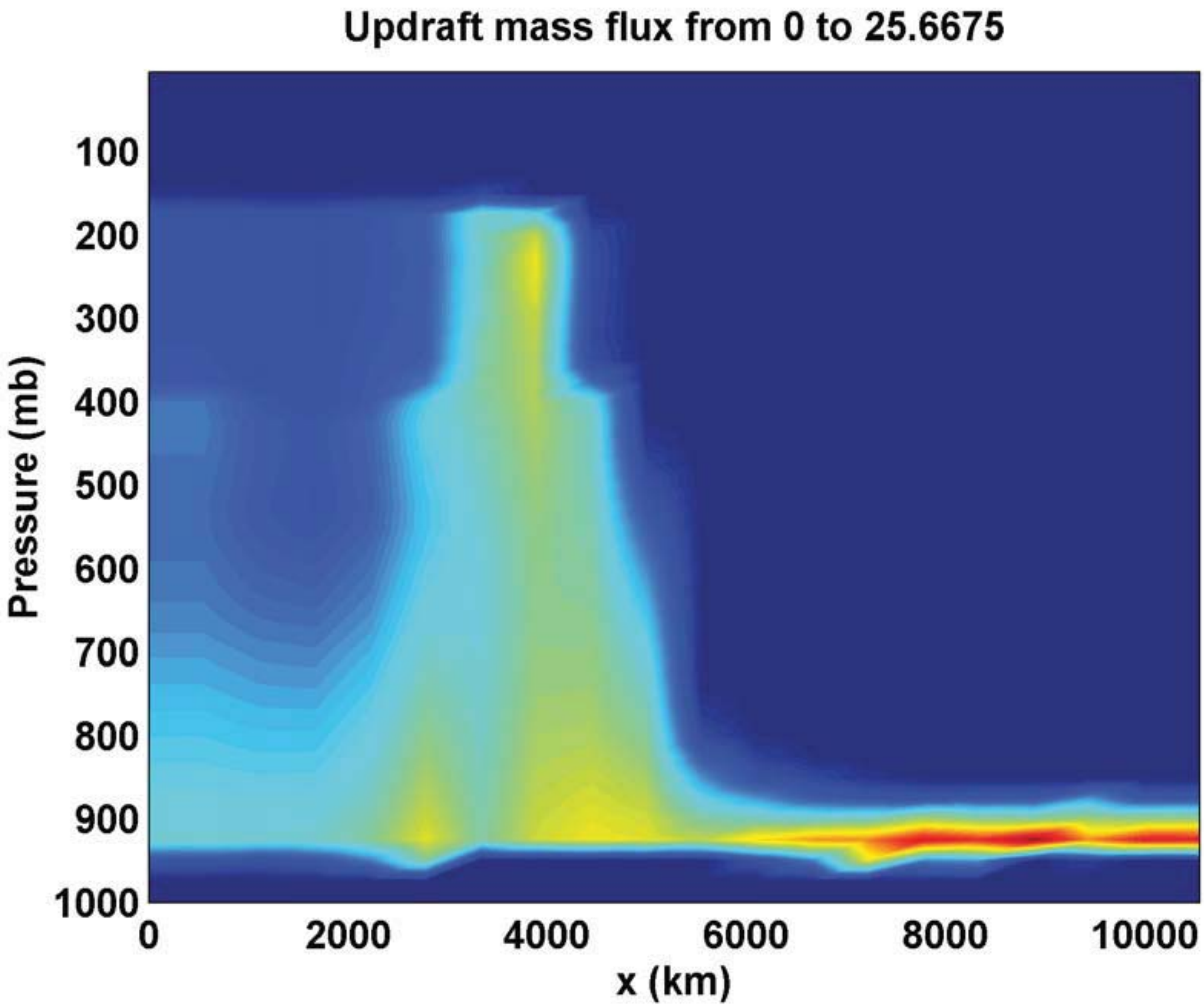
$$\Delta SST = 5^o\,C$$

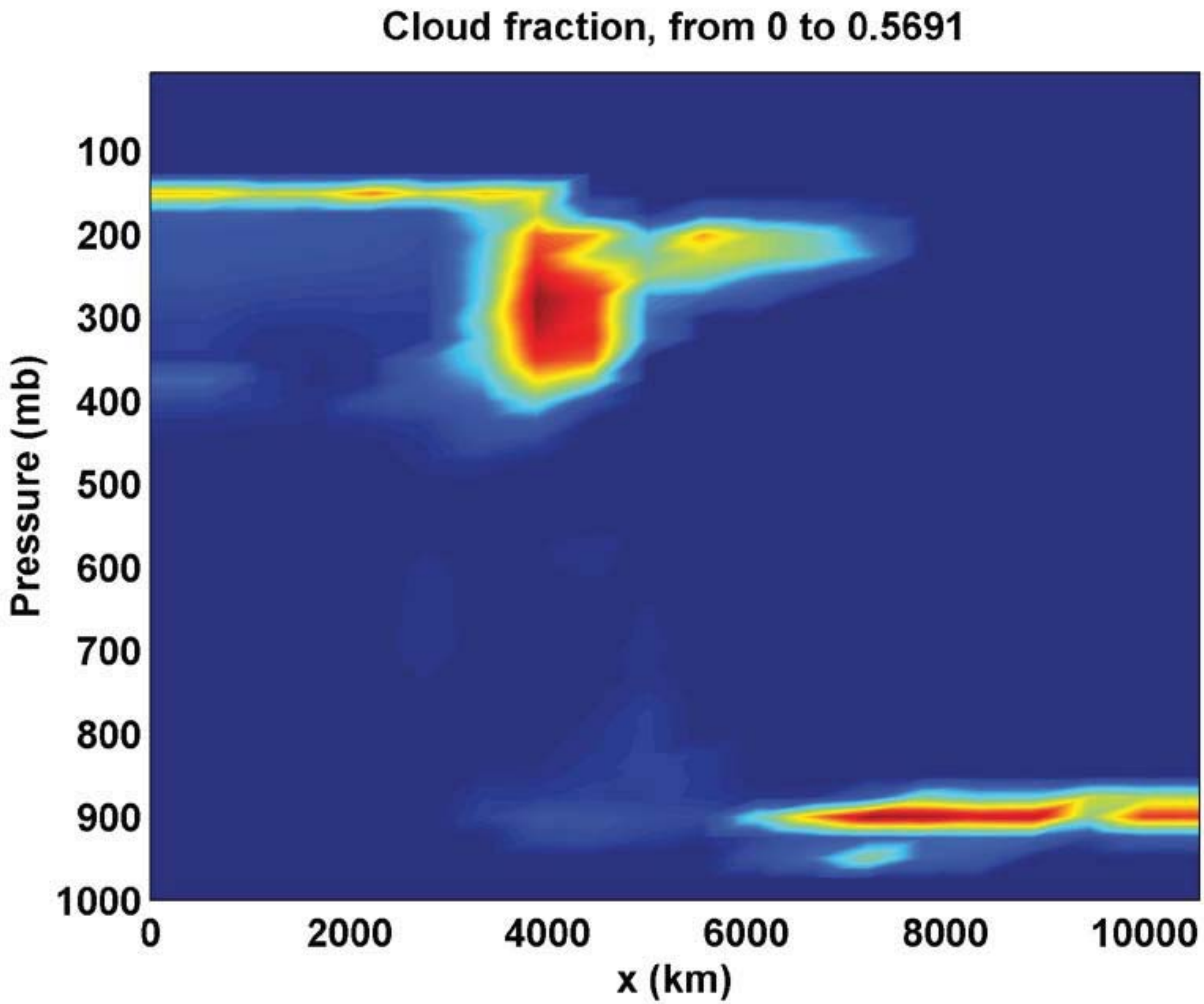


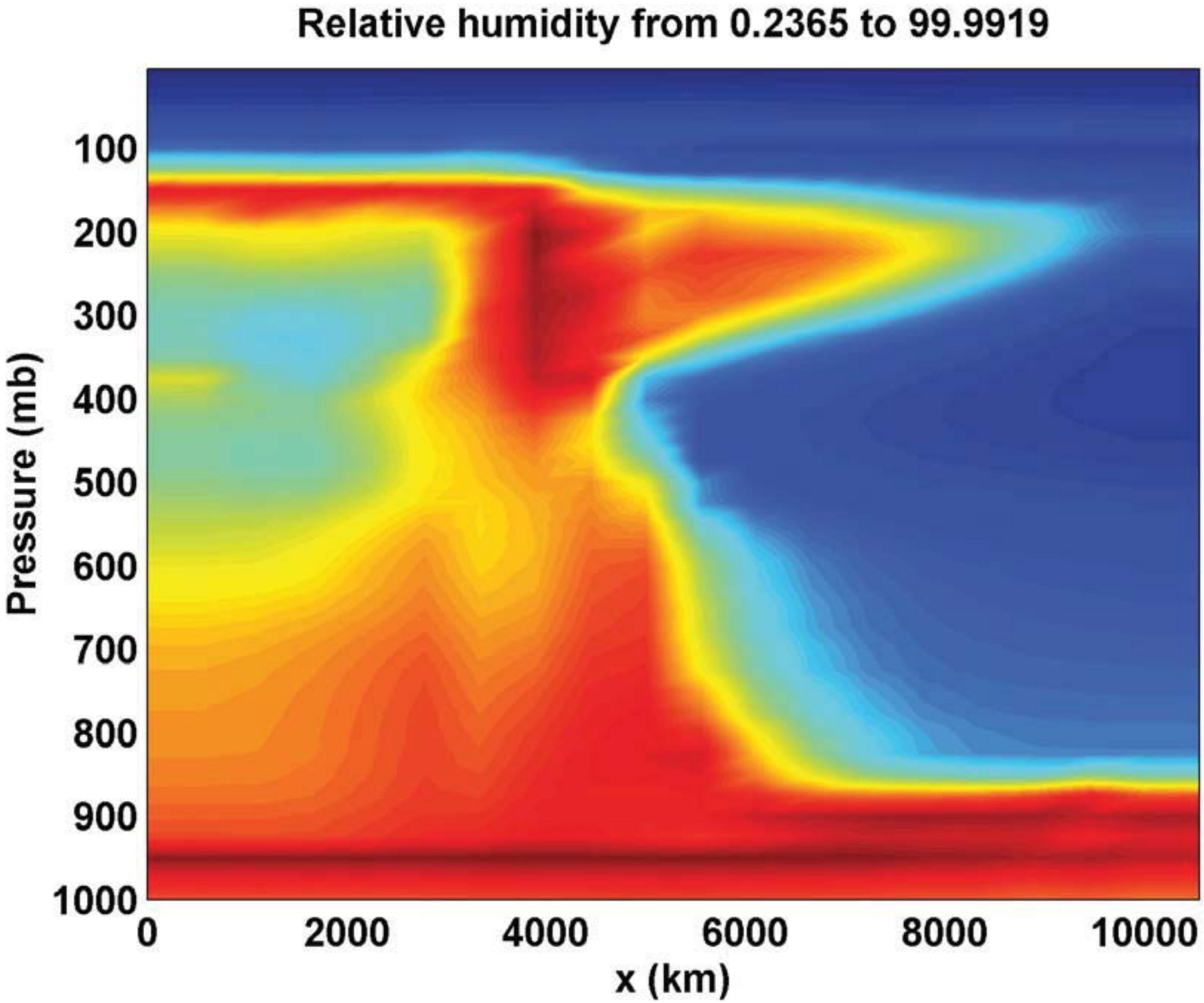

Surface u (m/s) from -18.5962 to 1.8273
time (days)
40
35
30
25
20
15
10
5
0
2000
4000
6000
8000
10000
x (km)

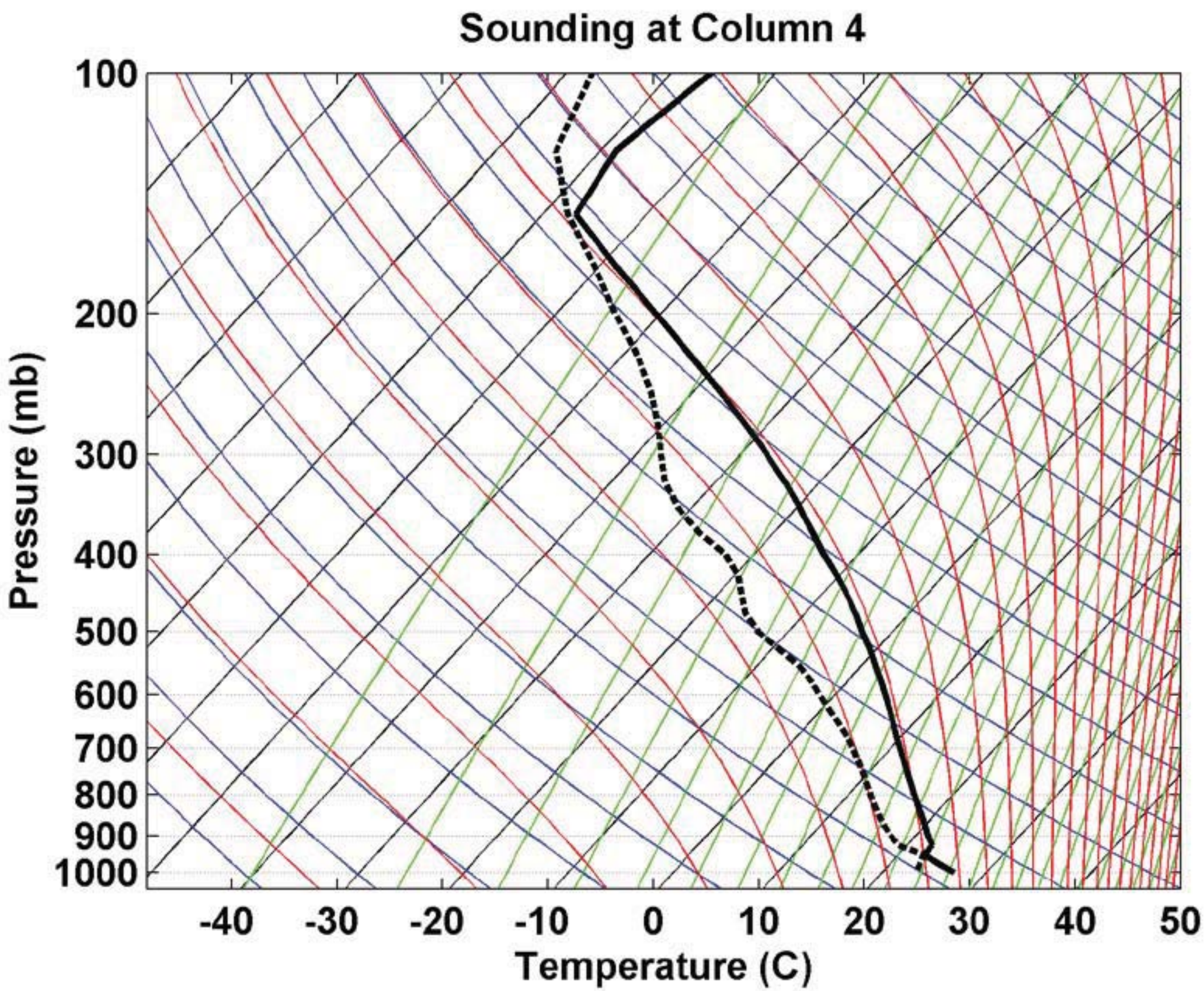

Outgoing longwave radiation (W/m2) from 137.4147 to 323.3652
time (days)
40
35
30
25
20
15
10
5
0
2000
4000
6000
8000
10000
x (km)

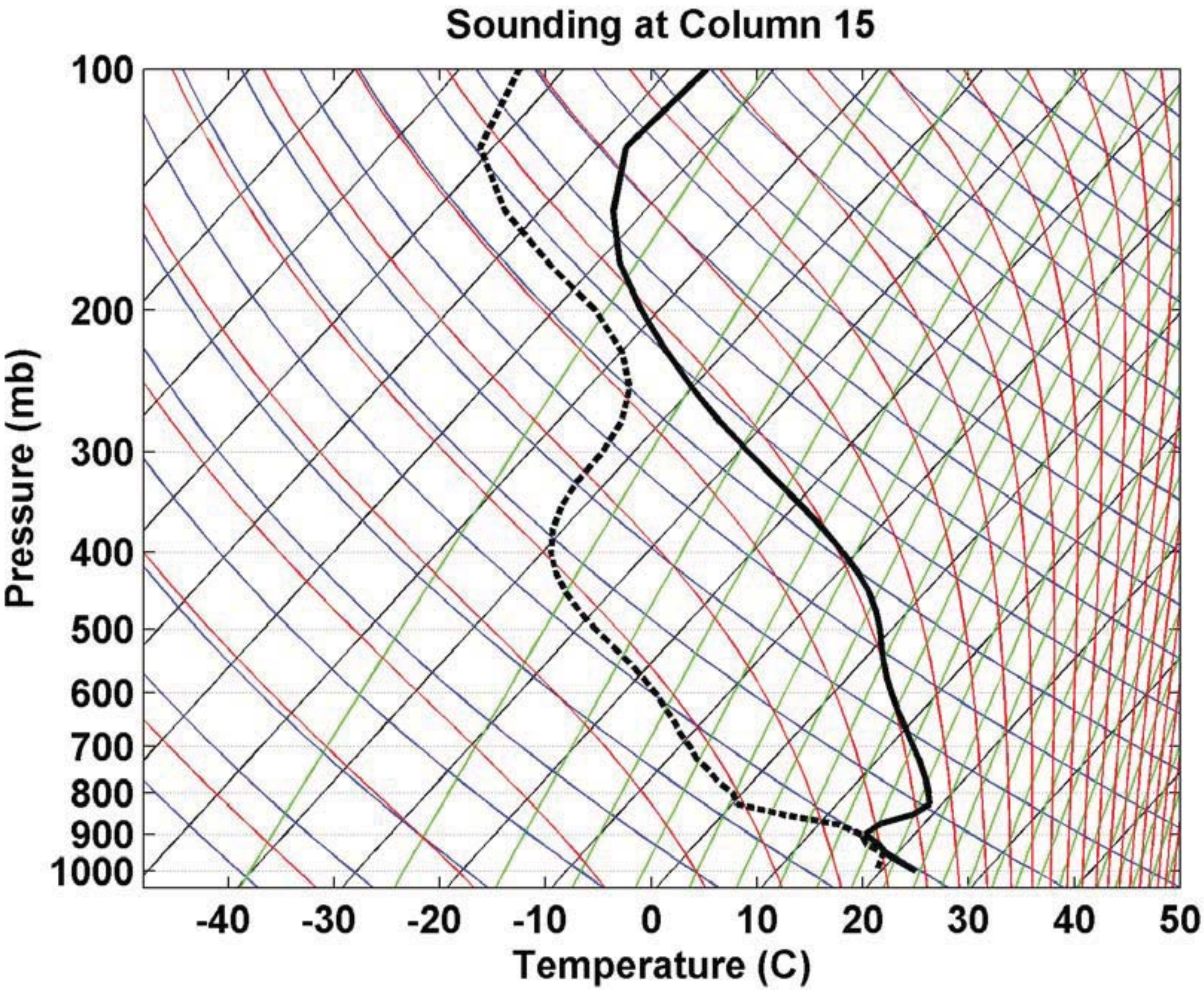

Streamfunction from -1.8921 to 0.2086
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
2000
4000
6000
8000
10000
x (km)


Updraft mass flux from 0 to 25.6675
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)


Cloud fraction, from 0 to 0.5691
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)


Relative humidity from 0.2365 to 99.9919
Pressure (mb)
100
200
300
400
500
600
700
800
900
1000
0
2000
4000
6000
8000
10000
x (km)


Sounding at Column 4
100
200
300
400
500
600
700
800
900
1000
Pressure (mb)
-40
-30
-20
-10
0
10
20
30
40
50
Temperature (C)



Sounding at Column 15
100
200
300
400
500
600
700
800
900
1000
Pressure (mb)
-40
-30
-20
-10
0
10
20
30
40
50
Temperature (C)

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