Interactions between planetary-scale flow and convection in an idealized Walker circulation

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Mathematical Perspectives on Clouds, Convection and Tropical Meteorology
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Outline

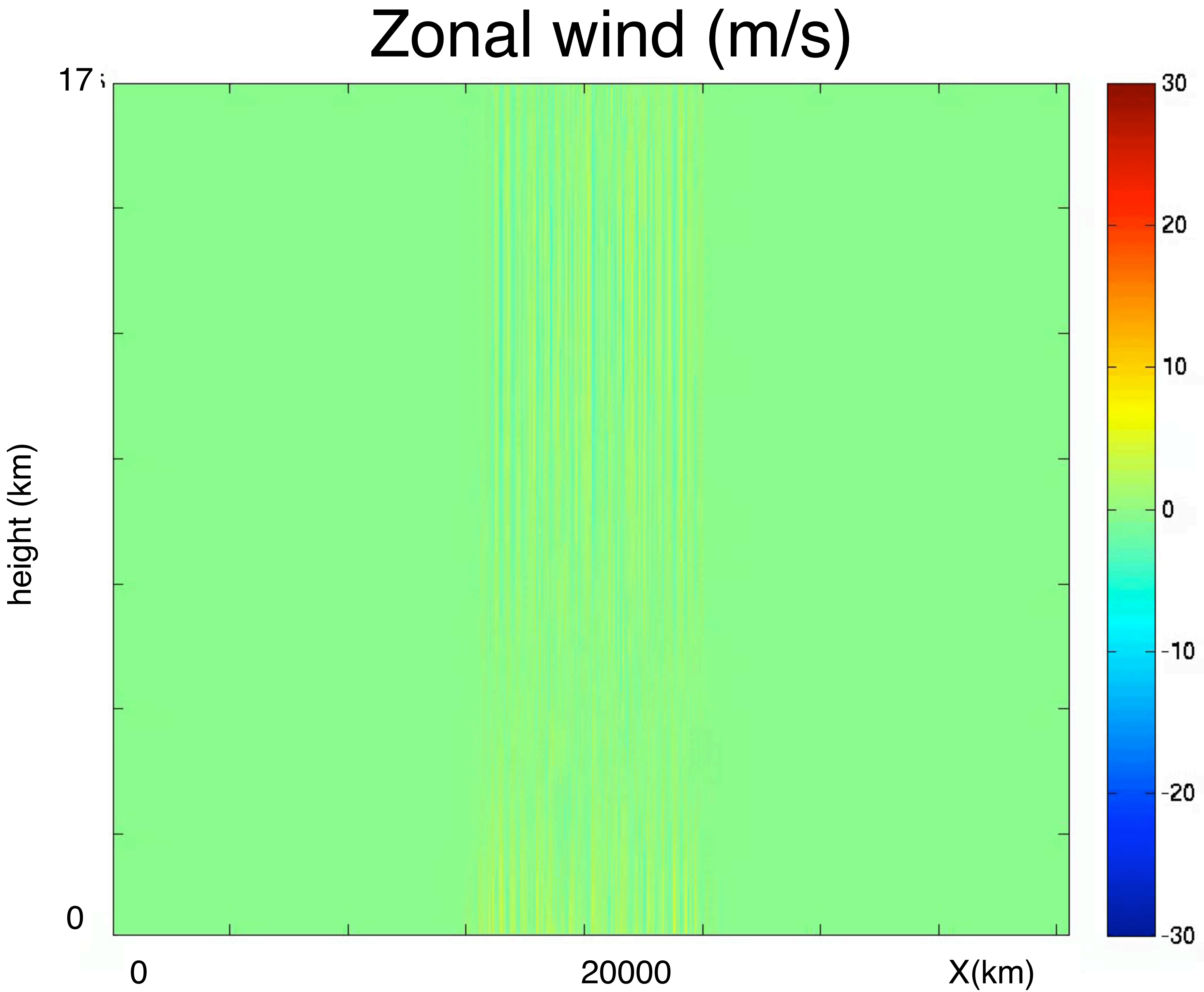
- How do we analyze convective motions and their interactions with large-scale flows in high-resolution simulations?

In this talk:

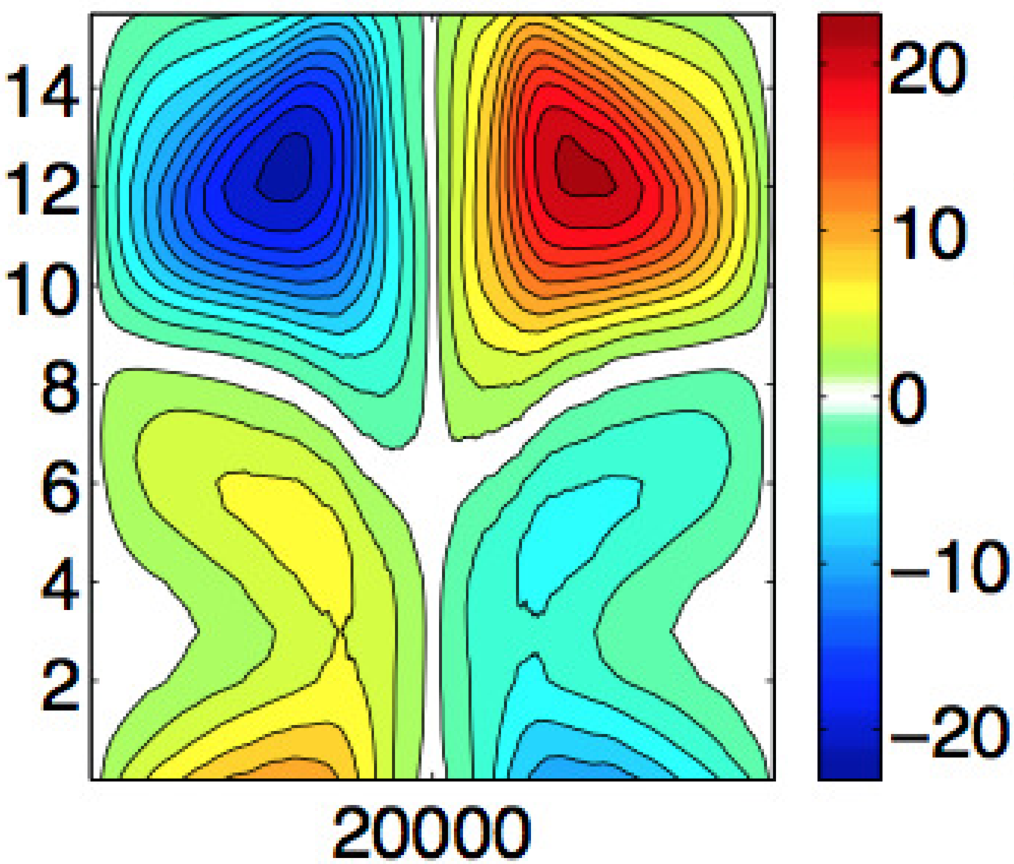
- Idealized Walker circulation
- Introduce the isentropic analysis of convective motions.
- Applied this technique to analyze convection in a complex multi-scale simulations.

1. Idealized Walker circulation

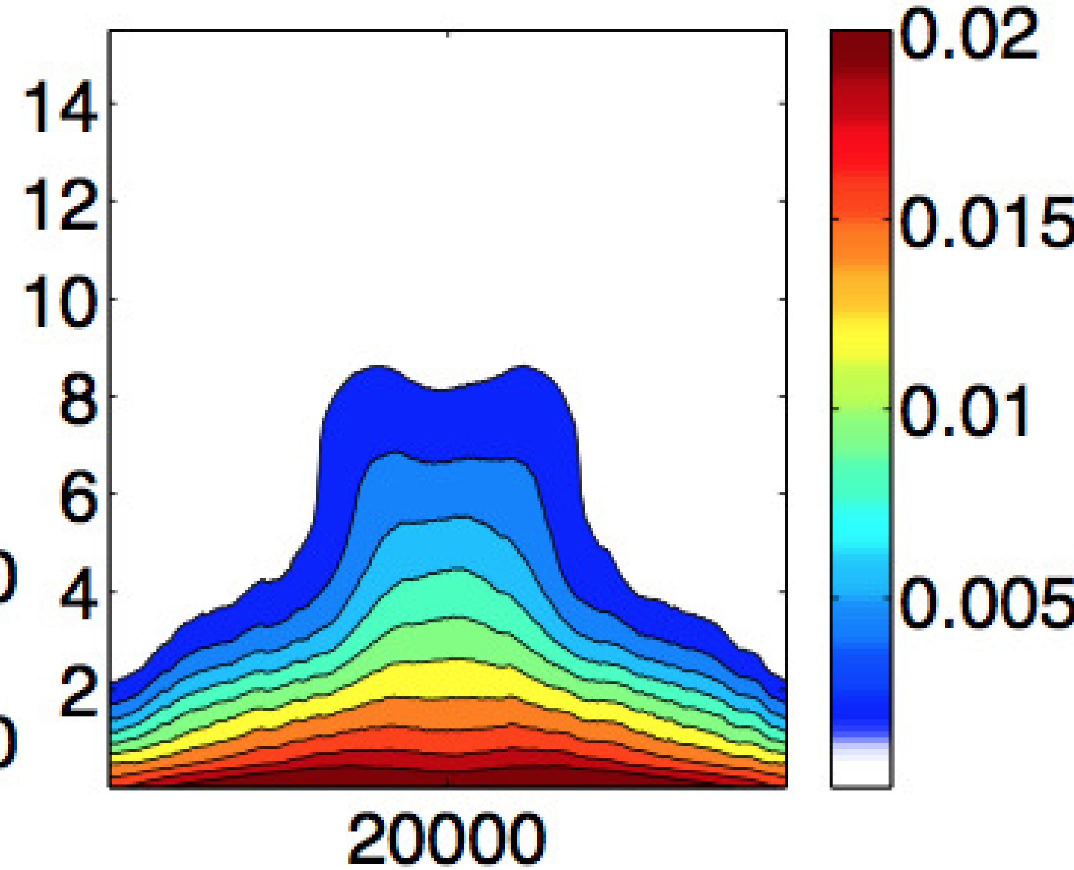
- 2-D cloud resolving (2km) simulation of idealized Walker cell on a large domain (40,000km).
- Circulation is forced by SST variations - max SST of 303.15K, min SST 299.15K.
- Long integration (~270 days) to analyze low frequency variability


Zonal wind (m/s)
17
0
height (km)
0
20000
X(km)
30
20
10
0
-10
-20
-30

Mean Walker circulation

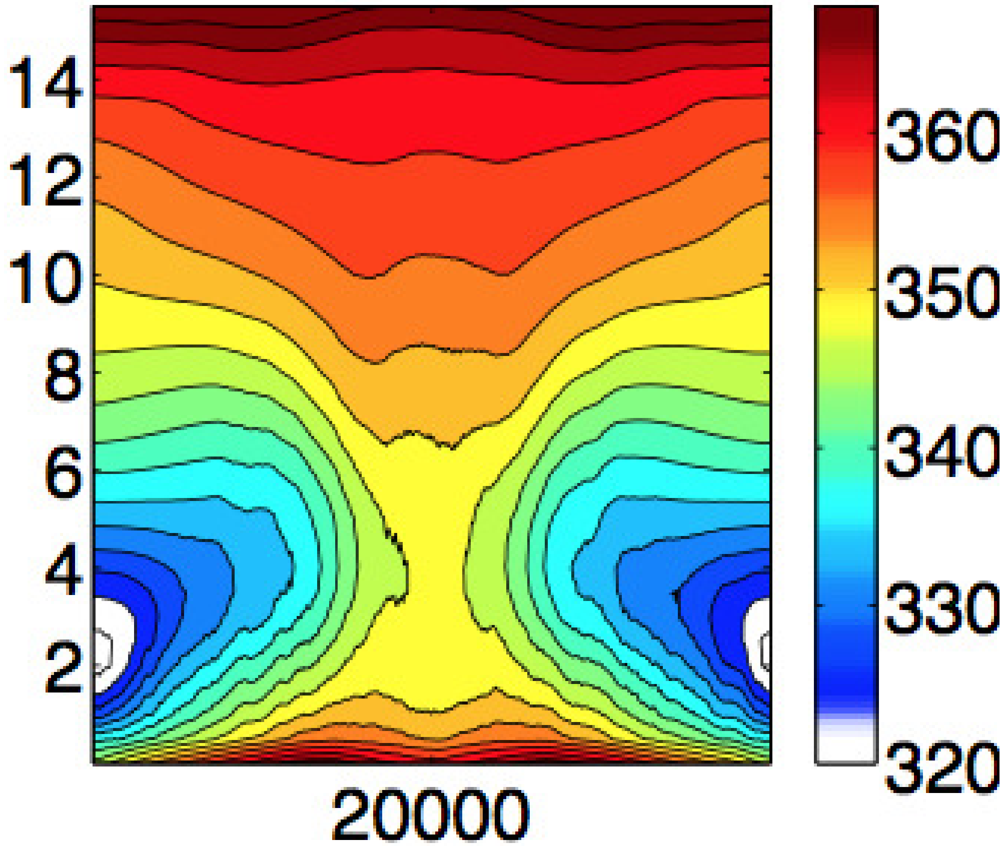


zonal wind

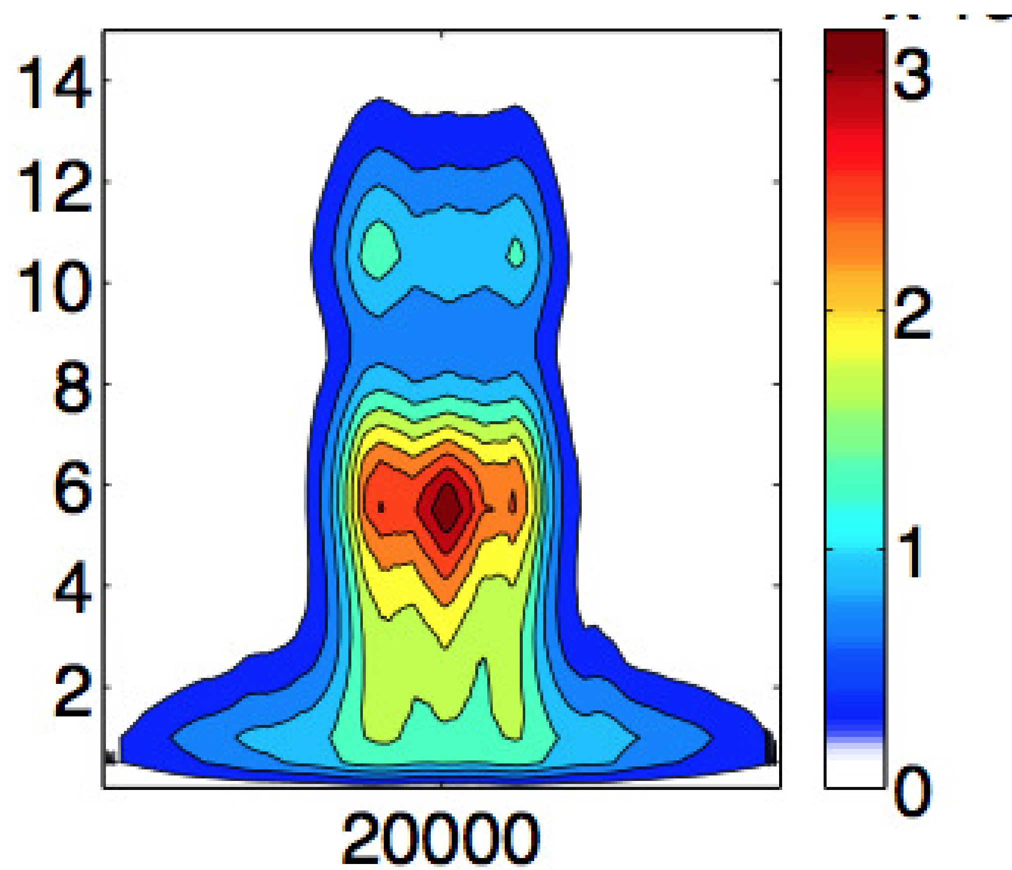


Specific humidity

Mean Walker circulation



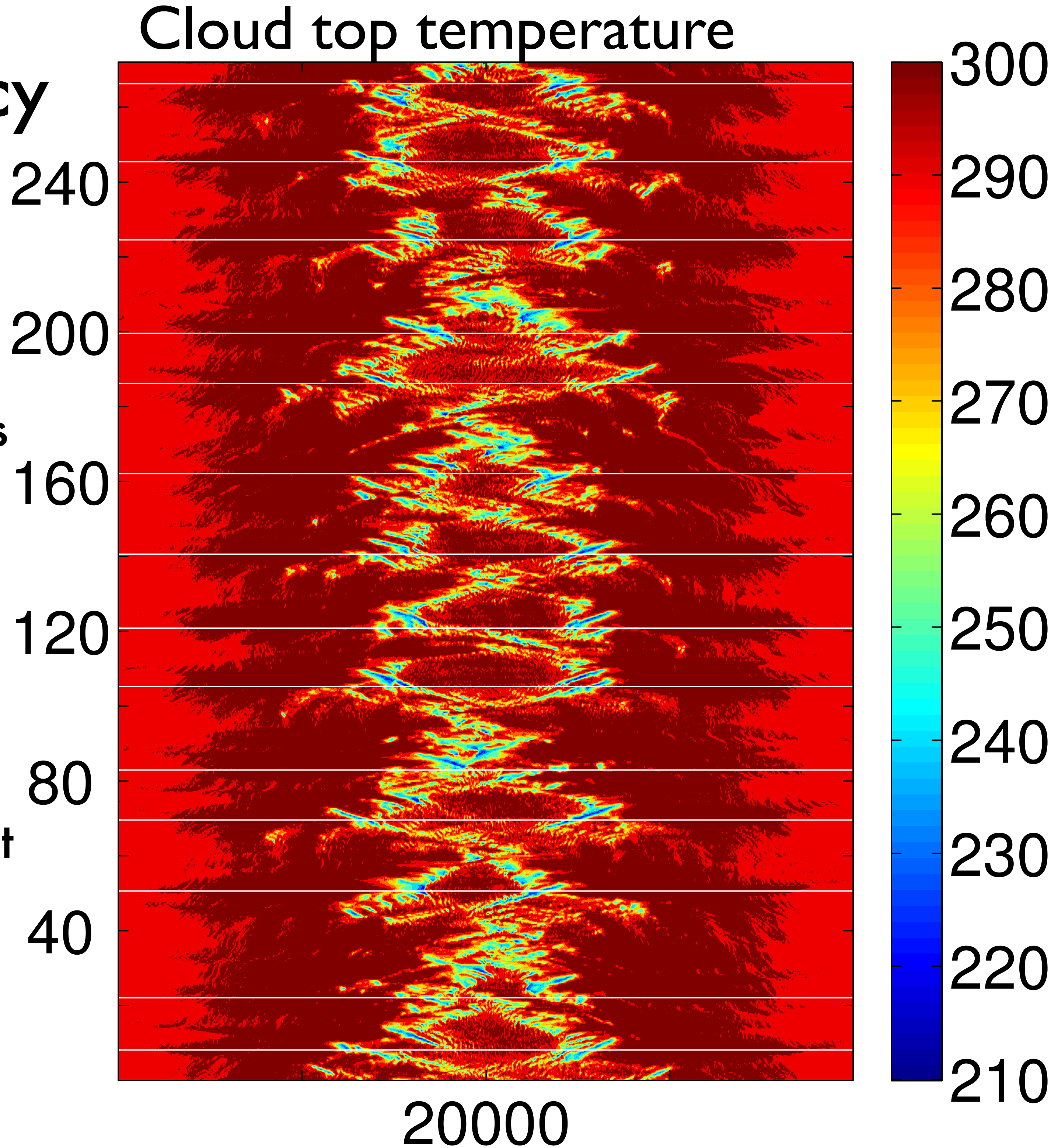
equivalent potential temperature



Cloud condensate

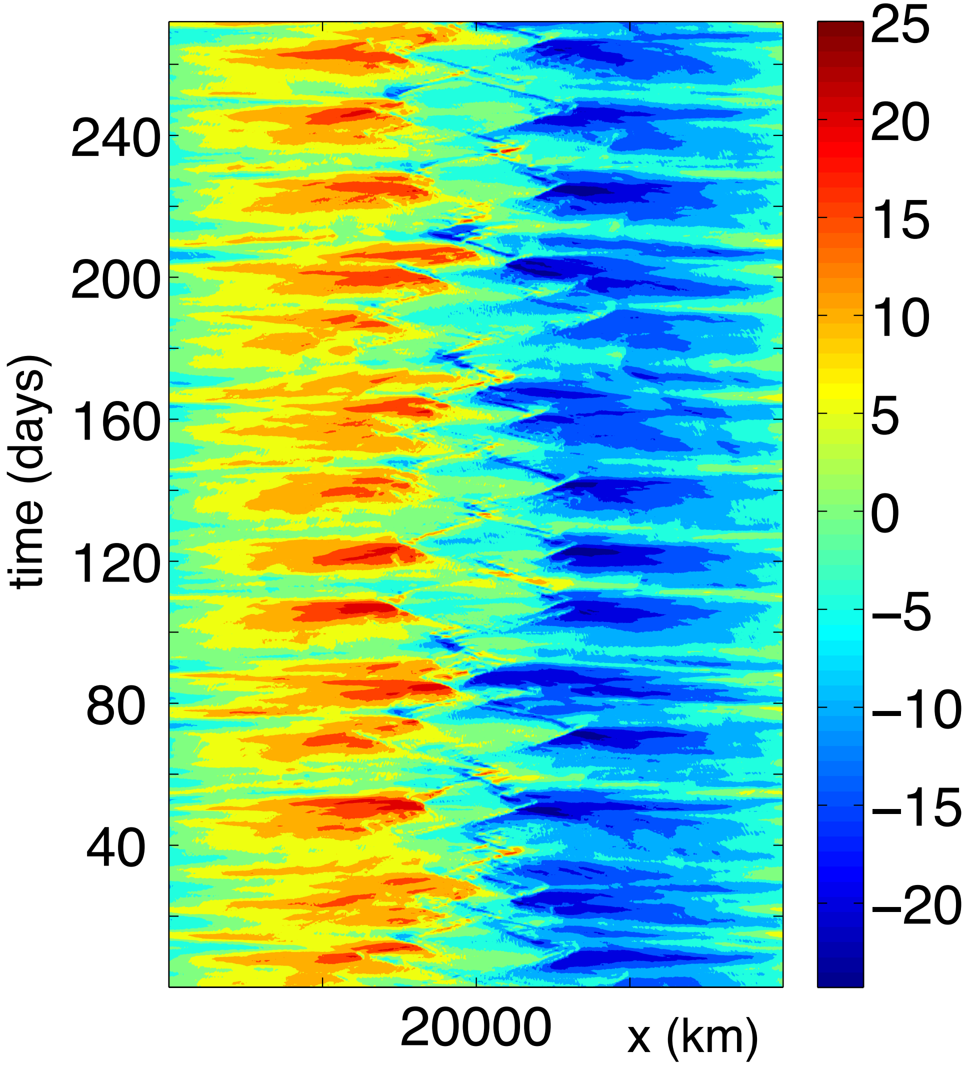
Low frequency variability

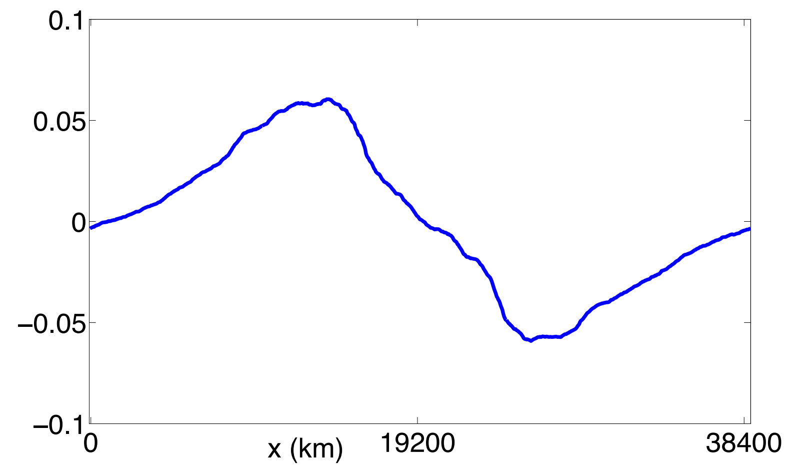
- Simulation exhibits broad range of variability from planetary to convective scales.
- Dominant low-frequency mode at about 20 days.



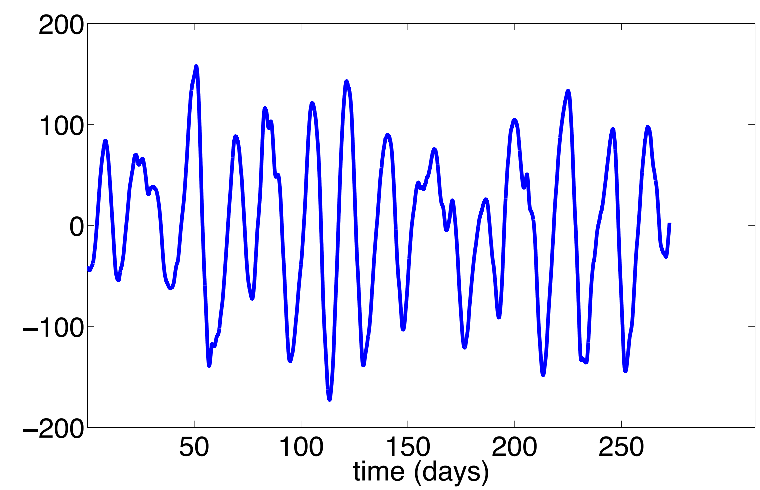
EOF Analysis of low frequency variabilty

Hovmoller diagram for surface wind (m s^{-1})



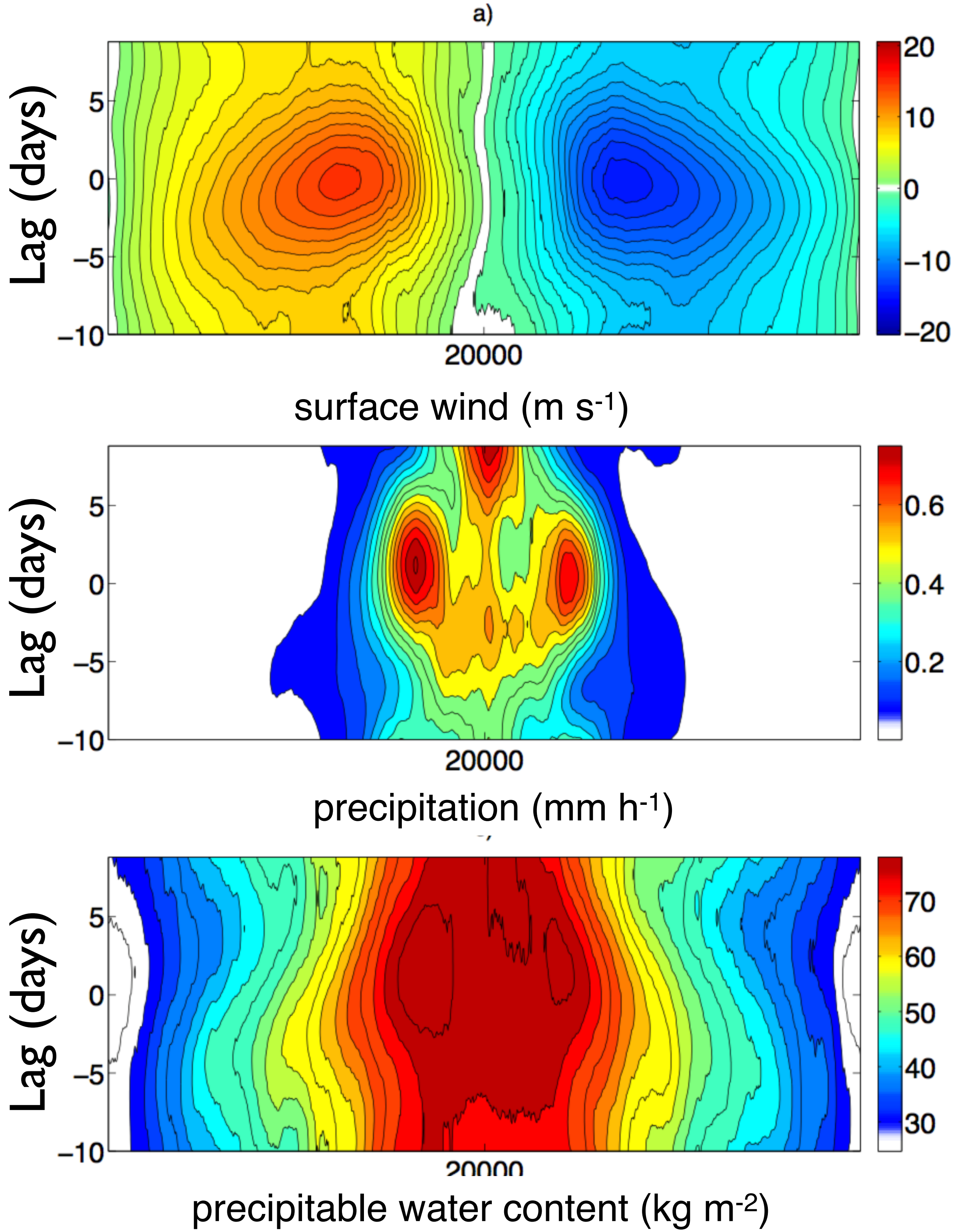


First EOF of SURFACE WIND

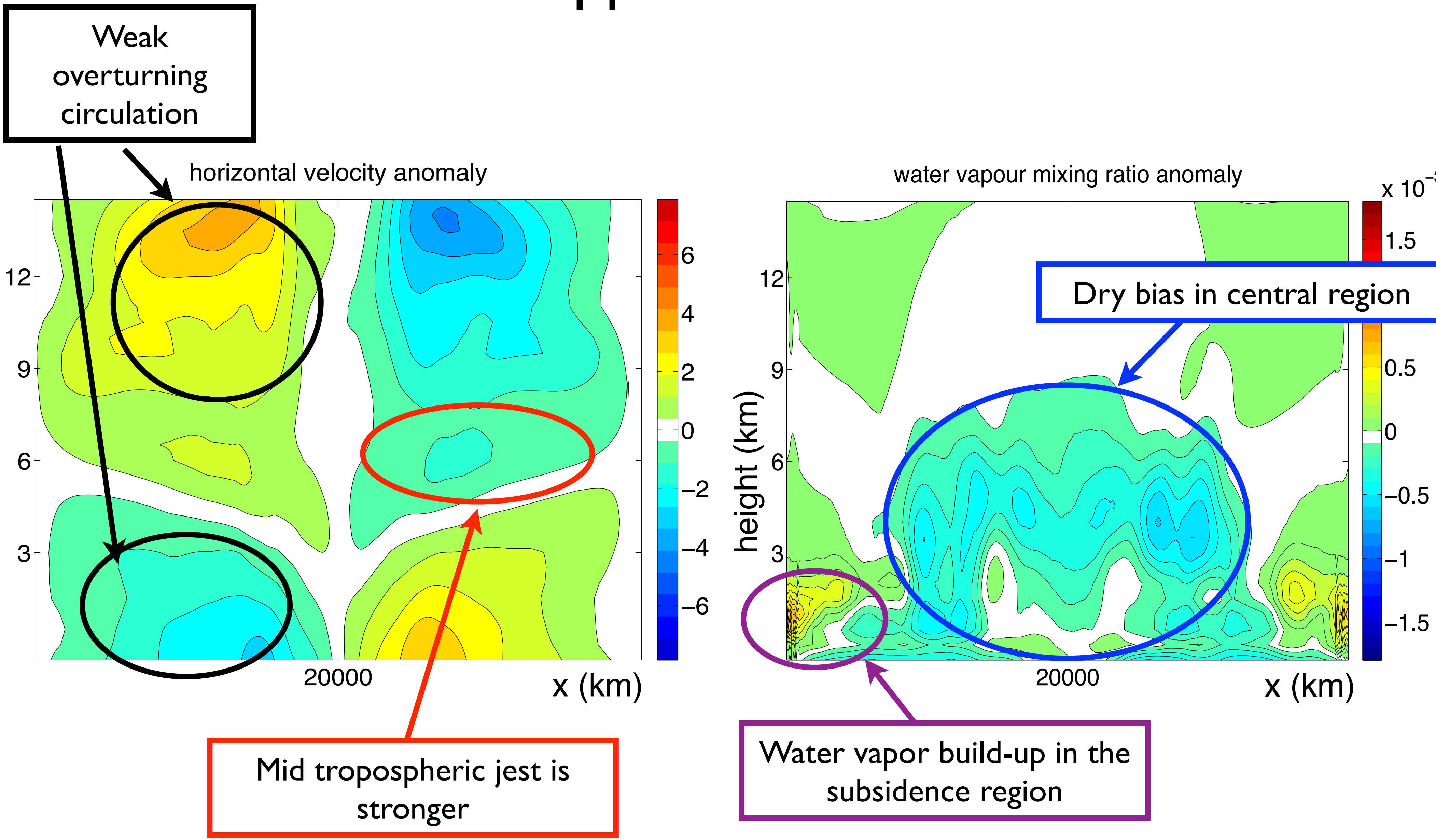


Principal component for first EOF of SURFACE WIND

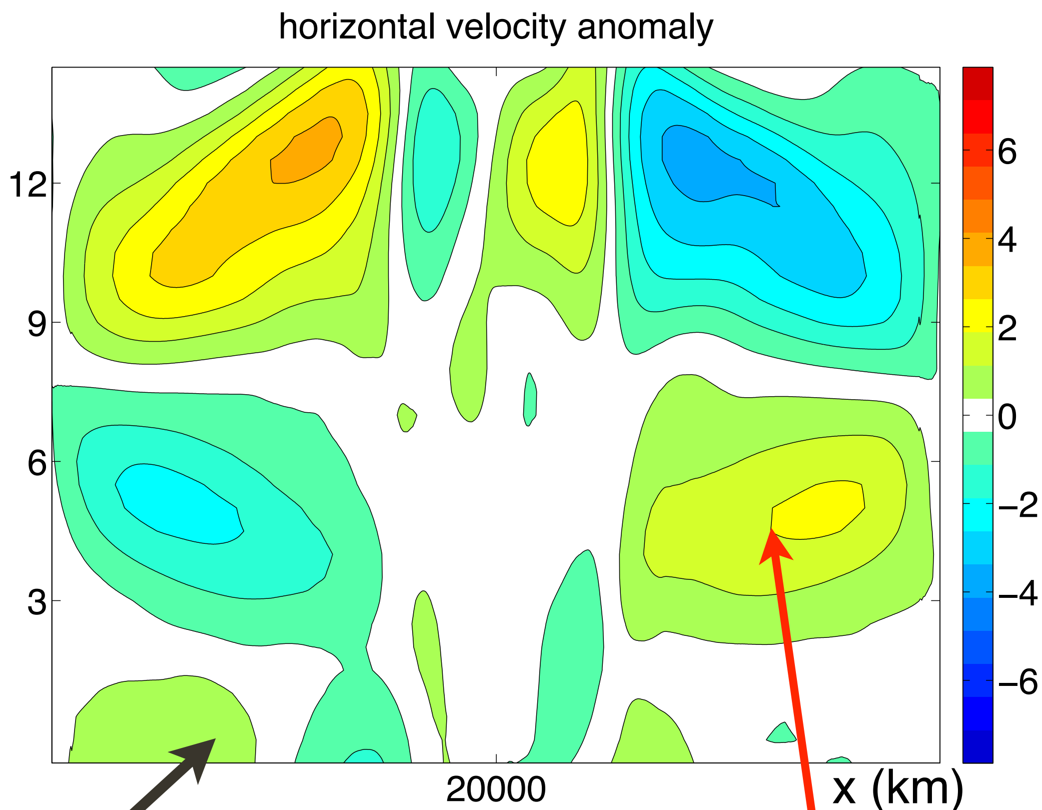
Lag regression of various on the first PC



Suppressed Phase

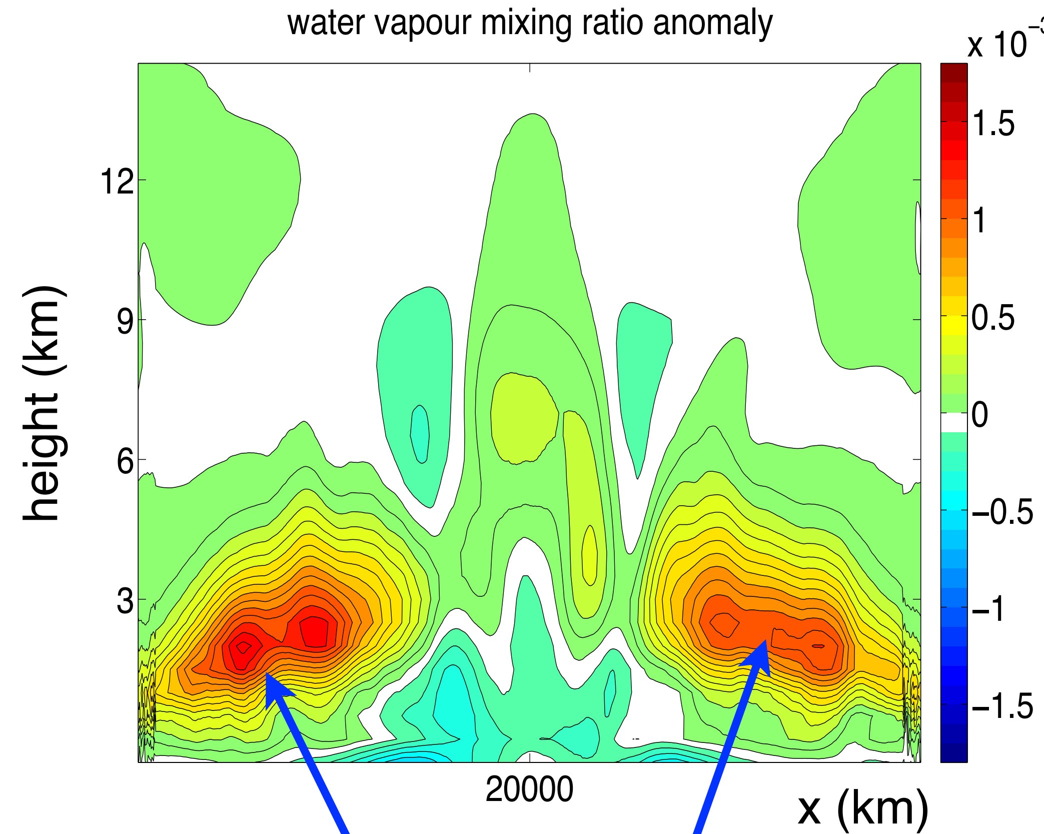


Strengthening phase



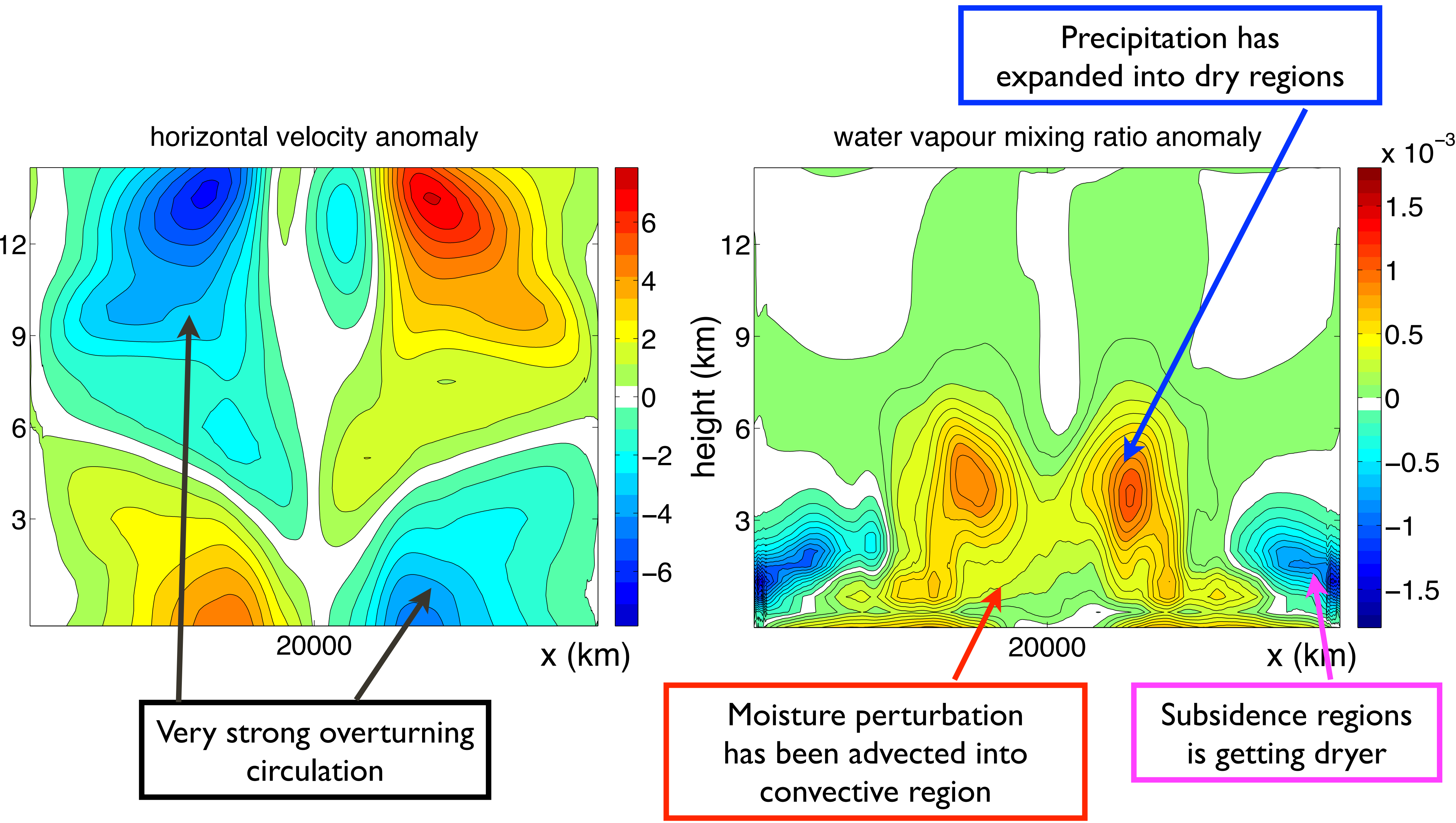
Low level inflow is strengthening

While the midlevel jet is weakening

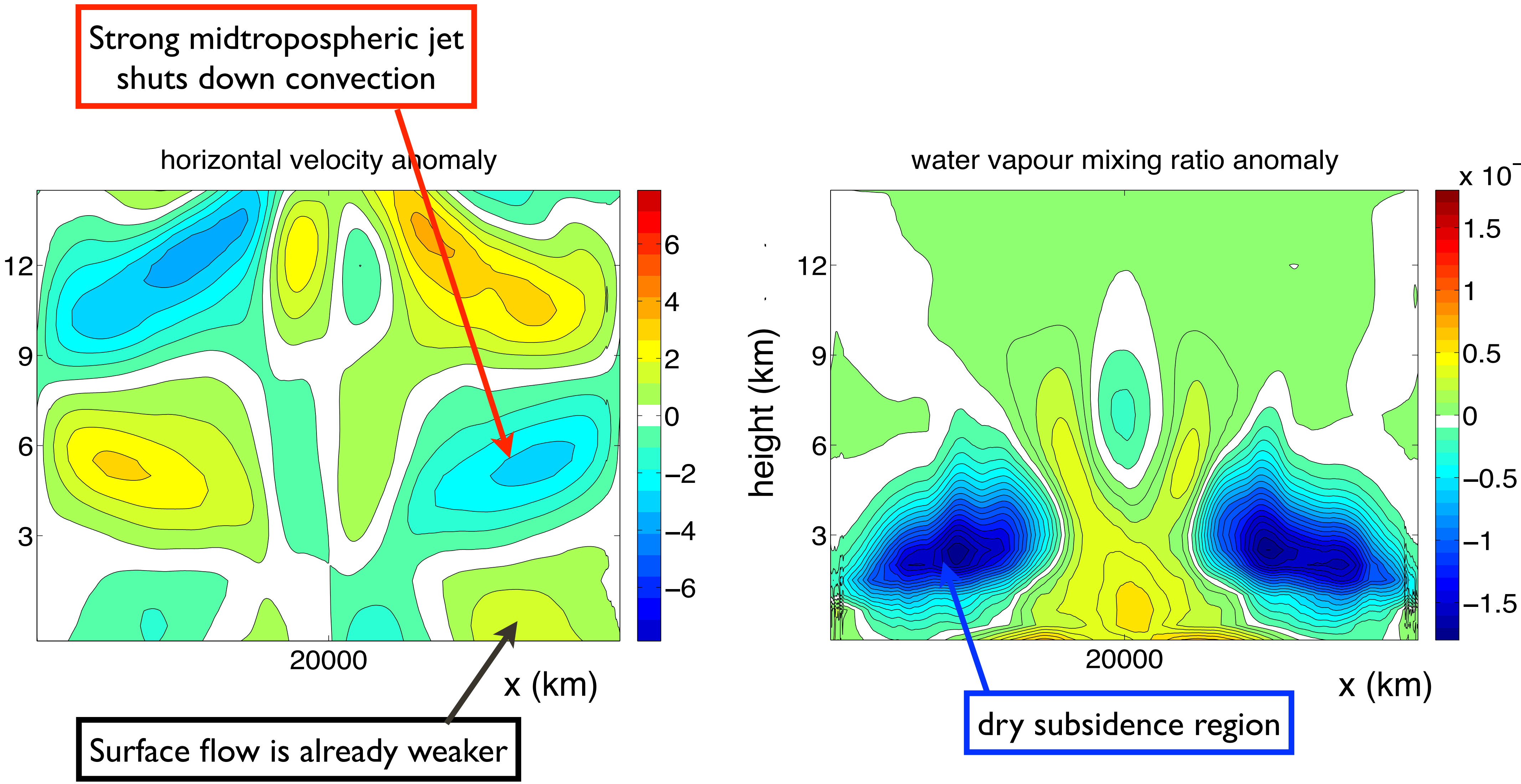


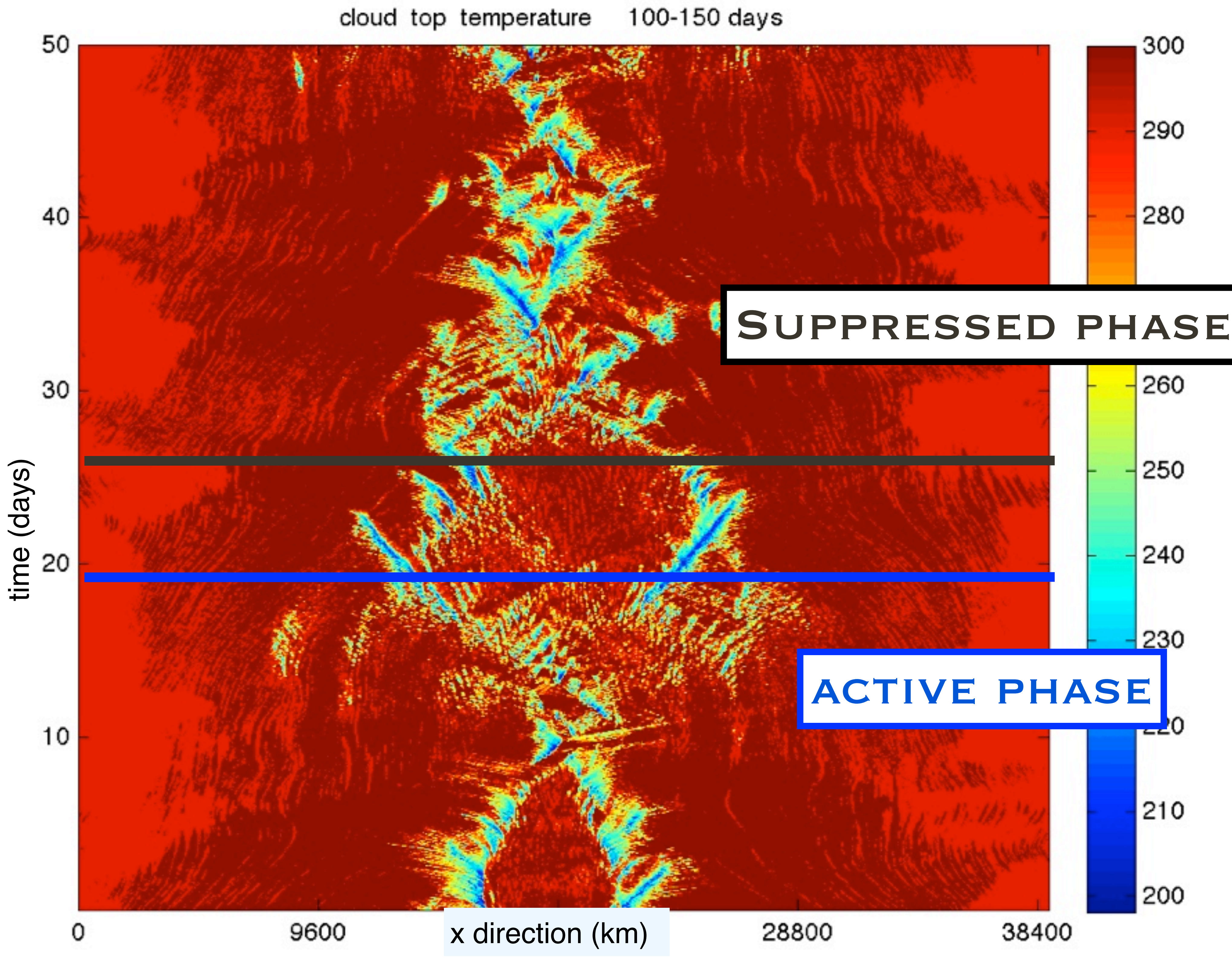
Water vapor has built up over the subsidence region

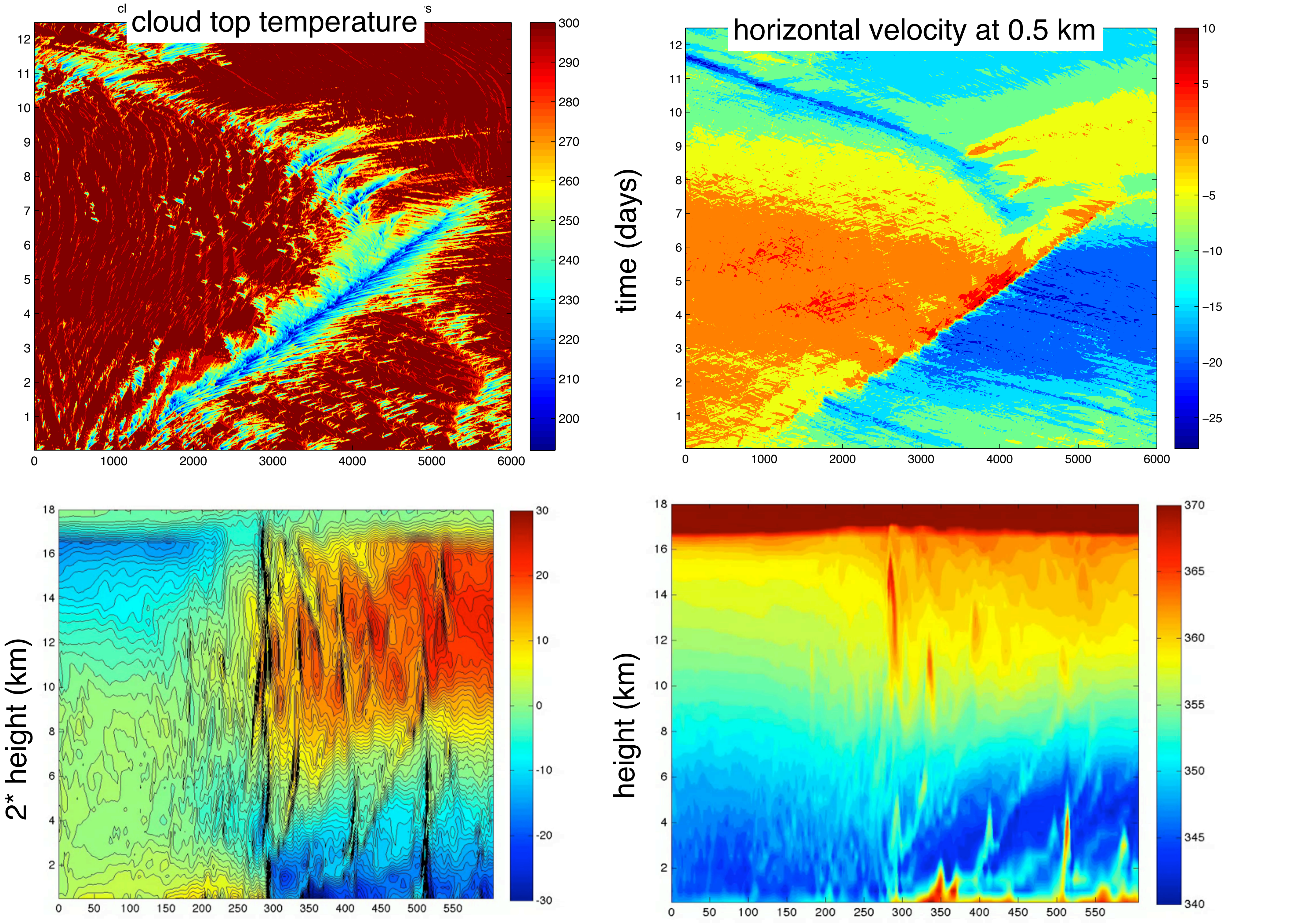
Active Phase



Decaying phase



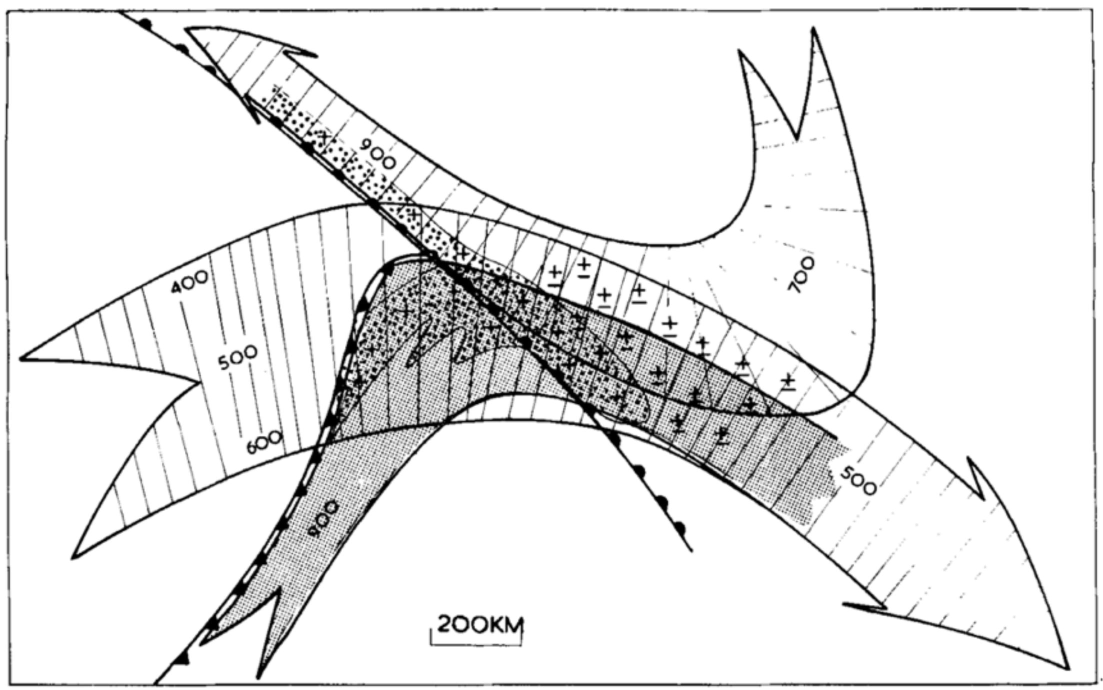

cloud top temperature 100-150 days
time (days)
x direction (km)
0
9600
28800
38400
10
20
30
40
50
300
290
280
260
250
240
230
220
210
200
SUPPRESSED PHASE
ACTIVE PHASE



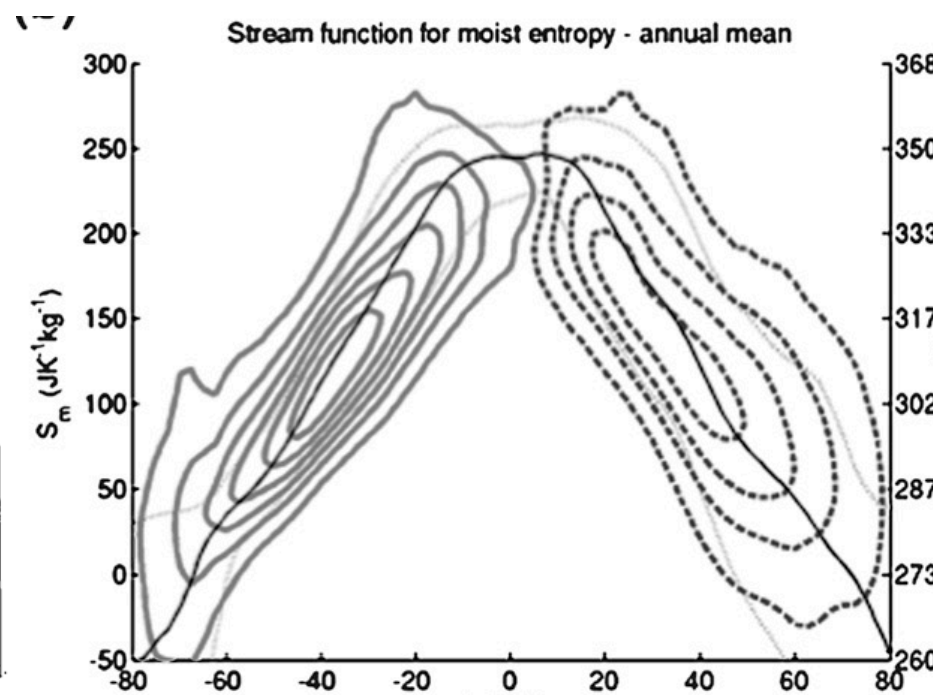
cloud top temperature
horizontal velocity at 0.5 km
time (days)
2* height (km)
height (km)
0 1000 2000 3000 4000 5000 6000
300 290 280 270 260 250 240 230 220 210 200
10 5 0 -5 -10 -15 -20 -25
30 20 10 0 -10 -20 -30
370 365 360 355 350 345 340
0 50 100 150 200 250 300 350 400 450 500 550

Isentropic analysis

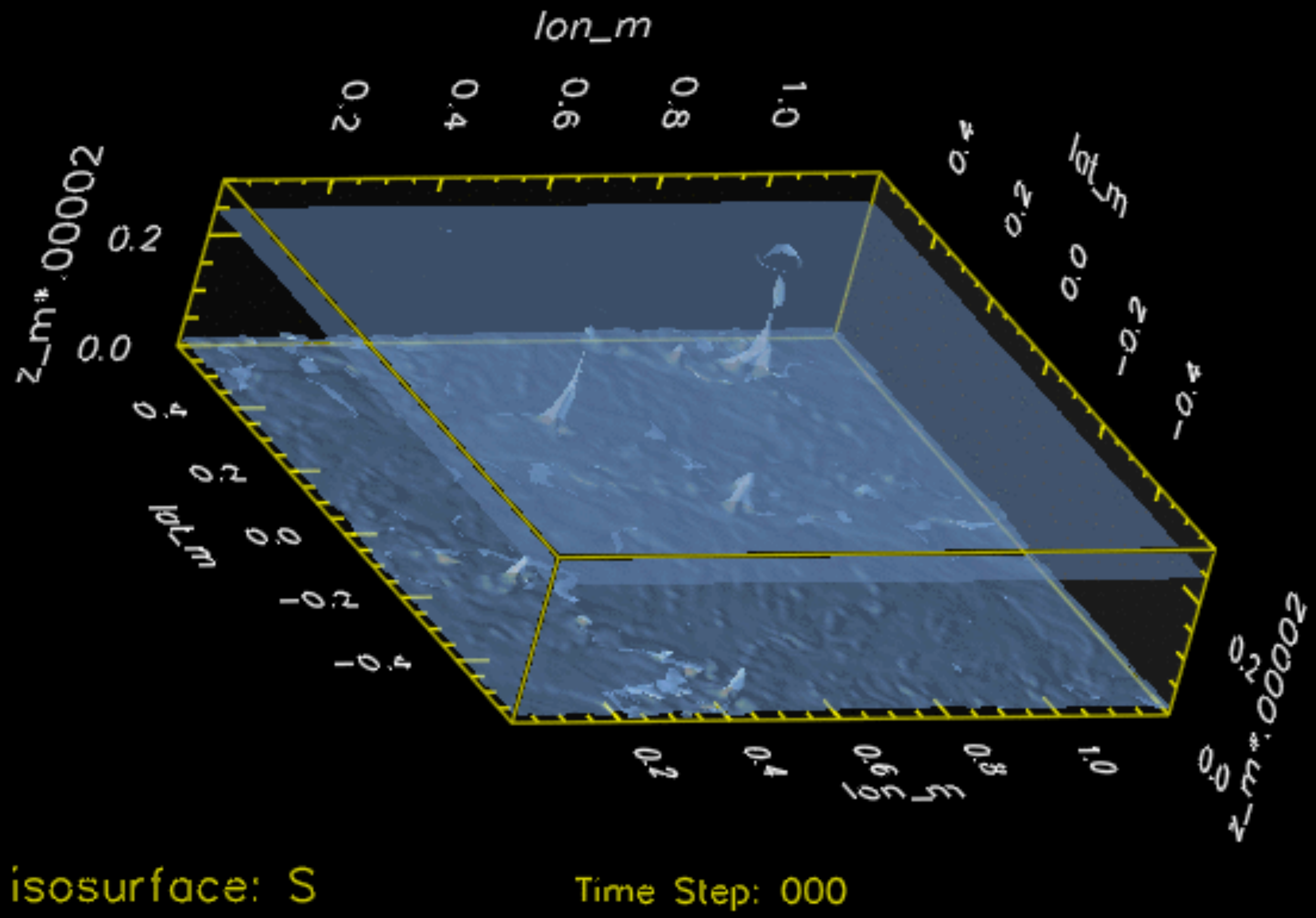
Take advantage of quasi conservation of entropy to track parcels trajectory and separate rapid oscillations from irreversible overturning.



Harrold (1973)



Pauluis etal. (2010)


lon_m
0.2
0.4
0.6
0.8
1.0
lat_m
0.4
0.2
0.0
-0.2
-0.4
z_m*.00002
0.2
0.0
isosurface: S
Time Step: 000

A similar approach can be taken to analyze convective motions. Here, we will replace both horizontal coordinates (x and y) by the equivalent potential temperature.

In practice, we introduce an integral on 'isentropic slice:'

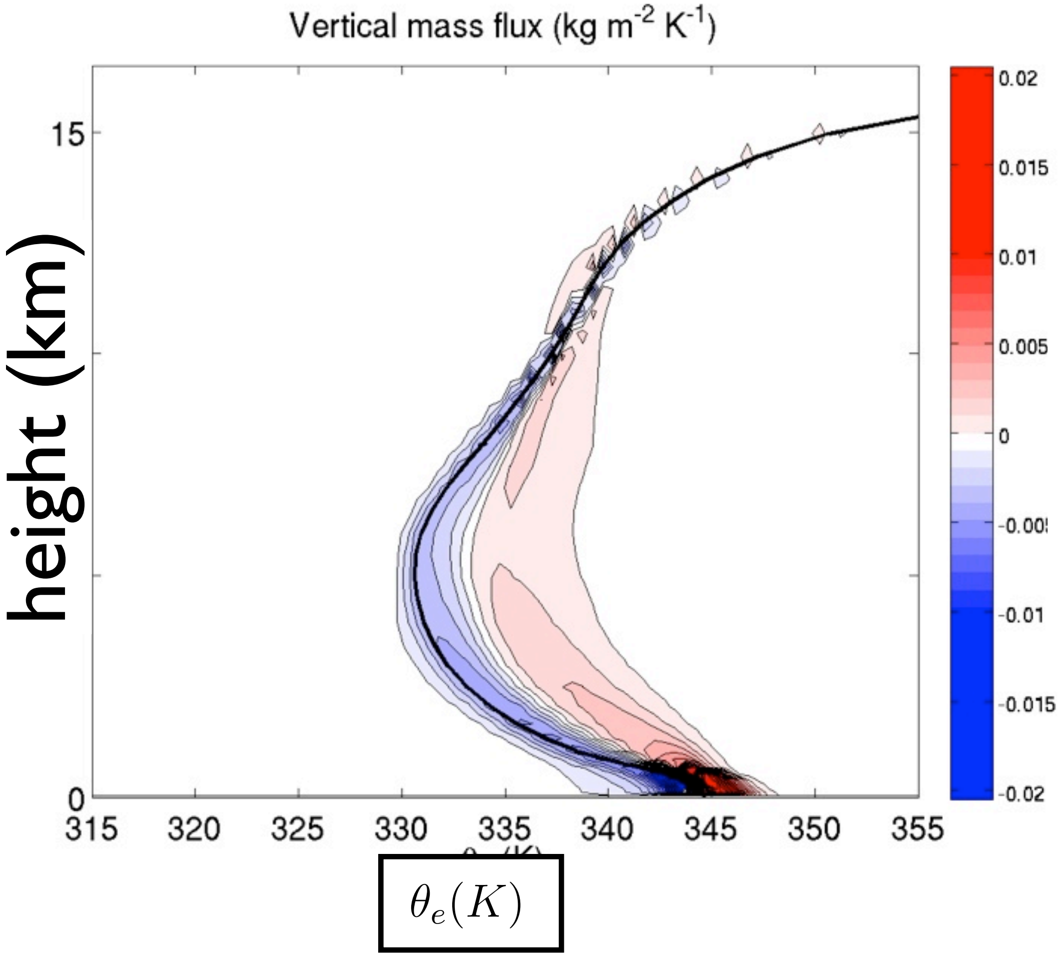
$$\langle f \rangle (z, \theta_{e0}) = \frac{1}{P L_x L_y} \int_0^P \int_0^{L_y} \int_0^{L_x} f(x, y, z, t) \delta(\theta_{e0} - \theta_e(x, y, z, t)) dx\, dy\, dt$$

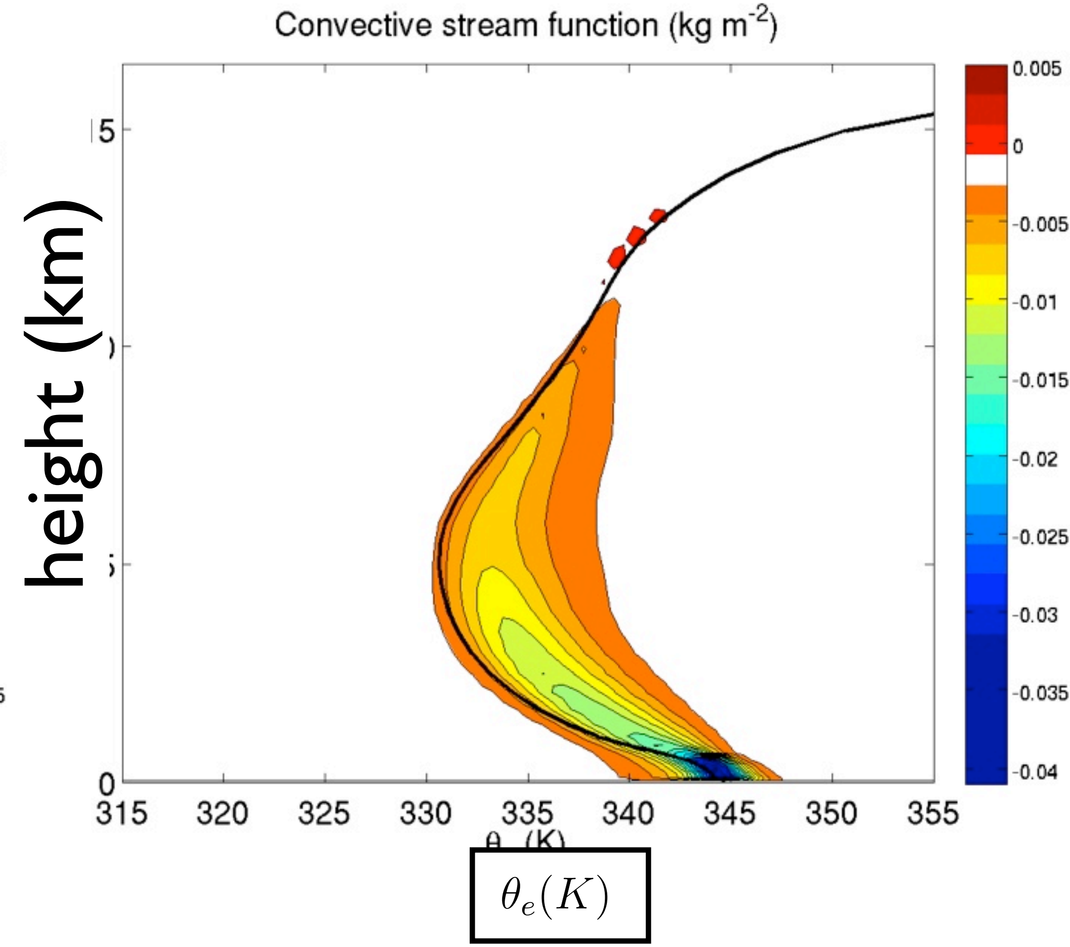
We then compute the mean upward isentropic mass flux

$$\langle \rho w \rangle (z, \theta_e)$$

and the isentopic streamfunction:

$$\boxed{\begin{aligned} \Psi(z, \theta_{e0}) &= \int_{-\infty}^{\theta_{e0}} \langle \rho w \rangle (z, \theta_e') d\theta_e' \\ &= \frac{1}{P L_x L_y} \int_0^P \int_0^{L_y} \int_0^{L_x} \rho w H(\theta_{e0} - \theta_e) dx\, dy\, dt \end{aligned}}$$



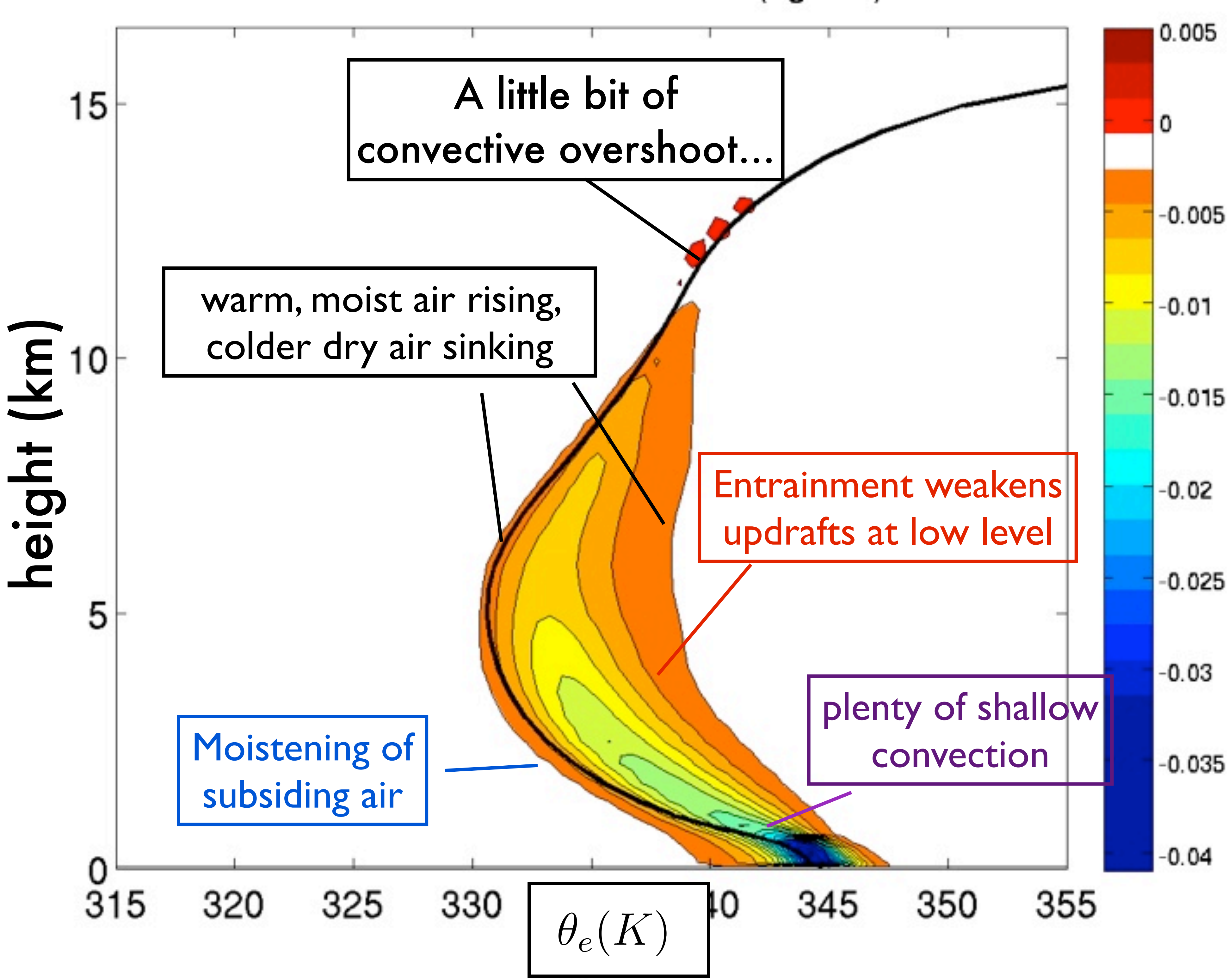


Upward mass flux

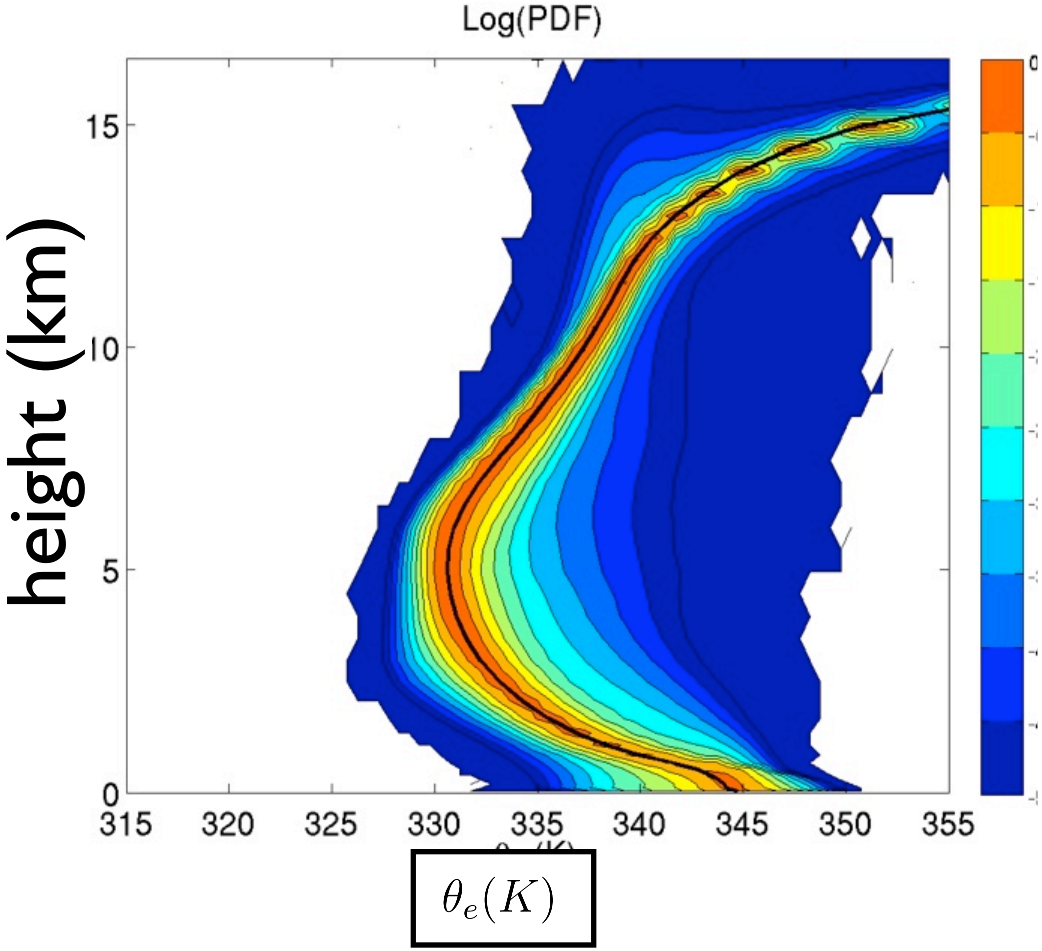
$$\langle \rho w \rangle (z, \theta_e)$$

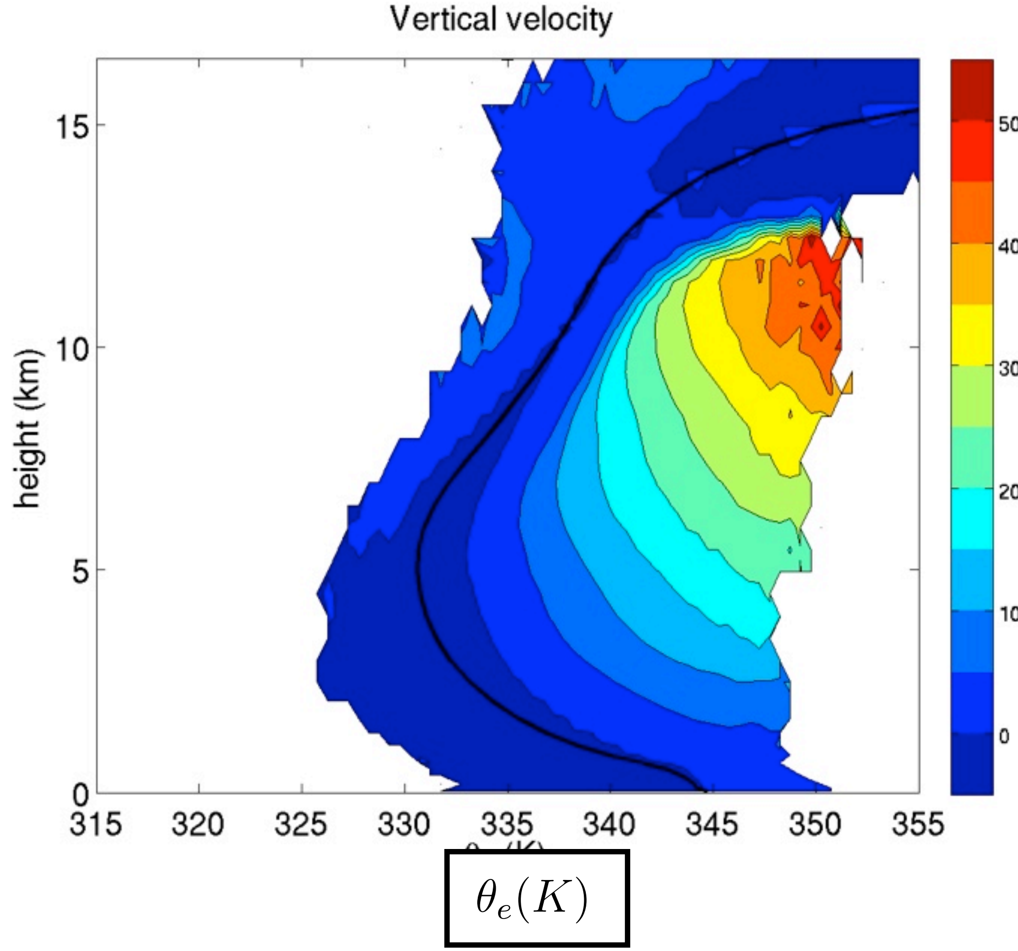
Isentropic streamfunction

$$\Psi(z, \theta_{e0}) = \int_{-\infty}^{\theta_{e0}} \langle \rho w \rangle (z, \theta_e') d\theta_e'$$



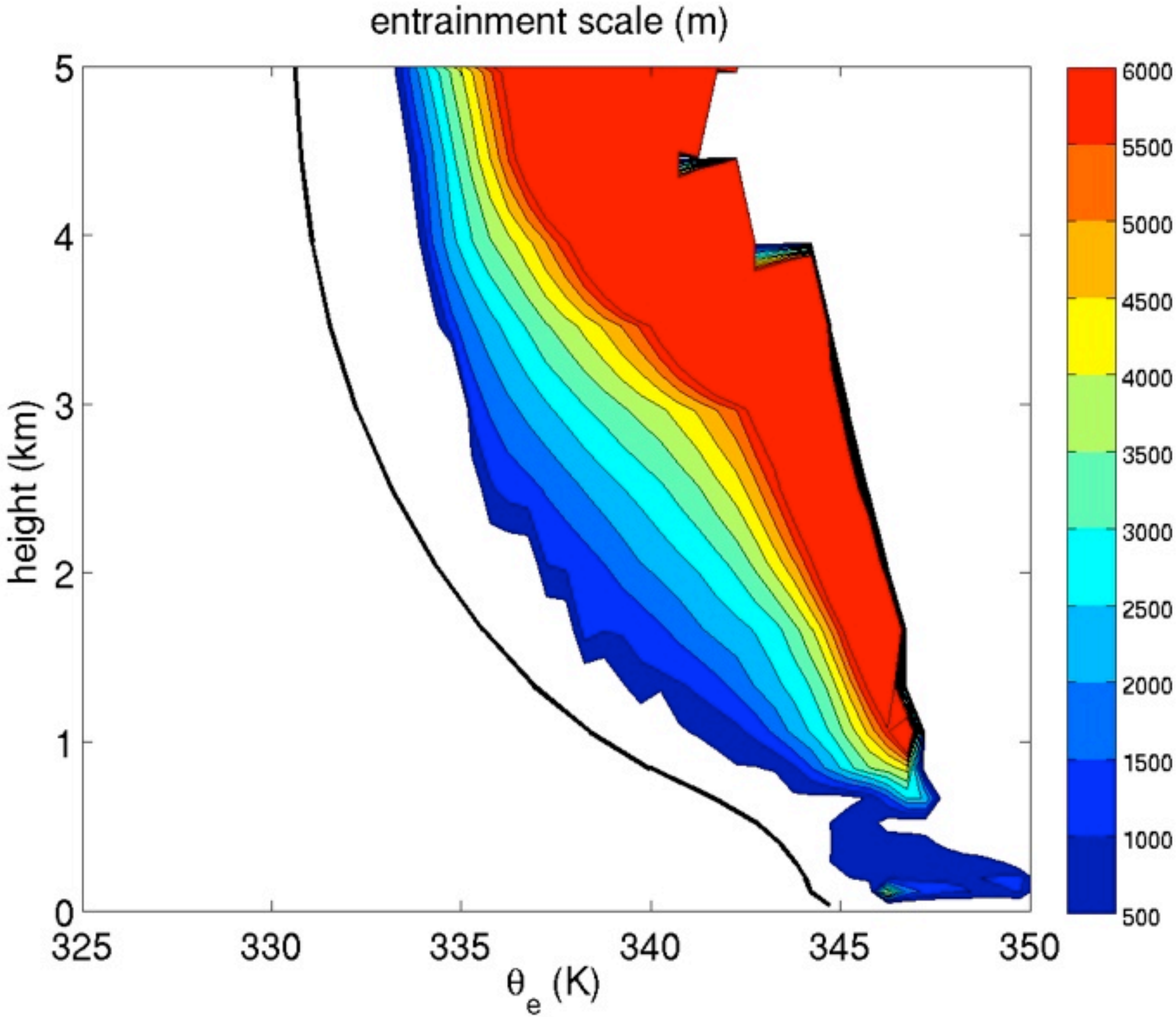
A little bit of convective overshoot...
warm, moist air rising, colder dry air sinking
Entrainment weakens updrafts at low level
Moistening of subsiding air
plenty of shallow convection
height (km)
$\theta_e(K)$
0
5
10
15
315
320
325
330
345
350
355
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
-0.04





$$PDF(z, \theta_e) = \frac{\langle \rho \rangle}{\overline{\rho}(z)}$$

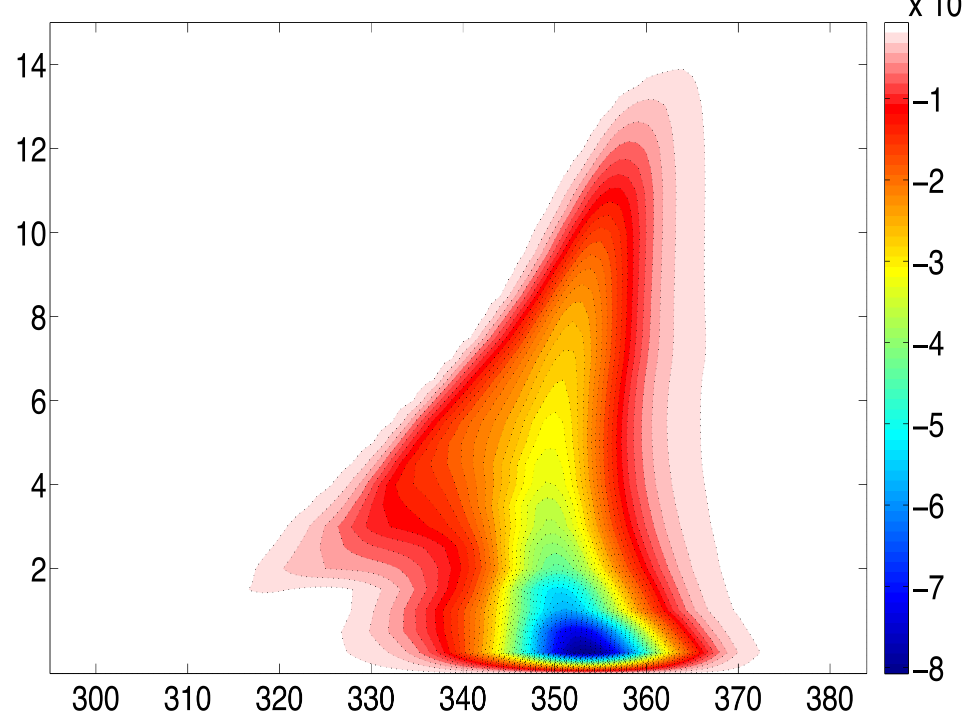
$$\tilde{W}(z, \theta_e) = \frac{\langle \rho w \rangle}{\langle \rho \rangle}$$


entrainment scale (m)
height (km)
0
1
2
3
4
5
325
330
335
340
345
350
θe (K)
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000

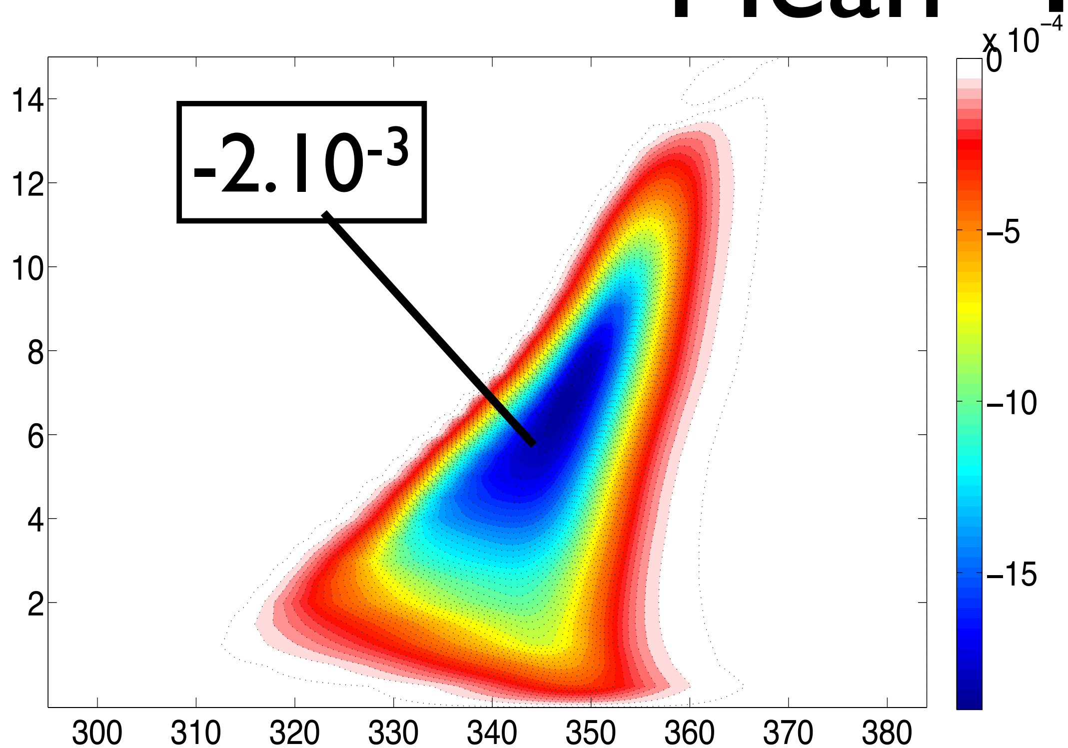
Isentropic analysis

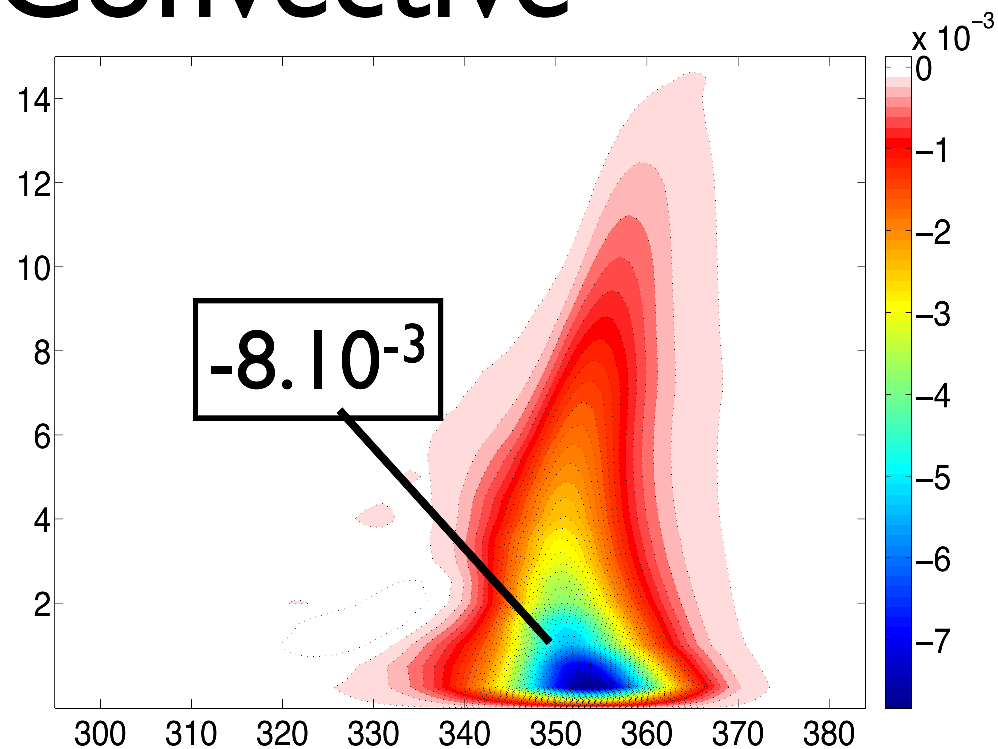
1. Separate the domain in 64 subdomains to separate between ‘large’ and ‘convective scales.
2. Compute the average isentropic streamfunction for each days in individual subdomains.
3. Look at the variability of the convection based on the isentropic stresmfunction

Total

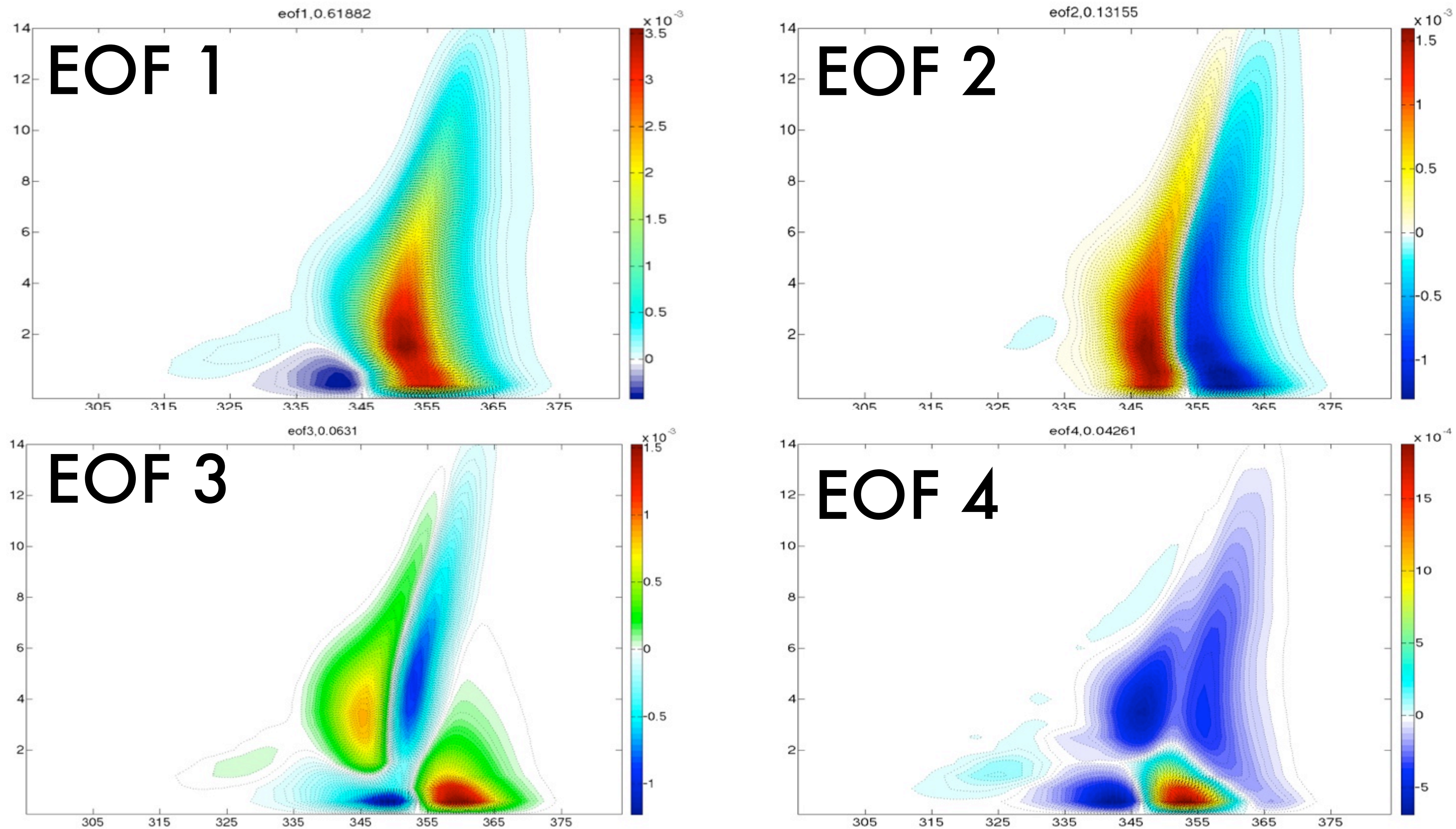


= Mean + Convective



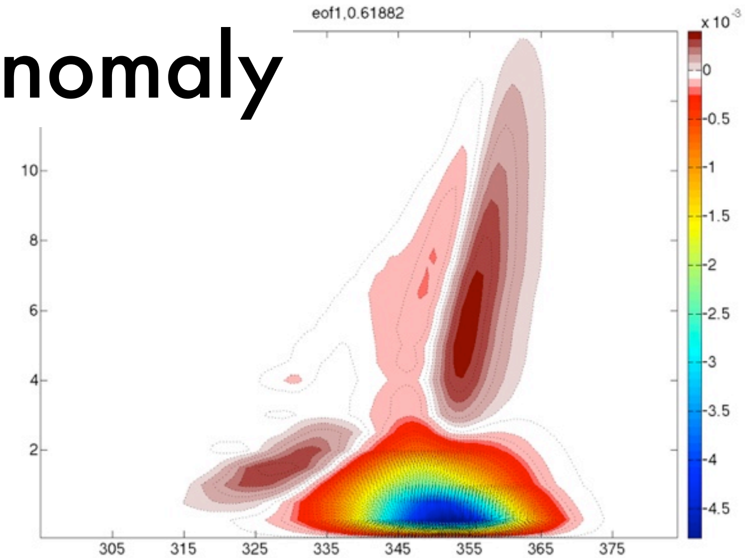


Convective regimes

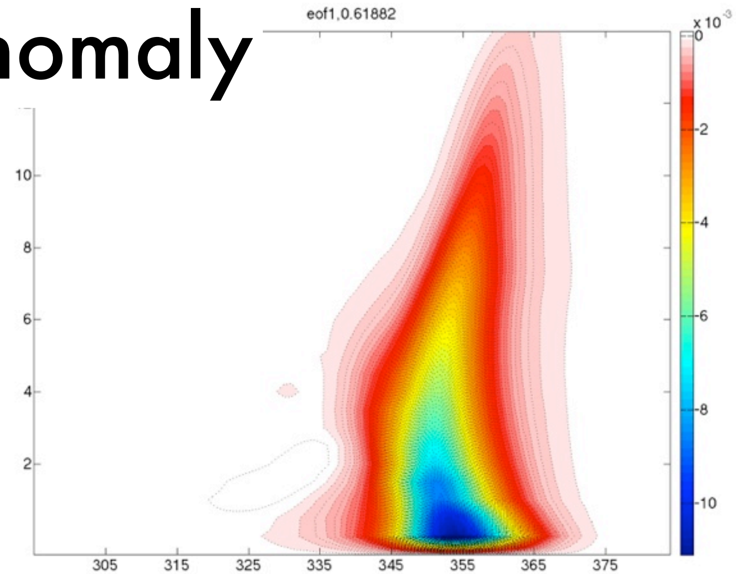


Perform an EOF analysis of the 64x273 snapshots of the streamfunction to identify the main patterns of variability

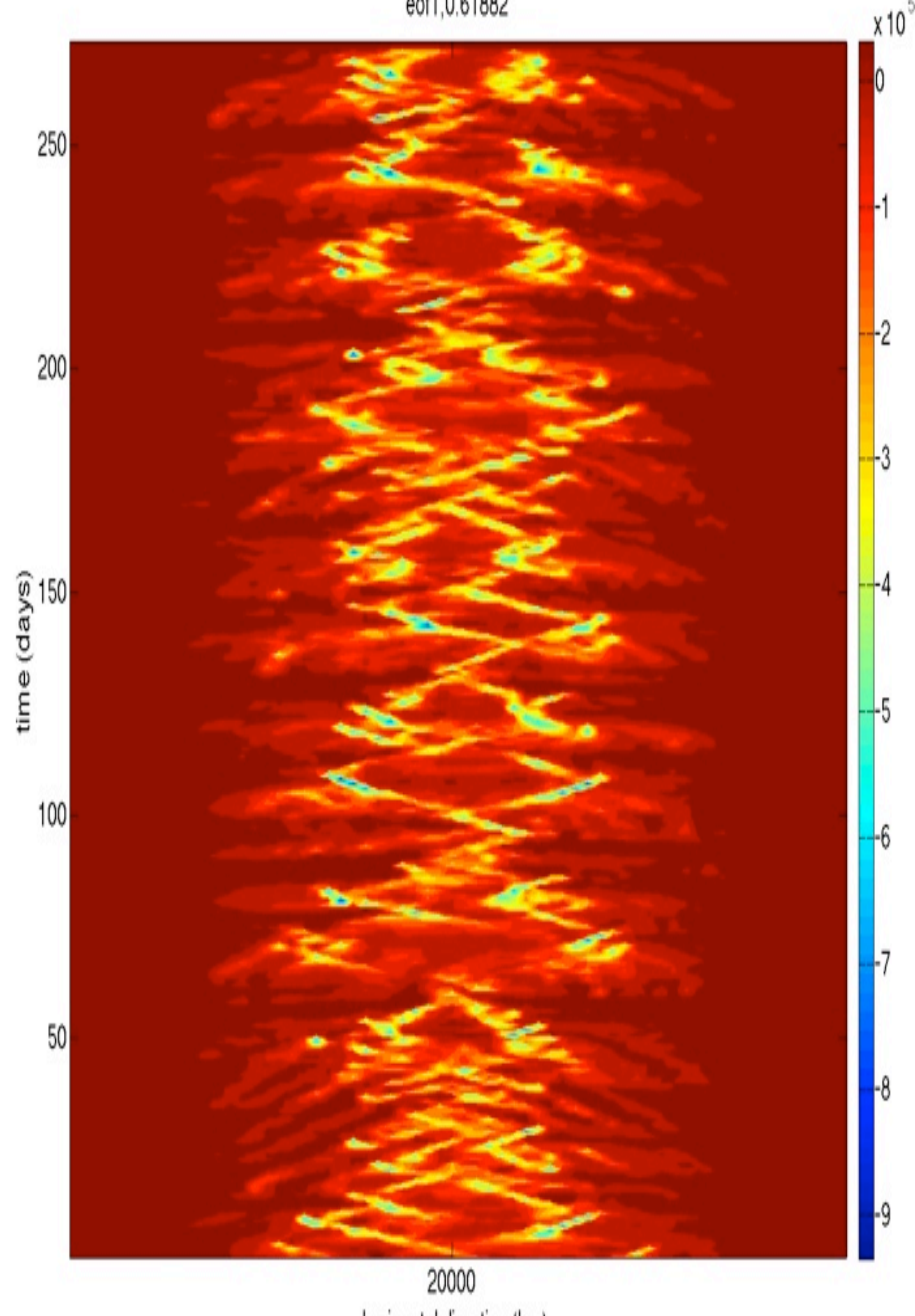
+ anomaly



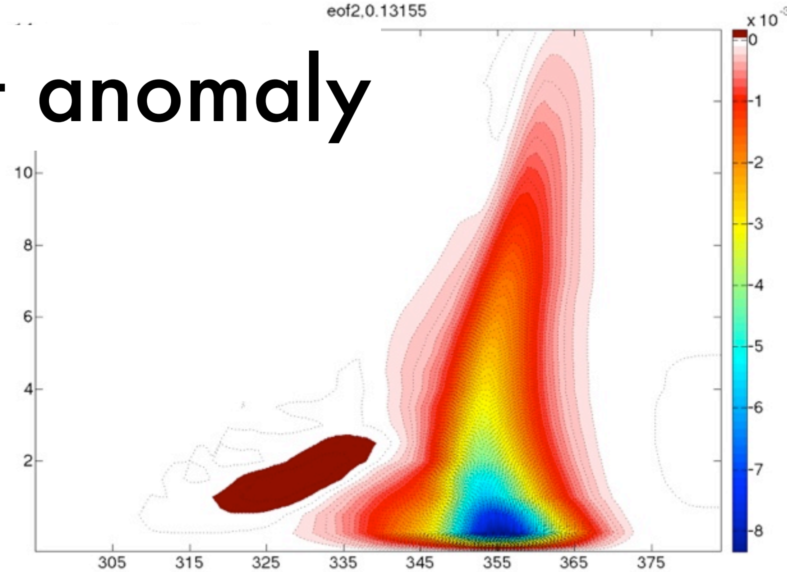
- anomaly



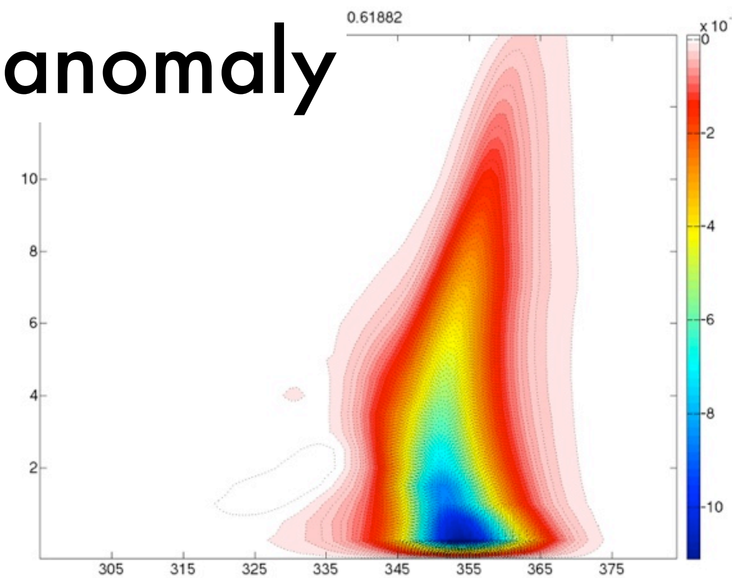
1st EOF reflects variability of deep convection



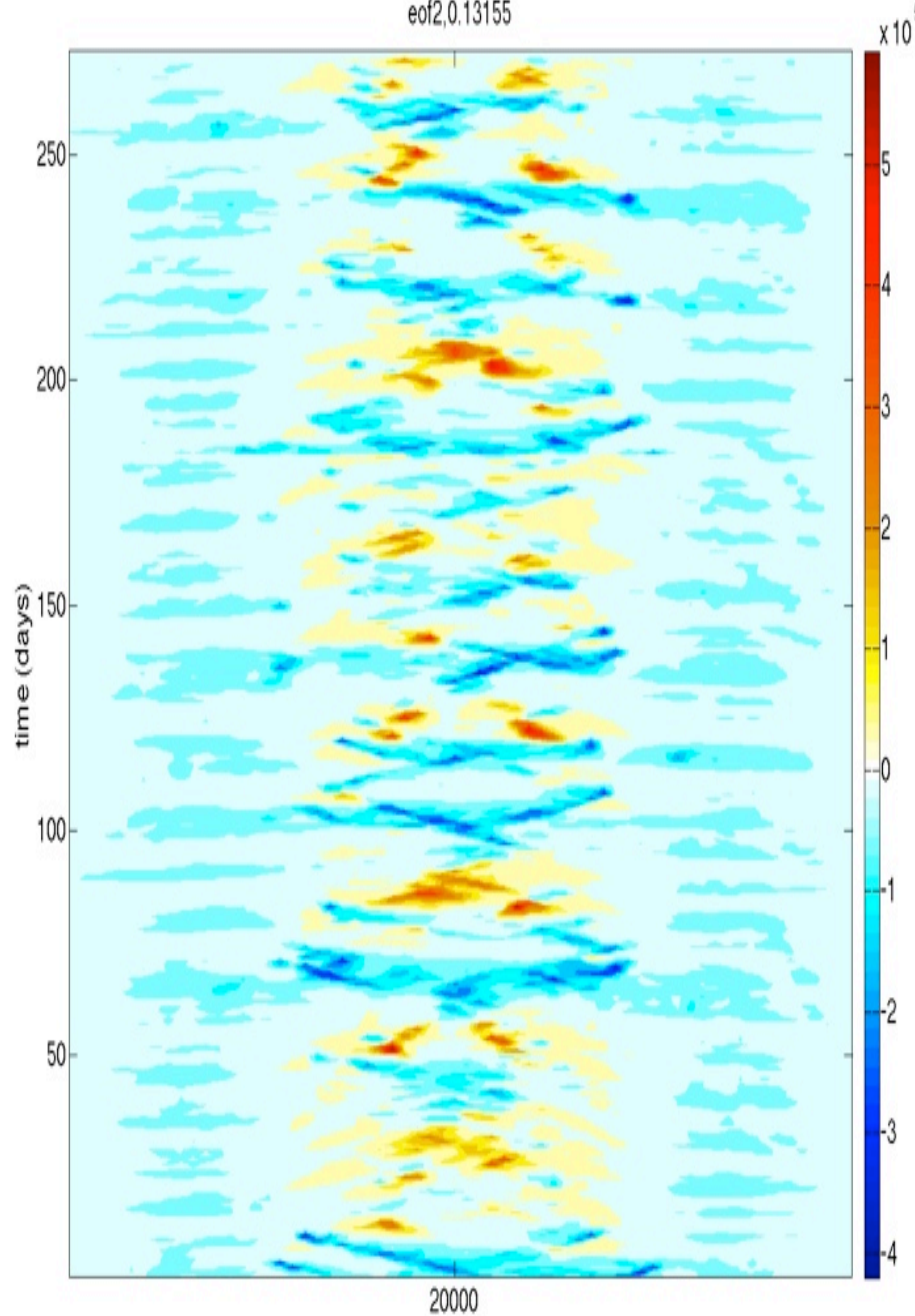
+ anomaly



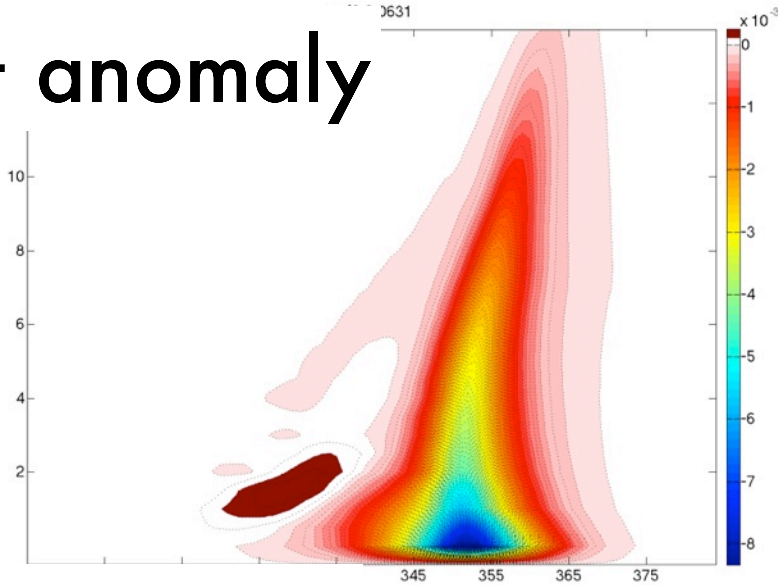
- anomaly



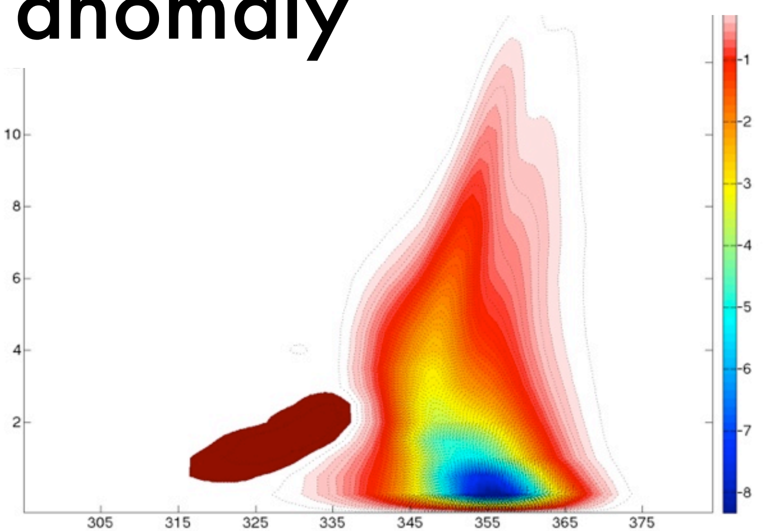
2nd EOF accounts for warmer/colder ascending air



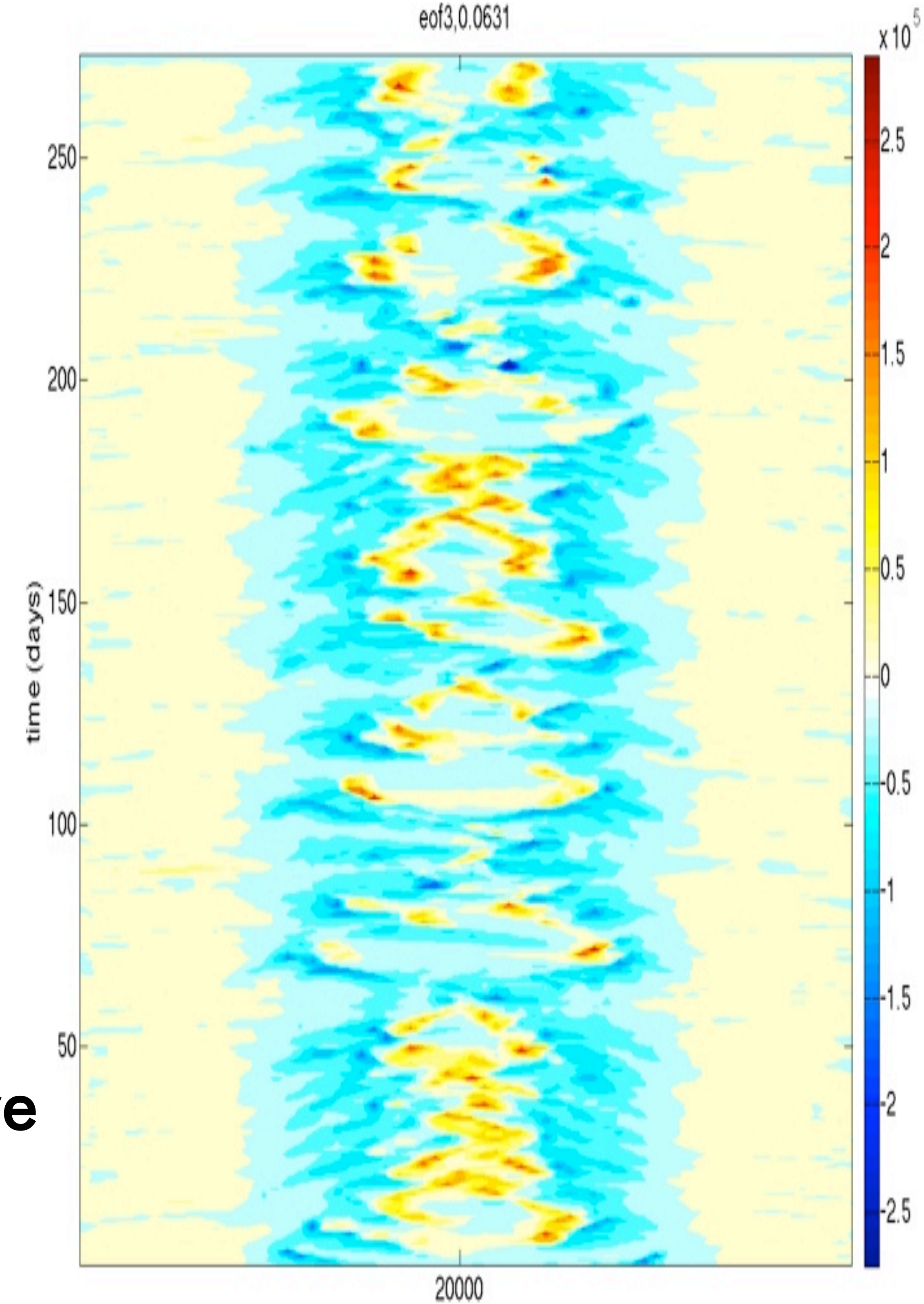
+ anomaly



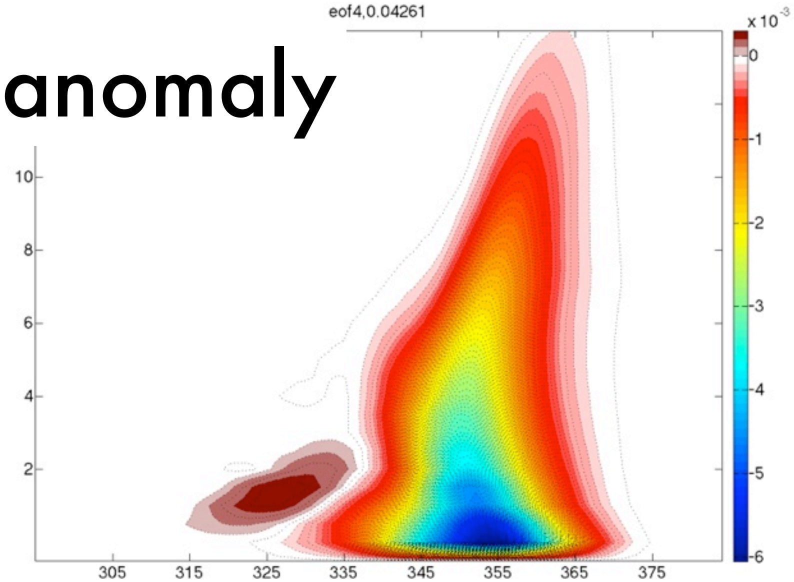
- anomaly



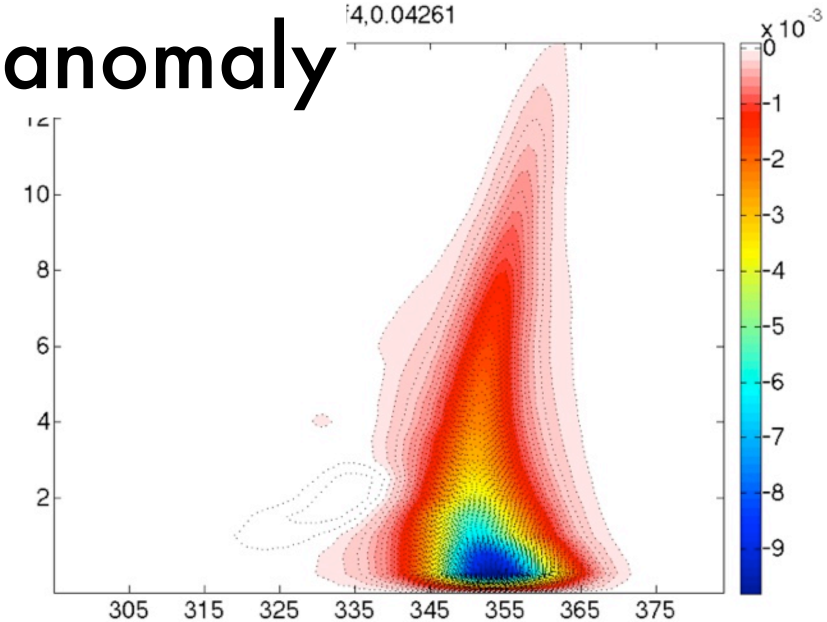
3rd EOF shows convection with less/more entrainment of dry air

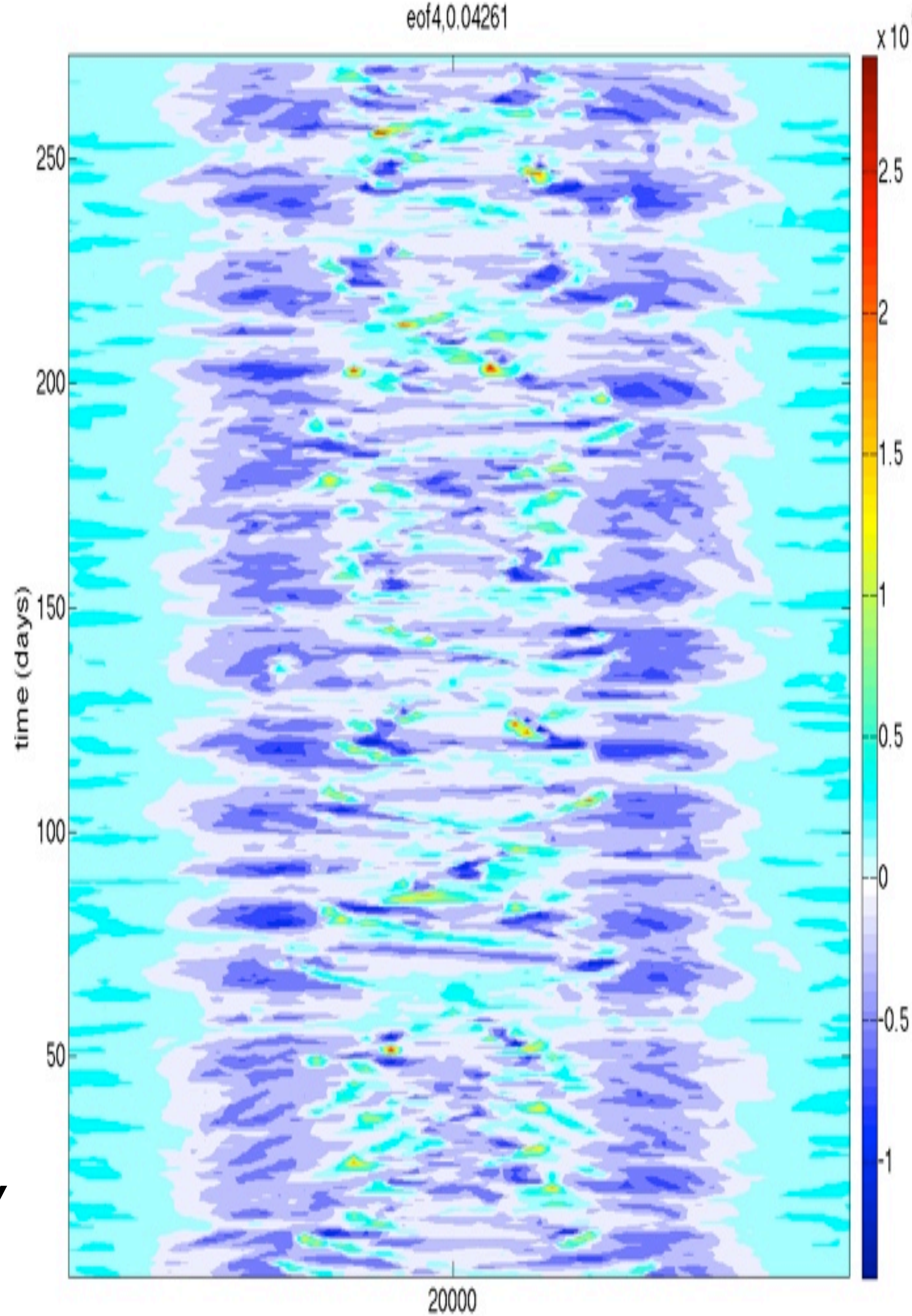


+ anomaly

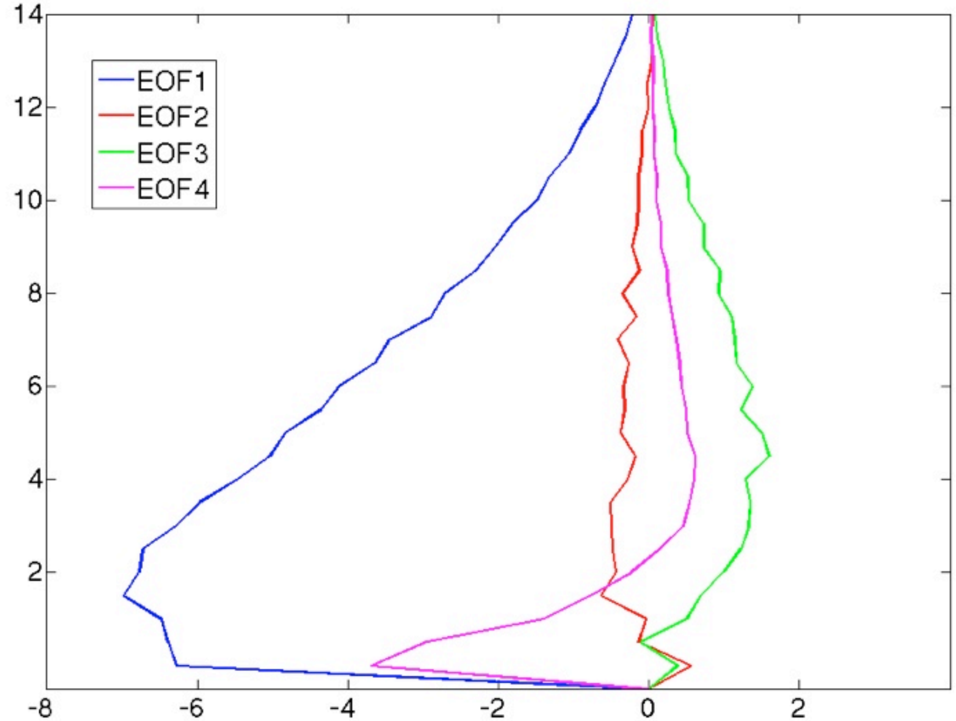


- anomaly



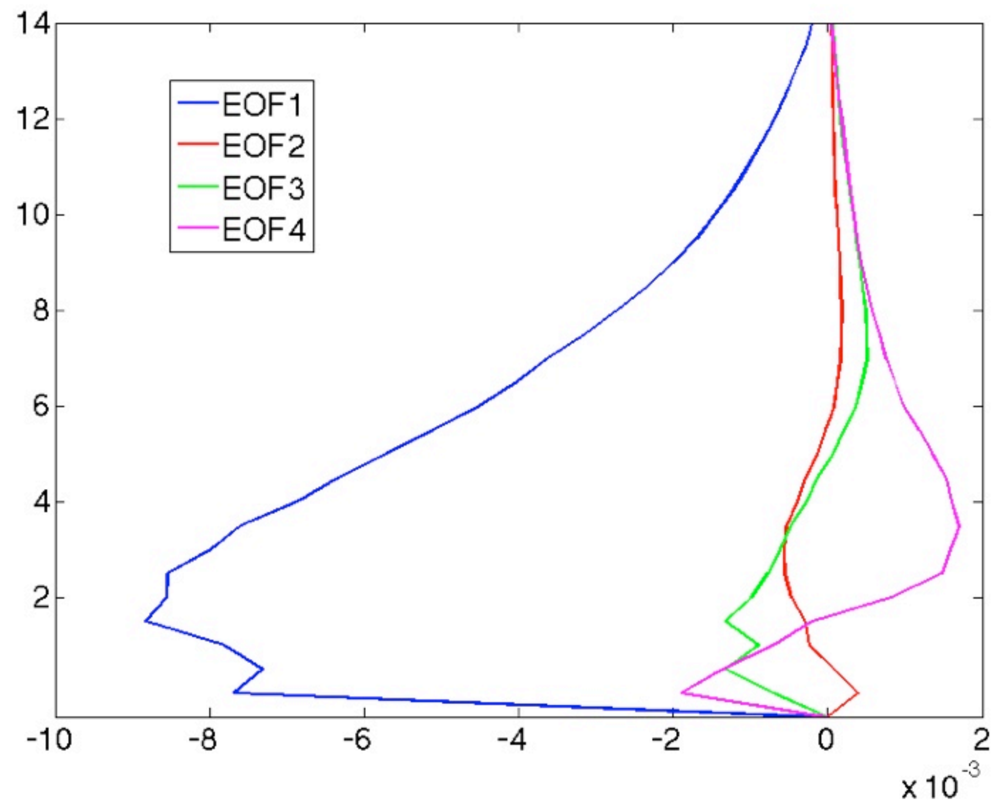


3rd EOF: (+) anomaly corresponds to more intense startiform convection, (-) anomaly to more shallow convection



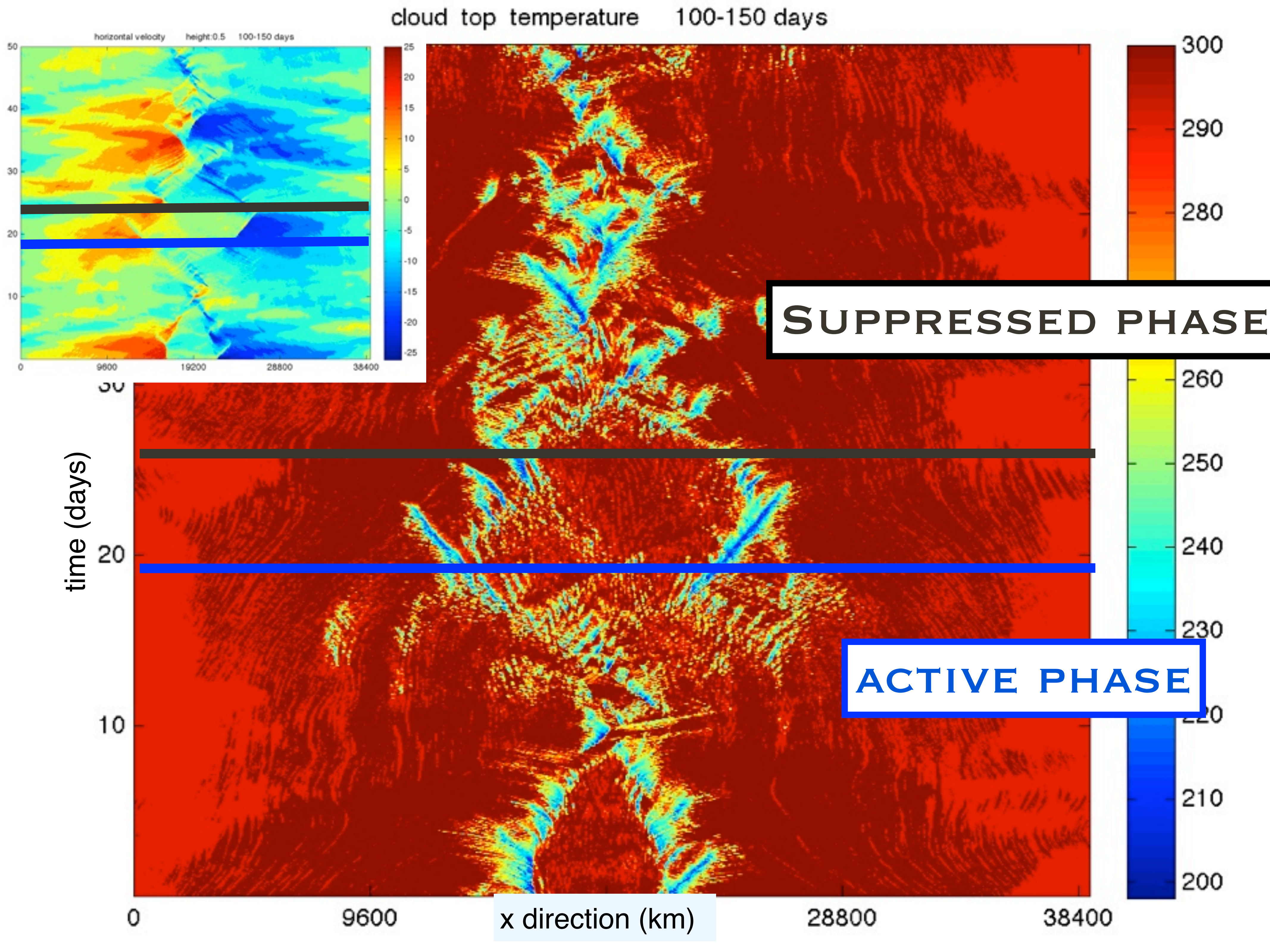
Contribution of the EOF's to the convective mass transport

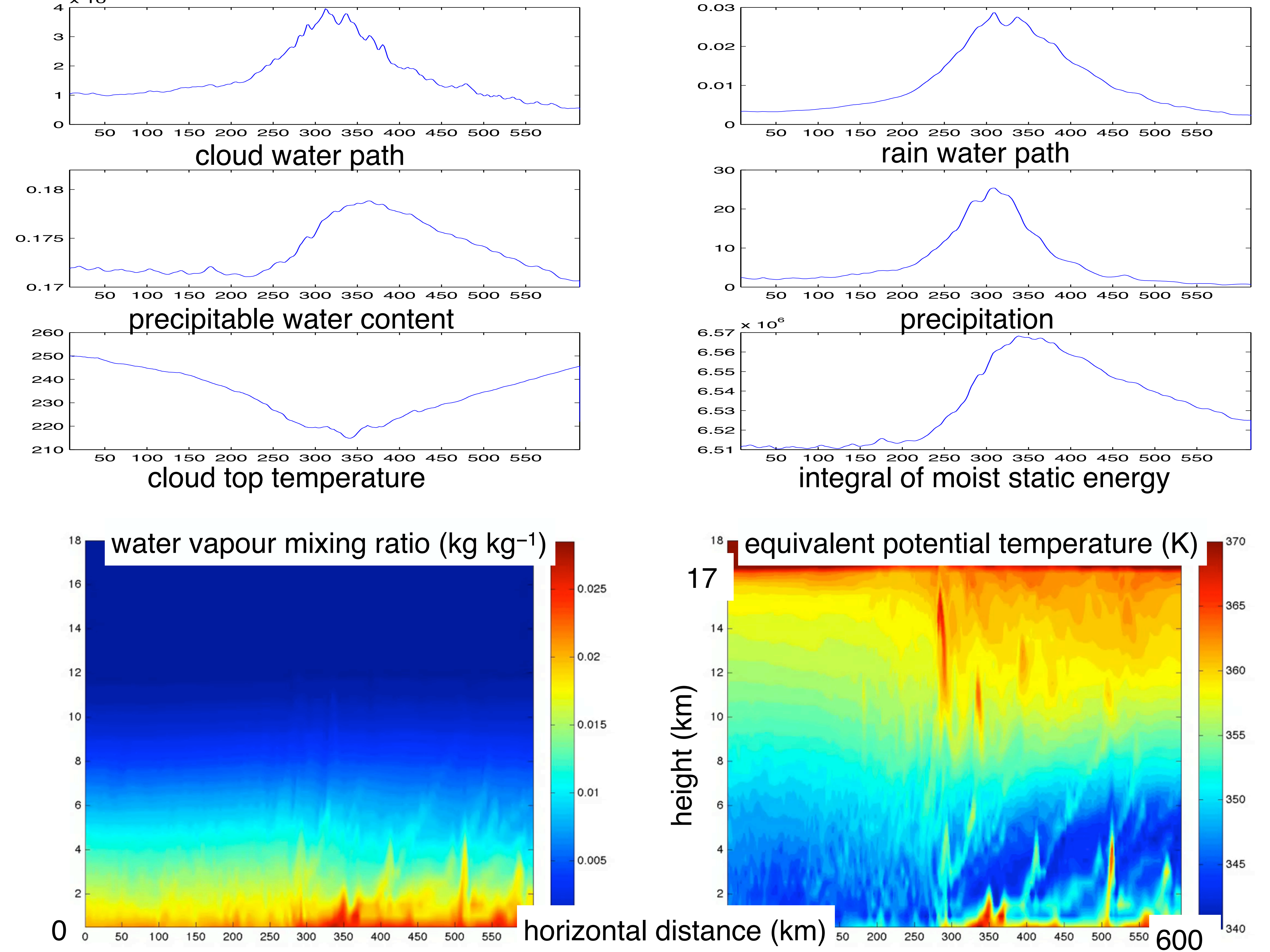
Contribution of the EOF's to the convective heat transport

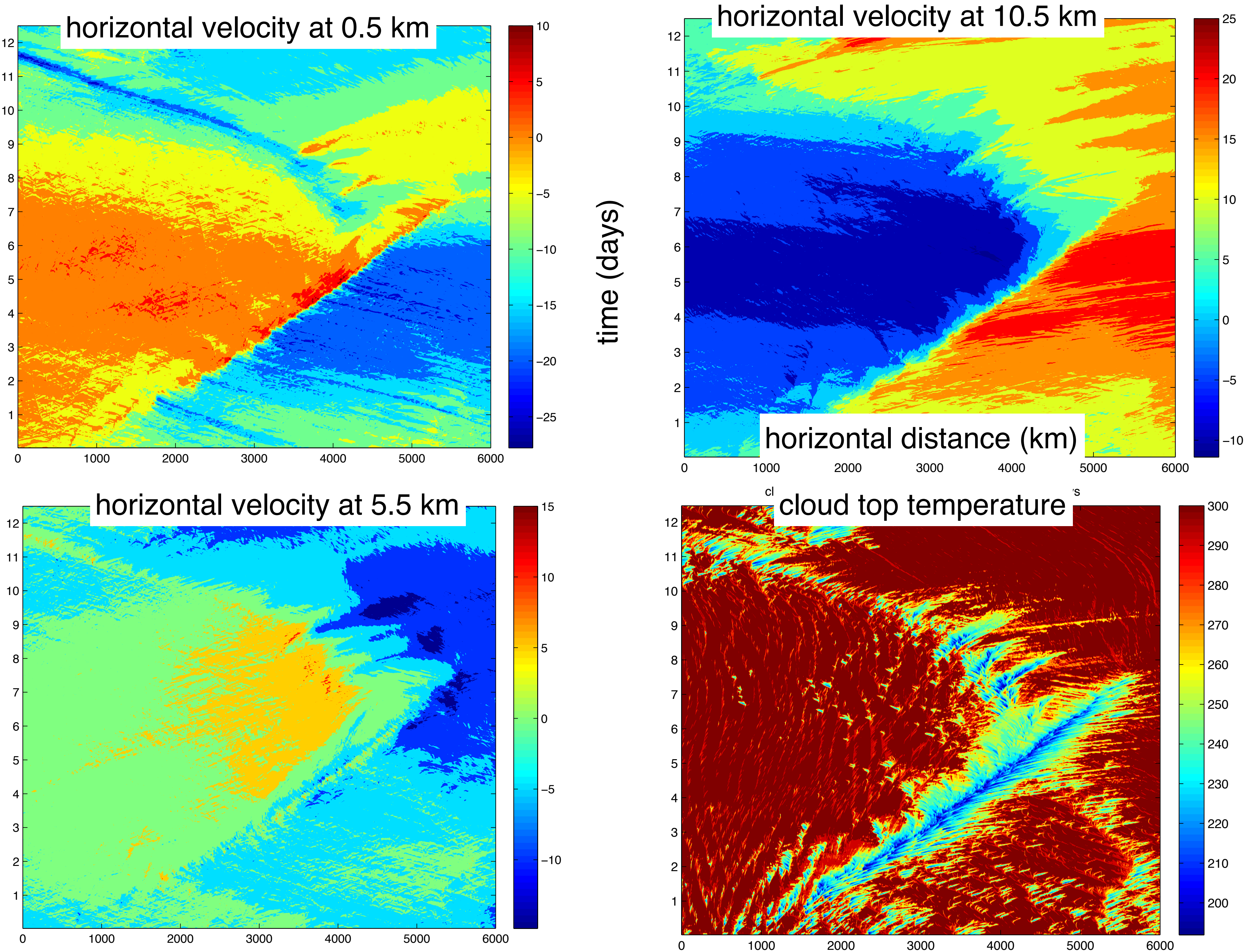


Conclusion

- Benchmark simulation of idealized Walker circulation that exhibits complex low frequency variability.
- Importance of advection of water vapor and vertical structure of the flow for LF variability
- Introduce the concept of isentropic analysis for convective motions
- Show how the variability of convection can be tied to different regimes in high-resolution simualtion


cloud top temperature 100-150 days
horizontal velocity height:0.5 100-150 days
time (days)
x direction (km)
0
9600
28800
38400
10
20
300
290
280
260
250
240
230
210
200
Suppressed phase
active phase


cloud water path
rain water path
precipitable water content
precipitation
cloud top temperature
integral of moist static energy
water vapour mixing ratio (kg kg⁻¹)
equivalent potential temperature (K)
height (km)
horizontal distance (km)
17
0
600


horizontal velocity at 0.5 km
horizontal velocity at 10.5 km
time (days)
horizontal distance (km)
horizontal velocity at 5.5 km
cloud top temperature