Isentropic analysis and atmospheric circulation.

Olivier Pauluis

Courant Institute of Mathematical Sciences

Thanks to Arnaud Czaja, Robert Korty and Frederic Laliberte

Sept. 1, 2009

Keck Institute for Space Studies, Caltech, CA

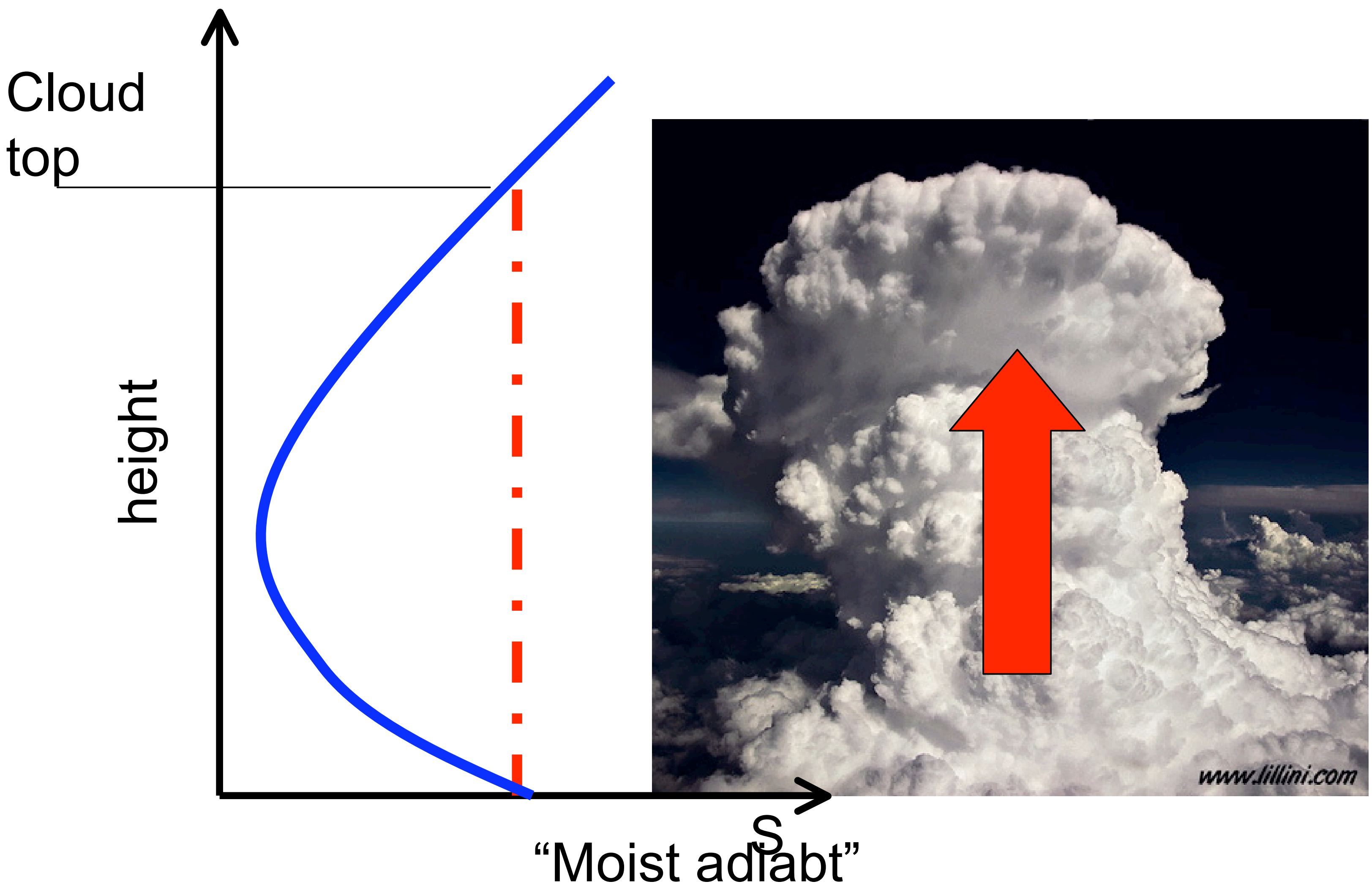
Entropy and circulation

- Entropy is a good quantity to analyze the global circulation:
  - Heating and cooling maintain large-scale entropy gradient;
  - entropy can be viewed as a conserved tracer;
  - and entropy transport is tied to mechanical work.

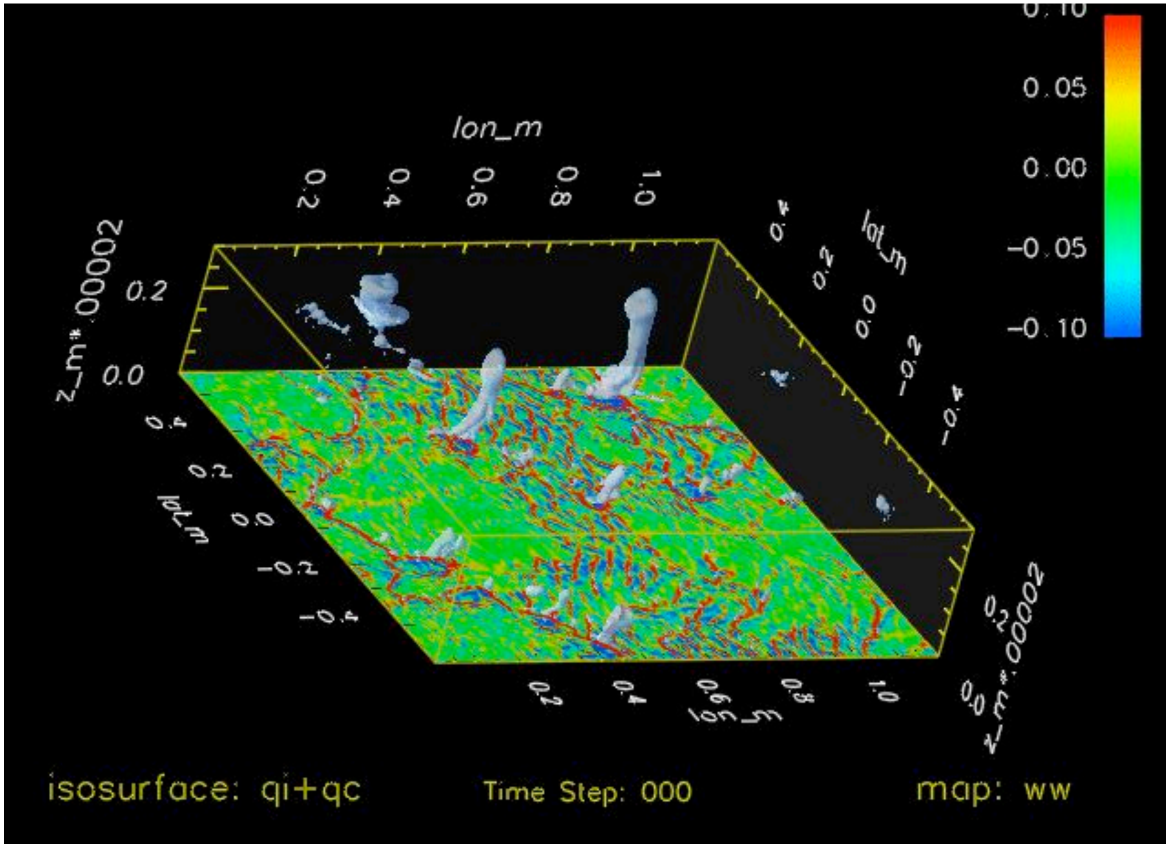
✔First order description of the circulation as reversible transport

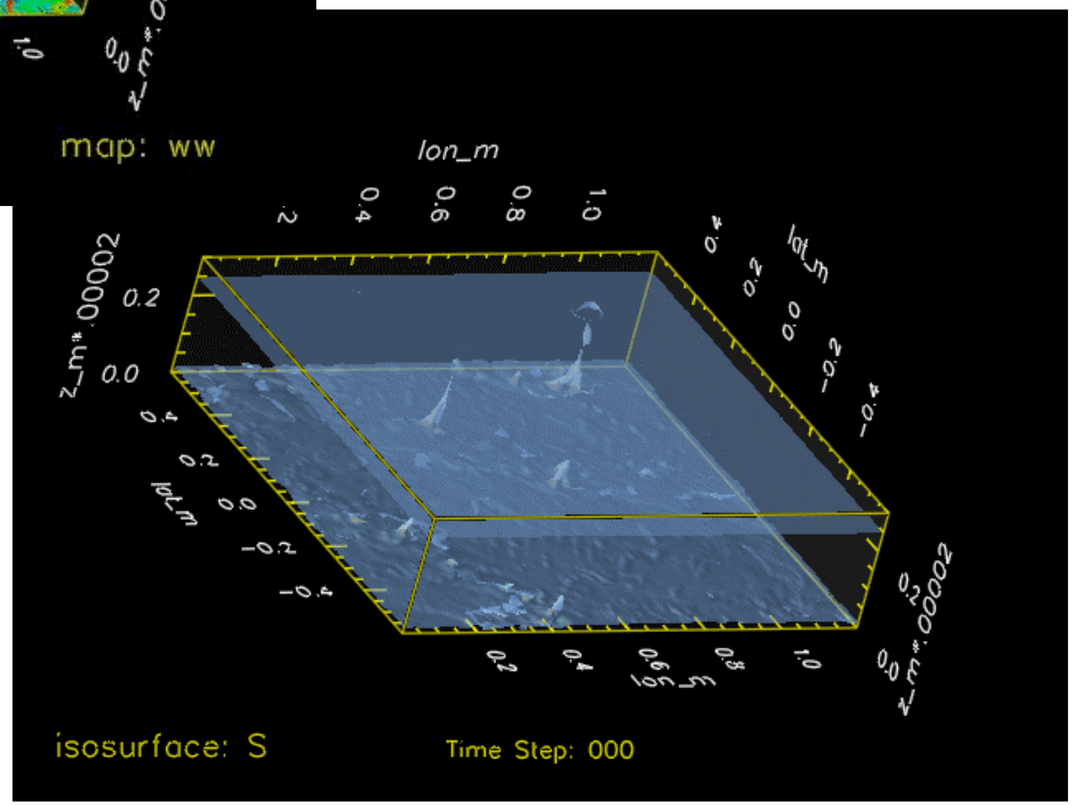
☒ But not all processes are reversible!

Moist convection

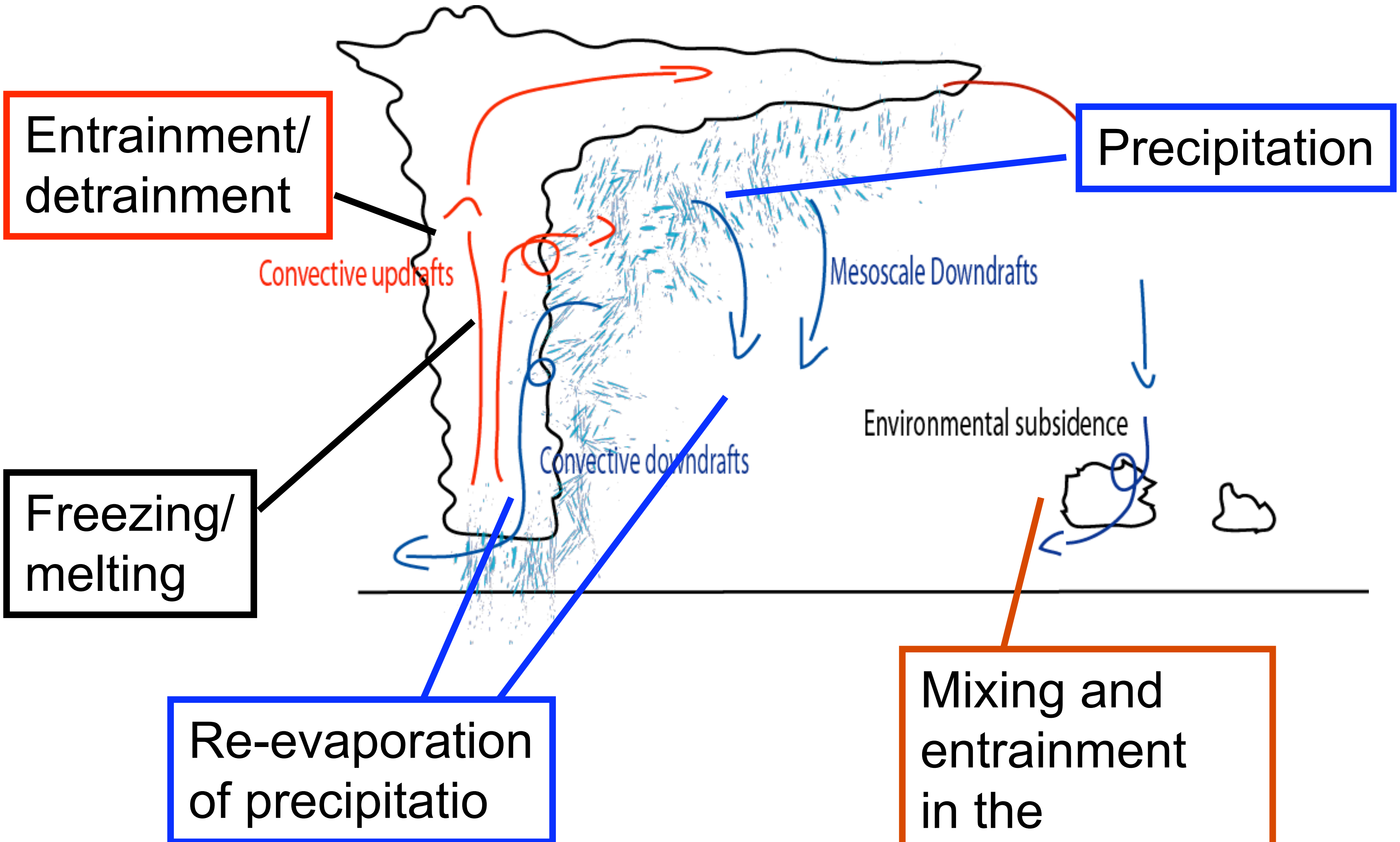


Photograph by Marco Lillini (http://cloudappreciationsociety.org)

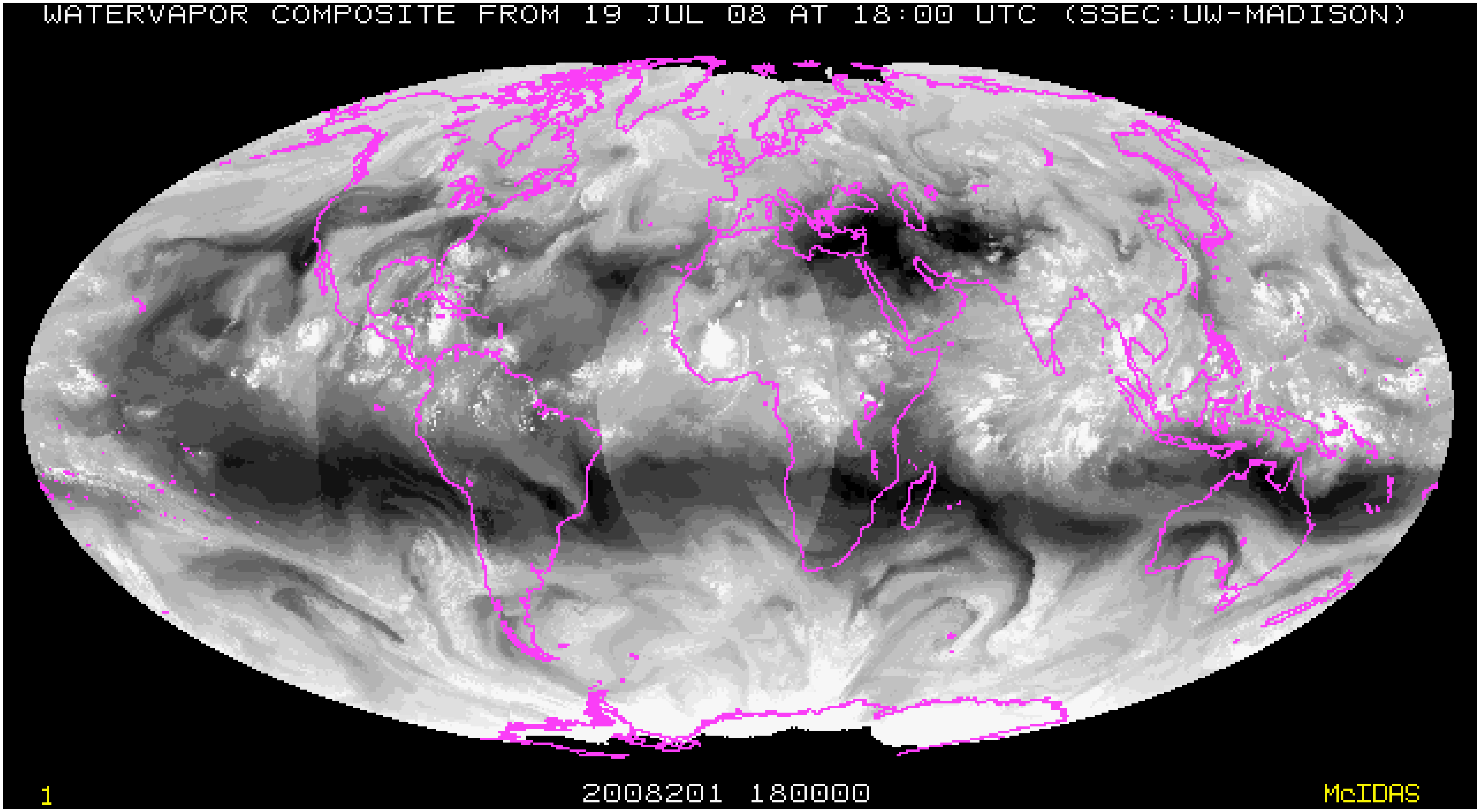

0.10
0.05
0.00
−0.05
−0.10
lon_m
lat_m
z_m*.00002
isosurface: qi+qc
Time Step: 000
map: ww

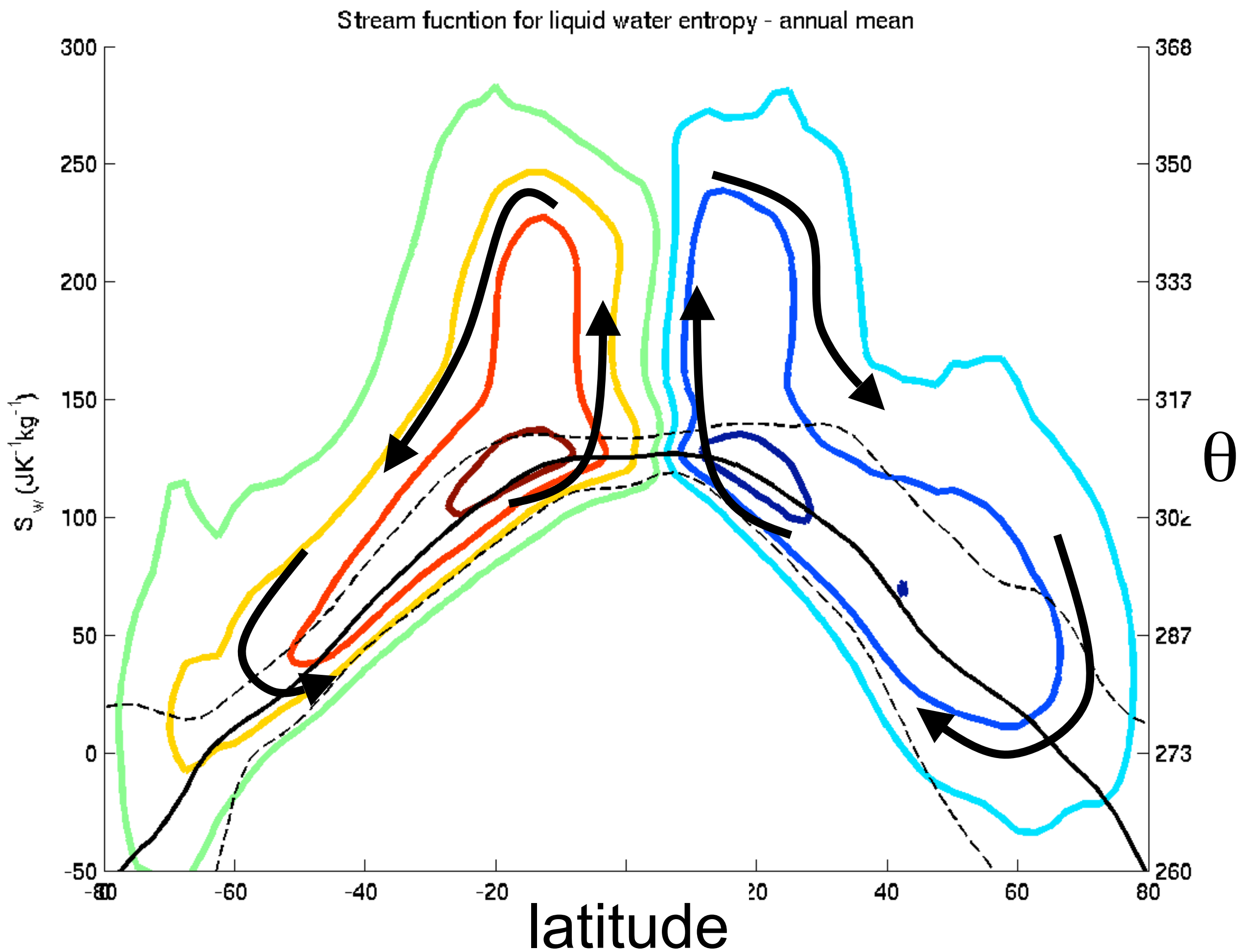

lon_m
lat_m
z_m*.00002
isosurface: S
Time Step: 000

Not all processes involved with convection are reversible.



Stormtracks

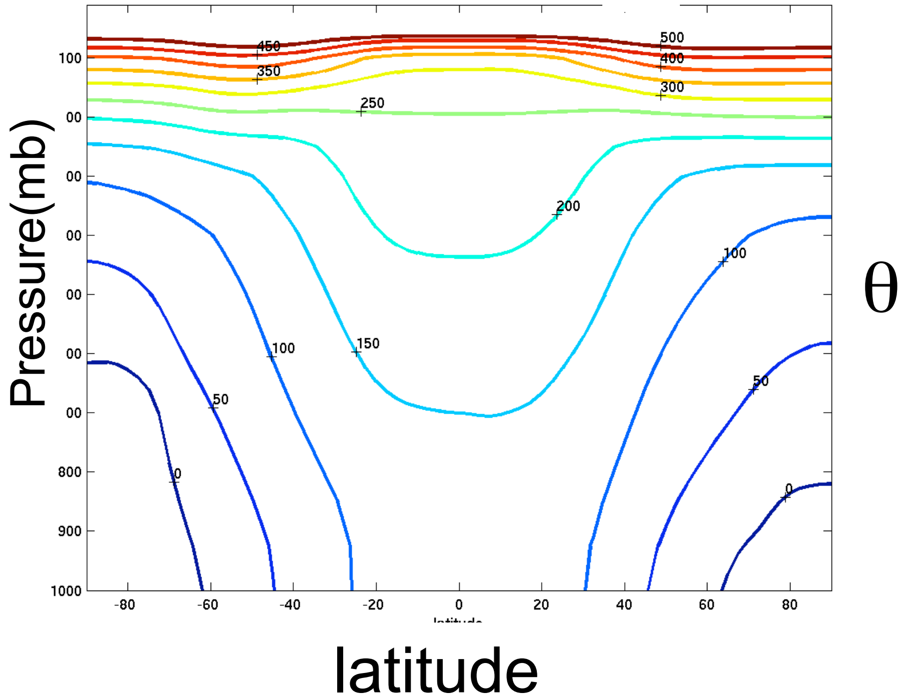




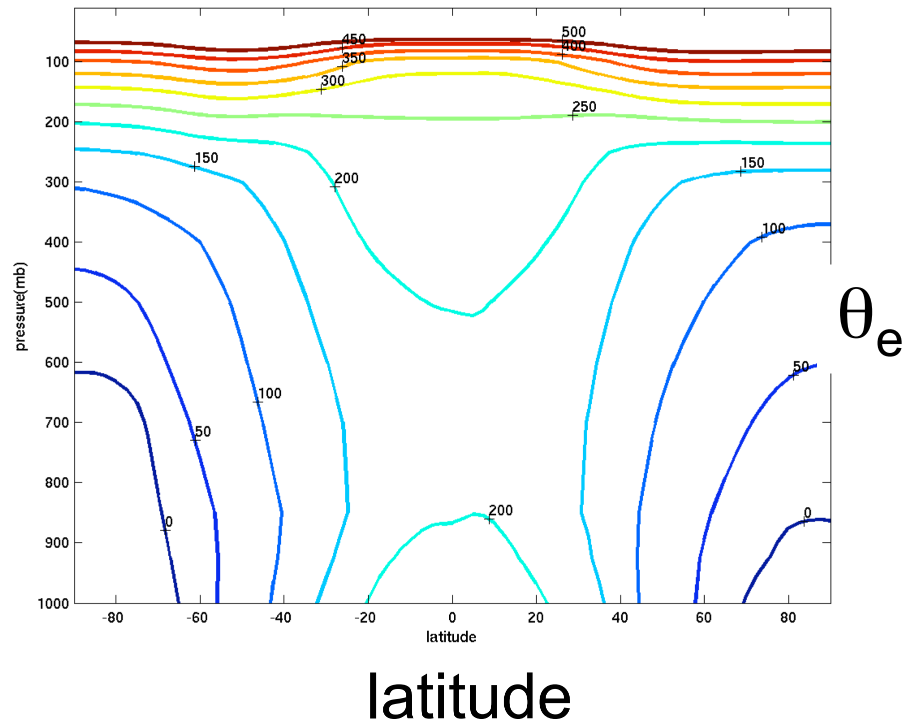
Circulation on dry isentropes

$$\Psi_\theta(\varphi,\theta) = \int_0^\theta 2\pi \overline{\rho_\theta v}^\theta a \cos\varphi d\theta$$

'Dry isentropes': $\theta = cst$

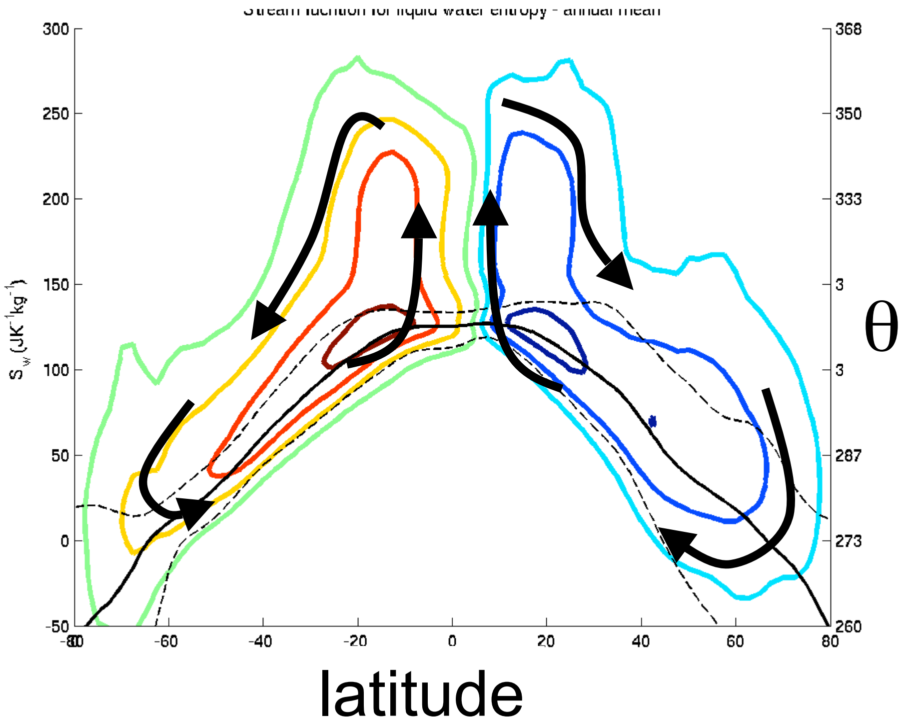


'Moist isentropes': $\theta_e = cst$

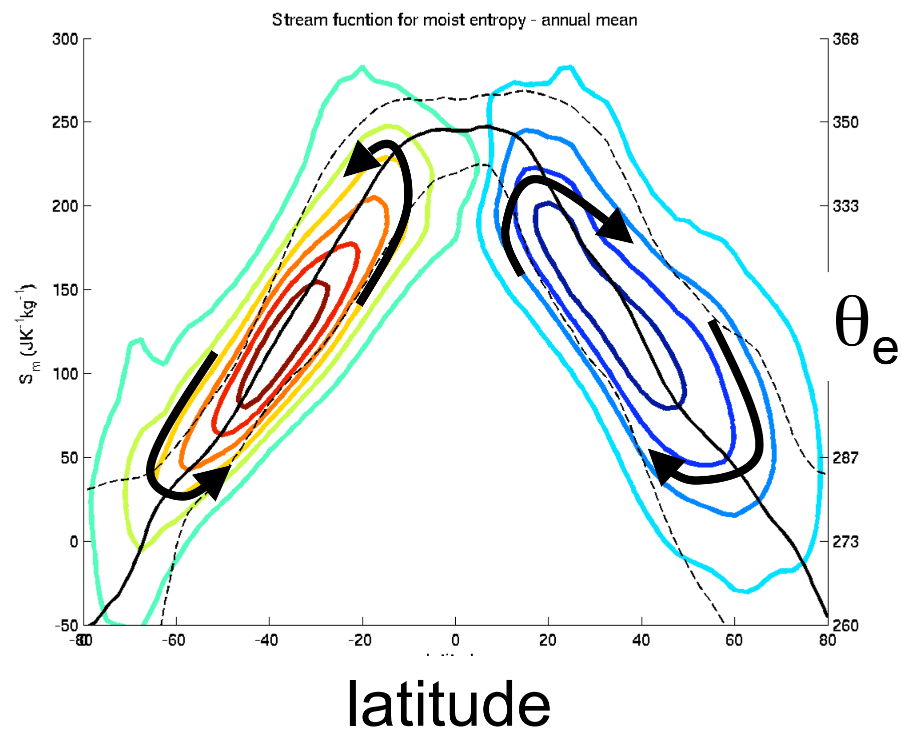


- Instead of averaging the circulation on potential temperature surfaces, one can use surfaces of constant equivalent potential temperature.
- θ_e includes a contribution from the latent heat content, and has often a minimum in the middle of the atmosphere.

Stream function on dry isentropes

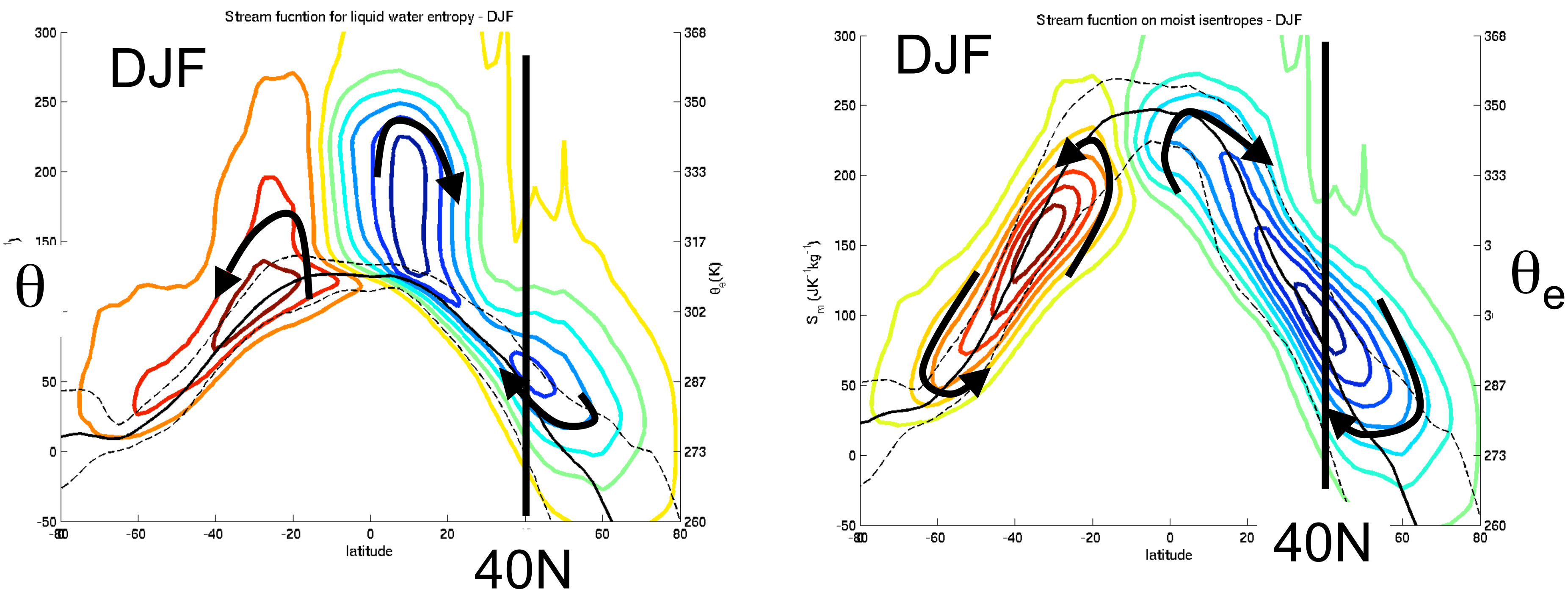


Stream function on moist isentropes



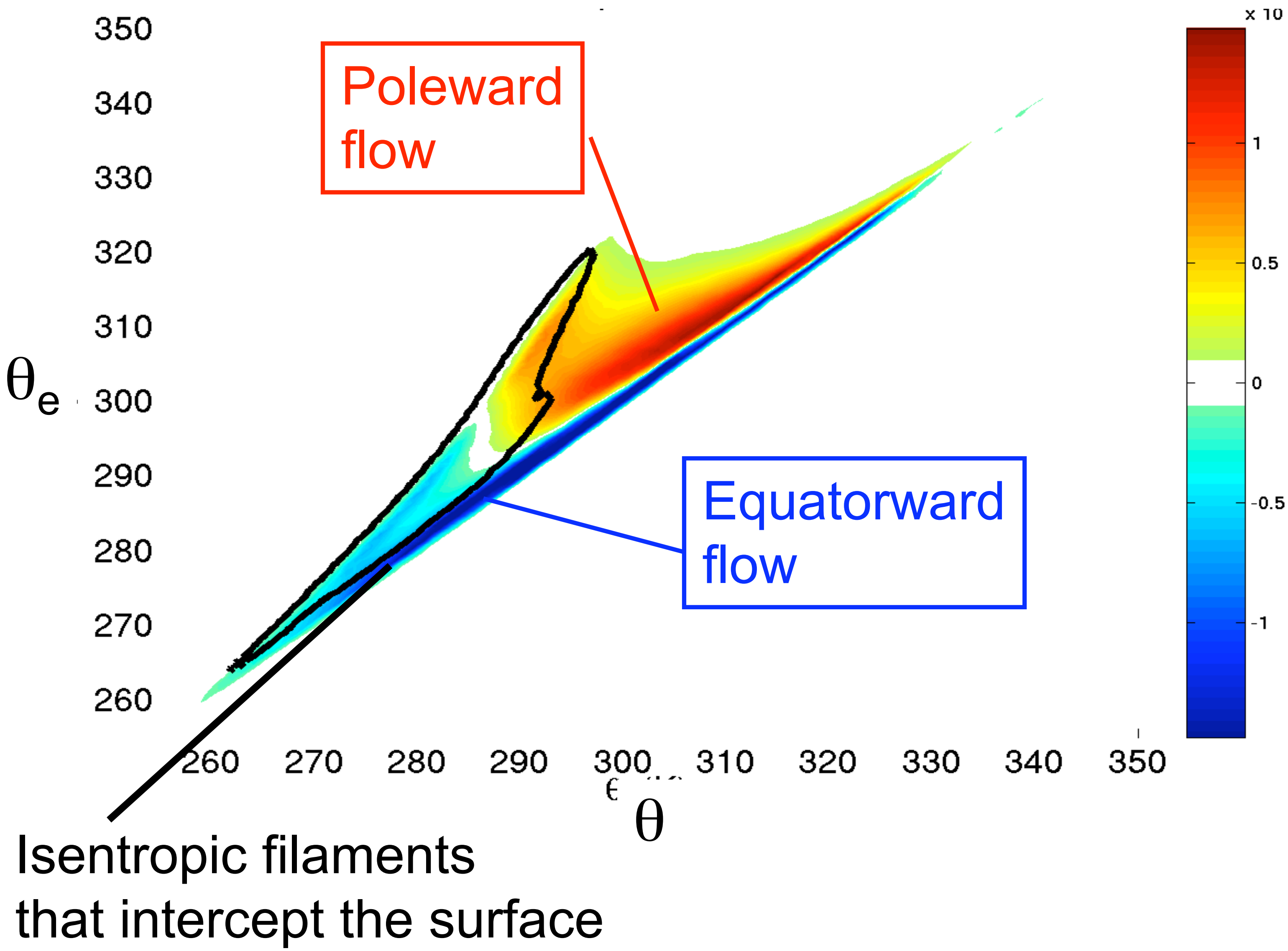
- Same single cell structure…
- But amplitude of the circulation differs!

In the Midlatitudes:



- Circulation on moist isentropes is larger than that on dry isentropes.

Mass flux distribution at 40N - DJF



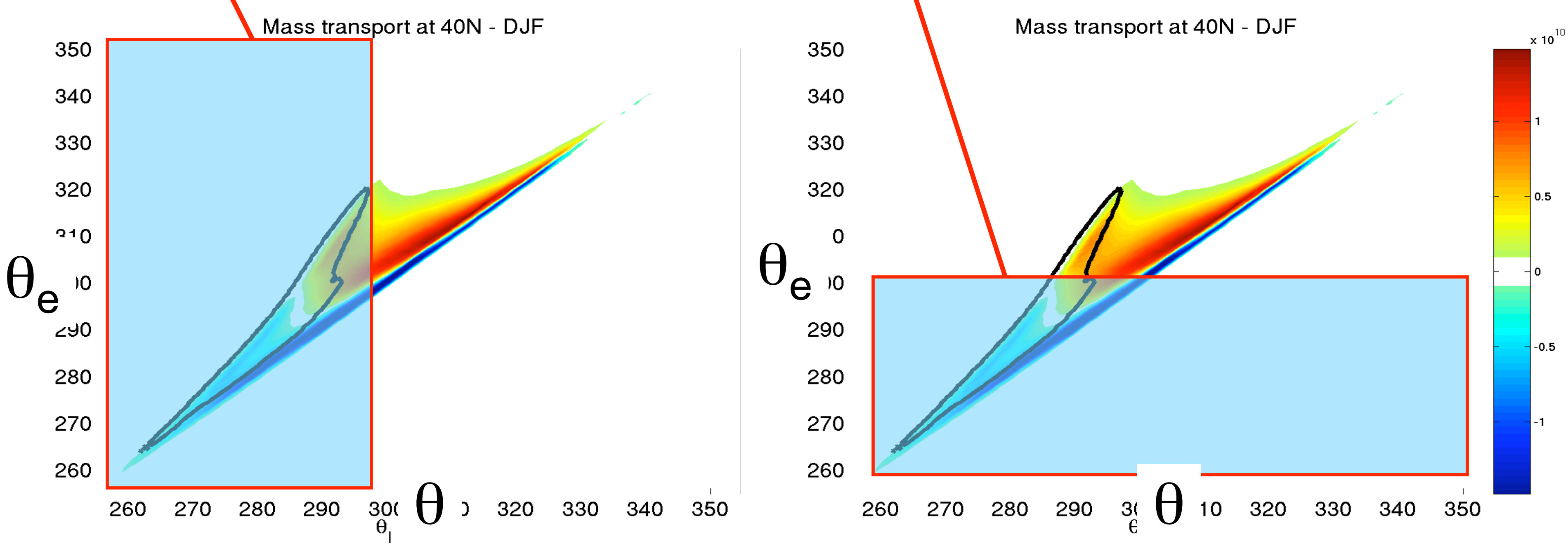
Mass flux and stream function at 40N

Stream function on dry isentropes:

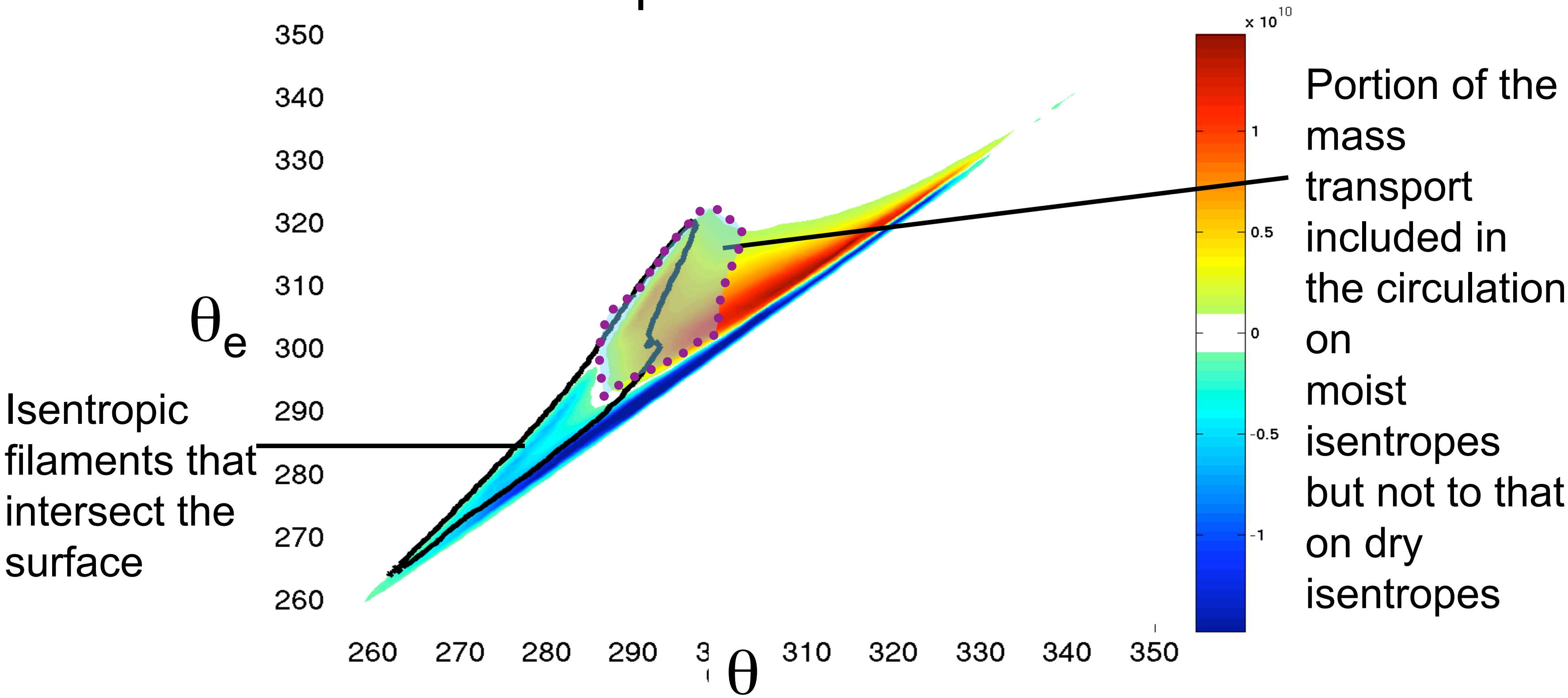
$$\Psi_{\theta_e}(\theta_e, \phi) = \int_{-\infty}^{\theta_e} \left(\int_{-\infty}^{\infty} M(\theta_e', \theta_l', \phi) d\theta_l' \right) d\theta_e'$$

Stream function on moist isentropes:

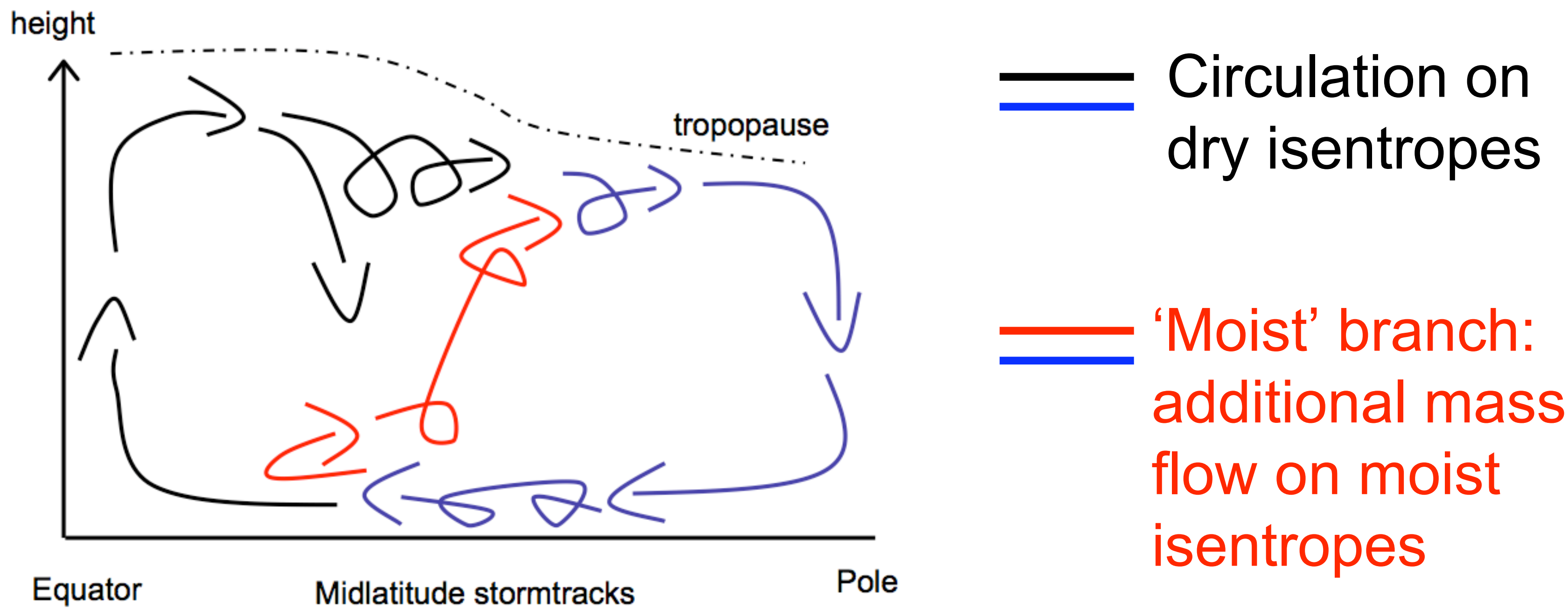
$$\Psi_{\theta_l}(\theta_l, \phi) = \int_{-\infty}^{\theta_l} \left(\int_{-\infty}^{\infty} M(\theta_e', \theta_l', \phi) d\theta_e' \right) d\theta_l'$$



Mass transport at 40N - DJF



- The additional mass transport on moist isentropes takes place filaments near the Earth's surface.
- The equivalent potential temperature corresponds to upper tropospheric value of the potential temperature.
- This corresponds to a poleward flow of warm, moist air near the surface that is ready to rise into the upper troposphere.



- In the midlatitudes, global circulation high entropy air poleward in two distinct branches:
  - an upper tropospheric branch;
  - an a lower branch of warm, most air that ascents into the upper troposphere within the stormtracks.
- Mass transport is comparable in each branch.

Entropy sources and sinks

- Governing equation for dry and moist entropy:

Atmospheric Entropy transport Must balance sources And sinks

$$\frac{d}{dt}S_m = \frac{L_v}{T_0}E + \frac{Q}{T} + \delta S_{irr}$$

Evaporation
Is a source for S_m

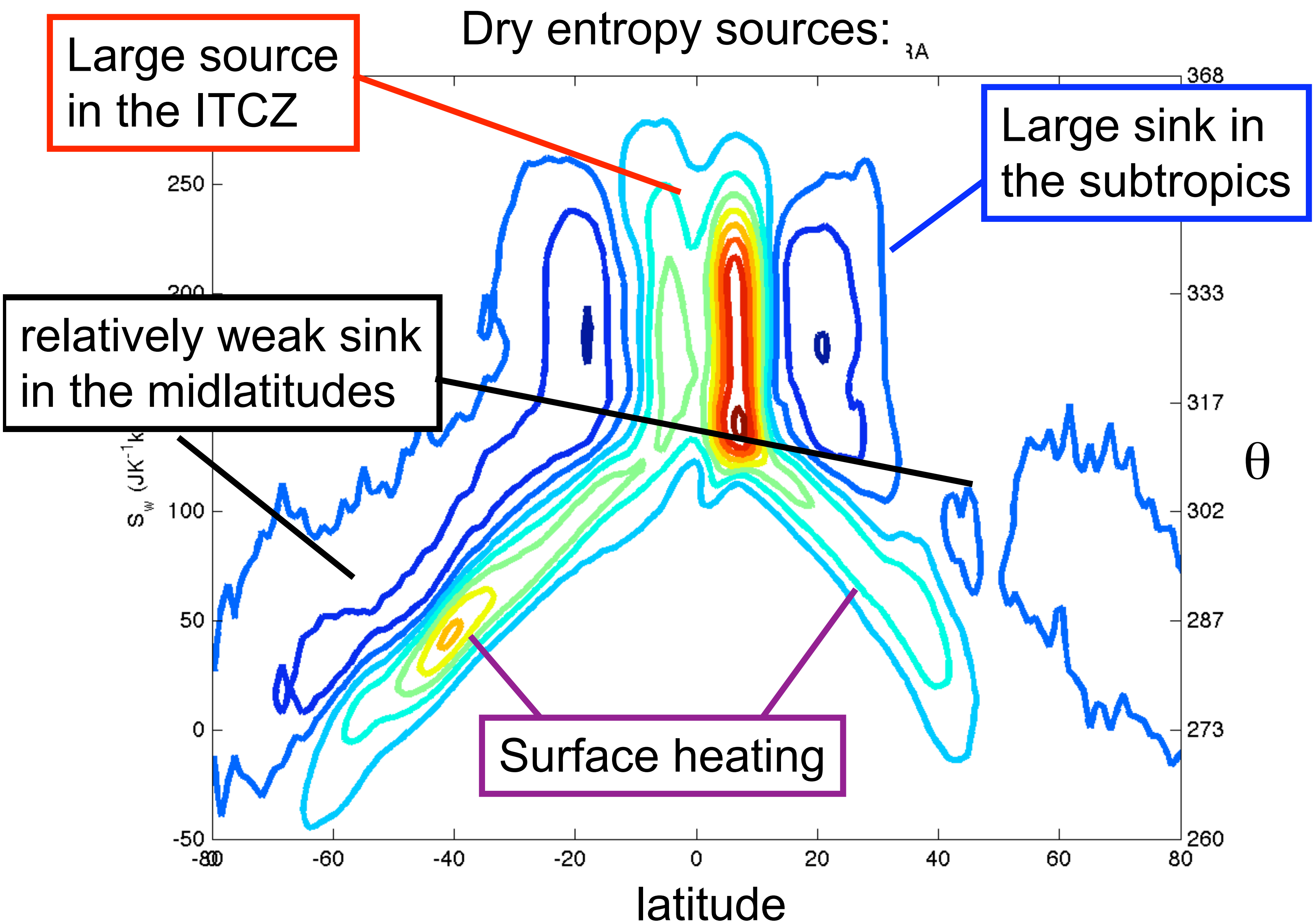
$$\frac{d}{dt}S_l = \frac{L_v}{T_0}P + \frac{Q}{T} + \delta S_{irr}$$

Precipitation
Is a source for S_l

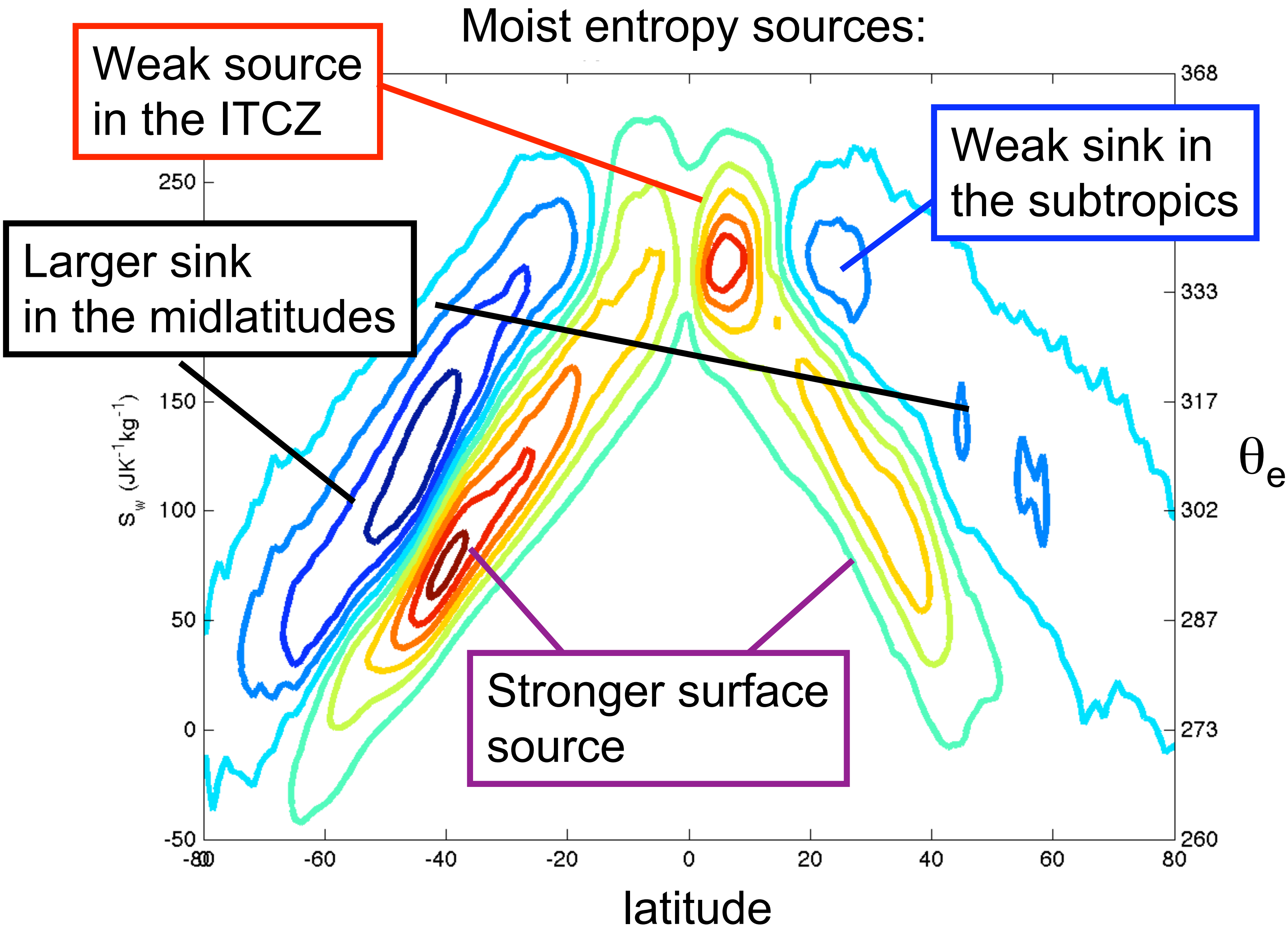
Radiation and irreversible production are the same

The right-hand side can be obtained from the streamfunction:

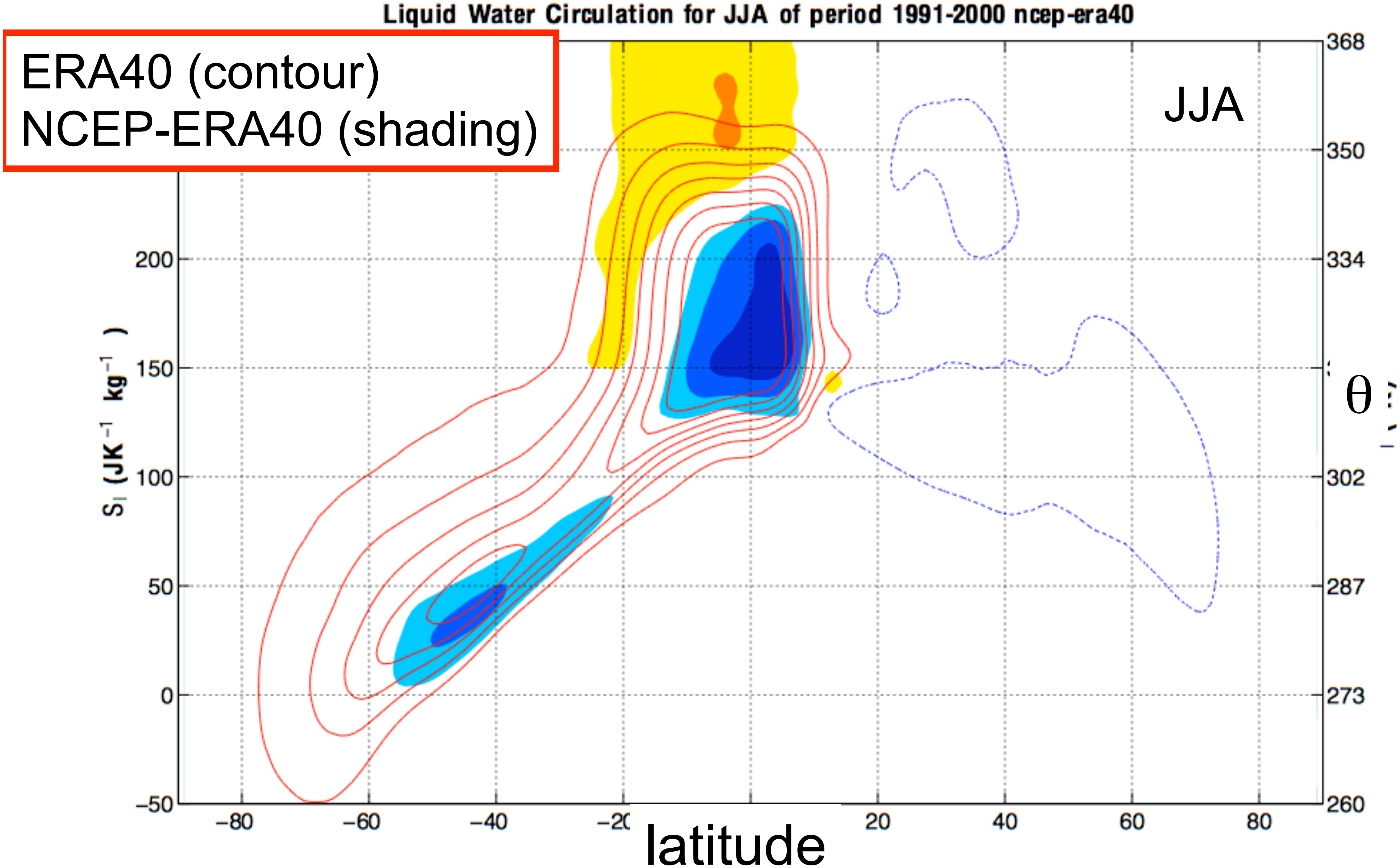
$$\overline{\rho_S \dot{S}} = \frac{\partial \Psi_S(S,\varphi)}{\partial \varphi}$$



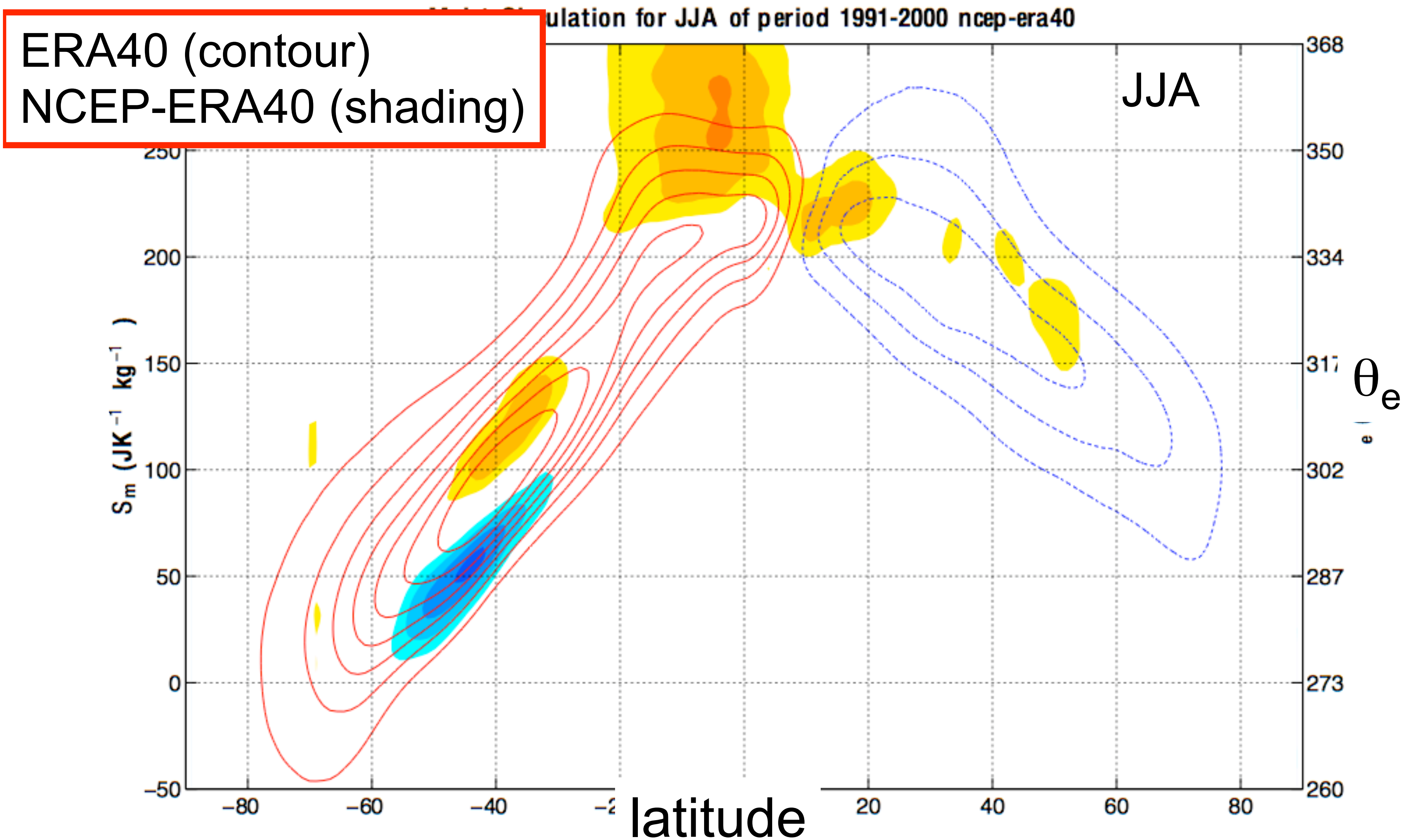
Dry entropy sources:
Large source in the ITCZ
Large sink in the subtropics
relatively weak sink in the midlatitudes
Surface heating
250
200
100
50
0
-50
368
333
317
302
287
273
260
θ
-80
-60
-40
-20
0
20
40
60
80
latitude



Moist entropy sources:
Weak source in the ITCZ
Weak sink in the subtropics
Larger sink in the midlatitudes
Stronger surface source
S_w (JK^{-1}kg^{-1})
250
150
100
50
0
-50
368
333
317
302
287
273
260
θ_e
-80
-60
-40
-20
0
20
40
60
80
latitude

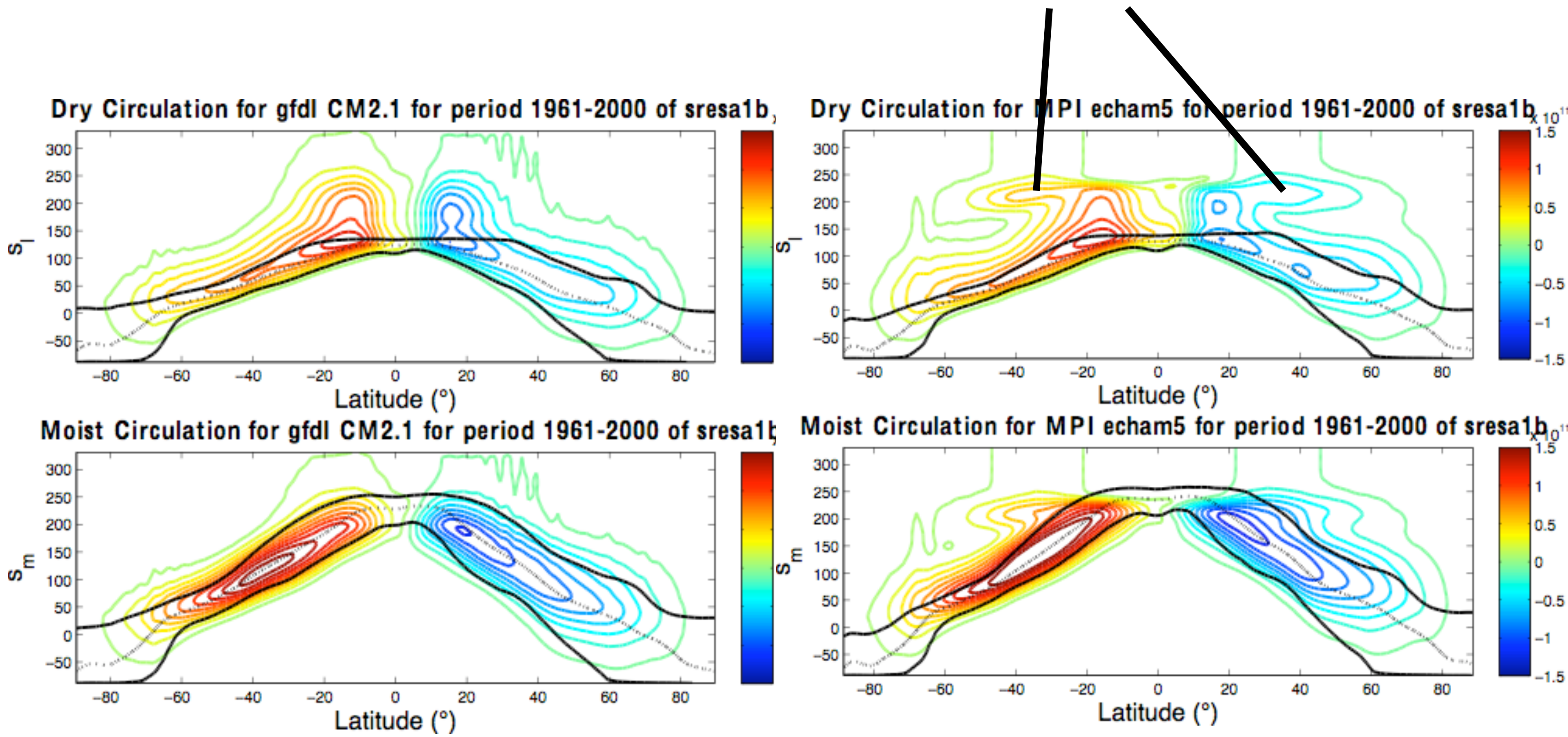


ERA40 has stronger dry circulation both in the Tropics and in the midlatitudes of the Southern hemisphere



Smaller difference between circulation: NCEP makes up for a weaker dry circulation by transporting more moist air poleward

Extra-tropical recirculation is a common feature in many GCMs



GFDL CM 2.1 **ECHAM 5**

But it is not present in neither CM2.1 nor the NCEP reanalysis

Conclusions

- Isentropic analysis can provide many insights on the dynamics of convection and the midlatitudes.
- Moist processes are important in both the tropics and the midlatitudes.
- ‘Reversible adiabatic’ approach for the circulation offers a useful first order approximation,
- But there are key processes that do not fit into that mold.

Open questions:

- What is the nature of the midlatitude ascent (convection, slantwise ascent, ‘moist conveyor belt’)?
- How does it affect the transport of chemical tracers into the upper troposphere?
- What are the impacts of irreversible processes (precipitation, mixing and re-evaporation) on the dynamics of midlatitude storms?
- What is the variability of the global circulation?