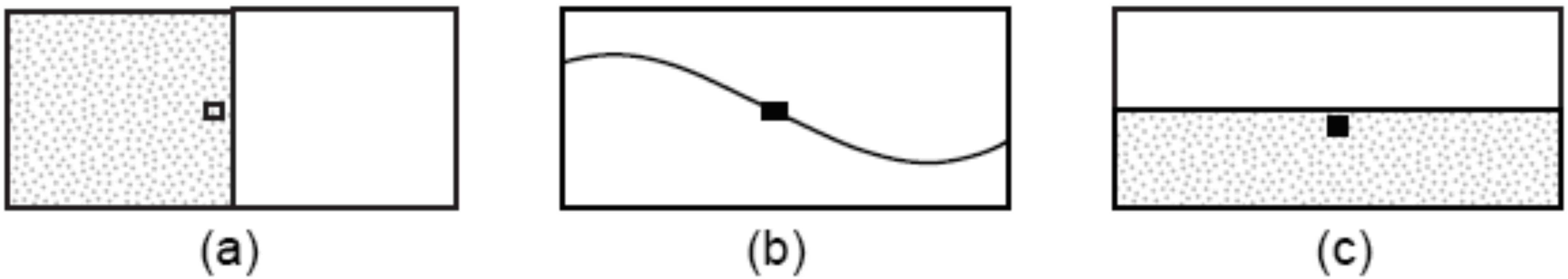
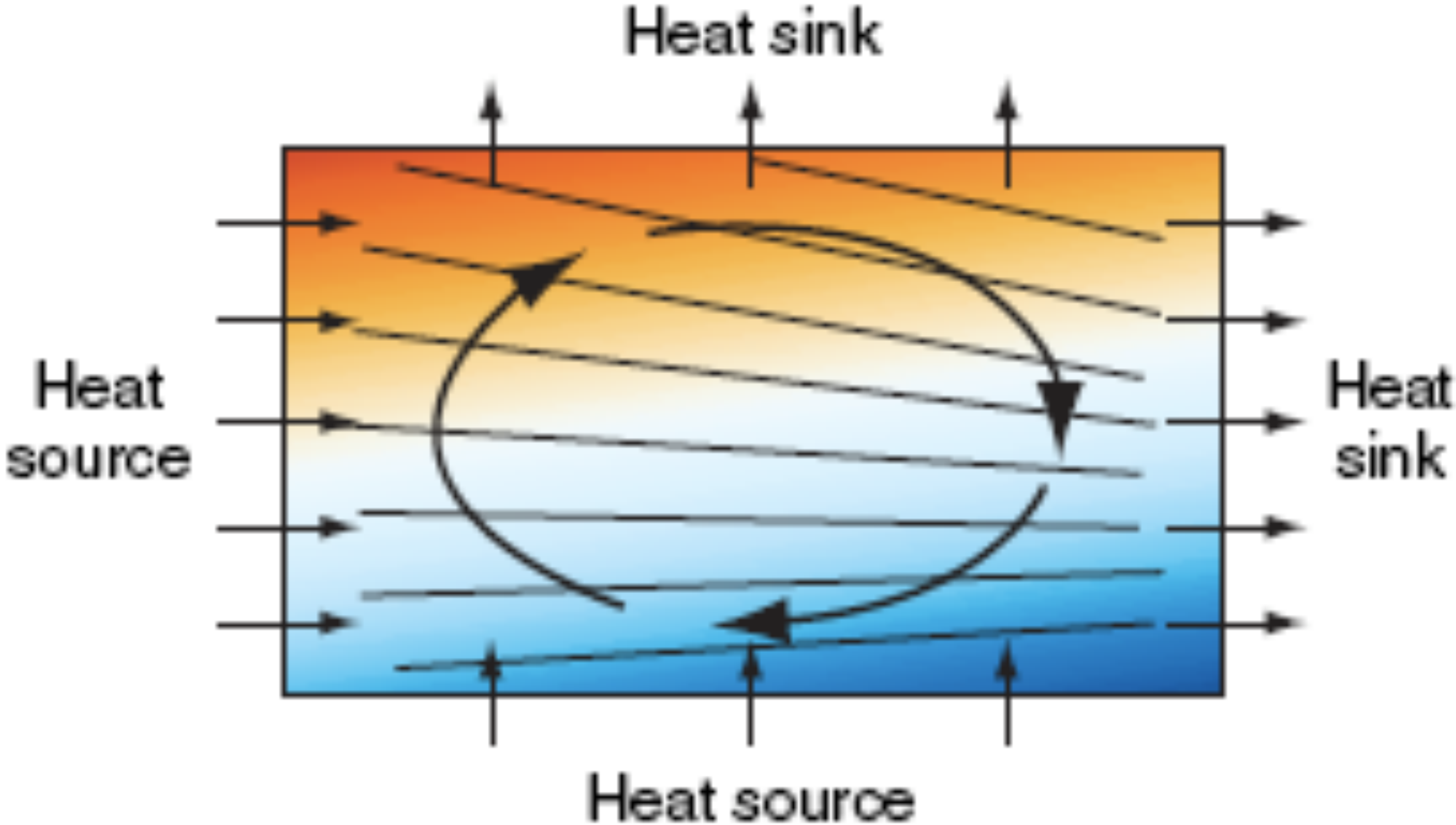
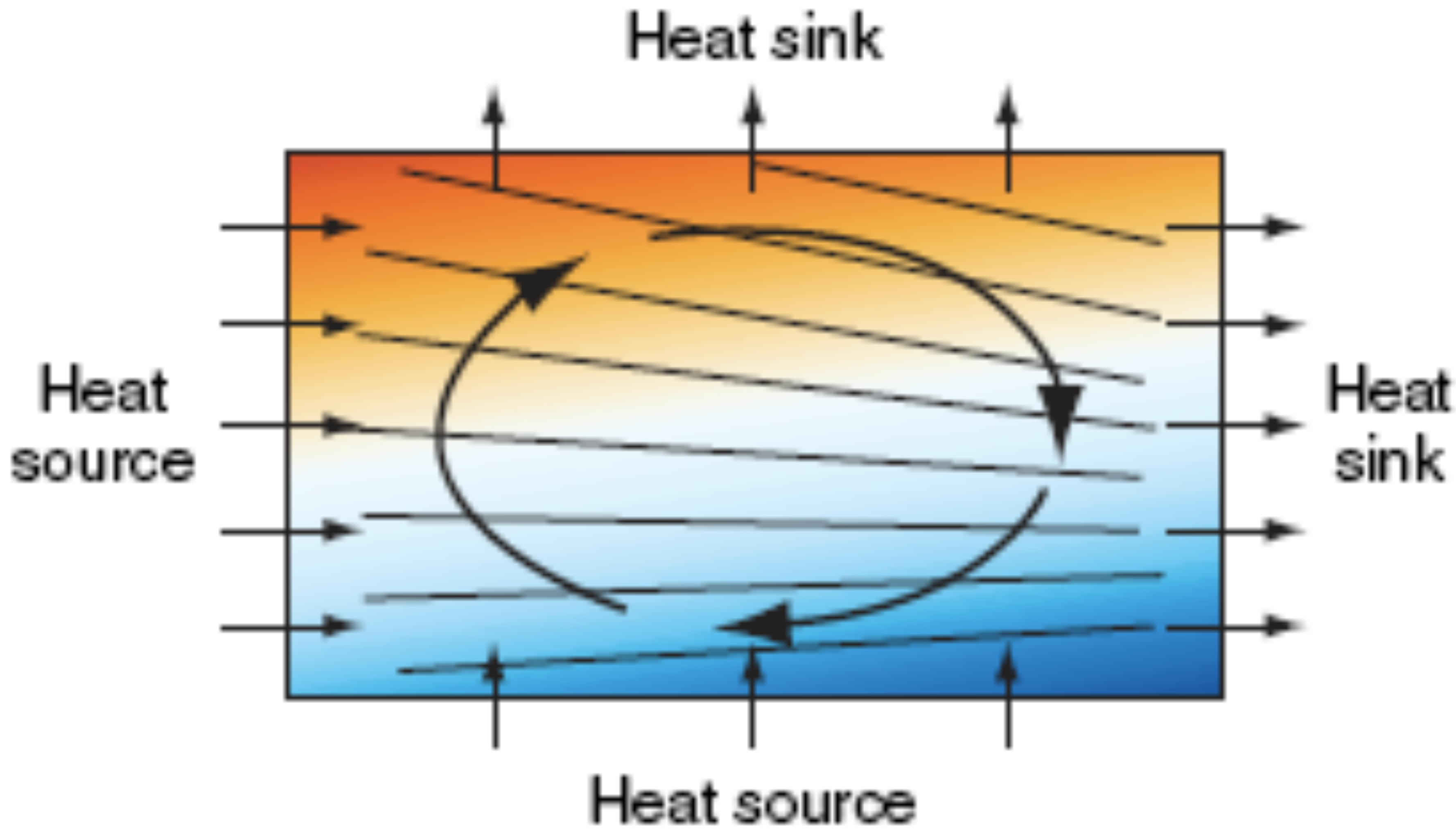
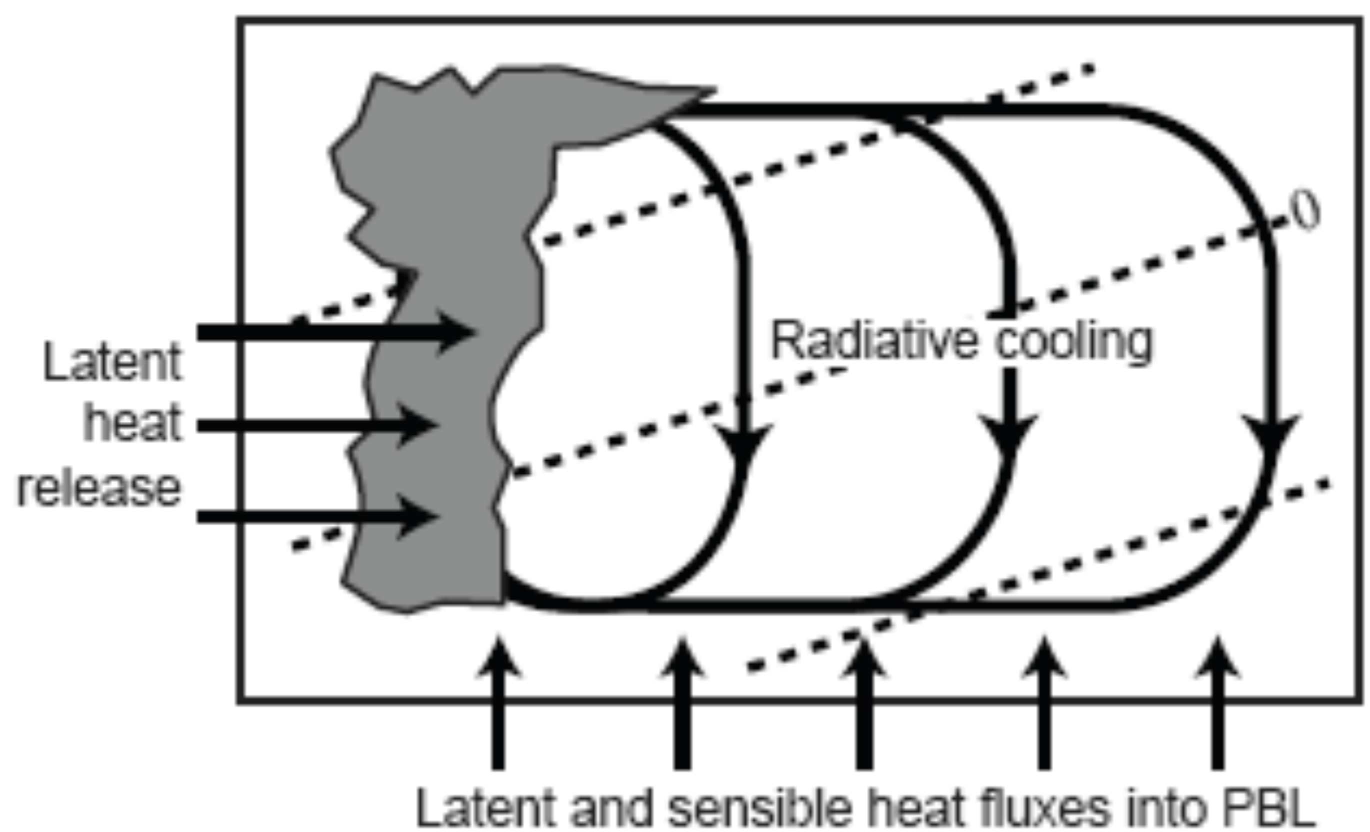
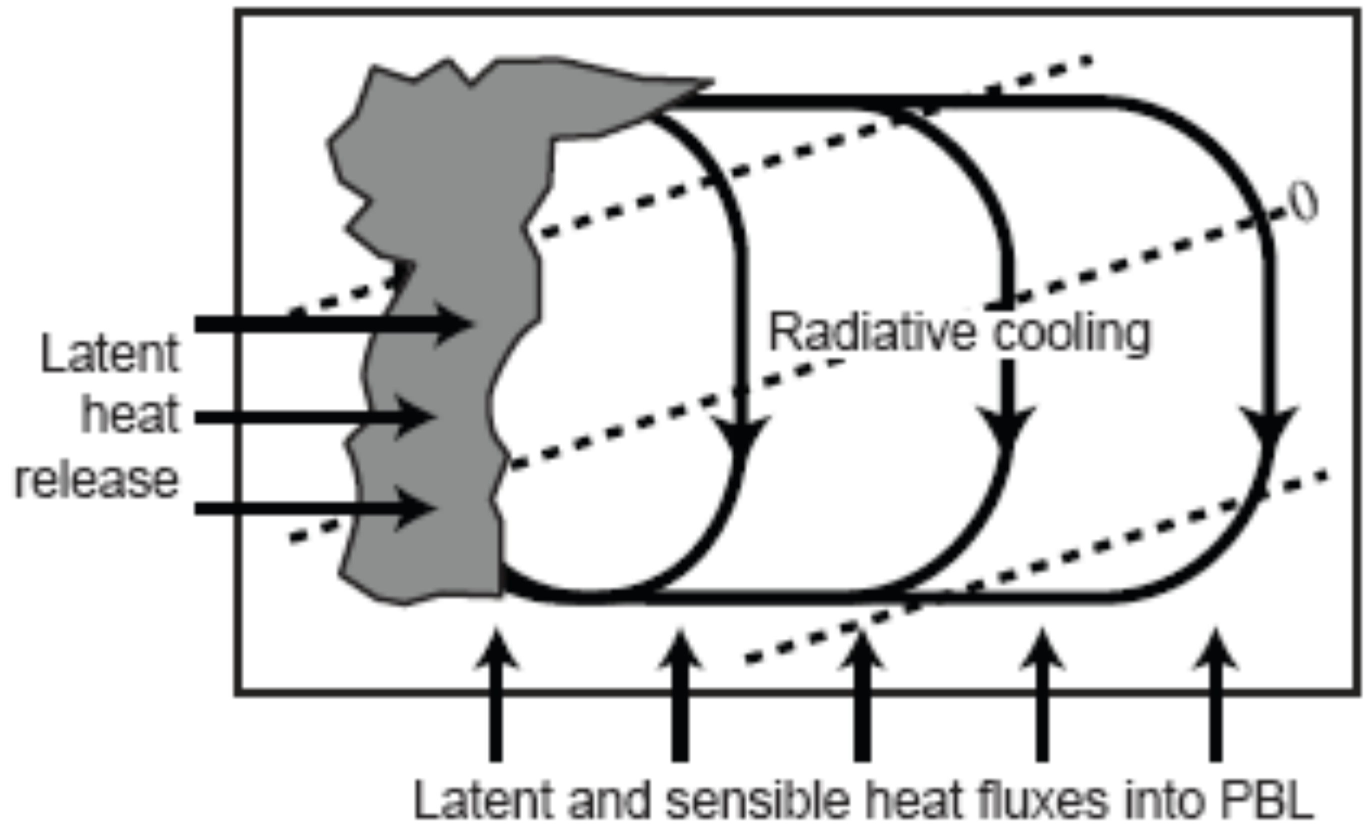

(a)
(b)
(c)

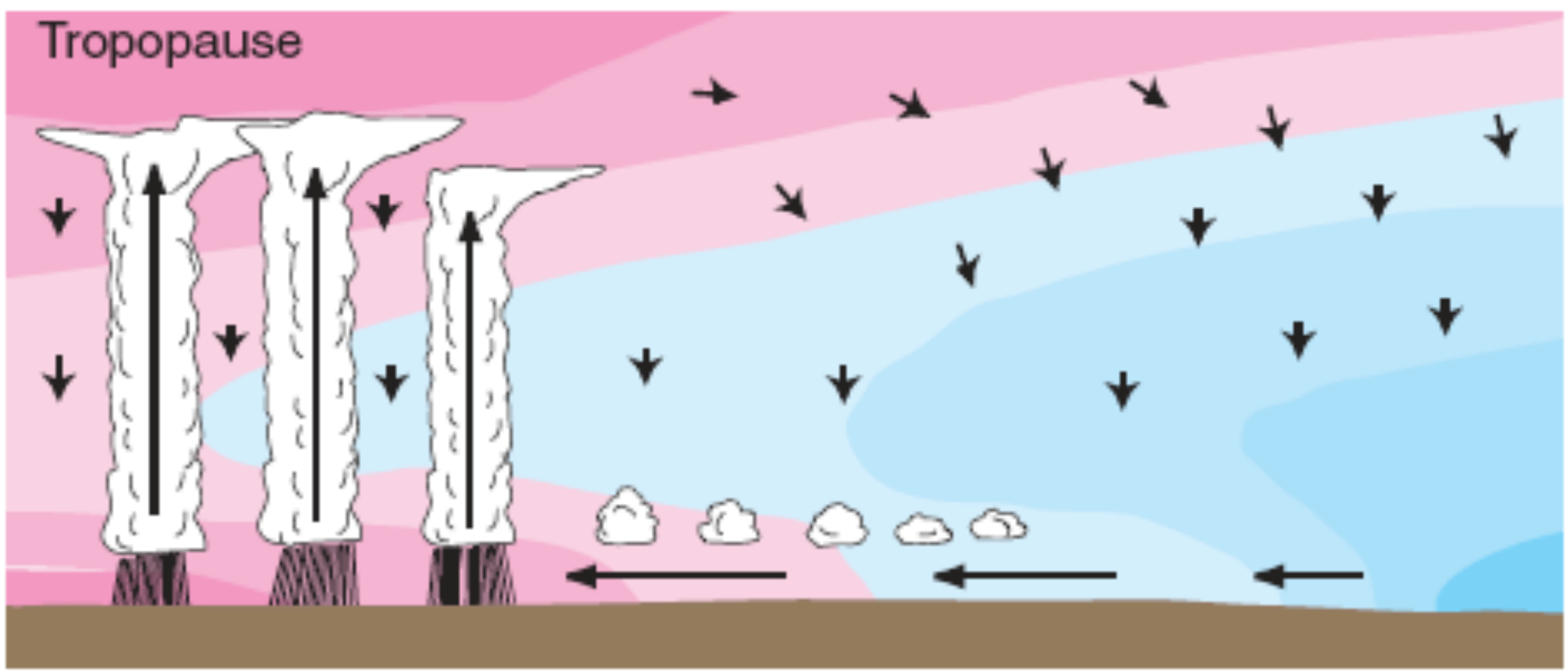

POTENTIAL ENERGY
KINETIC ENERGY
INTERNAL ENERGY


Heat sink
Heat source
Heat sink
Heat source

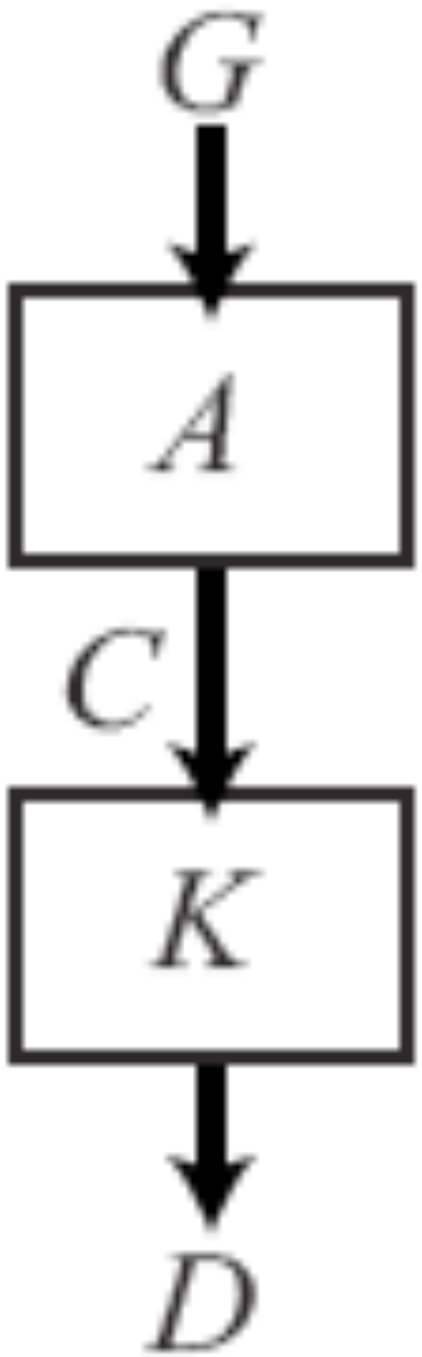

Heat sink
Heat source
Heat sink
Heat source


0
Radiative cooling
Latent heat release
Latent and sensible heat fluxes into PBL


Latent
heat
release
Radiative cooling
θ
Latent and sensible heat fluxes into PBL


Tropopause

# The kinetic energy cycle




generation of APE $\overline{Q''T''}$

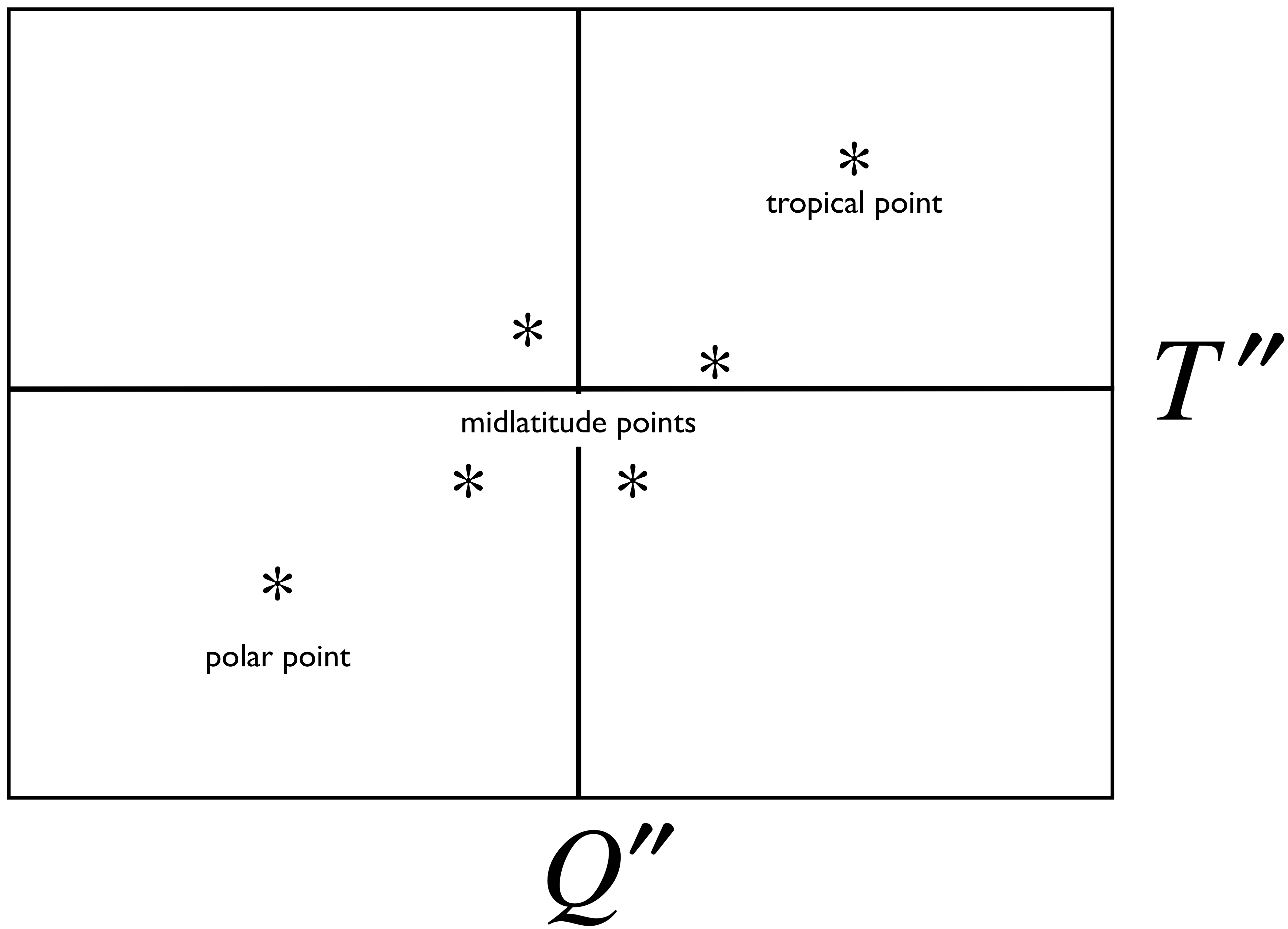
APE reservoir $\overline{T''^2}$

conversion term $-\omega T$ or $-\vec{V} \cdot \nabla\Phi$

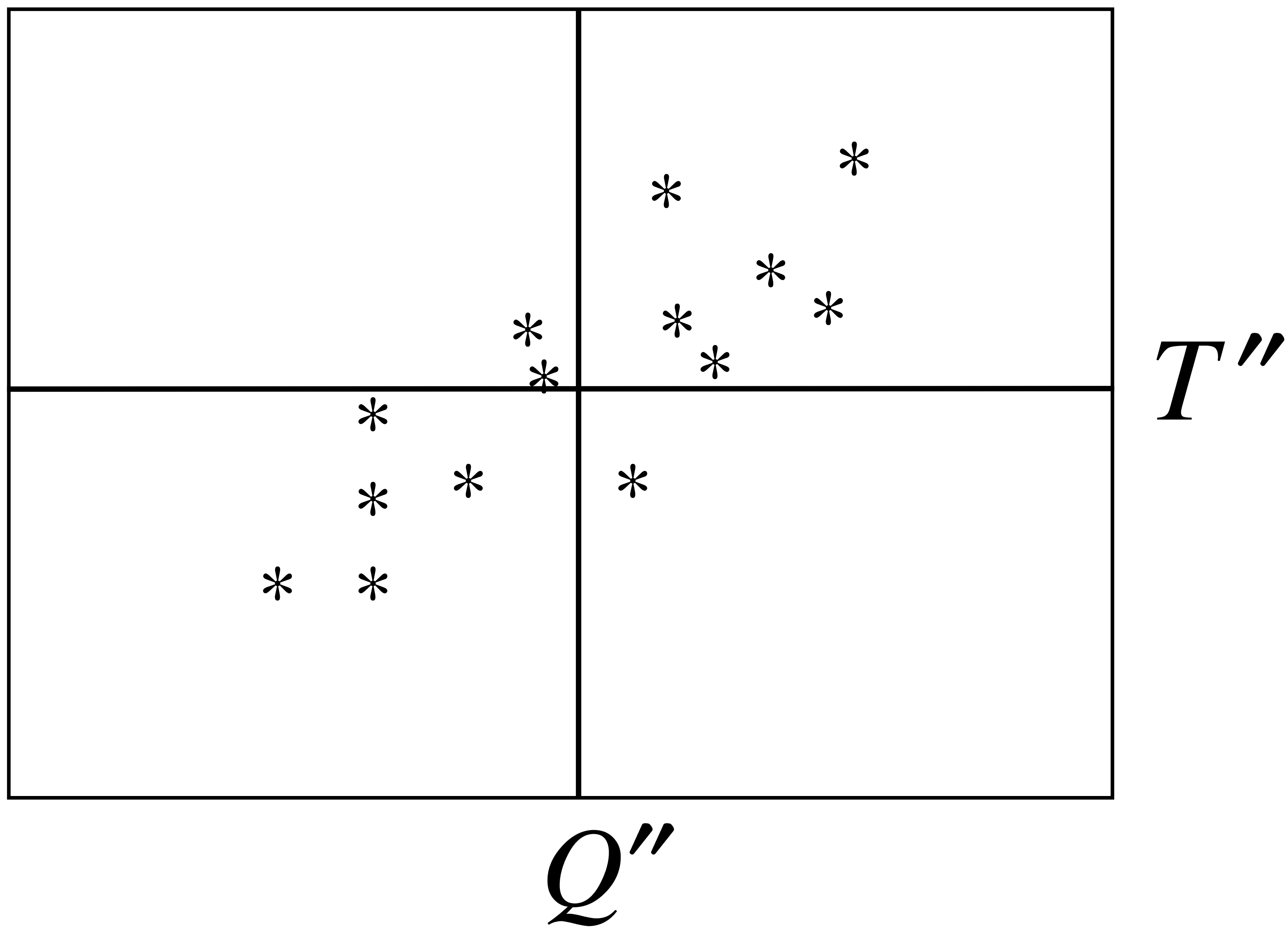
KE reservoir $\overline{V^2}$

dissipation of KE $-\vec{F} \cdot \vec{V}$

*A* and *K* involve variances; *G*, *C* and *D* involve covariances

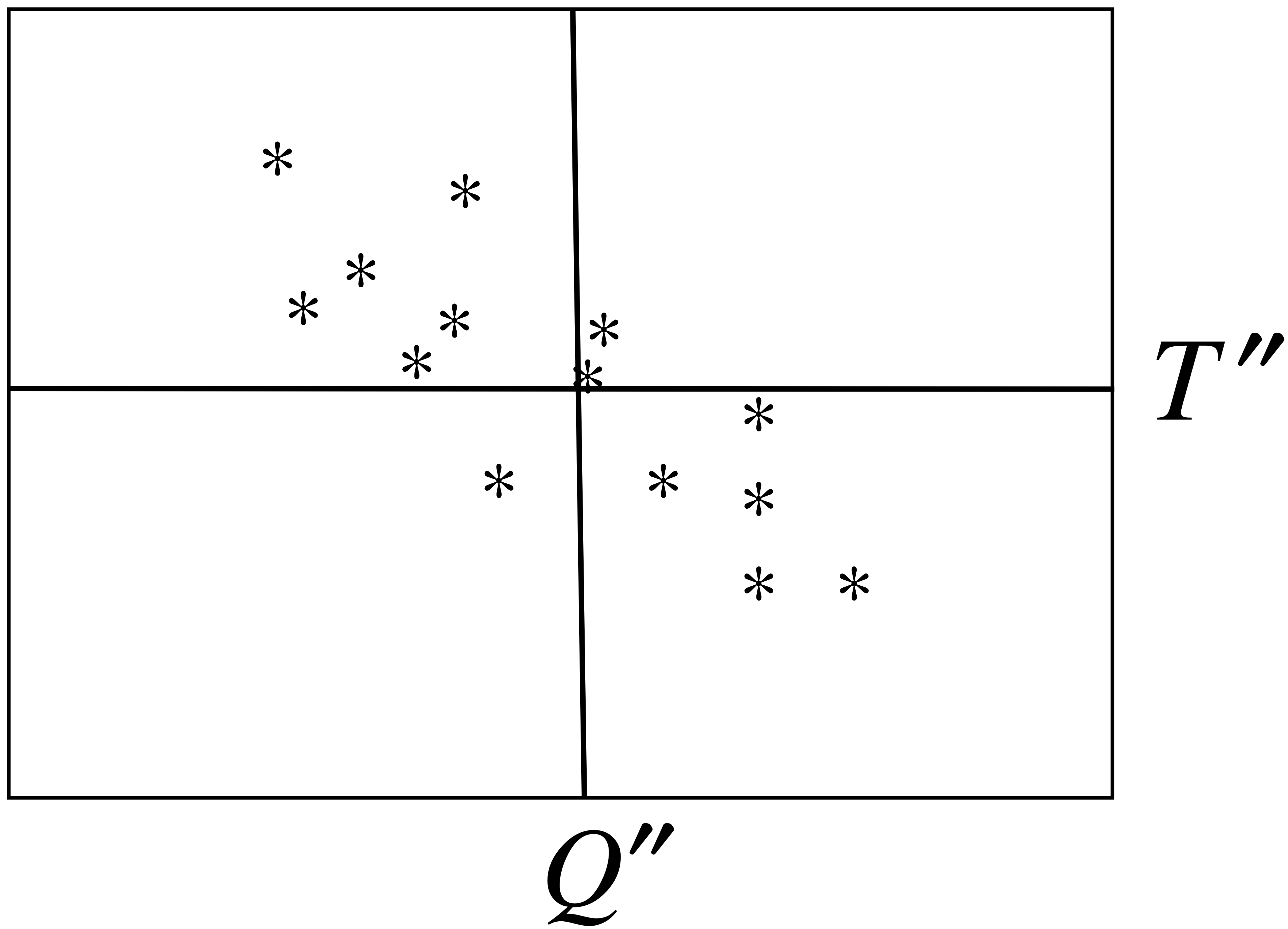

tropical point
midlatitude points
polar point
T″
Q″

sample scatter plot

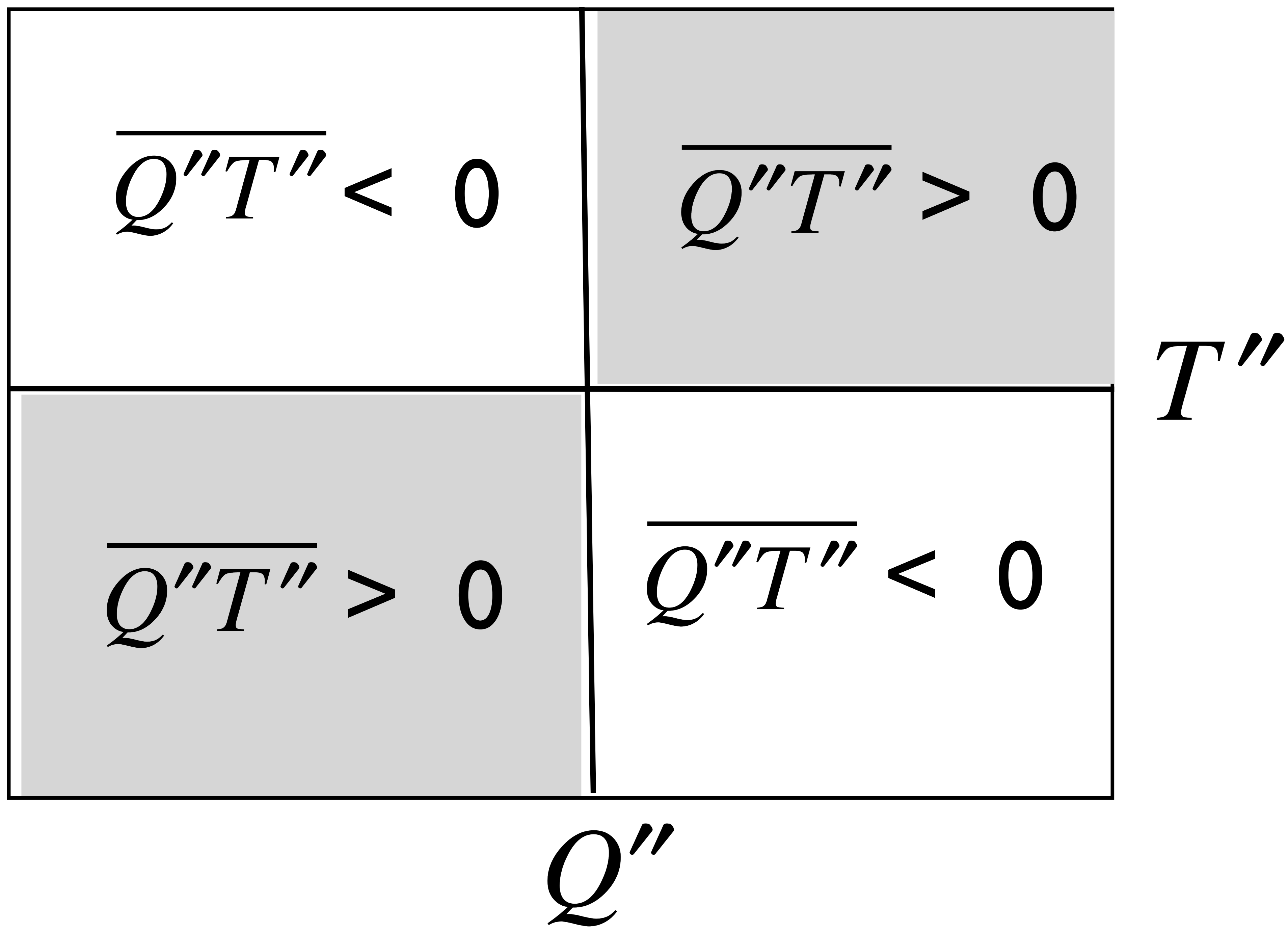



$$\overline{Q''T''} > 0$$

# sample scatter plot




$\overline{Q''T''} < 0$



$\overline{Q''T''} < 0$
$\overline{Q''T''} > 0$
$T''$
$\overline{Q''T''} > 0$
$\overline{Q''T''} < 0$
$Q''$

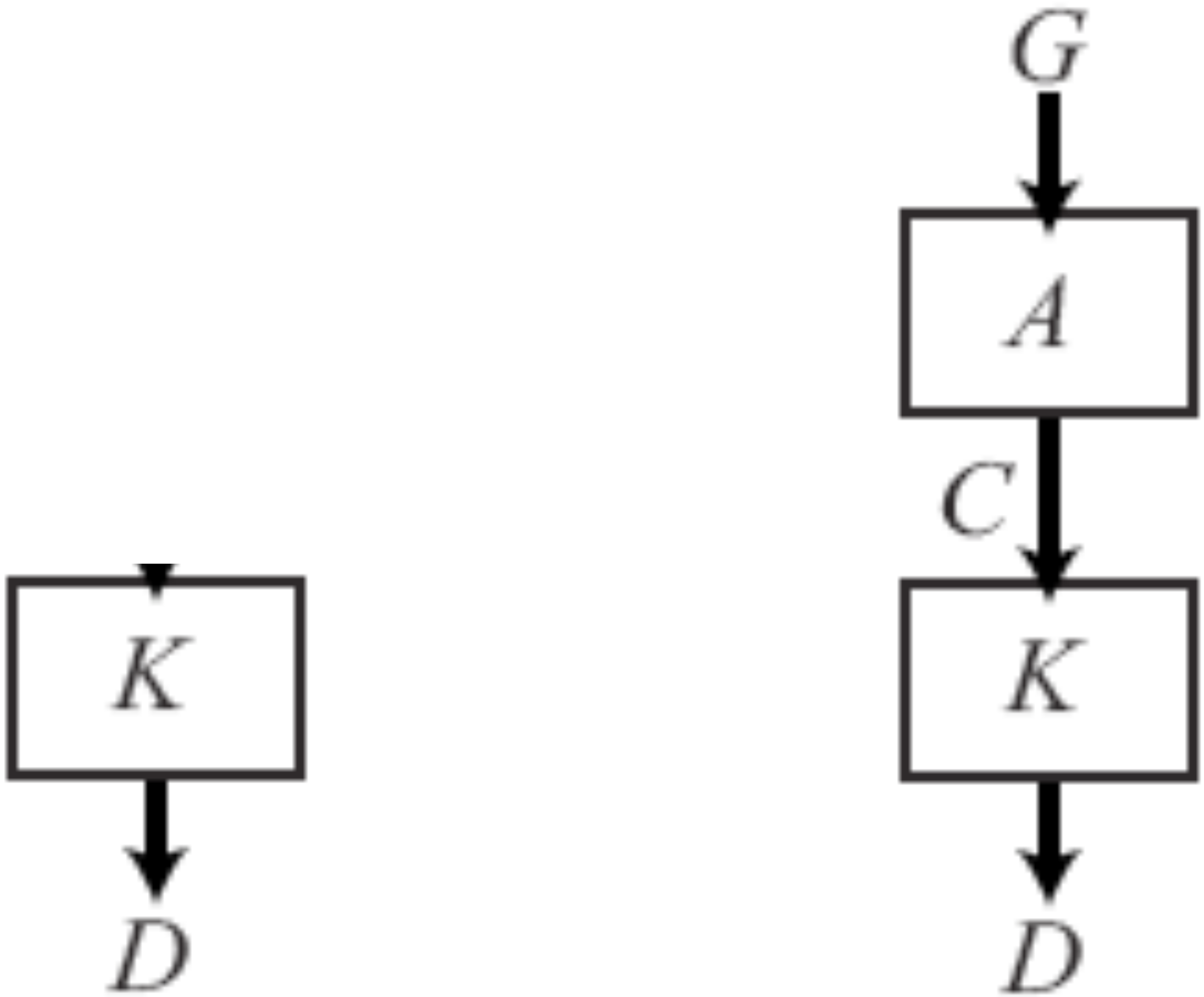
# Order of magnitude estimates of *A* and *K*

$$\overline{A} = \frac{1}{2}\int_0^{p_0} \frac{1}{\overline{\overline{T}}} \overline{\frac{T''^2}{(\Gamma_d - \overline{\Gamma})}} dp$$

$$\sim \frac{1}{2} \times \frac{15^2\ \mathrm{K}^2}{250\ \mathrm{K} \times 3.5\ \mathrm{K\ km}^{-1}} \times 10^3\ \mathrm{m\ km}^{-1} \times 10^5\ \mathrm{N\ m}^{-2} = 10^7\ \ \mathrm{J\ m}^{-2}$$

$$\overline{K}\ \sim\ \frac{1}{2} \times 15\ \mathrm{m}^2\mathrm{s}^{-2} \times \frac{10^5\ \mathrm{N\ m}^{-2}}{9.8\ \mathrm{m\ s}^{-2}} \sim\ 10^6\ \mathrm{J\ m}_{-2}$$

$$\overline{A} / \overline{K} \sim 10$$




$$\overline{K} / \overline{D} \sim days \qquad (\overline{A} + \overline{K}) / \overline{D} \sim weeks$$

# The energy conversion *A to K*

$-\omega T$ equation of state $-\omega\alpha$

$-\omega\alpha$ hypsometic equation $\omega\frac{\partial\Phi}{\partial p}$

$\omega\frac{\partial\Phi}{\partial p}$ integration by parts $-\Phi\frac{\partial\omega}{\partial p}$

$-\Phi\frac{\partial\omega}{\partial p}$ continuity equation $\Phi\, Div\, V$

$\Phi\, Div\, V$ integration by parts $-\vec{V}\cdot\nabla\Phi$

# Interpretation of the energy conversion term *A to K*

$$-\omega T$$

rising of warm air sinking of cold air
flattening of isentropes, release of A

$$-\omega\alpha$$

rising of lighter air sinking of denser air
lowering of center of mass, release of A

$$-\Phi\frac{\partial\omega}{\partial p}$$

stretching of vortex lines

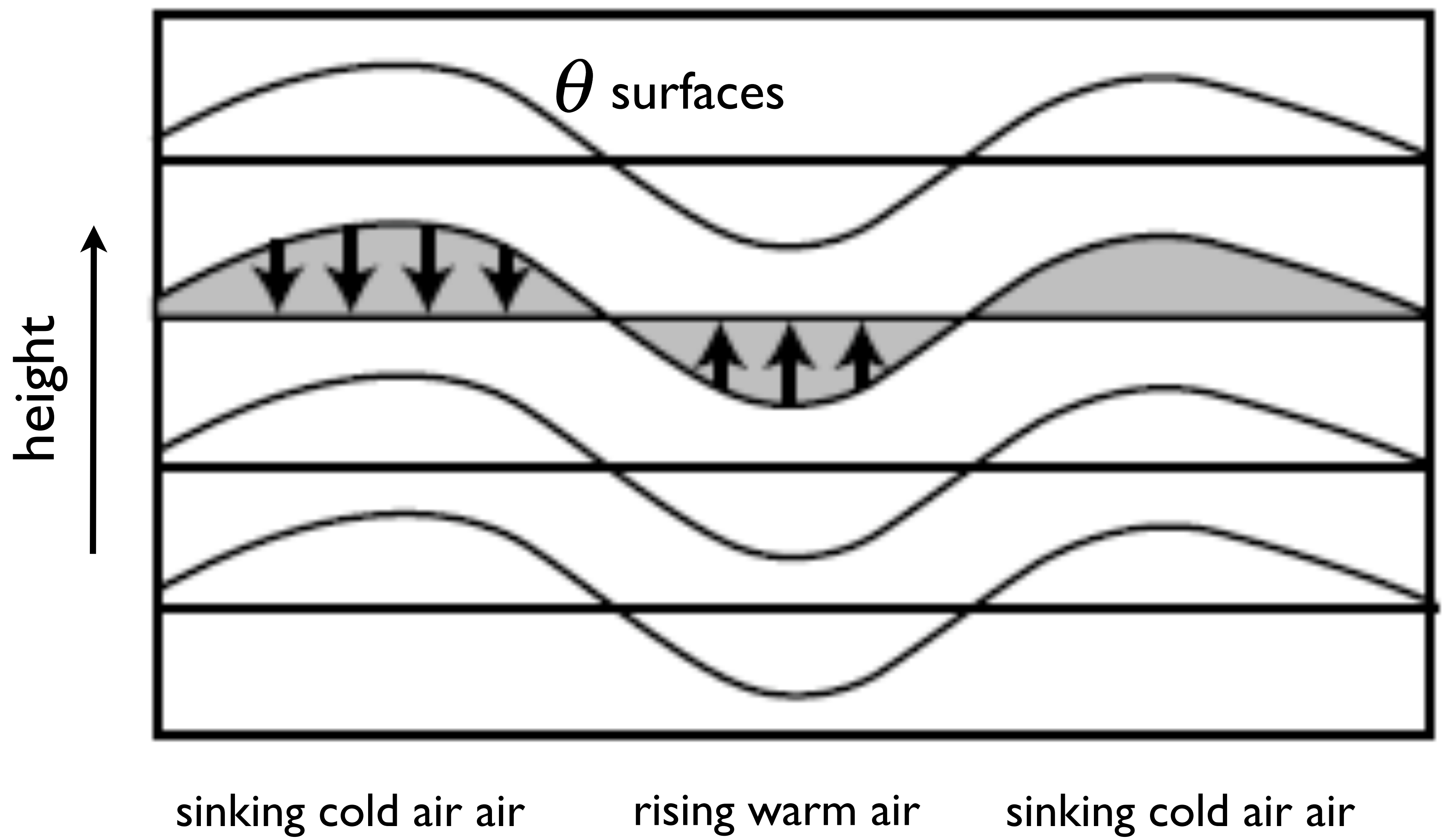
$$\Phi\, Div\; V$$

divergence out of highs, convergence into lows

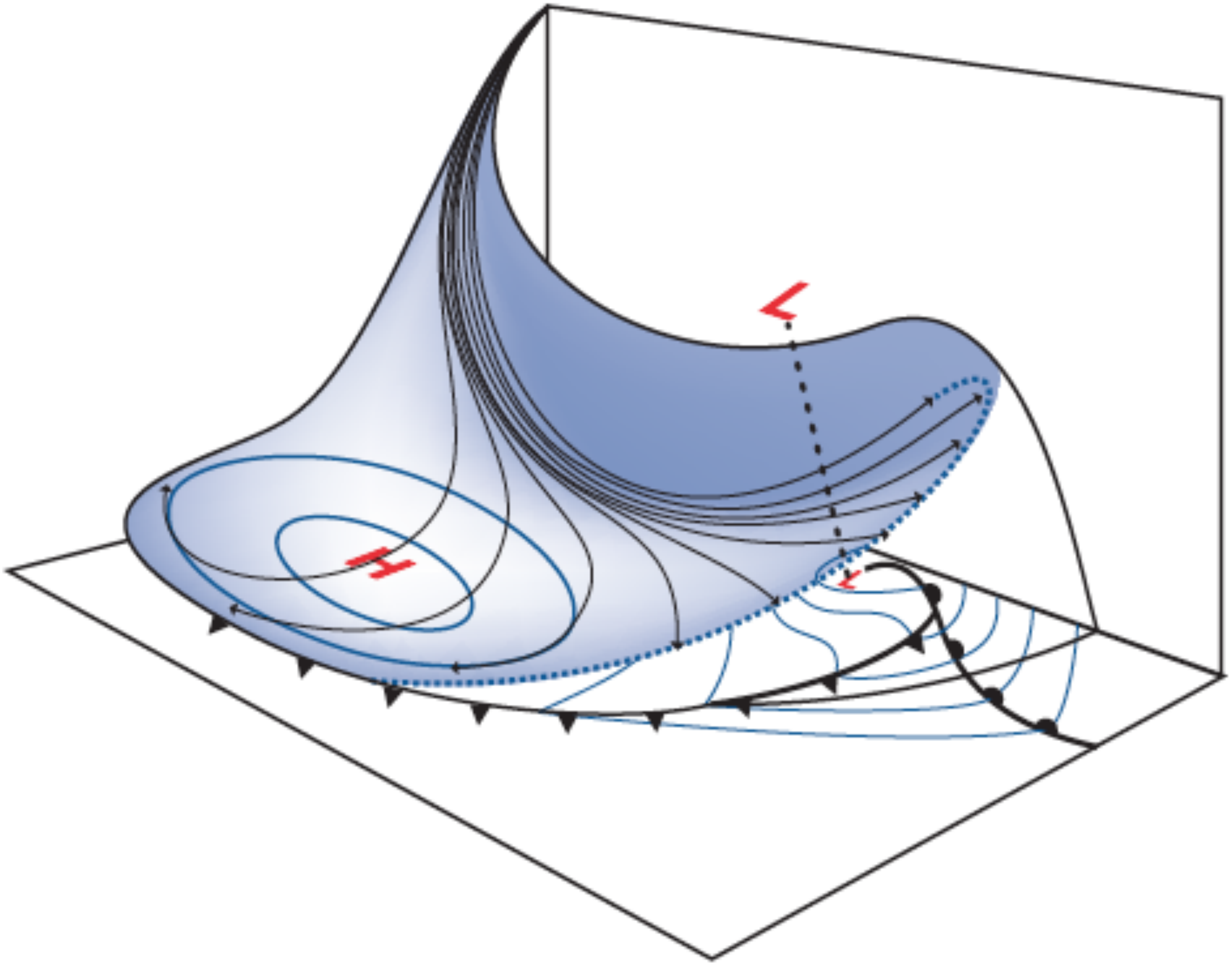
$$-\vec{V}\cdot\nabla\Phi$$

cross-isobar flow toward lower pressure
pressure field does work on air parcels

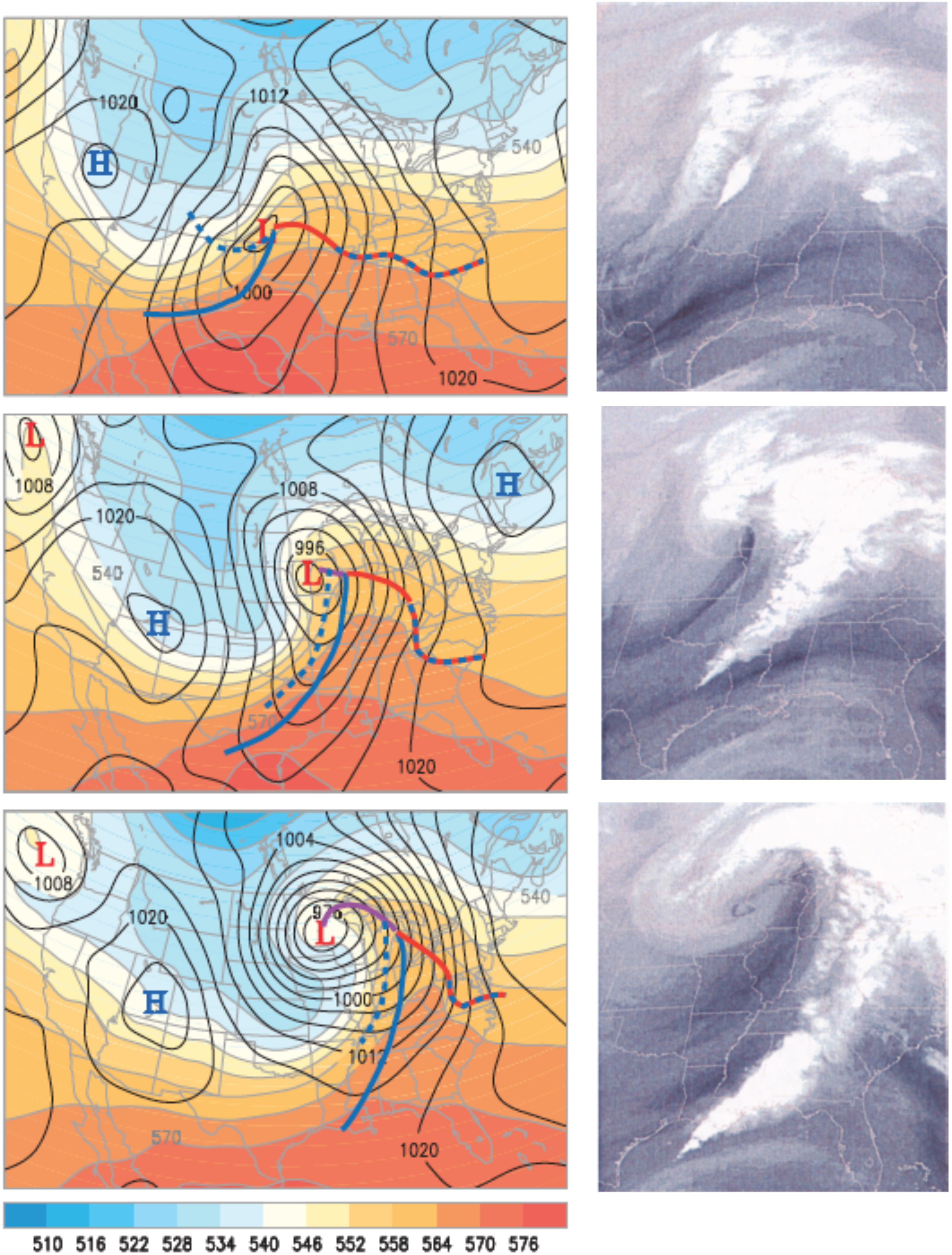
# Release of available potential energy



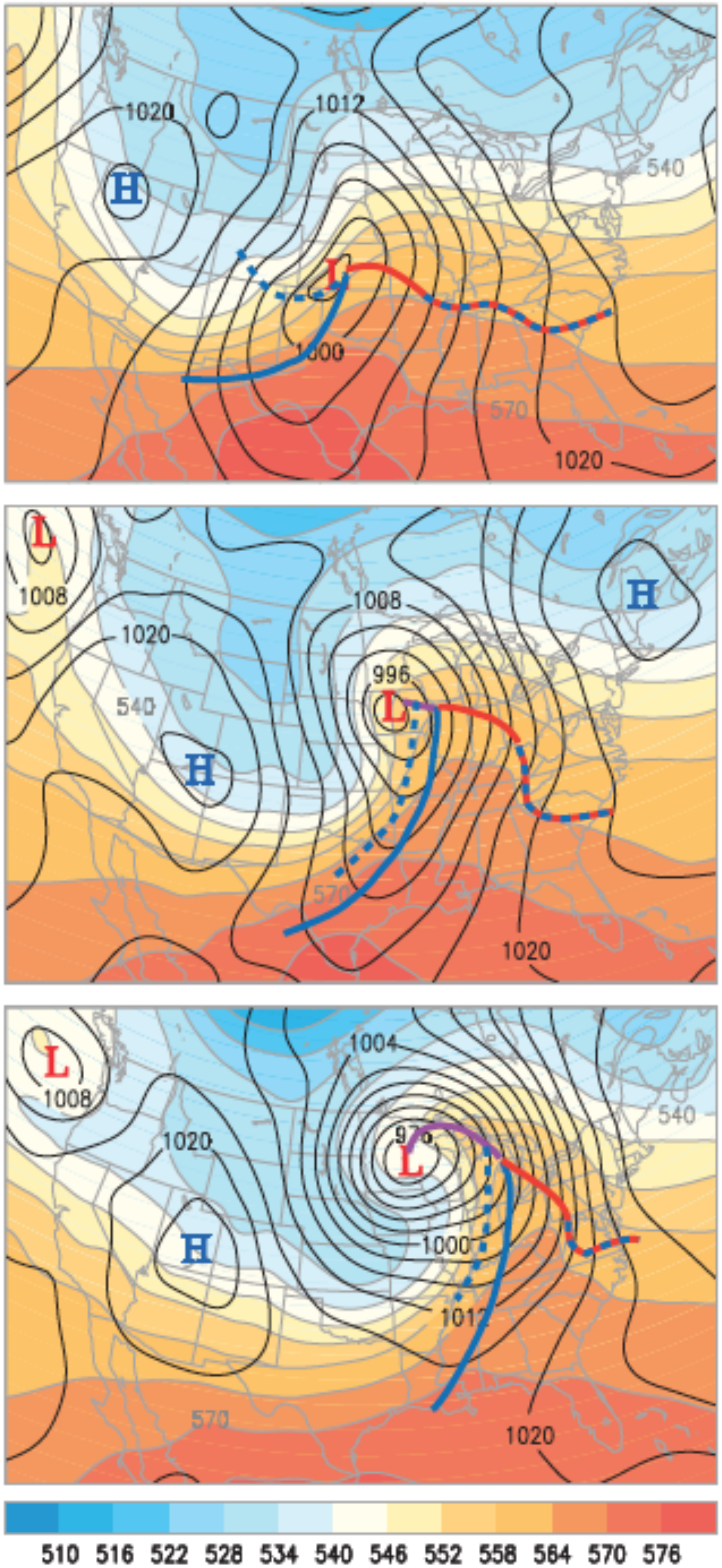

flattening of potential temperature surfaces

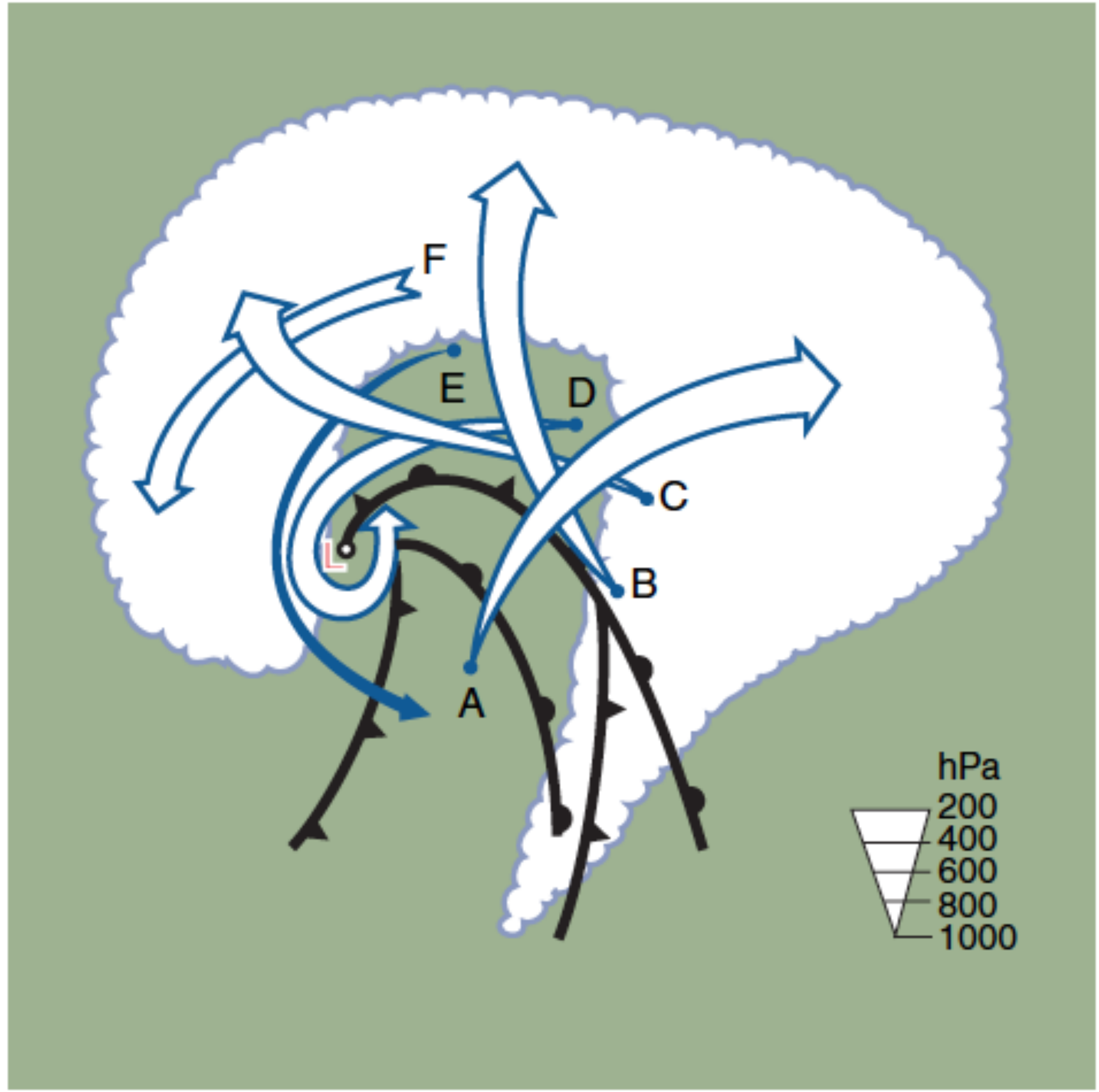



sinking cold air trajectories

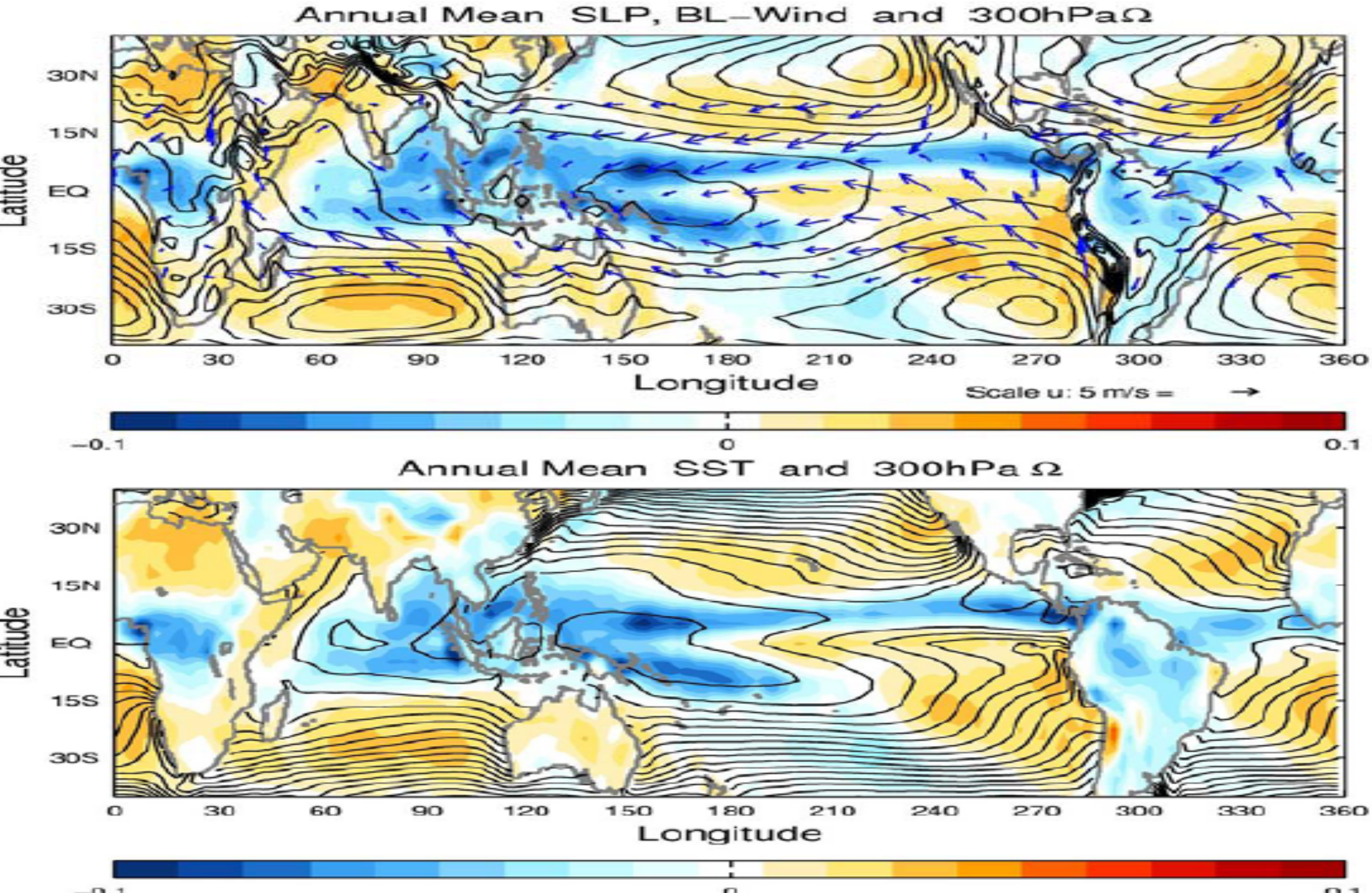



Cloud pattern in water vapor imagery shows rising of warm air ahead of cold front



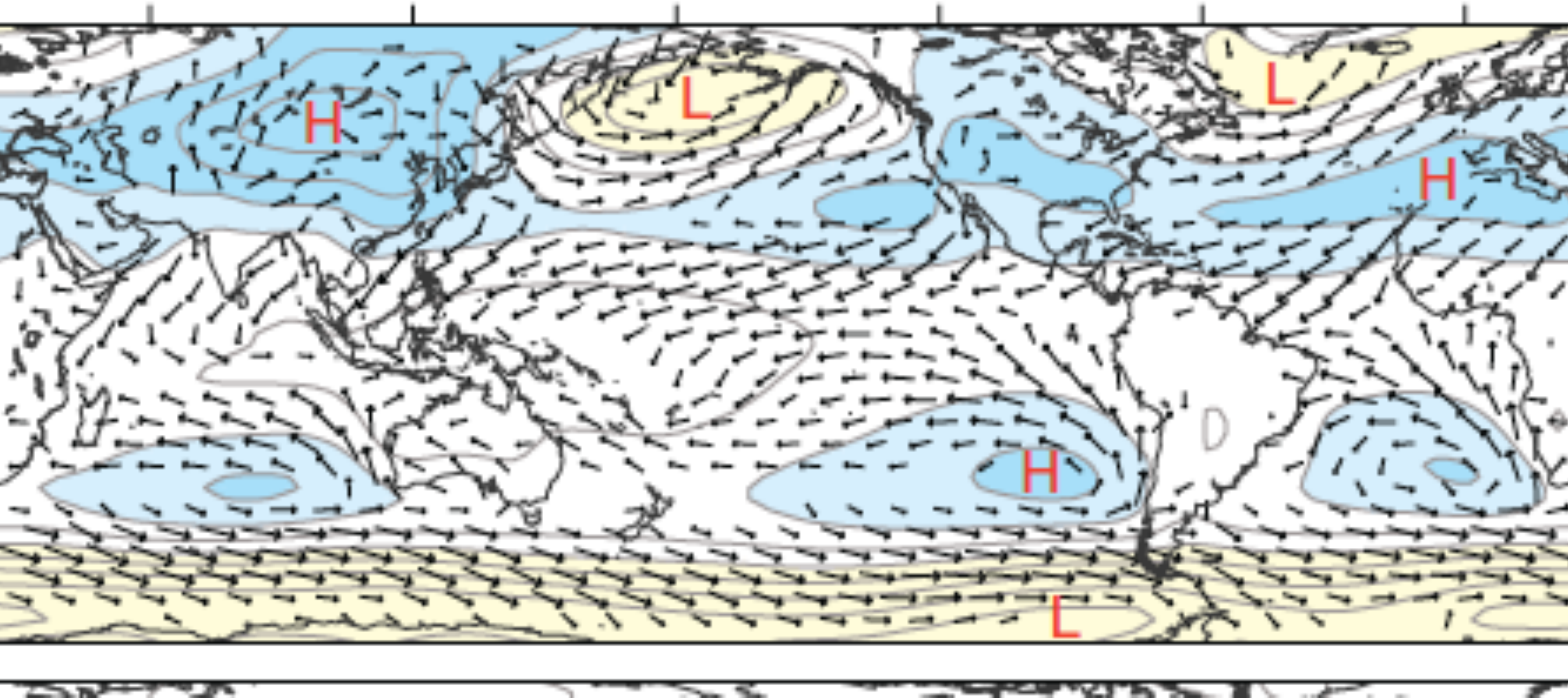

rising warm air trajectories



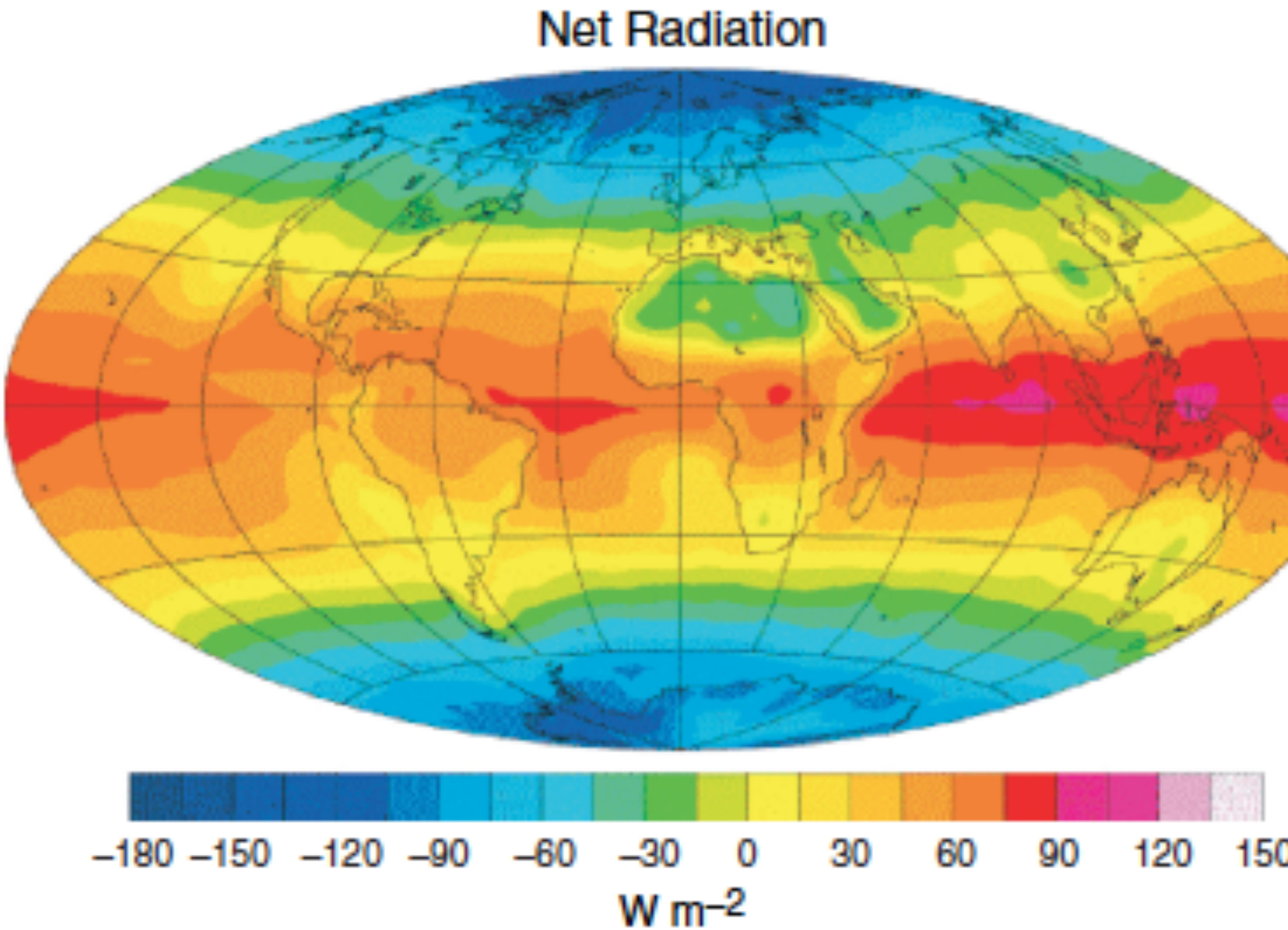

rising motion sinking motion

Ascent over warm SST; cross-isobar flow toward lower pressure

# DJF SLP and surface wind climatology NCEP




note downgradient cross-isobar flow




Note the surplus of net radiation in the tropics, where temperatures are above the global mean and a deficit poleward of 38°N/S, where temperatures are below the global mean.

Characteristics of *thermally direct* circulations

- $A$ converted to $K$
- warm air rising, cold air sinking
- cross-isobar flow toward lower pressure
- driven by horizontal gradients in diabatic heating

Examples:

- Hadley cell
- baroclinic waves
- tropical cyclones
- equatorial planetary waves
- seasonally reversing stratospheric jets

Analogy: heat engine

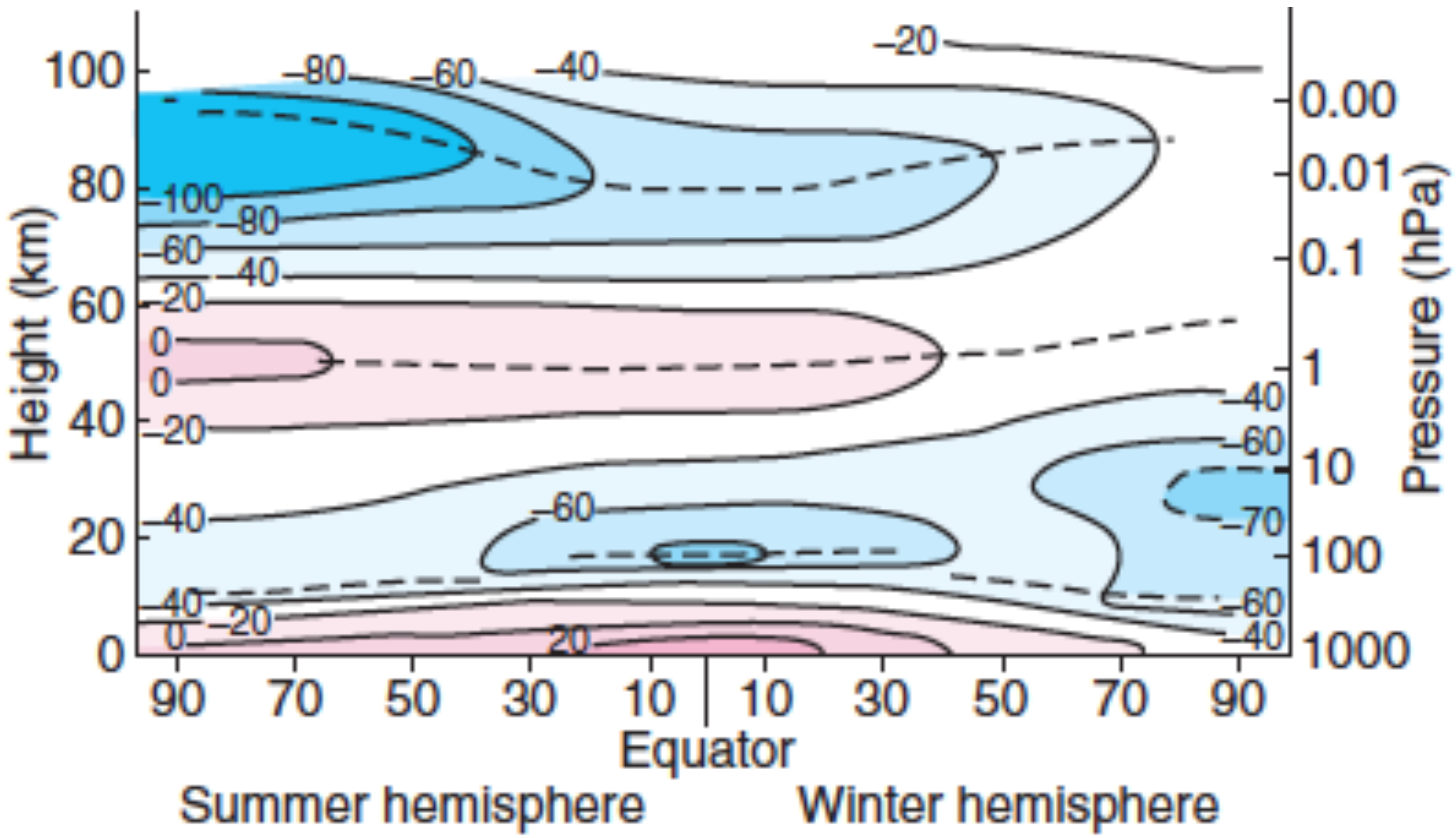
Characteristics of *thermally indirect* circulations

- *K* converted to *A*
- cold air rising, warm air sinking
- cross-isobar flow toward higher pressure
- mechanically driven
- induce horizontal gradients in diabatic heating

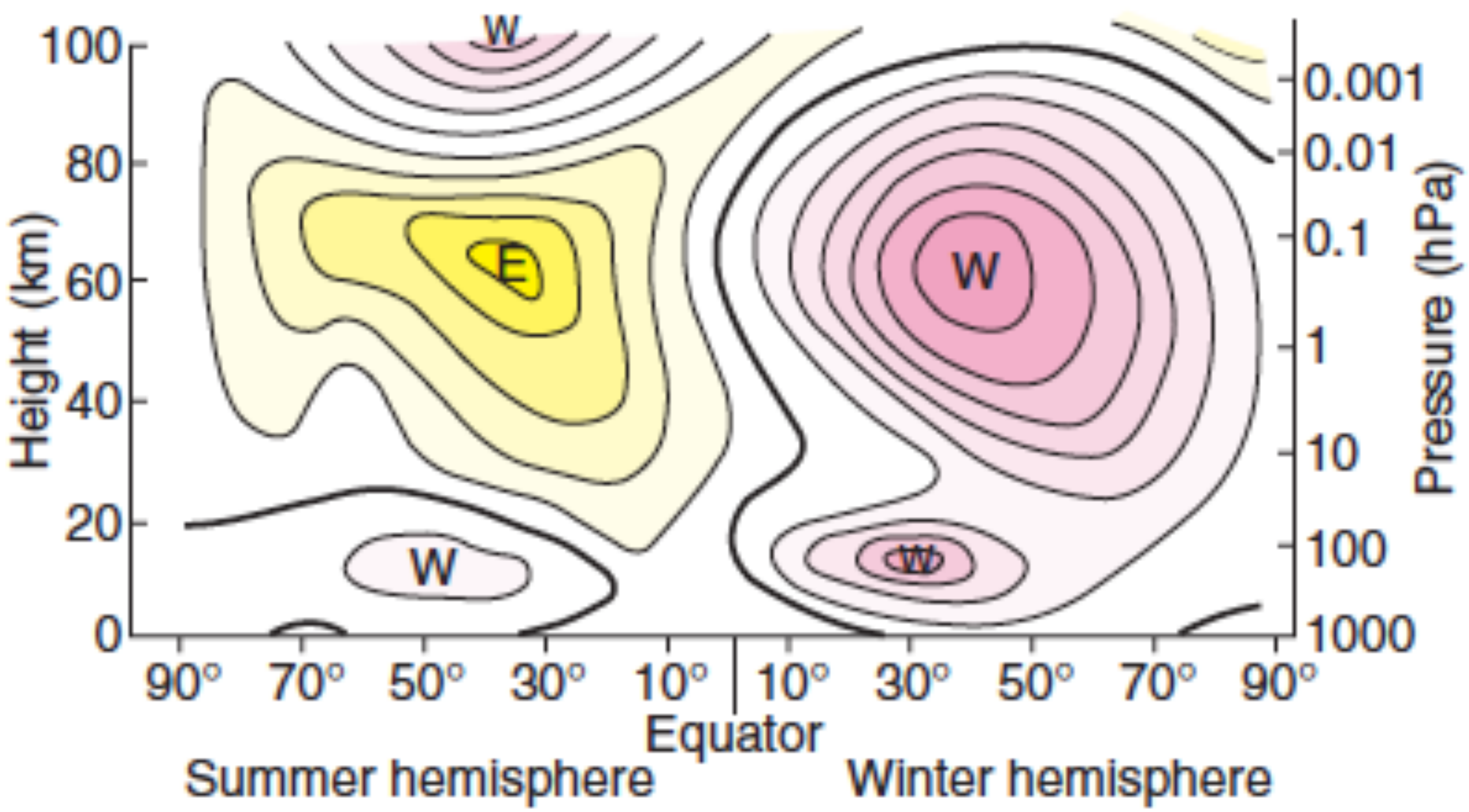
Examples:

- Brewer-Dobson circulation in cold tongue region
- Ferrell cell
- stratospheric signature of baroclinic waves
- eye of tropical cyclones
- 100 hPa *w*, *T* anomalies in equatorial planetary waves
- seasonally reversing mesospheric jets
- deserts

Analogy: refrigerator



–20
–80
–60
–40
–100
–80
–60
–40
–20
0
0
–20
–40
–60
–40
–60
–70
–40
–20
0
20
–60
–40
Height (km)
Pressure (hPa)
0.00
0.01
0.1
1
10
100
1000
100
80
60
40
20
0
90
70
50
30
10
10
30
50
70
90
Equator
Summer hemisphere
Winter hemisphere

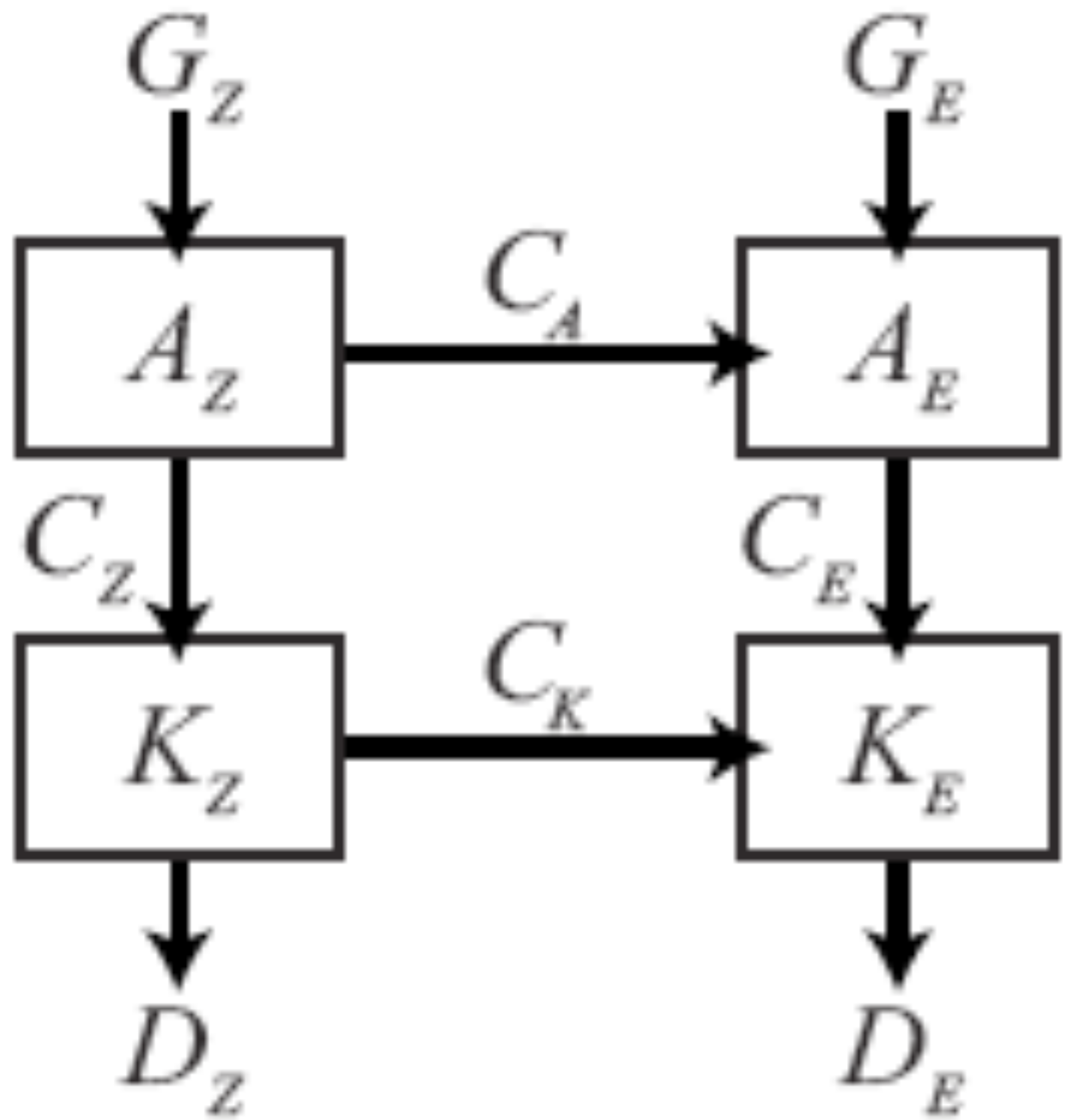



W
E
W
W
W
Height (km)
Pressure (hPa)
100
80
60
40
20
0
0.001
0.01
0.1
1
10
100
1000
90°
70°
50°
30°
10°
10°
30°
50°
70°
90°
Equator
Summer hemisphere
Winter hemisphere

## Some caveats

- more complicated when applied to an open system
- ignores external modes
- oversimplifies processes at bottom boundary
- static stability treated as invariant in space / time

# looking ahead




zonally symmetric flow

eddies