Conservation and boundary fluxes in CAM

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Part I
Energy

Ensuring energy conservation

We need to enforce this equation:

$$\frac{d\epsilon}{dt} = \alpha\frac{dp}{dt} - (\alpha\nabla p + \nabla\Phi)\cdot v + \alpha F \cdot v + Q\ , \tag{8}$$

where $\epsilon := \frac{1}{2}v^2 + c_v T + \alpha p$.

Ensuring energy conservation

We enforce this equation:

$$\frac{d\epsilon}{dt} = \alpha\frac{dp}{dt} - \overset{\text{dynamics}}{\boxed{(\alpha\nabla p + \nabla\Phi)\cdot v}} + \alpha F\cdot v + Q\ , \tag{8}$$

where $\epsilon := \frac{1}{2}v^2 + c_v T + \alpha p.$

Ensuring energy conservation

We enforce this equation:

$$\frac{d\epsilon}{dt} = \alpha\frac{dp}{dt} - \overset{\text{dynamics}}{\boxed{(\alpha\nabla p + \nabla\Phi)\cdot v}} + \overset{\text{physics}}{\boxed{\alpha F\cdot v + Q}}\,, \qquad (8)$$

where $\epsilon := \frac{1}{2}v^2 + c_vT + \alpha p.$

Ensuring energy conservation

We enforce this equation:

$$\frac{d\epsilon}{dt} = \overset{\text{adjustment}}{\boxed{\alpha \frac{dp}{dt}}} - \overset{\text{dynamics}}{\boxed{(\alpha \nabla p + \nabla \Phi) \cdot v}} + \overset{\text{physics}}{\boxed{\alpha F \cdot v + Q}}, \tag{8}$$

where $\epsilon := \frac{1}{2} v^2 + c_v T + \alpha p.$

Ensuring energy conservation

We enforce this equation:

$$\frac{d\epsilon}{dt} = \overset{\text{adjustment}}{\boxed{\alpha \frac{dp}{dt}}} - \overset{\text{dynamics}}{\boxed{(\alpha \nabla p + \nabla \Phi) \cdot v}} + \overset{\text{physics}}{\boxed{\alpha F \cdot v + Q}}\,, \tag{8}$$

where $\epsilon := \frac{1}{2} v^2 + c_v T + \alpha p.$

CAM-FV's “energy formulation error”
Williamson et al. 2015, submitted to J.Clim.

This talk

Ensuring energy conservation

We enforce this equation:

$$\frac{d\epsilon}{dt} = \overset{\text{adjustment}}{\boxed{\alpha\frac{dp}{dt}}} - \overset{\text{dynamics}}{\boxed{(\alpha\nabla p + \nabla\Phi)\cdot v}} + \overset{\text{physics}}{\boxed{\alpha F\cdot v + Q}}, \tag{8}$$

where $\epsilon := \frac{1}{2}v^2 + c_v T + \alpha p.$

Implied conservation law:

$$\begin{aligned}\partial_t \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, u_m \quad &= \quad -\int_{\mathcal{A}} dS \, p_t \, \partial_t \left[\Phi(\eta_t)\right] - \oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V \\ &\quad + \int_{\mathcal{A}} dS \, \dot{h}_s + \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \left(\alpha F\cdot v + Q + \dot{q} h_m\right) . \end{aligned} \tag{15}$$

where $u_m := \frac{1}{2}v^2 + c_v T + \Phi + Lq$ and $h_m = u_m + \alpha p.$

u_m is the total (kinetic + thermal + latent + potential) energy per unit mass of air.

$\partial_t \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, u_m \quad =$	**change in total energy**
$= \quad -\int_{\mathcal{A}} dS \, p_t \, \partial_t \left[\Phi(\eta_t)\right]$	**lid work**
$-\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$	**enthalpy flux divergence**
$+\int_{\mathcal{A}} dS \, \dot{h}_s$	**surface fluxes**
$+\int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$	**diabatic sources**
$+\int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$	**material change**

$$\partial_t \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, u_m \quad =$$

change in total energy

$$= \quad - \int_{\mathcal{A}} dS \, p_t \, \partial_t \left[\Phi(\eta_t) \right]$$

lid work

dynamics

$$- \oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \left(\alpha F \cdot v + Q \right)$$

diabatic sources

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \; \dot{q} h_m$$

material change

$$\partial_t \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, u_m \quad =$$

change in total energy

$$= \quad -\int_{\mathcal{A}} dS \, p_t \, \partial_t \left[\Phi(\eta_t)\right]$$

lid work

dynamics

$$-\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+\int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

physics

$$+\int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$$

diabatic sources

$$+\int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$$

material change

$$\partial_t \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, u_m \quad =$$

change in total energy

$$= \quad - \int_{\mathcal{A}} dS \, p_t \, \partial_t \left[\Phi(\eta_t) \right]$$

lid work

dynamics

$$- \oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

physics

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \left(\alpha F \cdot v + Q \right)$$

diabatic sources

hydrost. adjustment

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$$

material change

global energy budget

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] \;=$$

$$= \; -\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

dynamics
enthalpy flux divergence

$$+ \; \int_{\mathcal{A}} dS \, \dot{h}_s$$

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \left(\alpha F \cdot v + Q \right)$$

surface fluxes

physics

diabatic sources

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$$

hydrost. adjustment
material change

global energy budget

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] \quad =$$

$$= \quad -\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

dynamics

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

physics

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$$

diabatic sources

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$$

material change

Interim summary:

Energy conservation

requires

that pressure work from hydrostatic adjustment associated with material sources and sinks

be matched

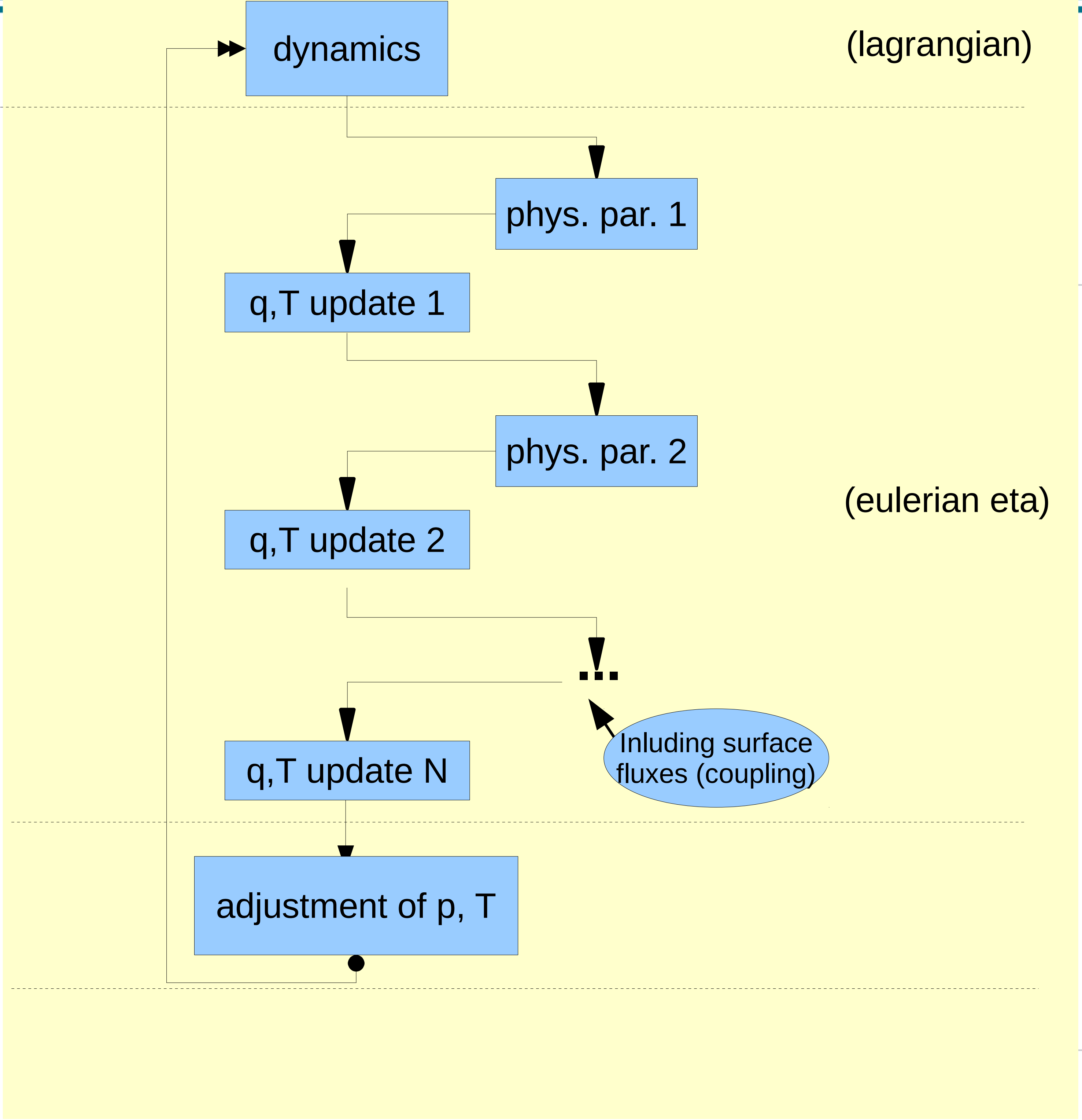
by fluxes of heat corresponding to the total enthalpy held by the exchanged material

The rest is details...

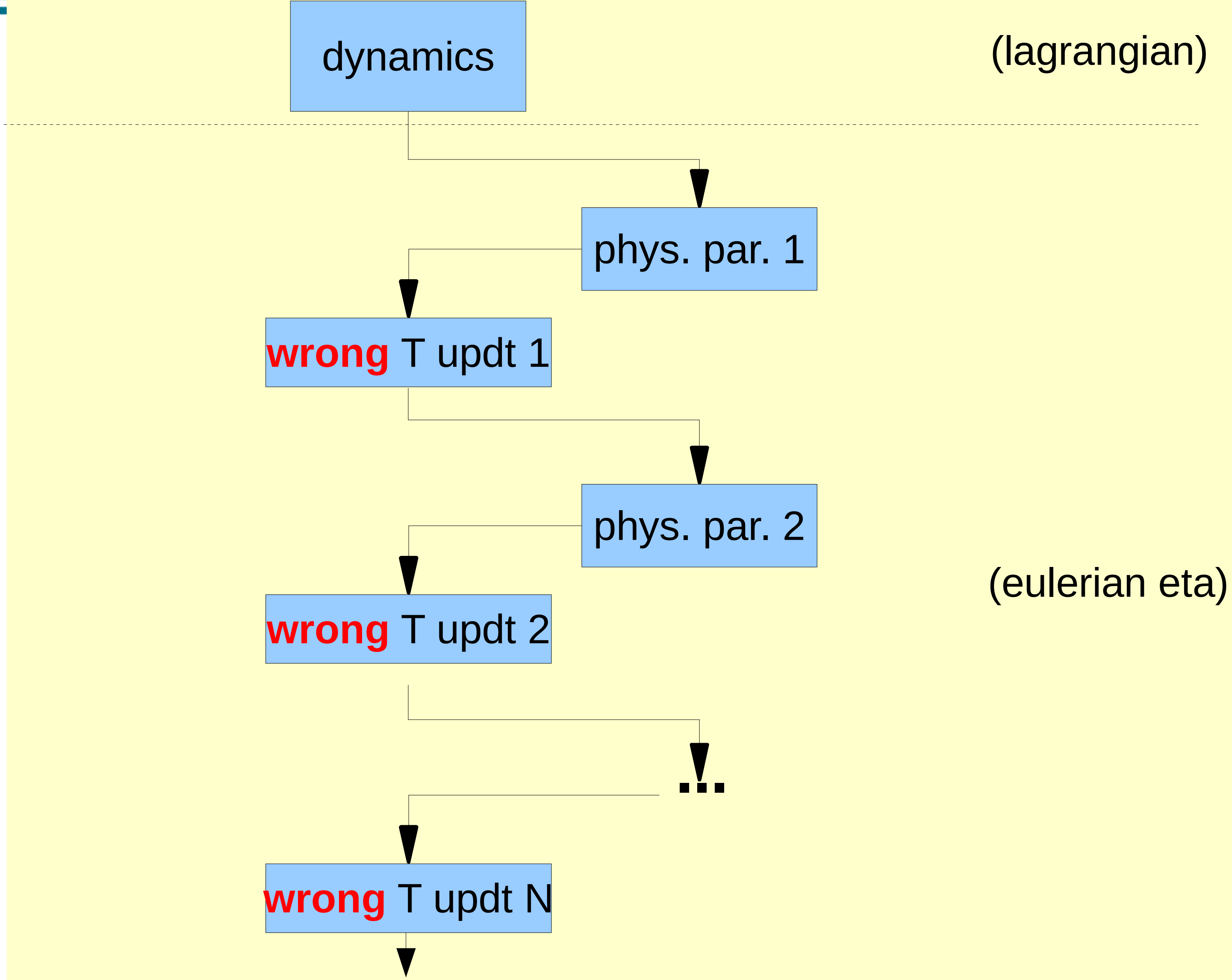
Details 1

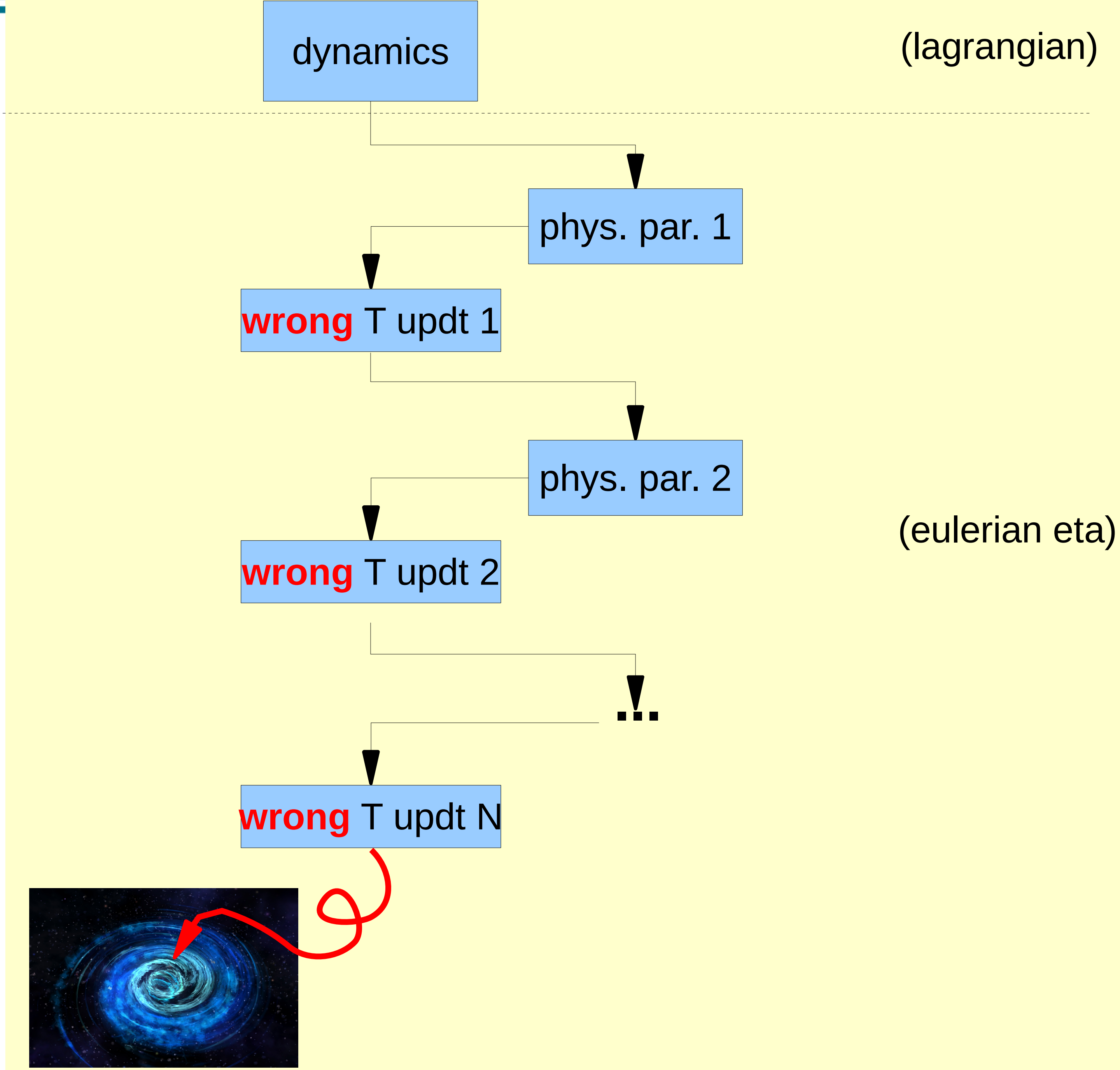
CAM's energy update problem

Time-stepping in CAM: conceptual outline



Time-stepping in CAM: ugly reality (old)





dynamics

(lagrangian)

phys. par. 1

wrong T updt 1

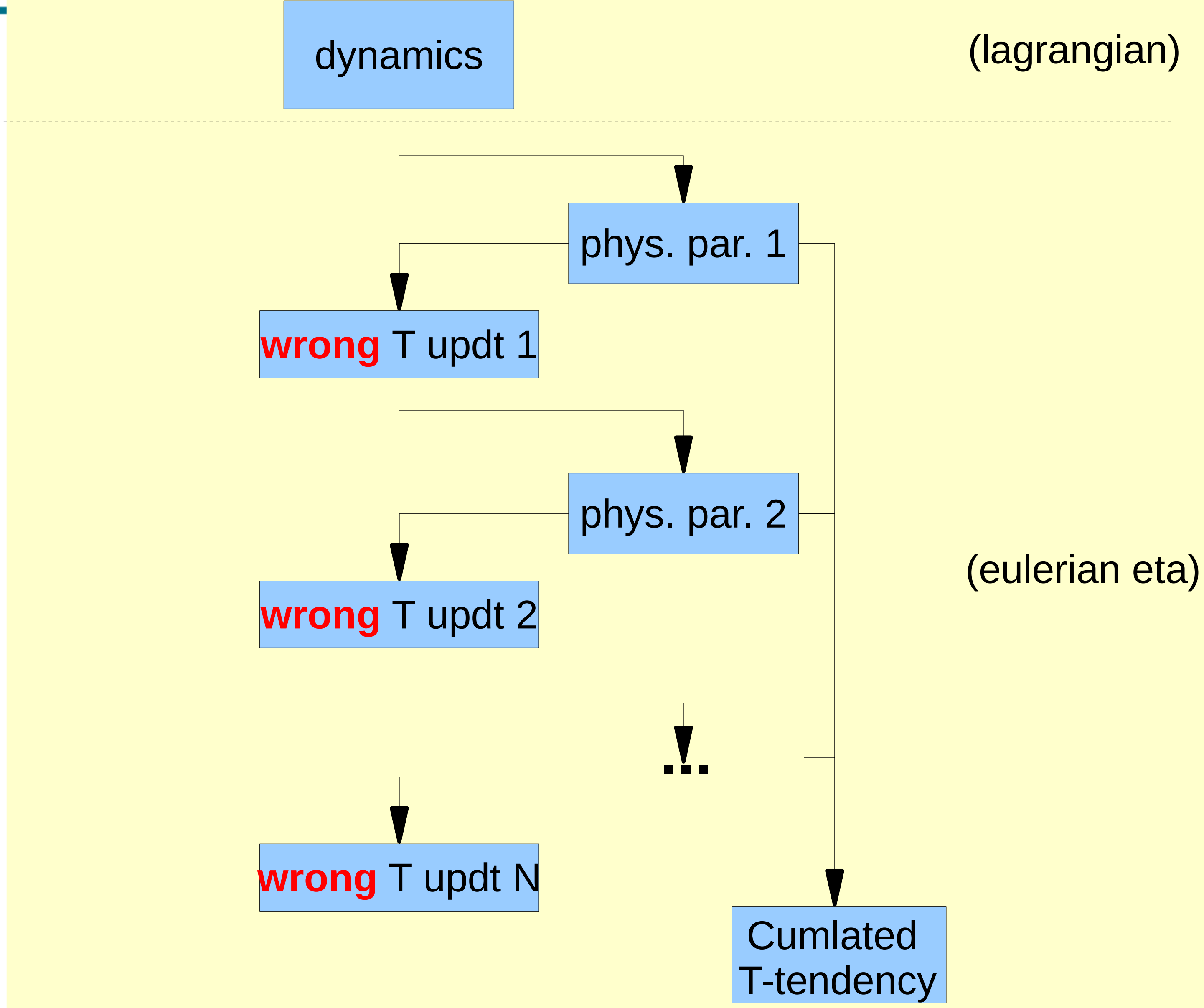
phys. par. 2

(eulerian eta)

wrong T updt 2

...

wrong T updt N



(lagrangian)

dynamics

phys. par. 1

wrong T updt 1

phys. par. 2

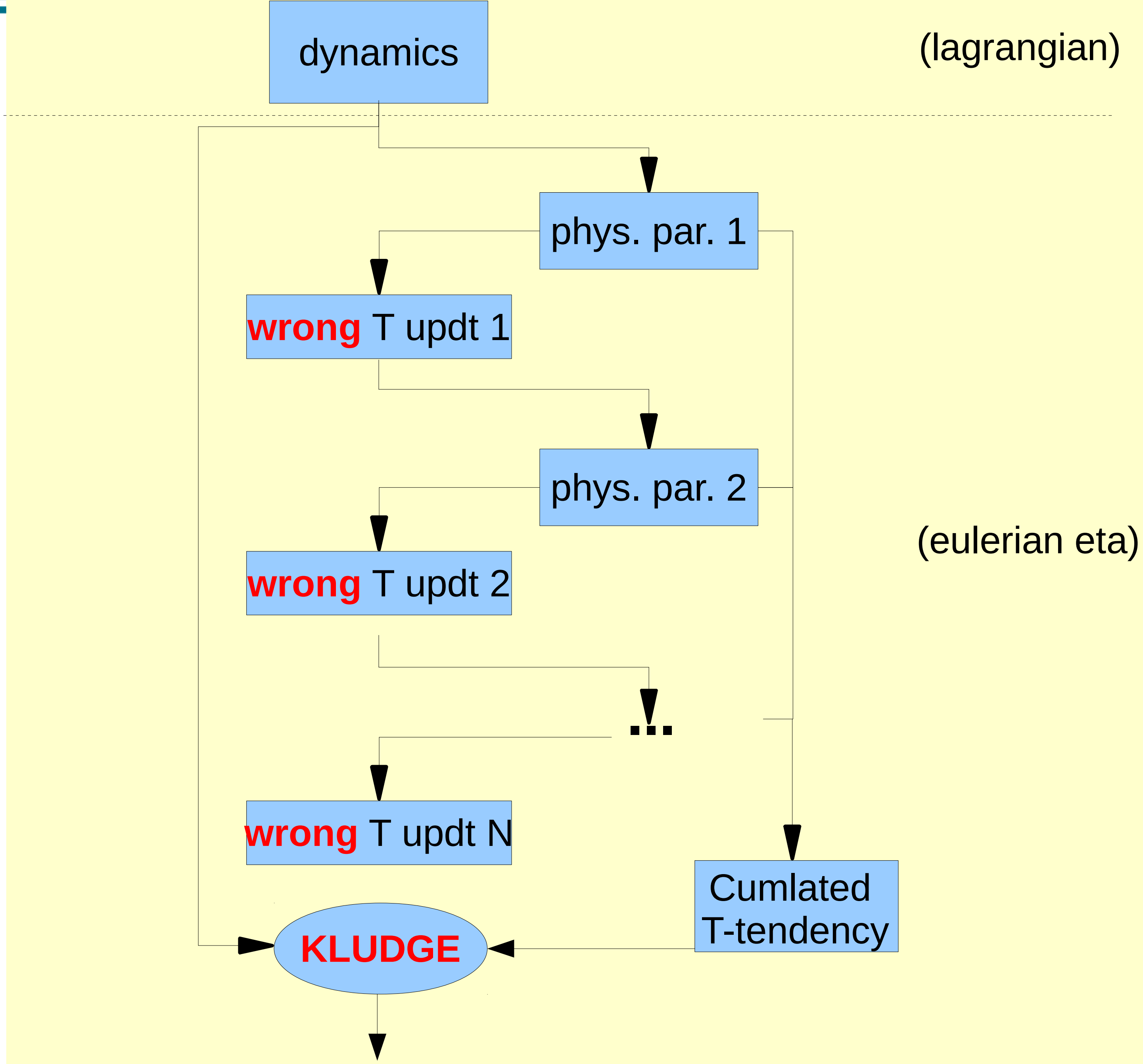
(eulerian eta)

wrong T updt 2

...

wrong T updt N

Cumlated T-tendency



dynamics

(lagrangian)

phys. par. 1

wrong T updt 1

phys. par. 2

wrong T updt 2

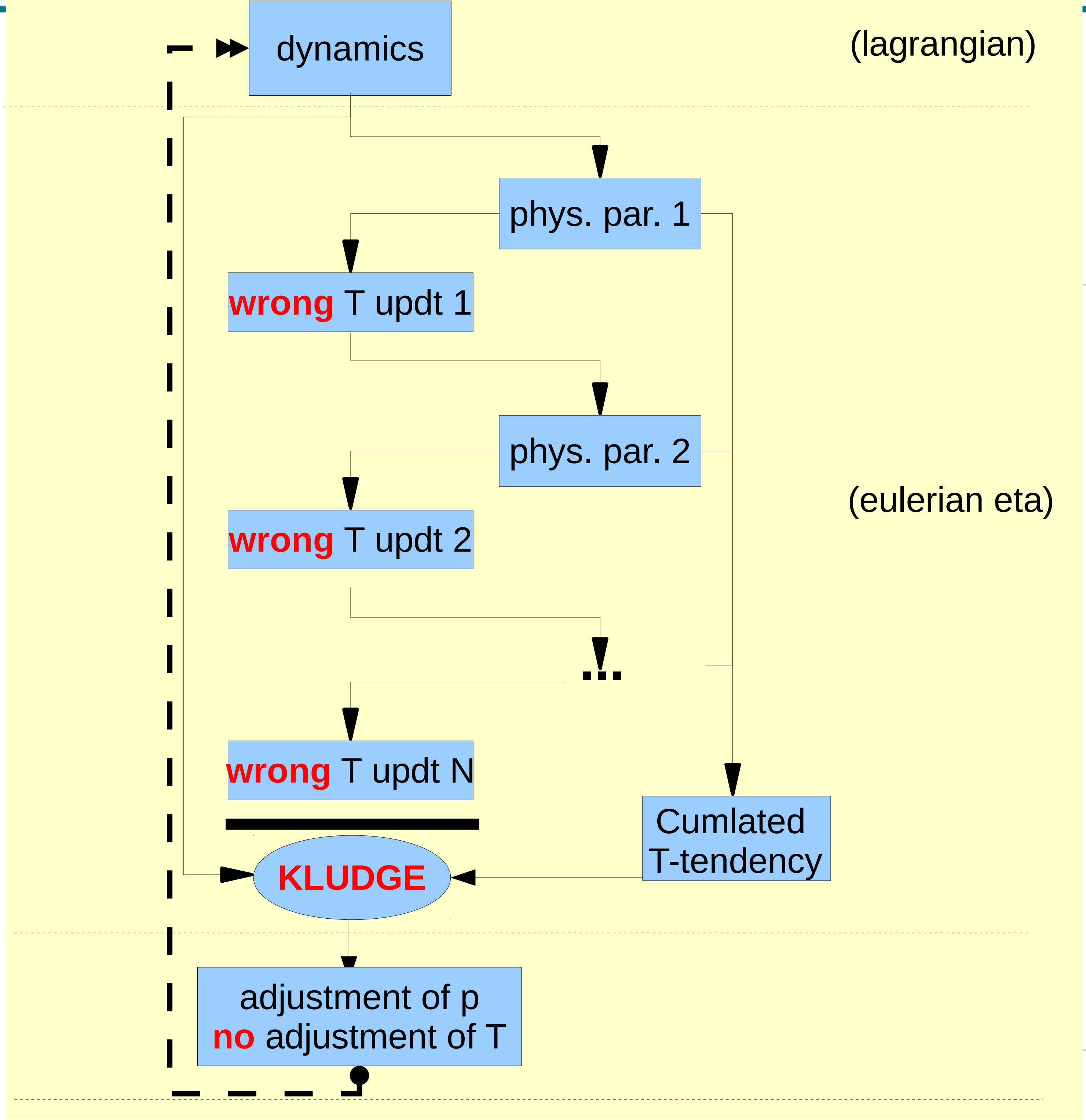
(eulerian eta)

...

wrong T updt N

Cumlated T-tendency

KLUDGE



dynamics

(lagrangian)

phys. par. 1

wrong T updt 1

phys. par. 2

(eulerian eta)

wrong T updt 2

...

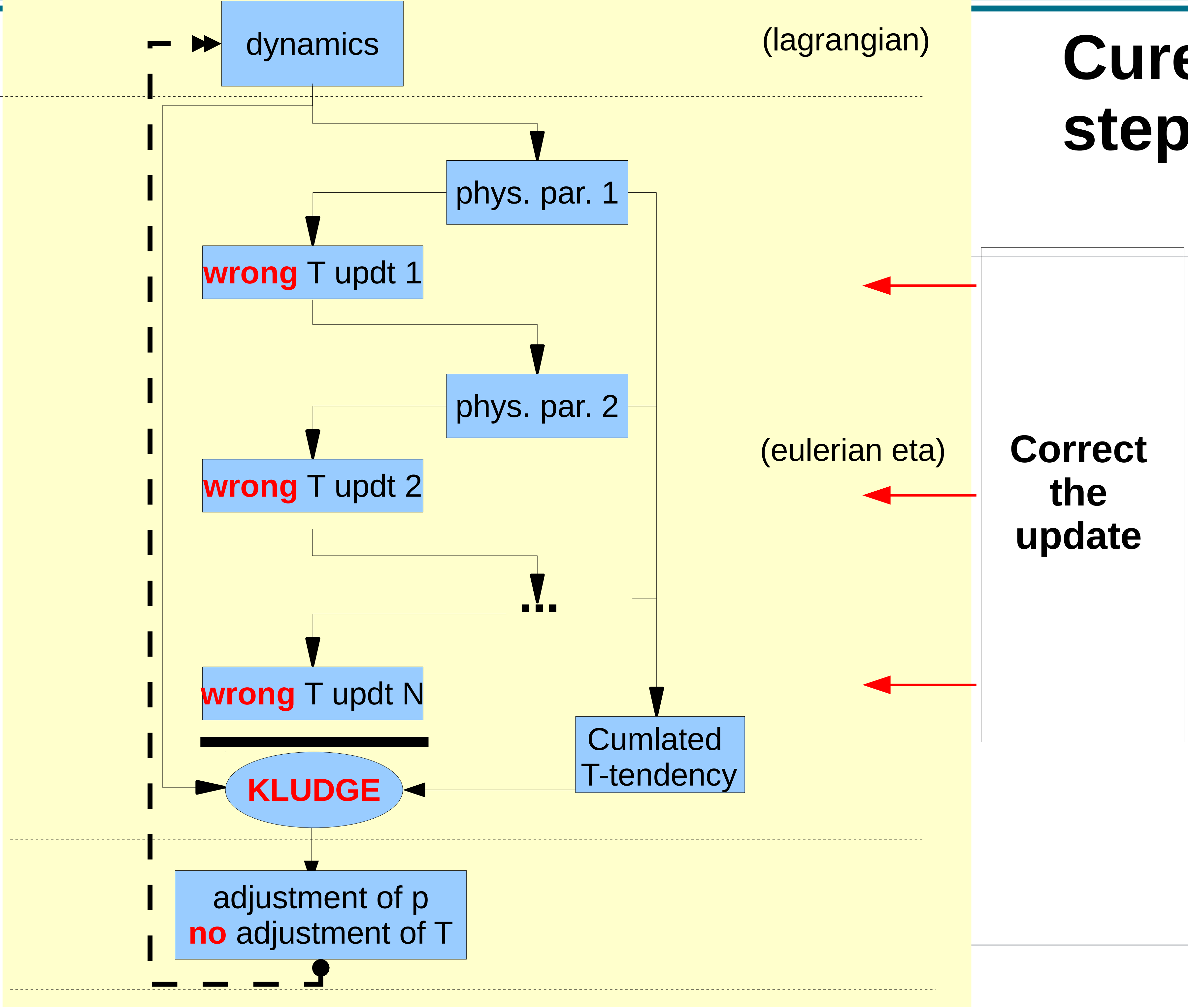
wrong T updt N

KLUDGE

Cumlated T-tendency

adjustment of p
no adjustment of T

Cure step 1



(lagrangian)

dynamics

phys. par. 1

wrong T updt 1

phys. par. 2

wrong T updt 2

...

wrong T updt N

(eulerian eta)

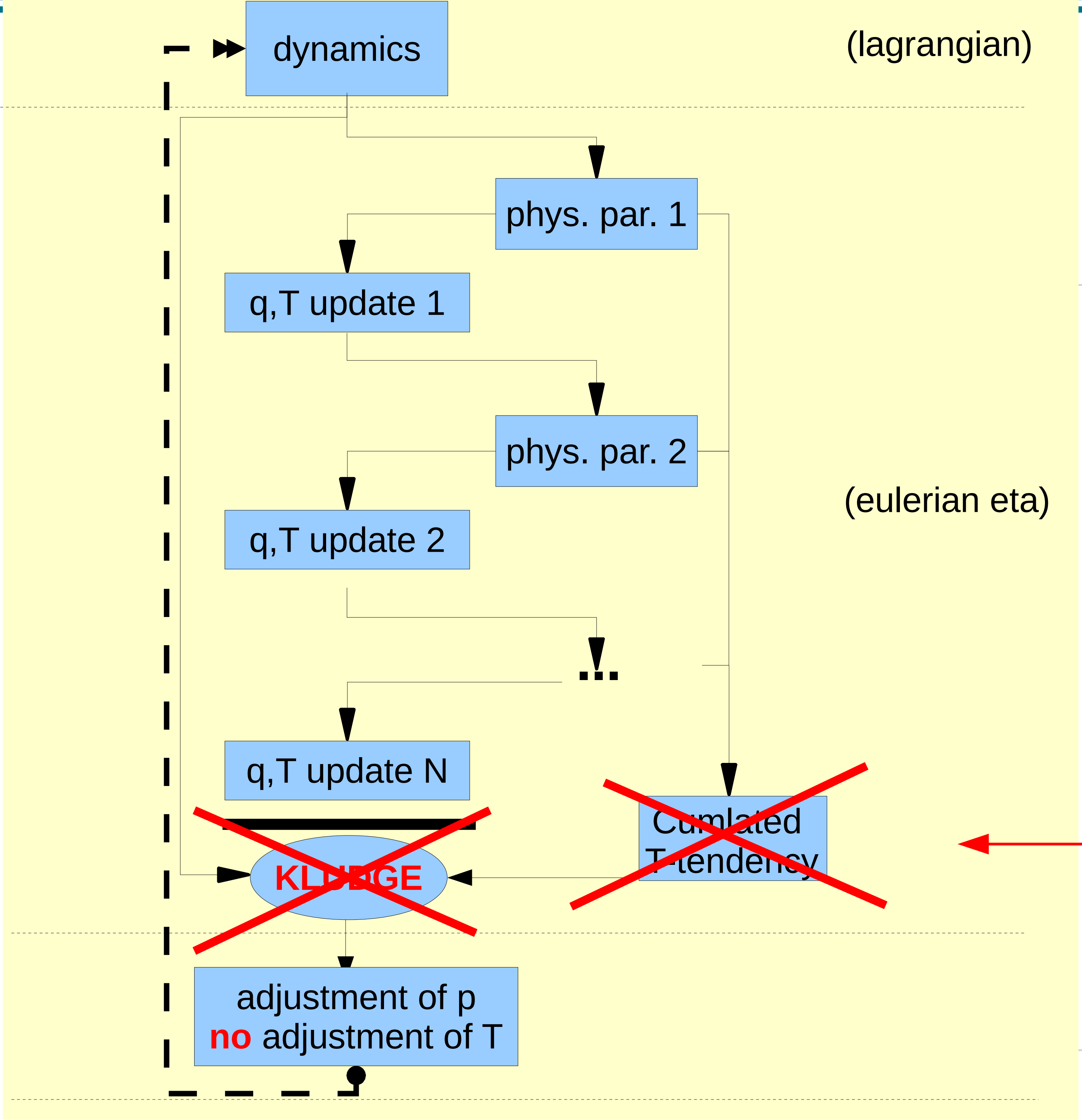
Cumlated T-tendency

KLUDGE

adjustment of p
no adjustment of T

Correct the update

Cure step 2



dynamics

(lagrangian)

phys. par. 1

q,T update 1

phys. par. 2

(eulerian eta)

q,T update 2

...

q,T update N

~~KLUDGE~~

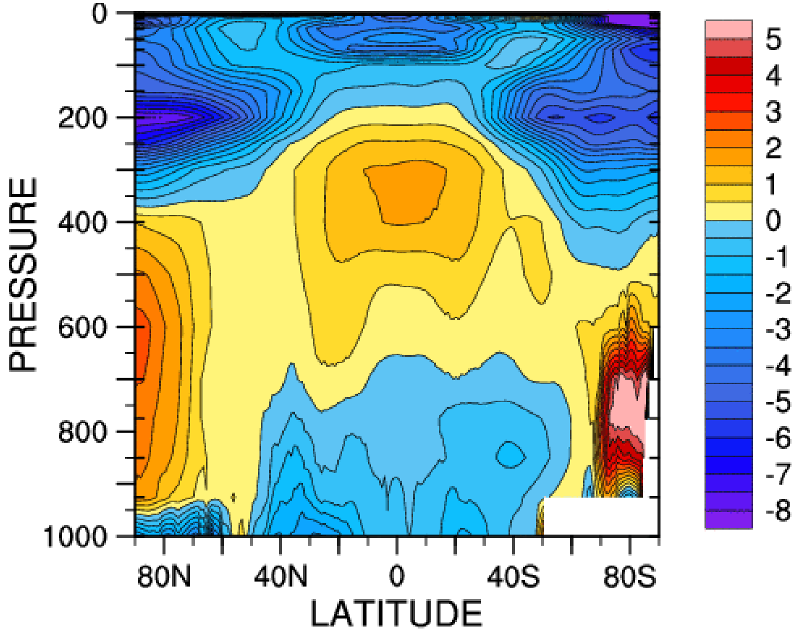
~~Cumlated T-tendency~~

adjustment of p
no adjustment of T

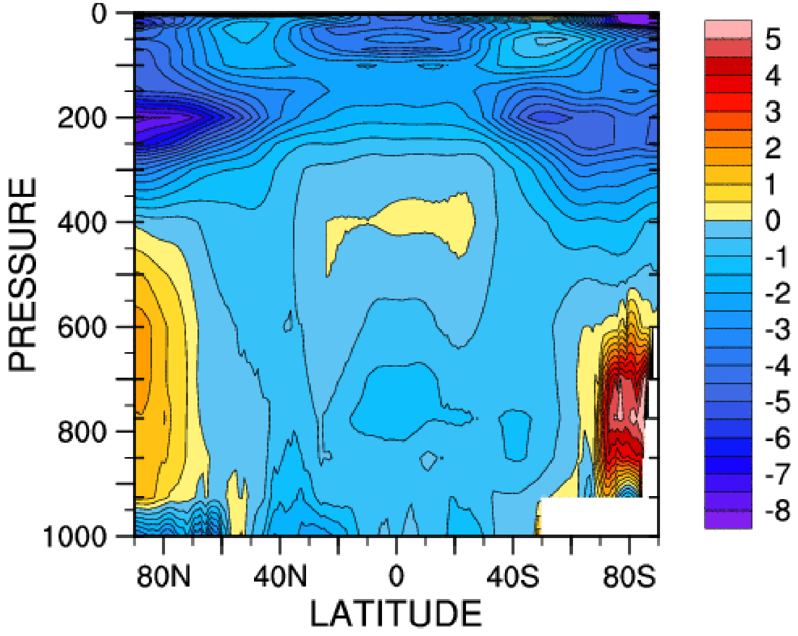
Remove old fixes

TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE

CORRECT ENERGY
minus ERA40



CAM5.2
minus ERA40

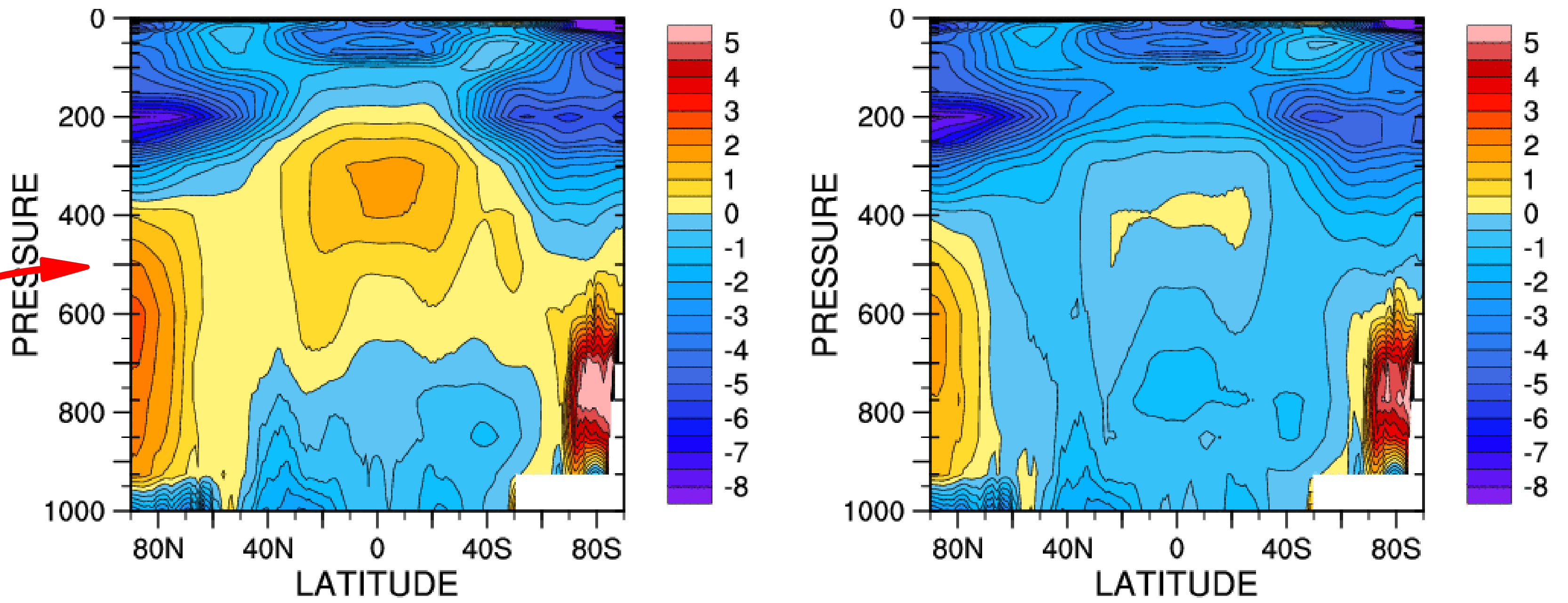


DLW et al., presentation at AMWG February 2014

TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE

CORRECT ENERGY
minus ERA40

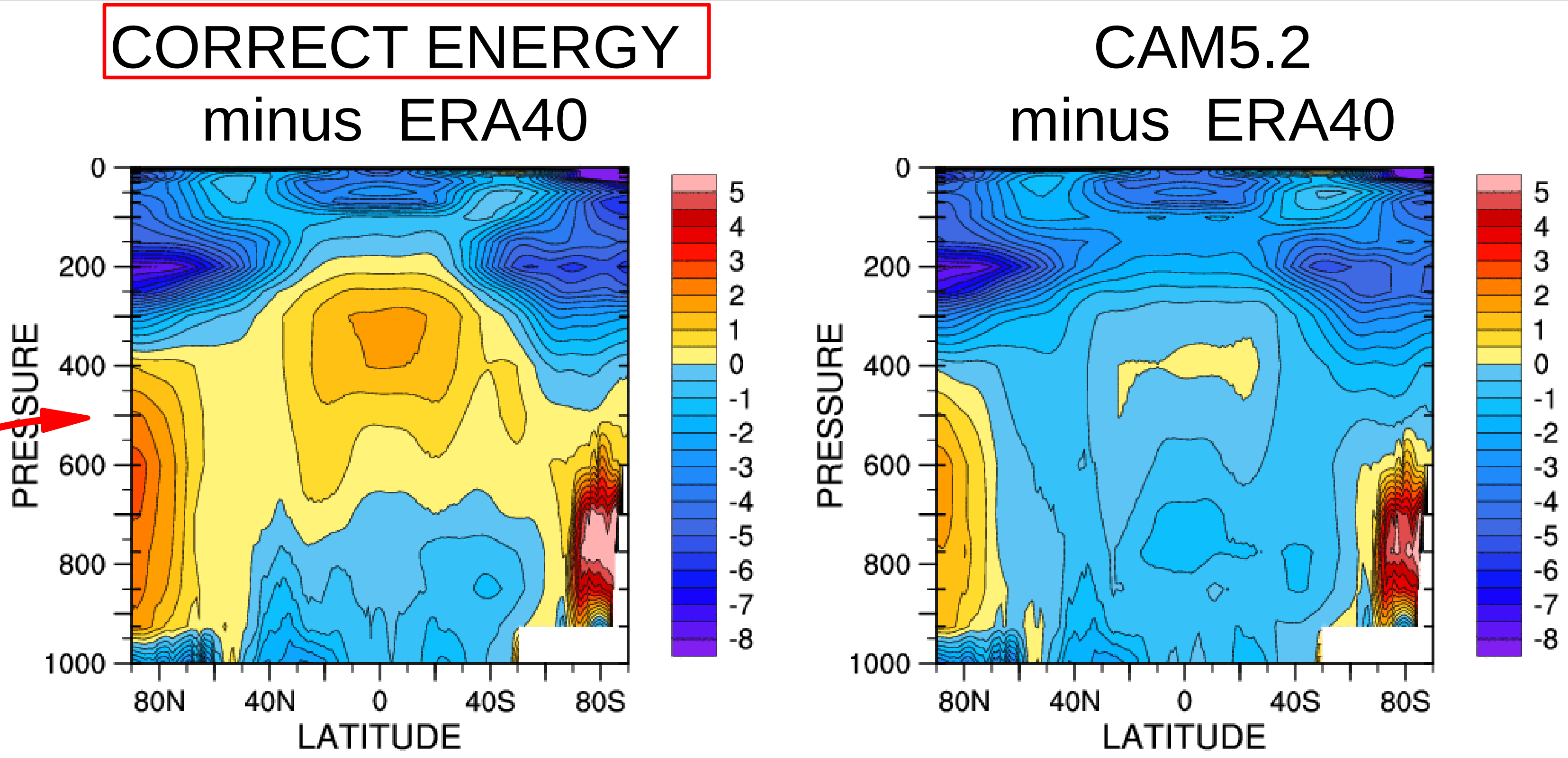
CAM5.2
minus ERA40



This was mainly due to an incorrect adjustment

DLW et al., presentation at AMWG February 2014

TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE



CORRECT ENERGY minus ERA40

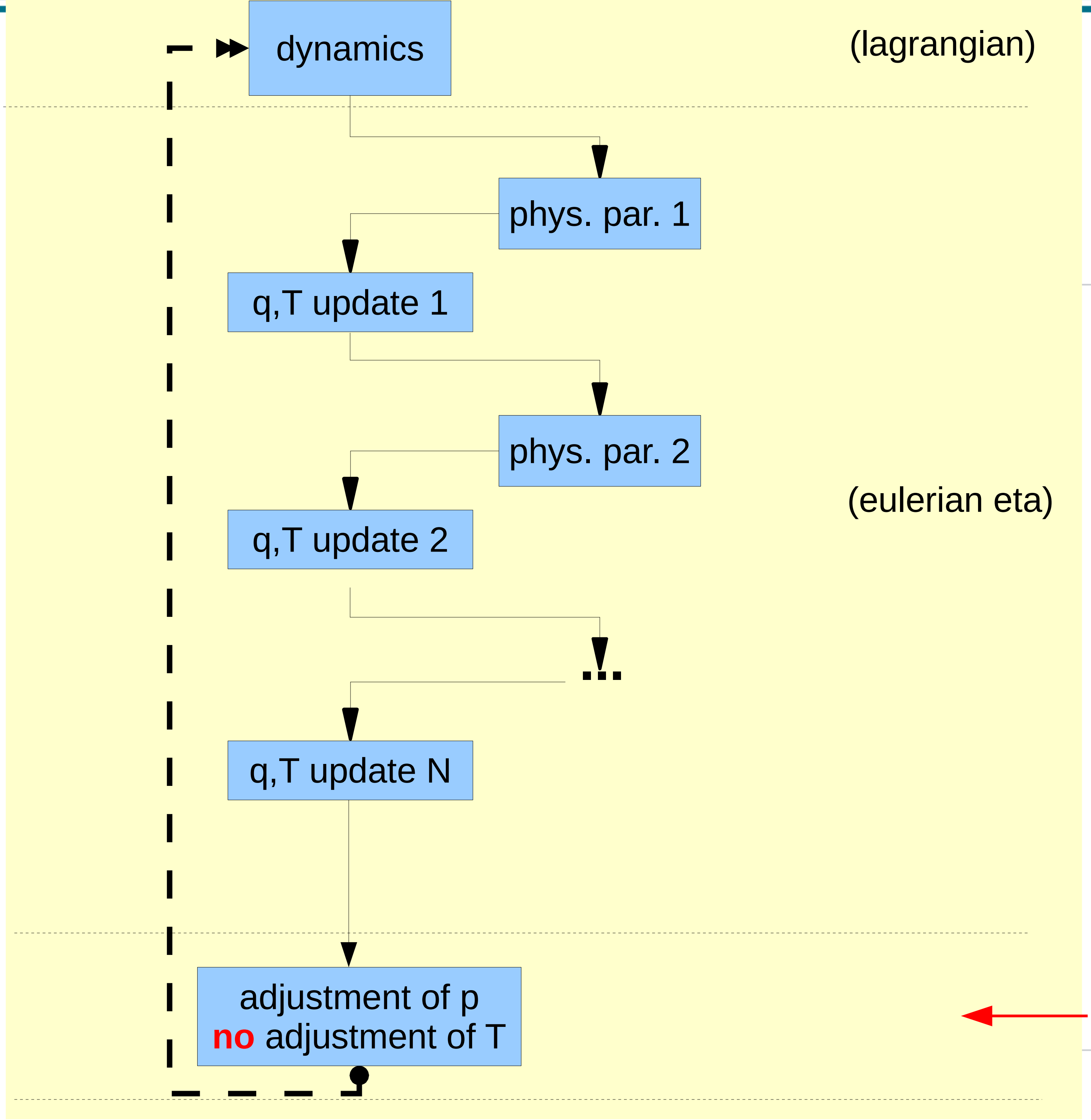
CAM5.2 minus ERA40

This was mainly due to an incorrect adjustment (which ***preserved*** energy!)

Details 2

CAM's erroneous formulation of energy conservation

Cure step 3



(lagrangian)

dynamics

phys. par. 1

q,T update 1

phys. par. 2

q,T update 2

(eulerian eta)

...

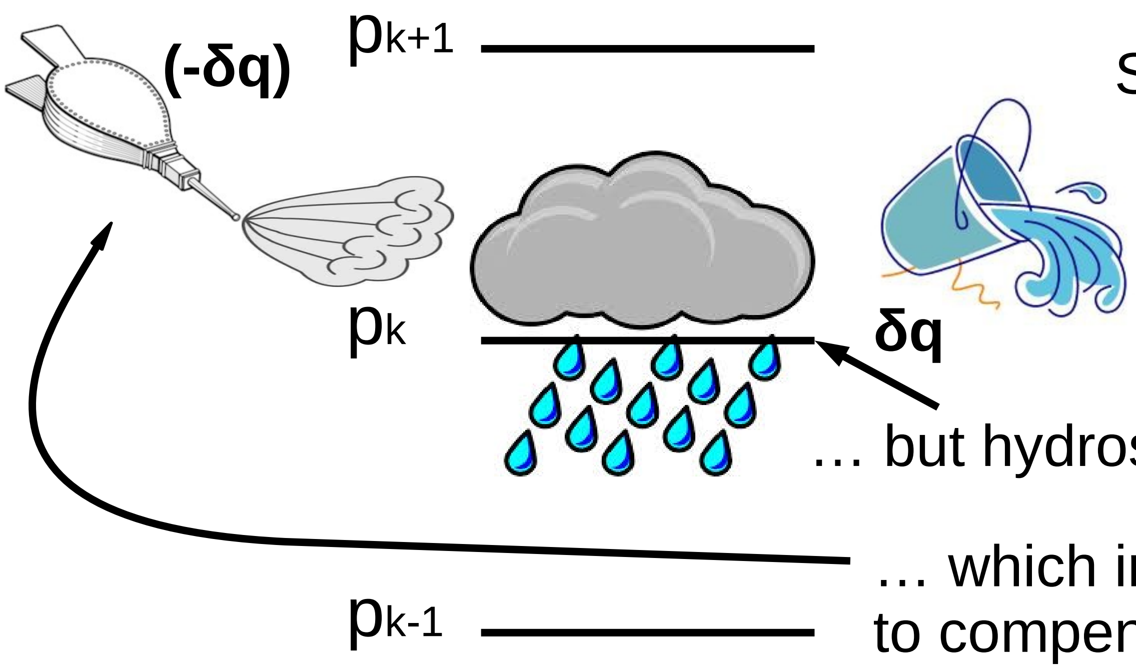
q,T update N

adjustment of p
no adjustment of T

Adjustment must also be corrected

CAM's hydrostatic “mass fixer” (`dme_adjust`)

Physics updates layer q and T but NOT layer-interface pressure.



So if e.g. precipitation is formed...

… then water is removed...

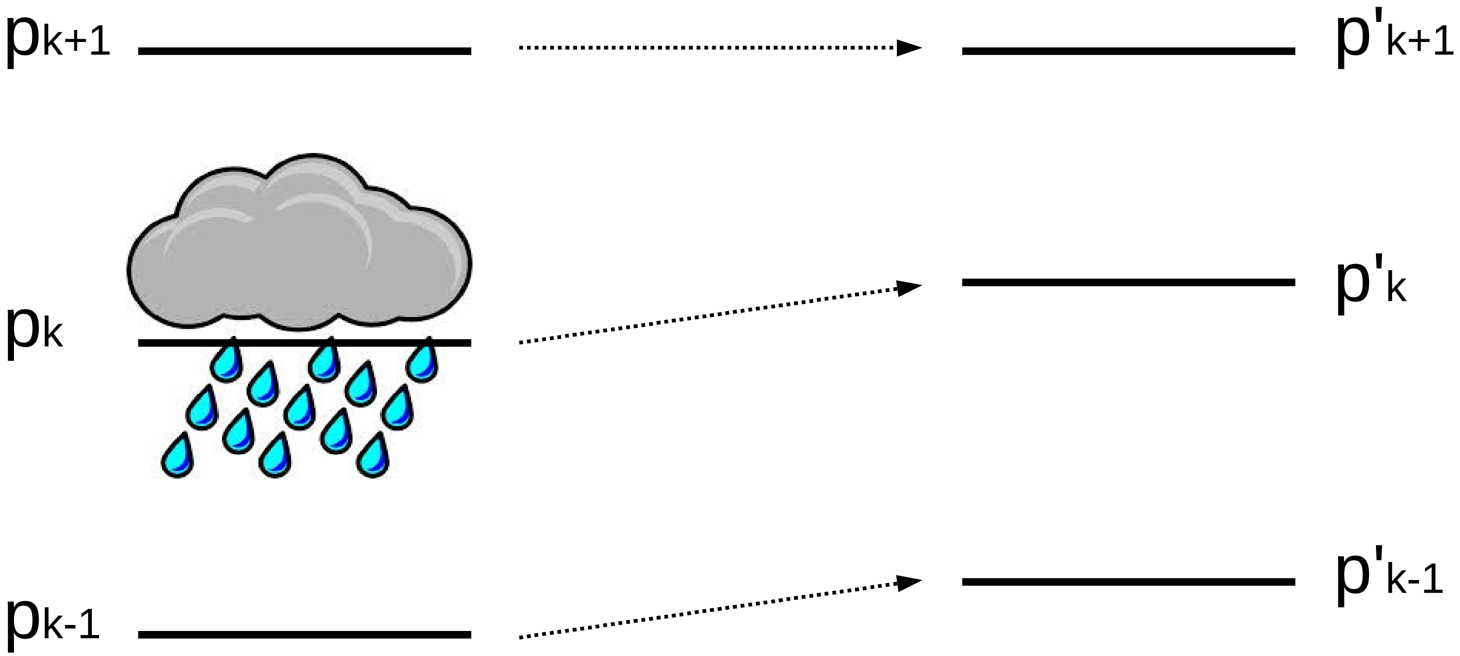
… but hydrostatic pressure is not changed...

… which implies that dry mass is added to compensate.

CAM's hydrostatic “mass fixer” (`dme_adjust`)

The dry mass and the hydrostatic pressure both need to be “adjusted” to ensure conservation of dry air.

In all version of CAM, this is done in `physics_dme_adjust` …



p_{k+1} → p'_{k+1}

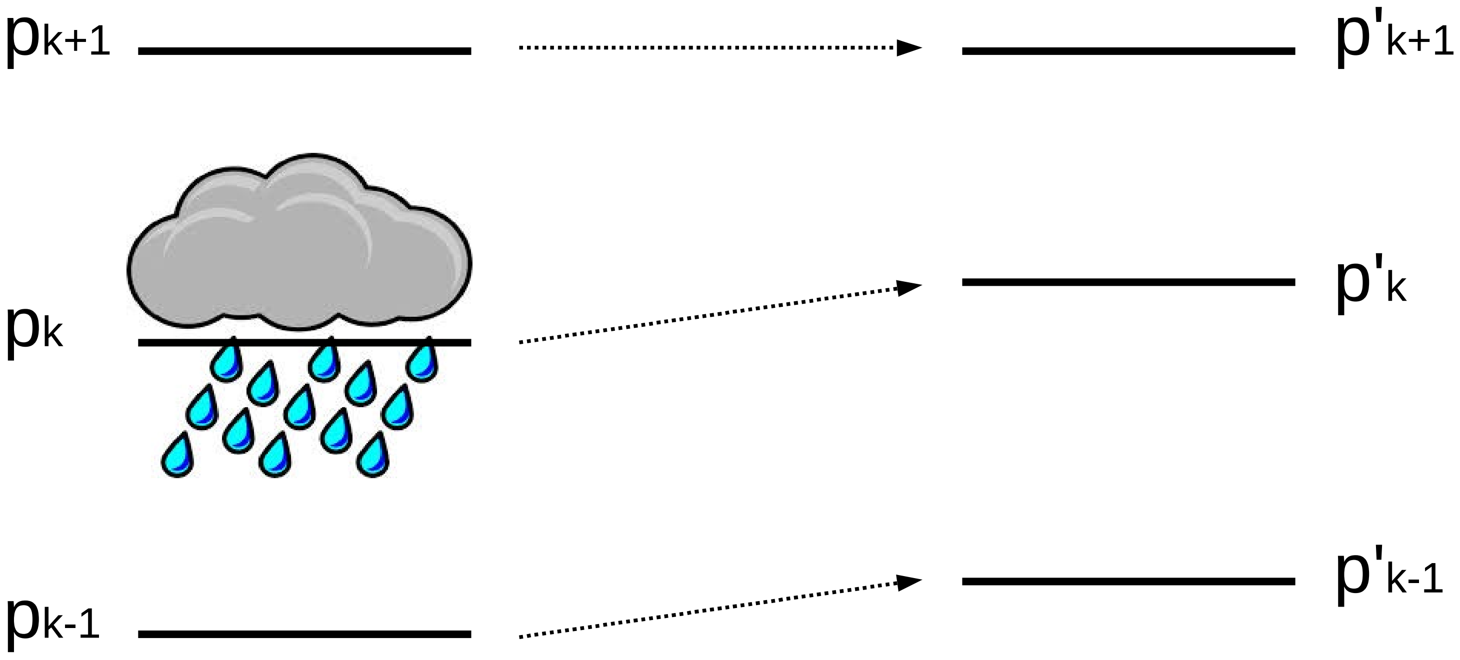
p_k → p'_k

p_{k-1} → p'_{k-1}

CAM's hydrostatic “mass fixer” (`dme_adjust`)

The dry mass and the hydrostatic pressure both need to be “adjusted” to ensure conservation of dry air.

In all version of CAM, this is done in `physics_dme_adjust` …



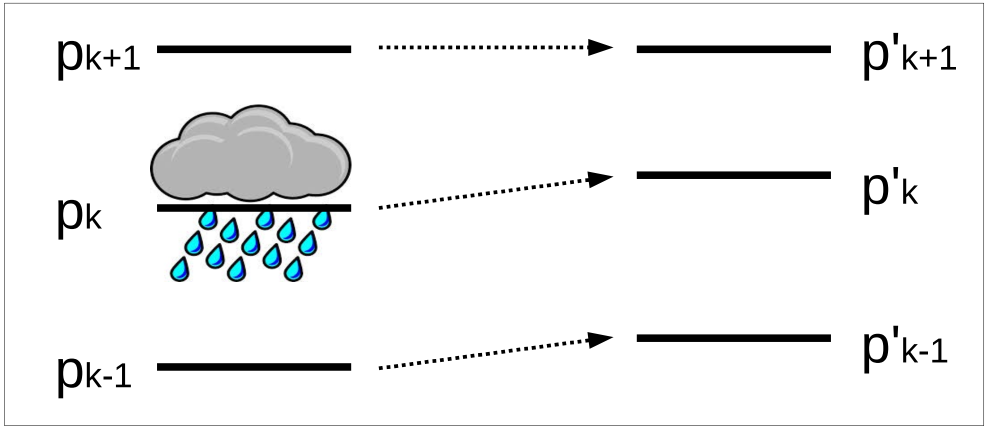
… then T is adjusted to “conserve” total column energy

Work associated with hydrostatic mass adjustment

First law of Thermodynamics:

$$\frac{d\epsilon}{dt} = \alpha \frac{dp}{dt}$$

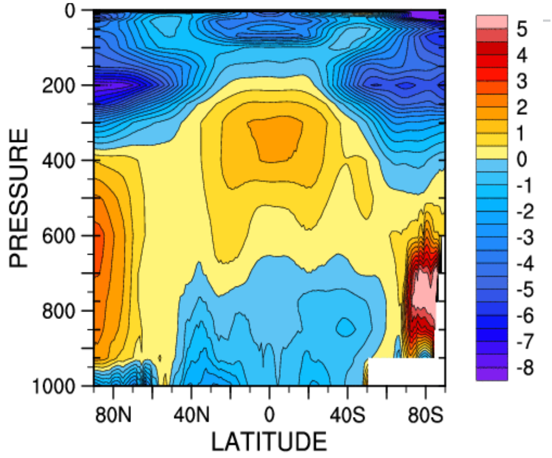
where **ε** is the specific internal enthalpy and α the specific volume.



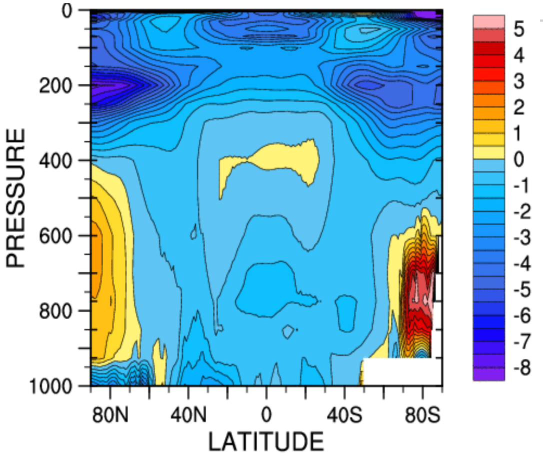
Physics parametrisations should keep correct energy budgets. But they don't. So this needs to be done in `dme_adjust`.

TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE

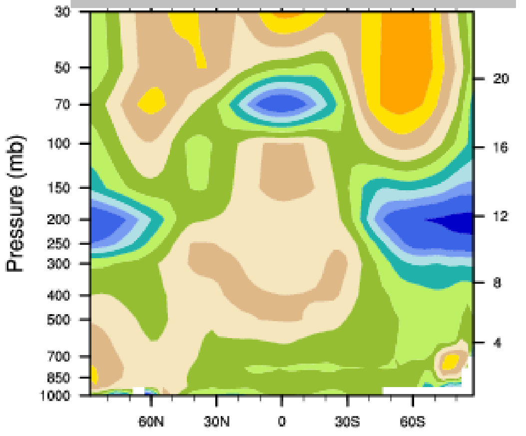
CORRECT ENERGY
minus ERA40



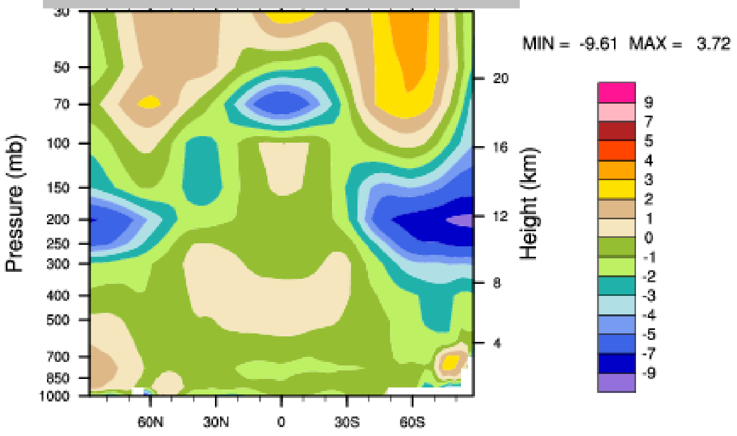
CAM5.2
minus ERA40



(a) *Pres.*adj.(Φ) – ERA/I: T

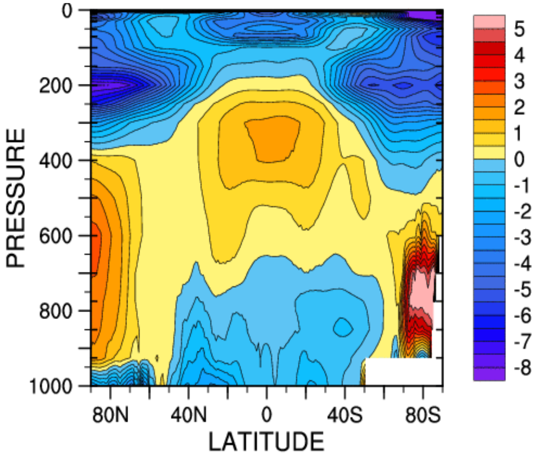


(b) Original CAM4 – ERA/I: T

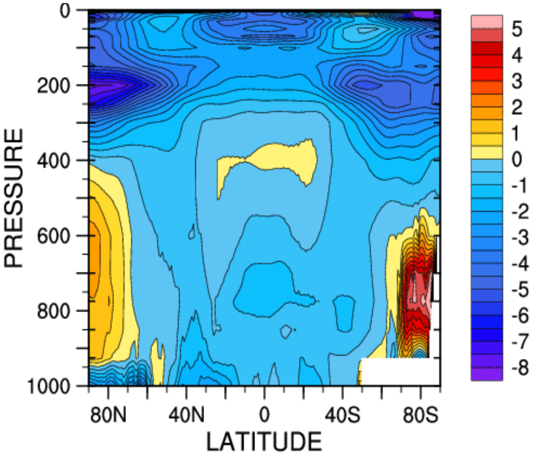


TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE

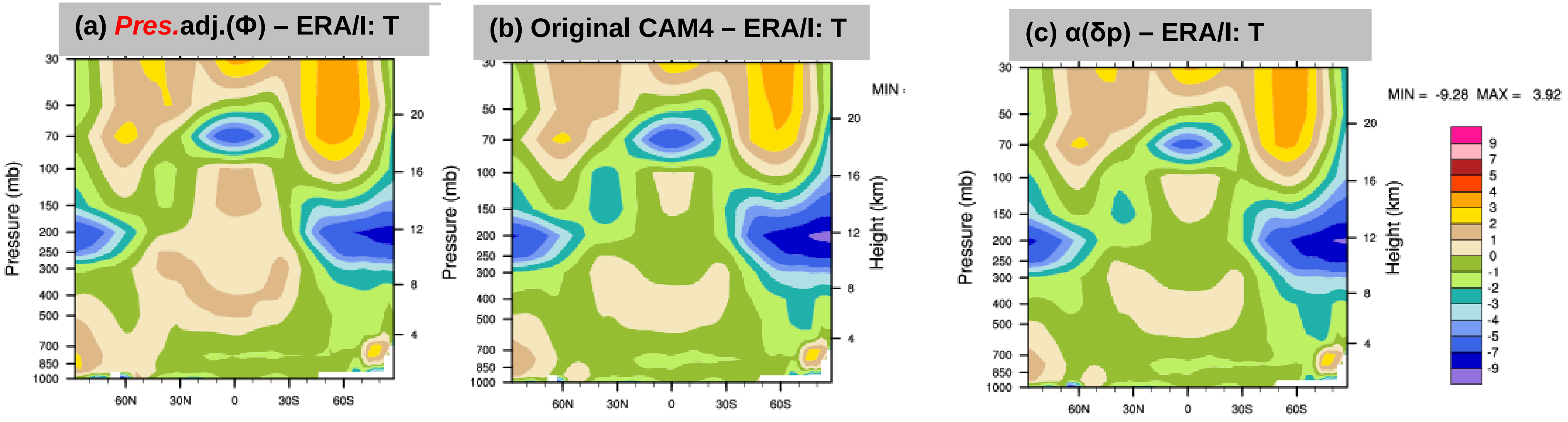
CORRECT ENERGY
minus ERA40



CAM5.2
minus ERA40



Consistent adjustment “saves” model climatology



(a) *Pres.*adj.(Φ) – ERA/I: T

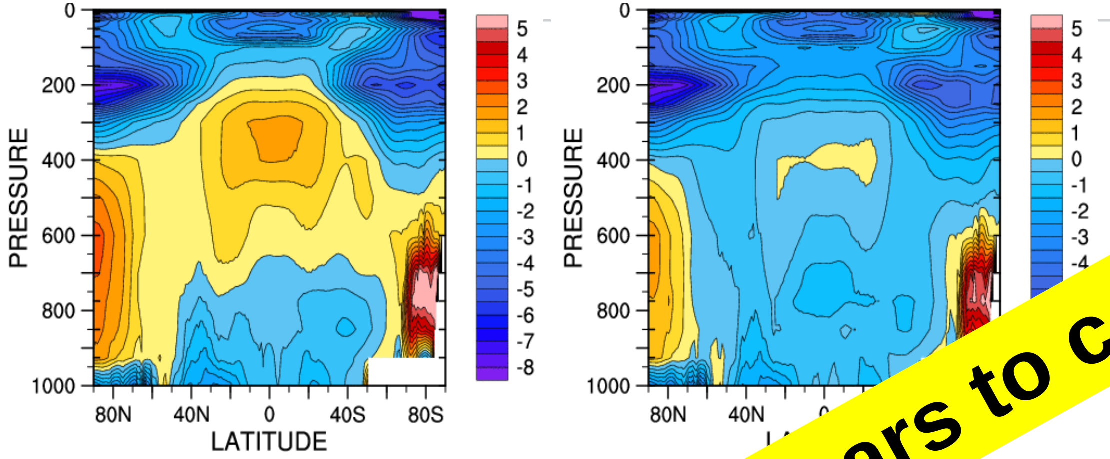
(b) Original CAM4 – ERA/I: T

(c) α(δp) – ERA/I: T

TEMPERATURE (K)
10 YEAR ANNUAL AVERAGE

CORRECT ENERGY
minus ERA40

CAM5.2
minus ERA40



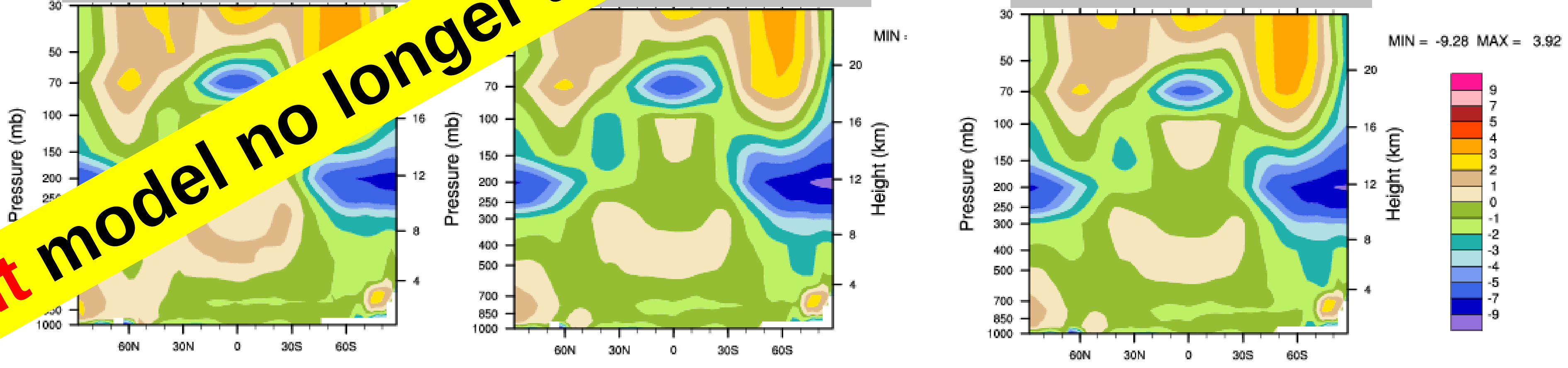
nt
stment
aves” model
climatology

But model no longer appears to conserve total energy!

(a) *Pres.*adj.(Φ) – ERA/I: T

CAM4 – ERA/I: T

(c) α(δp) – ERA/I: T



Details 3

How to fix it

global energy budget

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] =$$

$$= -\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$$

“physics”

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_m$$

material change

CAM's energy budget

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] =$$

$$= -\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$$

“physics”

$$\xcancel{+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p}$$

this term ignored

~~change~~

CAM's energy budget

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] =$$

$$= -\oint_{\delta\mathcal{A}} d\sigma \cdot \int_t^s \partial_\eta p \, d\eta \, h_m V$$

enthalpy flux divergence

$$+ \int_{\mathcal{A}} dS \, \dot{h}_s$$

surface fluxes

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, (\alpha F \cdot v + Q)$$

“physics”

+ energy fixer

residual, applied uniformly everywhere

CAM's energy budget

revised

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] \quad =$$

[...]

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \; \dot{q} h_m$$

mass change

CAM's energy budget

revised

$$\partial_t \int_{\mathcal{A}} dS \left[\Phi_s p_s + \int_t^s \partial_\eta p \, d\eta \, \epsilon_m \right] =$$

[...]

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} h_q$$

$$+ \int_{\mathcal{A}} dS \int_t^s \partial_\eta p \, d\eta \, \dot{q} (h_m - h_q)$$

mass source with specific enthalpy h$_q$

heat transfer between atmosphere and mass source

CAM's energy budget

revised

$\dot{q}(h_m - h_q)/c_{p,air}$

Air temperature increment associated with heat transfer between atmosphere and mass source

$\dot{q}h_q$

Additional boundary heat flux, output diagnostics `EFLX`

Now implemented in `physics_dme_adjust`

⇒ atmospheric energy budget closed only if considering `EFLX`

⇒ global heat budget closed only if `EFLX` **passed to other ES components**

h_q

It should be the job of each specific physics submodel/parametrisation to determine.

E.g., how much of its enthalpy does a raindrop retain?

- ☐ all (h_q=h_m)
- ☐ terminal velocity + thermal
- ☐ other

h_q

It should be the job of each specific physics submodel/parametrisation to determine.

E.g., how much of its enthalpy does a raindrop retain?

☑ all (→ terminal velocity ~ 300m/s !)

☐ terminal velocity + thermal

☐ other

h_q

It should be the job of each specific physics submodel/parametrisation to determine.

E.g., how much of its enthalpy does a raindrop retain?

☑ all (→ terminal velocity ~ 300m/s !)

☐ terminal velocity + thermal

☑ other, e.g. ocean and land models assume

$$T_q = T_{surf} \quad \Rightarrow \quad h_q = c_{p,water} T_{surf}$$

Details 4

Implications for surface fluxes

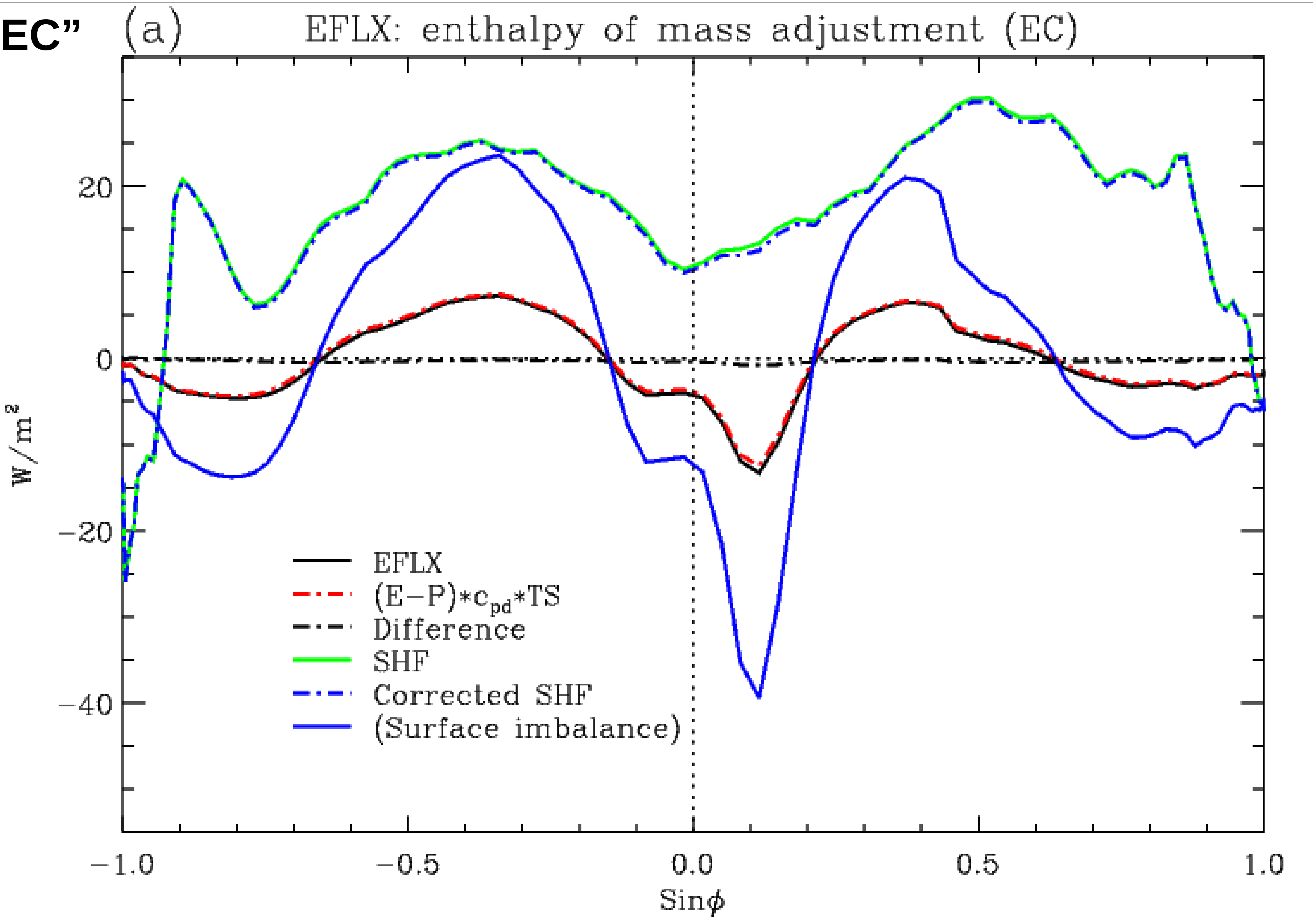
Preliminary note on Details 4

All net mass sources and sinks reside at the surface.

Therefore the net atmospheric column energy imbalance associated with mass changes must be closed by surface heat fluxes.

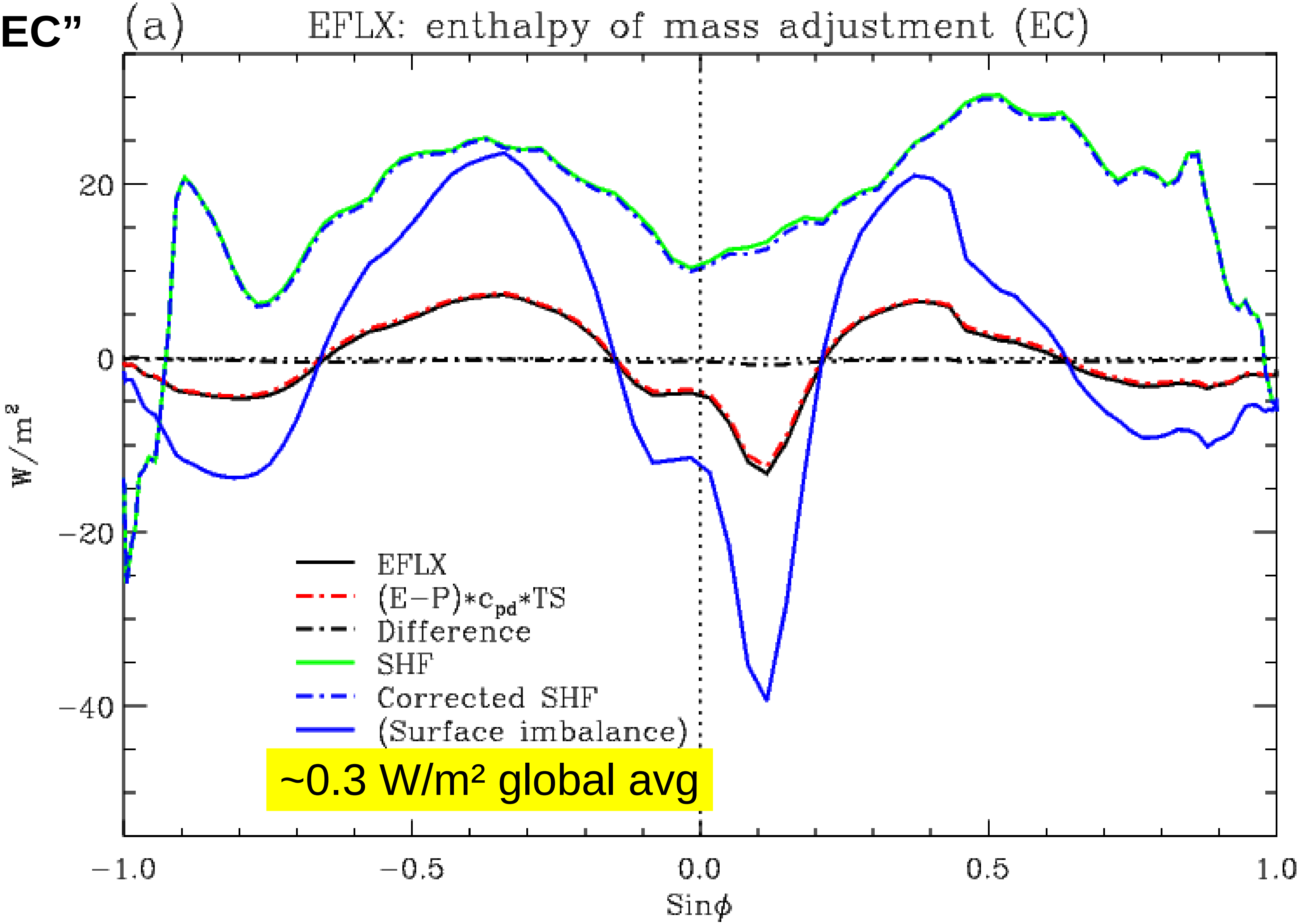
Surface heat fluxes

"EC"



Surface heat fluxes

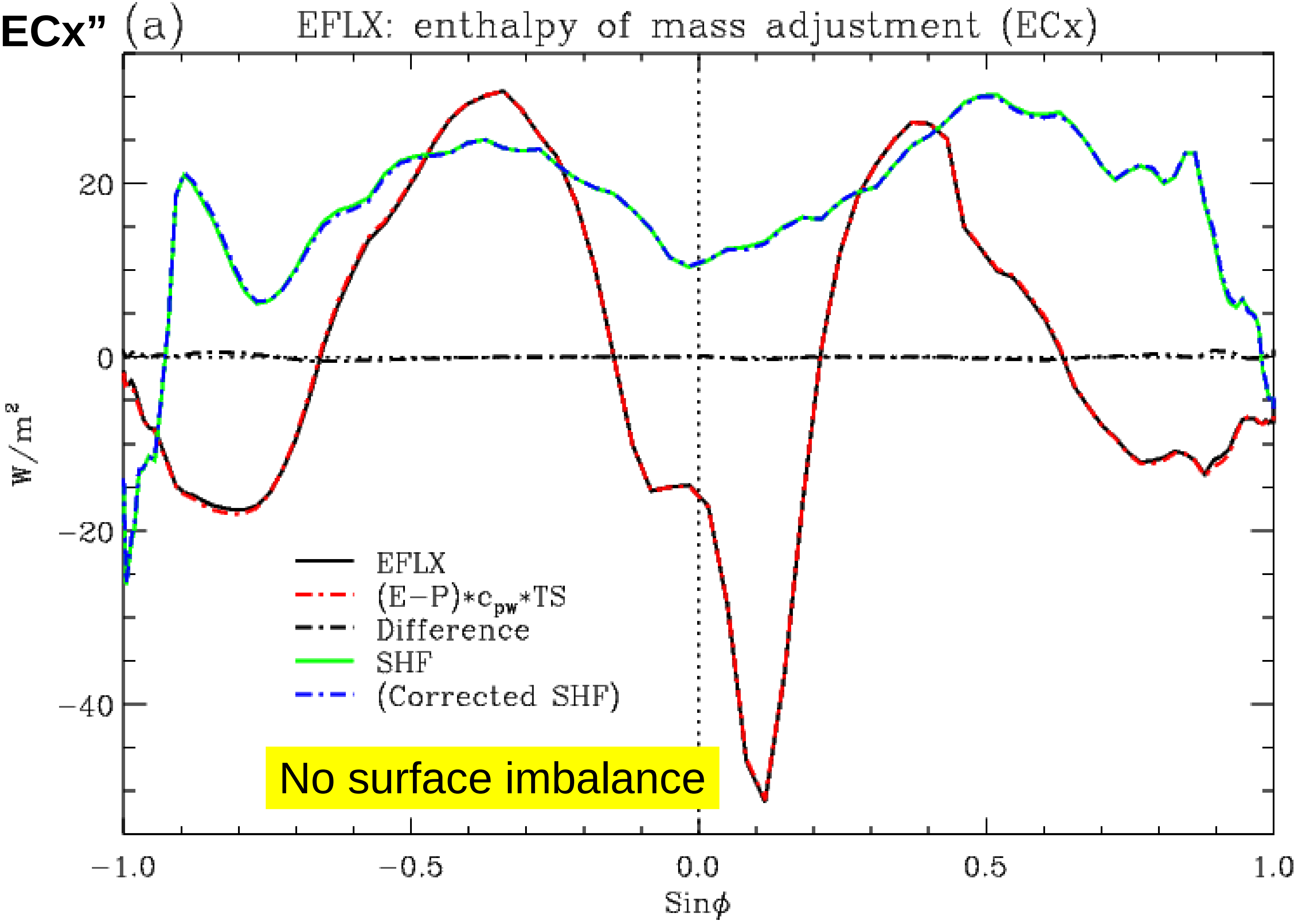
“EC”



~0.3 W/m² global avg

Surface heat fluxes

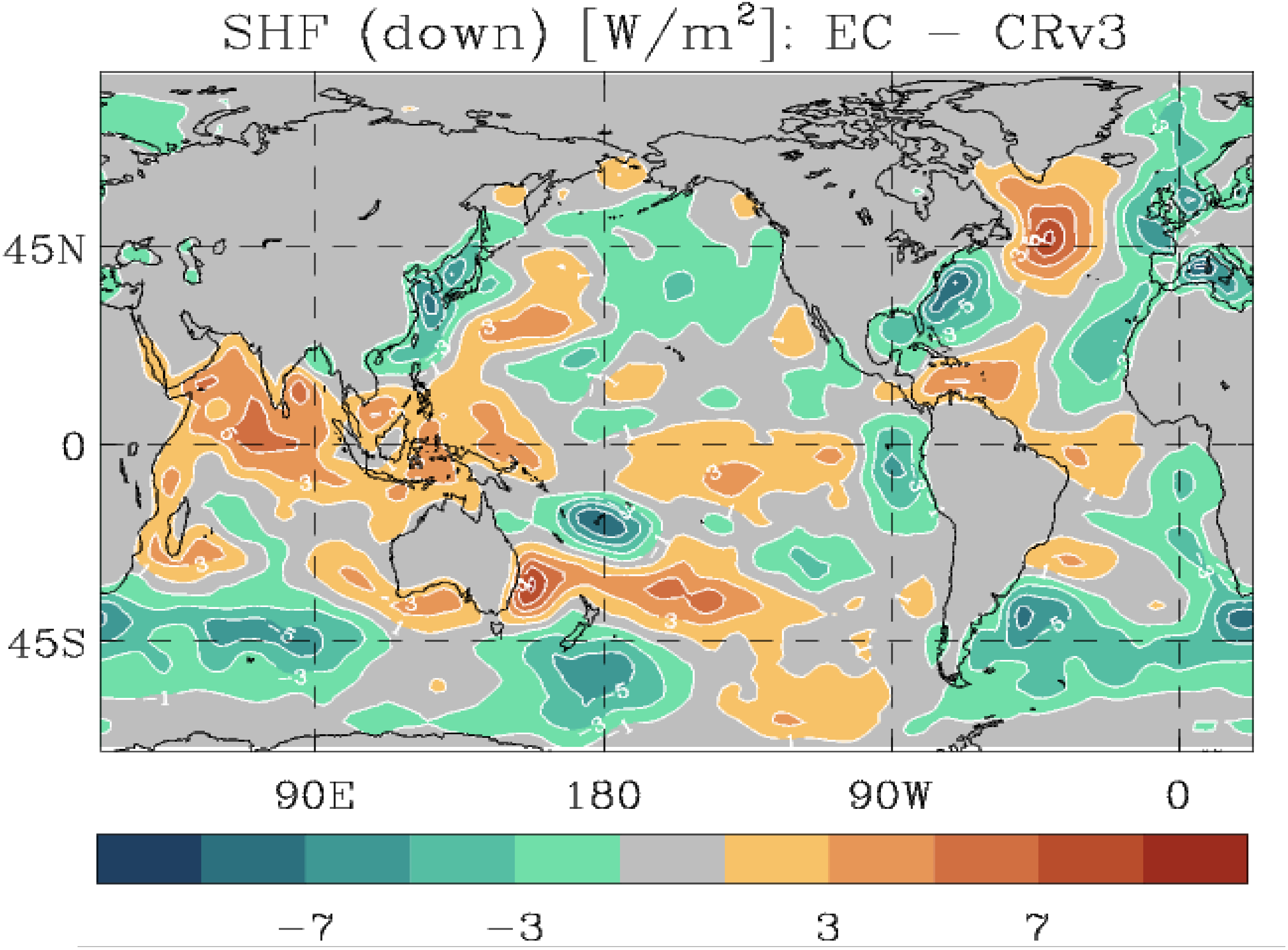
“ECx”

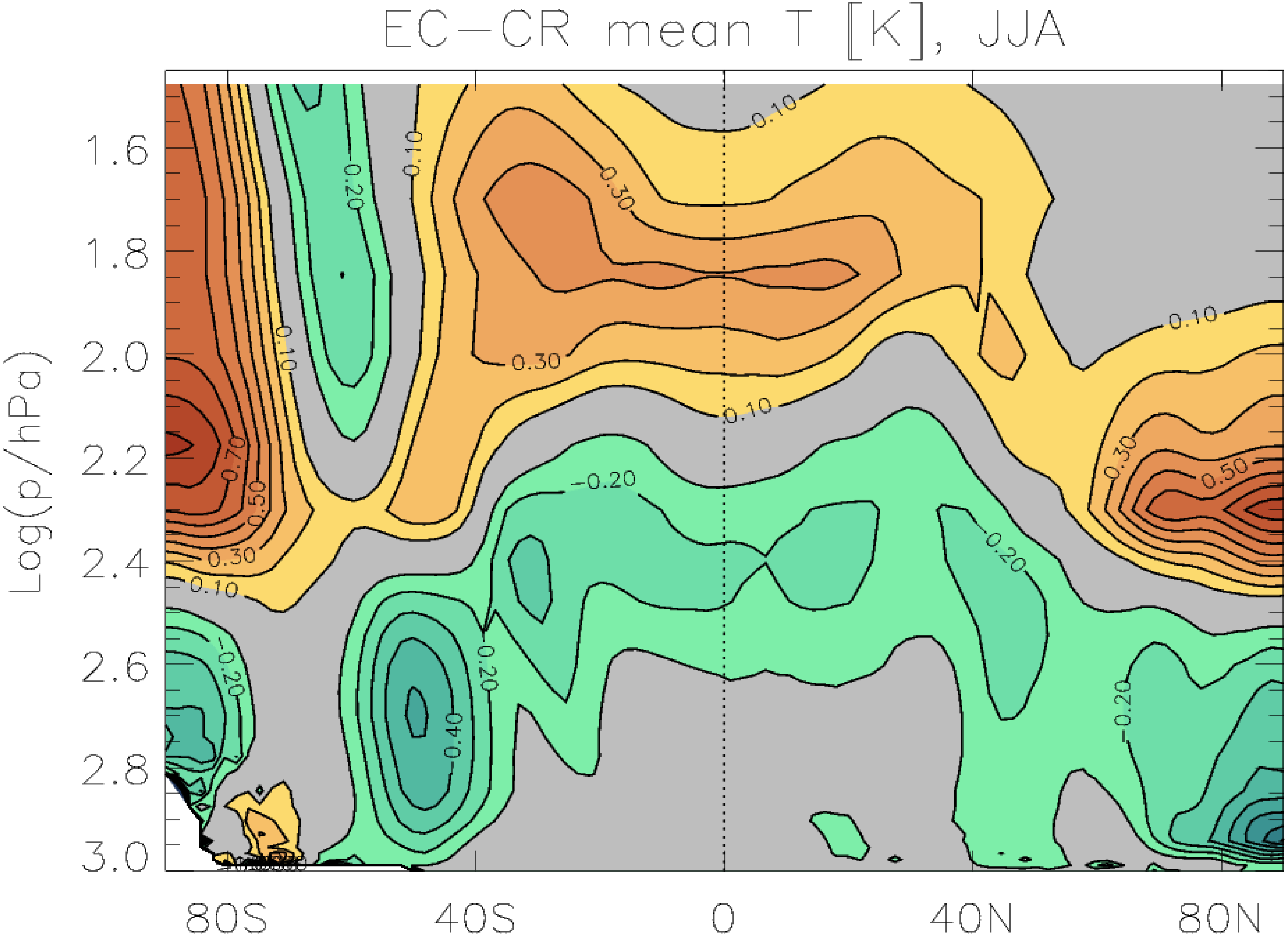


No surface imbalance

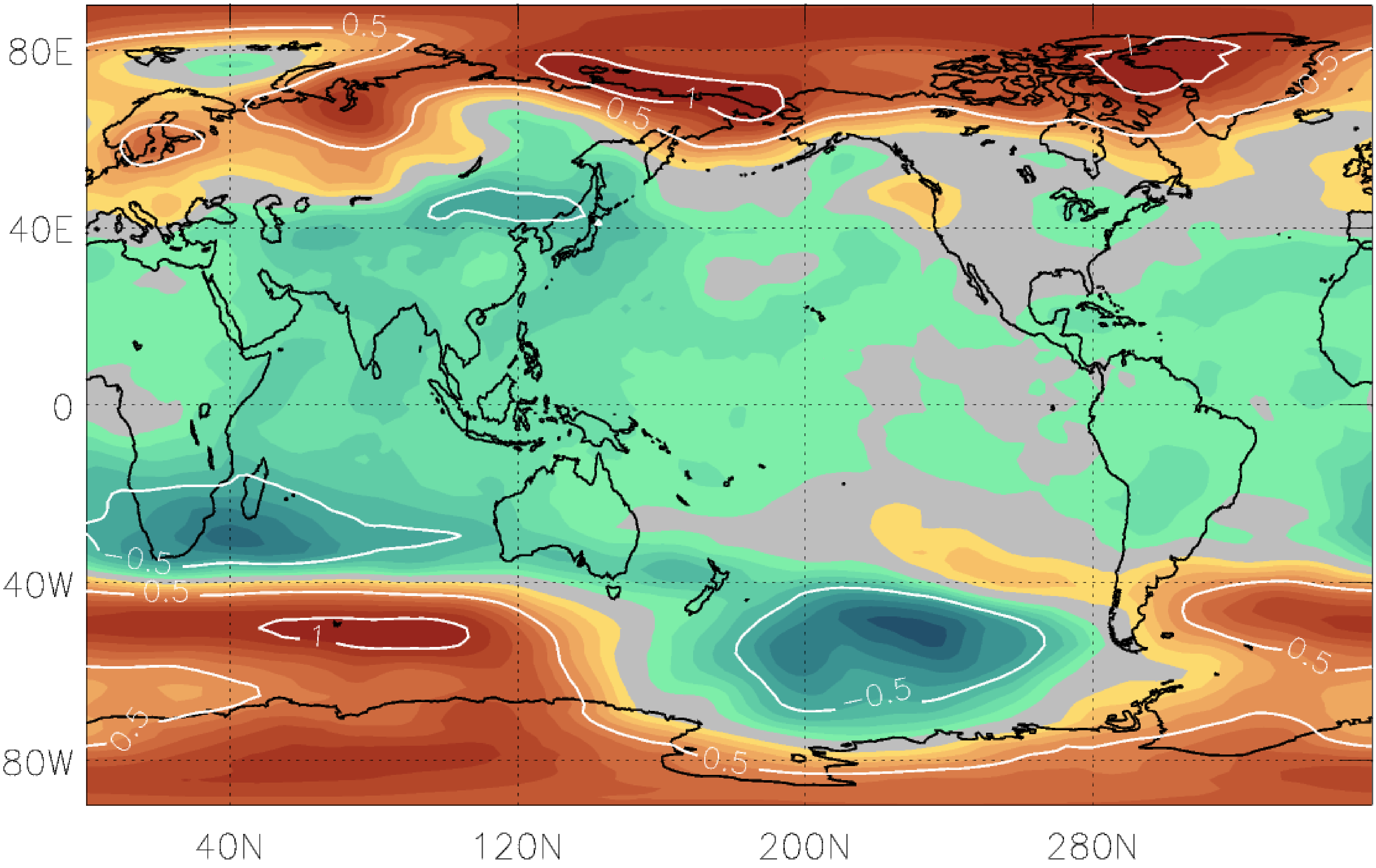
Details 5

Impacts on simulation results

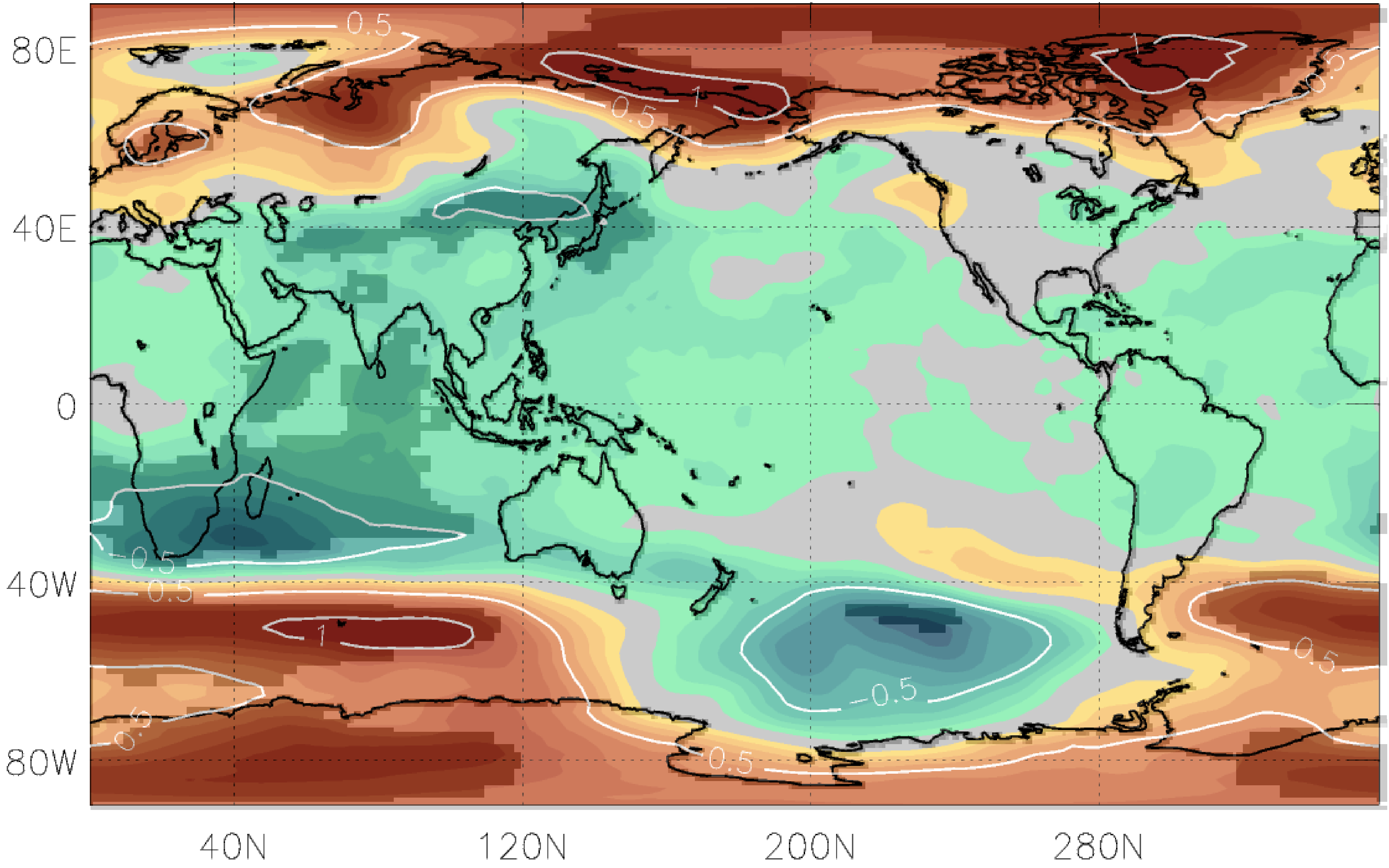

SHF (down) [W/m^2]: EC − CRv3
45N
0
45S
90E
180
90W
0
−7
−3
3
7

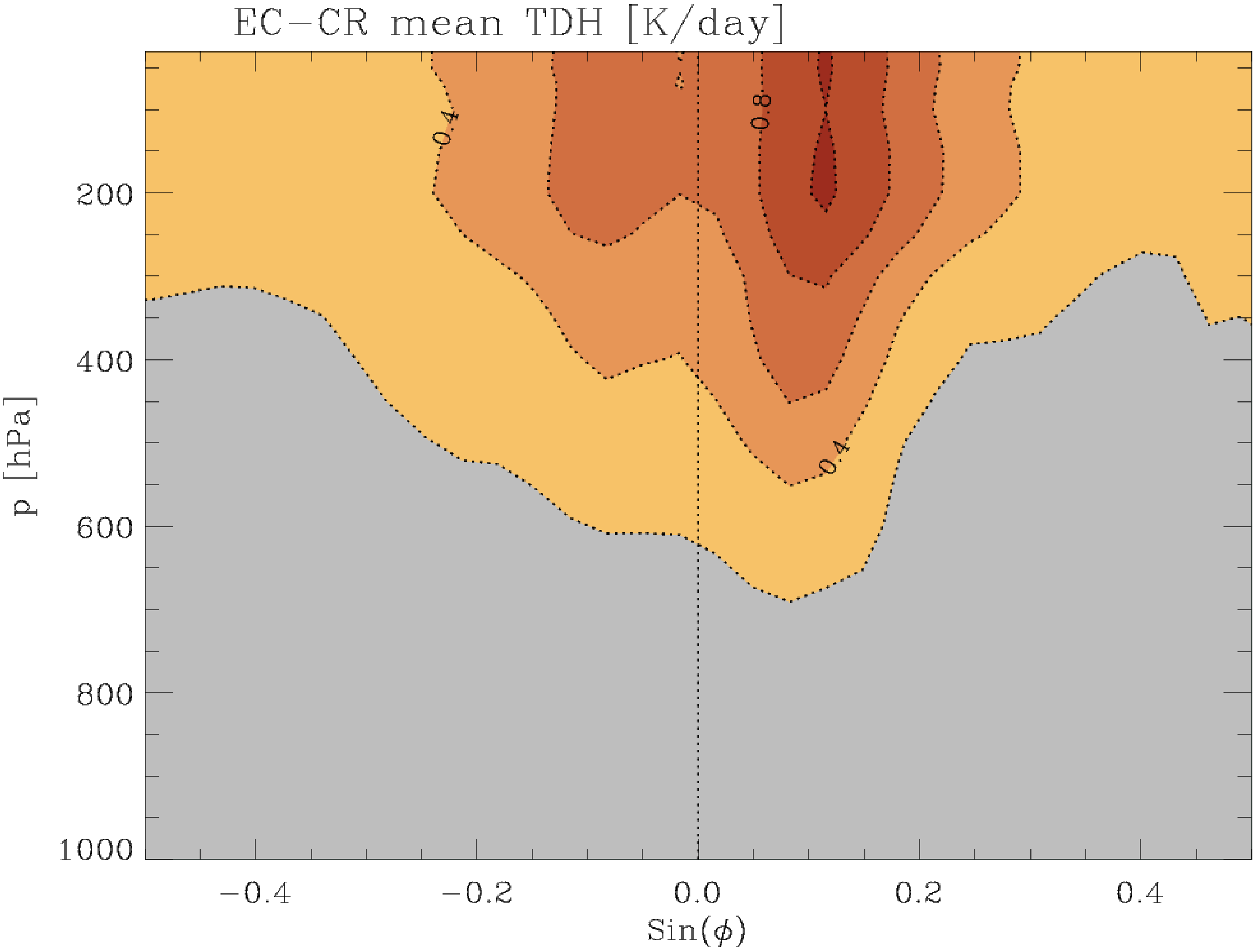

EC−CR mean T [K], JJA
Log(p/hPa)
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
80S
40S
0
40N
80N
0.10
0.20
0.30
0.50
0.70
−0.20
0.40

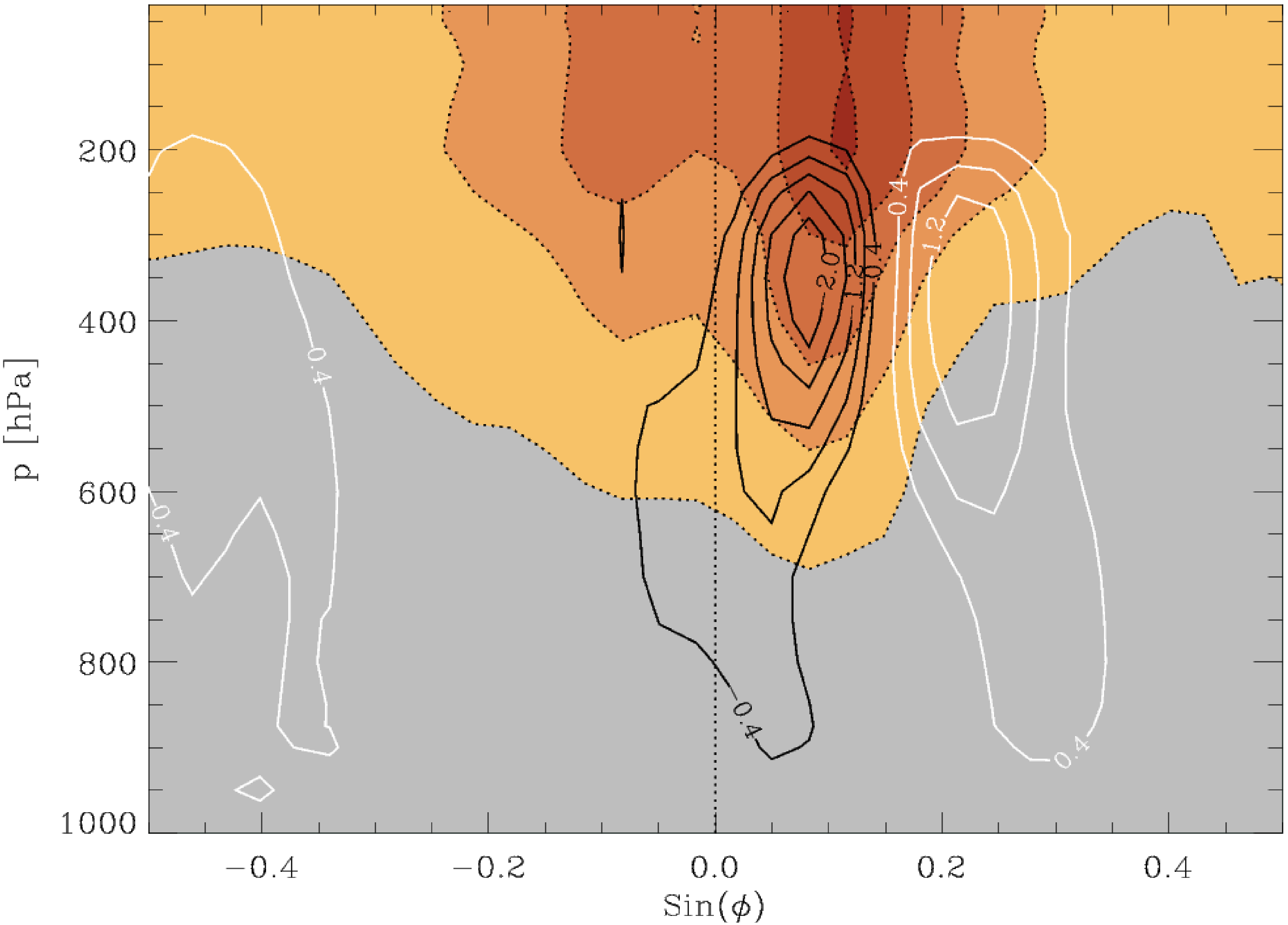
EC–CR mean T [K] @ 200hPa, JJA



EC−CR mean T [K] @ 200hPa, JJA




EC−CR mean TDH [K/day]
p [hPa]
200
400
600
800
1000
−0.4
−0.2
0.0
0.2
0.4
Sin(ϕ)
0.4
0.8
0.4


EC−CR mean TDH [K/day] and Ω [mb/day]

Summary: energy

- Correction of energy errors in CAM involves **3** changes:
  1. Temperature updating (`physics_update`)
  2. Hydrostatic pressure work of layer mass changes (`dme_adjust`)
  3. Enthalpy fluxes associated with mass and evt heat transfers (*eodem*)
- Need to account for boundary fluxes of enthalpy associated with mass exchanges (new diagnostics `EFLX`)
- Implementations given for two “no-physics” assumptions
  1. adiabatic $h_q = h_m$ (AMIP)
  2. “mass-less” $h_q = c_{p,water} T_{surf}$ (coupled)
- Impact on atmosph. mean thermal structure small in AMIP runs
- Impact on air-sea fluxes and diabatic tendencies **NOT** negligible
- Together with COARE boundary flux computation, significant improvements in AMIP and coupled climatologies (NorESM)

Conclusions

- Mass and energy conservation in CAM not exact
- Code revision necessary to enforce energy conservation
- Impact on surface fluxes stronger than on mean state in AMIP simulations