Coupling isobaric physics with isochoric dynamics

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Outline

- Nonhydrostatic model ASUCA
- Issues of suspicious convection growth seen in the JMA's regional model
  - are these issues due to simple coupling "isobaric physics with isochoric dynamics" ?
- Consideration and trial on coupling isobaric physics with isochoric (height-based) dynamics
  - To explore these issues, another coupling method which incorporates the change of cell volume in condensation is tested
    - Description of the coupling method
  - Tests and Results

specification of the dynamical core "ASUCA"

	ASUCA
Governing equations	Flux form Fully compressible equations
Prognostic variables	ρu, ρv, ρw, $\rho\theta_m$, ρ
Spatial discretization	**Finite volume method**
Time integration	Runge-Kutta 3rd (long and short)
Treatment of sound	Conservative Split explicit
Advection	Combining 3rd and 1st order upwind with flux limiter by Koren(1993)
Numerical diffusion	None
Treatment of rain-drop	Time-split
Coordinate	Generalized coordinate or Conformal mapping + **constant height-based**
Grid	Arakawa-C (hor.) Lorentz (ver.)

Time integration loop of ASUCA

(Simplified from the viewpoint of dynamics-condensation)

Start of time integration loop

Physical process

RK3 loop (long)

Advection, Colioris, Curvilinear, Rayleigh damping

Start of sound loop

Start of RK3 loop (short)

HE-VI

End of RK loop (short)

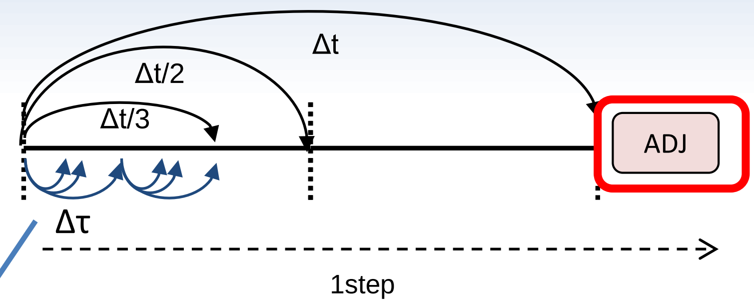
End of sound loop

End of RK loop (long)

Adjustment physics ← **Microphysics**

Time integration with the tendencies of adjustment physics

End of time integration loop

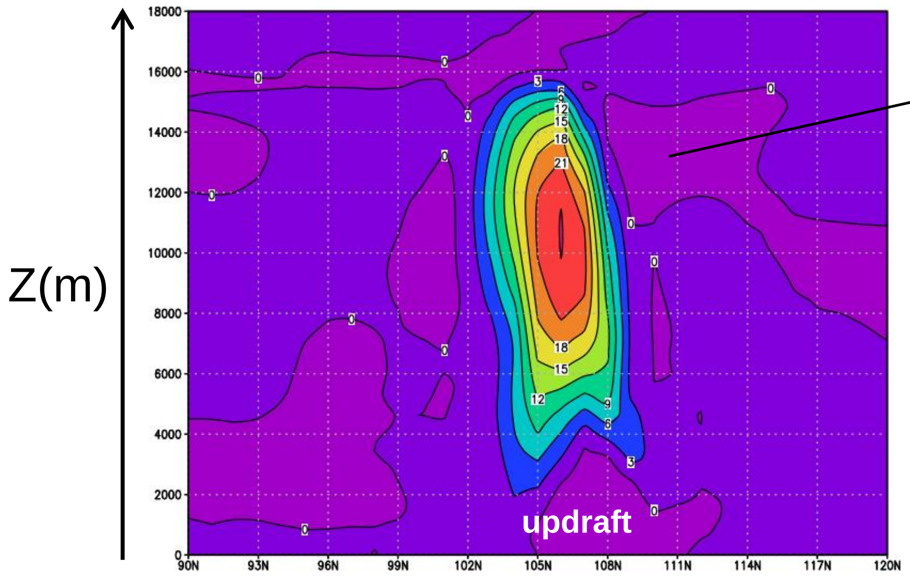


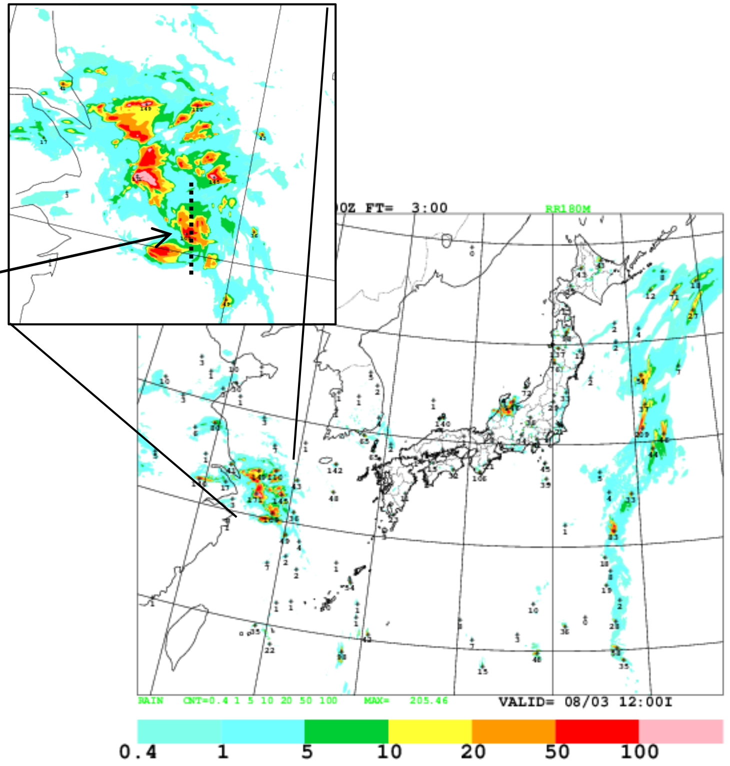
HE-VI:

- Time integration of $\rho u/J$, $\rho v/J$ ($\tau \rightarrow \tau + \Delta\tau$)
- Time integration of $\rho w/J$ ($\tau \rightarrow \tau + \Delta\tau$)
- Time integration of ρ/J ($\tau \rightarrow \tau + \Delta\tau$)
- Time integration of $\rho\theta m/J$ ($\tau \rightarrow \tau + \Delta\tau$)

motivation

- JMA's operational regional model
  - issues of suspicious convection growth

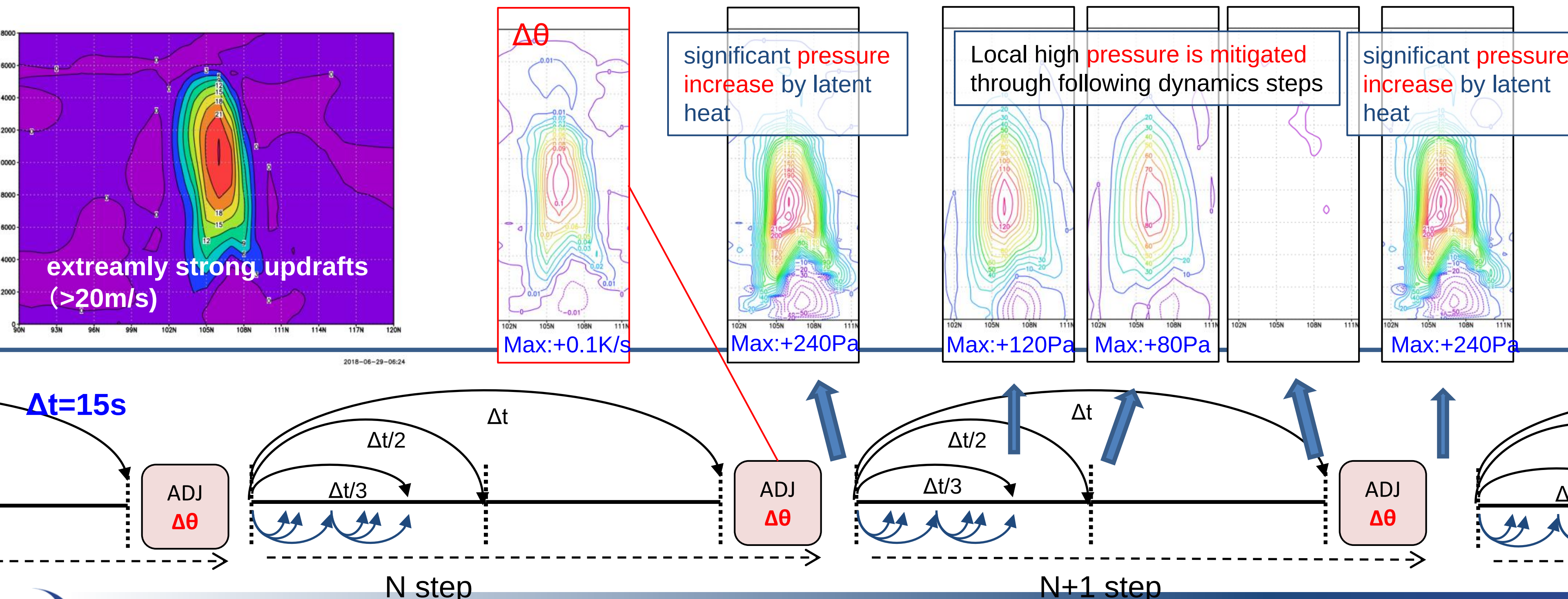




Operational regional model
Dx=dy=2km, dt=16.666s
For test: dt=15s for monitoring

motivation

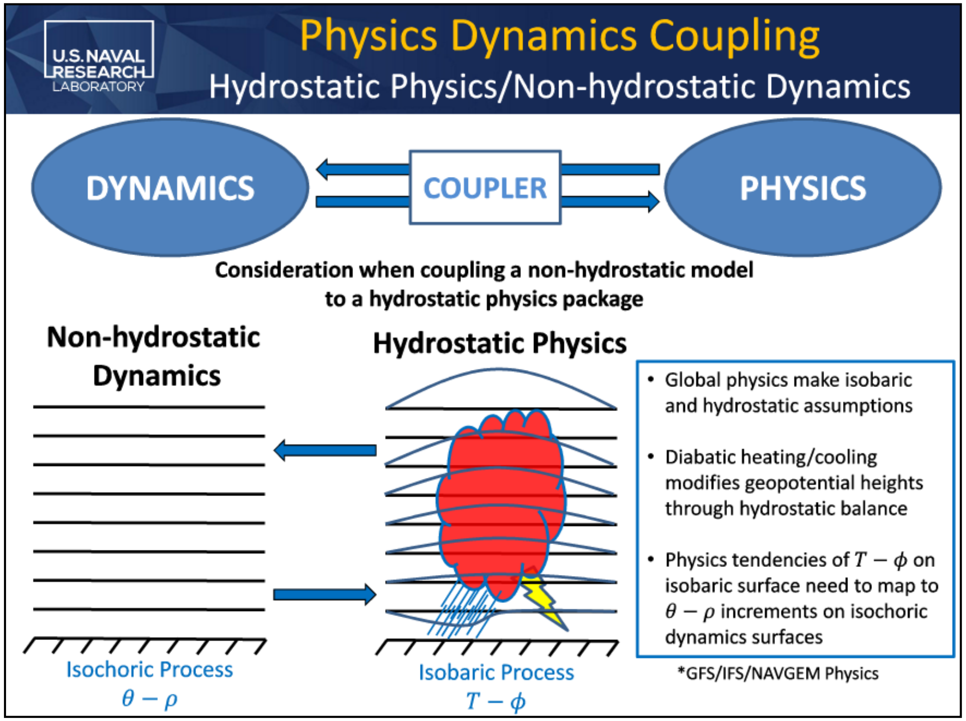
- at a column convection is occurred
  - repeat of local pressure increasing and decreasing
    - pressure increase (>2hPa/15s) by latent heat
    - mitigating local high pressure through following dynamics steps
    - are repeated every time step. It seems unrealistic.
- extremely strong updraft



motivation

- **Our suspicion: are these two issues due to simple coupling "isobaric physics with isochoric dynamics" ?**
  - explore the issues comparing to another coupling method which incorporates the change of cell volume in condensation.

↓ We refer to this slide concept



Alex Reinecke et al: COUPLING PHYSICAL PARAMETARZATION TO A THREE-DIMENSIONAL SEM MODEL.
ECMWF workshop:Shedding light on the greyzone
https://www.ecmwf.int/en/learning/workshops/shedding-light-greyzone

48h NEPTUNE forecast

- **Most significant difference in tropical upper troposphere**
- **Large difference associated with deep convection in tropics**

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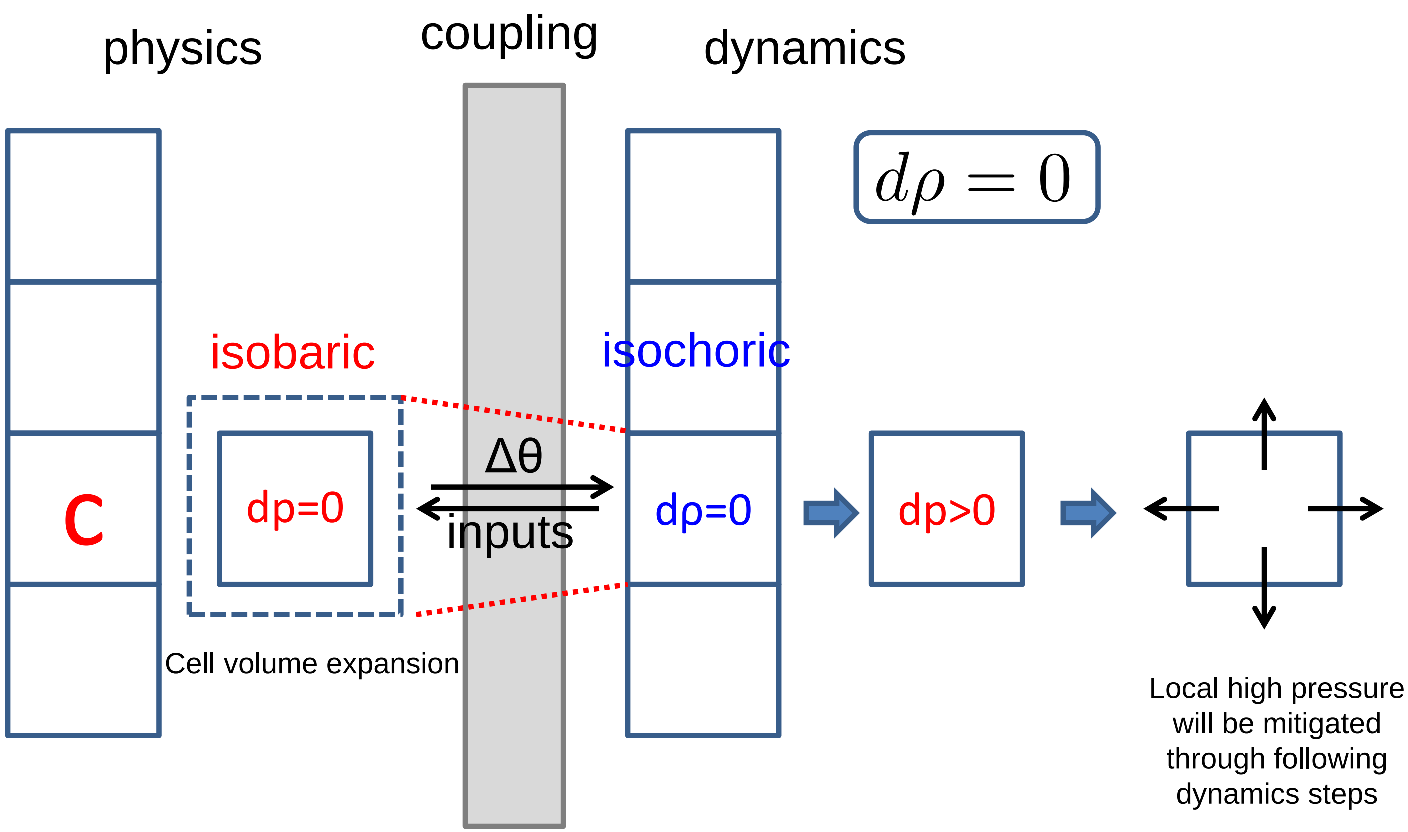
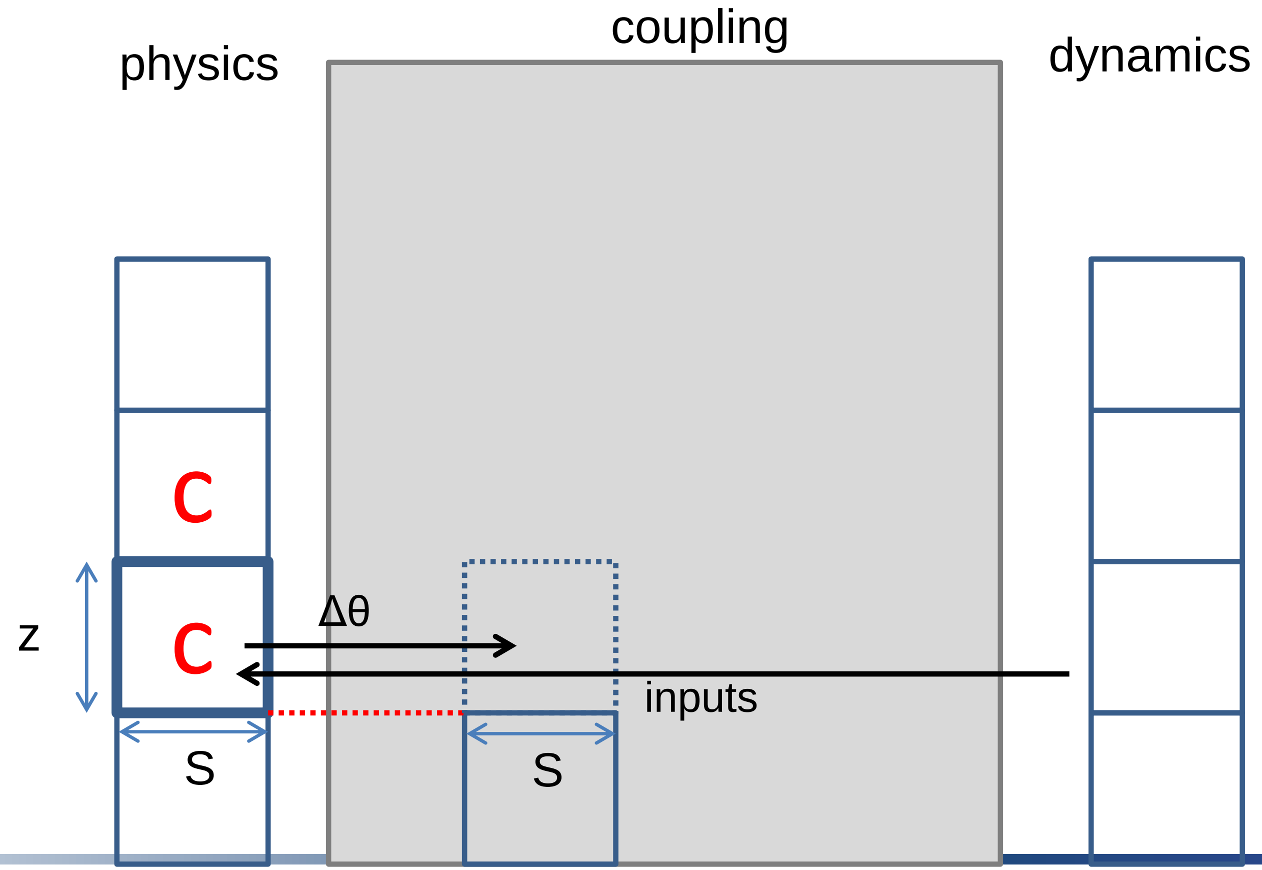
Coupling isobaric physics with isochoric dynamics

- Current coupling
  - passes **inputs** to physics, then receives **tendencies (Δθ)**
  - assume that total density in each cell is kept constant. ⇒ $dp \neq 0$



Coupling isobaric physics with isochoric dynamics

- Coupling (Test): incorporates the change of cell volume in condensation
  - passes **inputs** to physics, then receives **tendencies (Δθ)**
  - assume that pressure in each cell is kept constant. ⇒ $d\rho \neq 0$
    - incorporates the change of cell volume
    - Tendencies could be distributed to multiple cells



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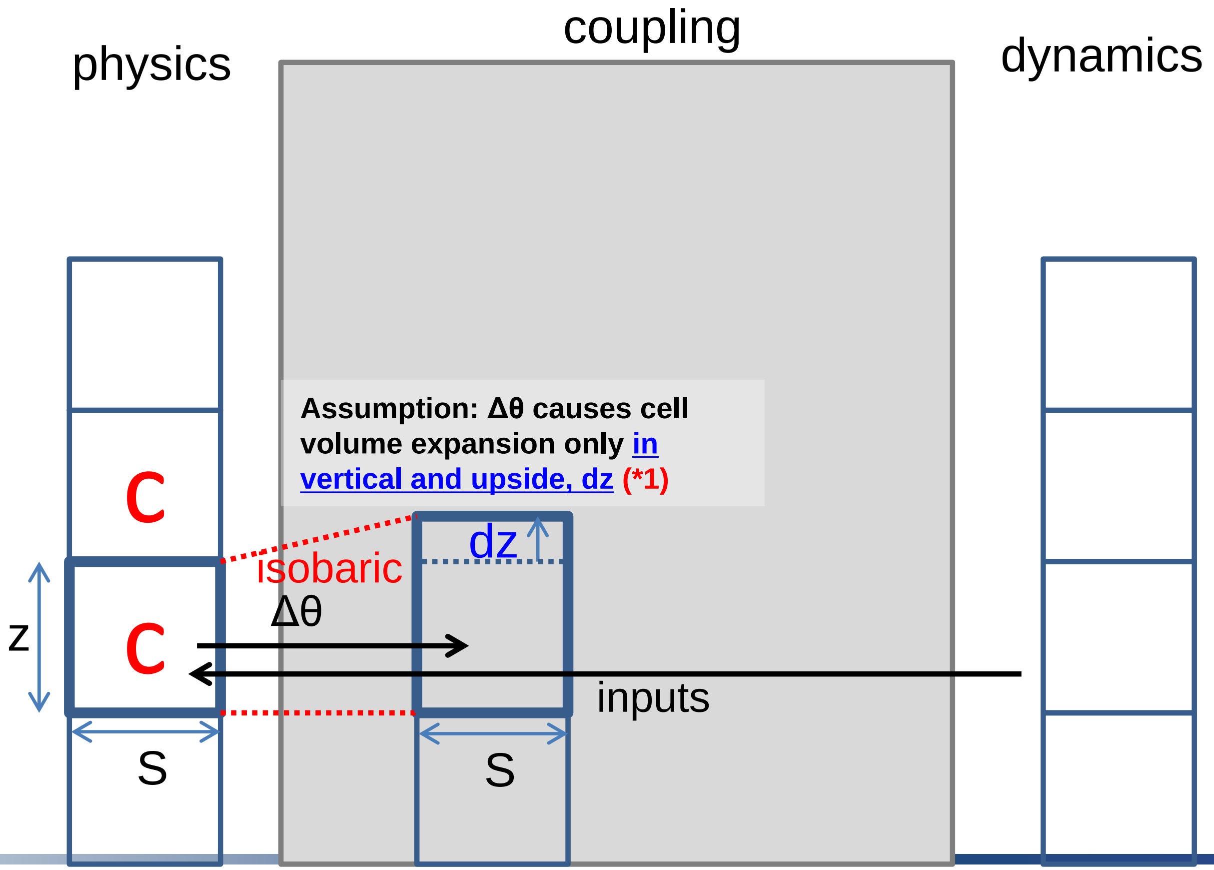
(*1)
(Assume isobaric process)
$dp = d\rho \cdot RT + \rho R \cdot dT = 0$
$\rightarrow d\rho = -\rho \cdot dT/T = -\rho\pi d\theta/T = -\rho \cdot d\theta/\theta$ (1)

(total mass conservation)
$d(\rho z S) = 0$
$\rightarrow dz = -z \cdot d\rho/\rho$ (2)

With (1) and (2)
$\Rightarrow dz = z \cdot d\theta/\theta$



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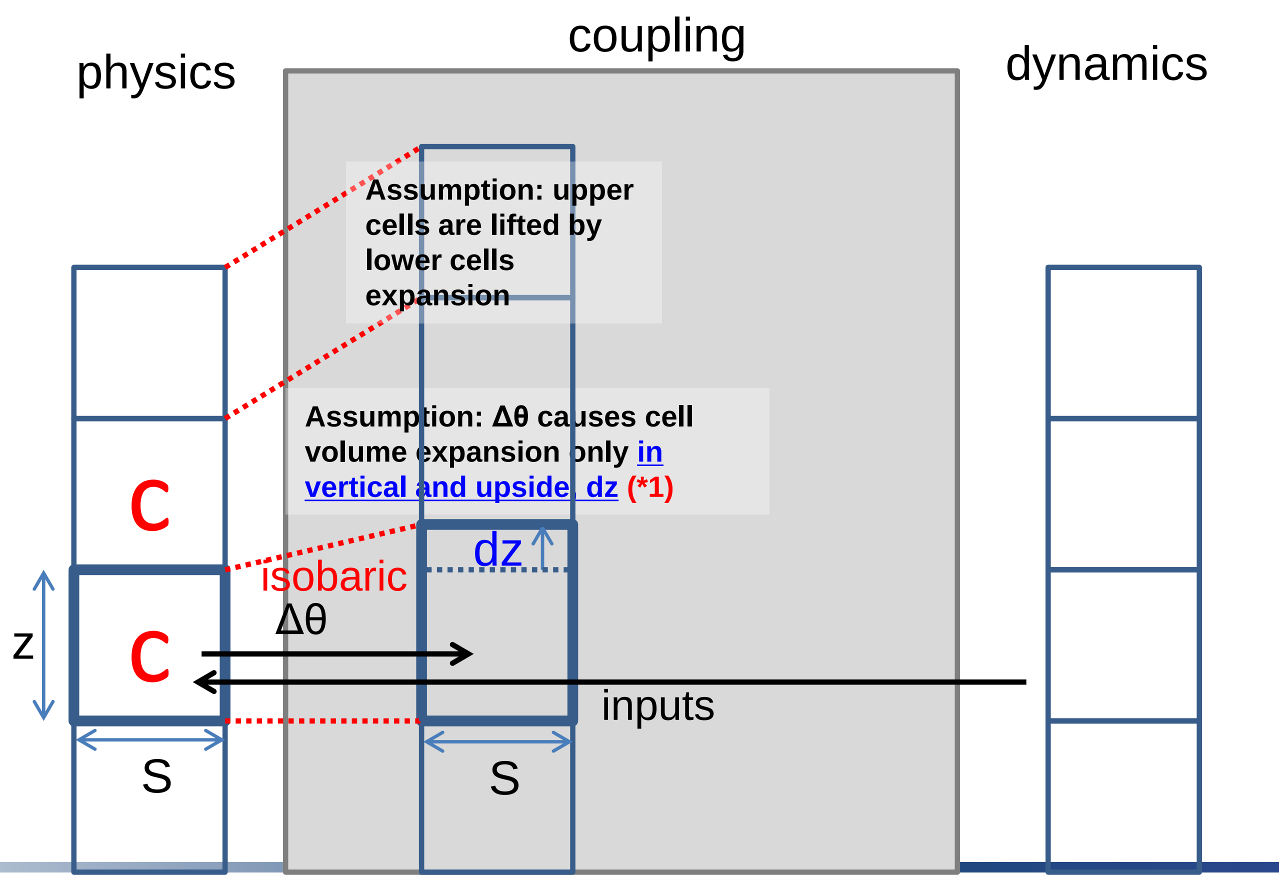

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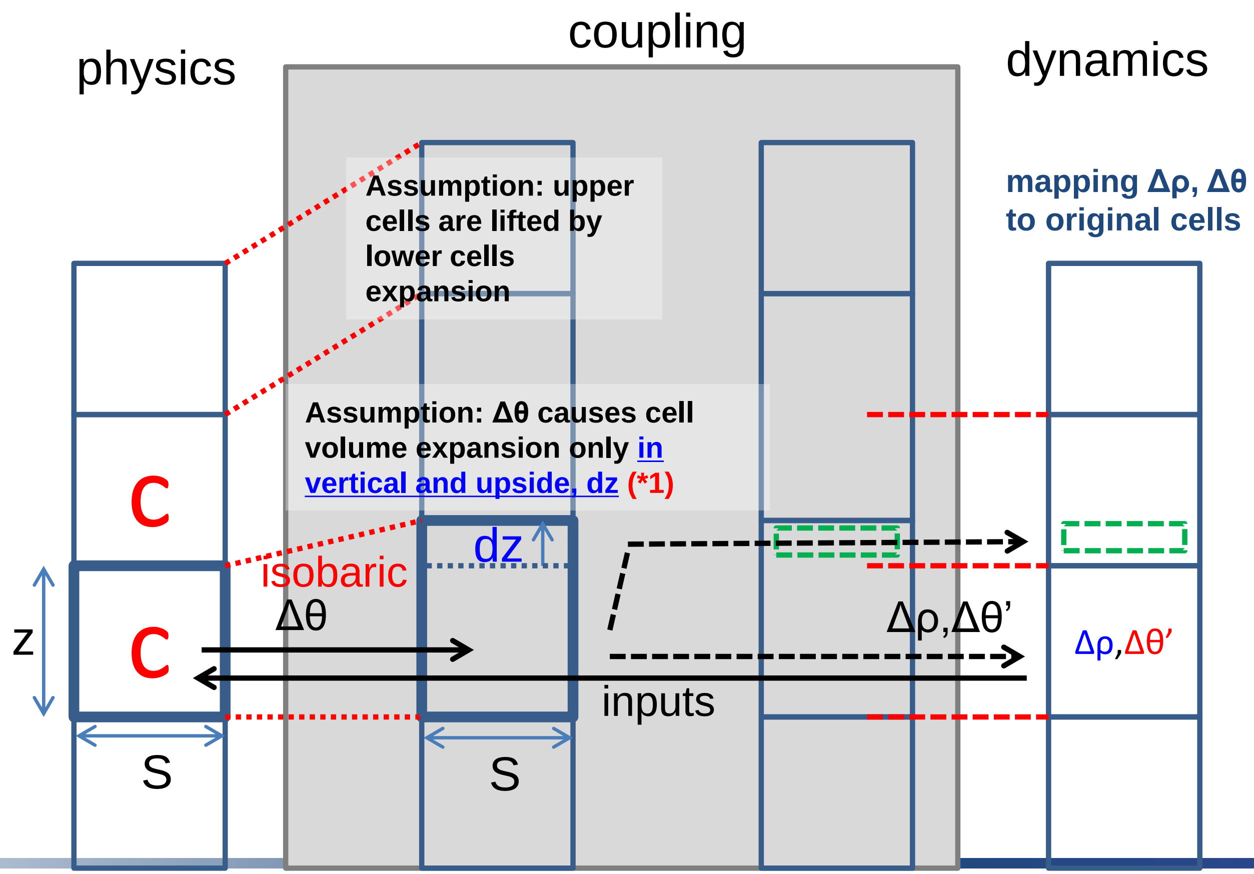

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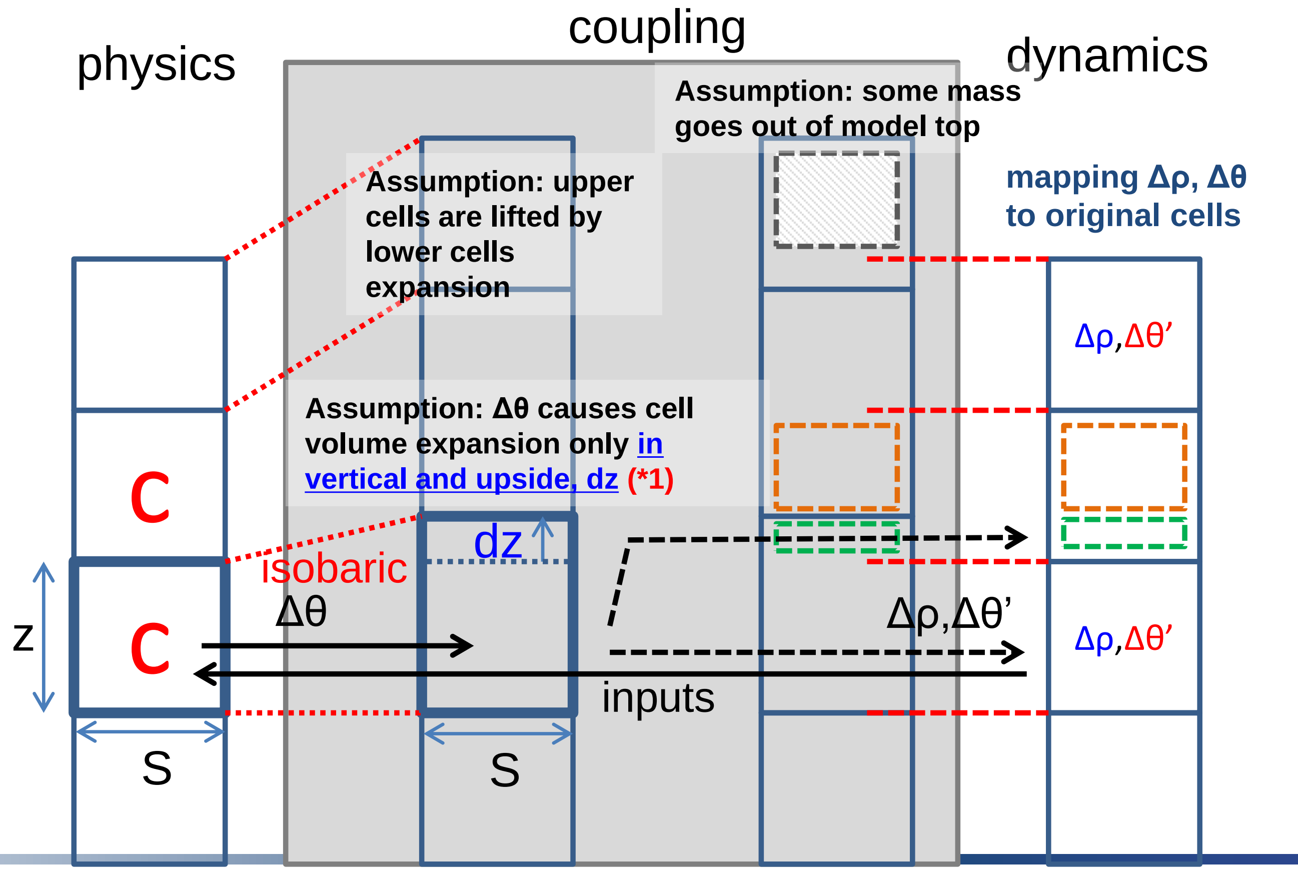

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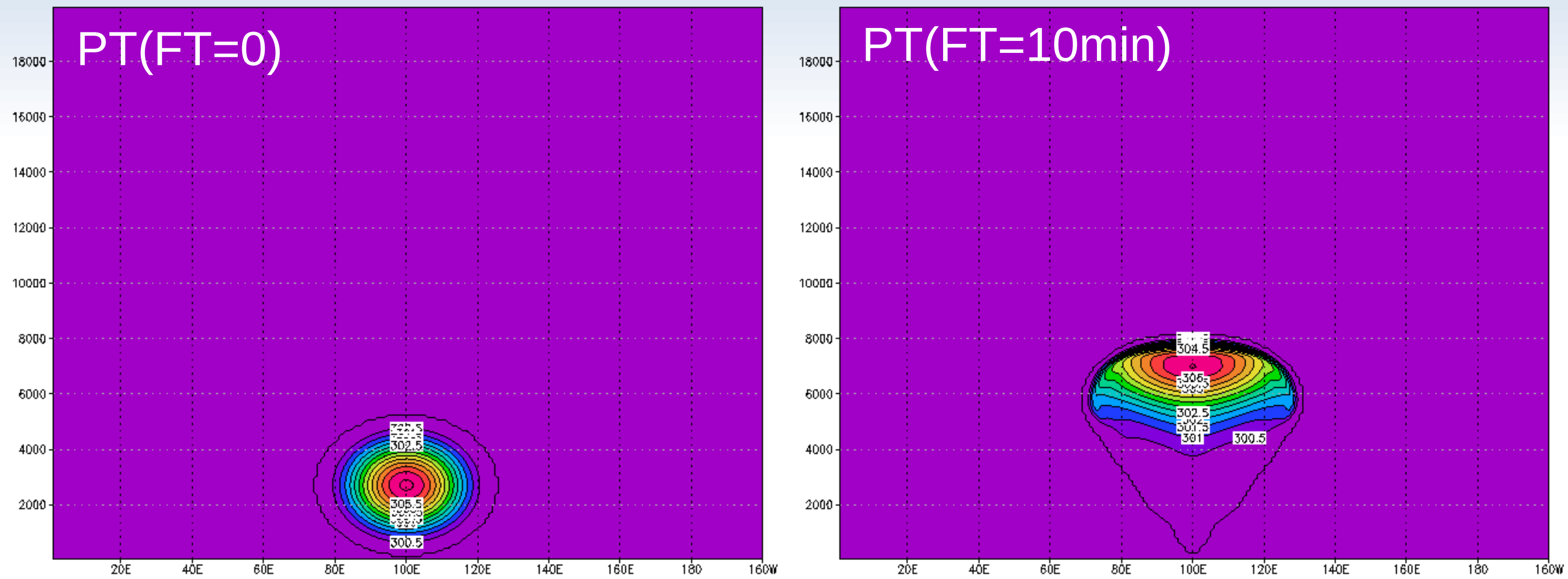
dx=dz=100m
dt=10s

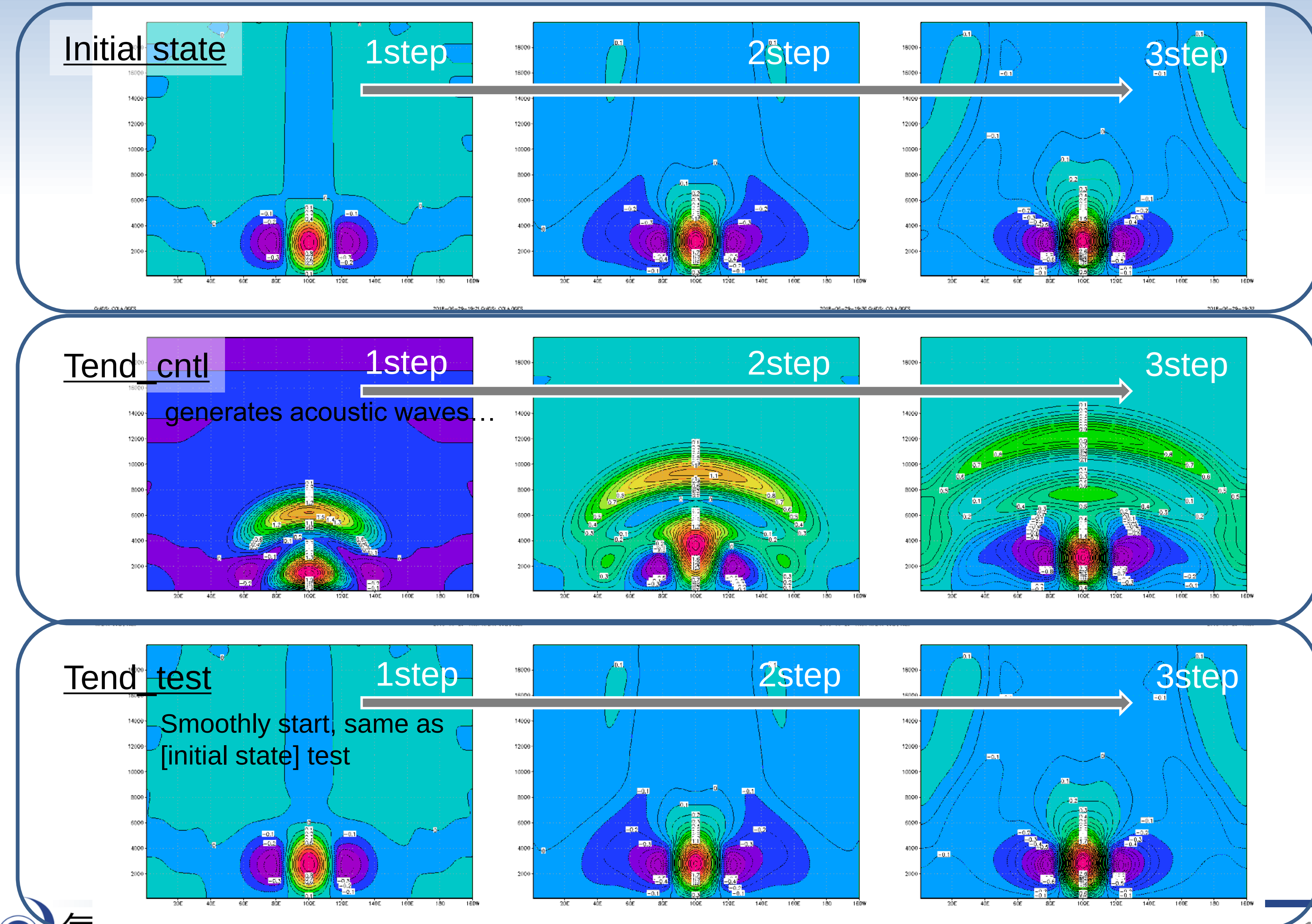
Warm bubble test



- Check the representation of warm bubble rising
  - **[Initial state]**: add PT perturbation(+6.6K), and make initial state (vertically balanced)
  - **[Tend_cntl]**: add PT tendency(+6.6K/Δt) at adjustment physics in 1st step with current coupling
  - **[Tend_test]**:add PT tendency (+6.6K/Δt) at adjustment physics in 1st step **with experimental coupling incorporates the change of cell volume**
- As for [**Tend_cntl**] and [**Tend_test**], does it work? How is the Initial behavior comparing to **[Initial state]**? Is there any obvious difference in the final distribution of W or PT among these tests?

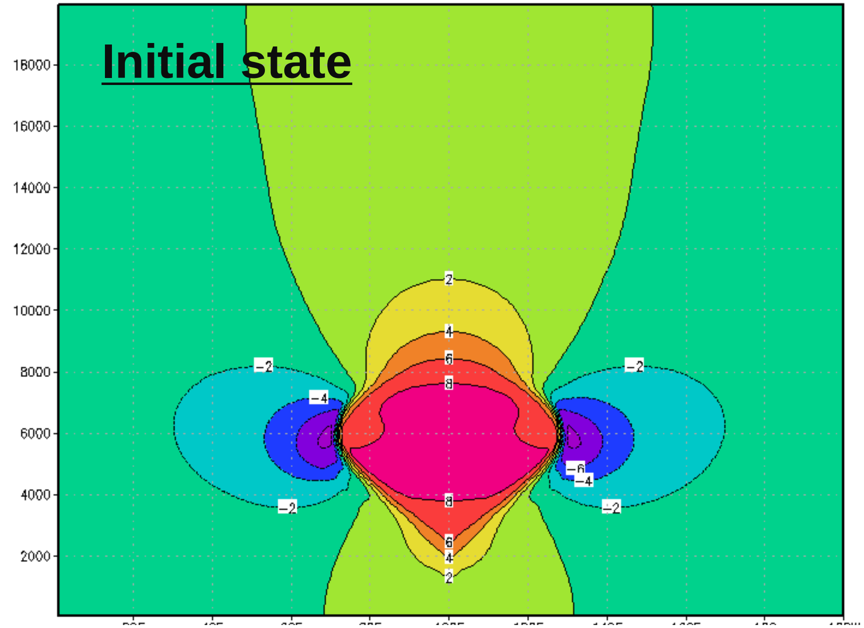
Initial behavior is different between [Tend_cntl] and [Tend_test]

W [m/s]

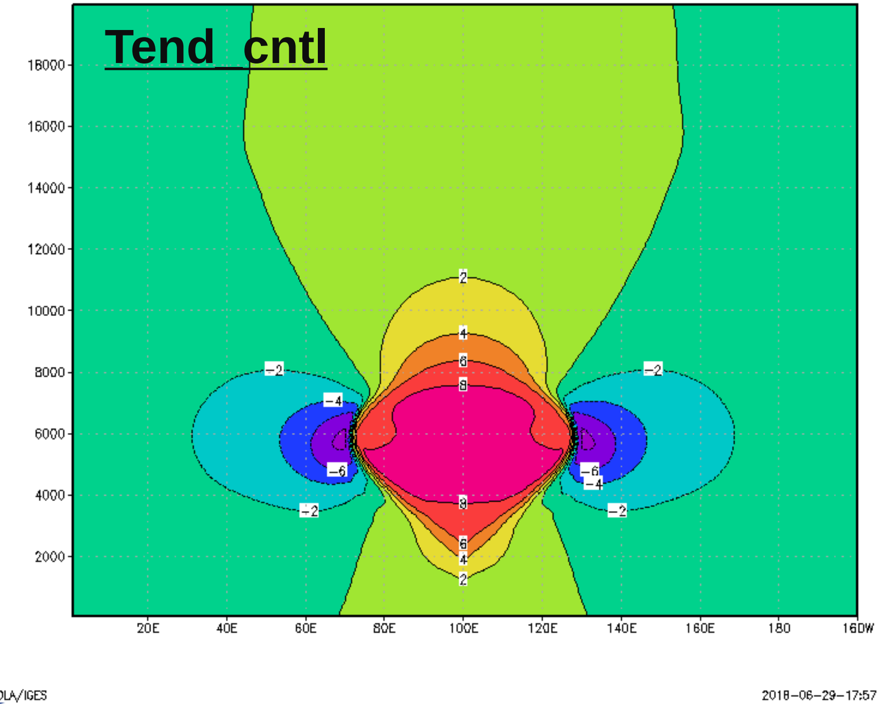


At 10min

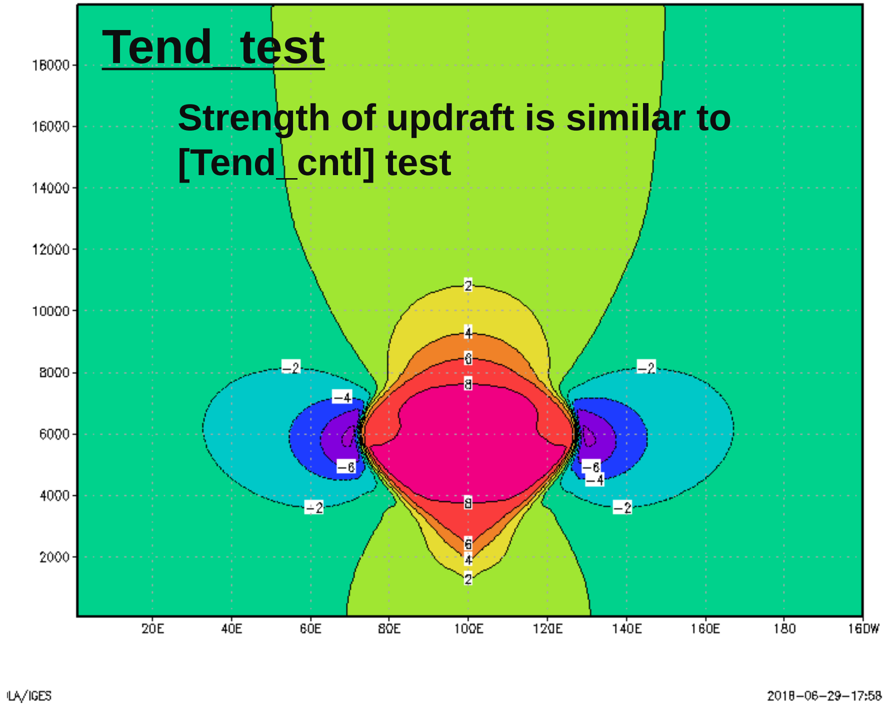
W [m/s]



Initial state
18000
16000
14000
12000
10000
8000
6000
4000
2000



Tend_cntl
18000
16000
14000
12000
10000
8000
6000
4000
2000
20E
40E
60E
80E
100E
120E
140E
160E
180
160W
GrADS: COLA/IGES
2018-06-29-17:57

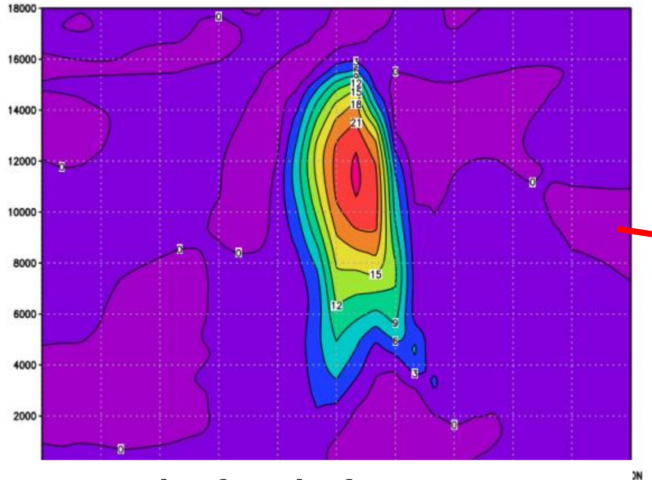


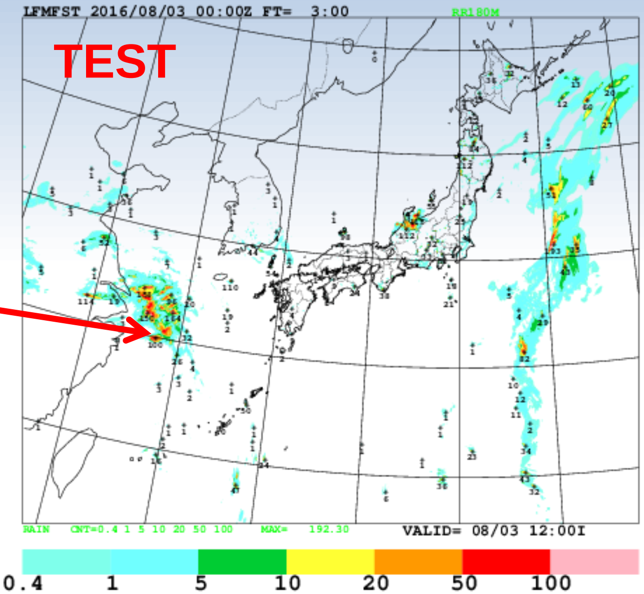
Tend_test
Strength of updraft is similar to [Tend_cntl] test
18000
16000
14000
12000
10000
8000
6000
4000
2000
20E
40E
60E
80E
100E
120E
140E
160E
180
160W
2018-06-29-17:58

From a warm bubble test

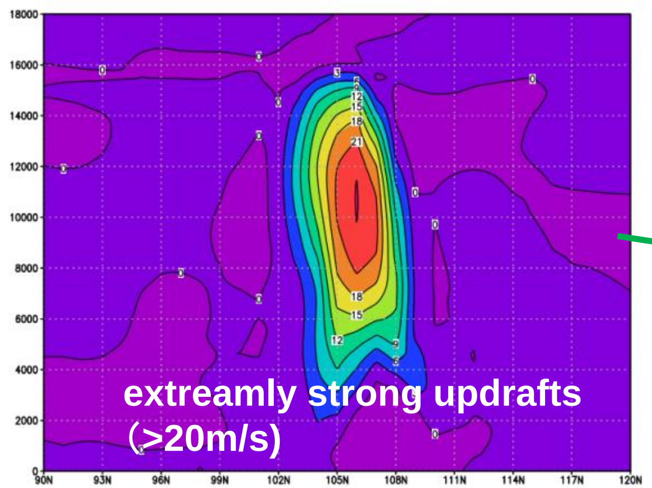
- Current coupling
  - can represents the main characteristics of rising warm bubble
    - strength of updraft does not change comparing to [initial state] test
  - tend to generate acoustic waves
    - by the repeat of local pressure increasing and decreasing
- Experimental coupling
  - can represents the main characteristics of rising warm bubble
    - strength of updraft does not change comparing to the current coupling
  - not generate acoustic waves
    - repeat of local pressure increasing and decreasing is modified, as expected

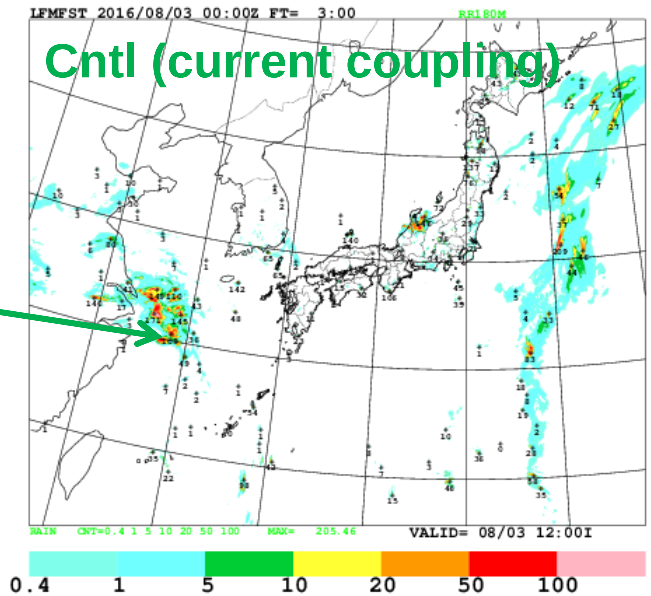
“extremely strong updrafts” case

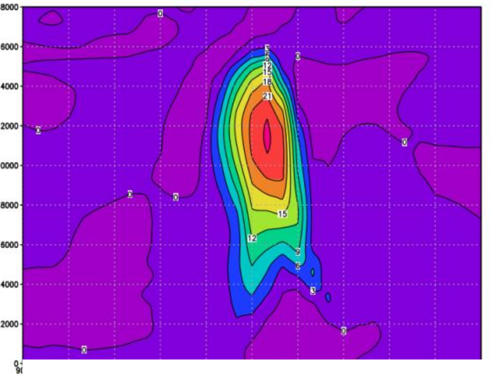




strength of updraft were not inherently changed.







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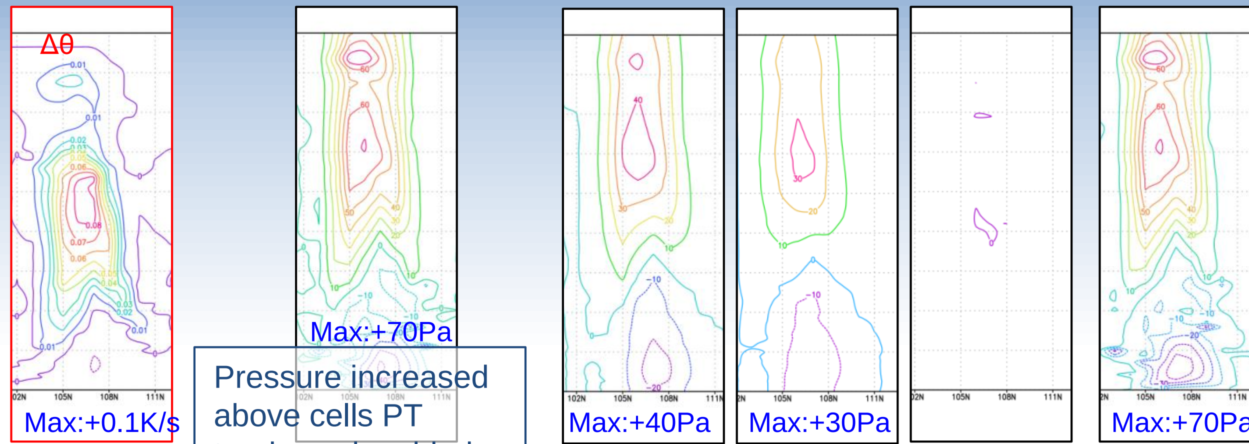
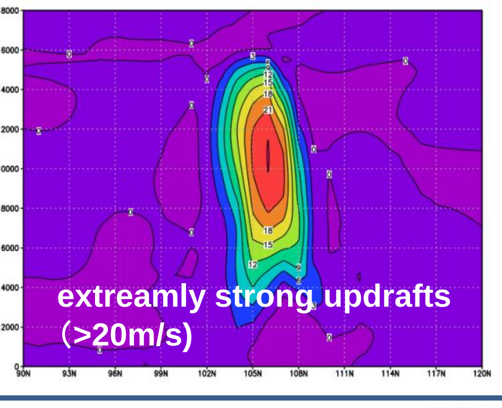
TEST

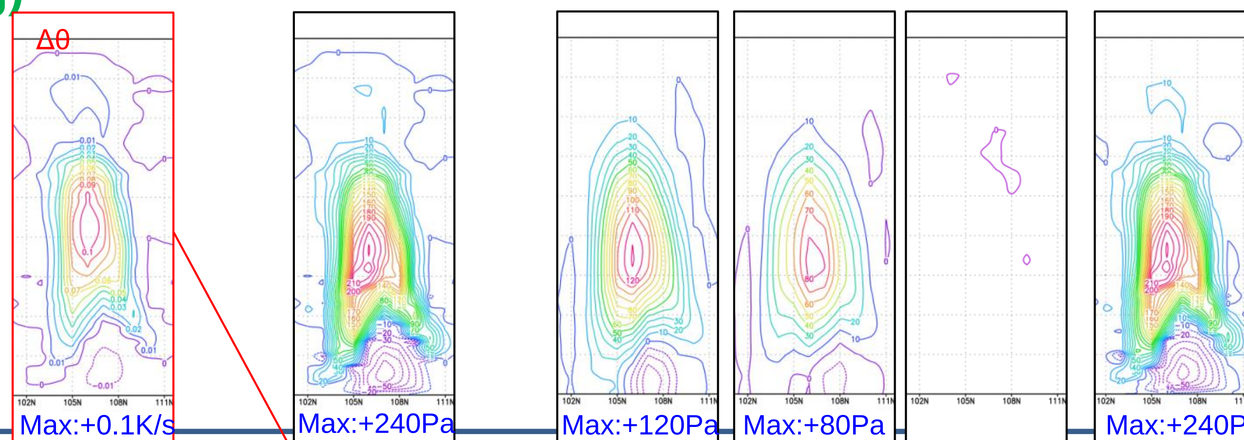


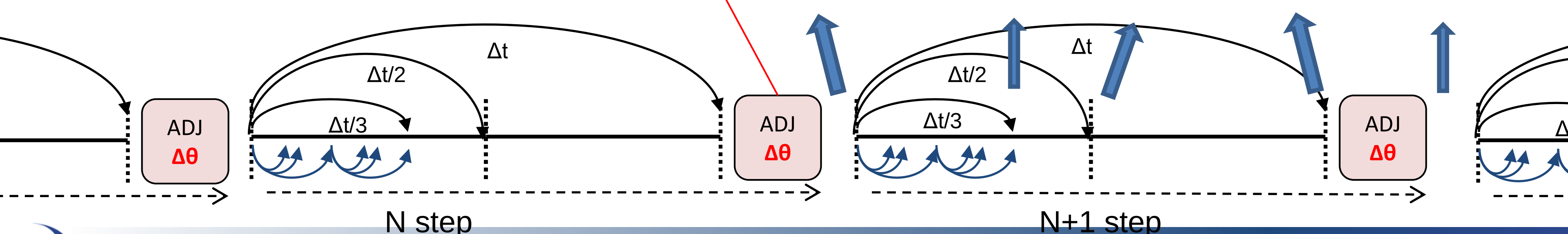
Pressure increased above cells PT tendency is added

Same behavior observed in warm bubble test

Cntl(current coupling)





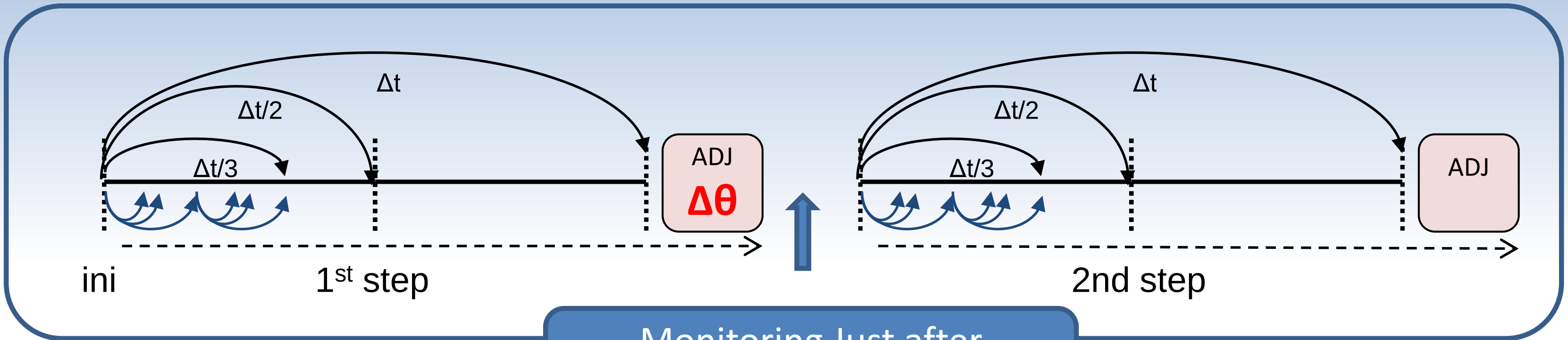


Conclusion

- Issues of suspicious convection growth seen in the JMA’s regional model
  - repeat of local pressure increasing and decreasing
  - extremely strong updraft
- Simple coupling method which incorporates the change of cell volume (isobaric) in condensation is tested
  - can mitigate repeat of local pressure increasing and decreasing
  - do not affect to mitigate the strength of updraft
    - we need to keep study to address the strong updraft issue including another approach other than PDC coupling

BACKUP

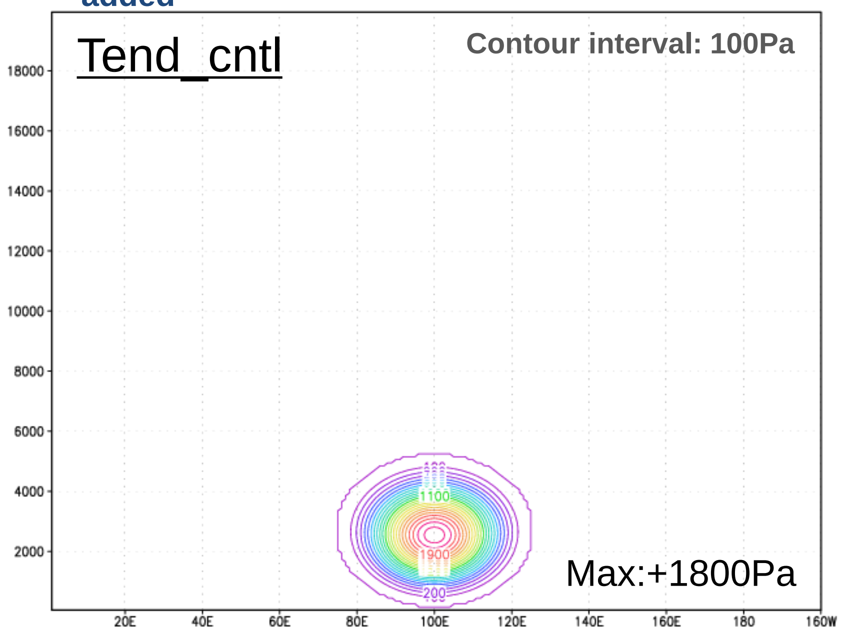
Reaction to the tendency in detail



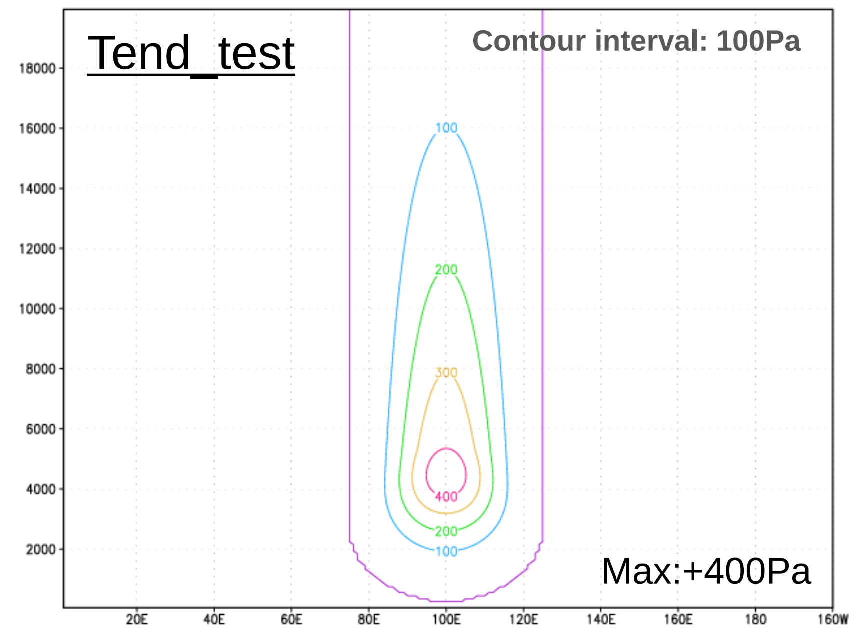
Monitoring Just after
the adjustment at 1st step

pressure change from initial state

Pressure increased at cells PT tendency is added



Pressure increased above cells PT tendency is added



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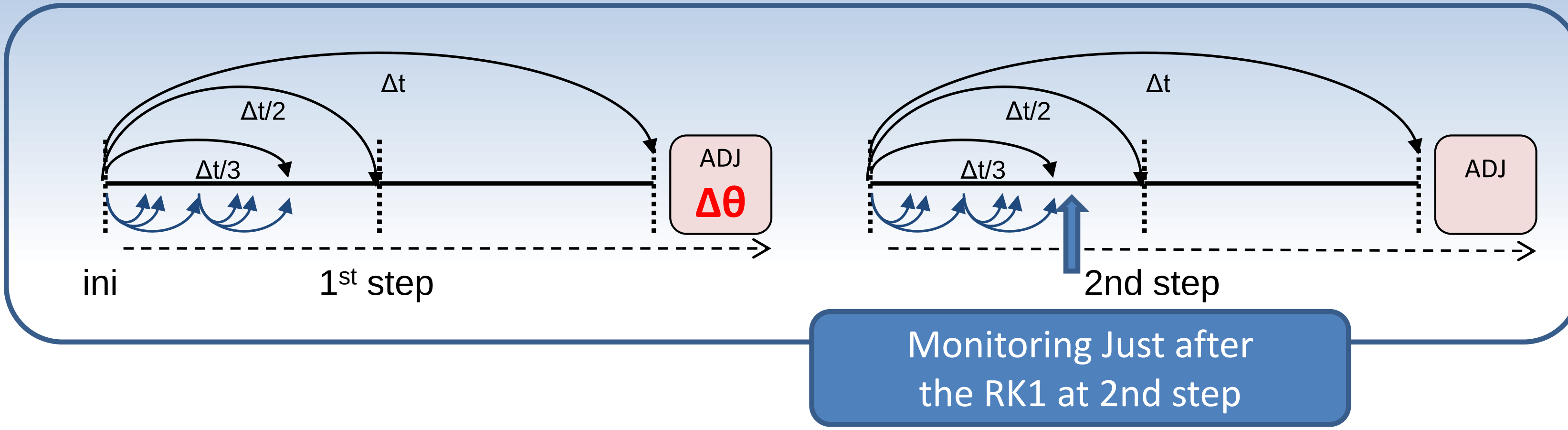
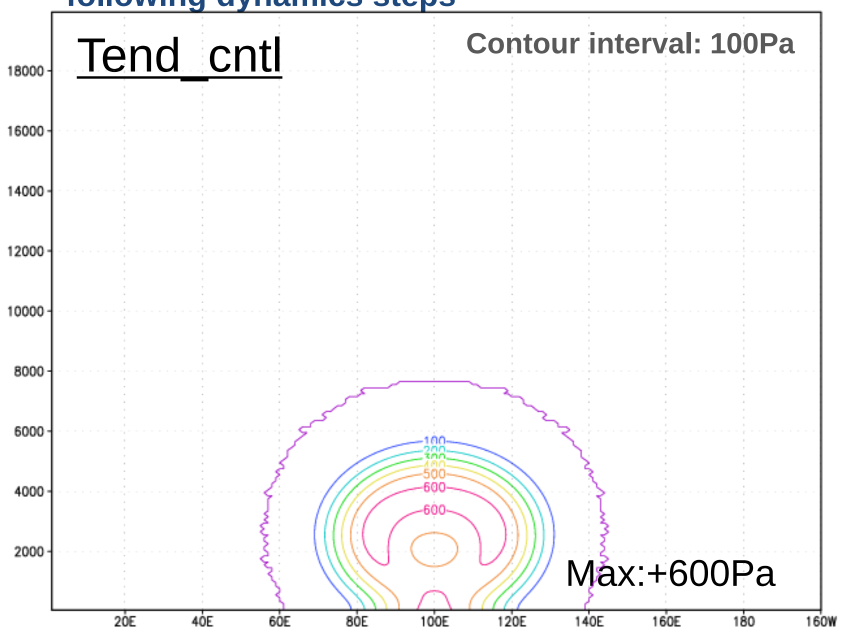
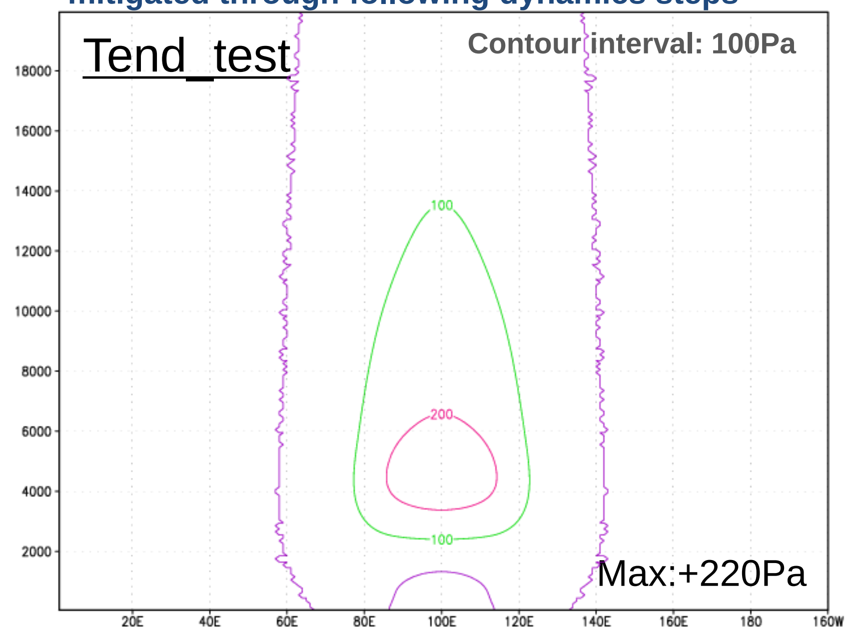


pressure change from initial state

Local high pressure is mitigated through following dynamics steps



Local high pressure (relatively small) is mitigated through following dynamics steps



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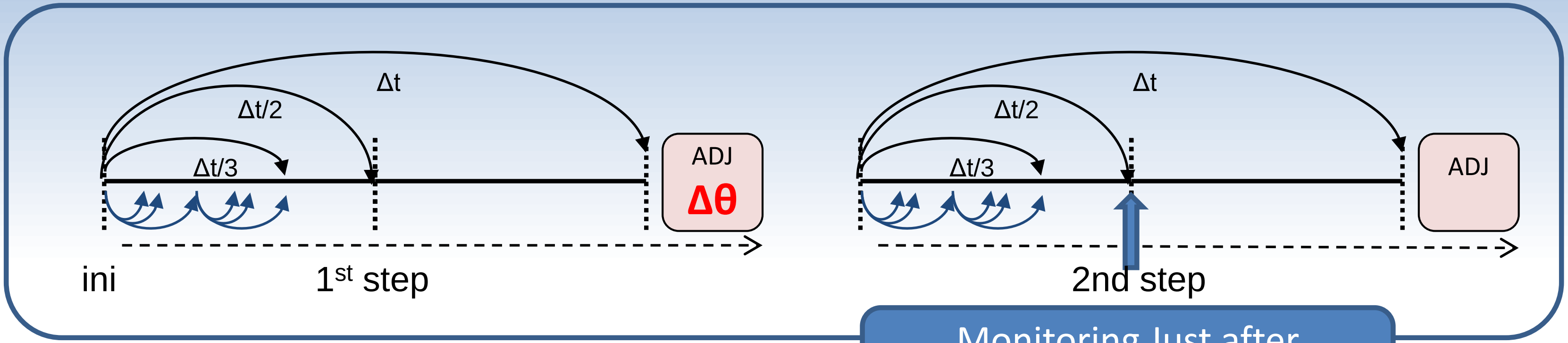
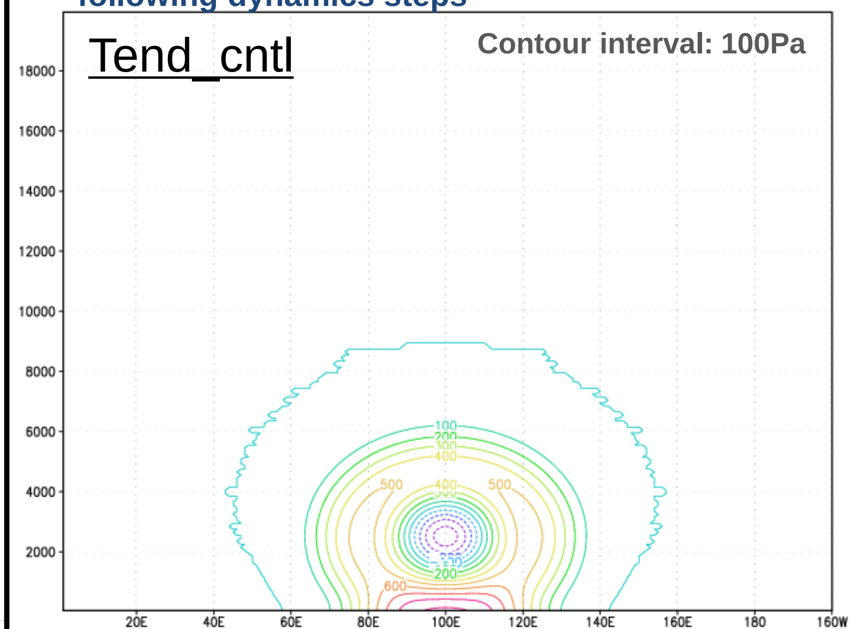


Monitoring Just after the RK2 at 2nd step

pressure change from initial state

Local high pressure is mitigated through following dynamics steps



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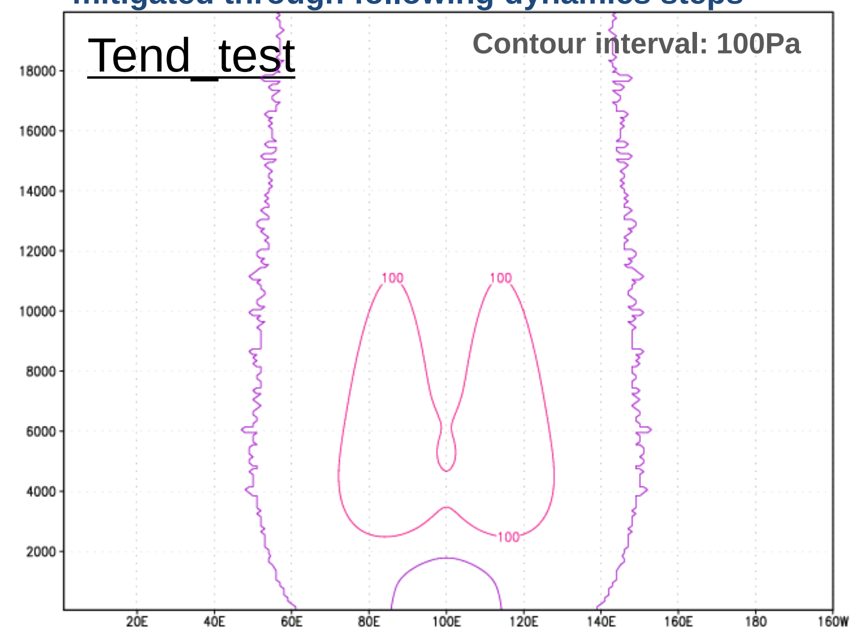

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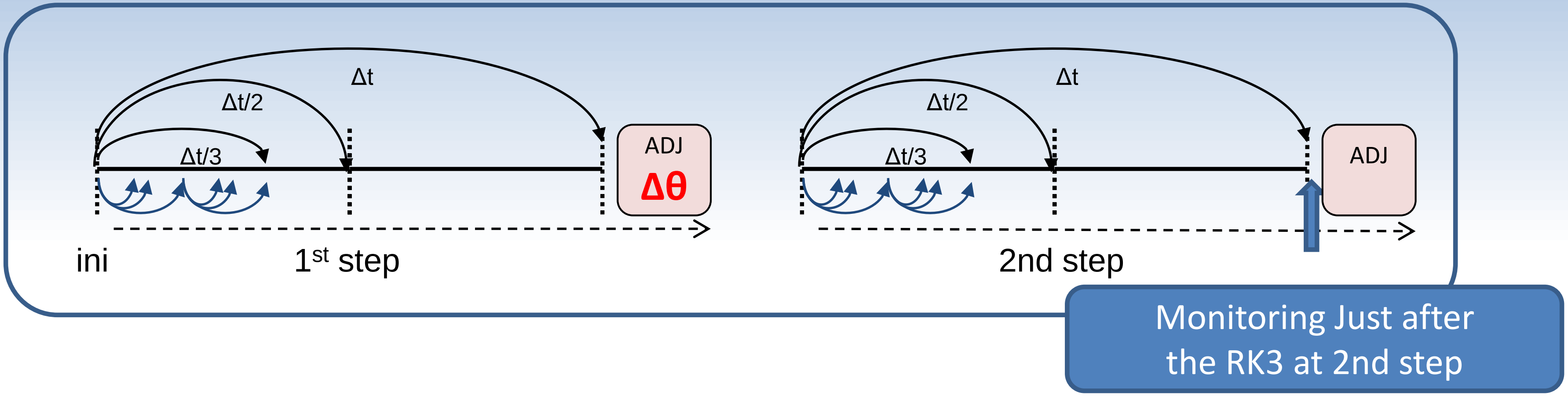

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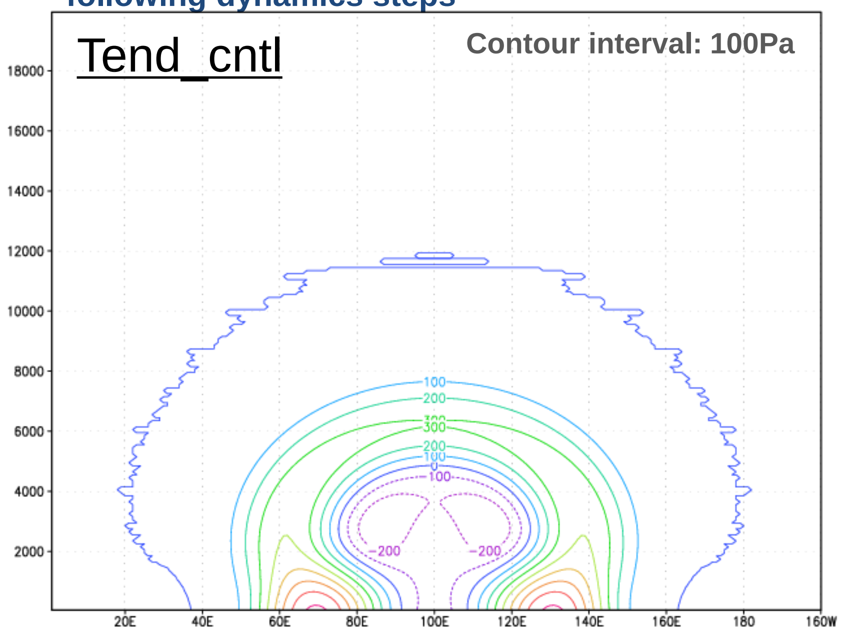

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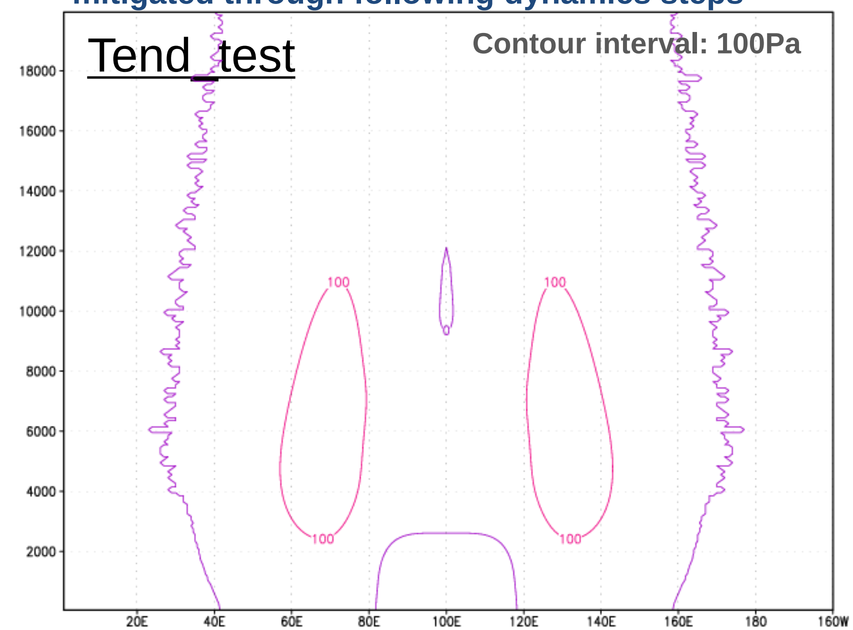


ASUCA's prognostic variable involved with energy

$$\rho\theta_{\mathrm{m}} = \rho\theta A$$

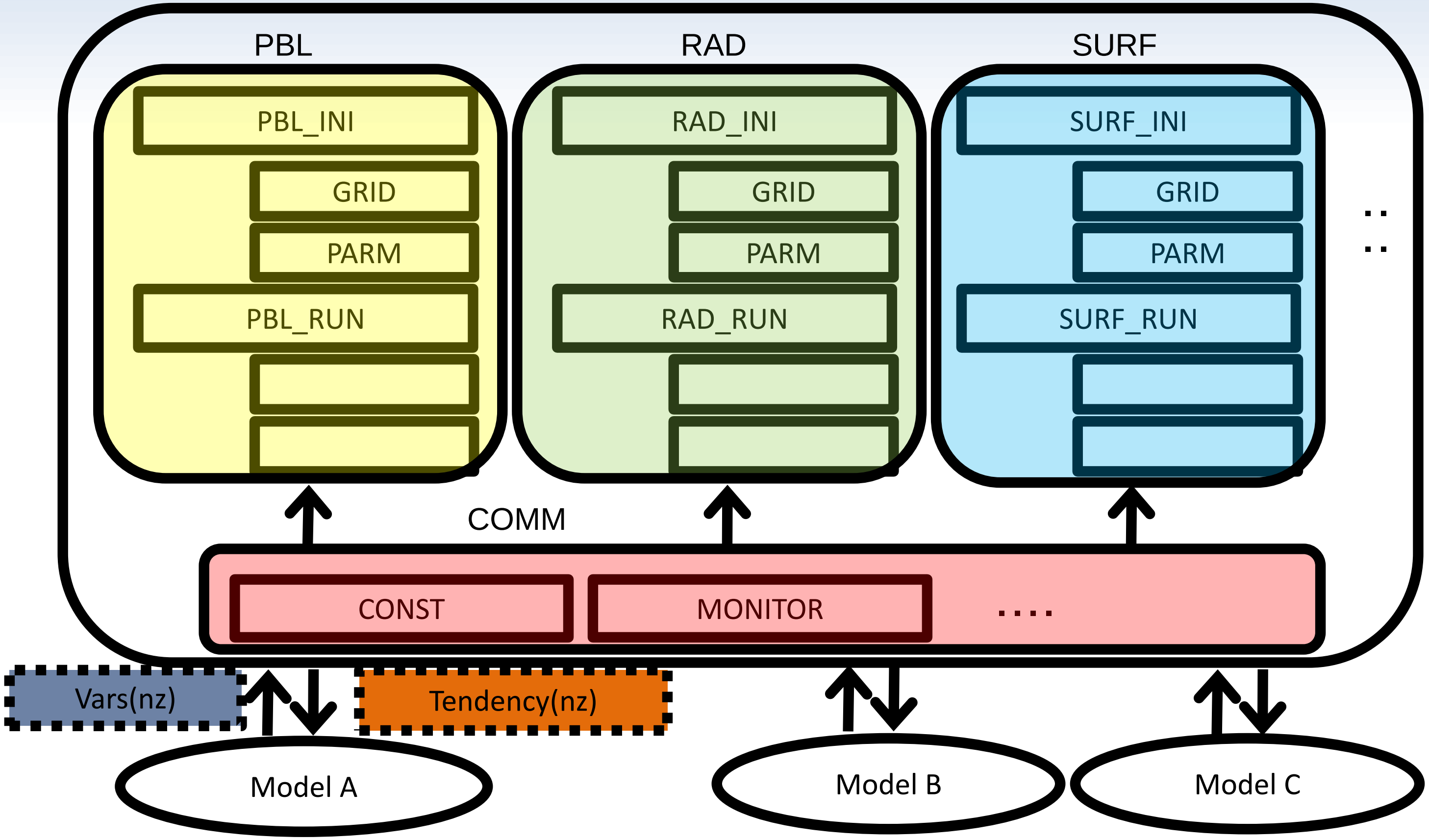
$$\rho = \rho_{\mathrm{d}} + \rho_{\mathrm{v}} + \rho_{\mathrm{c}} + \rho_{\mathrm{r}} + \cdots$$

$$A \equiv \frac{1}{\rho}(\rho_{\mathrm{d}} + \epsilon\rho_{\mathrm{v}}) = 1 + (\epsilon - 1)Q_{\mathrm{v}} - \sum_{\alpha \neq \mathrm{d,v}} Q_{\alpha}$$

Equation of state

$$\begin{aligned} p &= (\rho_{\mathrm{d}} R_{\mathrm{d}} + \rho_{\mathrm{v}} R_{\mathrm{v}})T \\ &= (\rho_{\mathrm{d}} + \epsilon\rho_{\mathrm{v}})R_{\mathrm{d}}T \qquad (\epsilon = R_{\mathrm{v}}/R_{\mathrm{d}}) \\ &= \rho A R_{\mathrm{d}} T \qquad (\rho_{\mathrm{d}} = \rho(1 - Q_{\mathrm{v}} - Q_{\mathrm{c}} - \cdots)) \\ &= \rho\theta A R_d \pi \end{aligned}$$

Schematic structure of the **"Physics Library"**



- The "Physics Library" is designed to be plugged in easily to any models
- The physical processes implemented in the "Physics Library" are vertically one-dimensionalized.
- ASUCA passes **inputs (Vars(nz))** to library, then receives **tendencies (tendency(nz))** from library.

Implementation of physical processes

- Physical processes are expected to provide tendencies. ASUCA just receives tendencies and temporally integrate with them.
- Column based physical processes include only the vertical one-dimensional loop
- The horizontal loops are parallelized using OpenMP.
- Modularity and high efficiency are satisfied.

```
real:: pt(nz,nx,ny), tend_pt(nz,nx,ny)
real:: qv(nz,nx,ny), tend_qv(nz,nx,ny)
real:: pt_1d(nz), tend_pt_1d(nz)

!$OMP PARALLEL DO SCHEDULE(DYNAMIC) &
!$OMP& PRIVATE(pt_1d,tend_pt_1d)
  do j = 1, ny
  do i = 1, nx
    pt_1d(1:nz) = pt(1:nz,i,j)
    qv_1d(1:nz) = qv(1:nz,i,j)
    call pp_A(i,j,tend_pt_1d,tend_qv_1d,pt_1d,qv_1d,…)
    tend_pt(1:nz,i,j) = tend_pt_1d(1:nz)
    tend_qv(1:nz,i,j) = tend_qv_1d(1:nz)
  end do
  end do
!$OMP END PARALLEL DO
```

kij -ordering `real(8) :: pt(nz, nx, ny)`
Three-dimensional arrays in space are stored sequentially in the order of z (k), x (i) and y (j).

kij-ordering
- Better load balance among PEs

kij-ordering
- Better cache hit ratio with vertical one dimensional calculation

In practice, physics tendencies are converted to those of ASUCA's prognostic variables