Characterising Convective Schemes by Their Linearised Responses

C. Daleu and B. Plant

Aim:
Study the response of convection to small temperature and moisture anomalies or tendencies using the a technique of Herman and Kuang (2013).
Results from :

- SCUM vn 11.6 using the 6A Mass Flux (MF) scheme
- SCUM vn 11.6 using the simple Betts-Miller (BM) scheme
- SCUM vn 11.1 using CoMorph (CM)

Results are also compared with those of the study of Herman and Kuang (2013).

Models:

- CRM: System for Atmospheric Modeling (SAM) -------Reference
- The Massachusetts Institute of Technology (MIT) SCM (MSCM)
- The Diabat3 (D3) toy cumulus parameterization incorporated into a 1-D

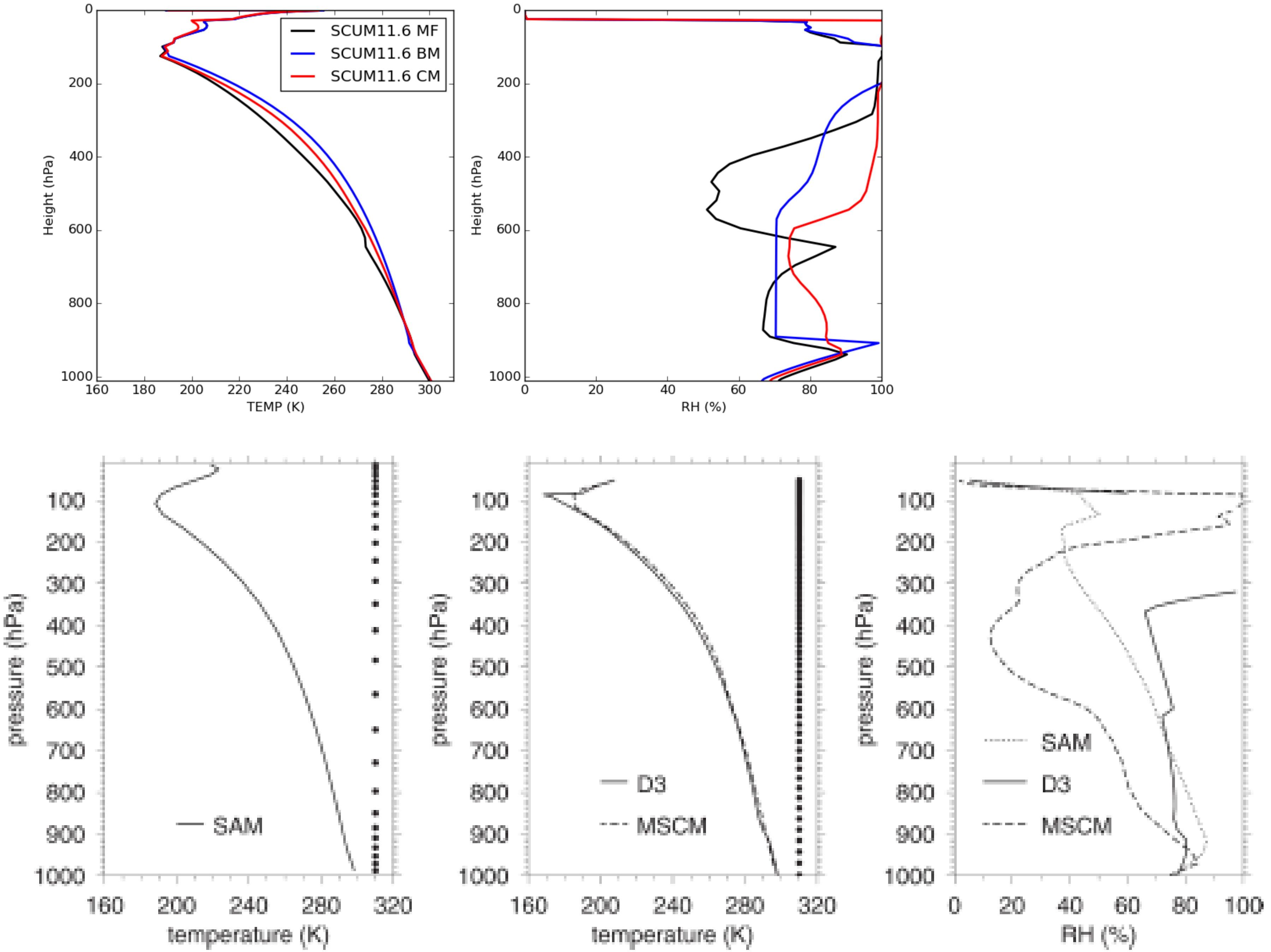
Run each model to RCE (control simulations)

-SST=$28^o c$, Surface wind speed of 4.8m/s (in SCMs)

-Radiatve cooling: fixed to -1.5K/d

- a relaxation of T and q_v profiles to the RCE profiles of the previous run is imposed near and above the tropopause

Comparing the RCE states



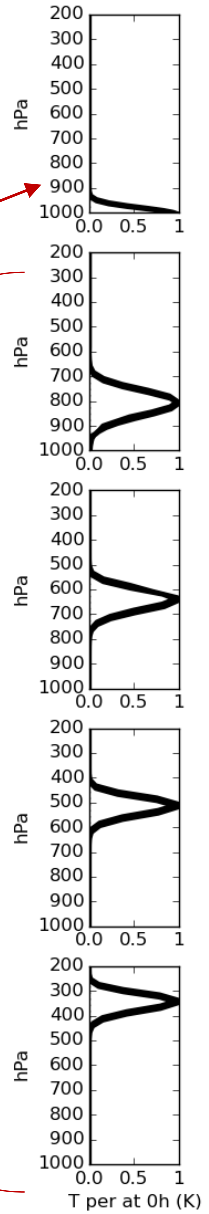
Herman and Kuang (2013).

Test-run with CoMorph:

Response to small temperature and moisture anomalies: $\frac{dx'}{dt} = Mx'$

Using the techniques and settings of Herman and Kuang (2013).

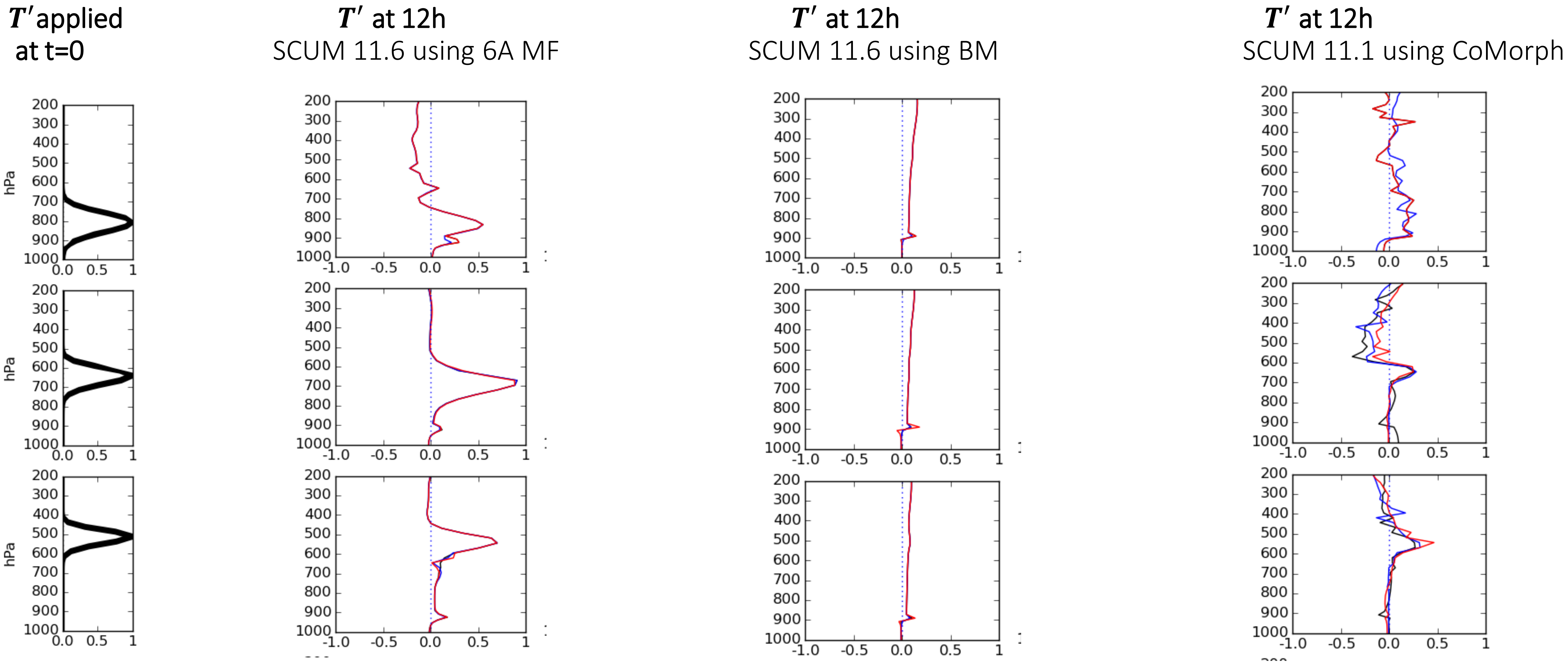
- Perform radiative-convective equilibrium (RCE) simulations (control simulation)
- Introduce small perturbation to T or q_v (at a single time step) of the form
  - $x_j(p_i) = exp\left[-\left(\frac{p_i - p_0}{30\ hPa}\right)^2\right]$ below cloud base (~900 hPa)
  - $x_j(p_i) = exp\left[-\left(\frac{p_i - p_0 + (j-1/2)}{75\ hPa}\right)^2\right]$ above cloud base
- Analyse the evolution of T and q_v following perturbations (up to hour 18)



LES simulations vs SCM version of the UM using CoMorph

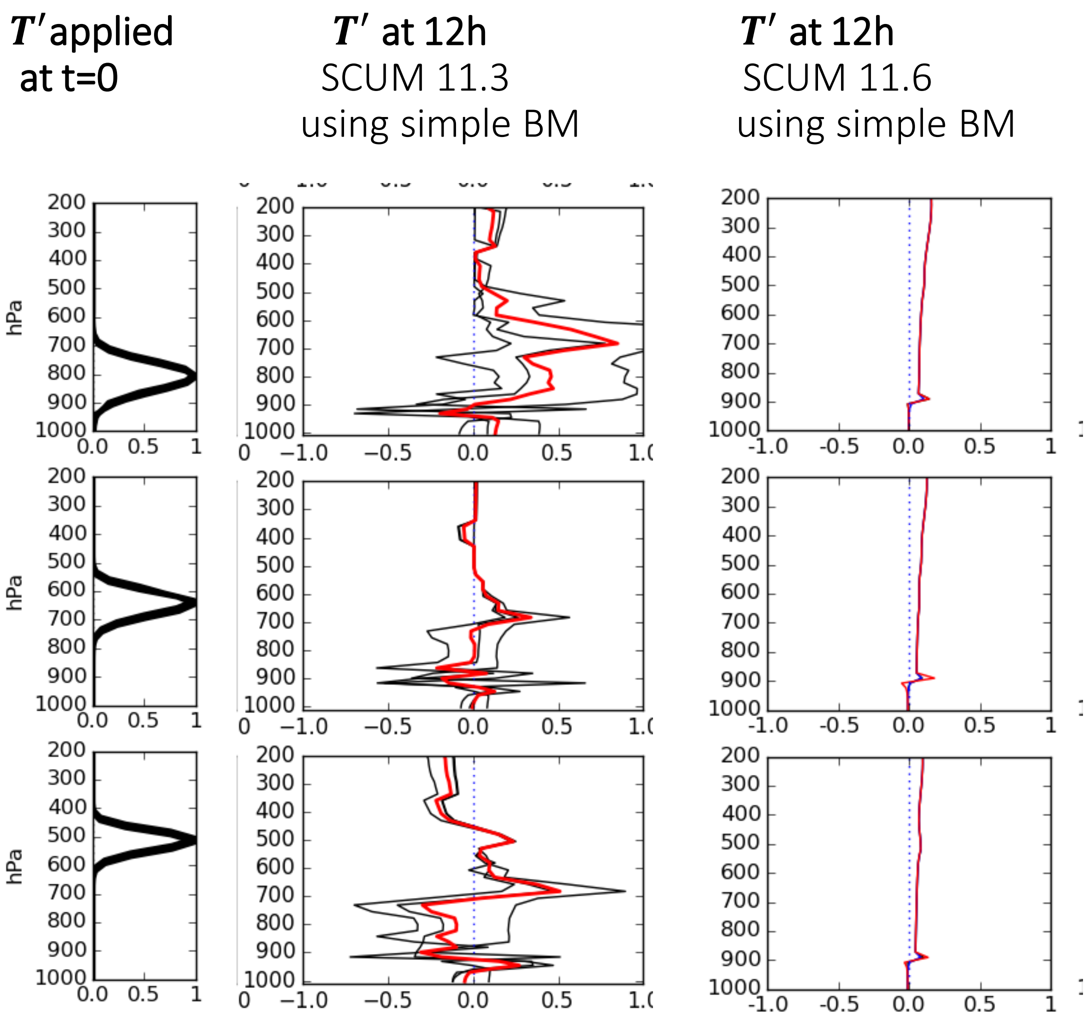
Results from UM using 6A MF scheme will be presented

Decay of anomalous temperature state vectors following applied temperature anomalies



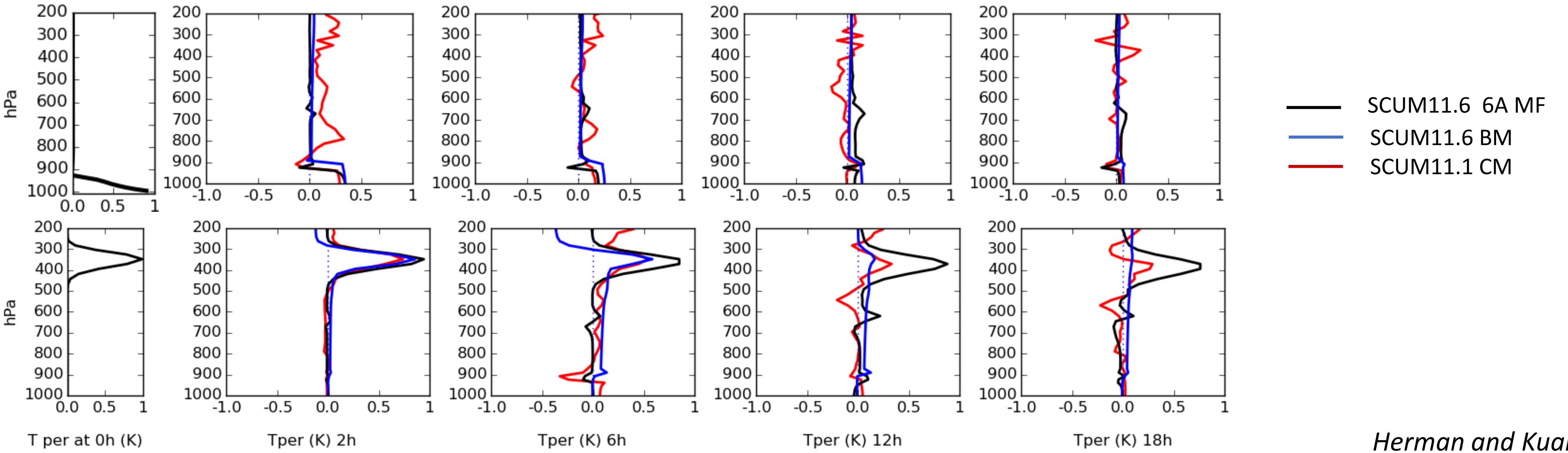
- Each of the 10 simulations is realised 3 times
- Our results: ensemble mean of 3 realisations are compared to
  the ensemble mean of 40 realisations in Herman and Kuang (2013)
- The results from the SCM using MF and BM schemes show are little variations from one realisation to the other
- the results from the SCM using CoMorph vary but overall, the quality of the results are consistent

Decay of anomalous temperature state vectors following applied temperature anomalies

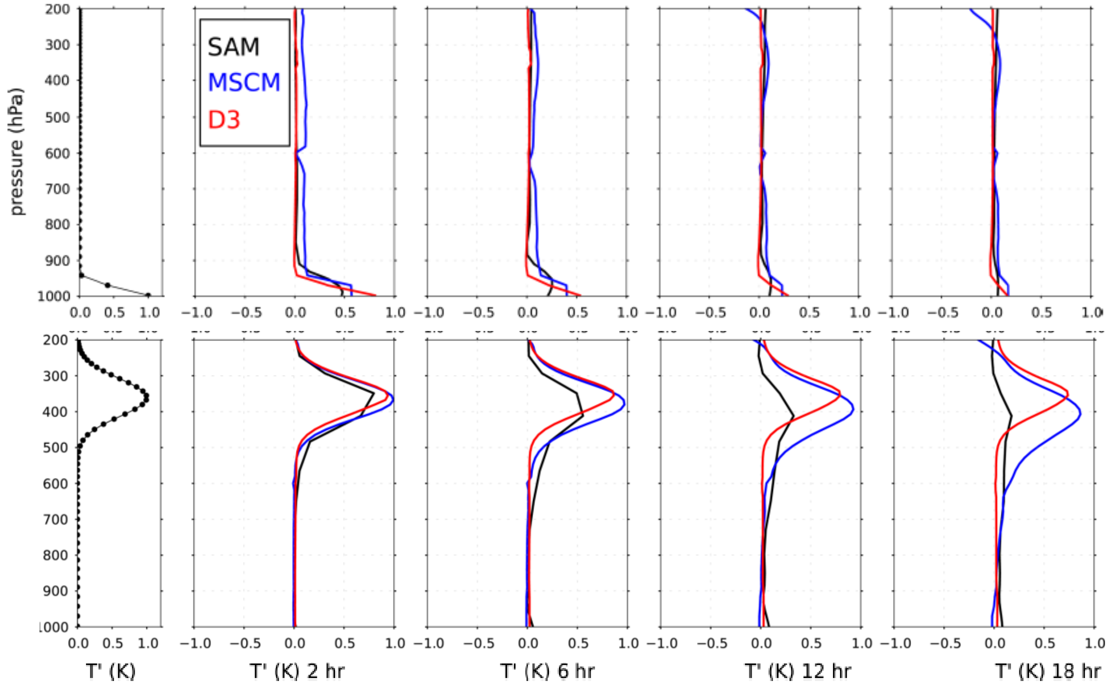


Simple BM scheme at 11.3	Simple BM scheme at 11.6
• **Parcel ascent code** The UM parcel ascent code (as is done in the 5a and 6a schemes)	→simple parcel ascent scheme (written by Mike)
• **Moisture conservation** Vertical integrals using wrong levels (rho levels/theta levels) in multiple locations →spotted when checking moisture conservation.	→This bug was fixed at 11.6.
• **All column based code within the convection call** UM parcel ascent code- the ascent happens on the grid (the call to convection is not a column based call like the rest of the BM code)	→The implementation of the new parcel ascent code is now all column based.
• **Excess wrapping code**	→removed

Decay of anomalous temperature state vectors following applied temperature anomalies at different levels

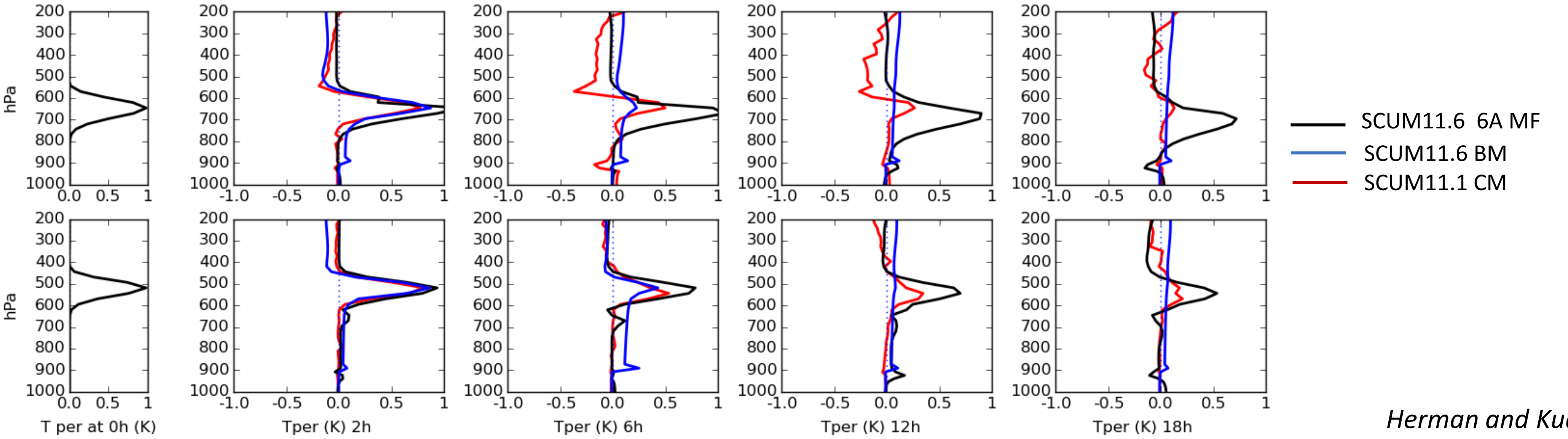


Herman and Kuang (2013)

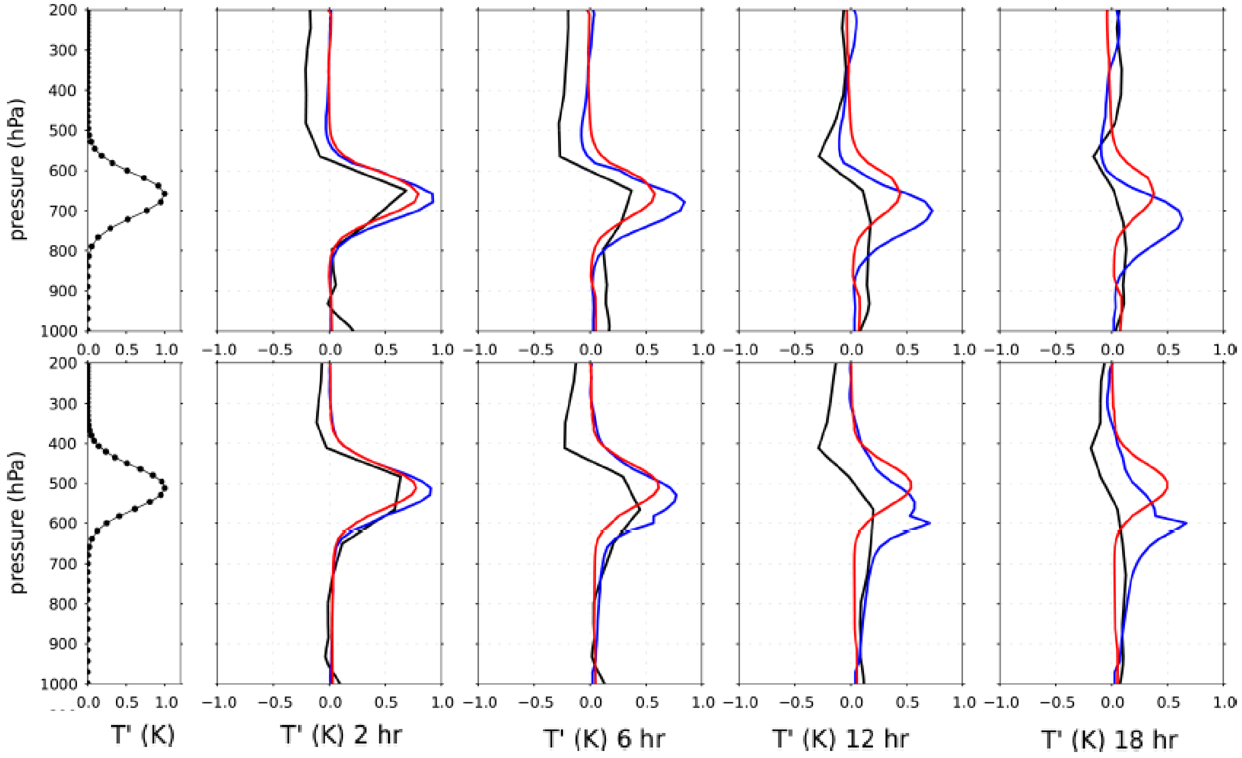


- All three schemes nearly eradicate the near surface warm anomalies after 12 hours
- In the upper troposphere
  - BM (like SAM) nearly eradicates warm anomalies after 18h
  - CoMorph: the amplitude of the warm anomalies is reduced
  - MF tends to keep perturbations for longer

Decay of anomalous temperature state vectors following applied temperature anomalies at different levels

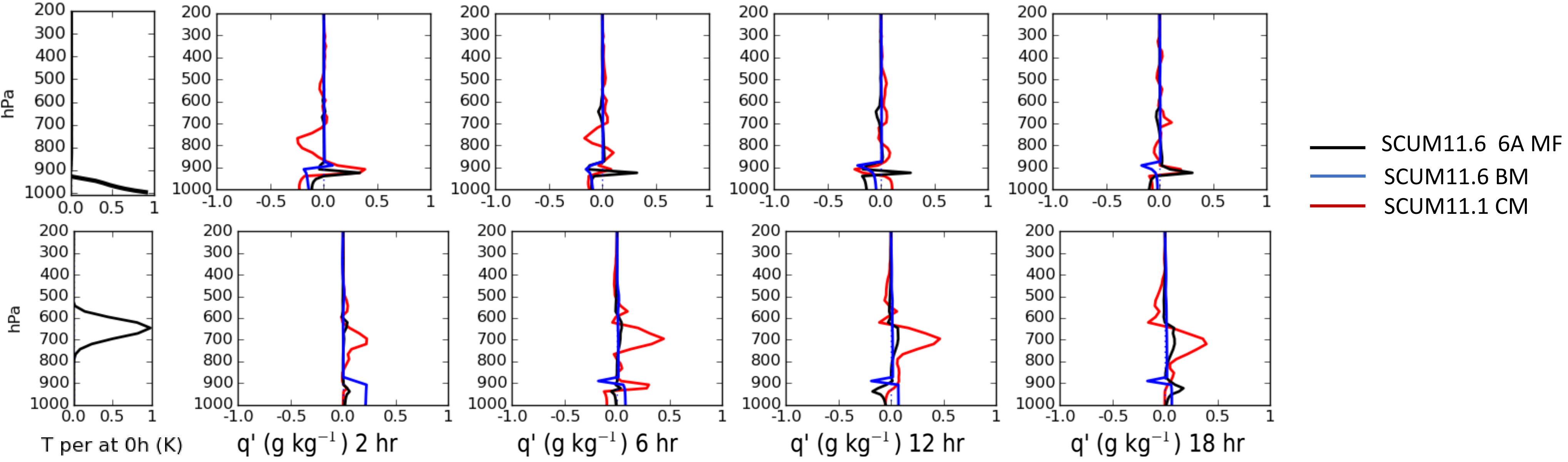


Herman and Kuang (2013)



- In the free troposphere:
    - Warm anomalies applied at 650 hPa
        - CoMorph shows a cold anomalies above the perturbations levels between hours 6-12 compared to hours 2-6 in SAM
    - MF tends to keep perturbations for longer
    - BM and CoMorph (as SAM) nearly eradicate the warm anomalies

Evolution of moisture state vectors following applied warm temperature anomalies

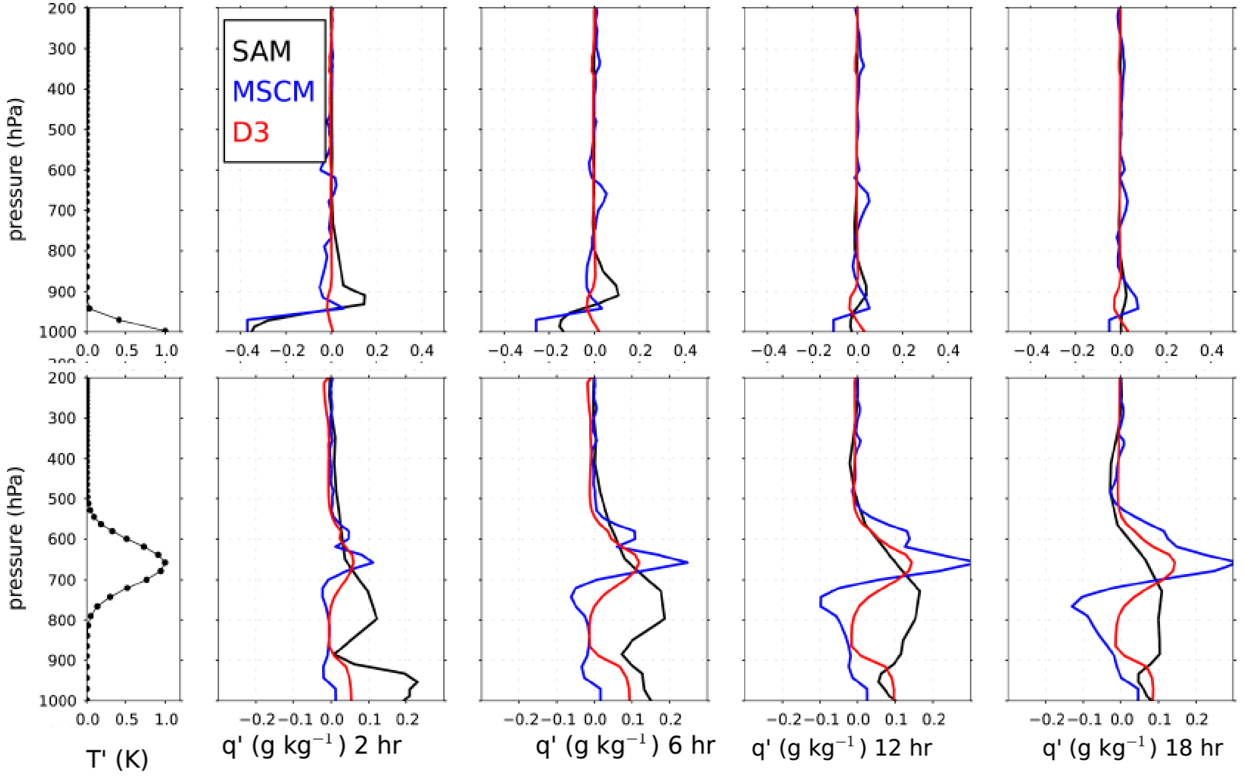


Warm anomalies near the surface:

- All schemes show drying of the subcloud layer after 2 hour
  - The anomalous drying is damped after 18 hours

In the free troposphere

- SAM: anomalous moistening below the perturbed layer that extends to the surface.
  - Not represented in MF and BM schemes
  - Represented in CoMorph but does not extend to the surface



Test-run with CoMorph:

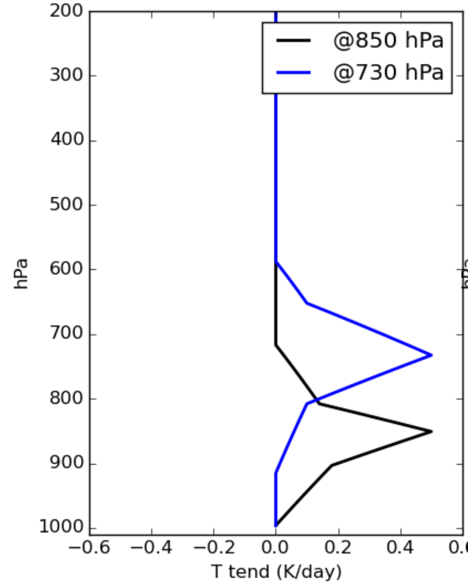
Response to small temperature and moisture tendencies: $x' = M^{-1}\frac{dx'}{dt}$

Using the techniques and settings of Herman and Kuang (2013).

- Perform radiative-convective equilibrium (RCE) simulations (control simulation)
  - SST=$28^{o}c$
  - Surface wind speed of 4.8m/s, Nudge U=4.8 m/s, V=0 with a relaxation timescale of 3 hours
  - Radiative cooling: fixed to -1.5K/d
- Perform separate runs with positive/negative perturbations to $\frac{dT}{dt}$ or $\frac{dq_v}{dt}$ of the form

$$f_j(p_i) = \delta_{ij} + exp\left[-\left(\frac{p_j - p_i}{75\ hPa}\right)^2\right]$$

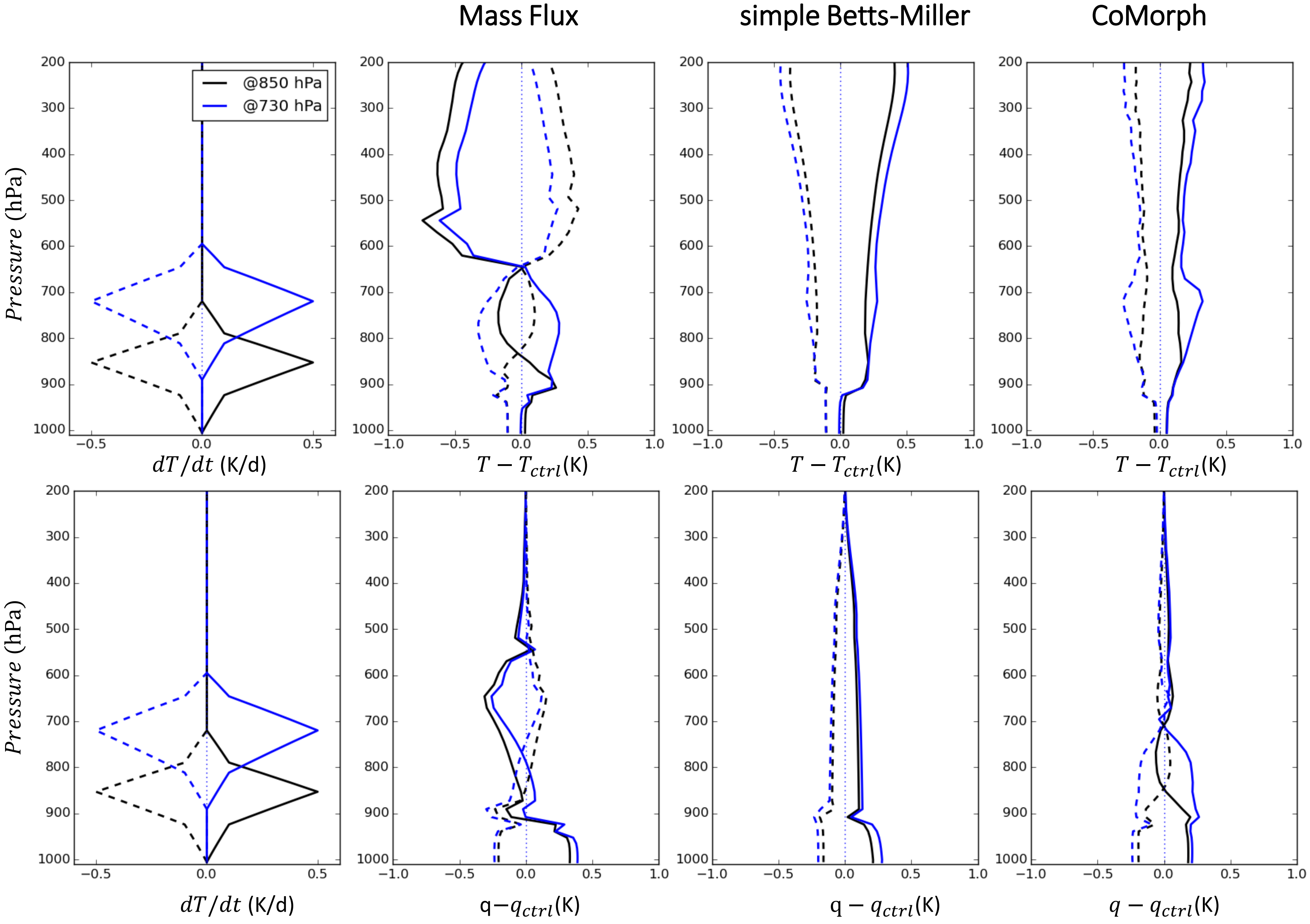
  - Examples of perturbation tendencies applied @ 850 and 730 hPa
  - Maintain the tendency until a new RCE state under the additional forcing is achieved
  - Analyse the column anomalous $T\ and\ q_v$ (with respect to the control simulation)
  - Our results = average responses of +ve and –ve tendencies



LES simulations vs SCM version of the UM using CoMorph

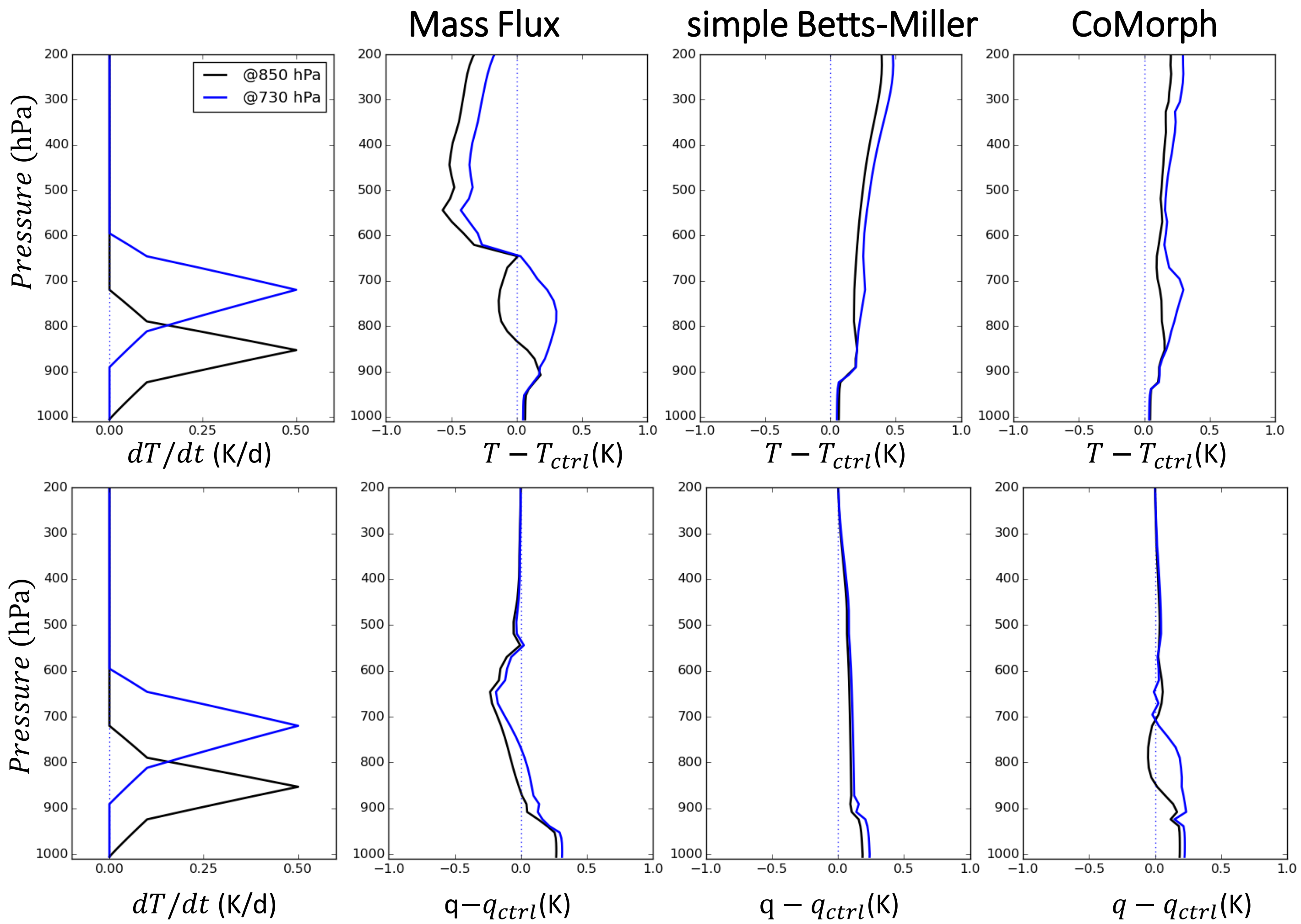
Results from UM using 6A MF scheme will be presented

Linear responses? (warm and cold anomalies)

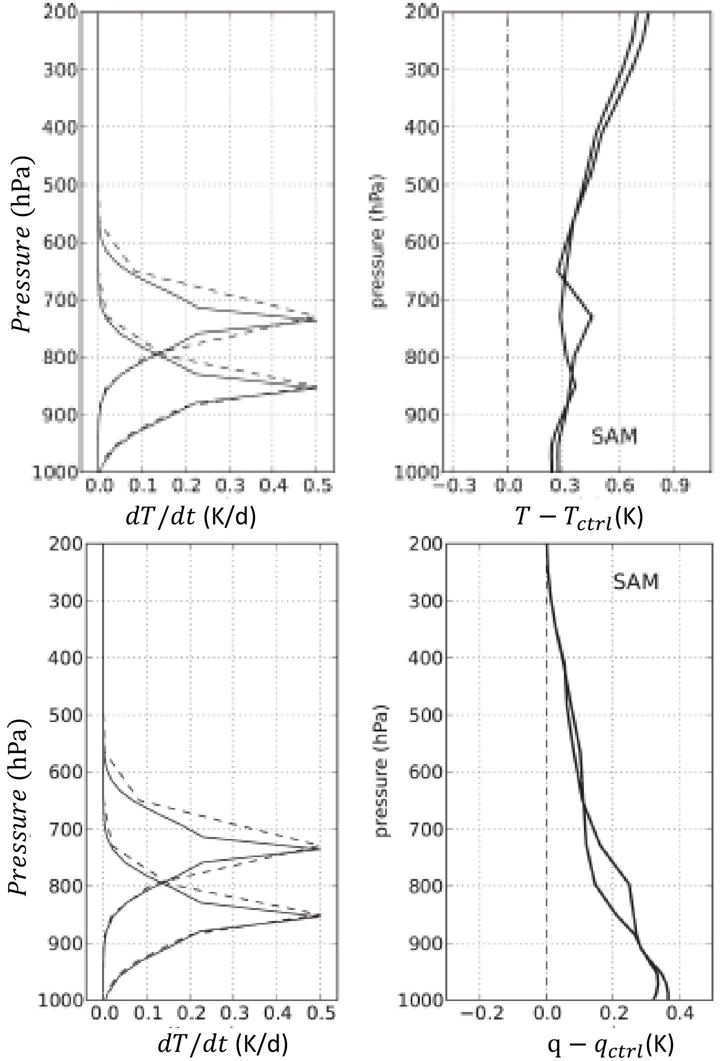


- The responses of the SCM using MF are not linear.
- The responses of the SCM using CoMorph and BM are close to be linear in the free troposphere but not in the subcloud layer
- Our results = average responses of +ve and –ve tendencies

Anomalous T and qv profiles corresponding to apply temperature tendency perturbations

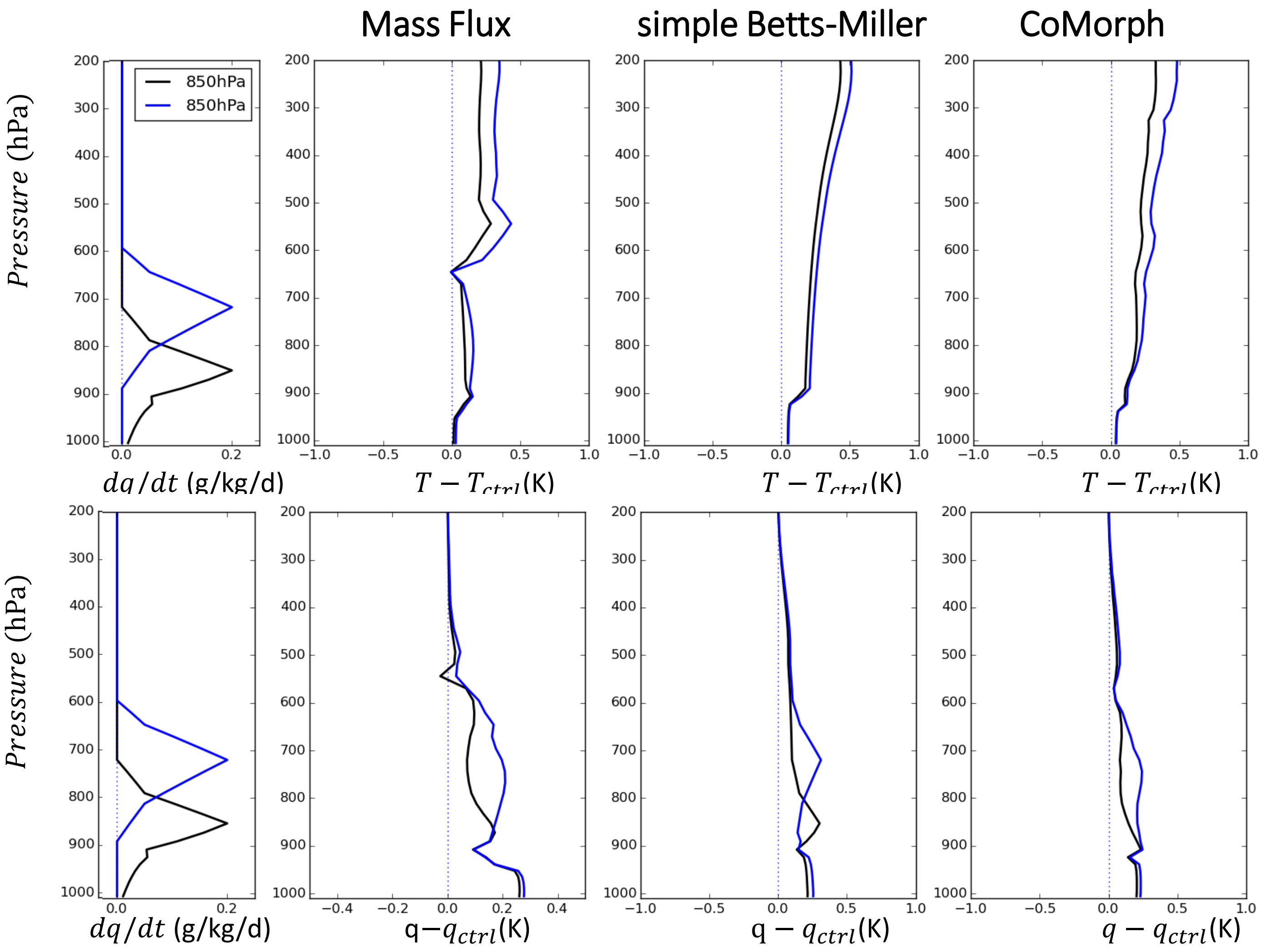


Herman and Kuang (2013)

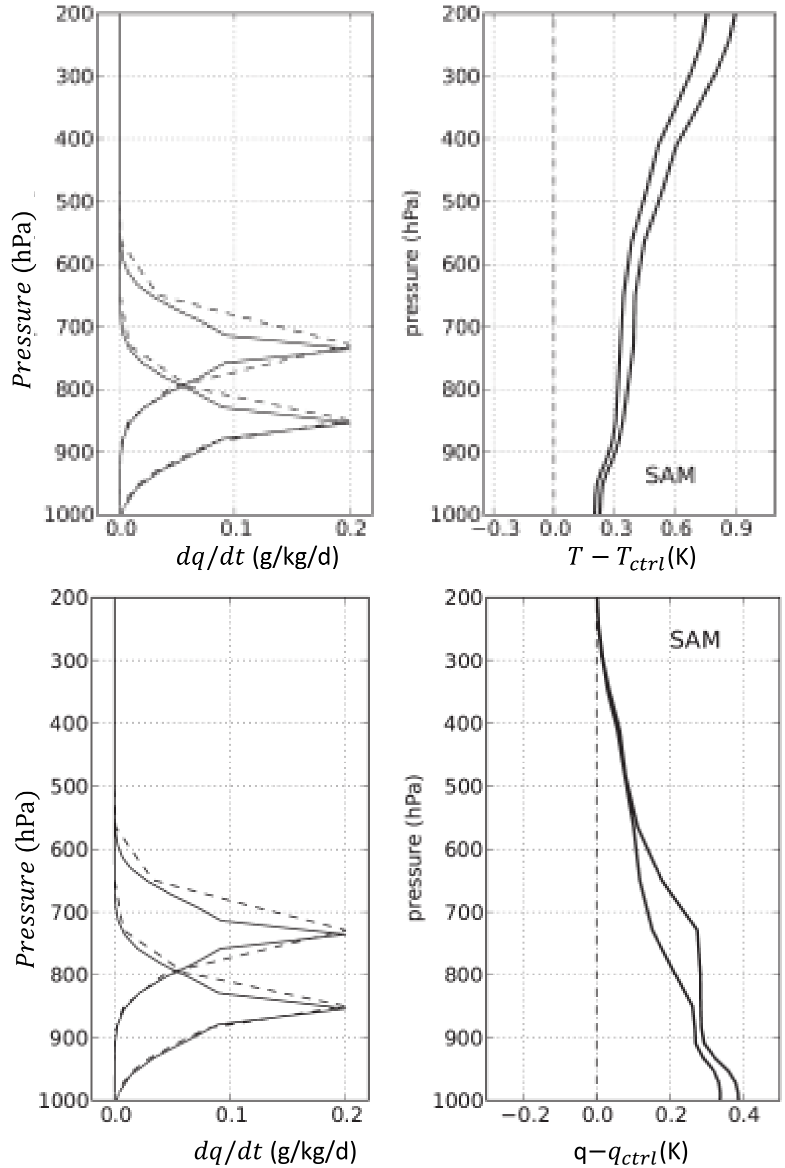


- BM and CoMorph (as SAM): warming through the depth of the column
- CoMorph: moistening of the layer below the perturbed layer and drying aloft
- BM moistens the whole column
- MF: T and qv responses to applied $\frac{dT}{dt}$ are significantly different to those of SAM
    - Cooling and drying of the layers above the perturbed layer

Anomalous T and qv profiles corresponding to applied moisture tendency perturbations



Herman and Kuang (2013)



- CoMorph (like SAM): warming and moistening through the depth of column
- BM: warming and moistening (more localized) through the depth of the column
- MF: T and qv responses to applied $\frac{dq_v}{dt}$ are closer to those of SAM (compared to the responses to applied $\frac{dT}{dt}$)

Test-run with CoMorph:

Response to small temperature and moisture tendencies: $x' = M^{-1}\frac{dx'}{dt}$

Let's derive M: the response matrix

Applied

$f_j(p_i) = \delta_{ij} + exp\left[-\left(\frac{p_j - p_i}{75\ hPa}\right)^2\right]$ to either T or q_v

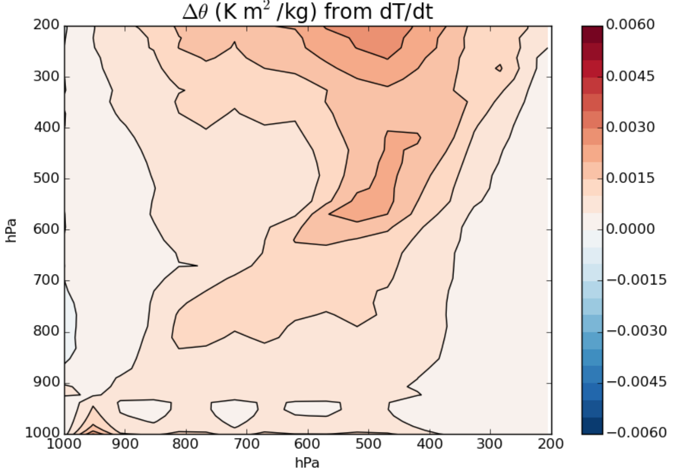
with an amplitude of 0.5K/d and 0.2g/kg/d, respectively

perturbation applied at every other model levels **Vs** all vertical model levels in Herman and Kuang (2013).

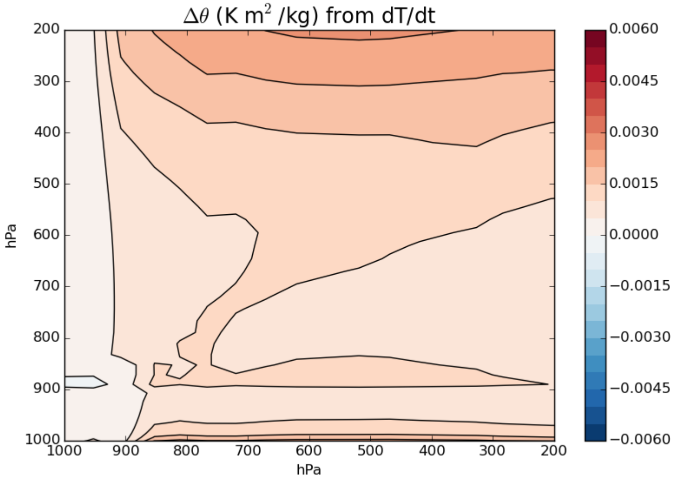
LES simulations vs SCM version of the UM using CoMorph

Results from UM using 6A MF scheme will be presented

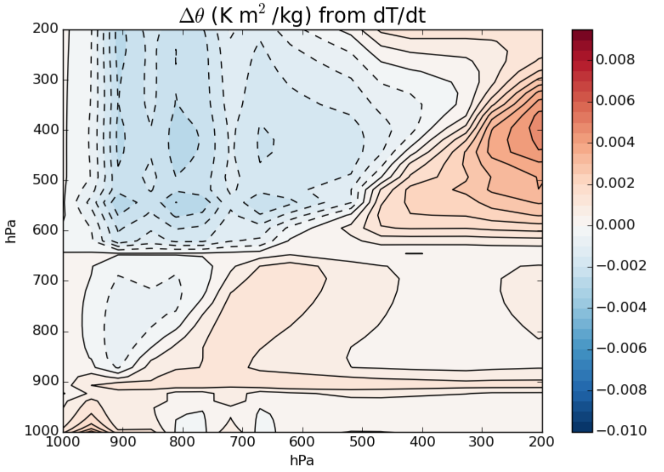
CoMorph



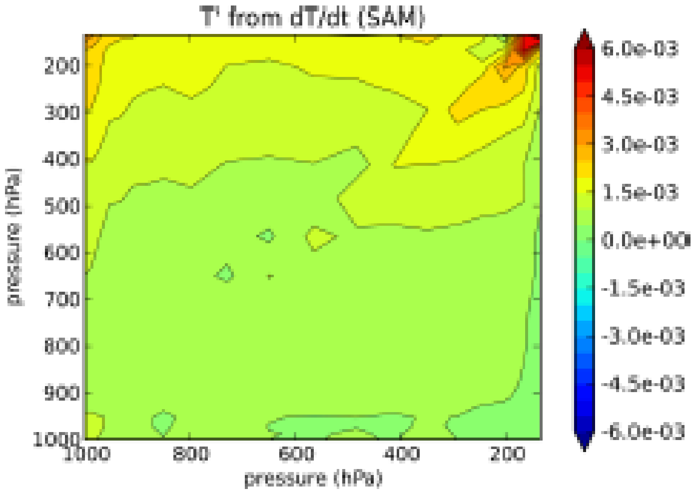
Betts-Miller



Mass Flux



SAM



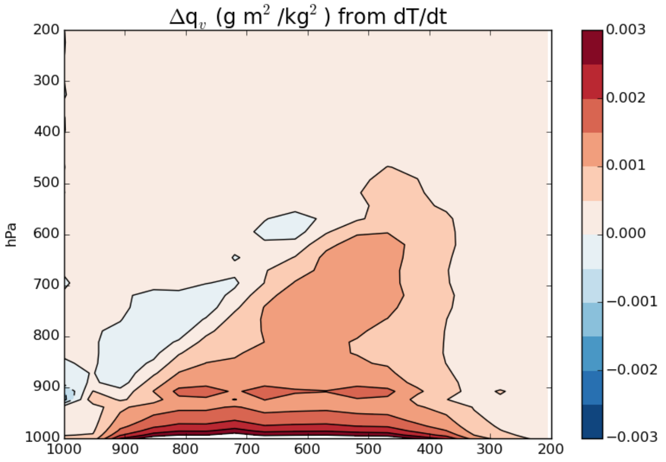
Herman and Kuang (2013)

T responses to applied warm tendencies

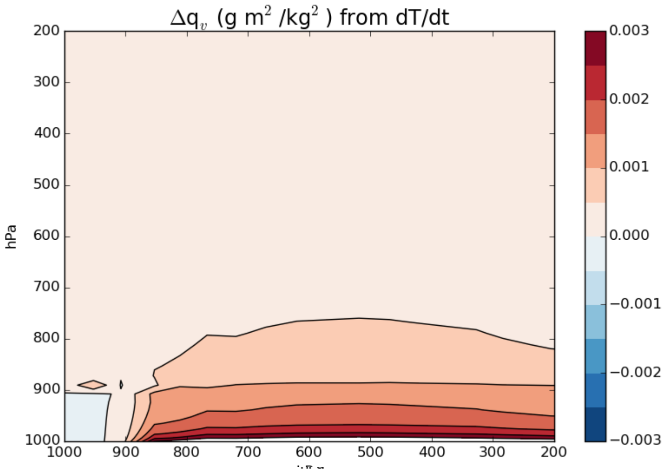
- SCM using simple BM scheme or using CoMorph (like SAM)
- Warming through the depth of the column

- SCM using MF scheme
  - Most negative values of T anomalies
  - Below 400 hPa: Cold anomalies above the perturbed layers
  - Above 400 hPa: T responses above 600 hPa are too strong

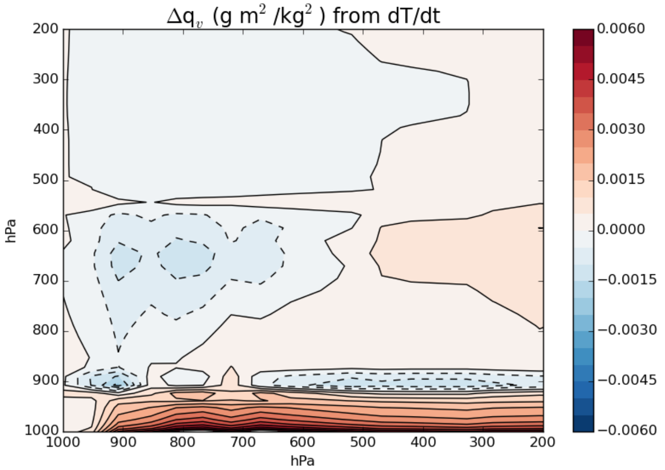
CoMorph



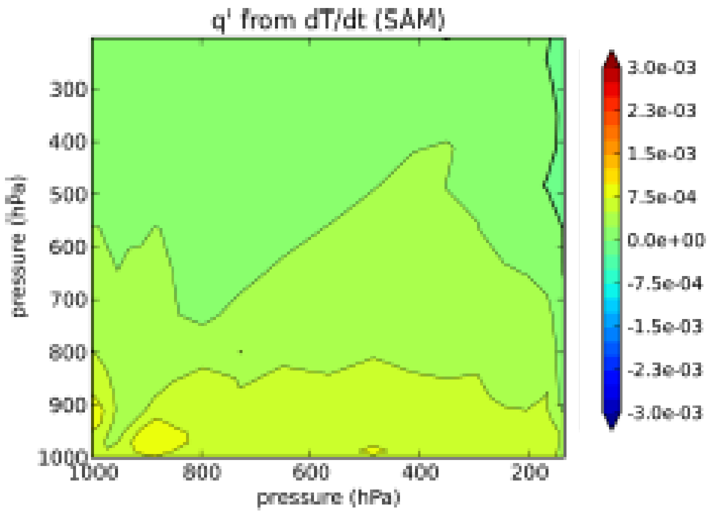
Betts-Miller



Mass Flux



SAM



Herman and Kuang (2013)

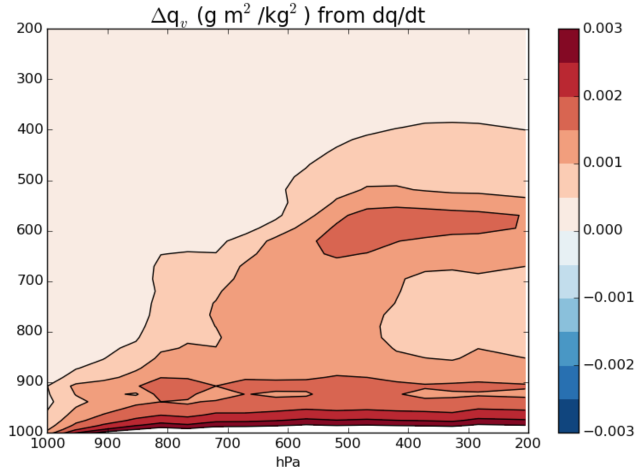
qv responses to applied warm tendencies

- SAM: moistening through the depth of the column

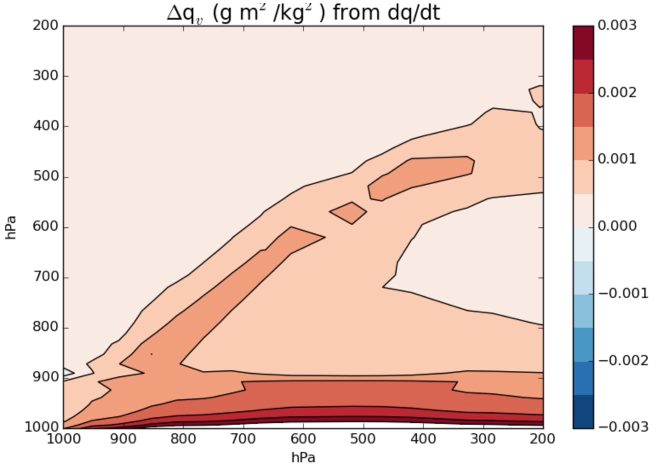
- SCM using simple BM scheme or using CoMorph
  - Moisture anomalies are mostly positive
  - CoMorph (like SAM): stronger moistening bellow the perturbed level
  - BM: stronger moistening below 800 hPa for perturbation levels 950-200 hPa

- SCM using MF scheme
  - Most negative values of moisture anomalies
  - Below 400 hPa: dry anomalies above the perturbed layers
  - Drying of the cloud base (for all perturbed layers)
  - Subcloud layer: qv responses are too strong

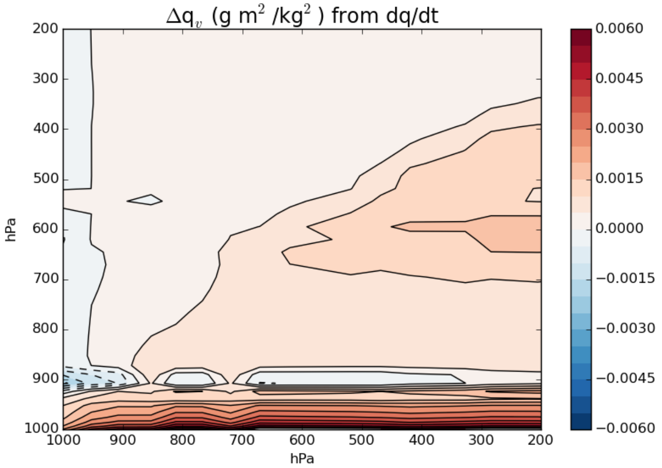
CoMorph



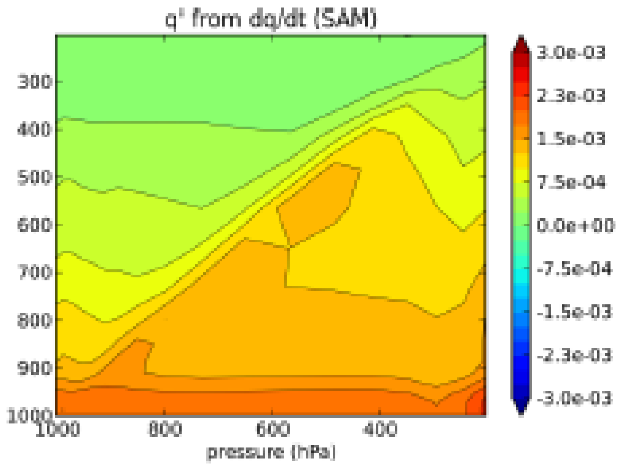
Betts-Miller



Mass Flux



SAM



Herman and Kuang (2013)

qv responses to applied moist tendencies

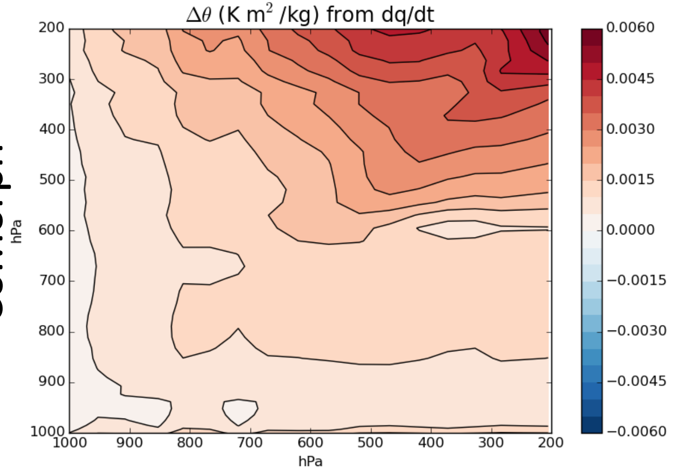
SCM using simple BF scheme or CoMorph (like SAME): changes are consistent:

- Moistening through the depth of the column
- qv response is stronger below the perturbed layer

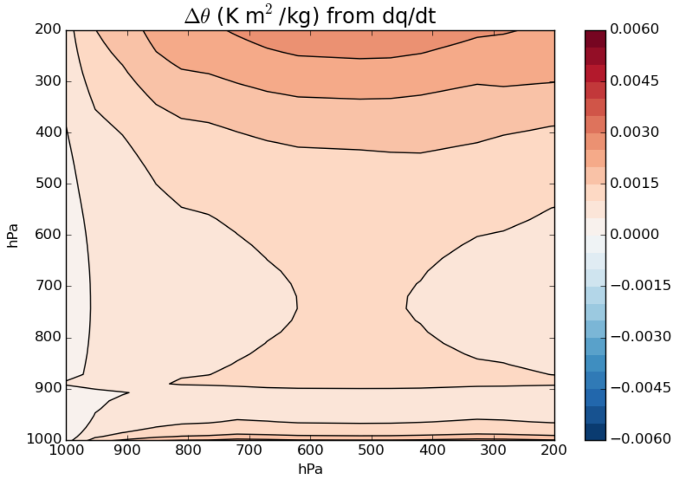
SCM using MF scheme

- Drying of cloud base
- Cloud base: qv responses too strong

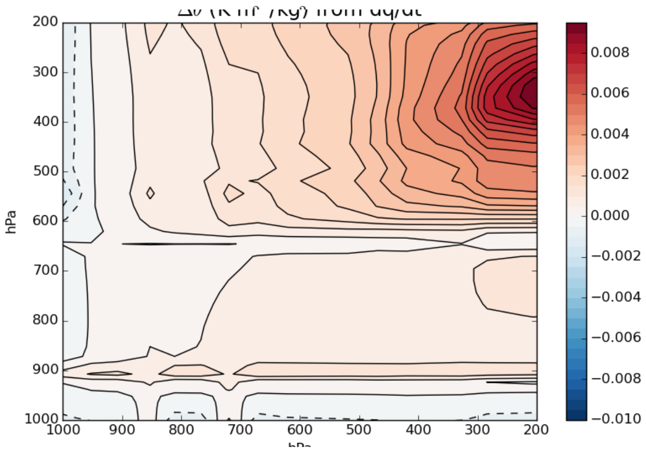
CoMorph



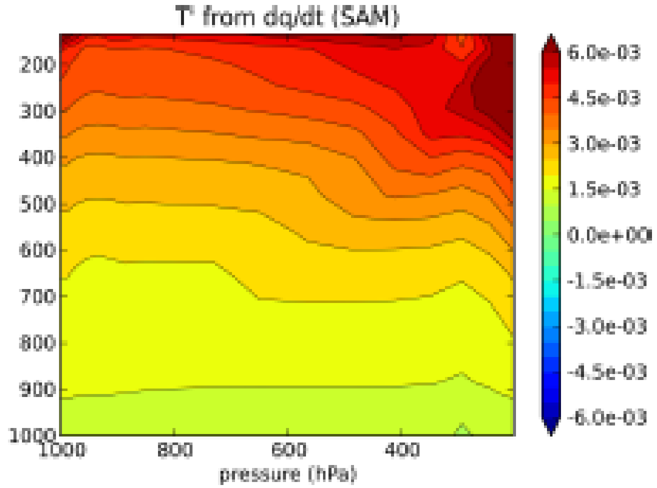
Betts-Miller



Mass Flux



SAM



Herman and Kuang (2013)

T responses to applied moist tendencies

SCM using simple BF scheme or CoMorph (as SAM): changes are consistent:

- Warming through the depth of the column.
- CoMorph: T responses (pattern) are very similar to that of SAM

SCM using MF

- Above 600 hPa: T responses are too strong (for all perturbation aboe 300 hPa)
- Weaker T responses around 650hPa (for all perturbation levels)
- Cooling of cloud base

Summaries

Results from the SCM using **CoMorph** have been compared against those from the SCM using **6A Mass Flux** and simple **Betts-Miller** schemes and compared against those from SAM (*Herman and Kuang (2013)*)

CoMorph is able to replicate some of the results from SAM:

- Warm anomalies applied near the surface → is eradicated after 12 hours
  - Anomalous drying of the subcloud layer after 2 hours and damped after 18 hours
- Warm anomalies applied in the free troposphere→ eradicated after 18 hours
  - Anomalous moistening that extends 100 hPa below the perturbed (that extends to the surface in SAM)

- Warm tendencies applied at all model levels
  - Warming through the depth of the column
  - Perturbations applied below 600 hPa → *moistening of the layer below the perturbed layer and drying aloft*

- Moist tendencies applied at all model levels → warming and moistening through the depth of the column
  - Strong moistening below the perturbation levels
  - T responses (pattern) are very similar to those of SAM

The results from the simple BM scheme are now more consistent (compared to those of SCUM11.3 using BM)
The results from CoMorph and the simple BM schemes are more consistent than those from the MF scheme

For an entirely new convection scheme; CoMorph is doing remarkably

Test-run with CoMorph: Convective memory

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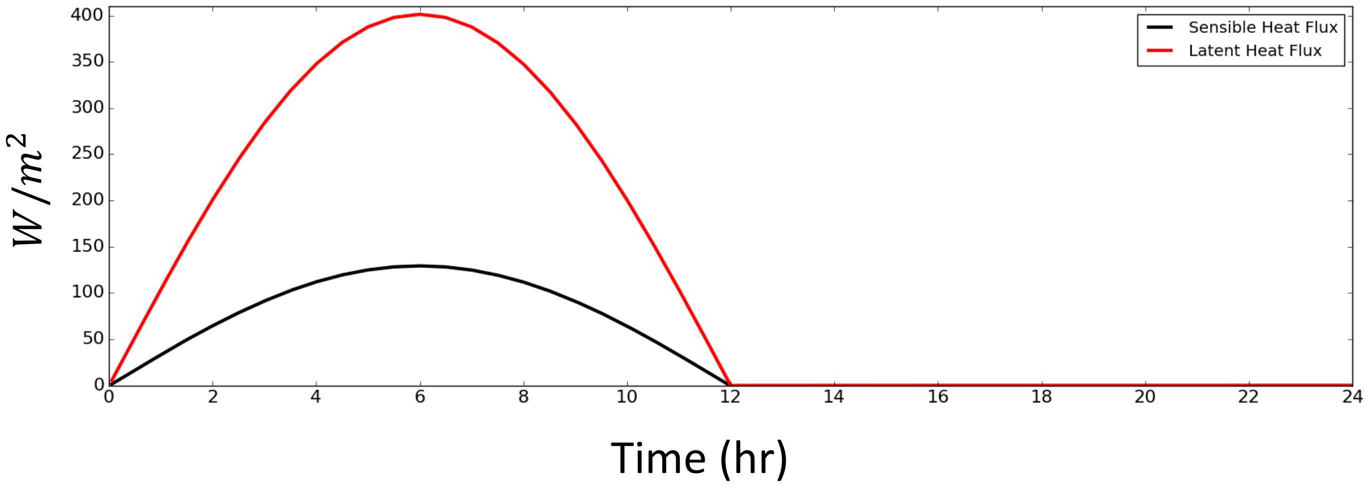
MONC- configuration

512×512 grid points
For most simulations presented here: $\Delta x = \Delta y = 200$ m → 100×100 km

Setup and forcing are based on the EUROCS case study



Control

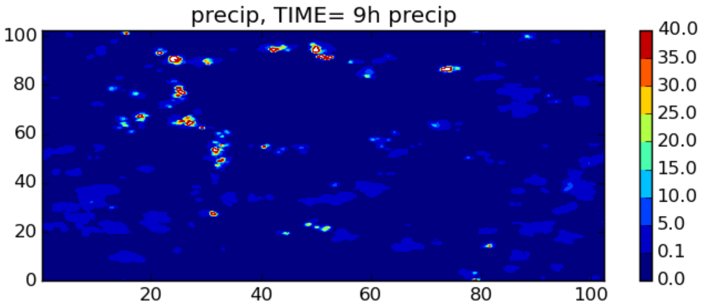
Peak SHF =130 w/m^2
Peak LHF= 400 w/m^2
RC=-1.75 K/day

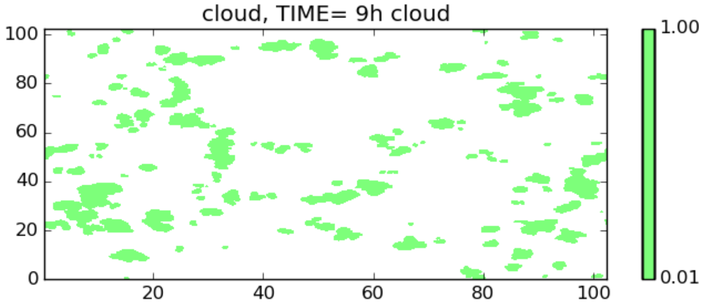
Sensitivity to the domain size and/or horizontal resolution

- Larger domain coarser resolution: $\Delta x = \Delta y = 500$ m → 250×250 km
- Smaller domain finer resolution: $\Delta x = \Delta y = 100$ m → 50×50 km

The memory properties presented here show very weak sensitivity to the domain size and/or horizontal resolution

Convection depends on its own history?





For each 2D surface precipitation field, a grid point (i,j) is masked as rainy if
$precip_{i,j} \geq 0.1\ mm/h$ ($0.5 \times \overline{< precip >}$ in the control sim)

Persistence of rainfall events within A: $P[R(A, t_0) \cap R(A, t_0 - \Delta t)]$

For random distributions, the probability of finding persistent rainfall by random chance:
$P^2[R(A, t_0, \Delta t)]$=$P[R(A, t_0)] \times P[R(A, t_0 - \Delta t)]$

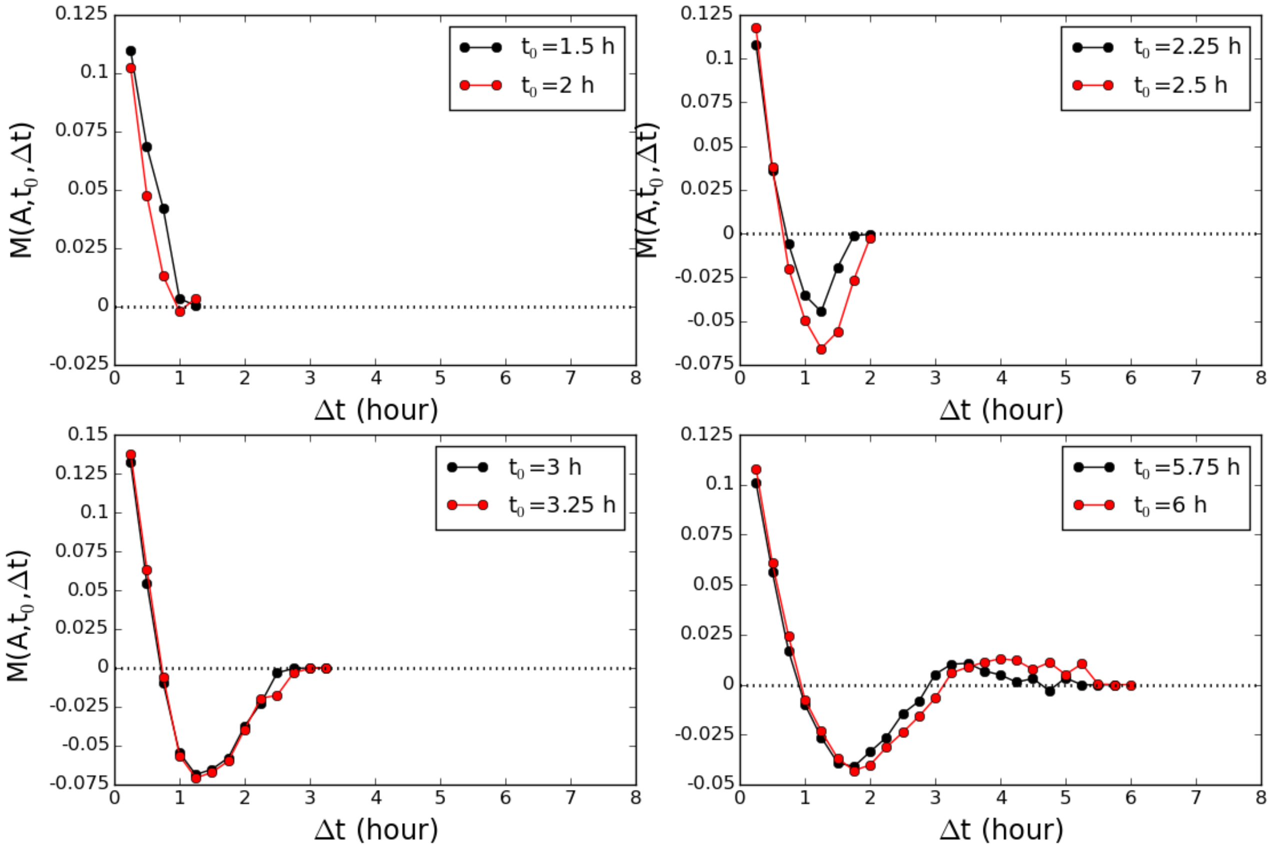
Convection depends on its history if $P[R(A, t_0) \cap R(A, t_0 - \Delta t)] \neq P^2(R(A, t_0, \Delta t)$

Memory function: $M[R(A, t_0, \Delta t)]$=$P[R(A, t_0) \cap R(A, t_0 - \Delta t)] - P^2(R(A, t_0, \Delta t)$

Convection depends on its own history?

$$M[R(A,t_0,\Delta t)]=P[R(A,t_0)\cap R(A,t_0-\Delta t)]\ -P^2(R(A,t_0,\Delta t)$$

example plot for A=4 $\times$ 4km^2



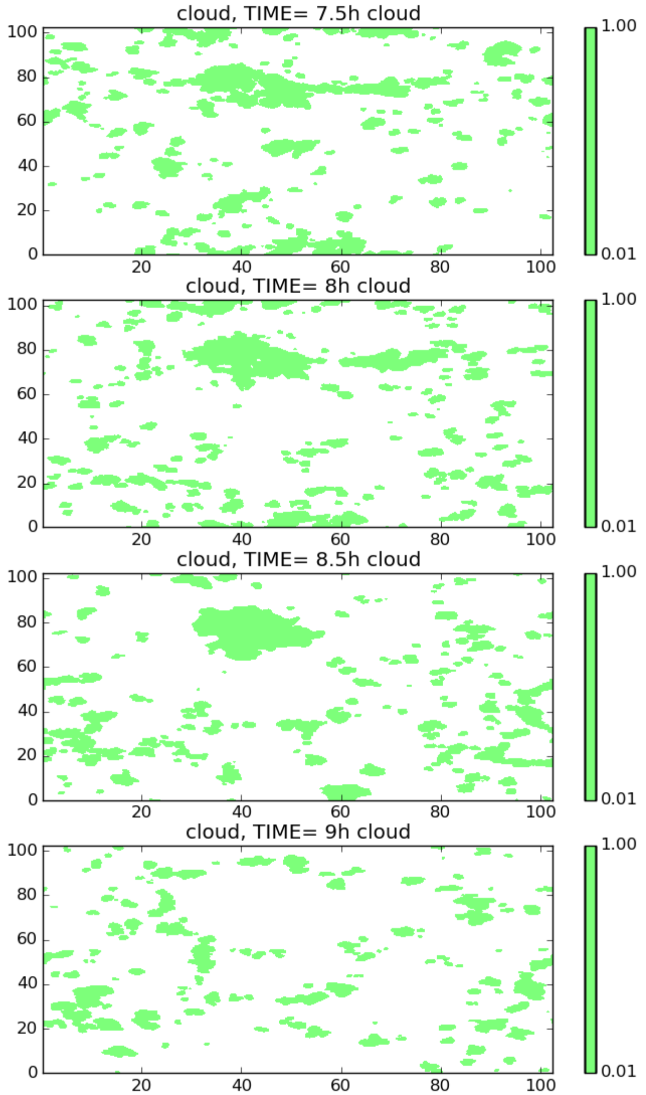
- Positive (negative) M→ convection at $t_0\ -\Delta t$ acts to enhance (suppress) convective activity at t_0.
- The minimum value of M represents the strongest suppressed state of conv
- Recovery time of convection→ transition from the strongest suppressed state to the state expected given no memory (the zero line)

- In the early stage of the diurnal cycle: persistence of the newly developing convection→ maintained for ~ 1 hour (1st phase)
- From t_0 =2.25h indication of local suppression (2nd phase):
  - initial persistence of convection is followed by a suppression for a further 1 h (at $t_0\ =2.25$h) to 2 h (from $t_0\ =3.25$h)
- From t_0 =5.75 h: a further enhancement of convection for Δt = 3 -5 hours (3rd phase)

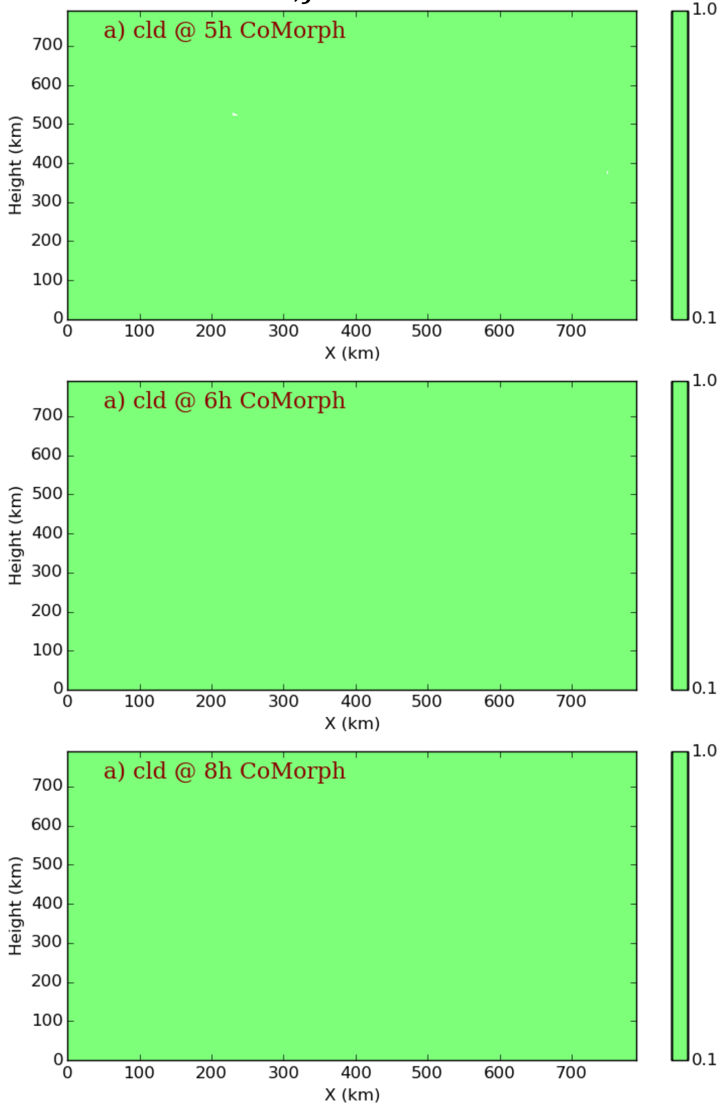
$M[R(A,t_0,\Delta t)]$: very week sensitivity to domain size and/or horizontal resolution, initial conditions, free tropospheric cooling rate, smaller Bowen ratio

For each 2D surface precipitation field, a grid point (i,j) is masked as rainy if

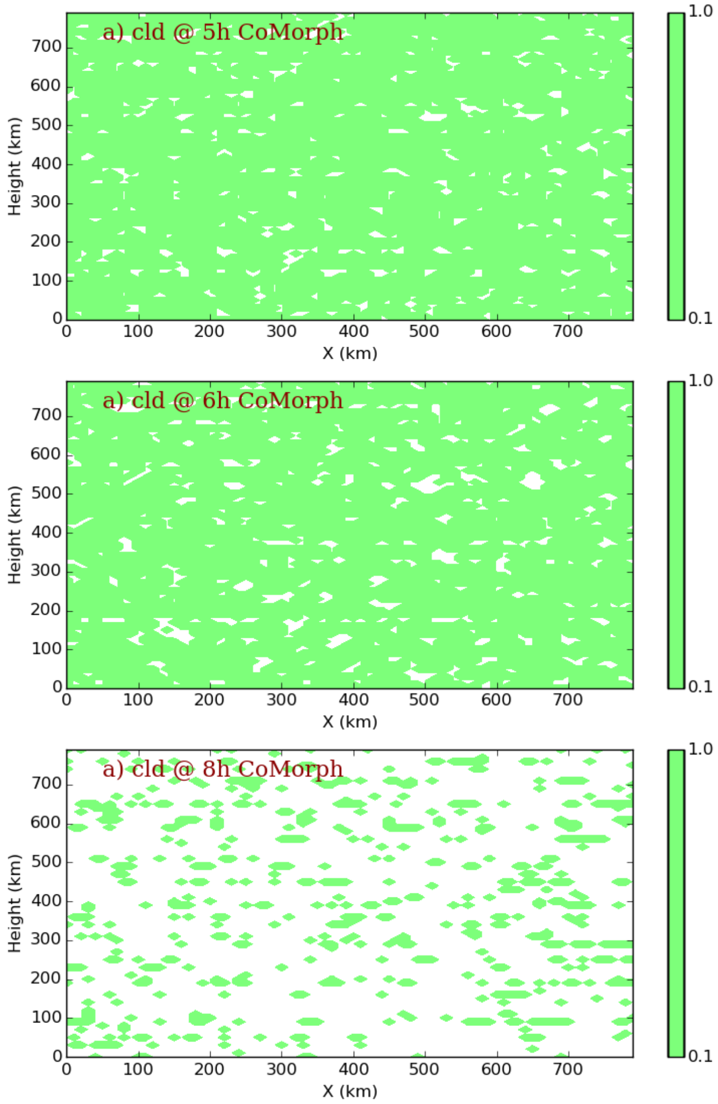
MONC
$precip_{i,j} \geq 0.1\ mm/h$



UM using CoMorph
$precip_{i,j} \geq 0.1\ mm/h$



UM using CoMorph
$precip_{i,j} \geq 0.5\ mm/h$

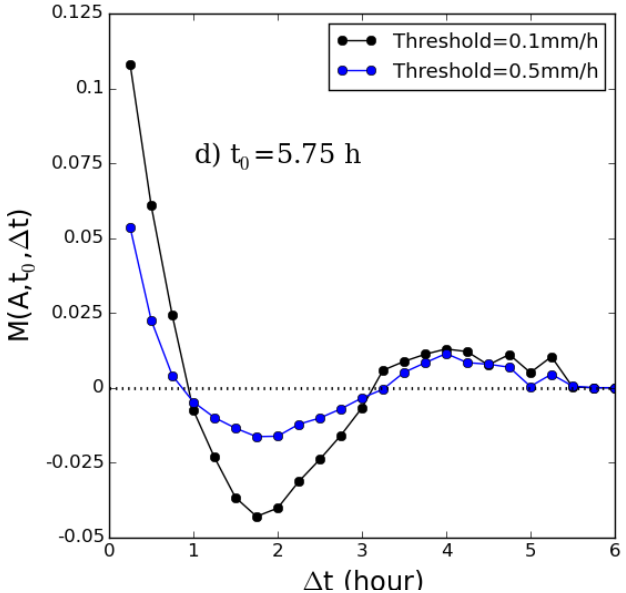


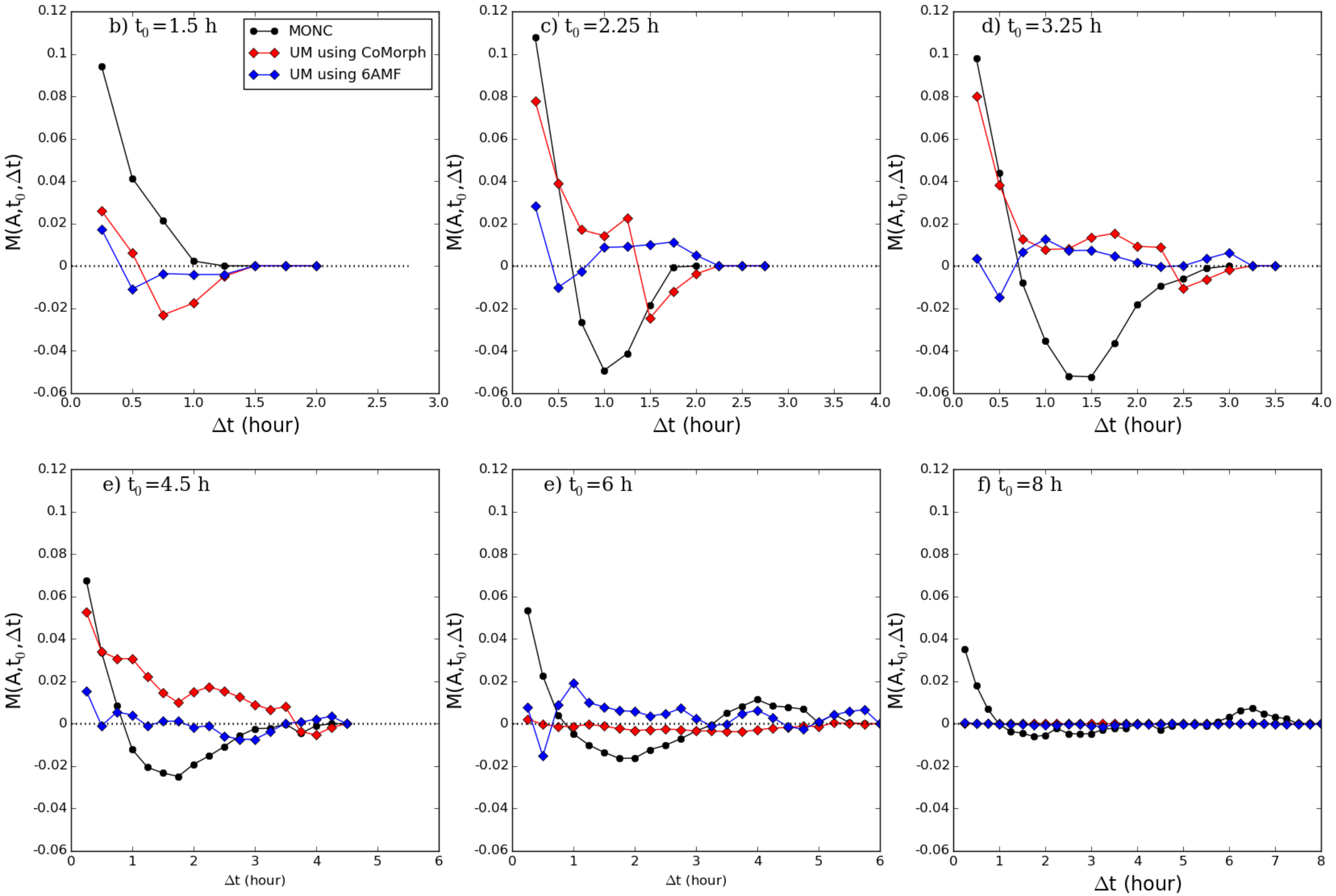
$M[R(A, t_0, \Delta t)]$ for A=4 × 4km^2: MONC vs UM using 6A MF or using CoMorph

Domain size $800 \times 800 km^2$ and Δx=4km

$precip_{i,j} \geq 0.5\ mm/h$ in all three simulations

Results from MONC with different precip thresholds





Compare to the memory properties in the LES

- 6A MF scheme
  - convective memory is negligible
- CoMorph
  - The 1st phase is represented but the timing is different
  - The 2nd phase is sometime represented but
    - not as strong as in the LES
    - convection recovers too quickly
    - the timing is different
  - The 3rd phase is not represented
  - From t_0 =6 h: no convective memory

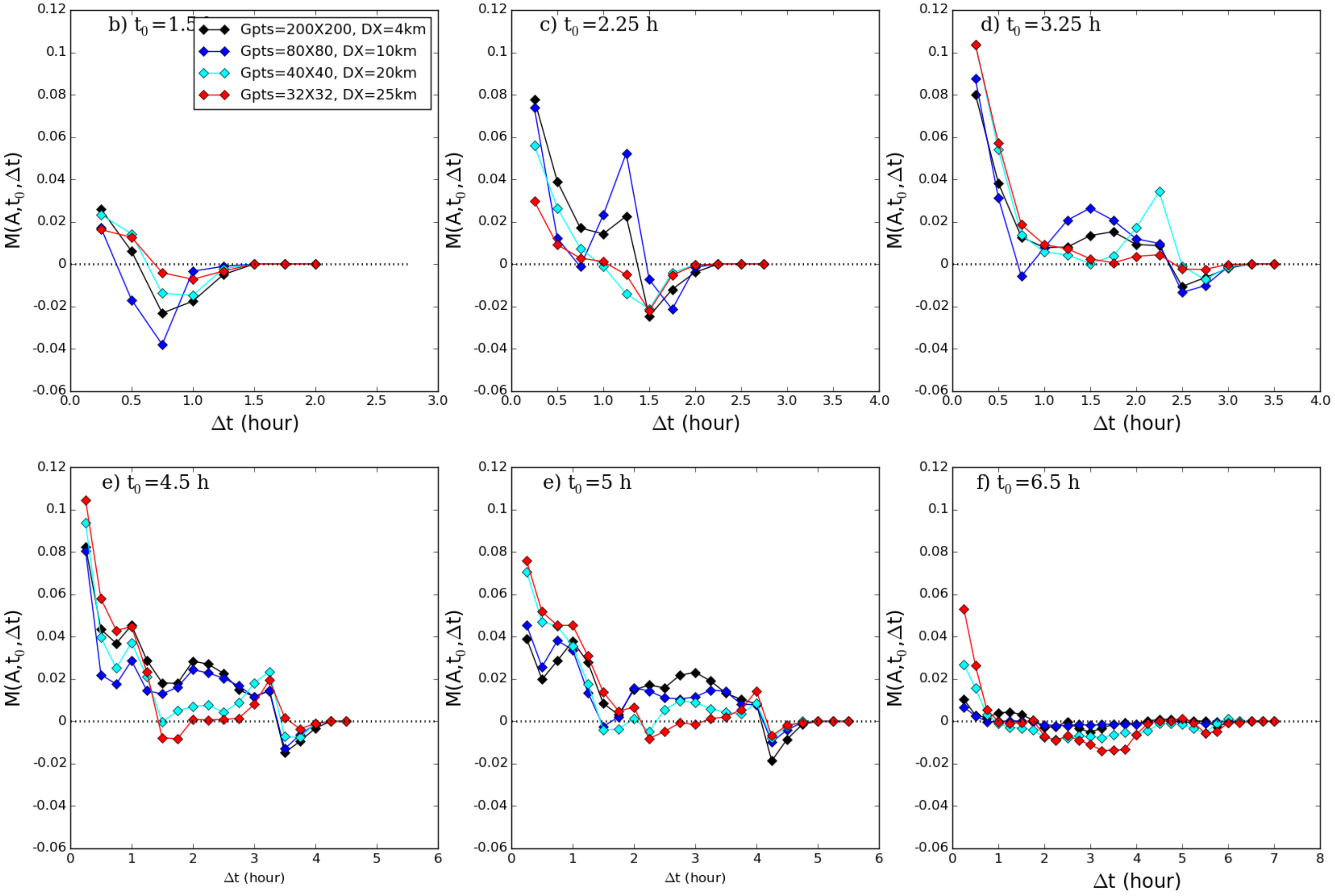
$M[R(A,t_0,\Delta t)]$ UM11.1 using CoMorph: **sensitivity to Δx**

Simulations with:

Domain size $800 \times 800km^2$ and different Δx

$precip_{i,j} \geq 0.5\, mm/h$

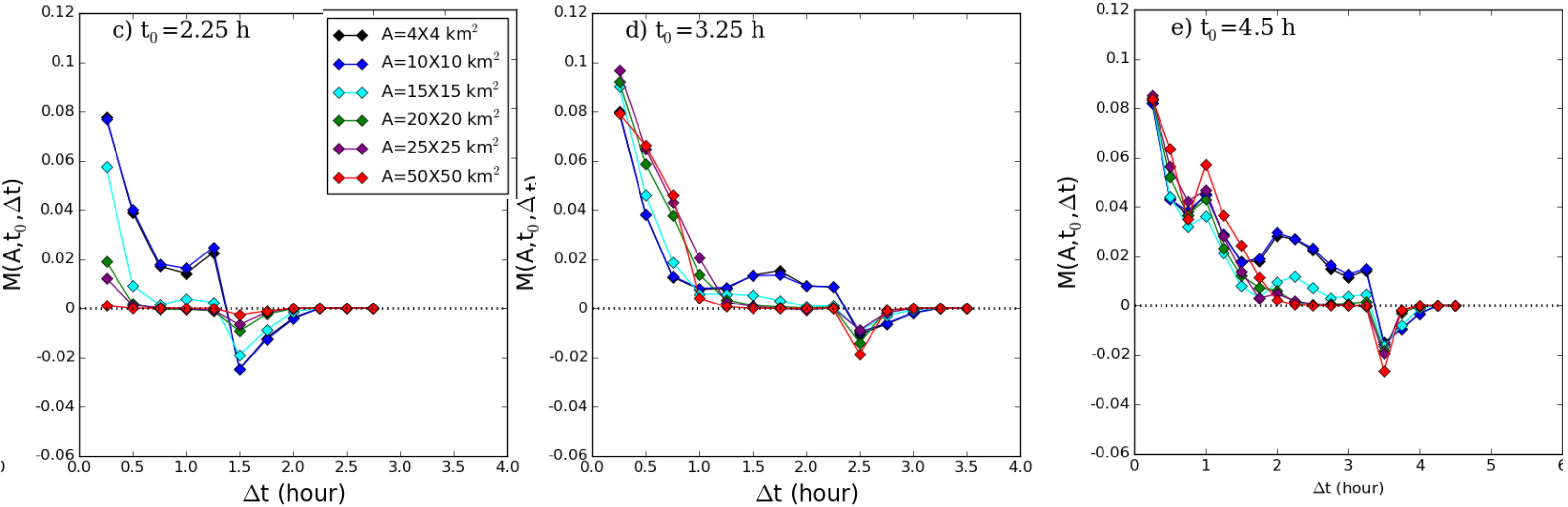
Some similarities (qualitative)



$M[R(A,t_0,\Delta t)]$ UM using CoMorph: sensitivity to A

Simulation with: Domain size $800 \times 800 km^2$ and Δx=4km

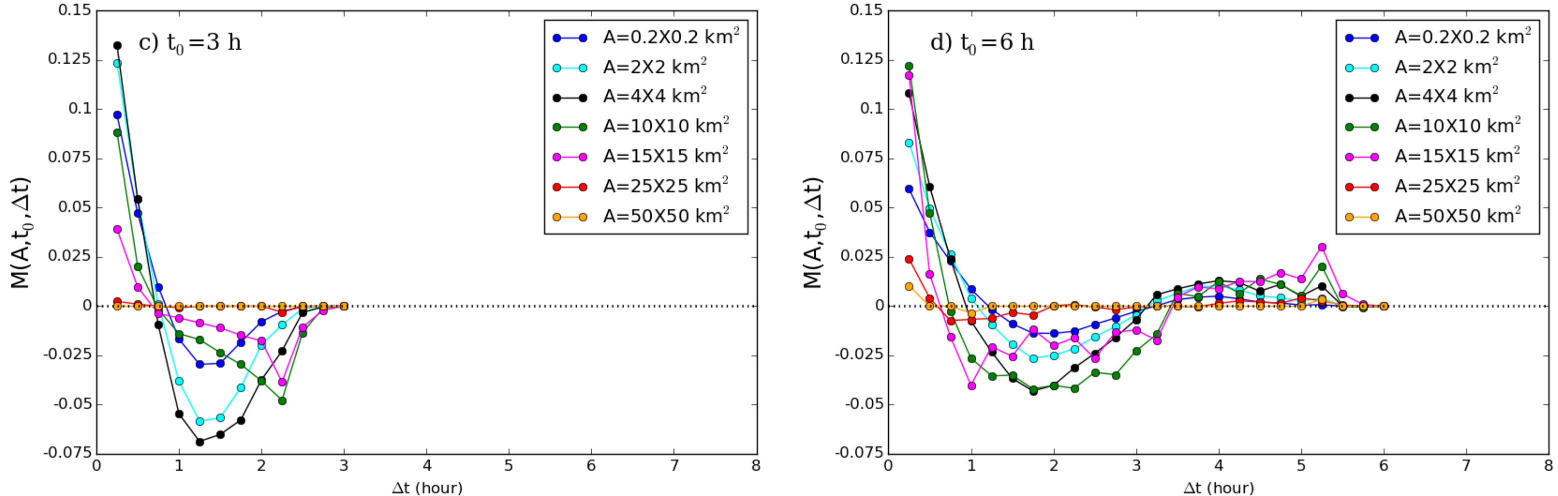
$precip_{i\ j} \geq 0.5\ mm/h$



Simulation using CoMorpgh

- $A = 4 \times 4 km^2$ and $10 \times 10 km^2$: memory properties are similar
- $A > 10 \times 10 km^2$: change of shapes
- $A > 15 \times 15 km^2$
  - For $t_0 \leq 2.25$h: M is reduced
  - For $t_0 > 2.25h$ M does not decrease with A

Simulation using MONC $100\times 100 km^2$ and Δx=200m



Reference simulations

- M is strongest at grey-zone scales ($4 \times 4 < A < 10 \times 10 km^2$)
- $A < 10 \times 10 km^2$: similar shapes
- $A > 10 \times 10 km^2$: change of shapes for
- $A = 25 \times 25 km^2$: M is reduced
- $A > 50 \times 50 km^2$: M~0

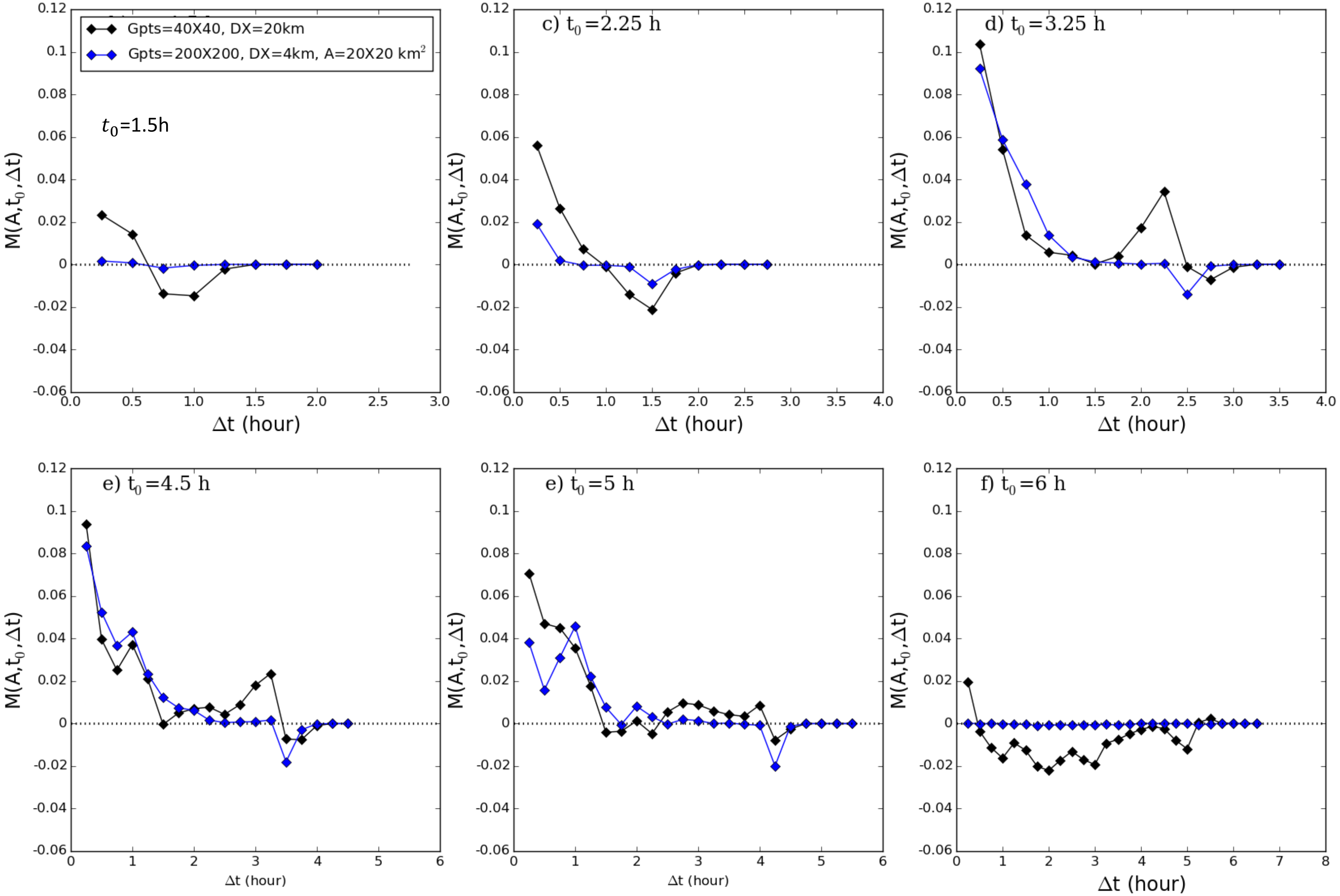
$M[R(A, t_0, \Delta t)]$ UM using CoMorph: grid-scale Vs coarse-grained scale

University of Reading

Domain size $800 \times 800 km^2$ and Δx=20km, $A = 20 \times 20 km^2$

Domain size $800 \times 800 km^2$ and Δx=4km , $A = 20 \times 20 km^2$

$precip_{i,j} \geq 0.5\ mm/h$



Grid-scale memory ?

- Memory properties at grid-scale shows some differences from those at coarse-grained scale
  - $t_0 = 1.5$h: no memory at coarse-grained scale
  - $t_0 = 6$h convection is more likely to be suppressed at grid scale

Summaries

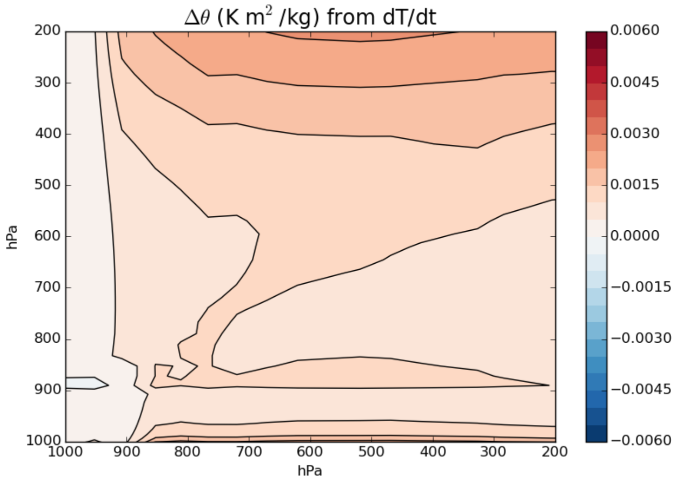
We are currently assessing **CoMorph** → that assessment is useful as part of its development
Results from the UM using **CoMorph** have been compared against those from high-resolution 3D simulations using MONC

- The 1st phase of the memory function (the persistence of convection) is represented
  - The timing is different from that obtained in the LES simulations
- The 2nd phase (suppression of convection in regions which were raining 1-3 h previously) is sometime represented
  - Not as strong as in the LES simulations
  - Convection recovers too quickly
- 3rd phase (secondary enhancement of convection):
  - CoMorph does not capture this 3rd phase via their feedbacks onto the resolved state
- The Memory function shows different sensitivity to A (compared to the sensitivity obtained in the LES simulations)
- Memory properties at grid-scale shows some differences from those at coarse-grained scale

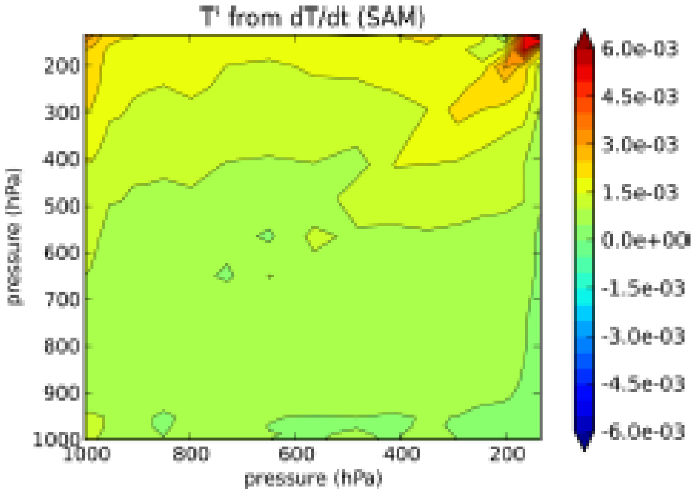
Questions

T responses to applied warm tendencies

SCUM11.6 using BM

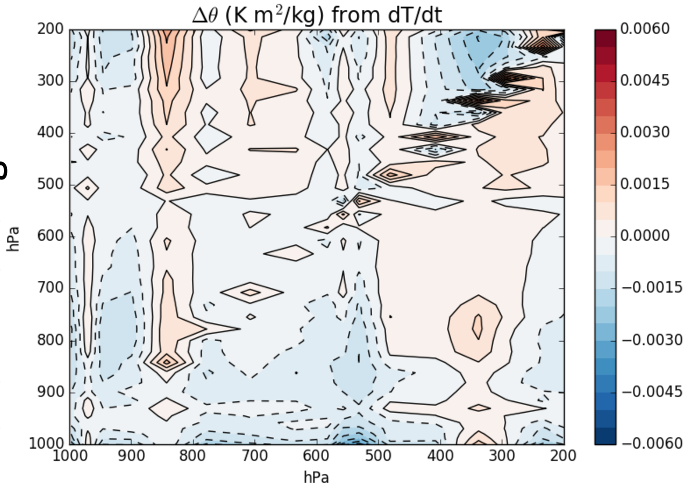


SAM

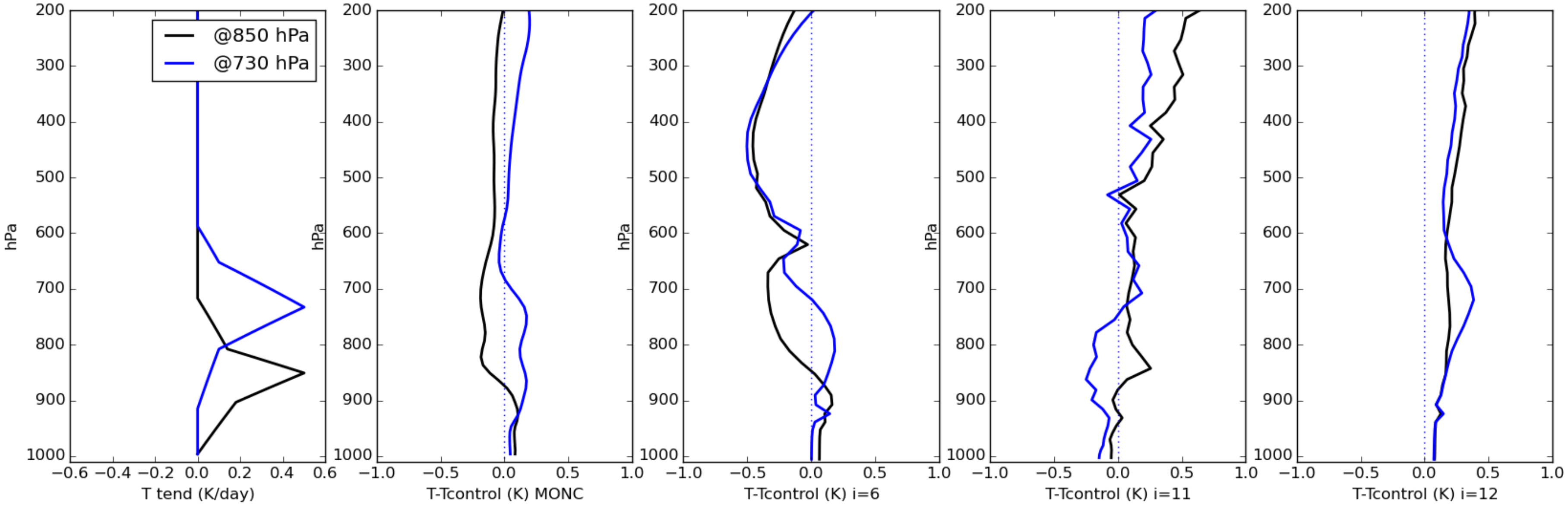


Herman and Kuang (2013)

SCUM11.3 using BM

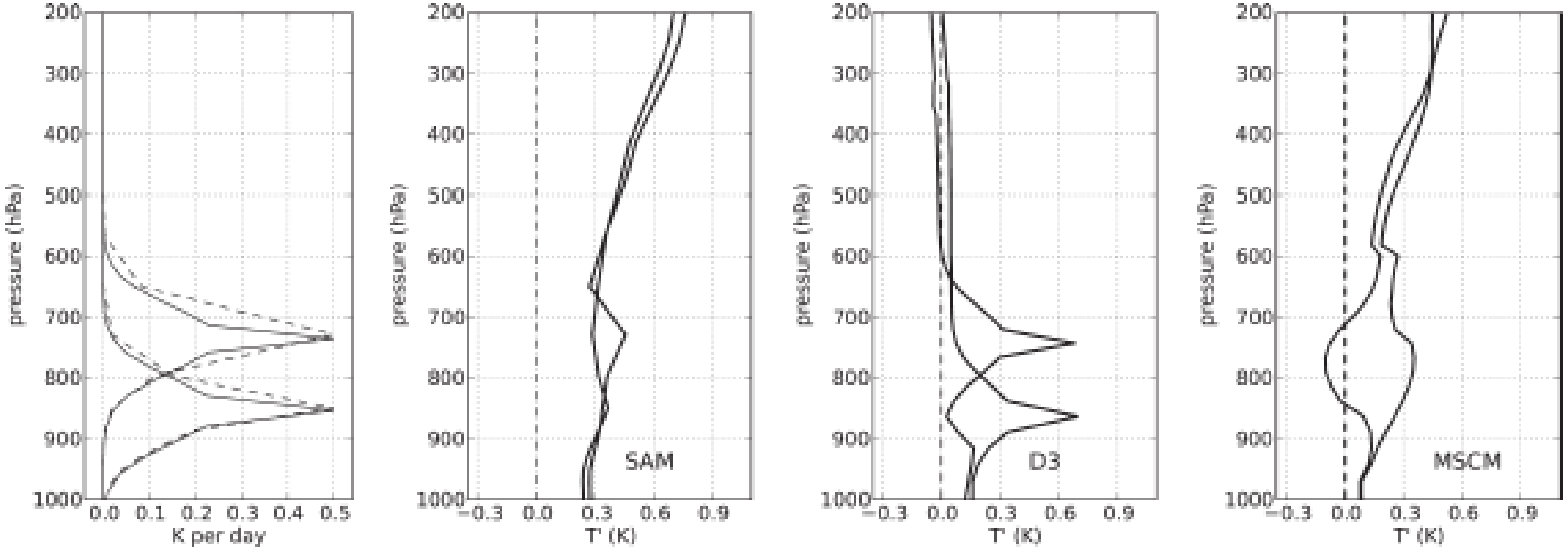


Anomalous temperature profiles corresponding to apply temperature tendency perturbations

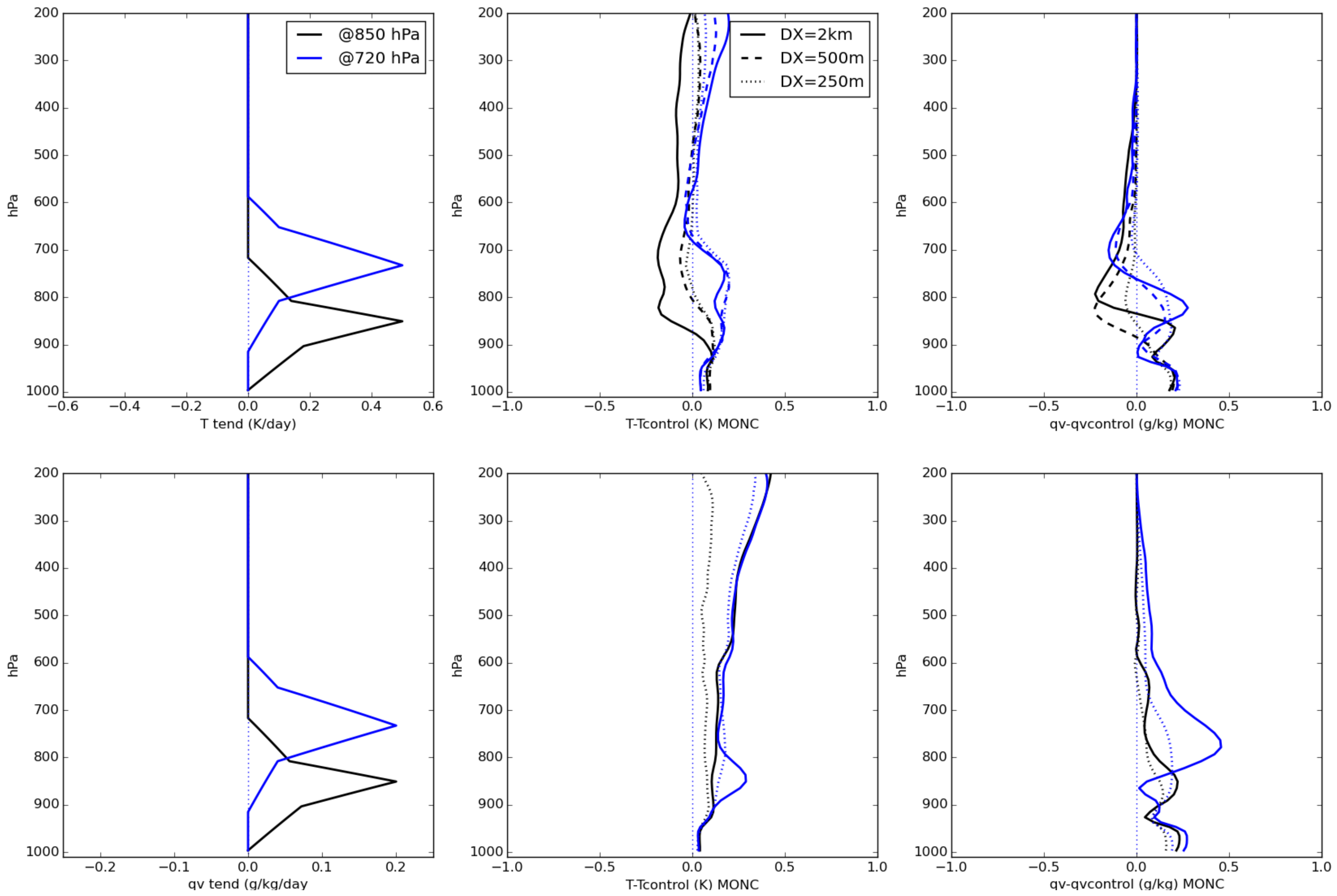


SCM version of the UM11.3 using
MF (i=6)
BM (i=11)

SCM version of the UM11.1 using
CoMorph (i=12)



Anomalous temperature profiles corresponding to applied temperature tendency perturbations near

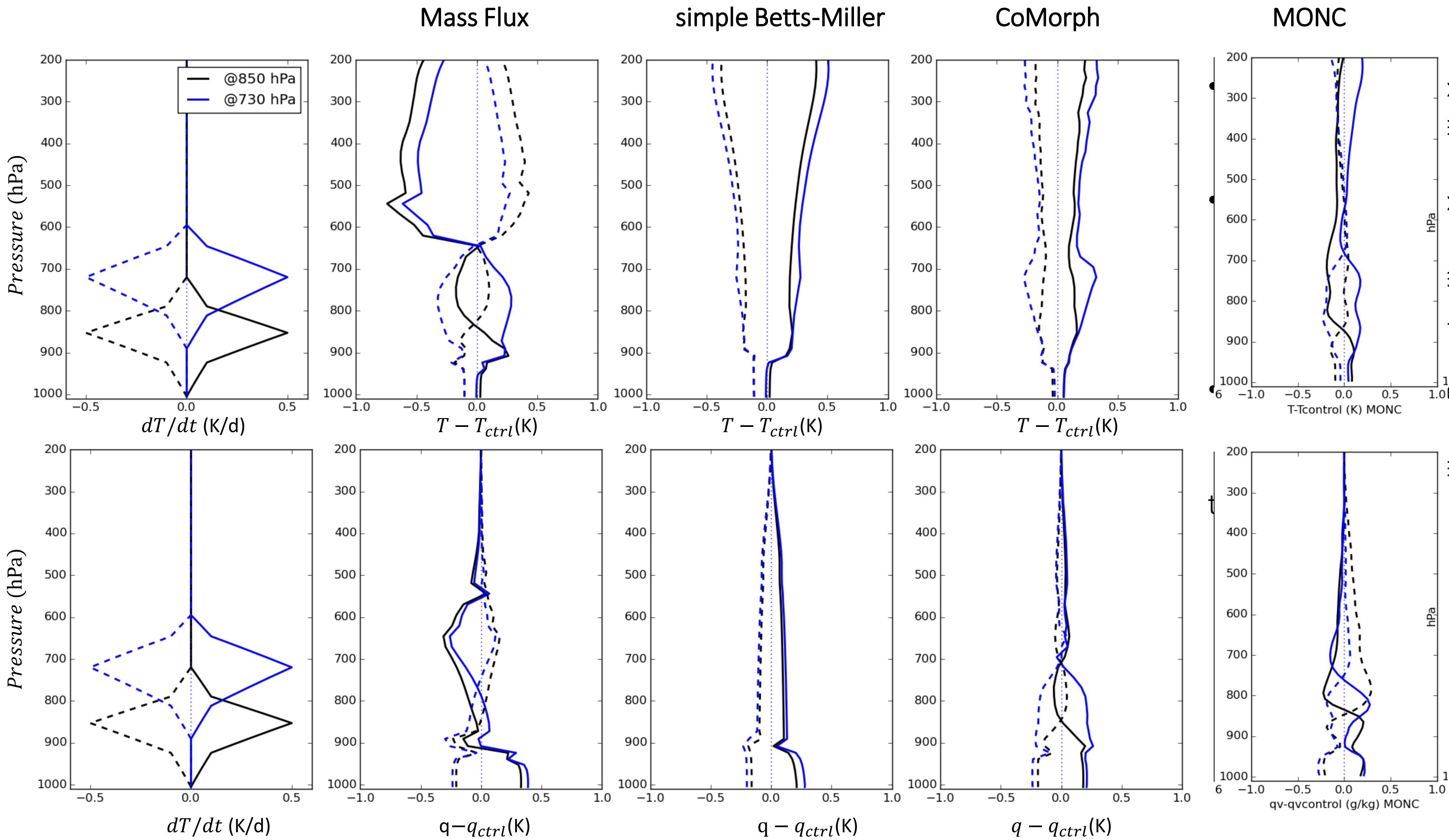


MONC sensitives to Hor. Res. ?

MONC simulations with
Hor. Res.= 2 km *(solid curves)*
Hor. Res.= 500 m *(dashed curves)*
Hor. Res.= 250m *(dotted curves)*

Anomalous temperature profiles corresponding to applied temperature tendency perturbations near

Linear responses? (warm and cold anomalies)



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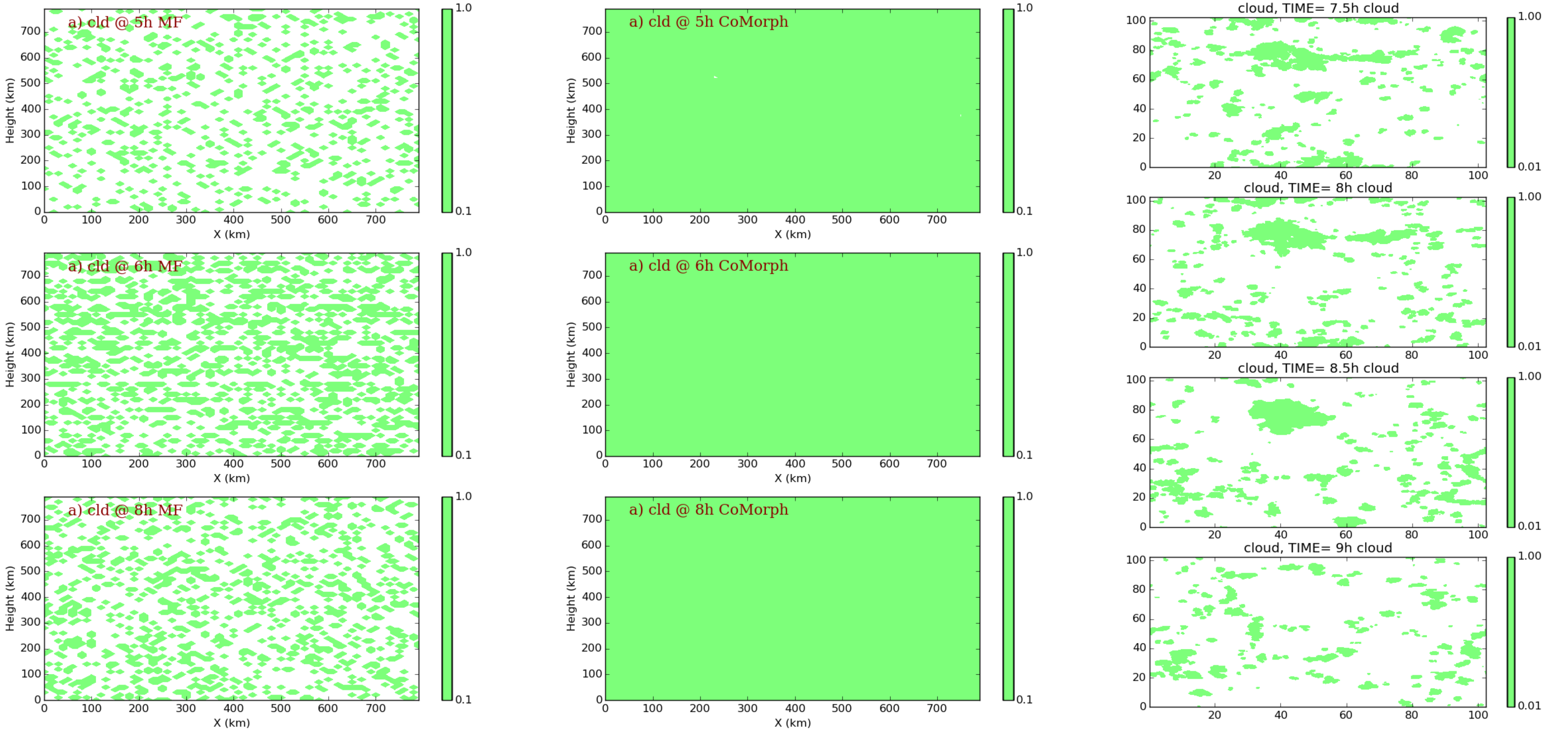
Three simulations, UM11.1 using the MF and CoMorph and simulation using MONC
UM : domain size =800*800km , hor res =10km MONC, domain size=100*100km, hor res=200m
Domain-mean daily mean precipitation rate~0.2mm/day in all three simulations.
Surface precipitation is masked using a threshold of 0.1mm/d

MF | CoMorph | MONC



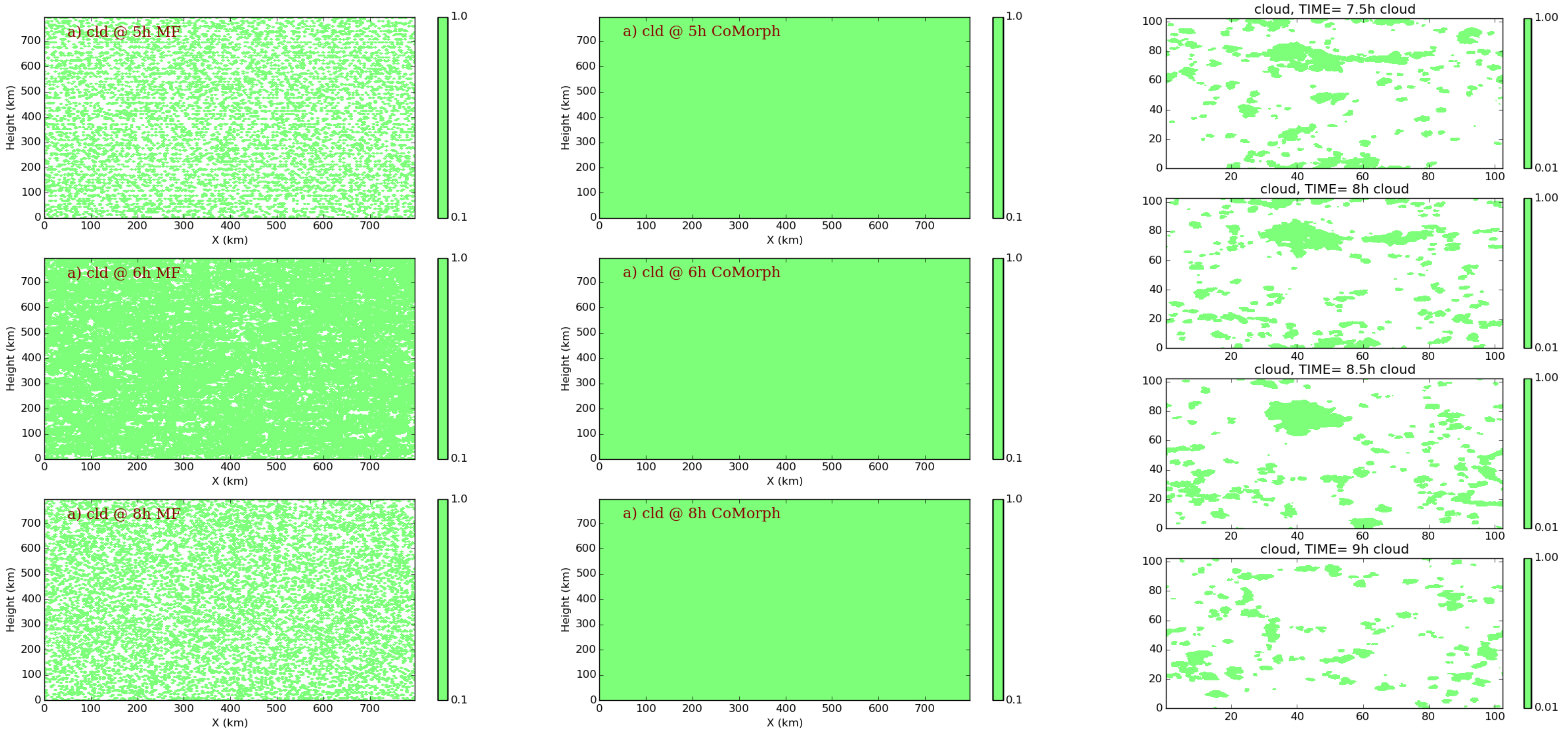
Three simulations, UM11.1 using the MF and CoMorph and simulation using MONC

UM : domain size =800*800km , hor res =4km MONC, domain size=100*100km, hor res=200m

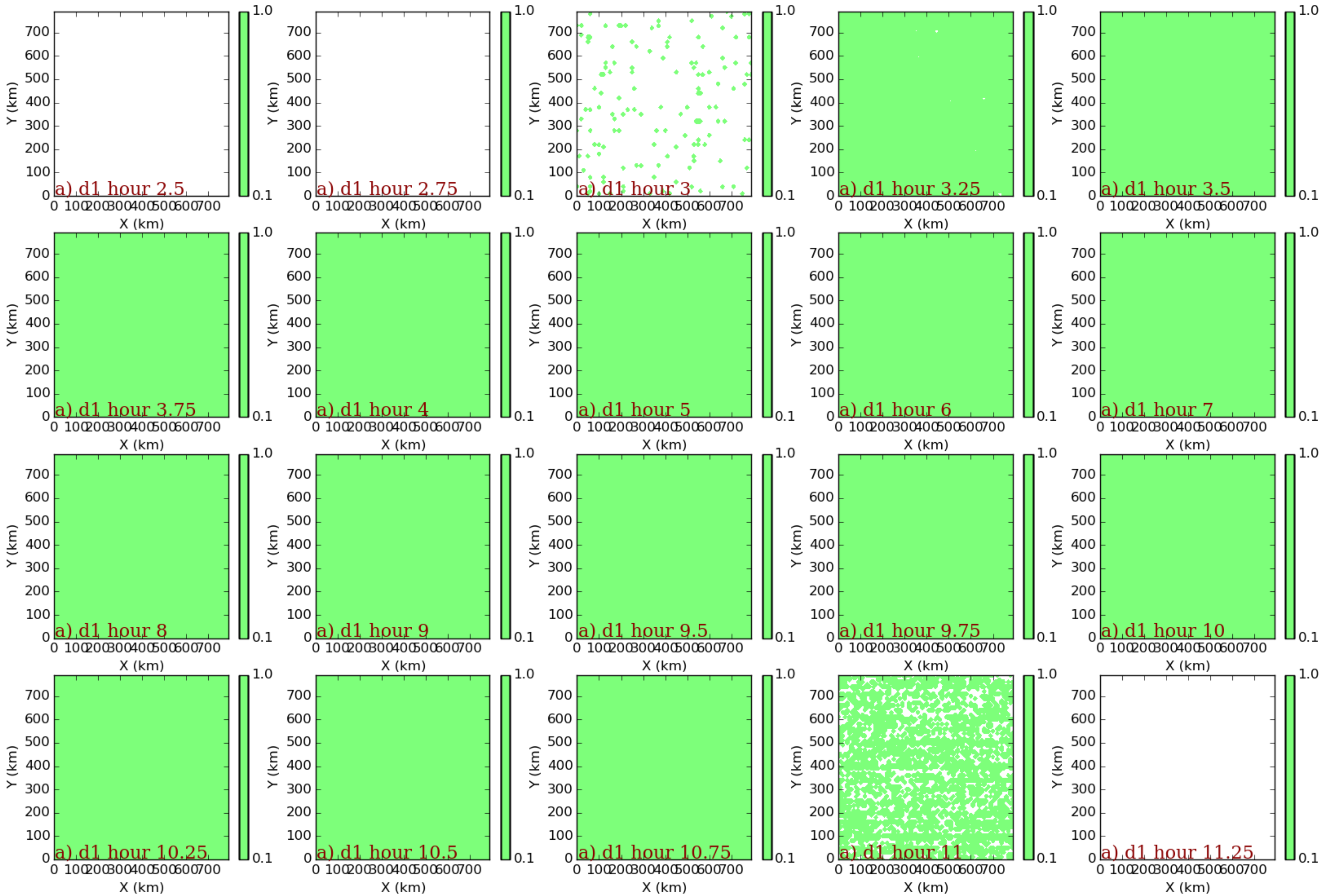
Domain-mean daily mean precipitation rate~0.2mm/day in all three simulations.

Surface precipitation is masked using a threshold of 0.1mm/day

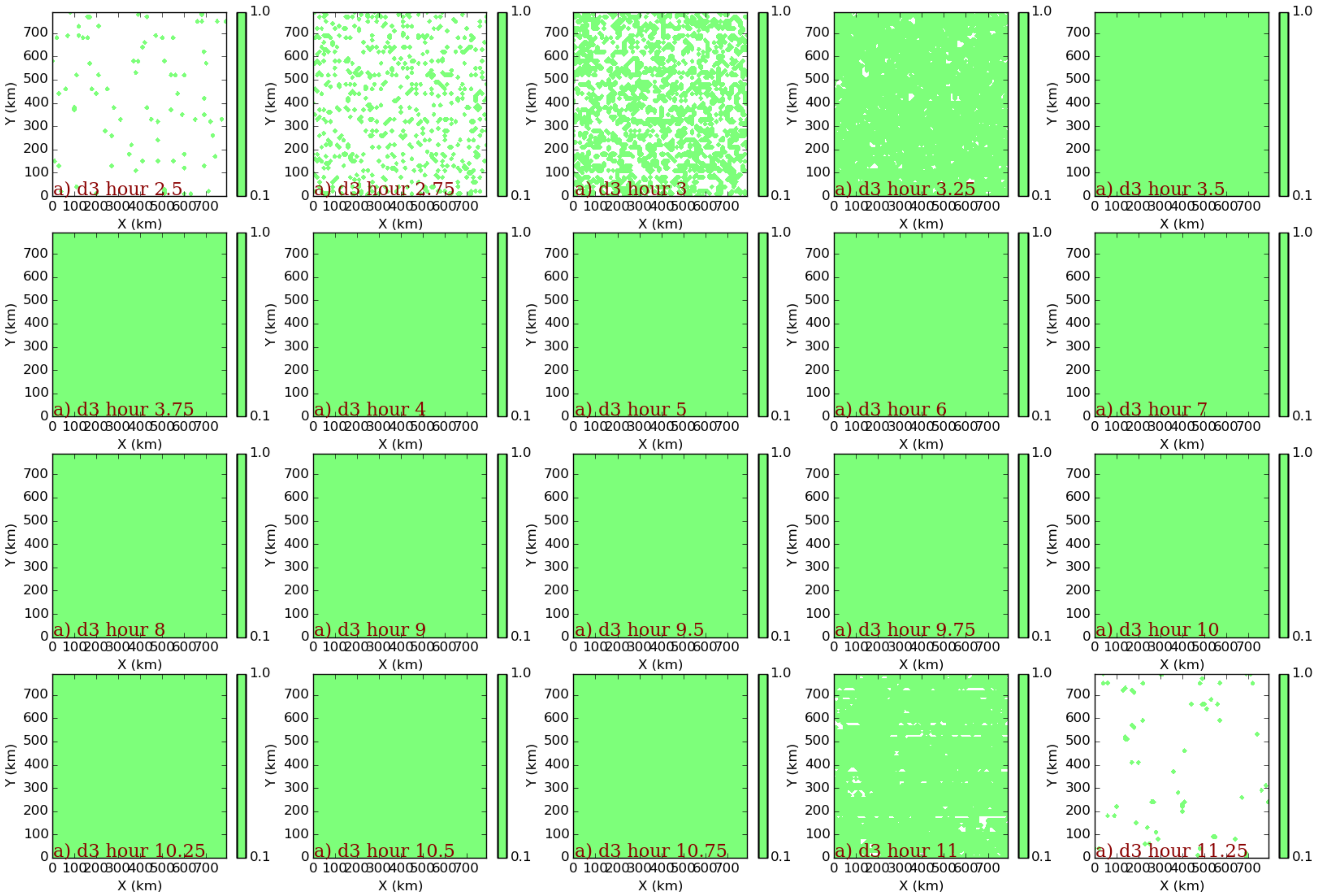
MF CoMorph MONC



UM11.1 using CoMorph
Precipitation threshold = 0.1mm/day
Results over the 1st diurnal cycle
Precipitation is quite uniform
between hours 3.5 and 10.75



UM11.1 using CoMorph
Precipitation threshold = 0.1mm/day
Results over the 2nd diurnal cycle
Precipitation is quite uniform
between hours 3.5 and 10.75



Three simulations, UM11.1 using the MF and CoMorph and simulation using MONC

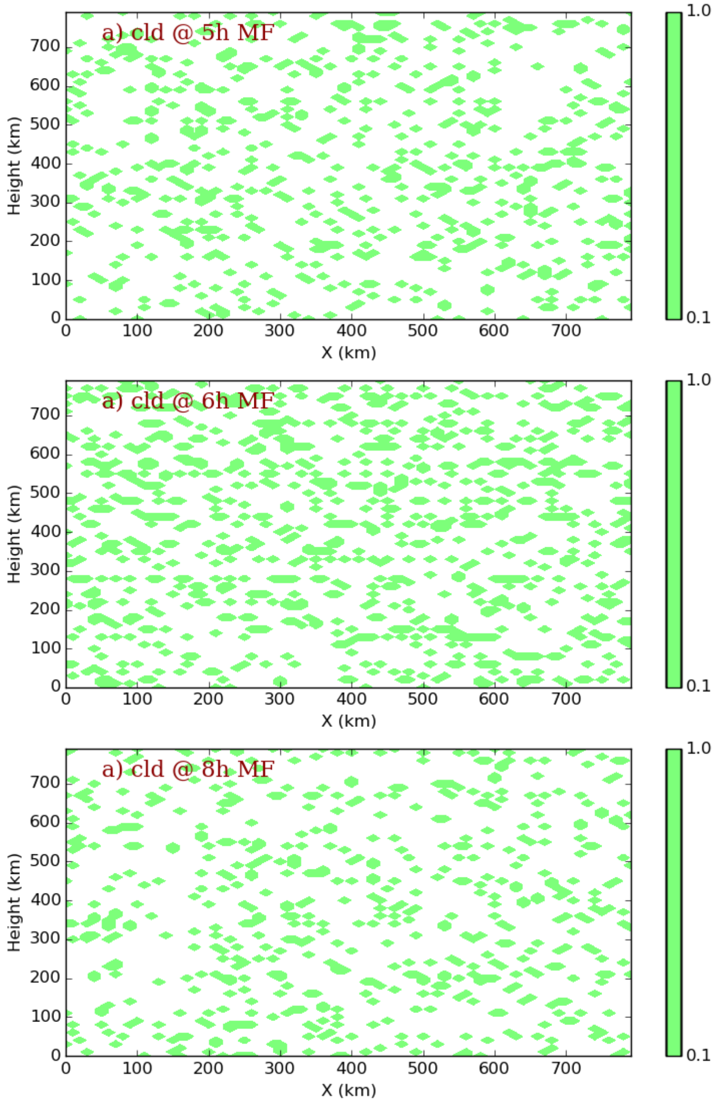
UM : domain size =800*800km , hor res =10km

MONC, domain size=100*100km, hor res=200m

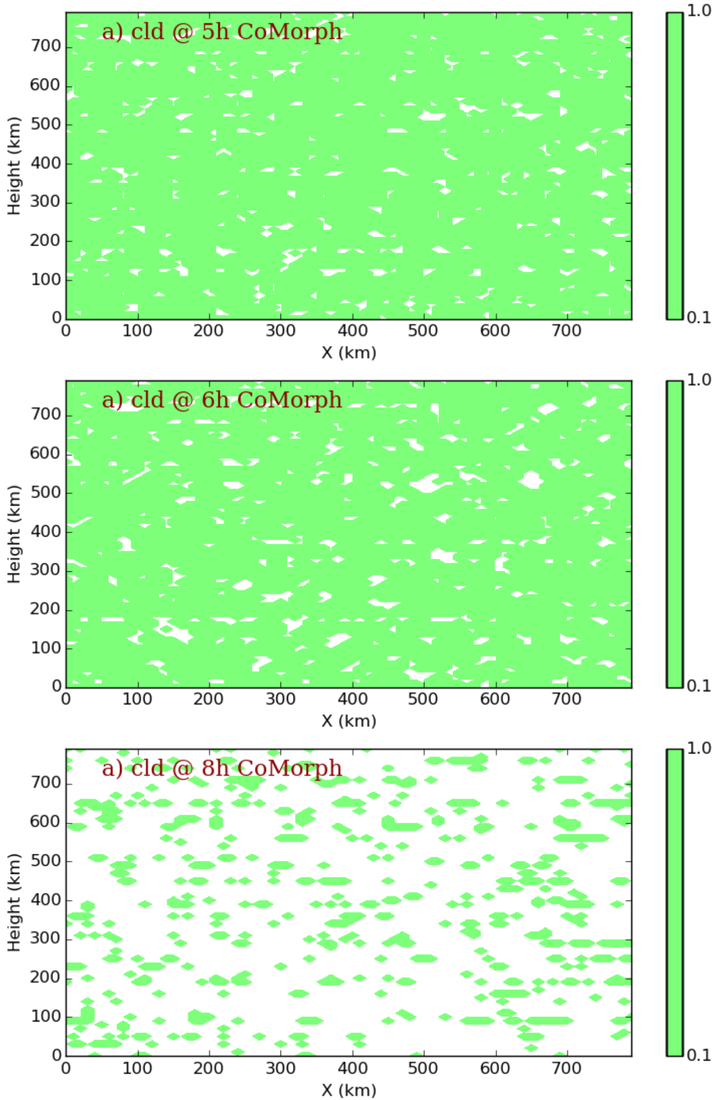
Domain-mean daily mean precipitation rate~0.2mm/day in all three simulations.

Surface precipitation is masked using a threshold of 0.5mm/day

MF



CoMorph



Three simulations, UM11.1 using the MF and CoMorph and simulation using MONC

UM : domain size =800*800km , hor res =4km

MONC, domain size=100*100km, hor res=200m

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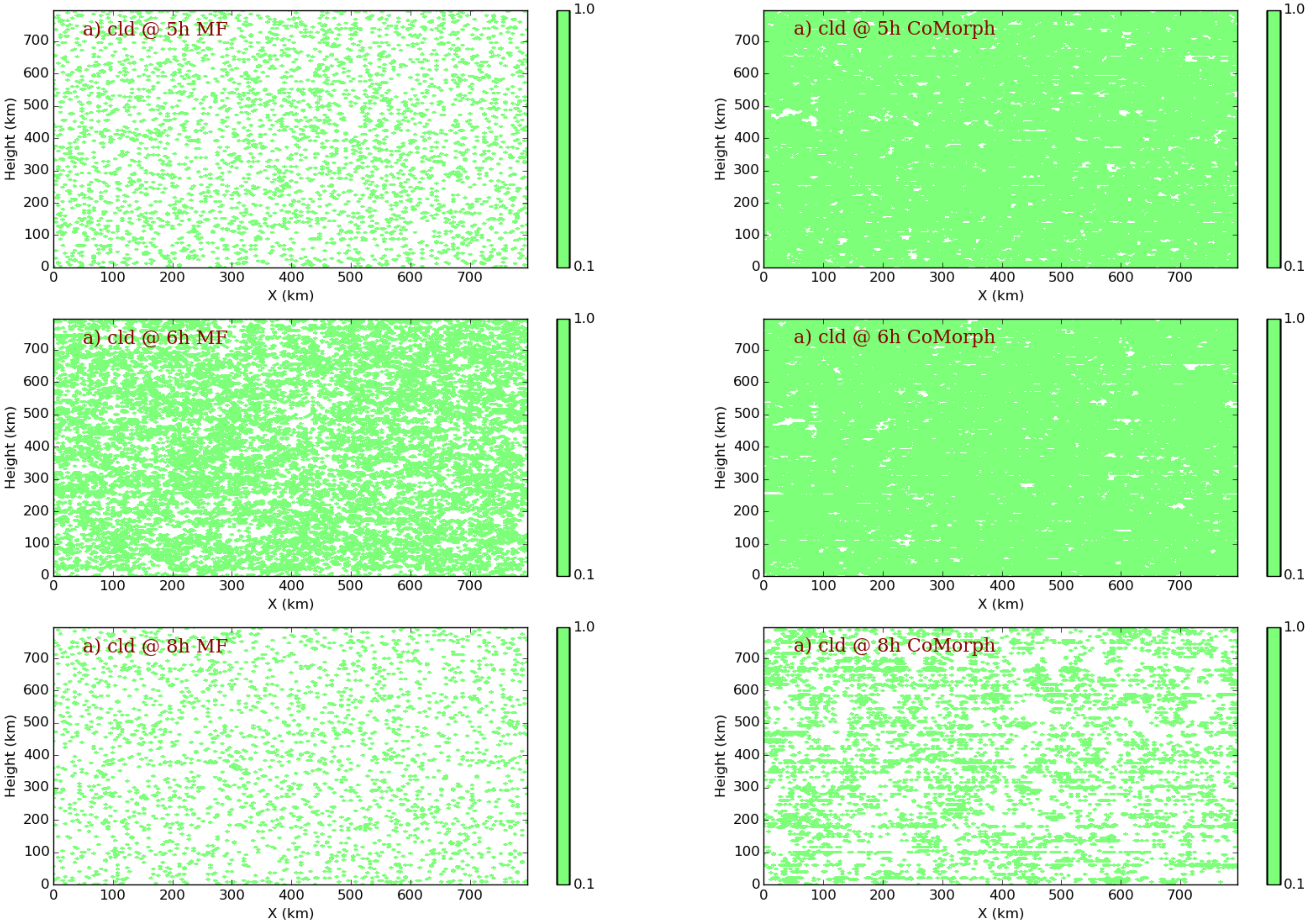
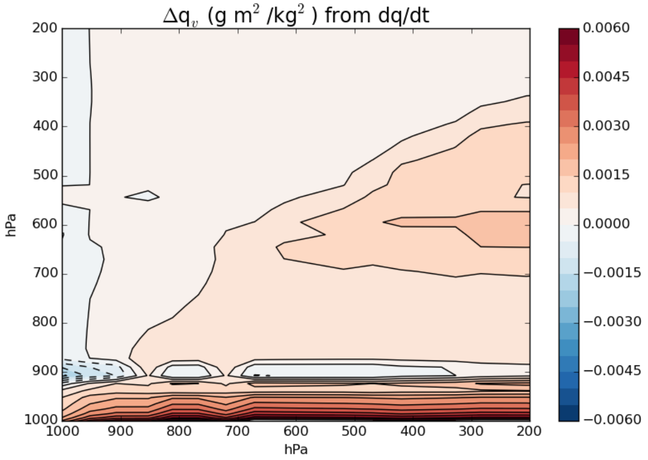
MF

CoMorph

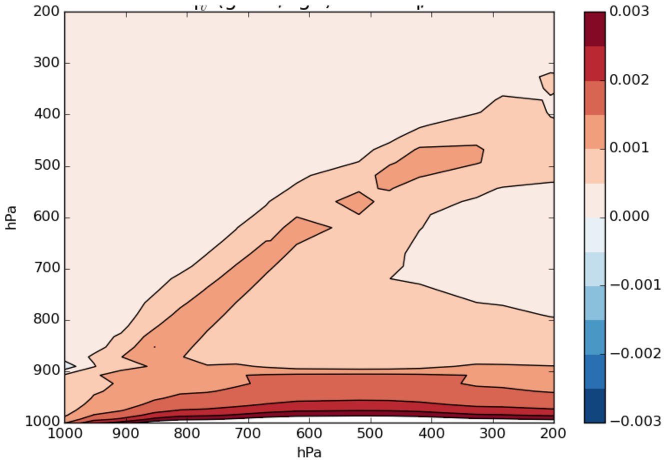


qv responses to applied moist tendencies

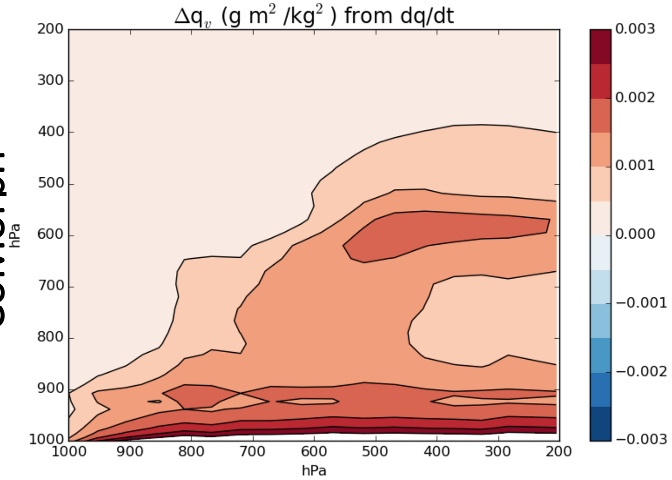
Mass Flux



Betts-Miller



CoMorph

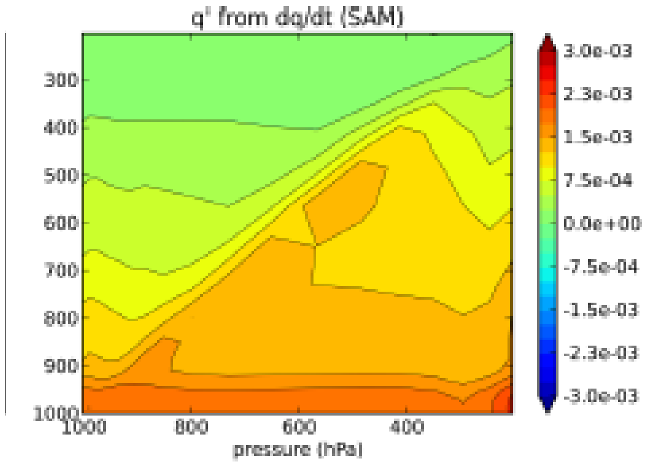


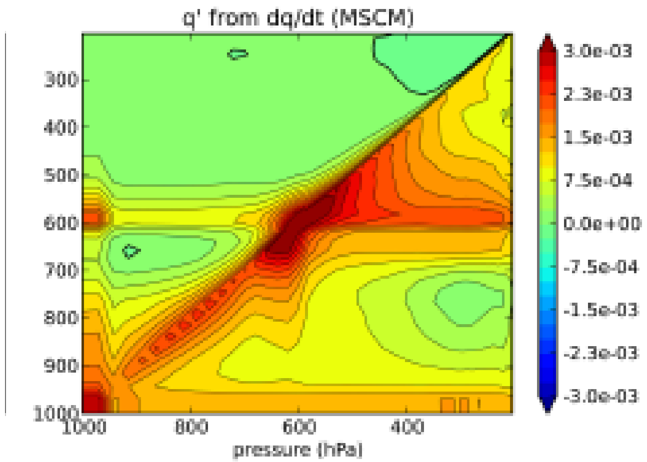
SCM using BF or CoMorph (like SAME):

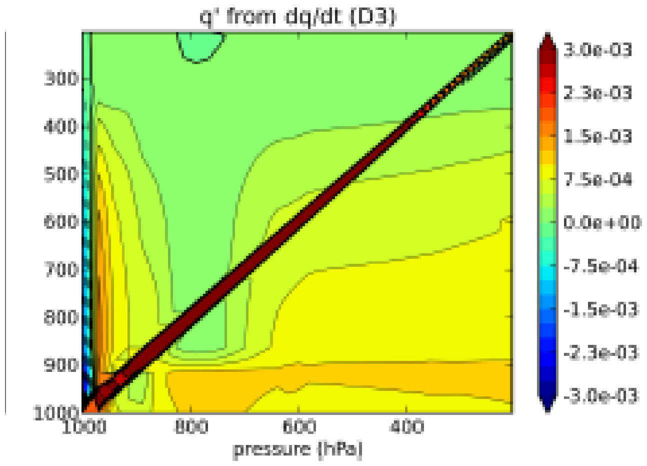
- changes are consistent:
- moistening through the depth of the column.
- the response is stronger below the perturbed layer

SCM using MF

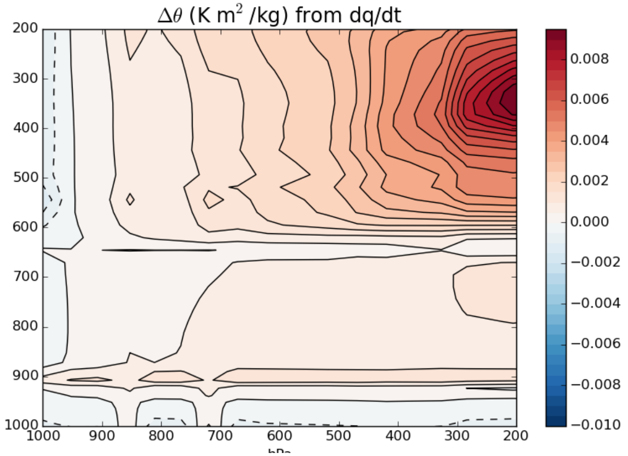
- Drying at cloud base
- Stronger responses (moistening) of the cloud base



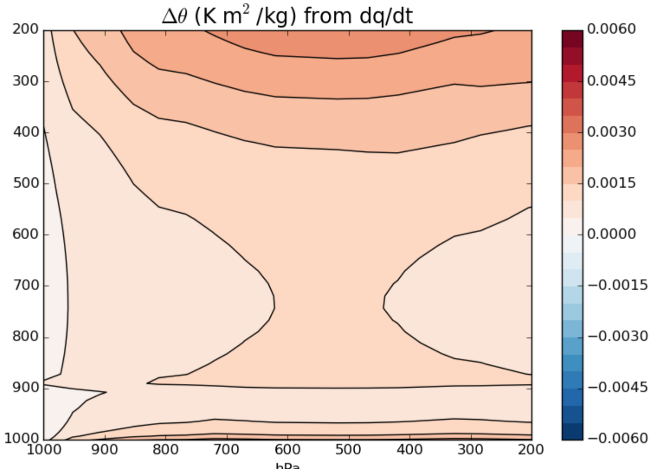




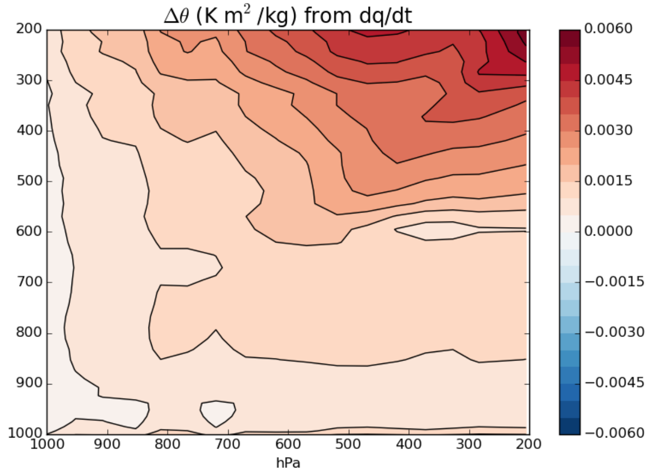
Mass Flux



Betts-Miller



CoMorph



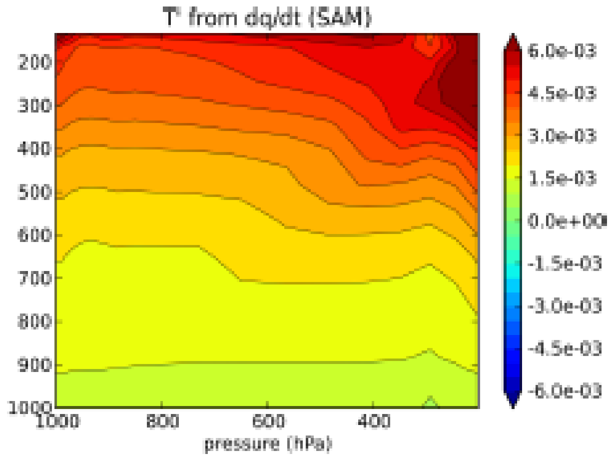
T responses to applied moist tendencies

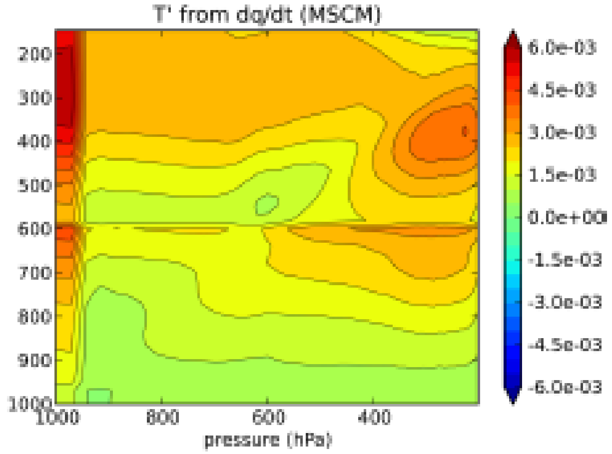
SCM using BF or CoMorph (as SAM):

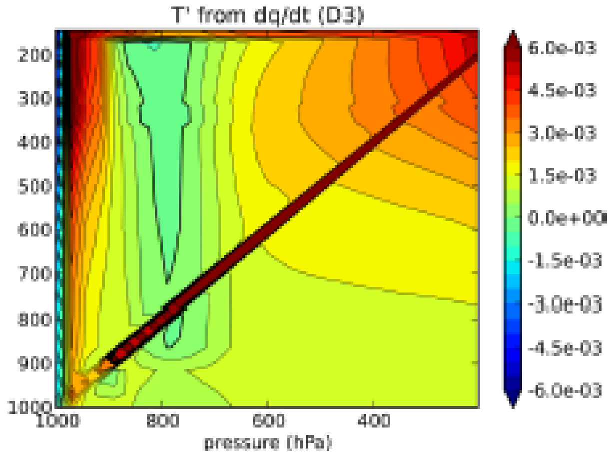
- changes are consistent:
- Warming through the depth of the column.
- CoMorph: the pattern is very similar to that of SAM

SCM using MF

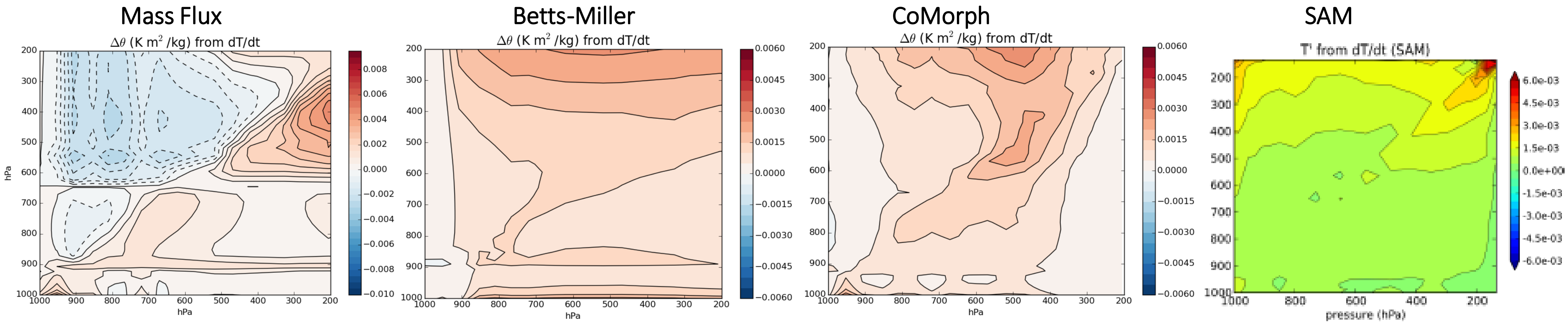
- The responses above 600 hPha are too strong
- Kinks at freezing levels
- Cooling of the cloud base



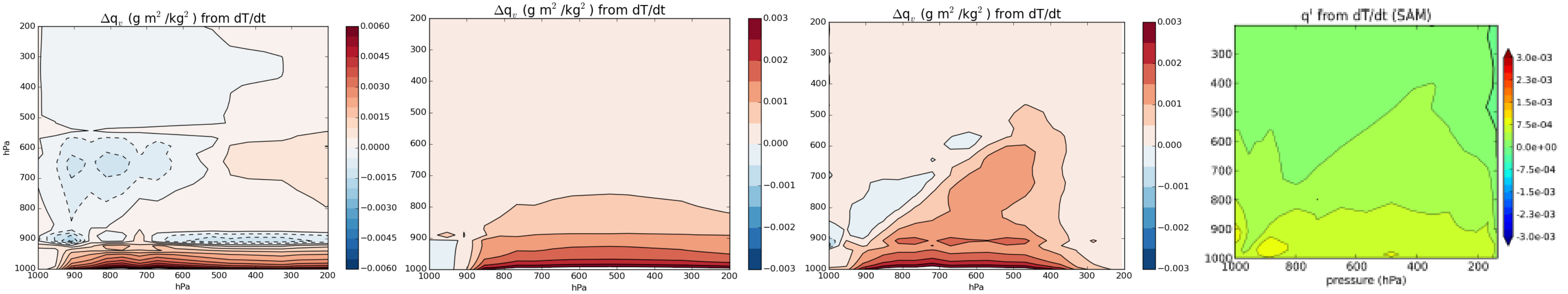




T responses to applied warm tendencies



qv responses to applied warm tendencies



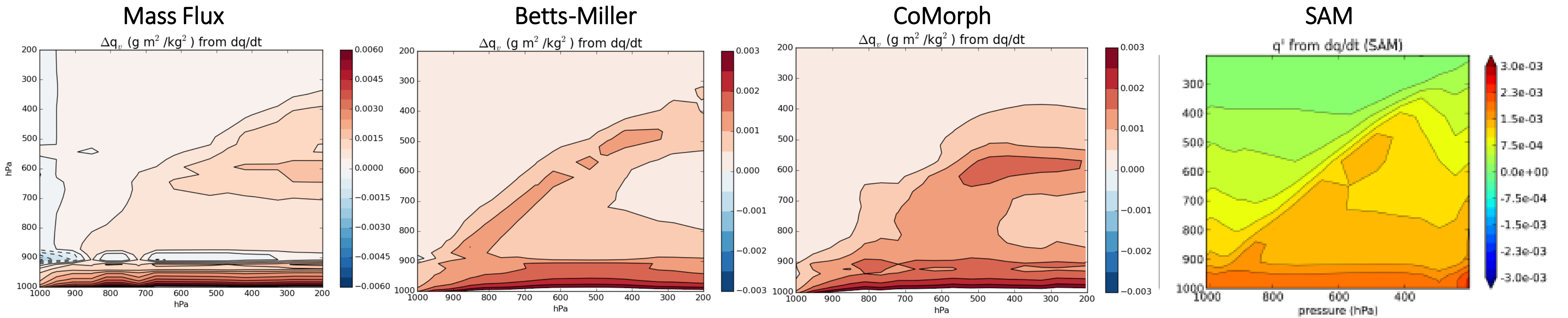
SCM using MF

- Below 400 hPa: Cold and dry anomalies above the perturbed layers
- Above 400 hPa: T responses above 600 hPa are too strong
- Drying of the cloud base (for all perturbed layers)

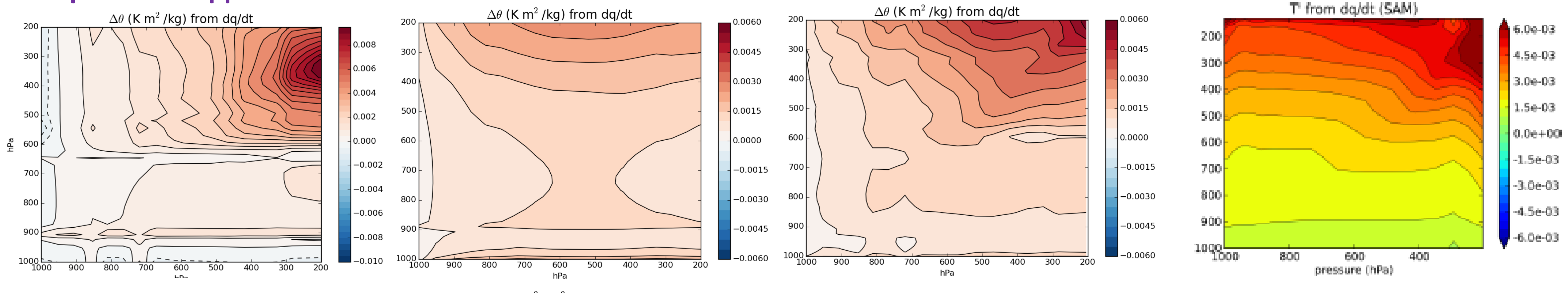
SCM using BM or using CoMorph (like SAM)

- Warming and moistening through the depth of the column
- CoMorph (like SAM): stronger moistening bellow the perturba level
- BM: stronger moistening below 800 hPa for pert levels 950-200 hPa

qv responses to applied moist tendencies



T responses to applied moist tendencies



SCM using MF

- Drying of cloud base and weaker qv responses around 650hPa
- Cloud base: qv responses are stronger, cooling
- Above 600 hPa: qv responses are too strong

SCM using BF or CoMorph (like SAME): changes are consistent:

- Moistening and warming through the depth of the column
- qv response is stronger below the perturbed layer
- CoMorph: T responses (pattern) are very similar to that of SAM