Large Eddy Simulations of Clouds and Boundary Layer Processes

ARM Summer Training
Final Presentation
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Image courtesy of Bjorn Stevens

Motivation and Outline

- What domains are needed to realistically simulate shallow cumulus?
- What are the properties of the simulated cloud field?
- What is the sensitivity of observations to cloud field variability?
- What is the sensitivity of the boundary layer depth to large-scale and local (e.g. sensible heat flux) forcings?

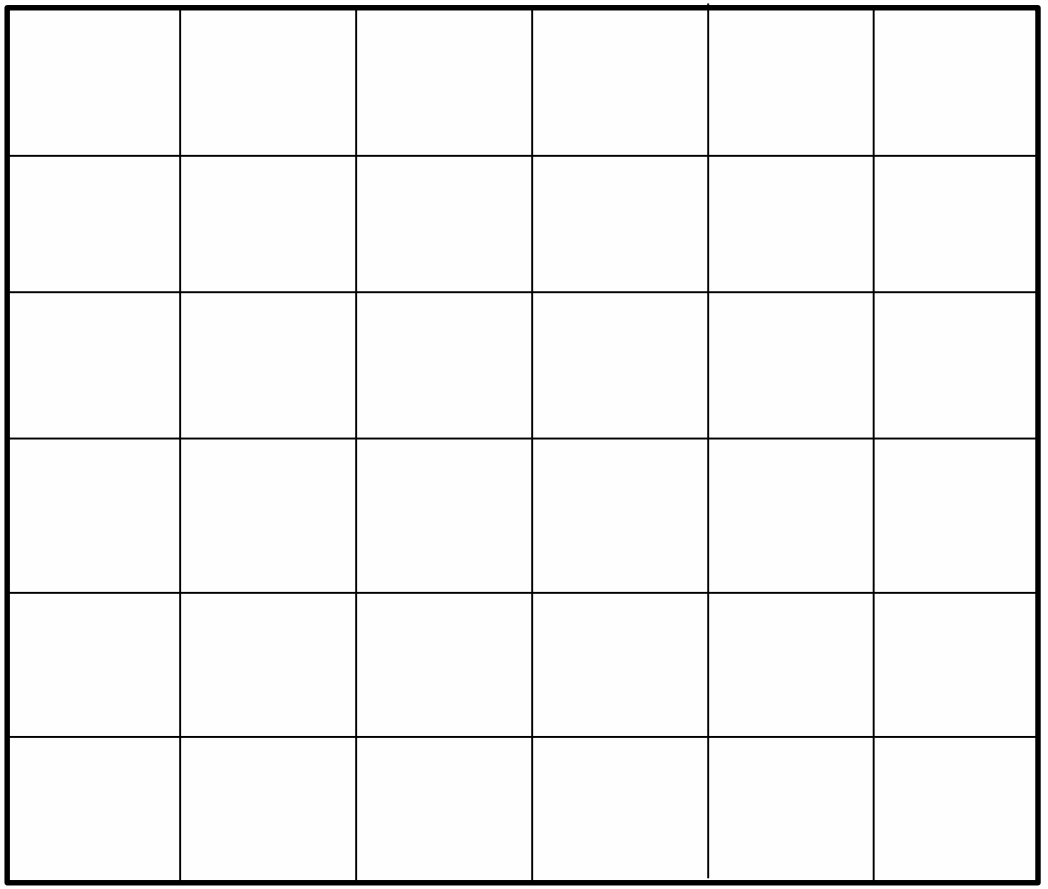
- Cloud simulations: Rain in Shallow Cumulus Over the Ocean (RICO; Rauber et al. 2007).

    - Model domain experiments
    - Cloud properties
    - Synthetic observations

- Boundary layer simulations: SGP observations.

    - Boundary layer depth estimation

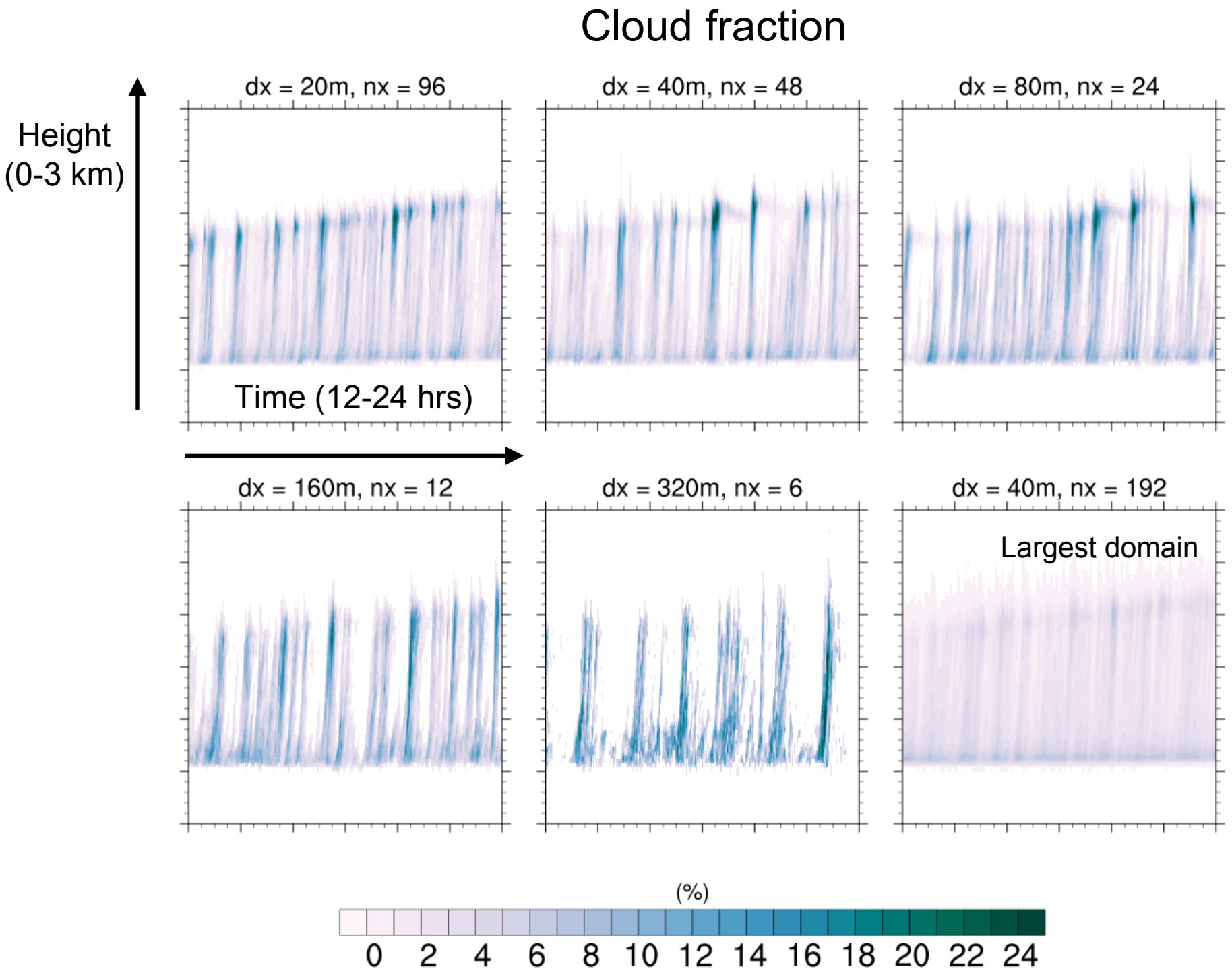
Model domain experiments

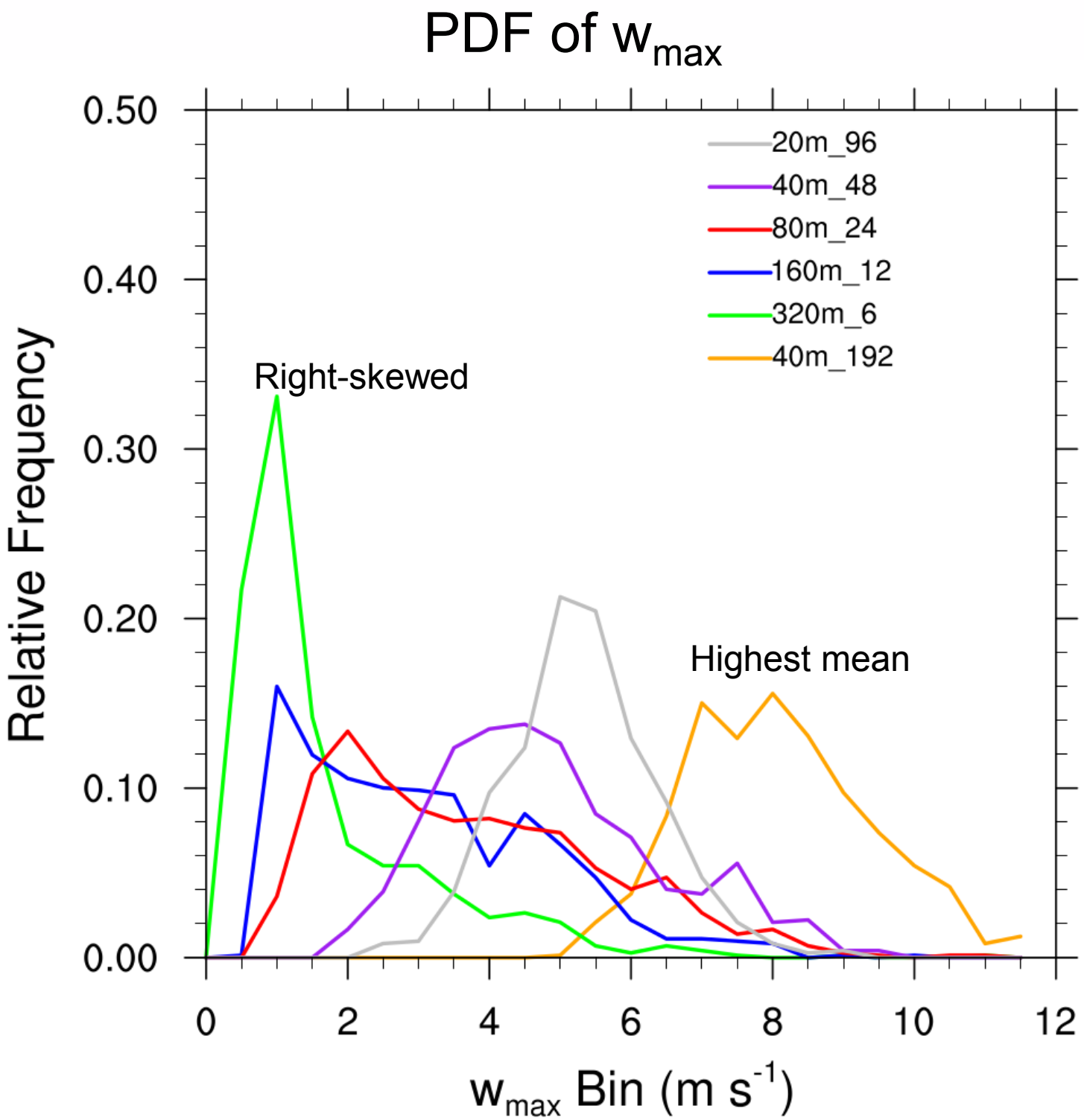


dx (m)	nx
20	96
40	48
80	24
160	12
320	6
40	192

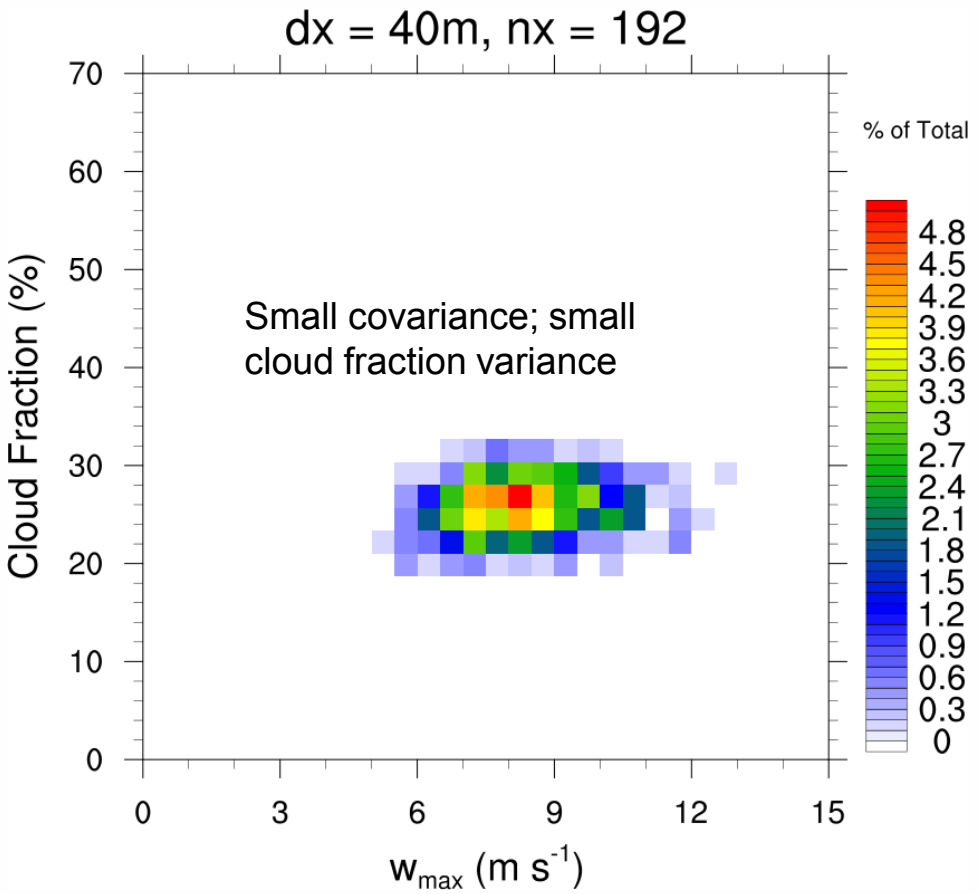
7680 m x 7680 m

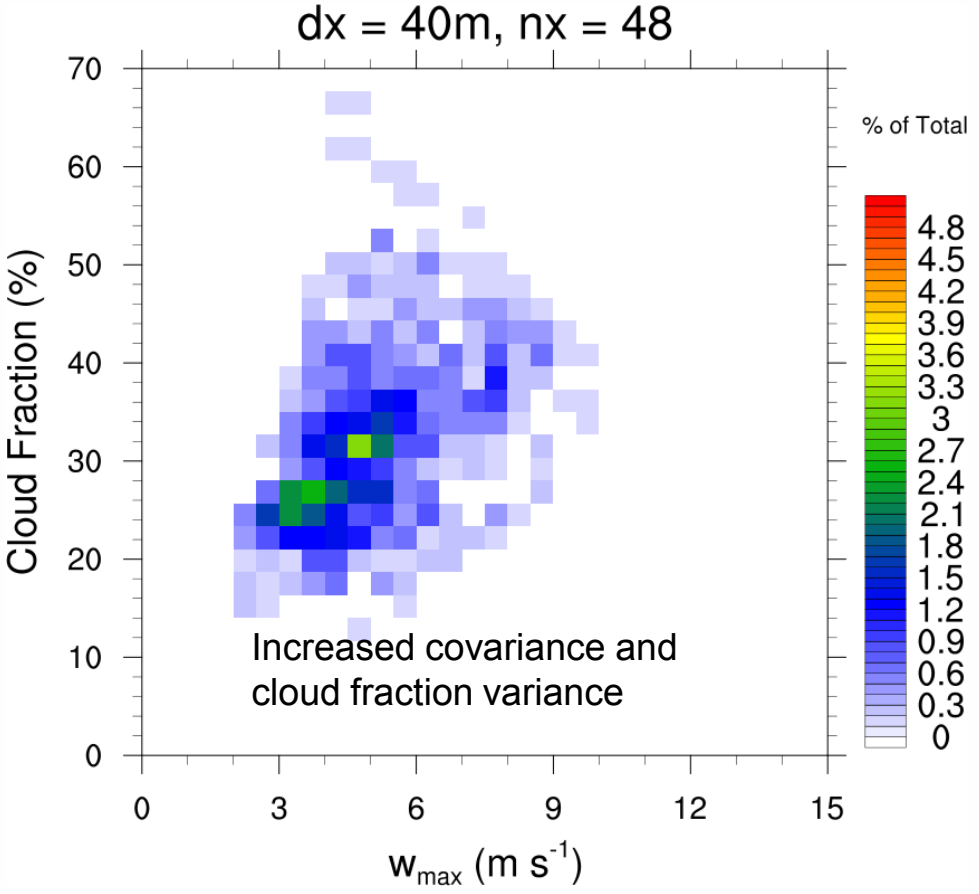
Dutch Atmospheric Large Eddy Simulation (DALES) model (Heus et al. 2010)


Cloud fraction
Height
(0-3 km)
dx = 20m, nx = 96
dx = 40m, nx = 48
dx = 80m, nx = 24
Time (12-24 hrs)
dx = 160m, nx = 12
dx = 320m, nx = 6
dx = 40m, nx = 192
Largest domain
(%)
0 2 4 6 8 10 12 14 16 18 20 22 24


PDF of w_{max}
0.50
0.40
0.30
0.20
0.10
0.00
Relative Frequency
20m_96
40m_48
80m_24
160m_12
320m_6
40m_192
Right-skewed
Highest mean
0
2
4
6
8
10
12
w_{max} Bin (m s^{-1})

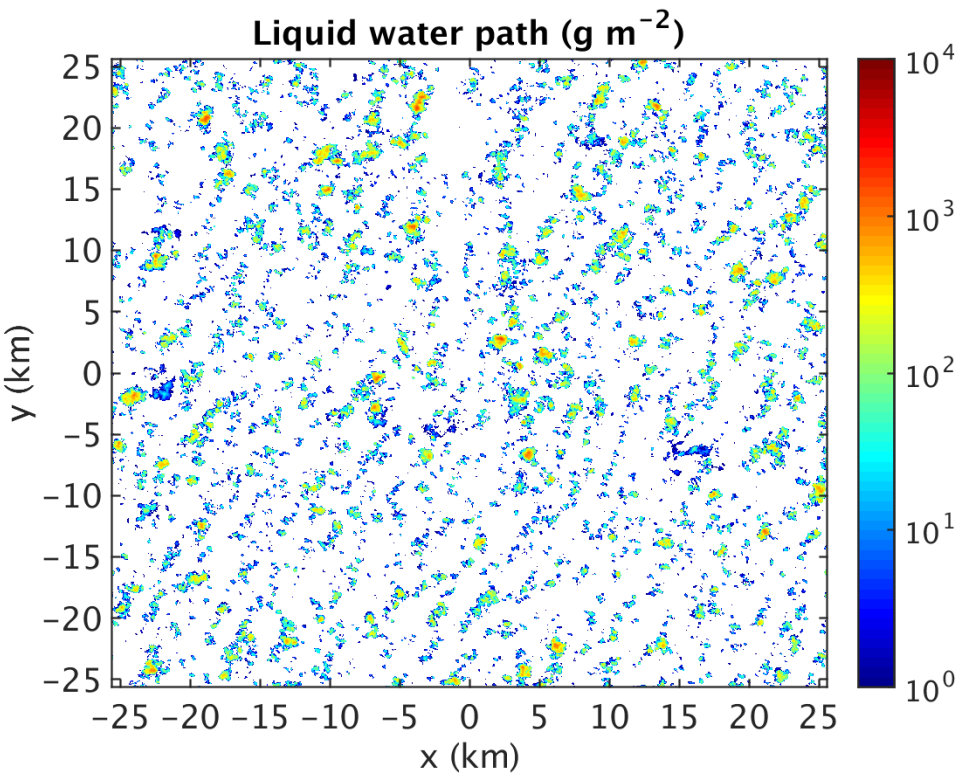
Joint PDFs of Cloud fraction and w_{max}

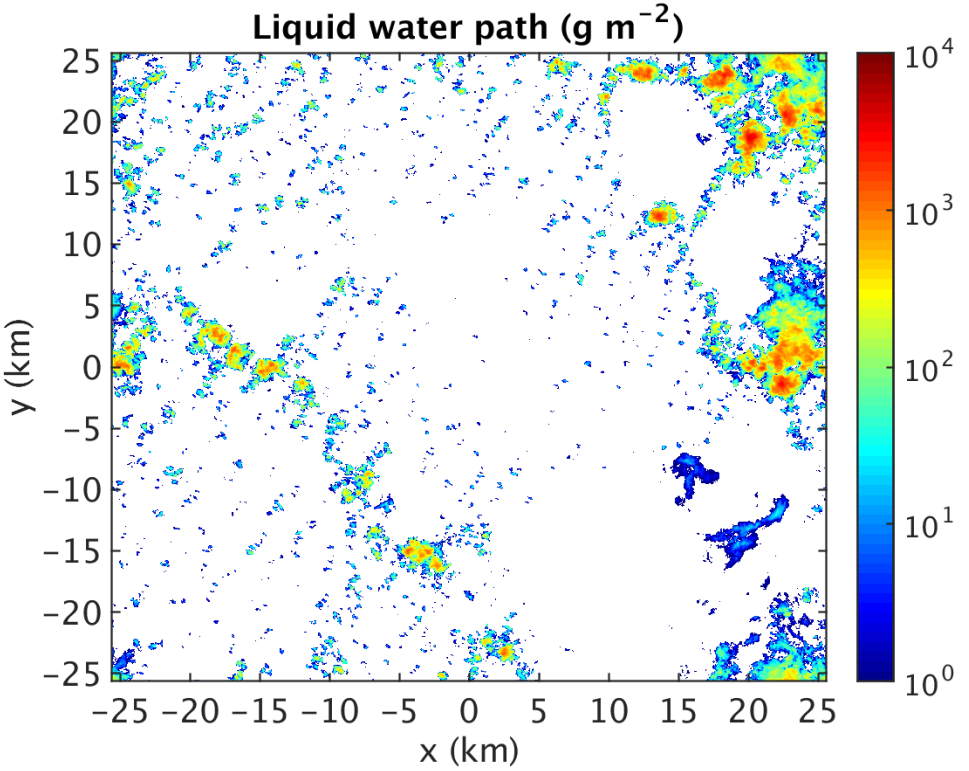




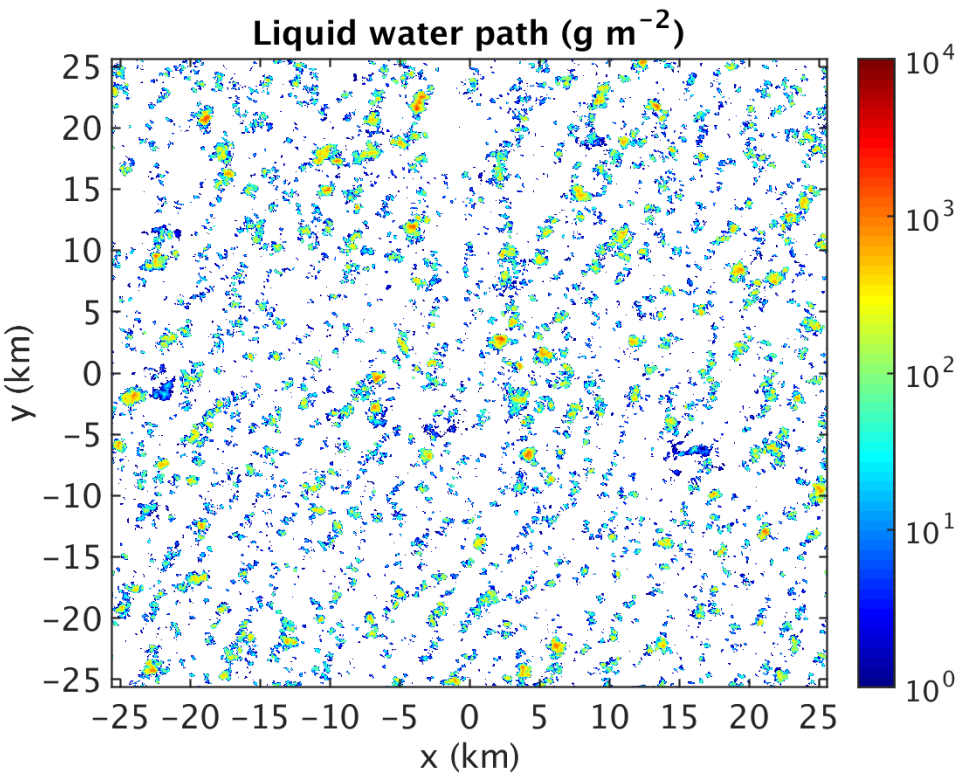
Implications for comparing LES models with observations (e.g. field of interest, observation time)

Simulated cloud properties

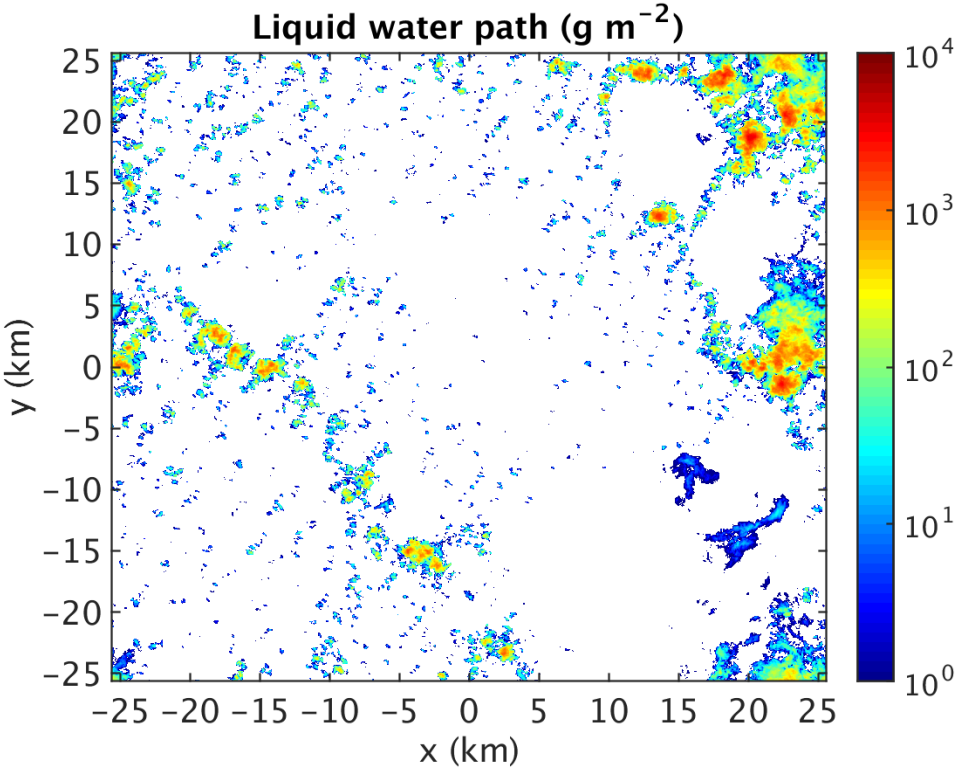




Development of clouds in the model domain



8 h



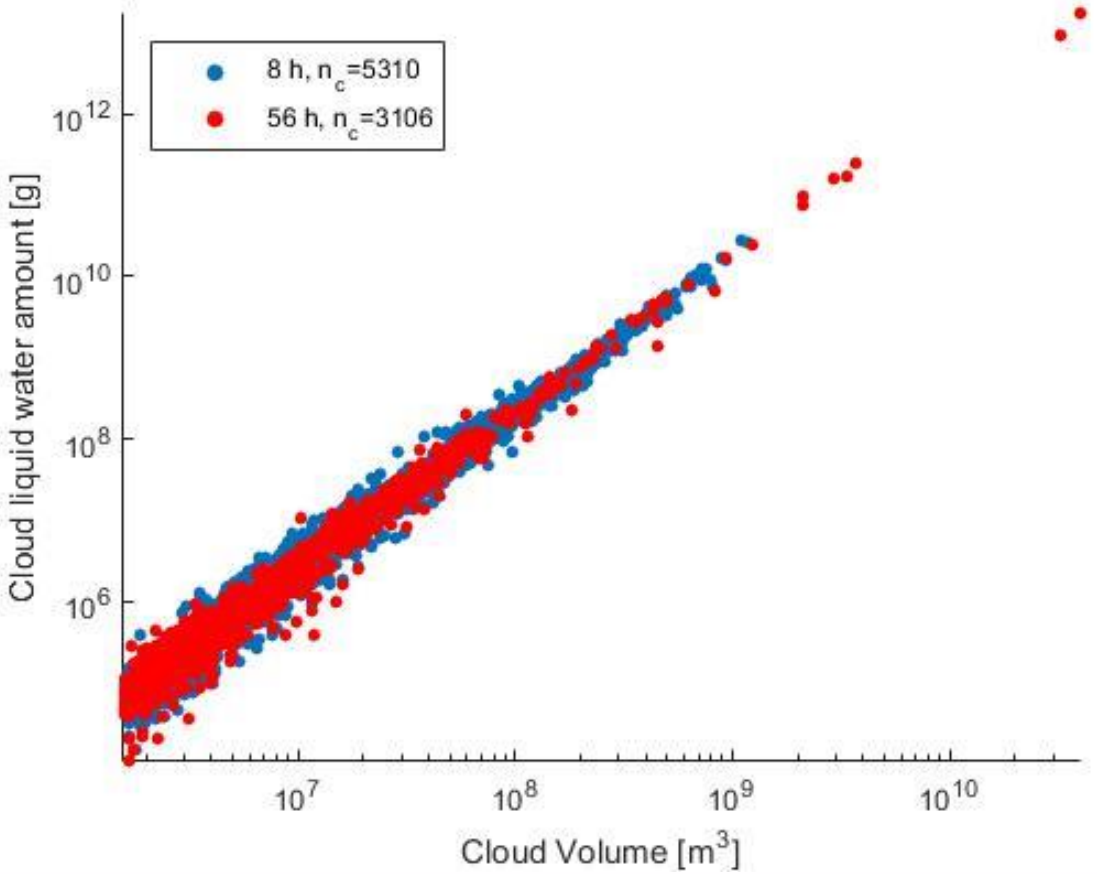
56 h

- Compare 3D cloud properties at different snapshots for the whole model domain

Cloud volume and mass

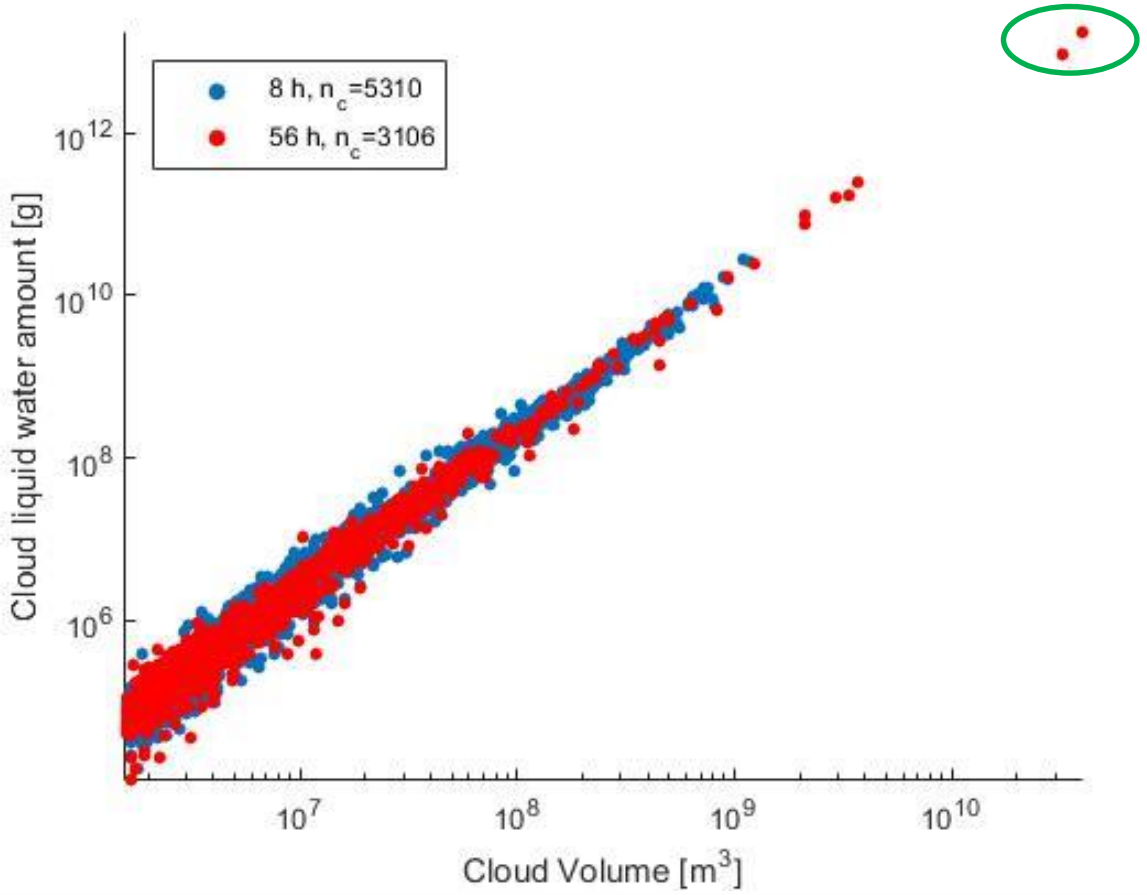
- Important: amount of liquid water describes the available energy

Cloud volume and mass



- Important: amount of liquid water describes the available energy

Cloud volume and mass



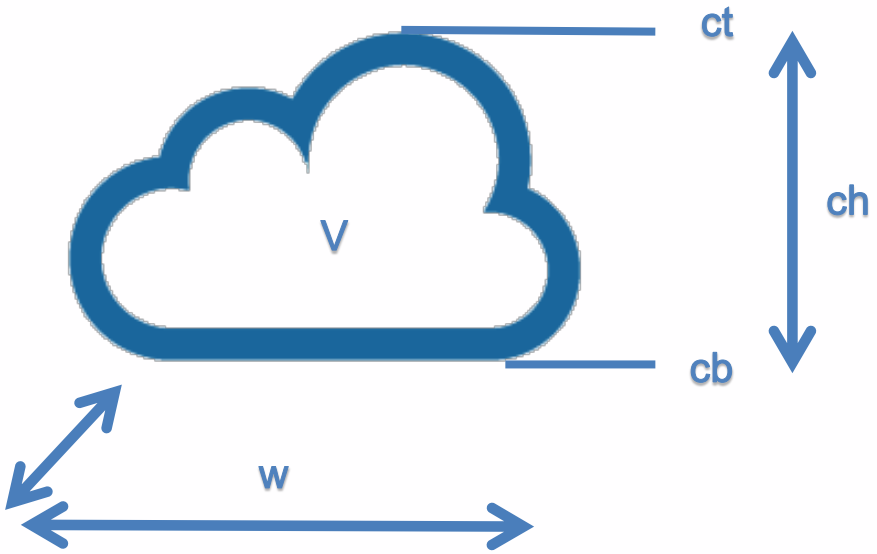
- Important: amount of liquid water describes the available energy

Cloud thickness and shape

Cloud thickness and shape

$$ch = ct - cb$$

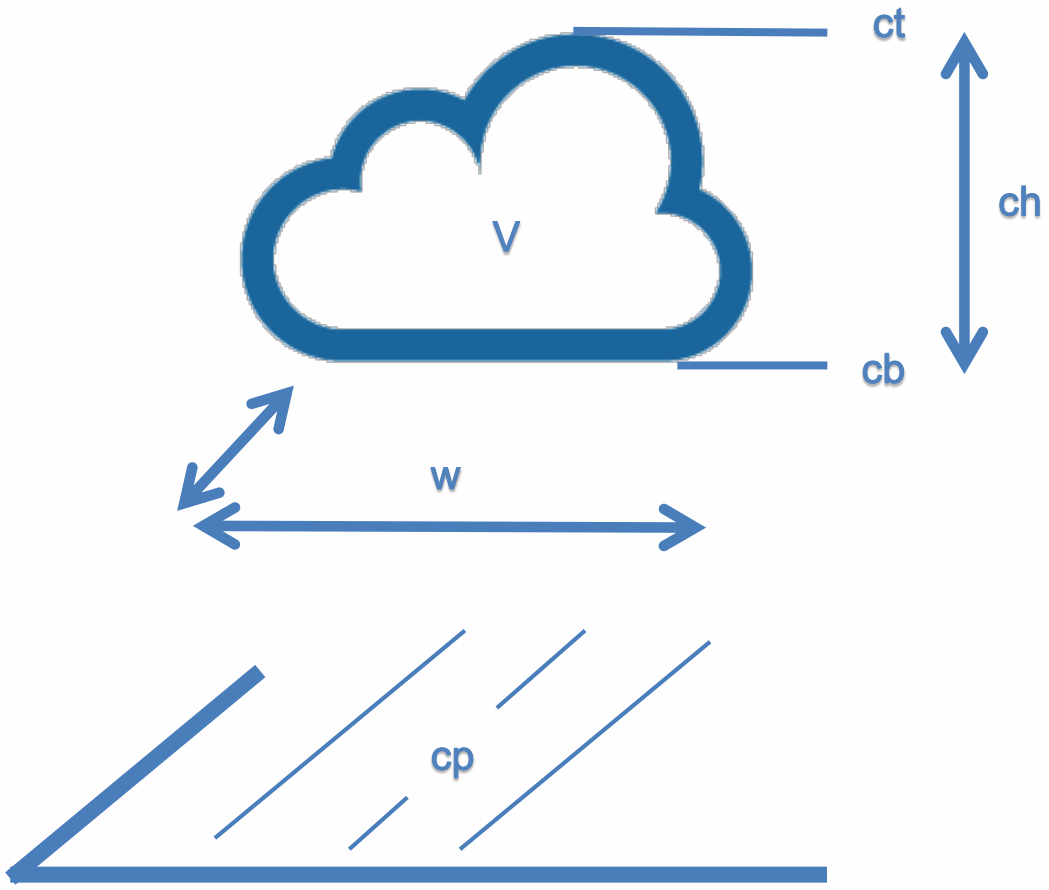
Cloud thickness and shape



$$ch = ct - cb$$

$$w = \frac{V}{ch}$$

Cloud thickness and shape



$$ch = ct - cb$$

$$w = \frac{V}{ch}$$

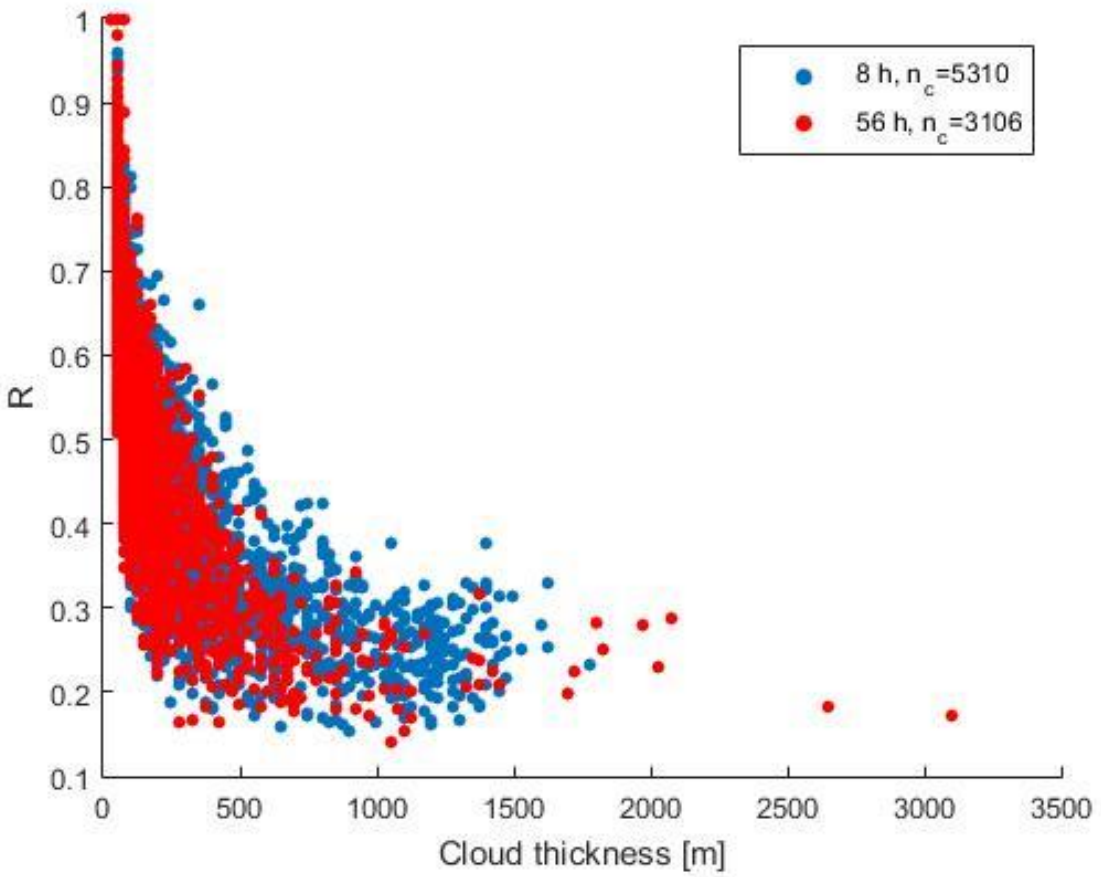
$$R = \frac{w}{cp}$$

Cloud overlap ratio

- Important: interaction with radiation!

$$R = \frac{w}{cp}$$

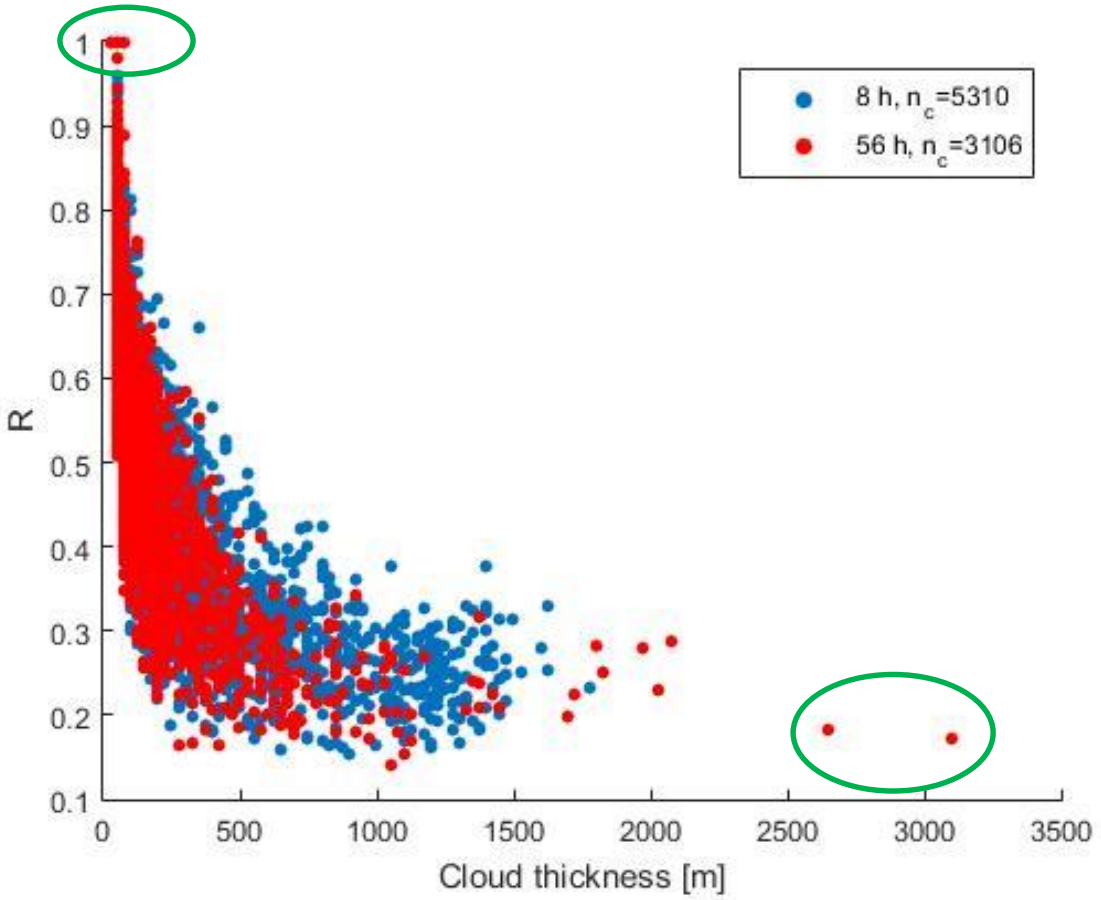
Cloud overlap ratio



- Important: interaction with radiation!

$$R = \frac{w}{cp}$$

Cloud overlap ratio



- Important: interaction with radiation!

$$R = \frac{w}{cp}$$

Synthetic observations: Motivation

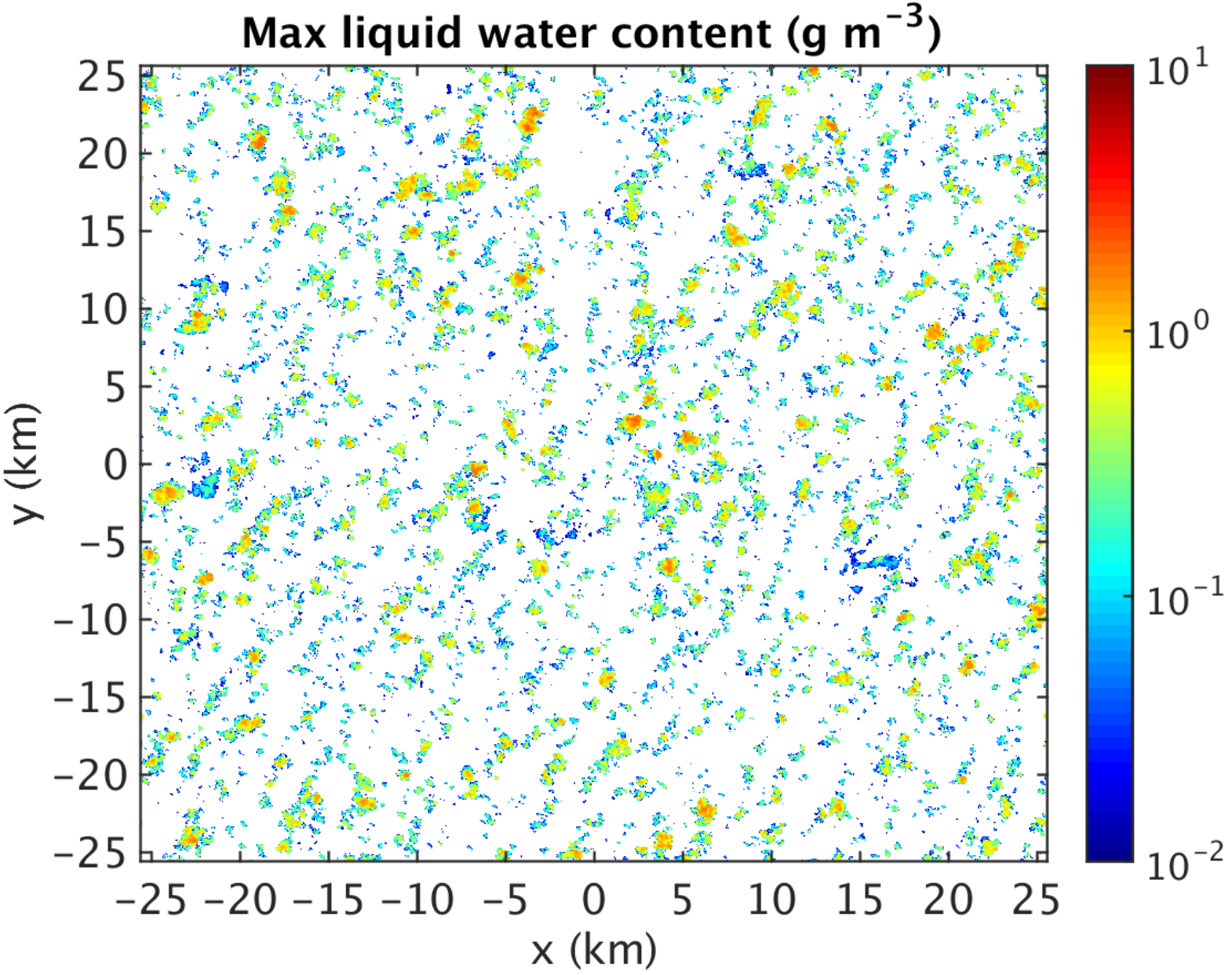
- Combine model output and instrument simulator (forward model) to generate simulated observations
- Provides a more comparable comparison to evaluate model performance
- Test the sensitivity of observations to instrument specifications and sampling strategies

Measure cloud fraction with ceilometer

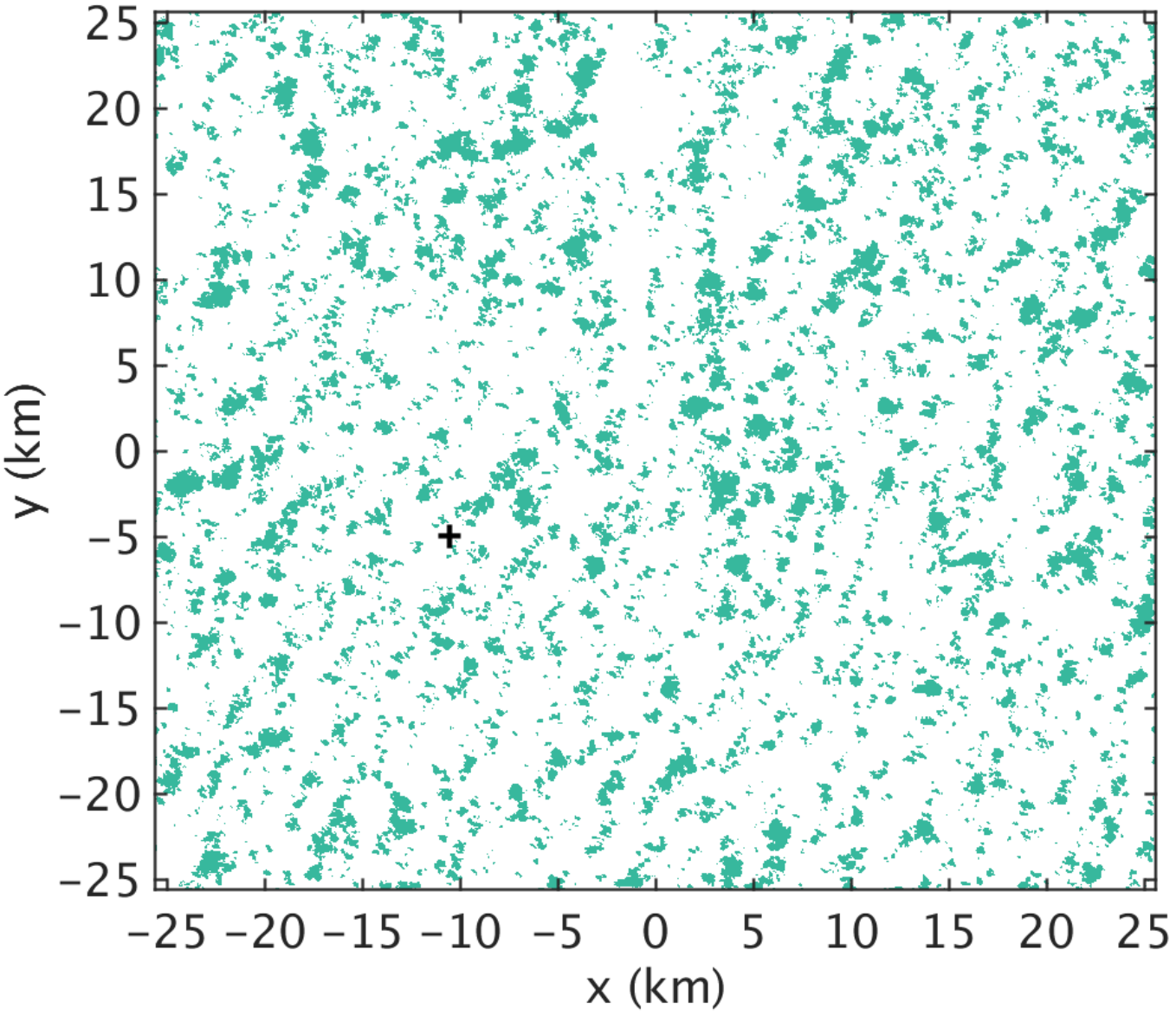
	Vaisala CL31[1]	**Simulated ceilometer**
Resolution	Beamwidth: 0.1° Vertical: 10 m	Ideal point (LES: 25 m by 25 m by 25 m)
Pulse frequency	thousands of pulses per second	
Average interval	2 sec	2 sec as baseline
Reporting interval	16 sec	16 sec
Wavelength	910 nm at 25° C	
Sensitivity	Could see clouds with LWC as low as 10^{-7} g m^{-3}, or lower!	10^{-7} g m^{-3} as baseline

1. Specification info from DOE/SC-ARM-TR-020; Sensitivity info from Dr. Ewan O'Connor

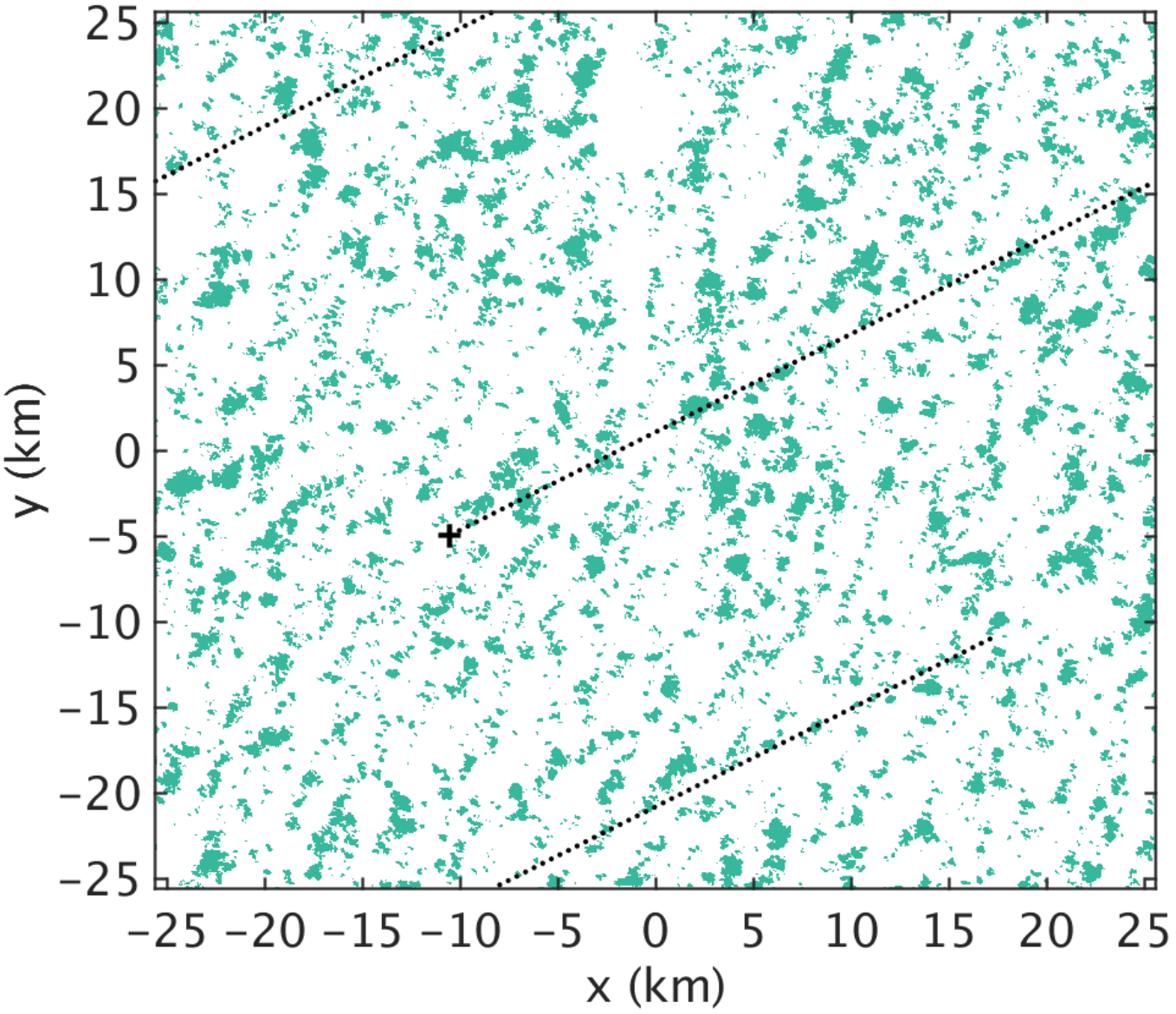
Cloud field


Max liquid water content (g m^{-3})
y (km)
x (km)
25
20
15
10
5
0
−5
−10
−15
−20
−25
10^{1}
10^{0}
10^{-1}
10^{-2}

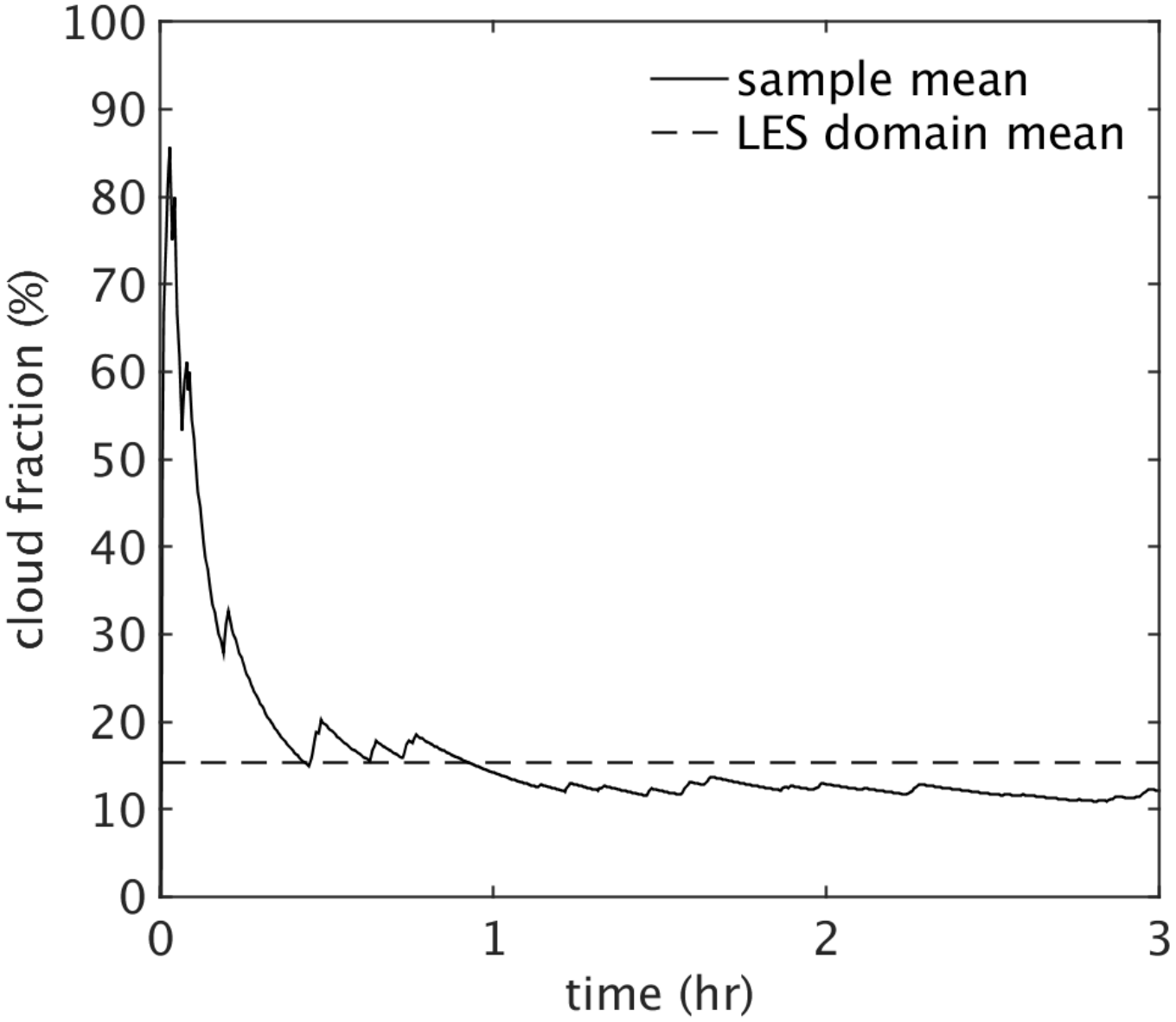
A demo

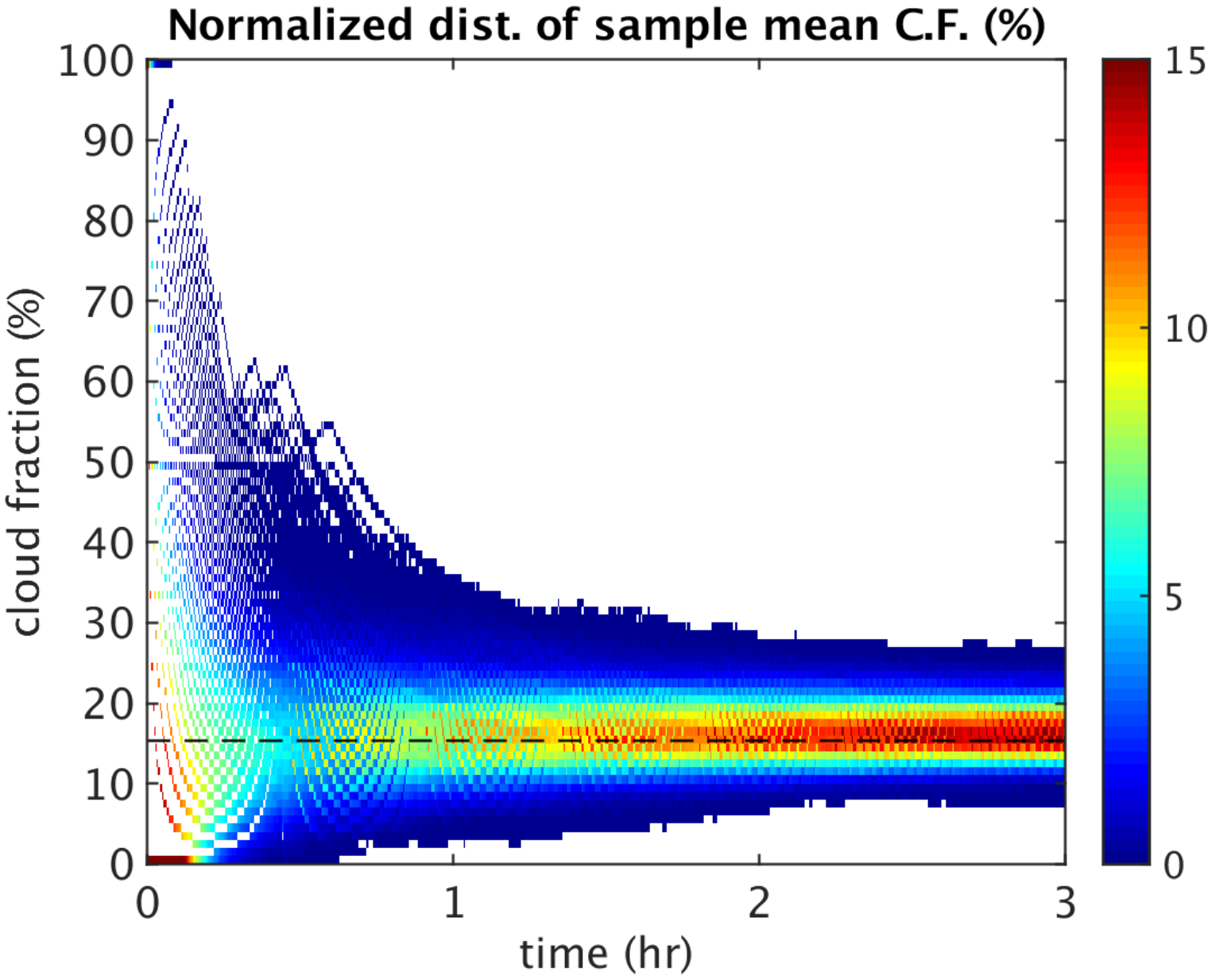


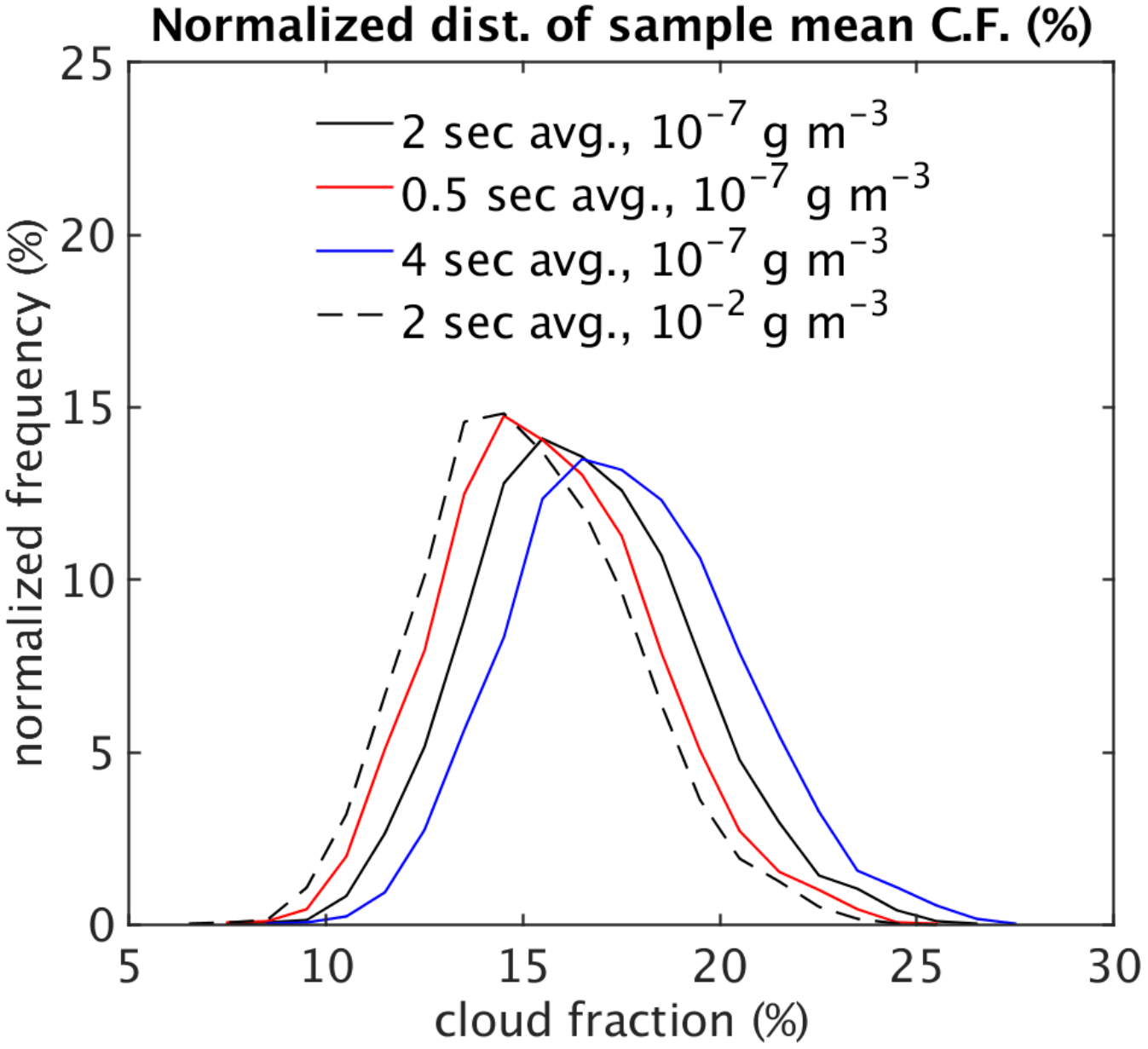
A demo



A demo


sample mean
LES domain mean
cloud fraction (%)
time (hr)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3

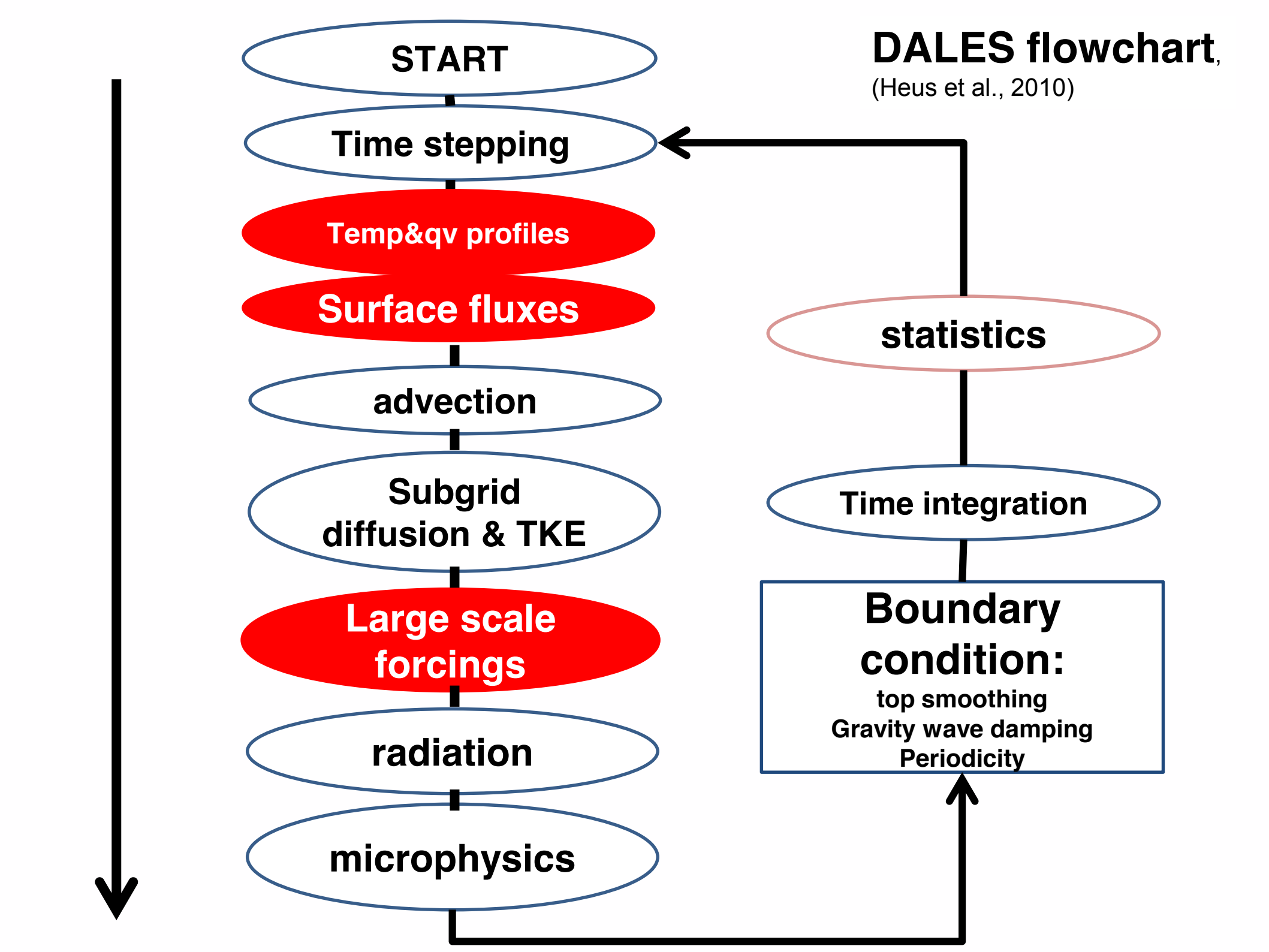

Normalized dist. of sample mean C.F. (%)
cloud fraction (%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
time (hr)
15
10
5
0


Normalized dist. of sample mean C.F. (%)
2 sec avg., 10^{-7} g m^{-3}
0.5 sec avg., 10^{-7} g m^{-3}
4 sec avg., 10^{-7} g m^{-3}
2 sec avg., 10^{-2} g m^{-3}
normalized frequency (%)
cloud fraction (%)
0
5
10
15
20
25
30

Boundary layer simulations: Model setup

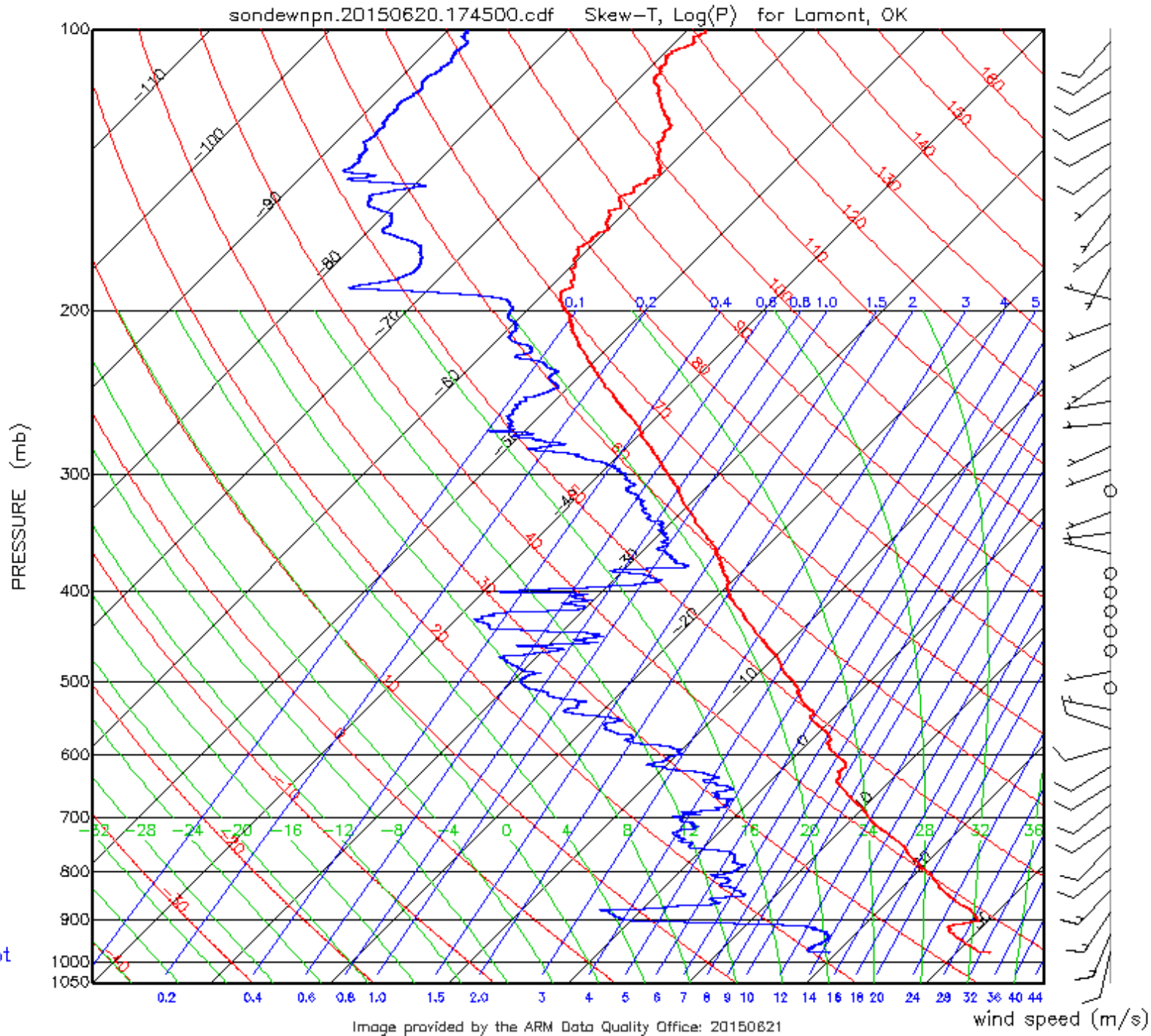
- Domain: 3840m x 3840m x 4500m
- Resolution: 40m(h), 40m(v)
- Grid points: 96 x 96 x 113

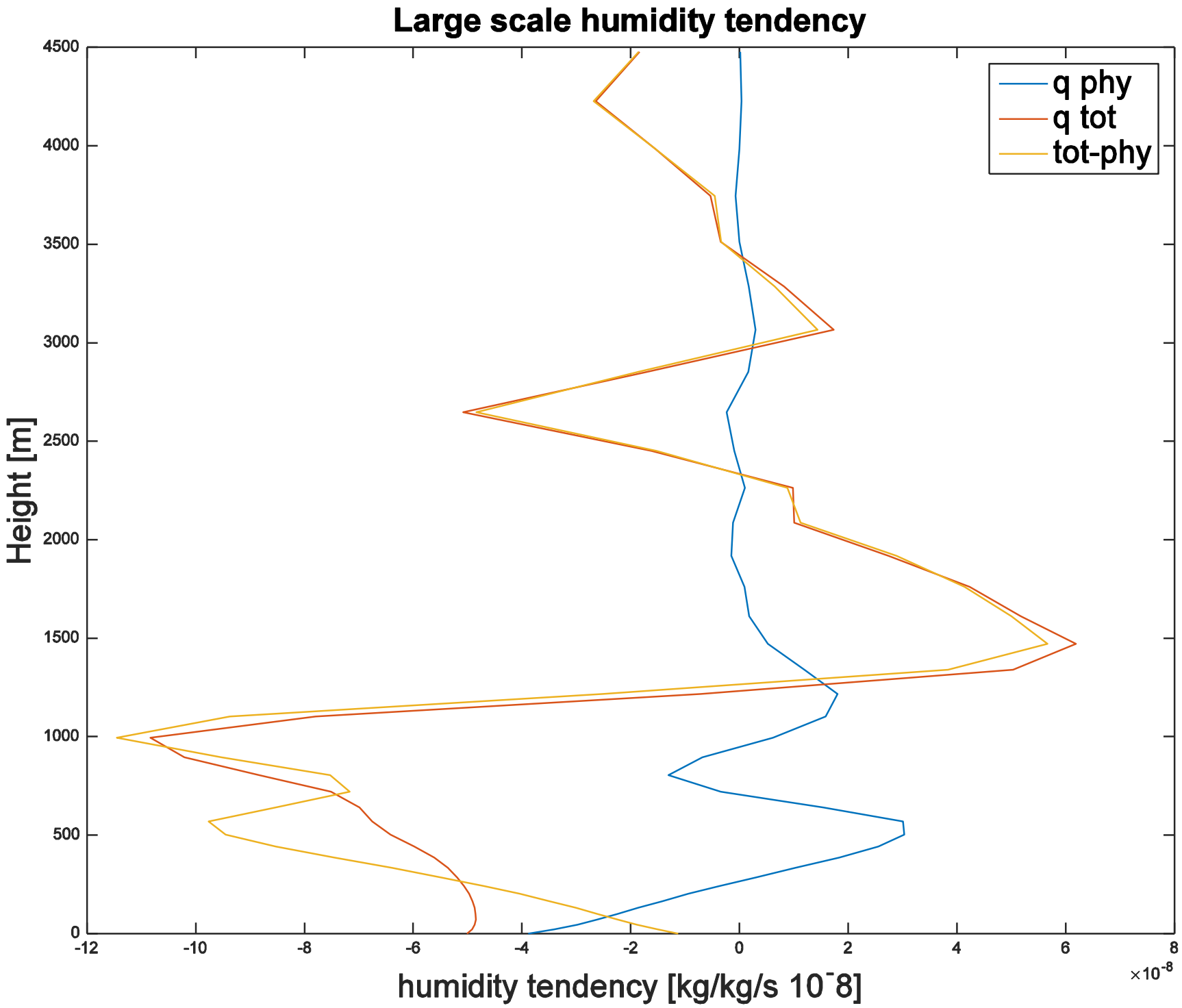
	Control	Test_1	Test_2
Theta, qv	Yes	Yes	Yes
Surface Flux	Yes	Yes	10% Decrease
Large Scale Forcing	Yes	No	Yes

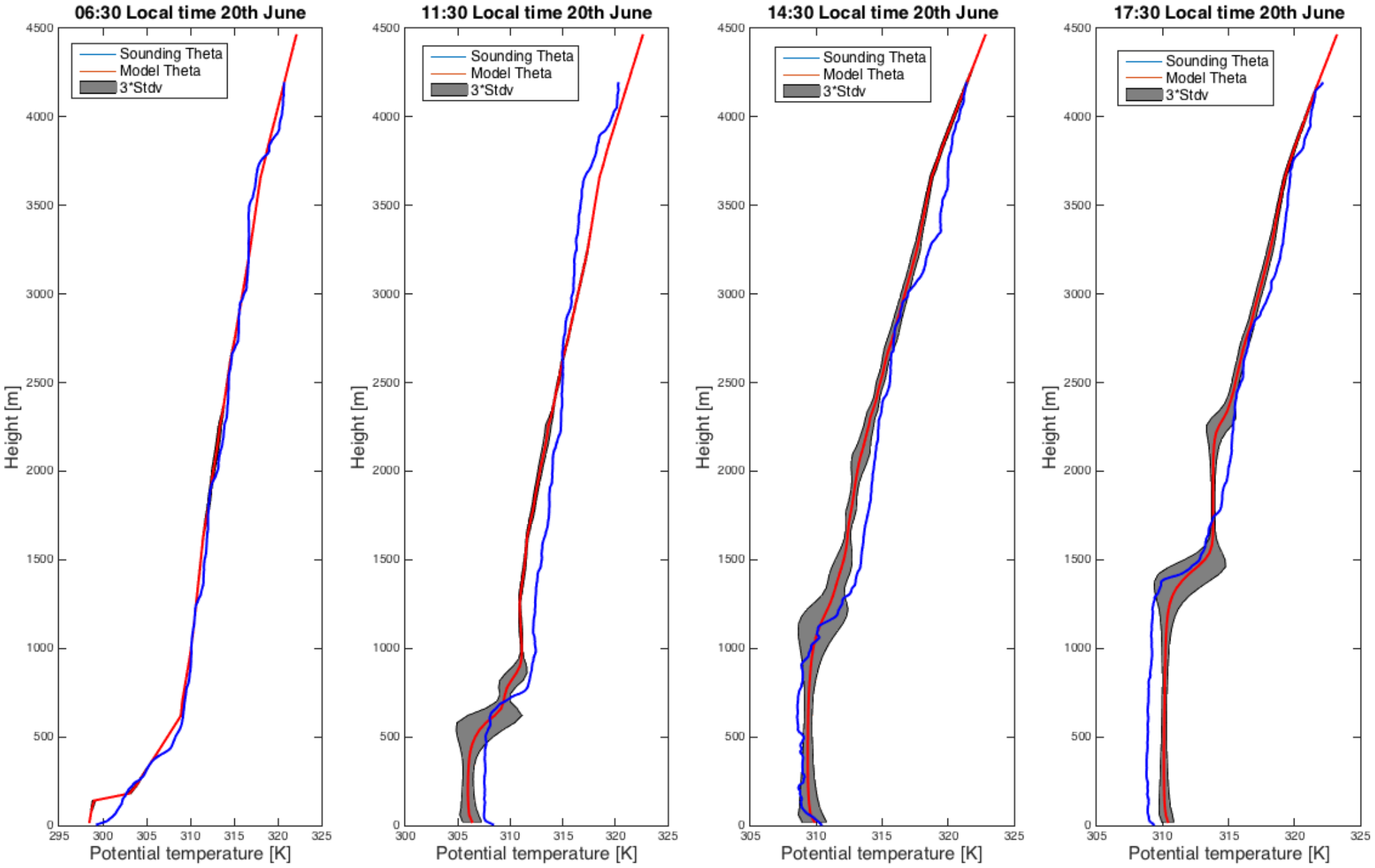

DALES flowchart,
(Heus et al., 2010)
START
Time stepping
Temp&qv profiles
Surface fluxes
advection
Subgrid
diffusion & TKE
Large scale
forcings
radiation
microphysics
statistics
Time integration
Boundary
condition:
top smoothing
Gravity wave damping
Periodicity

Observation data		Model input data
Data sources	Measured variables	Necessary variables
SONDE	T, Td, RH	Theta, qv, u, v
SONIC	Sensible heat flux [W/m^2] Latent heat flux [W/m^2]	wtsurf [K m/s] wqsurf [kg m/s]
ECMWF reanalysis	Temperature tendency [K/s] Specific humidity tendency [Kg/Kg/s]	ug, vg dqtdt dthlrad

06/20/2015
1730 UTC
11:30 am




Large scale humidity tendency
q phy
q tot
tot-phy
Height [m]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-12
-10
-8
-6
-4
-2
0
2
4
6
8
×10-8
humidity tendency [kg/kg/s 10^8]

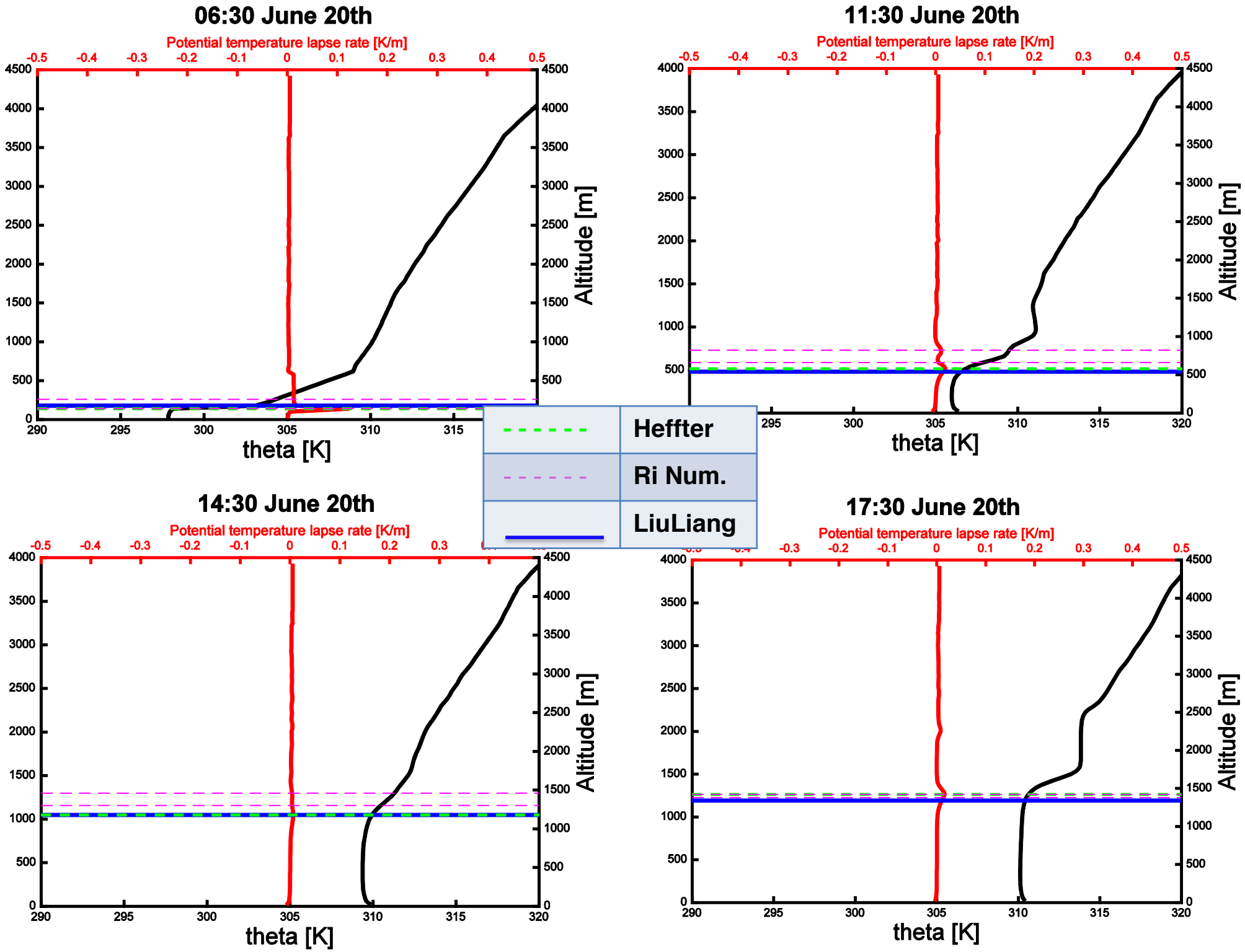


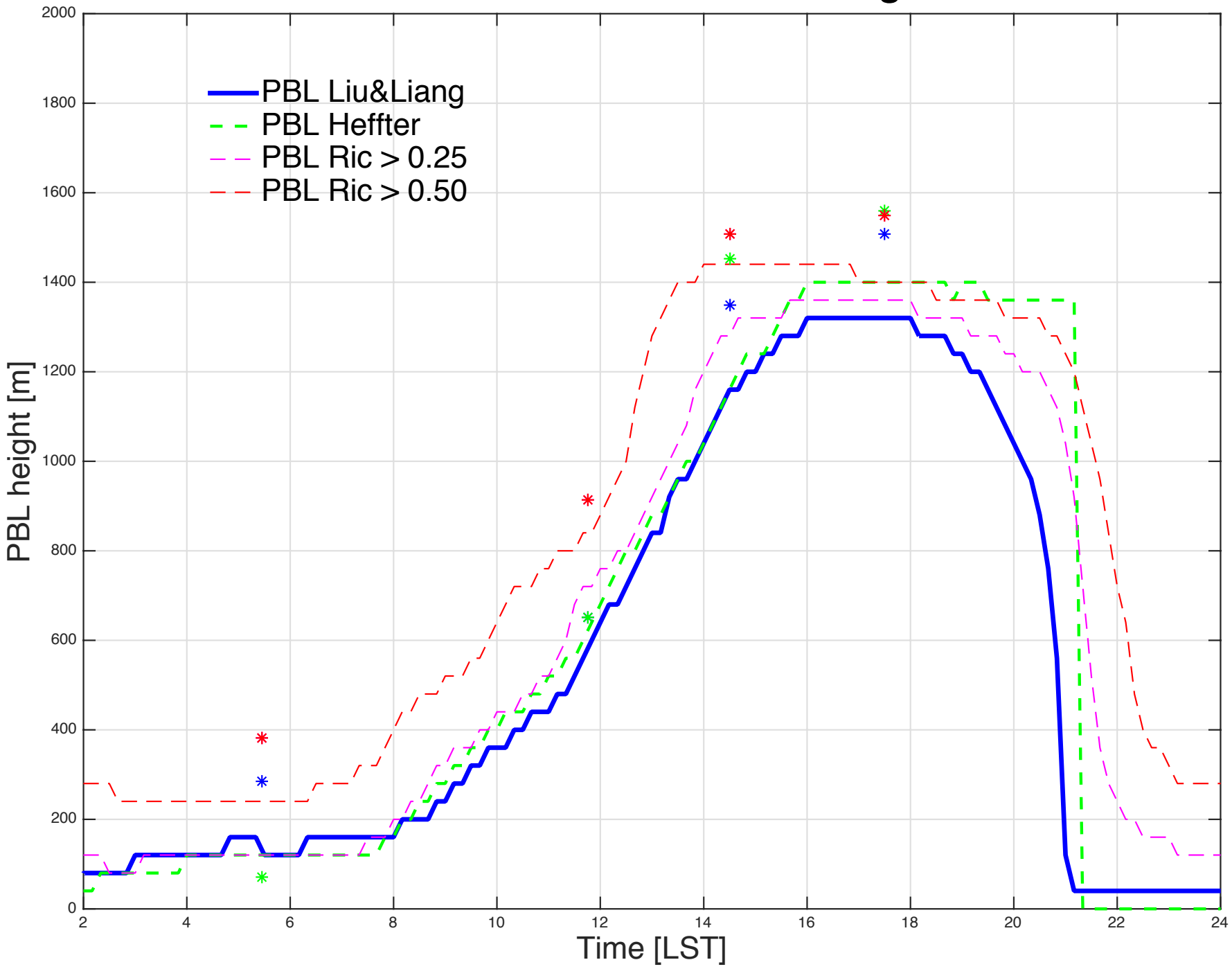
Theta range [295K : 5K : 325K]

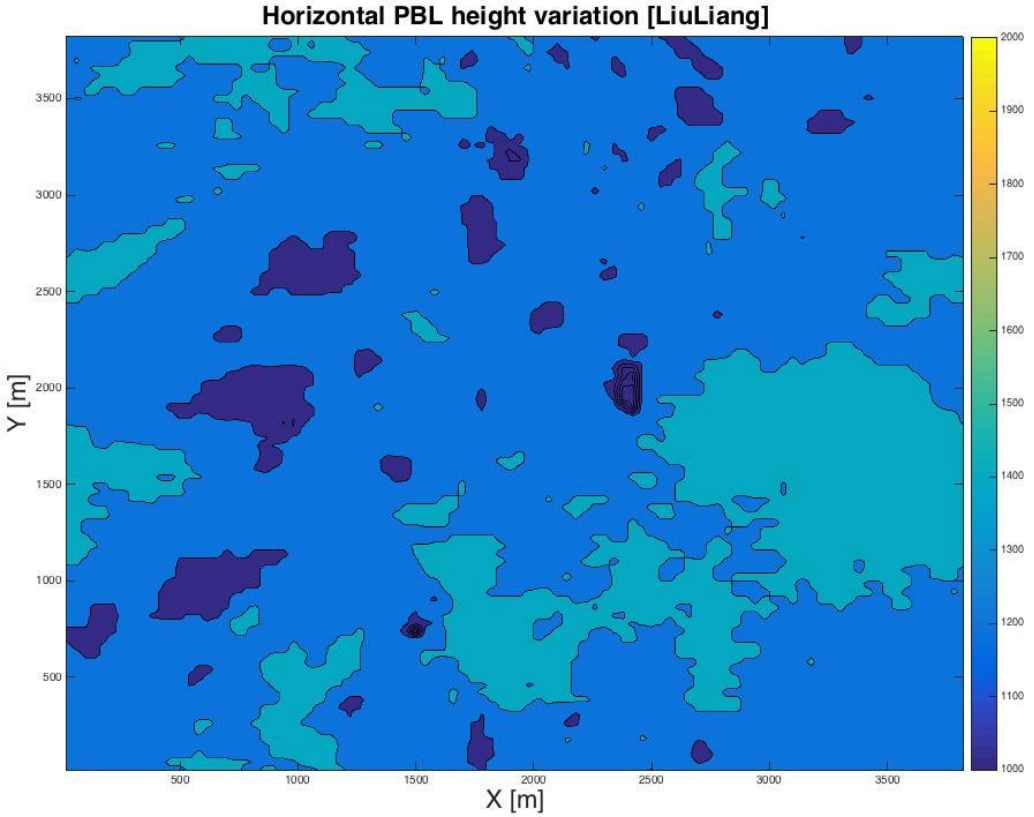
PBL Height calculation method

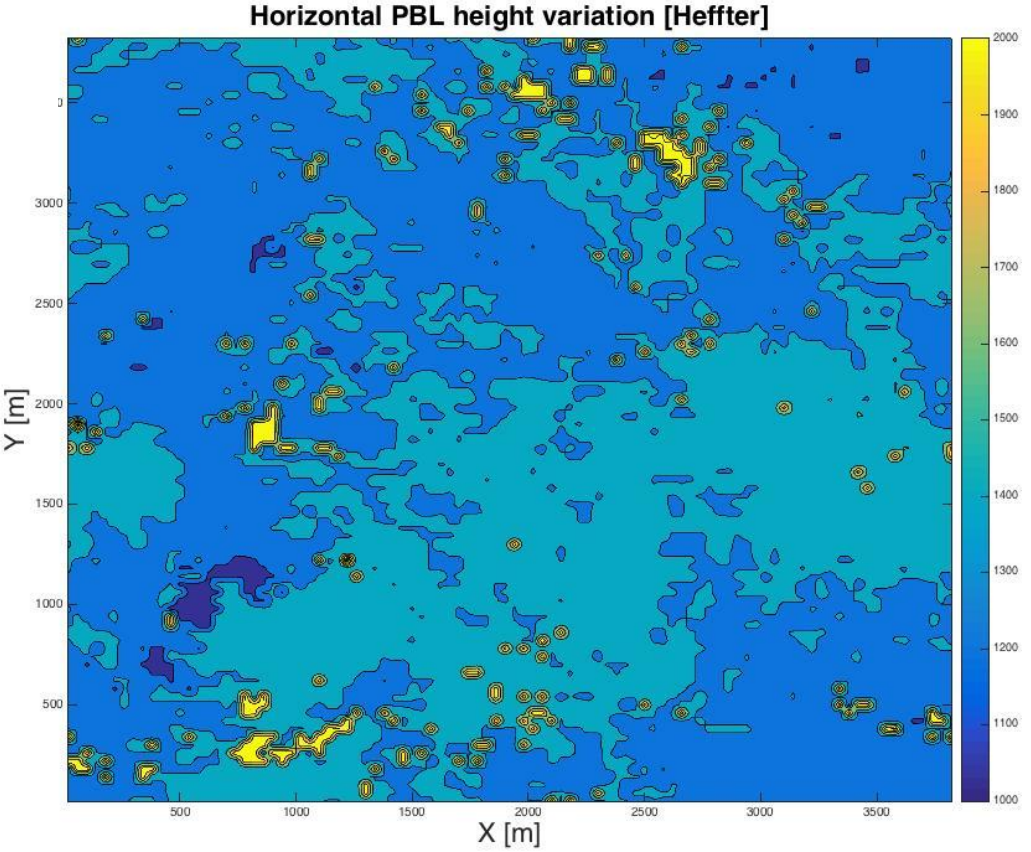
- LiuLiang: lowest level of both criteria are met
  - –dtheta/dz > 4K/km
  - –theta_k - theta_1 >= 0.5K
- Heffter: Max dtheta/dz level within 4km
- Bulk Richardson:

$$Ri_b = \left(\frac{gz}{\theta_{v0}}\right)\left(\frac{\theta_{vz}-\theta_{v0}}{u_z^2+v_z^2}\right)$$


06:30 June 20th
11:30 June 20th
14:30 June 20th
17:30 June 20th
Potential temperature lapse rate [K/m]
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5
Altitude [m]
theta [K]
290 295 300 305 310 315 320
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Heffter
Ri Num.
LiuLiang


June 20 2015 DALES PBL height
PBL Liu&Liang
PBL Heffter
PBL Ric > 0.25
PBL Ric > 0.50
PBL height [m]
Time [LST]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2
4
6
8
10
12
14
16
18
20
22
24


Horizontal PBL height variation [LiuLiang]
Y [m]
X [m]
500
1000
1500
2000
2500
3000
3500
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000


Horizontal PBL height variation [Heffter]
Y [m]
X [m]
500
1000
1500
2000
2500
3000
3500
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

Conclusions

- Choice of model domain depends on:
  - –Computational constraints
  - –Quantities of interest (e.g. cloud fraction, LWC, PBL height)
- Cloud properties (e.g. LWC, volume, overlap ratio) and subsequent interactions with radiation depend on the how the cloud organization is represented by the model
- Models allow for:
  - –estimates of the responses to various forcings to be made
  - –Instrument observational procedures to be tested, provided a valid forward model is available