Large-Eddy Simulation Study of Moist Convection Initiation over Heterogeneous Surface Fluxes

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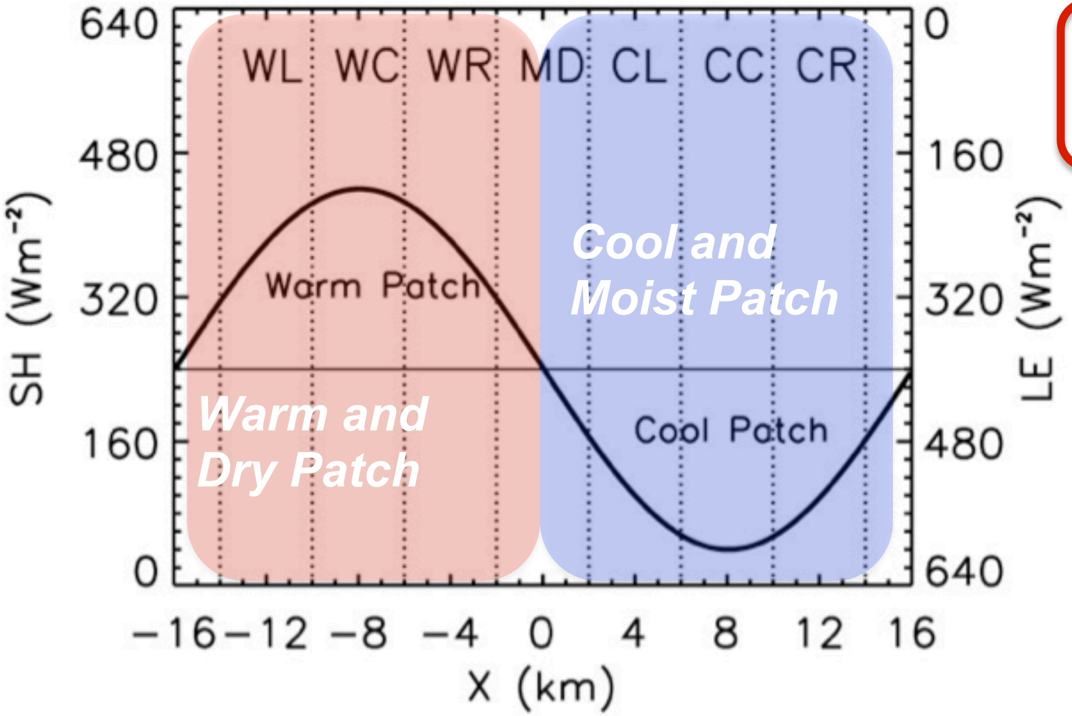
20th Symposium on Boundary Layer and Turbulence, Boston MA, 9-13 July 2012

Introduction

This study investigates the sensitivity of moist convection initiation (CI) to the amplitudes of surface energy balance (SEB) heterogeneity on a scale of 10s of kilometers:

1) under a zero background wind
2) with a strong capping inversion of the CBL.

SEB Heterogeneity



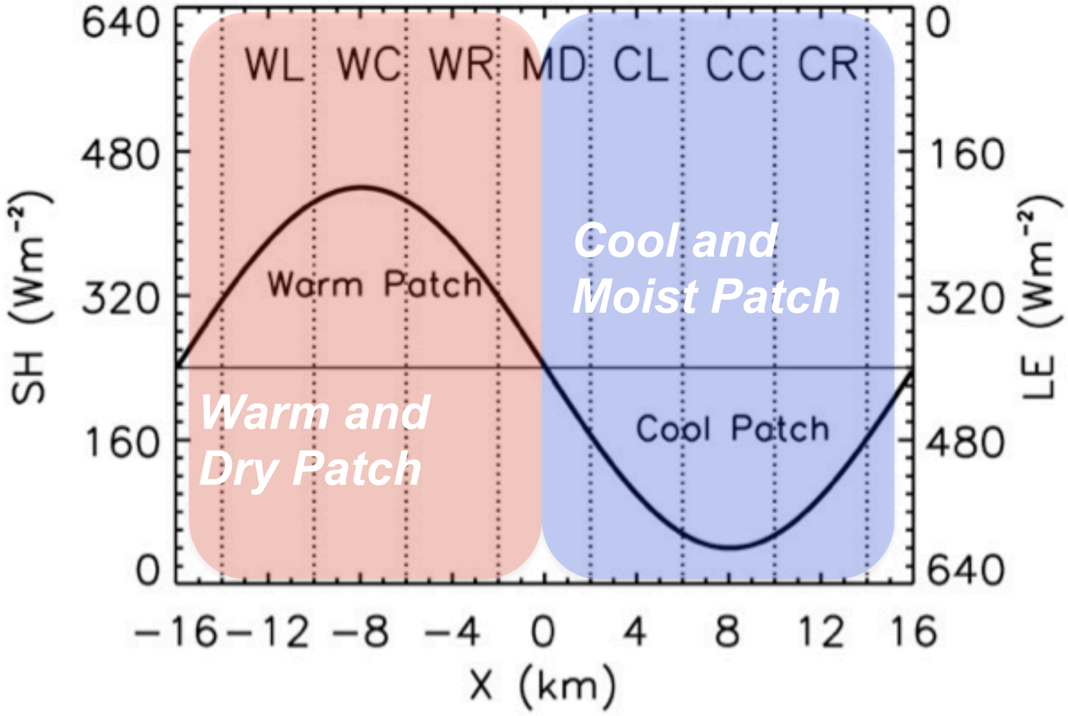
$$\boxed{R_{net} - G} = \rho C_p \overline{w'\theta'} + \rho L_v \overline{w'r'}$$

$= \text{Constant}$

$= 640\ Wm^{-2}$

Surface sensible and latent heat fluxes are prescribed with the surface energy balance (SEB) constraint.

SEB Heterogeneity



$$R_{net} - G = \rho C_p \overline{w'\theta'} + \rho L_v \overline{w'r'}$$

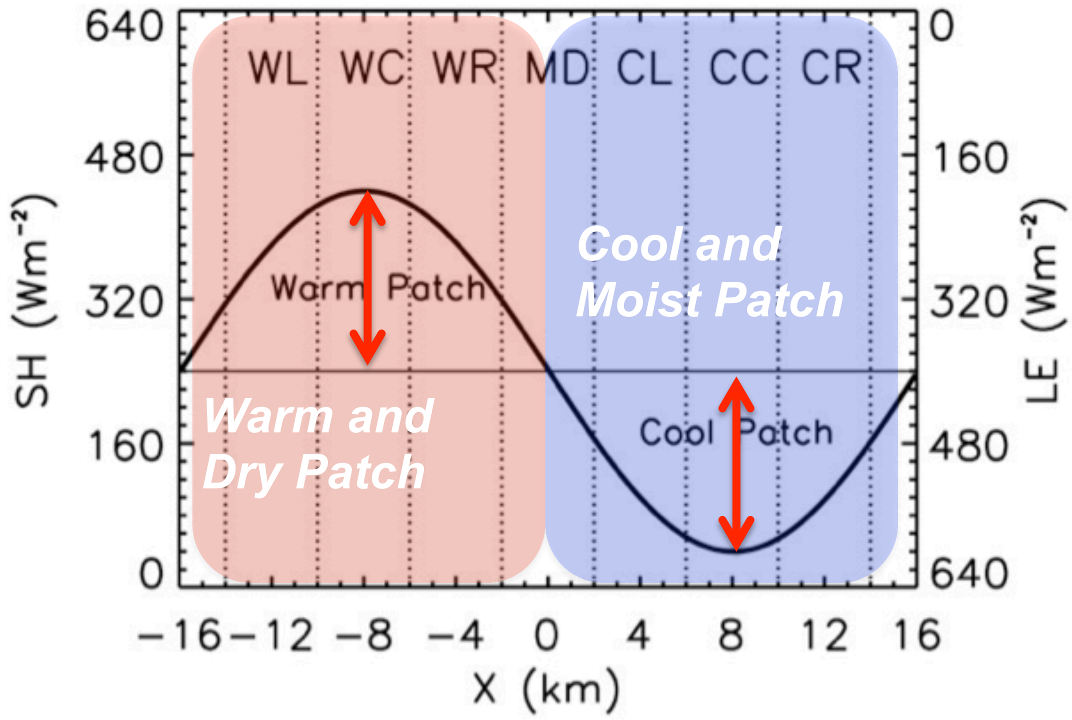
$$F_{w\theta}(x) = \langle F_{w\theta} \rangle + A_{w\theta} \sin\left(\frac{2\pi}{\lambda}x\right)$$

$$F_{wr}(x) = \langle F_{wr} \rangle - A_{wr} \sin\left(\frac{2\pi}{\lambda}x\right)$$

Surface sensible heat flux has a 180 degree phase lag relative to surface latent heat flux. Thus, warm and dry versus cool and moist surfaces are prescribed.

SEB Heterogeneity

CASE A200B06



$$F_{\mathrm{w}\theta}(x) = \langle F_{\mathrm{w}\theta} \rangle + A_{\mathrm{w}\theta} \sin\left(\frac{2\pi}{\lambda} x\right)$$

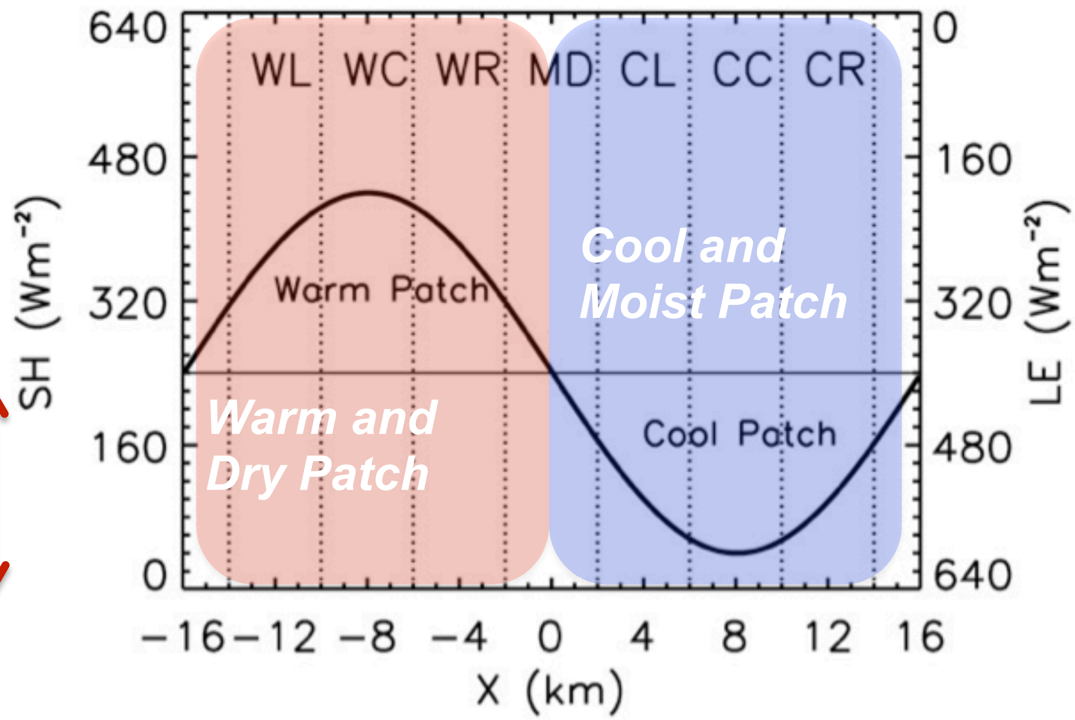
$$F_{\mathrm{wr}}(x) = \langle F_{\mathrm{wr}} \rangle - A_{\mathrm{wr}} \sin\left(\frac{2\pi}{\lambda} x\right)$$

Amplitude = 200 Wm^{-2}

This particular case has a SEB heterogeneity amplitude of 200 Wm^{-2}.

SEB Heterogeneity

CASE A200**B06**



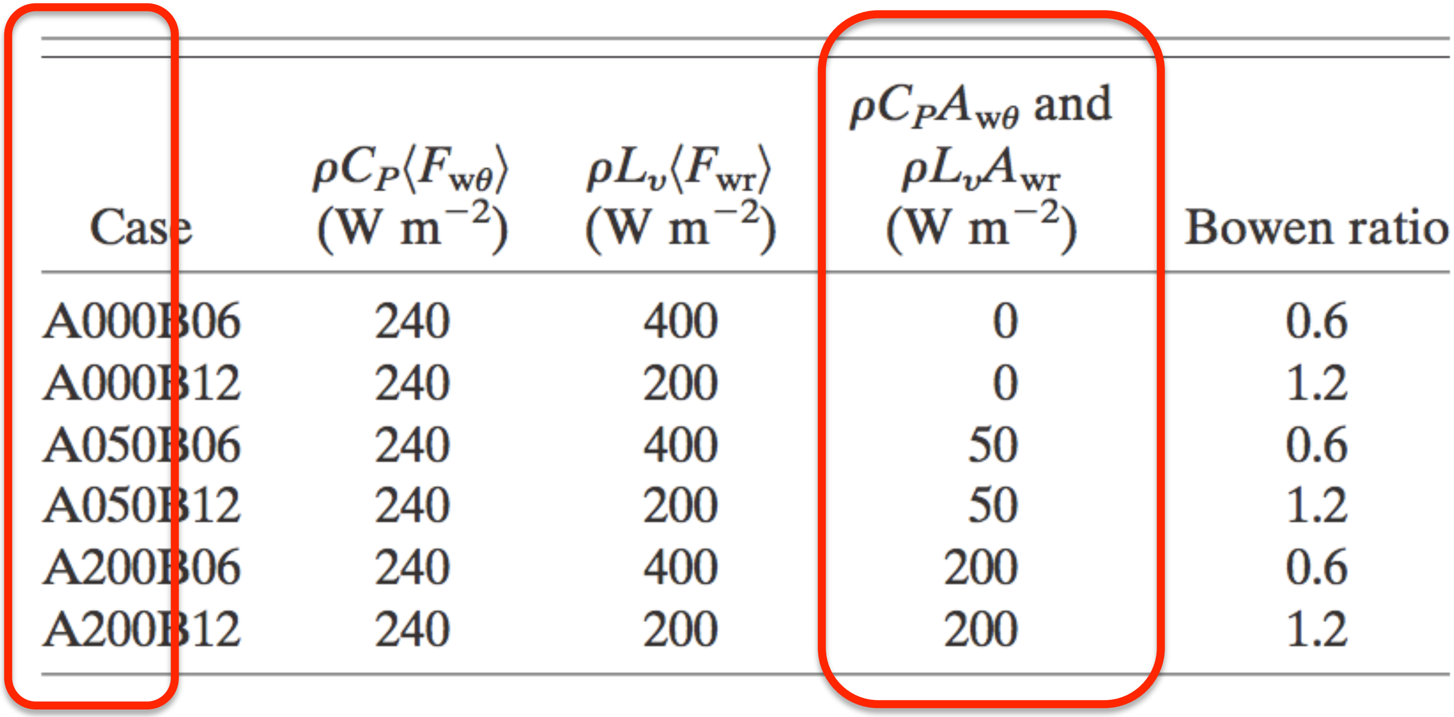
Mean LE = 400 Wm^{-2}

Mean SH = 240 Wm^{-2}

Bowen ratio = SH/LE = 240 Wm^{-2}/400 Wm^{-2} = 0.6

This particular case has a domain average Bowen ratio of 0.6.

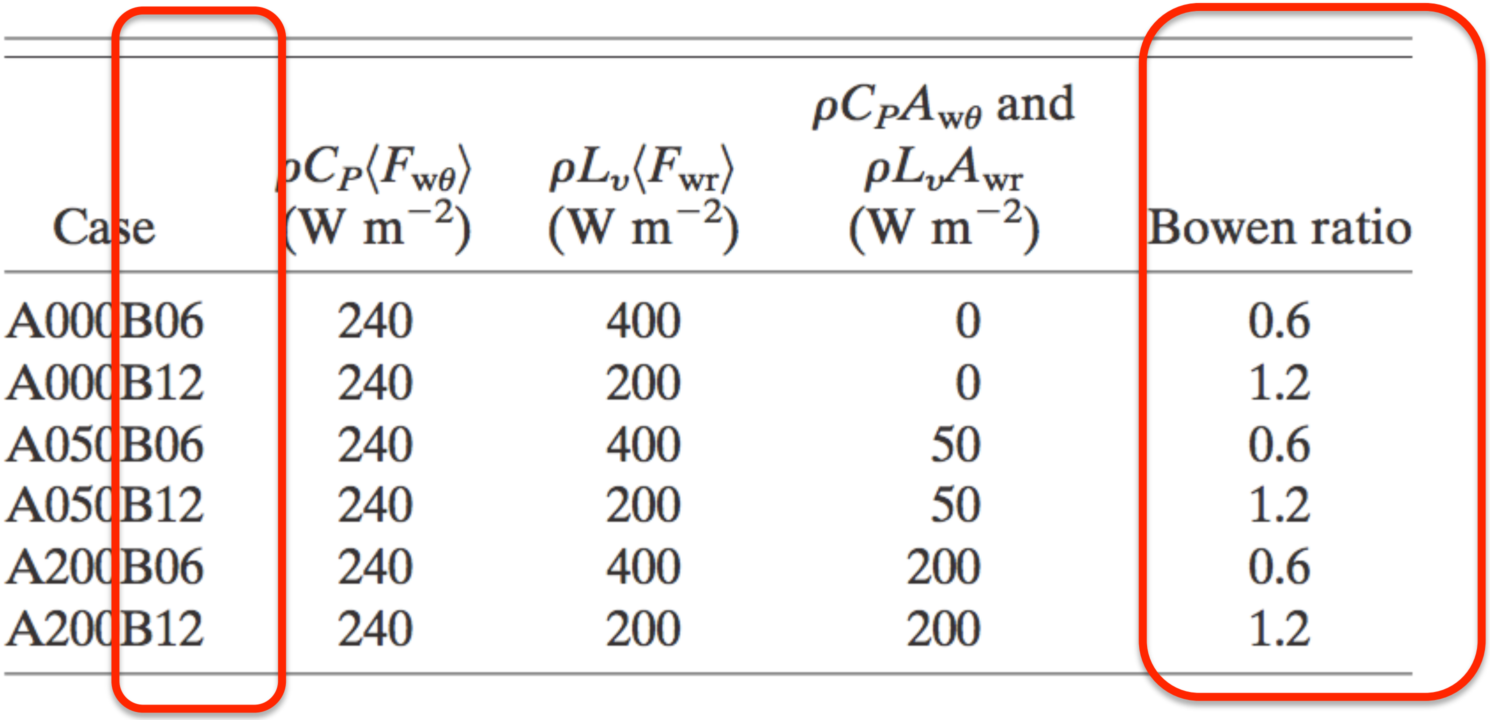
Numerical Experiment Cases



Case	$\rho C_P \langle F_{w\theta} \rangle$ (W m^{-2})	$\rho L_v \langle F_{wr} \rangle$ (W m^{-2})	$\rho C_P A_{w\theta}$ and $\rho L_v A_{wr}$ (W m^{-2})	Bowen ratio
A000B06	240	400	0	0.6
A000B12	240	200	0	1.2
A050B06	240	400	50	0.6
A050B12	240	200	50	1.2
A200B06	240	400	200	0.6
A200B12	240	200	200	1.2

The amplitude varies among 0 Wm^{-2} (homogeneous), 50 Wm^{-2} (weakly heterogeneous), and 200 Wm^{-2} (strongly heterogeneous).

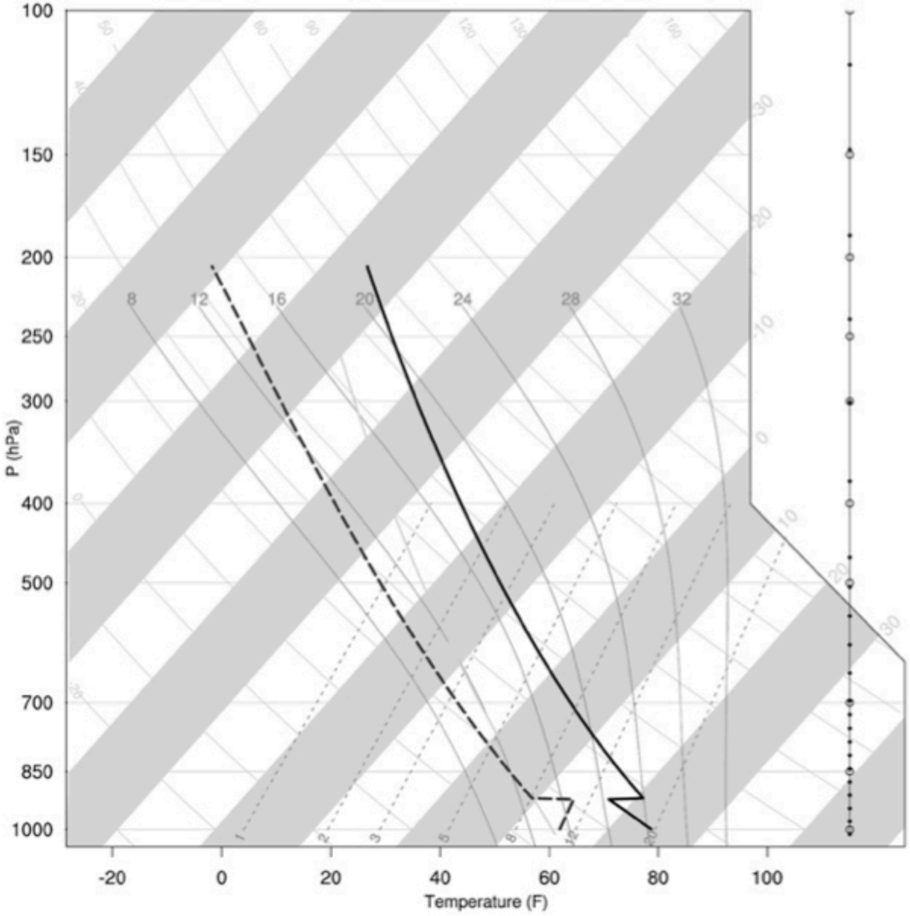
Surface Flux Heterogeneity



Case	$\rho C_P \langle F_{w\theta} \rangle$ (W m^{-2})	$\rho L_v \langle F_{wr} \rangle$ (W m^{-2})	$\rho C_P A_{w\theta}$ and $\rho L_v A_{wr}$ (W m^{-2})	Bowen ratio
A000B06	240	400	0	0.6
A000B12	240	200	0	1.2
A050B06	240	400	50	0.6
A050B12	240	200	50	1.2
A200B06	240	400	200	0.6
A200B12	240	200	200	1.2

The domain-averaged Bowen ratio varies between 0.6 (wet surface) and 1.2 (dry surface).

Initial Atmospheric Condition



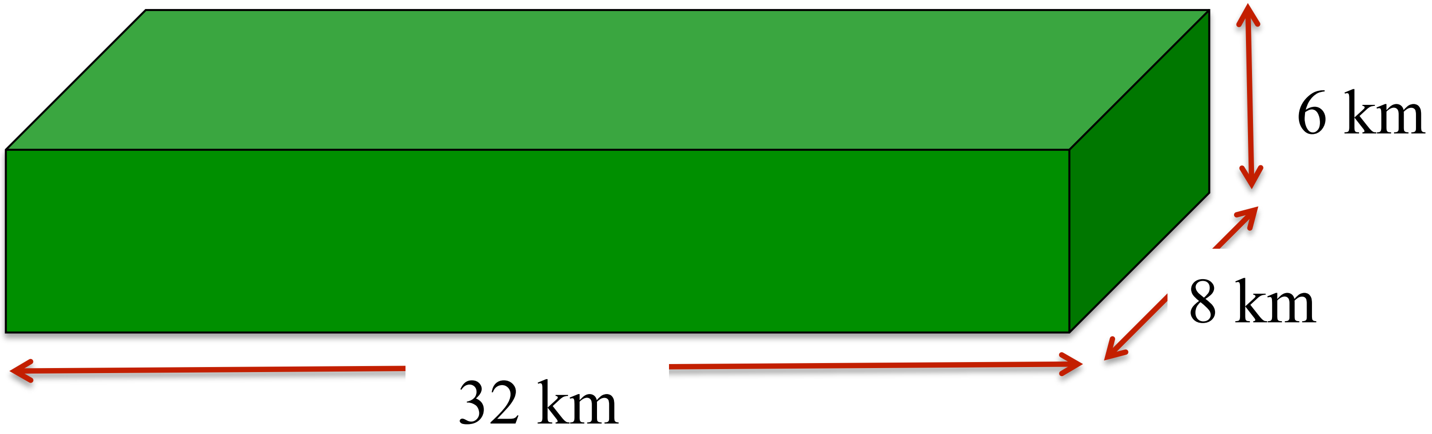
Sounding modified from Weisman and Klemp (1982).

- CBL with strong capping inversion
- Drier than the original sounding

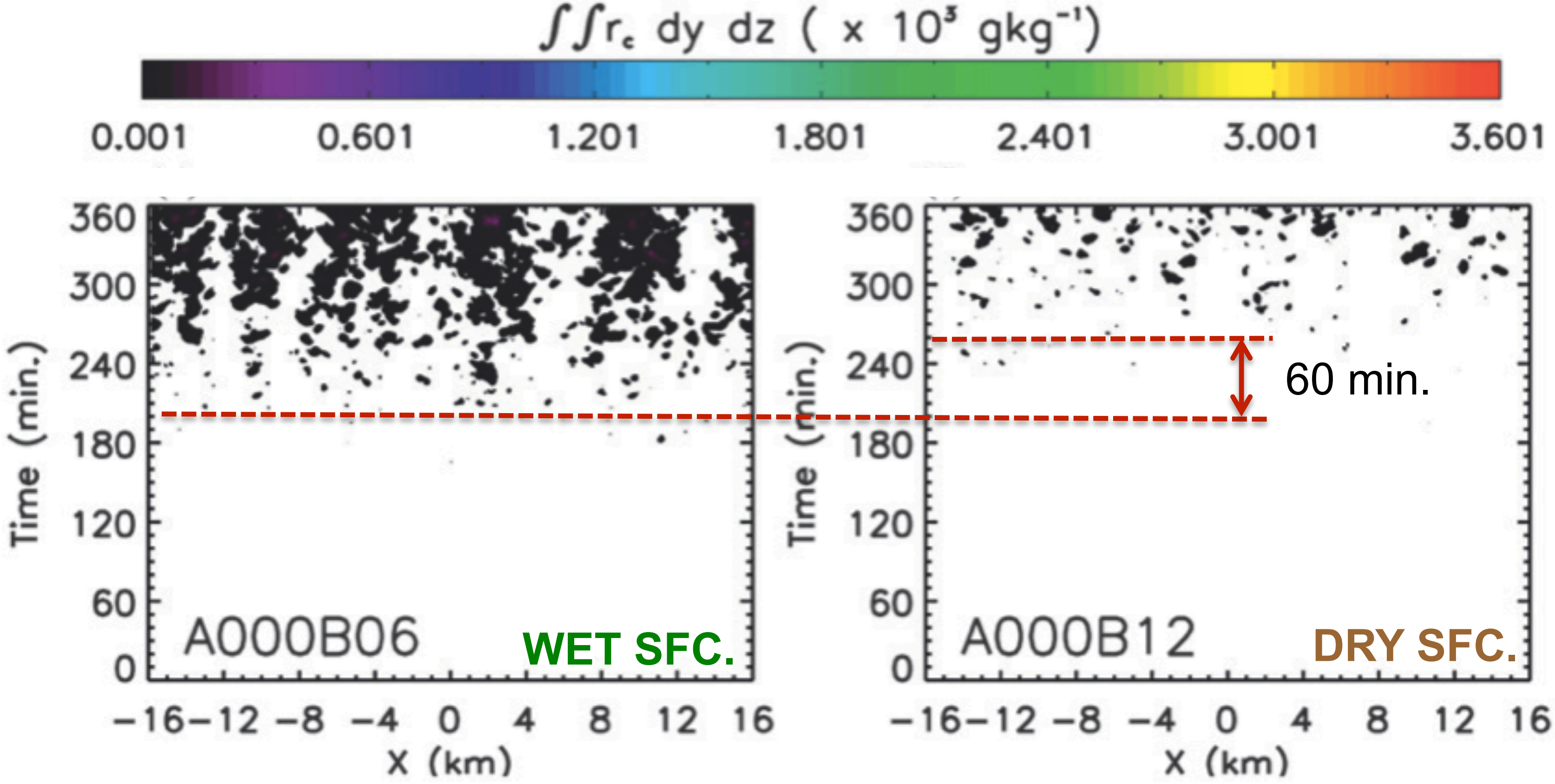
CAPE: 230 J kg^{-1}
CIN: 170 J kg^{-1}
CBL height: 810 m
LCL: 1.2 km

About Numerical Model and Domain

- Nonhydrostatic model of Bryan and Fritsch (2002)
- SFS model: TKE scheme
- Periodic LBCs
- Dx :100 m
- Dz : 40 m (lower than 4 km), 40-120 m (4-6 km)
- 6 hour integration (Dt = 1 s; Output interval = 100 s)

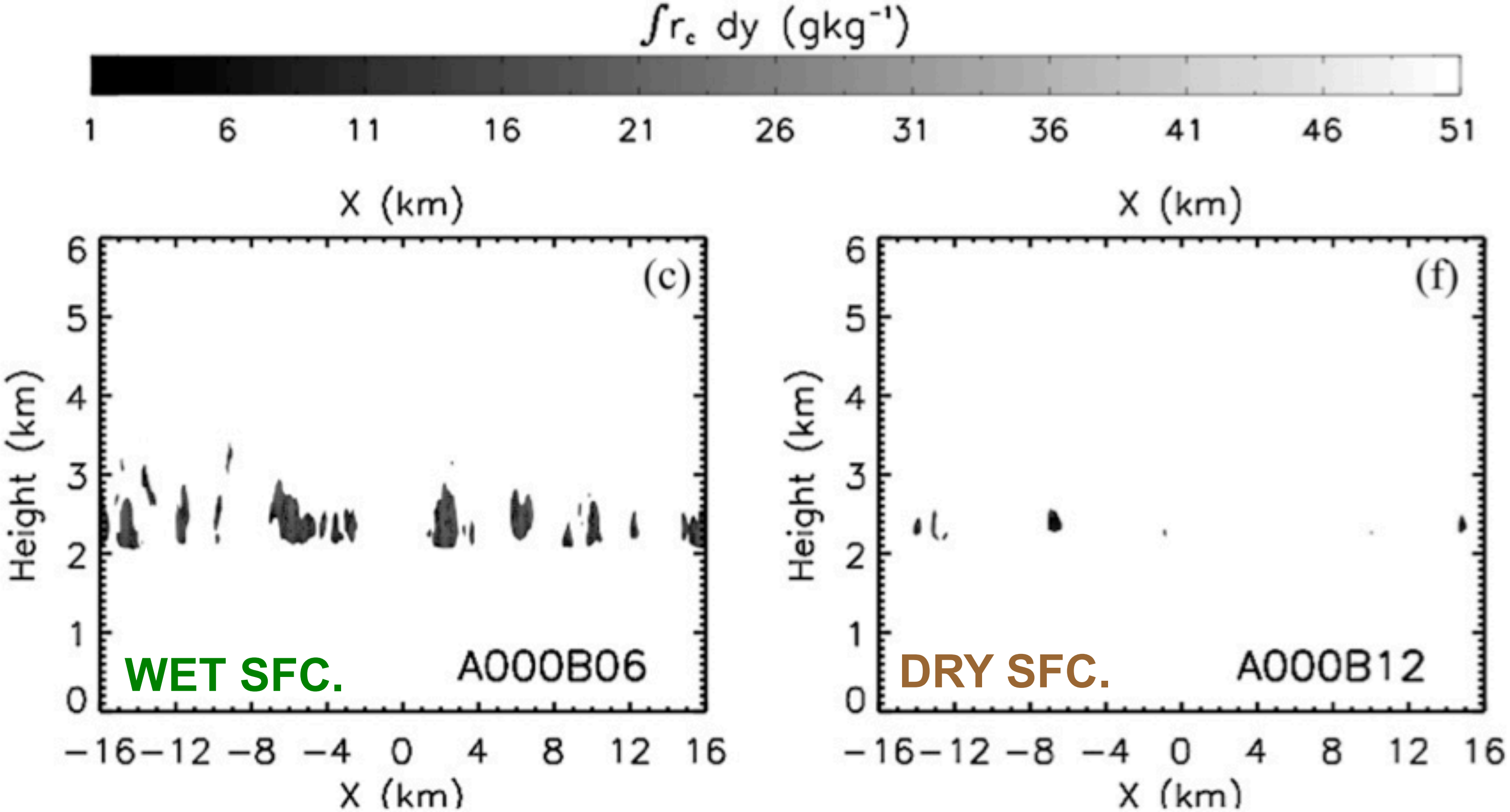


Time evolutions of cloud water (colors) and rainwater (contours) mixing ratio



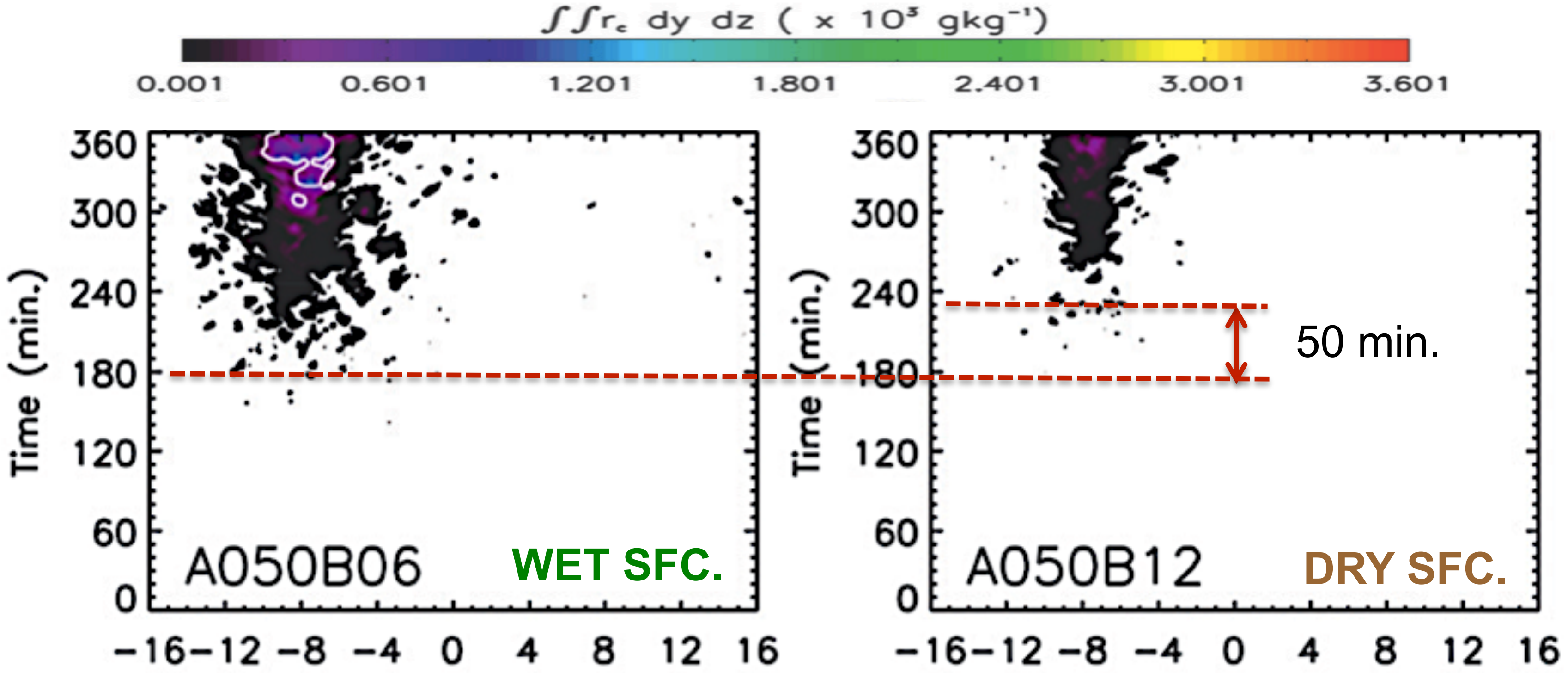
- *Moist convection is randomly scattered throughout the domain*
- *Earlier start of moist convection and more cloud water over the "WET SFC"*

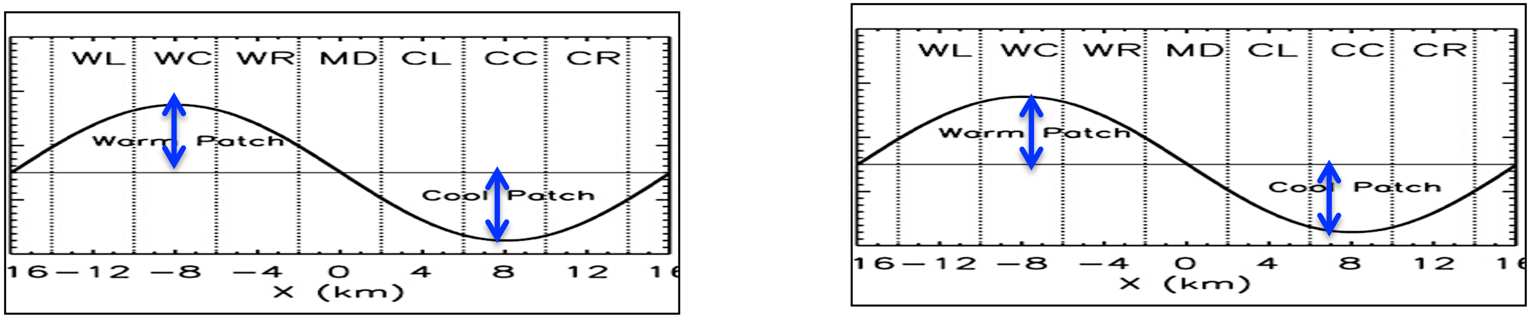
Time evolutions of cloud water (shades) and rainwater (contours) mixing ratio



- *The transition from shallow convection into deep precipitating convection is identified.*
- *Within 6 hrs, neither the "WET SFC" nor the "DRY SFC" develops deep moist convection*

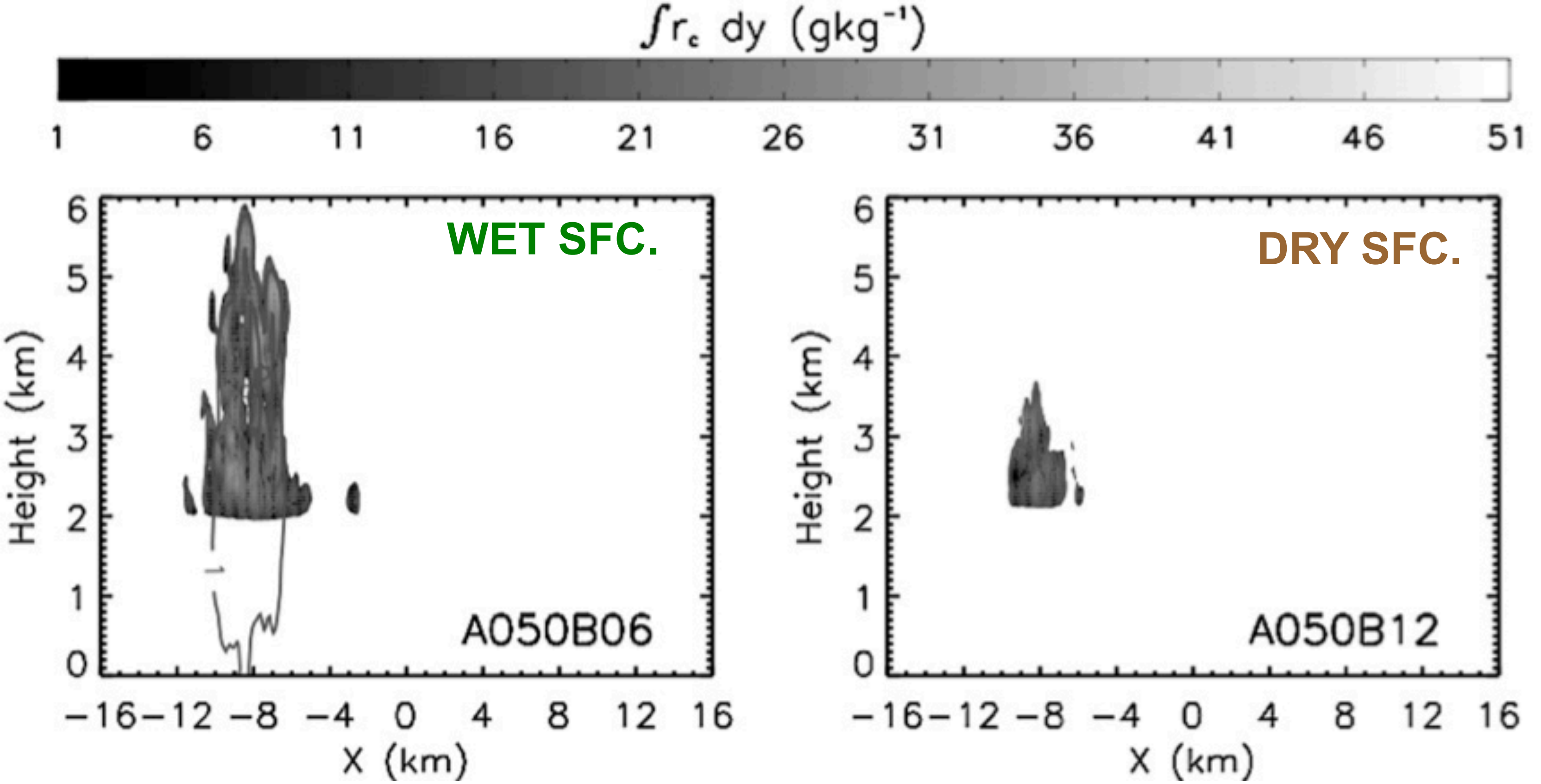
Time evolutions of cloud water (colors) and rainwater (contours) mixing ratio





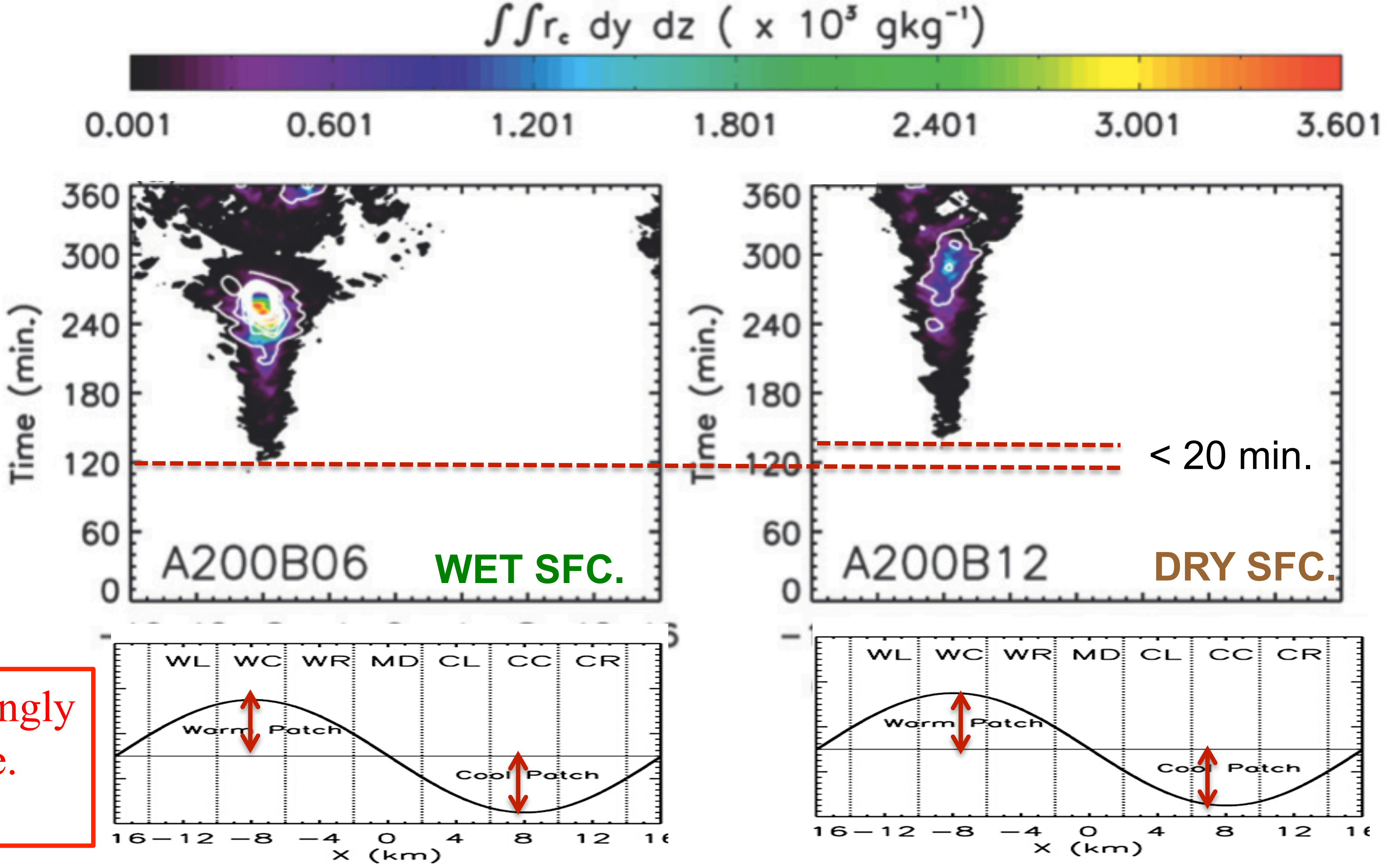
Weakly
Hete.
Sfc.

Time evolutions of cloud water (colors) and rainwater (contours) mixing ratio



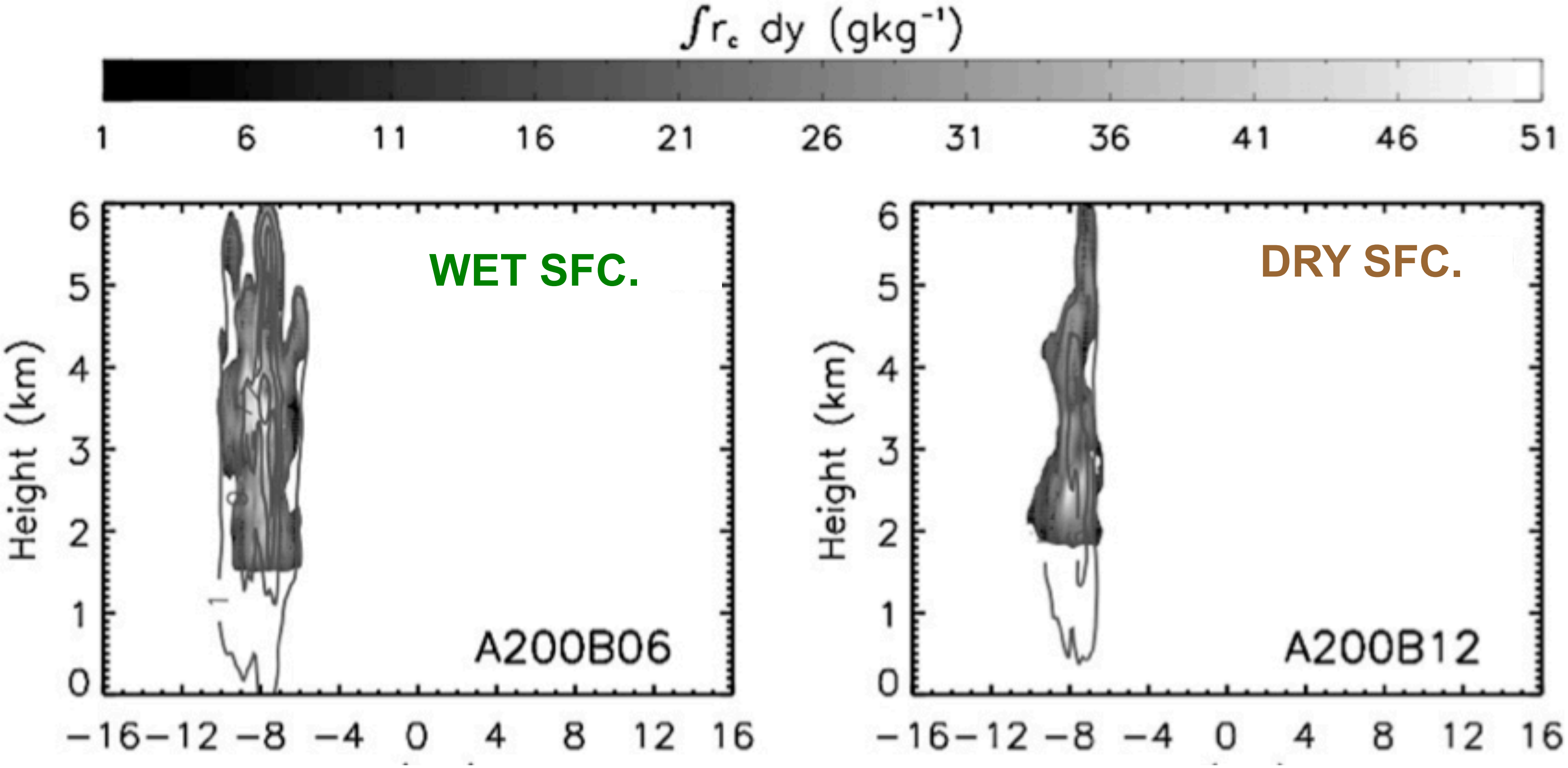
- *Over the "WET SFC", moist convection grows to reach the height of 6 km at 345 min.*
- *However over the "DRY SFC", moist convection does not reach the model top 6 km within 6 hours.*

Time evolutions of cloud water (colors) and rainwater (contours) mixing ratio



Strongly
Hete.
Sfc.

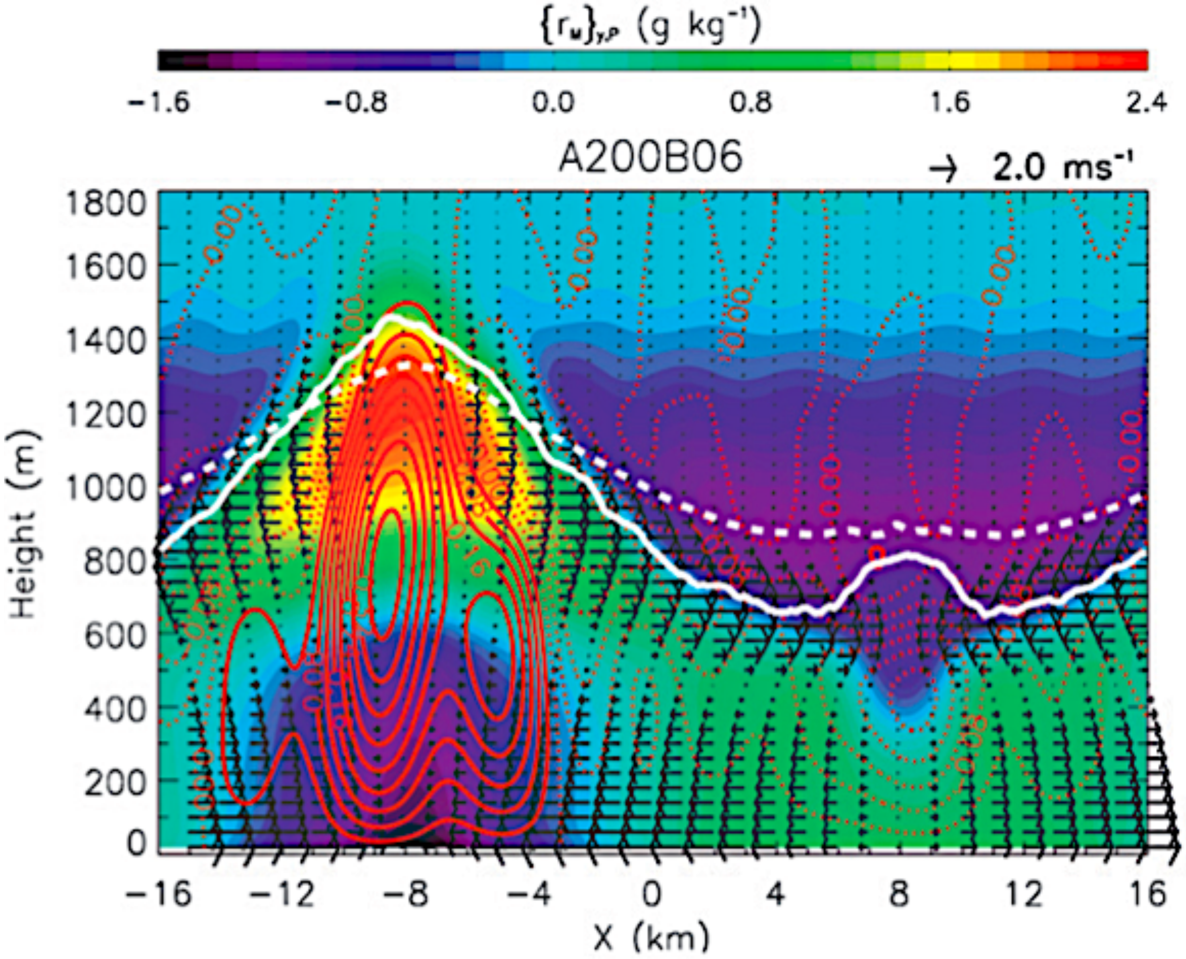
Time evolutions of cloud water (colors) and rainwater (contours) mixing ratio



For both over the "WET SFC" and "DRY SFC", moist convections grow to reach the height of 6 km at 230 min and 275 min respectively.

Mesoscale structure over the 30-min pre-CI period

Spatially averaged over the y dimension and temporally averaged over the 30-min pre-CI period



Water vapor mixing ratio : Colors

Vertical Wind: Contours

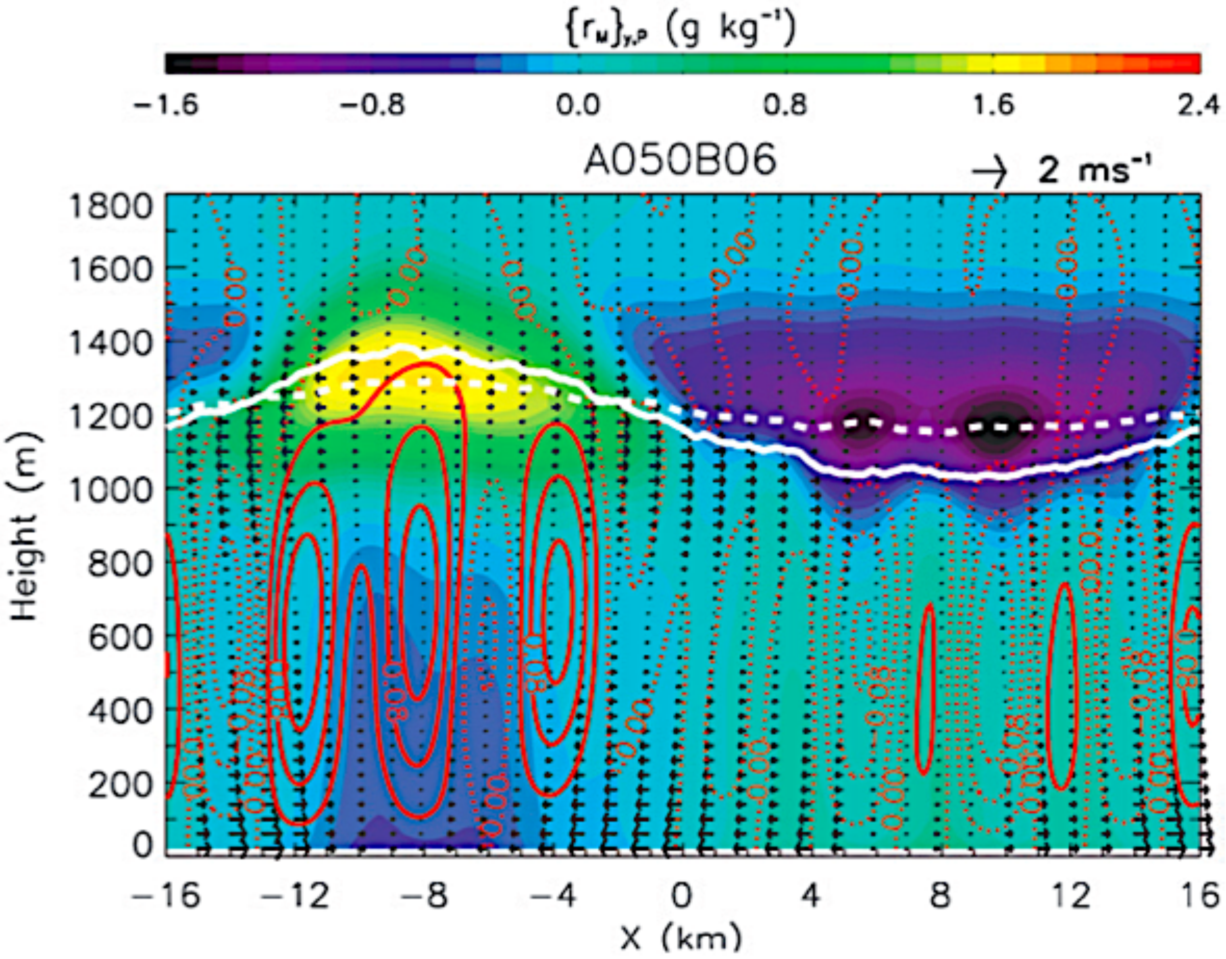
Horizontal Wind: Vectors

White Solid Line: ABL height

White Dotted Line: LCL

Mesoscale structure over the 30-min pre-CI period

Spatially averaged over the y dimension and temporally averaged over the 30-min pre-CI period



Water vapor mixing ratio : Colors

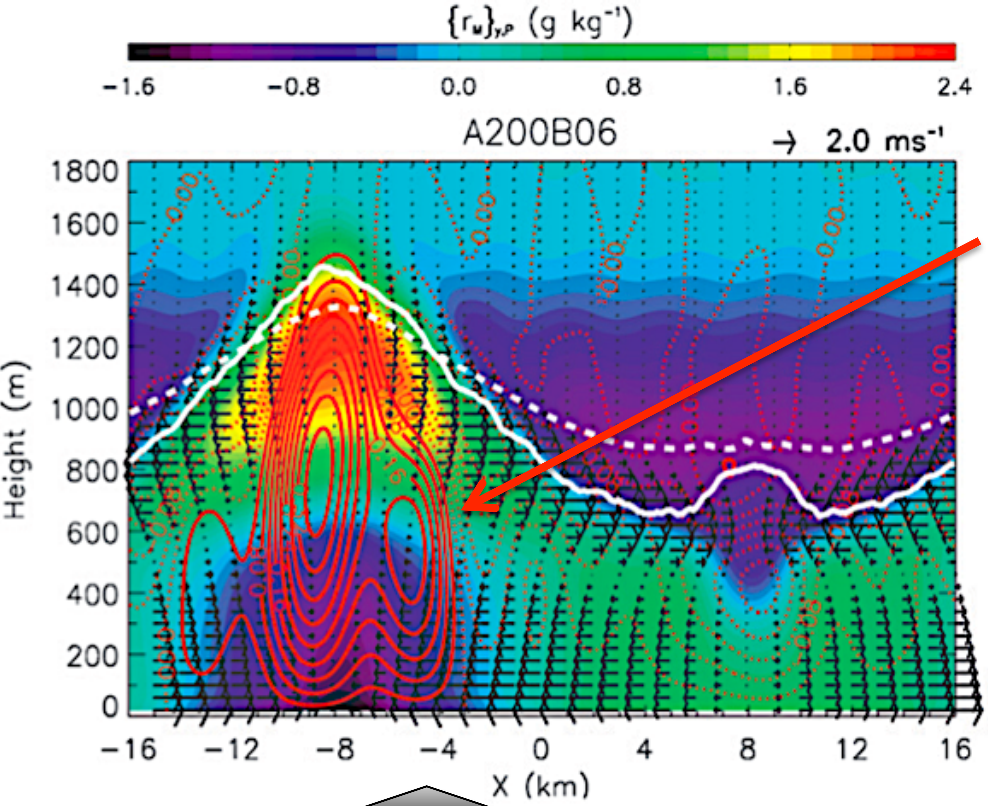
Vertical Wind: Contours

Horizontal Wind: Vectors

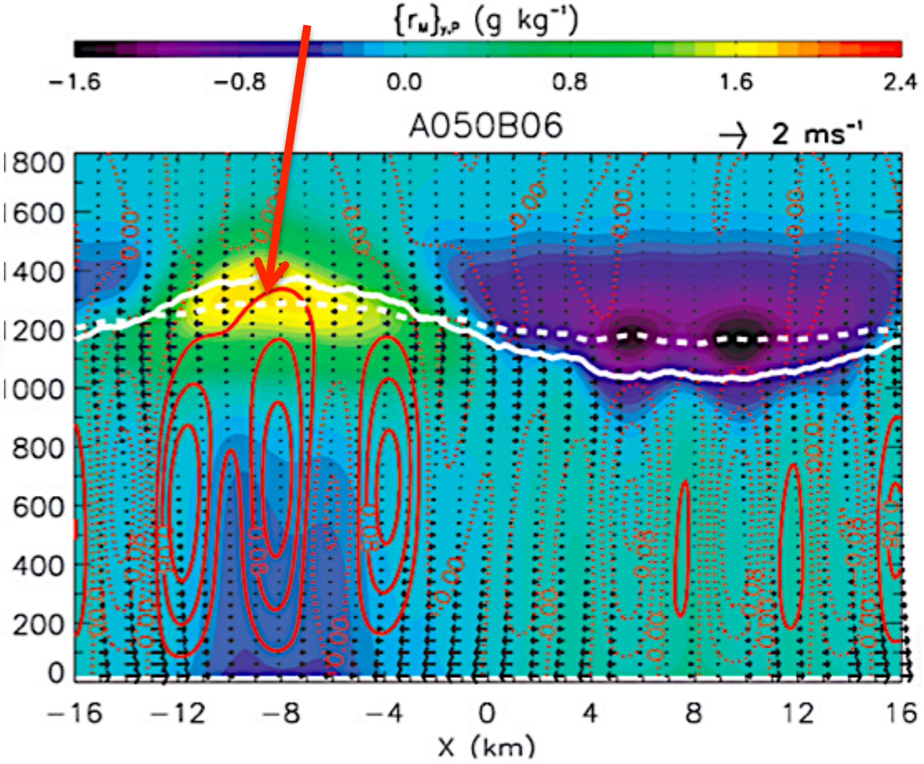
White Solid Line: ABL height

White Dotted Line: LCL

Mesoscale fluctuation structure over the 30-min pre-CI period



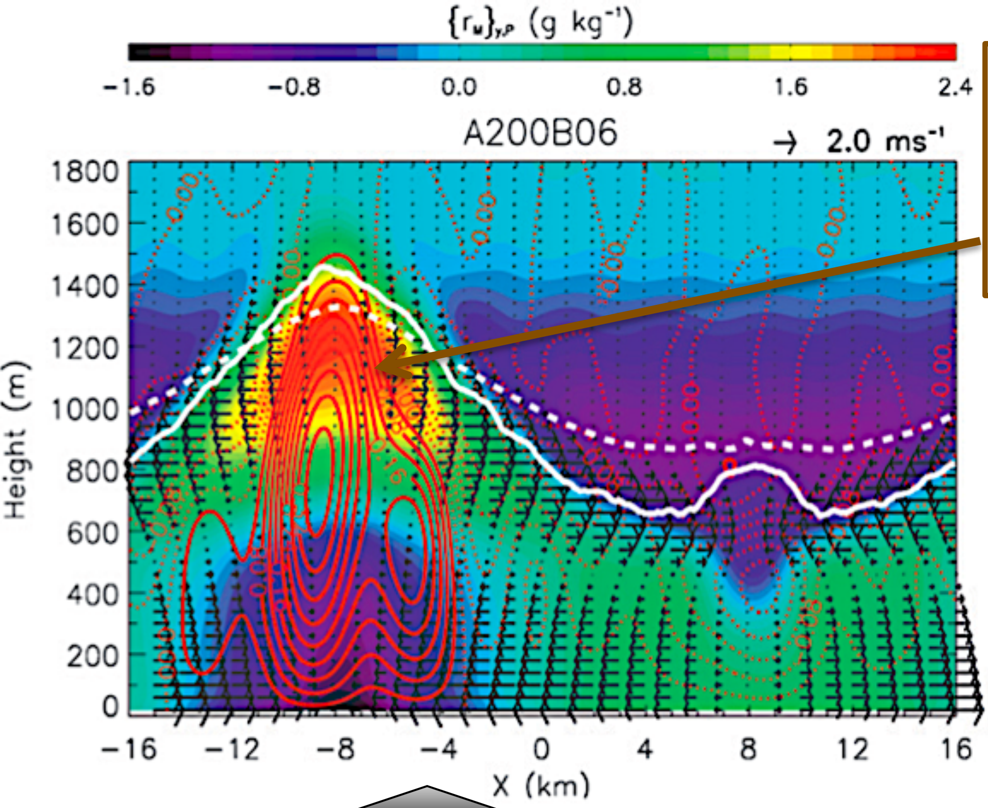
Stronger Mesoscale Upward Motion



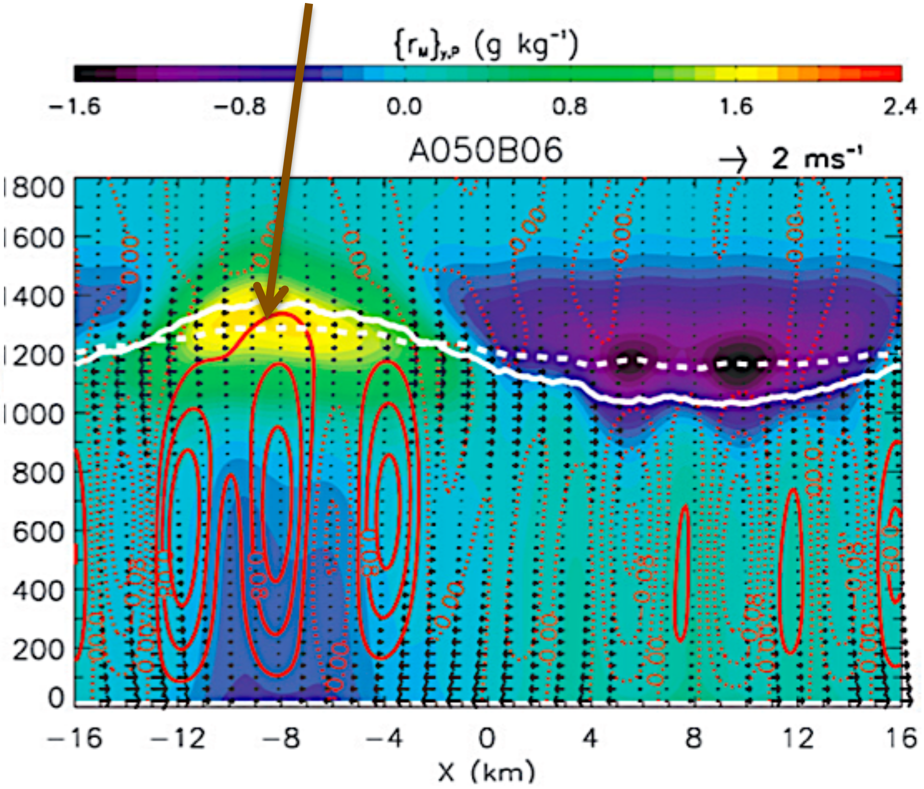
Strongly Hete. Sfc.

Weakly Hete. Sfc.

Mesoscale fluctuation structure over the 30-min pre-CI period



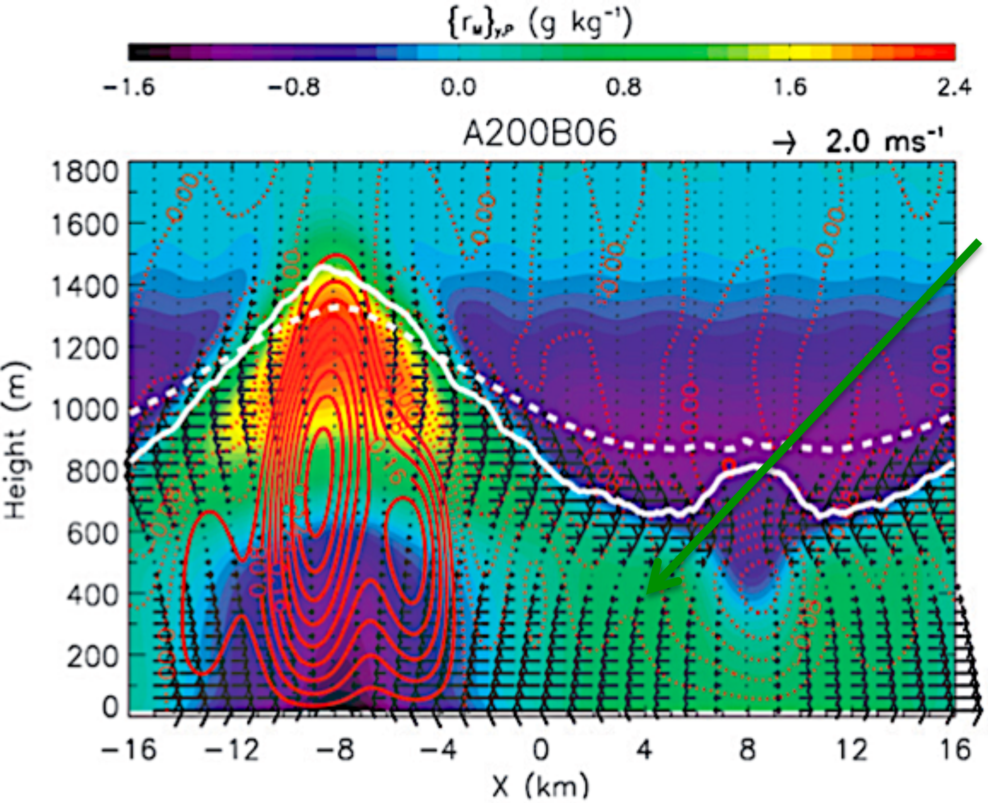
Reduced effects of the entrainment: Less warming and drying



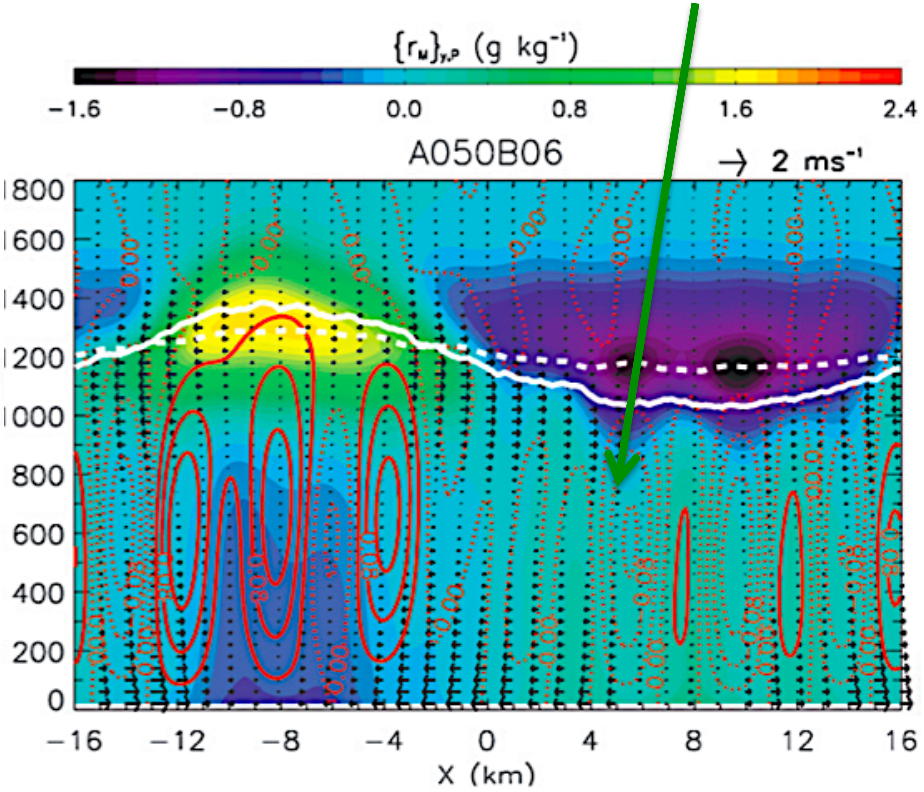
Strongly Hete. Sfc.

Weakly Hete. Sfc.

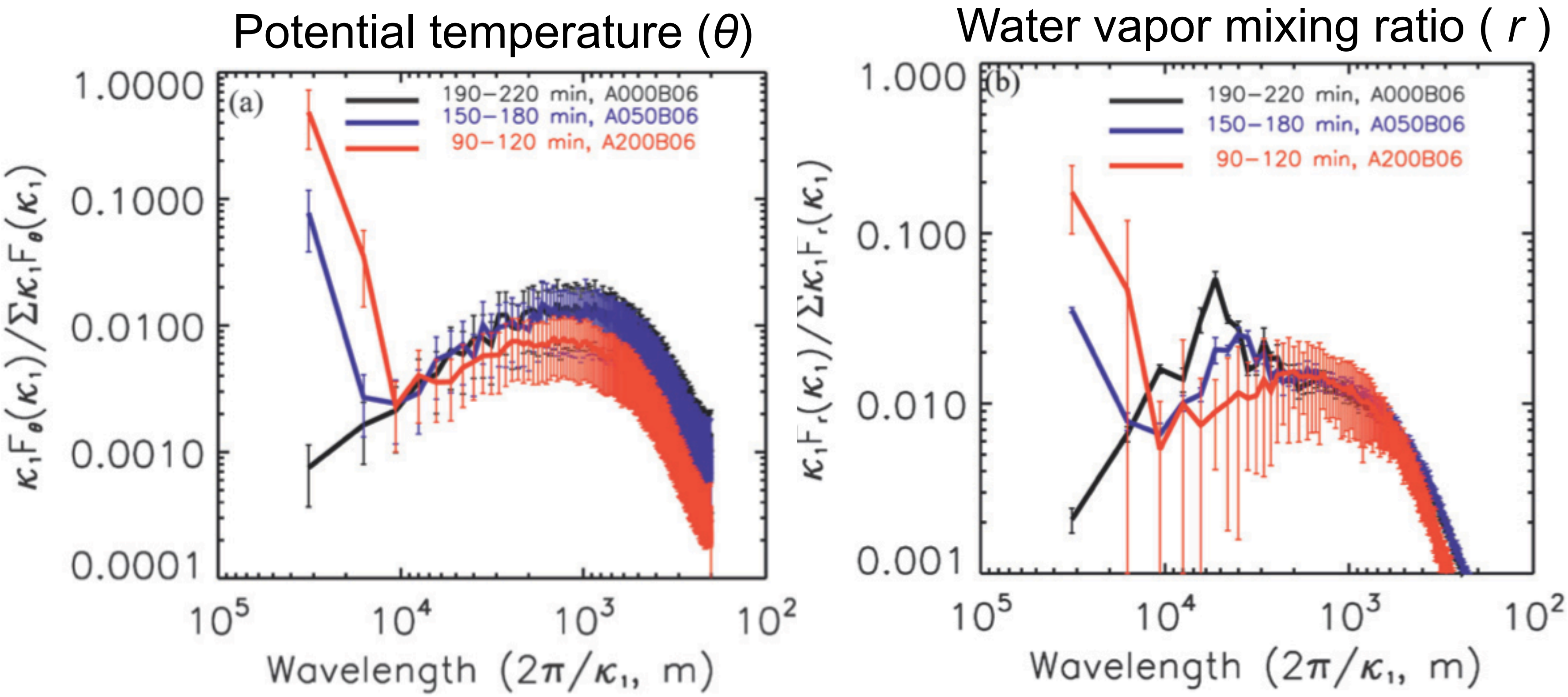
Mesoscale fluctuation structure over the 30-min pre-CI period



Different characteristics of mesoscale moisture fluctuations



Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period


Potential temperature (θ)

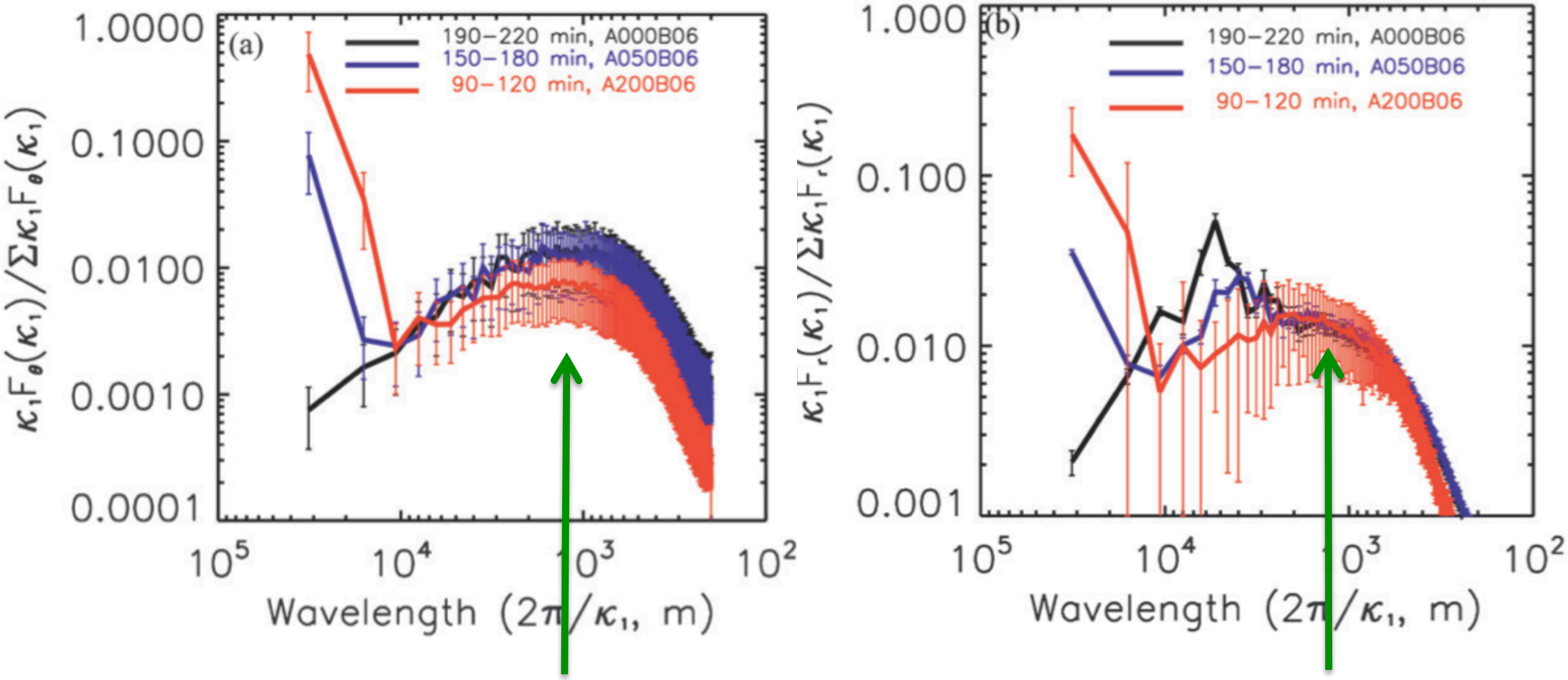
Water vapor mixing ratio (r)

Black: The horizontally homogeneous ABL
Blue: The ABL over weakly heterogeneous ABL
Red: The ABL over strongly heterogeneous ABL

Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period

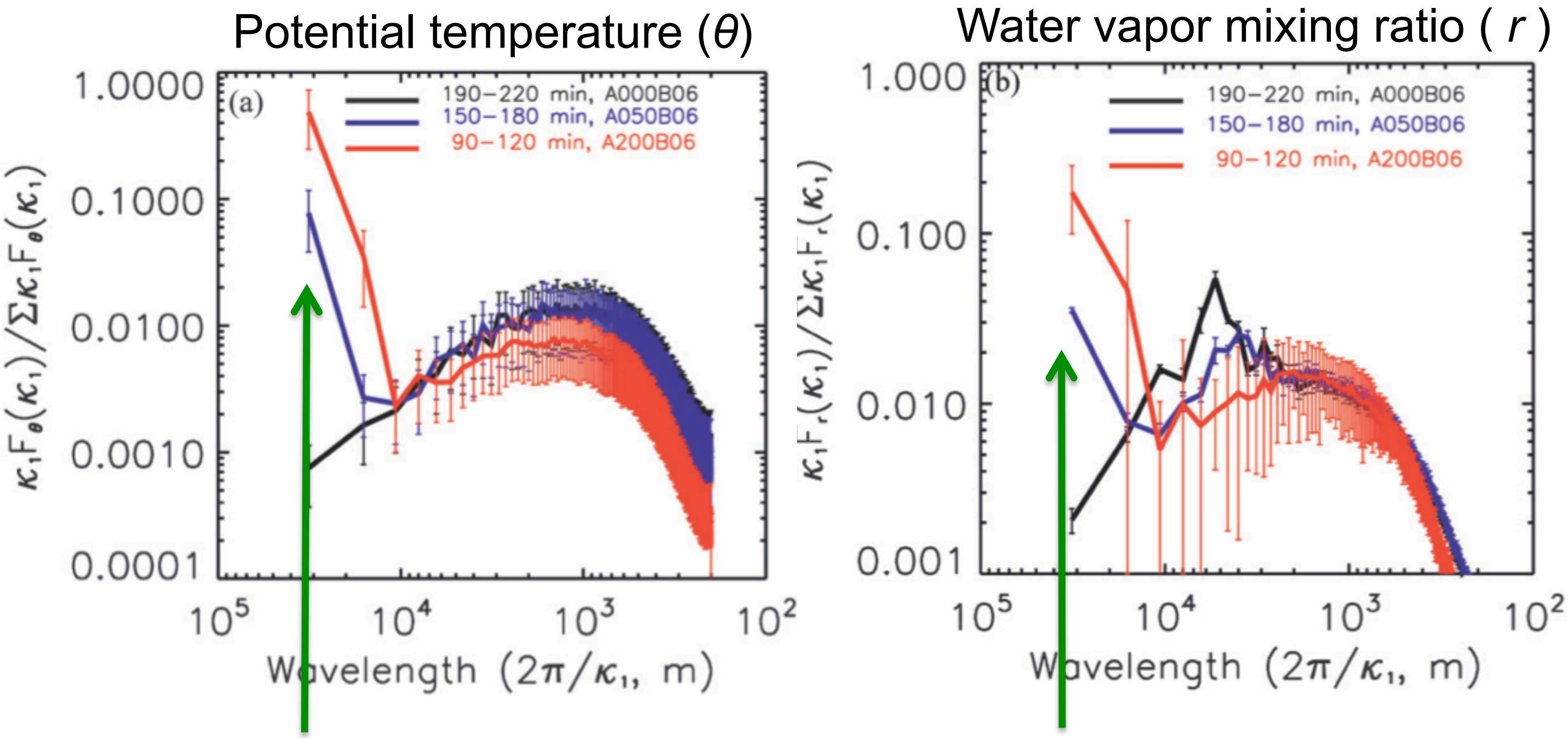
Potential temperature (θ)

Water vapor mixing ratio (r)



The spectral density peaks associated the ABL turbulence

Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period

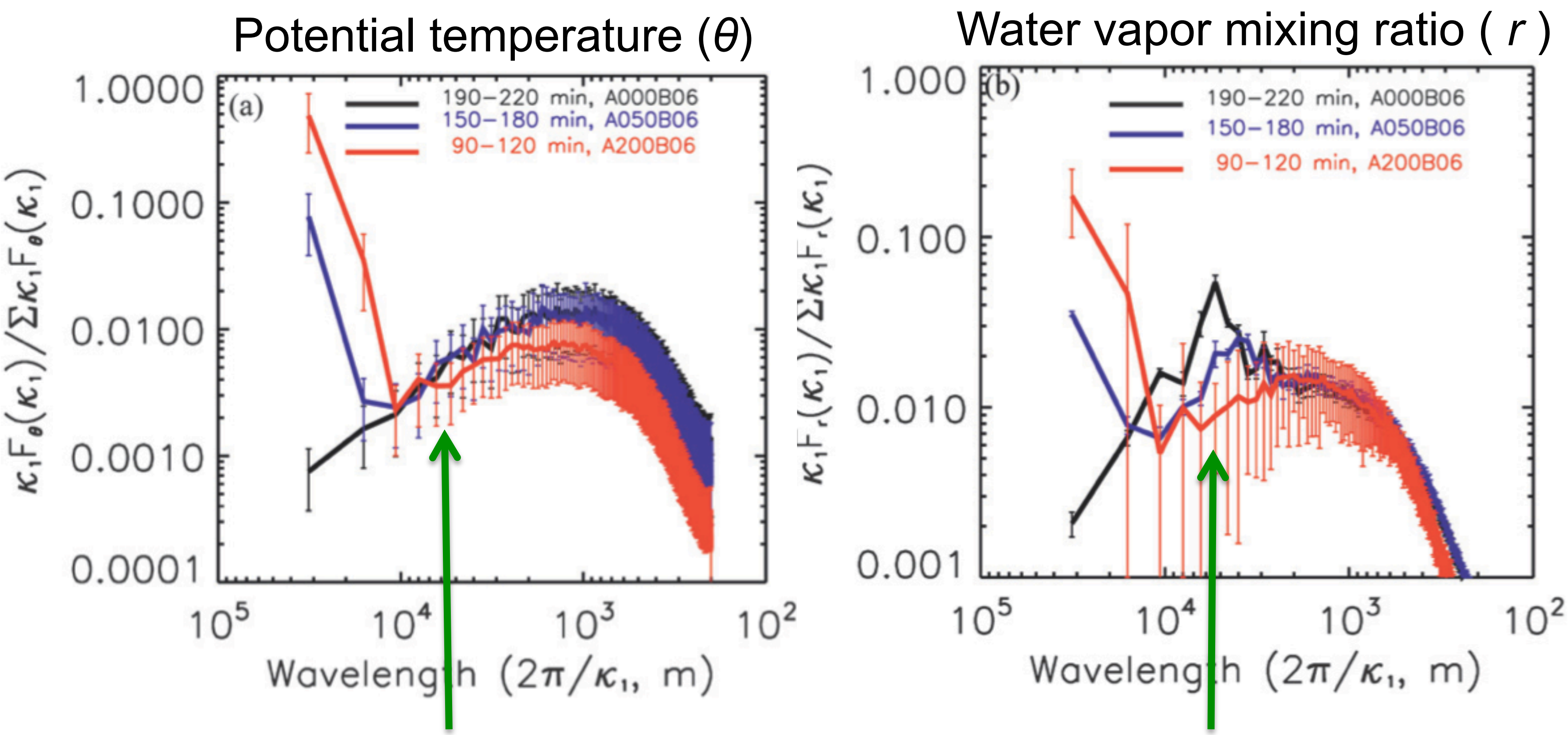


Potential temperature (θ)

Water vapor mixing ratio (r)

The spectral density peaks associated the prescribed mesoscale surface heterogeneity

Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period

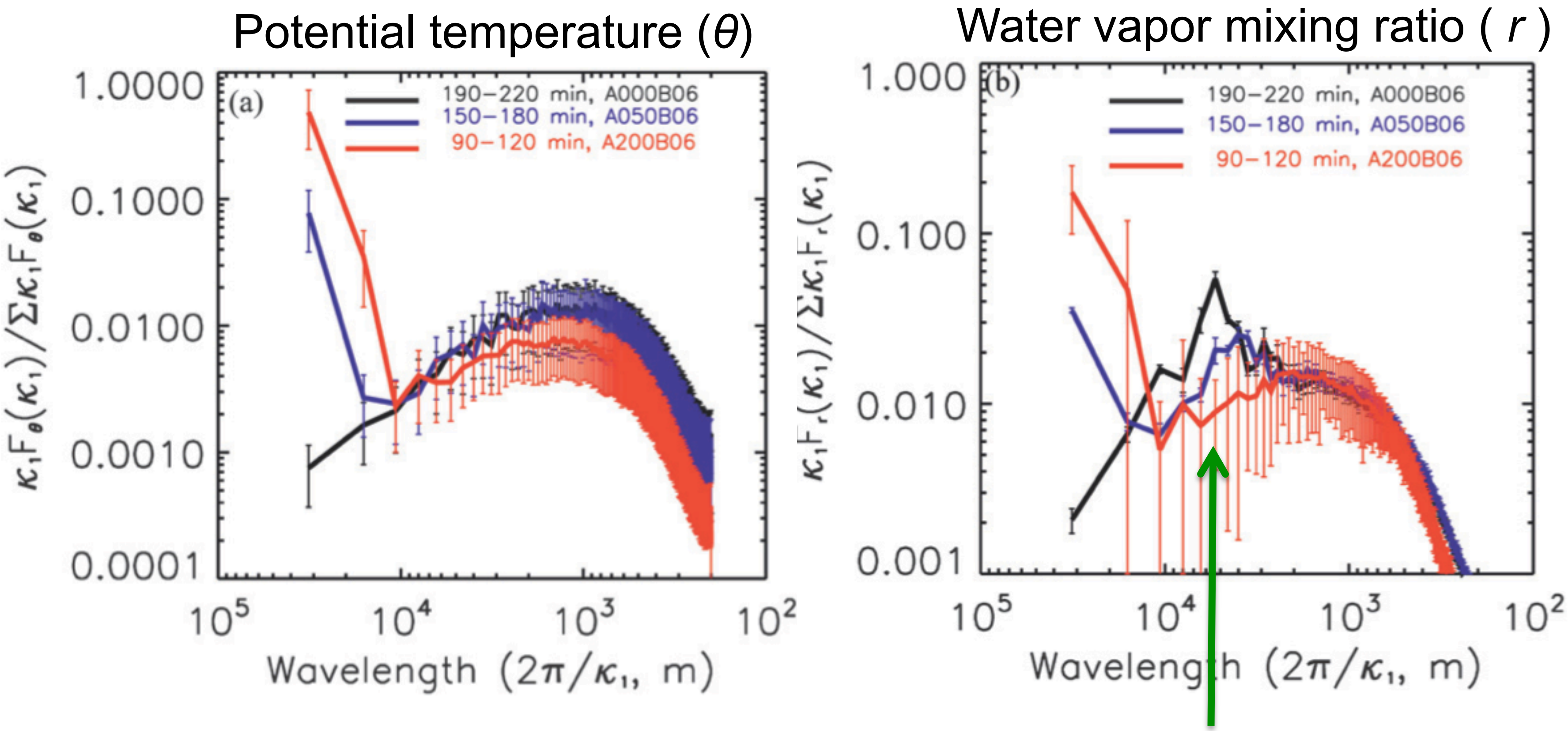


Potential temperature (θ)

Water vapor mixing ratio (*r*)

What are the third spectral density peaks existed only in the *r* spectra from cases the homogeneous ABL and the weakly heterogeneous ABL?

Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period



Potential temperature (θ)

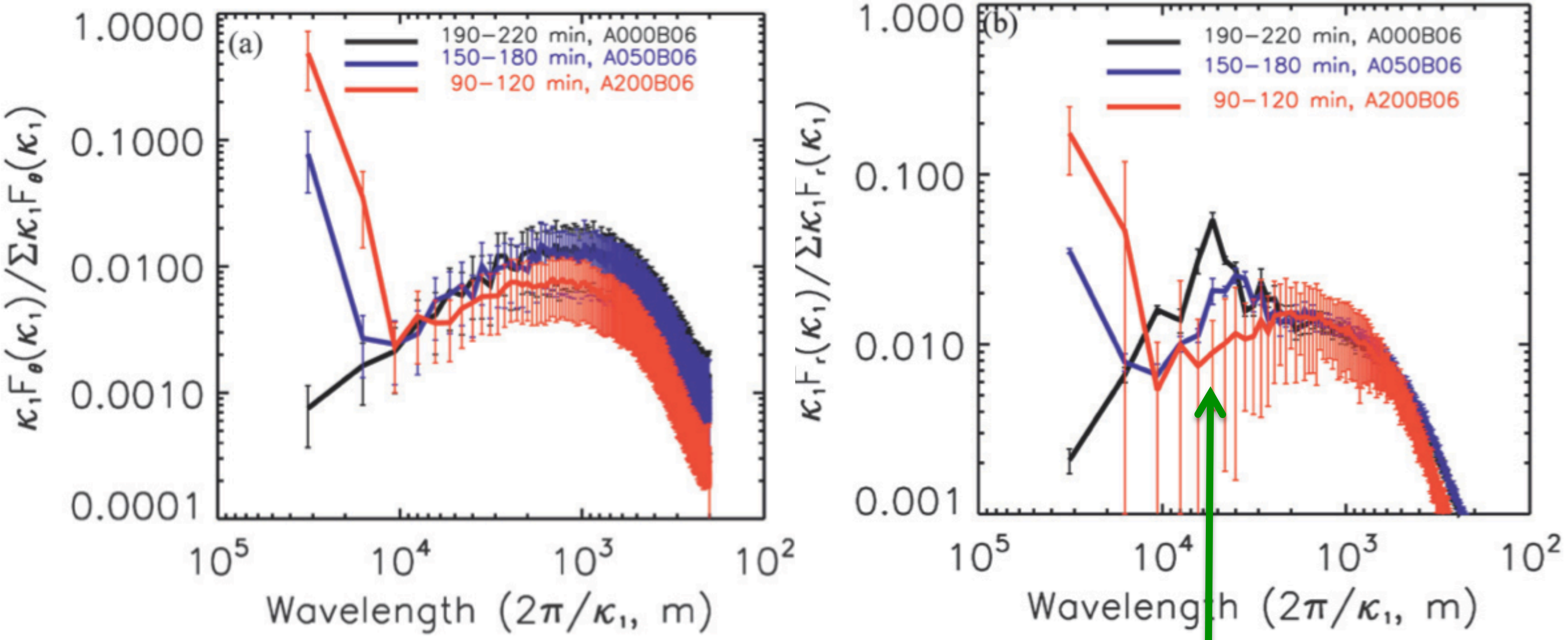
Water vapor mixing ratio (r)

Meoscale fluctuations of *r* grown from turbulence (Jonker et al. 1999)

Spectra of θ and r at 140 m above ground averaged over the 30-min pre-CI period

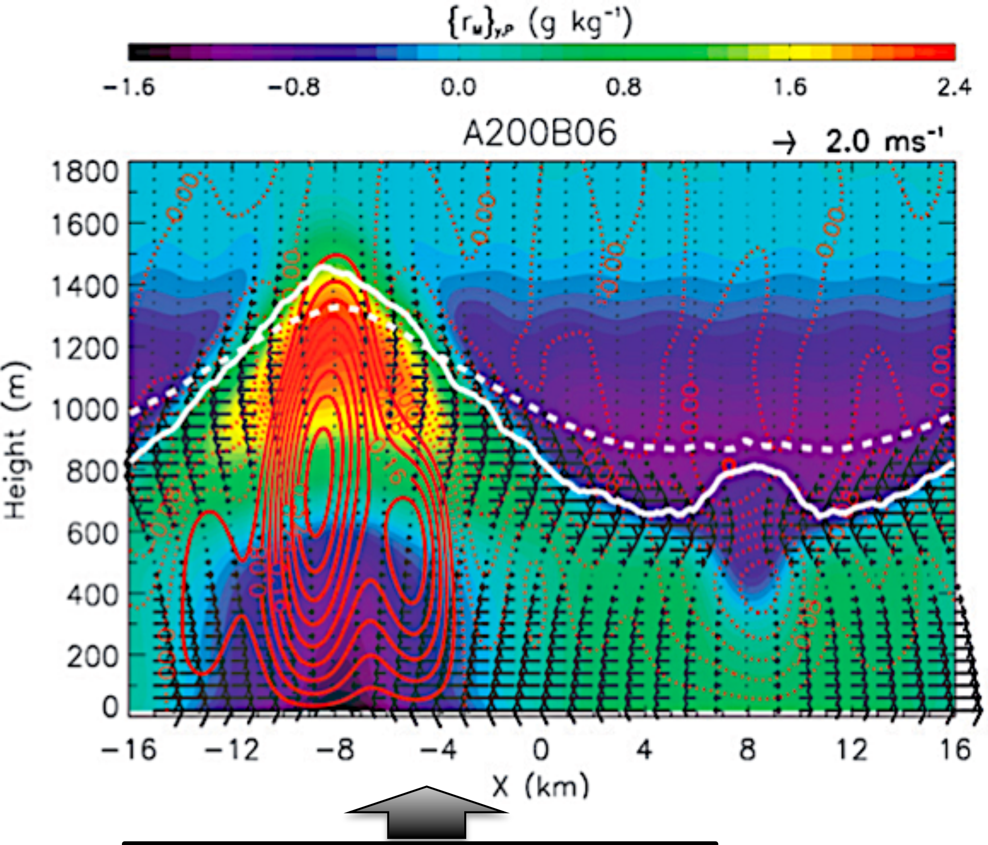
Potential temperature (θ)

Water vapor mixing ratio (r)



Characteristic length scale of r somewhat larger than that of θ (Couvreux et al. 2005; Mahrt 1991; LeMone and Meitin 1984)

Mesoscale fluctuation structure over the 30-min pre-CI period



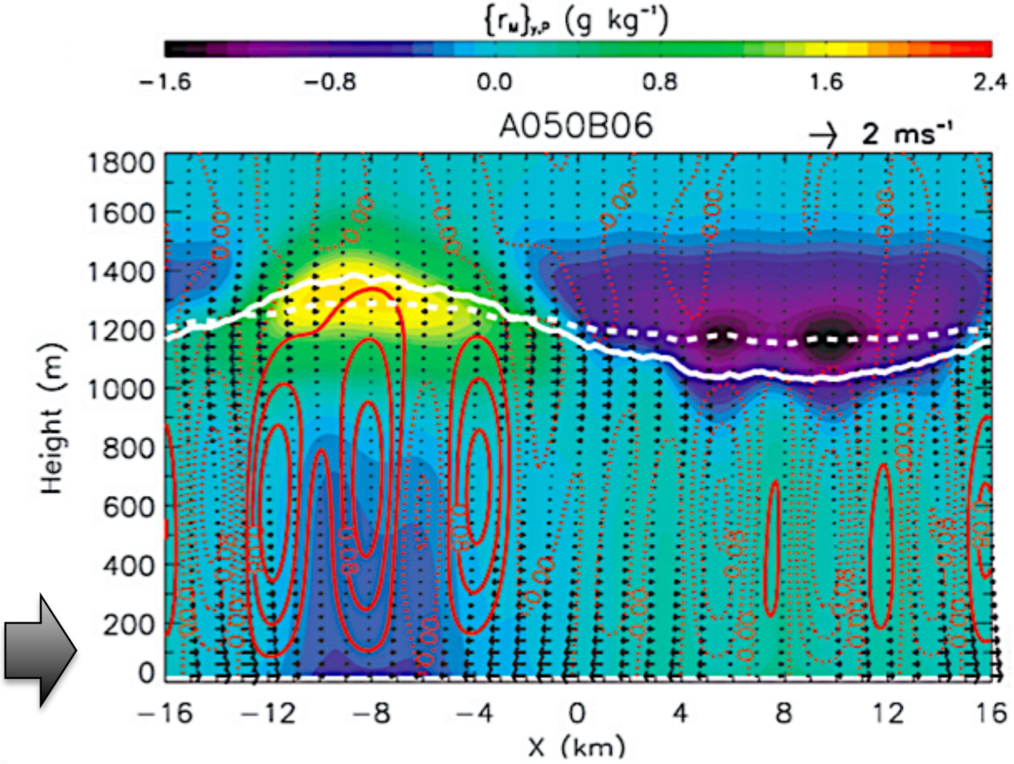
Strongly Hete. Sfc.

Mesoscale fluctuations of *r* on the sfc. heterogeneity scal

Mesoscale fluctuation structure over the 30-min pre-CI period

Mesoscale fluctuations of *r* on the sfc. heterogeneity scale and the scales smaller than the heterogeneity scale

Weakly Hete. Sfc.



Conclusions

1. The mesoscale convergence zone of this circulation develops over the relatively warm surface, and this is where clouds first form.
2. With higher amplitude of the surface flux heterogeneity, CI occurs earlier in a more focused region over the center of the warm patch.

Conclusions

3. With the same amplitude of sensible heat flux heterogeneity, the relatively wet surface (lower Bowen ratio) yields earlier CI.
4. Over weakly heterogeneous and homogeneous surfaces, surface latent heat flux is especially significant for determining the development of deep moist convection.

Conclusions

5. Over strongly heterogeneous surfaces, moisture fluctuations on a scale larger than turbulence are generated only by the surface heterogeneity.
6. Over strongly heterogeneous surfaces, greater magnitude of mesoscale upward motion more significantly reduces the warming and drying effect by the entrainment of the free atmosphere into the CBL.

For the details,

- Please refer to “Kang and Bryan, 2011: A Large-Eddy Simulation Study of Moist Convection Initiation over Heterogeneous Surface Fluxes, *Mon. Wea. Review* 139 : 2901-2917”