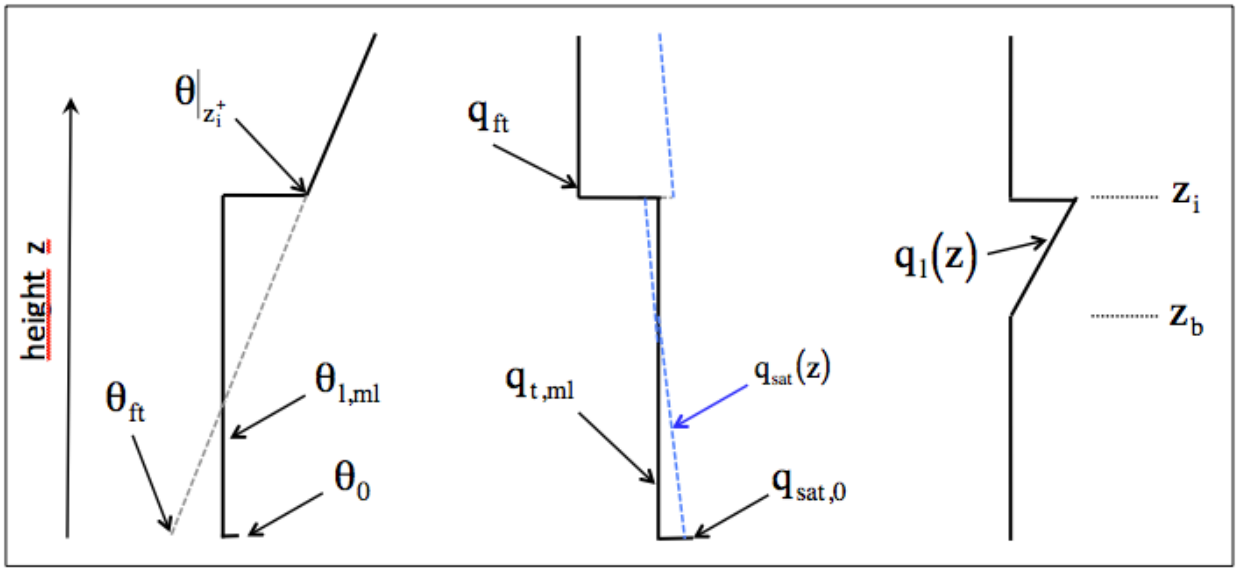
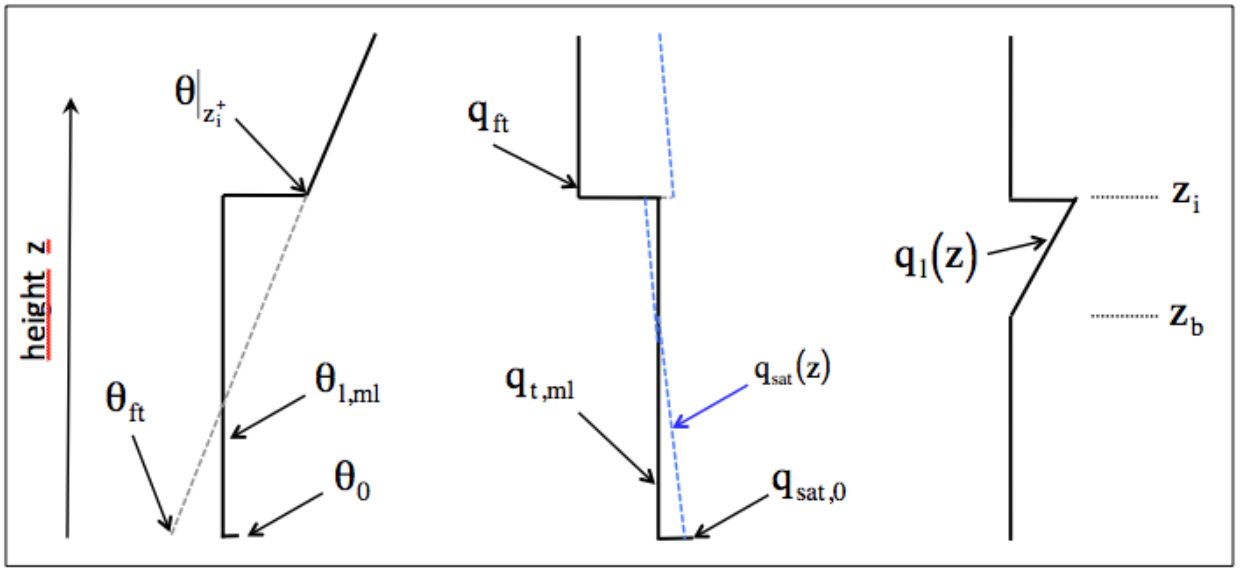
The stratocumulus response to a single perturbation in cloud controlling factors



Stephan de Roode, Pier Siebesma, Sara Dal Gesso,

Harm Jonker, Jerôme Schalkwijk and Jasper Sival

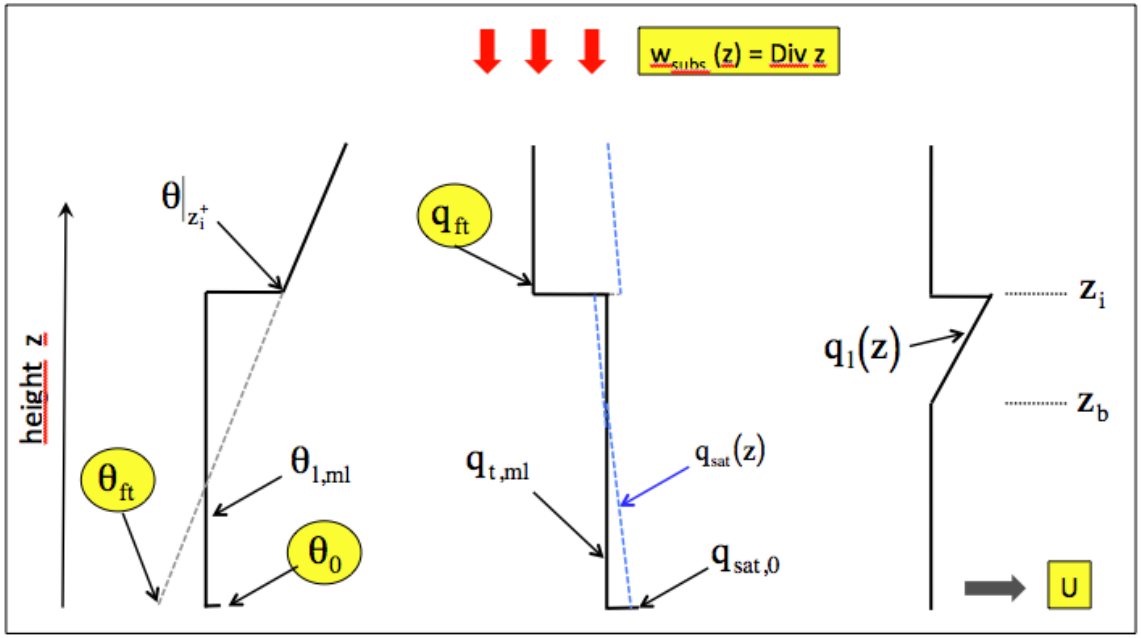
The boundary layer budget equation for a conserved variable



$$z_i \frac{\partial \psi_{ml}}{\partial t} = C_d U(\psi_0 - \psi_{ml}) + w_e(\psi|_{z_i^+} - \psi_{ml}) - \Delta S_\psi$$

surface flux entrainment flux source term

The cloud controlling factors



Variable φ	Units	Reference value
θ_0	(K)	288.0
D	(s^{-1})	$5 \cdot 10^{-6}$
U	(ms^{-1}	10.0
ΔF	(Kms^{-1})	0.035
θ_{ft}	(K)	[285,301]
q_{ft}	(g kg^{-1})	[0,9]
Γ_θ	(K km^{-1})	6.0

Equilibrium State Solutions

$$q_{\mathrm{t,ml}} = q_{\mathrm{sat},0} + \frac{w_{\mathrm{e}}(q_{\mathrm{ft}} - q_{\mathrm{sat},0})}{w_{\mathrm{e}} + C_{\mathrm{d}}U}$$

$$\theta_{\mathrm{l,ml}} = \theta_0 + \frac{w_{\mathrm{e}}(\theta_{\mathrm{l}}|_{z_{\mathrm{i}}^+} - \theta_0) - \Delta F}{w_{\mathrm{e}} + C_{\mathrm{d}}U}$$

$$w_{\mathrm{e}} = D z_{\mathrm{i}}$$

Partial derivatives with respect to SST (for **fixed** entrainment rate):

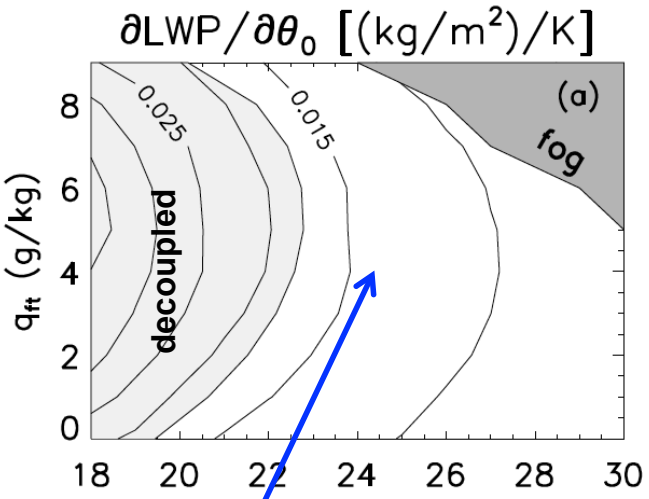
$$0 < \frac{\partial \theta_{\mathrm{l,ml}}}{\partial \theta_0} = \frac{\partial q_{\mathrm{t,ml}}}{\partial q_{\mathrm{sat},0}} = \frac{C_{\mathrm{d}}U}{w_{\mathrm{e}} + C_{\mathrm{d}}U} < 1$$

Warmer SST -> warmer and moister boundary layer

What about LWP response?

LWP response to SST change (fixed entrainment rate)

fixed entrainment



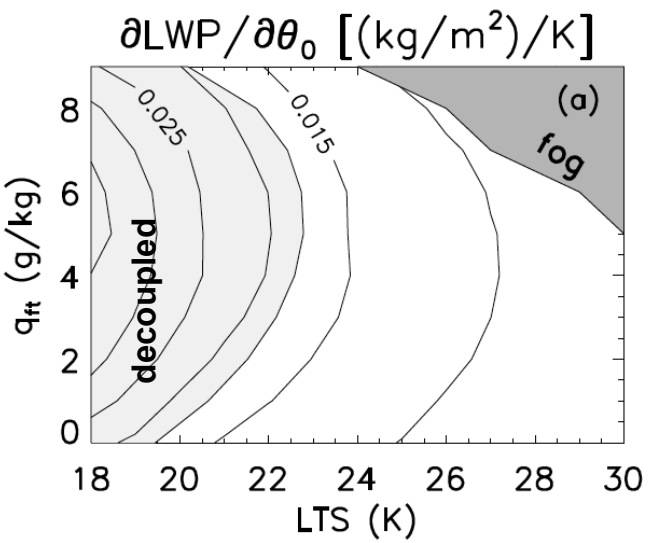
LTS = $\theta_{3km} - \theta_0$ (reference case value)

cloud thickening (cloud base lowers)

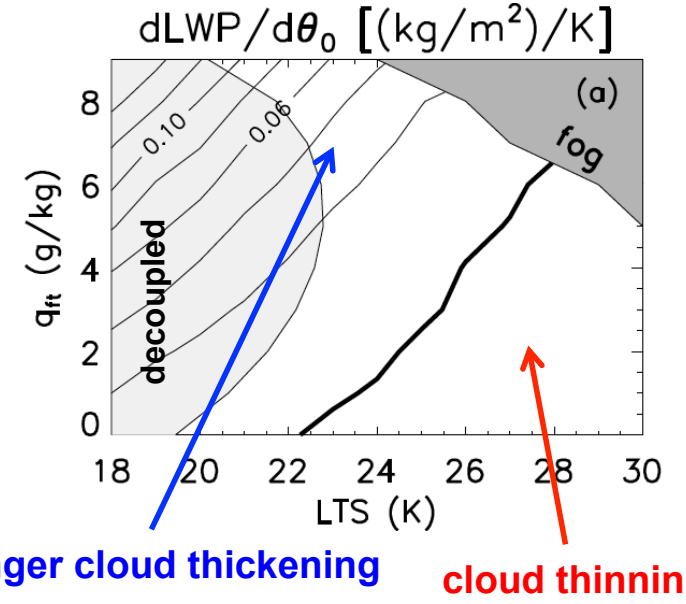
Partial and total derivatives

(entrainment parameterization from Nicholls and Turton 1986)

fixed entrainment



with entrainment response



Liquid water path (LWP) response to a perturbation in a cloud controlling factor ϕ_i

$$\underbrace{\left(\frac{d\mathrm{LWP}}{d\varphi_i}\right)}_{\text{total}} \approx \underbrace{\left(\frac{\partial \mathrm{LWP}}{\partial \varphi_i}\right)_{w_e}}_{\text{direct}} + \underbrace{\left(\frac{\partial \mathrm{LWP}}{\partial w_e}\right)_{\varphi_i}}_{\text{multiplier}} \times \underbrace{\left(\frac{\partial w_e}{\partial \varphi_i}\right)}_{\text{entrainment response}}$$

depends on reference state, thermodynamics

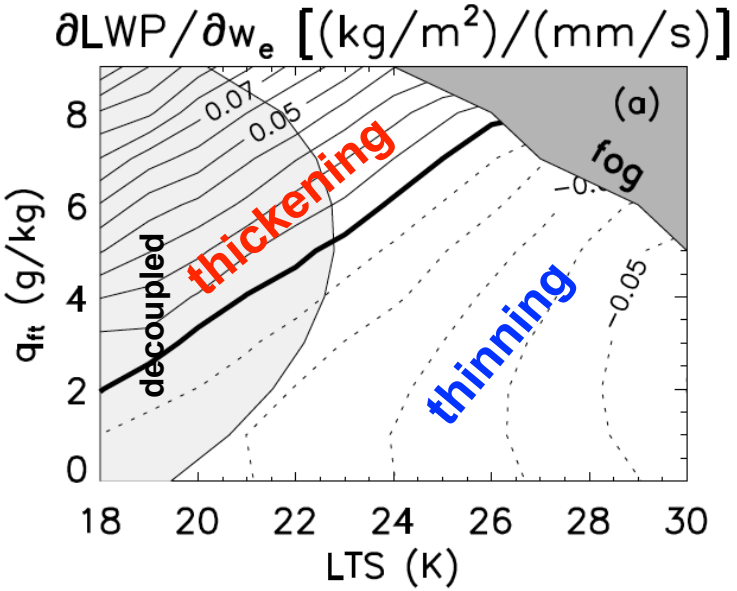
model property

$$\frac{\partial \theta_{\mathrm{l,ml}}}{\partial w_\mathrm{e}} = \frac{C_\mathrm{d}U(\theta_\mathrm{ft} - \theta_0) + \Delta F + w_\mathrm{e}\frac{\Gamma_\theta}{D}(w_\mathrm{e} + 2C_\mathrm{d}U)}{(w_\mathrm{e} + C_\mathrm{d}U)^2} > 0$$

$$\frac{\partial q_{\mathrm{t,ml}}}{\partial w_\mathrm{e}} = \frac{C_\mathrm{d}U(q_\mathrm{ft} - q_{\mathrm{sat},0})}{(w_\mathrm{e} + C_\mathrm{d}U)^2} < 0.$$

The total response

$$\underbrace{\left(\frac{d\mathrm{LWP}}{d\varphi_i}\right)}_{\text{total}} \approx \underbrace{\left(\frac{\partial \mathrm{LWP}}{\partial \varphi_i}\right)_{w_e}}_{\text{direct}} + \underbrace{\left(\frac{\partial \mathrm{LWP}}{\partial w_e}\right)_{\varphi_i}}_{\text{multiplier}} \times \underbrace{\left(\frac{\partial w_e}{\partial \varphi_i}\right)}_{\text{entrainment response}}$$



thinning : $dz_b > dz_i$

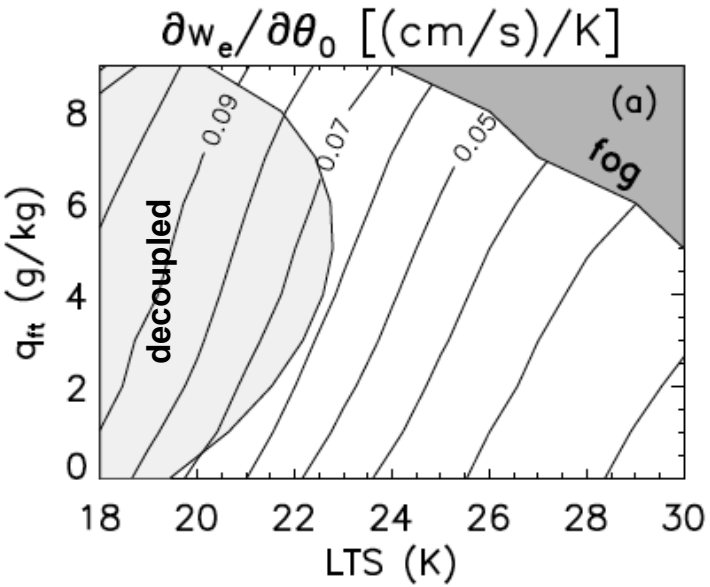
thickening : $dz_b < dz_i$

"cloud deepening through entrainment"

(Randall,1984)

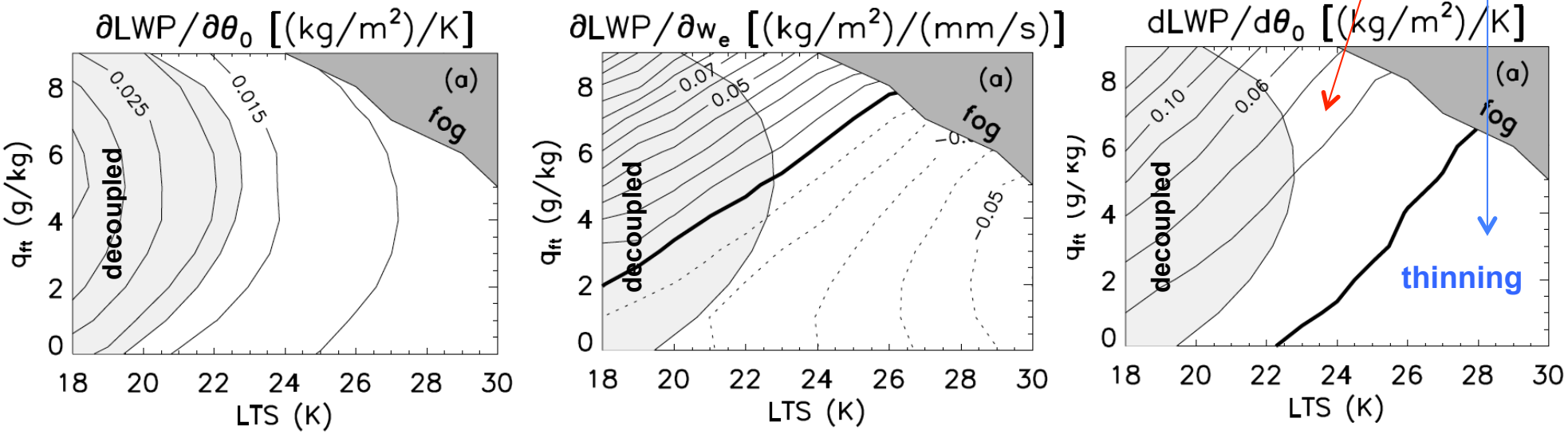
The entrainment response

(parameterization from Nicholls and Turton 1986)



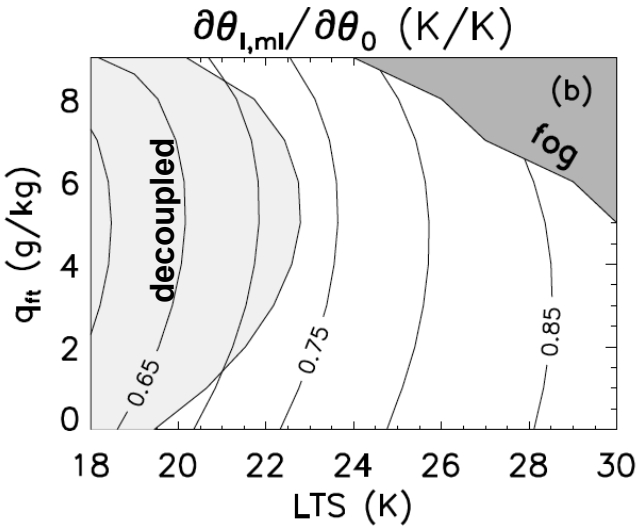
more entrainment if SST is increased

indirect effect		$\left(\frac{\partial \mathrm{LWP}}{\partial \varphi_i}\right)_{w_e}$ direct	$\left(\frac{\partial \mathrm{LWP}}{\partial w_e}\right)_{\varphi_i}$ multiplier	$\frac{\partial w_e}{\partial \varphi_i}$ entrainment	$\left(\frac{d\mathrm{LWP}}{d\varphi_i}\right)$ total
Amplifying	*i*	>0	>0	>0	$\frac{d\mathrm{LWP}}{d\varphi_i} > \frac{\partial \mathrm{LWP}}{\partial \varphi_i} > 0$
	ii	>0	<0	<0	
	iii	<0	<0	>0	$\frac{d\mathrm{LWP}}{d\varphi_i} < \frac{\partial \mathrm{LWP}}{\partial \varphi_i} < 0$
	iv	<0	>0	<0	
Counteracting	*i*	>0	>0	<0	$\frac{d\mathrm{LWP}}{d\varphi_i} < \frac{\partial \mathrm{LWP}}{\partial \varphi_i}$
	ii	>0	<0	>0	
	iii	<0	<0	<0	$\frac{d\mathrm{LWP}}{d\varphi_i} > \frac{\partial \mathrm{LWP}}{\partial \varphi_i}$
	iv	<0	>0	>0	



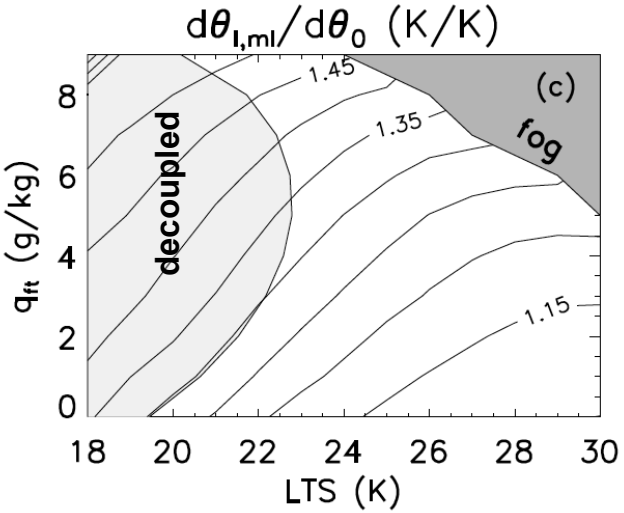
Partial and total derivatives

fixed entrainment



increase in sensible heat flux

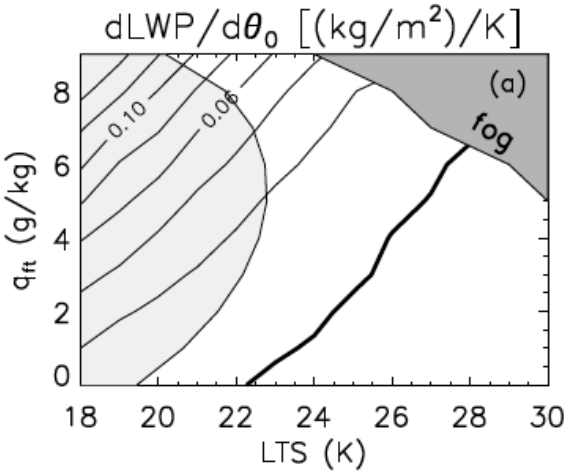
with entrainment response



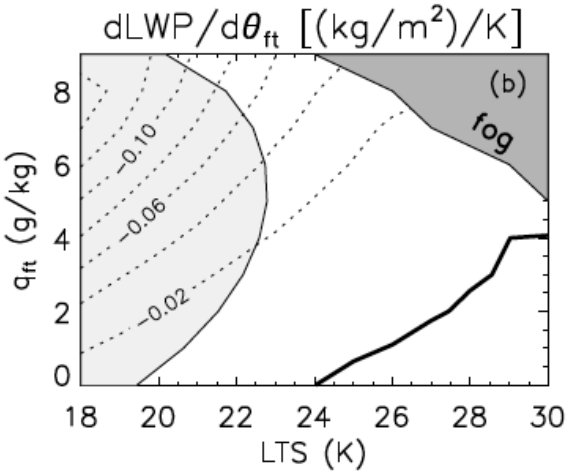
decrease in sensible heat flux

Total LWP response (including entrainment response)

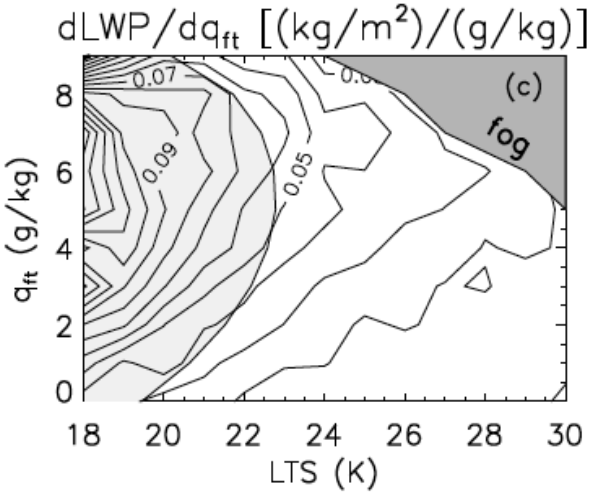
SST



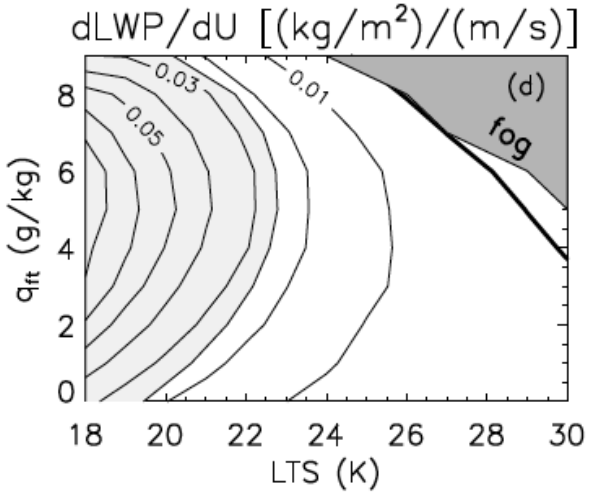
free tropospheric temperature



free tropospheric humidity



wind speed



Conclusions

Entrainment multiplier

Entrainment response can change sign of the LWP response

Single changes

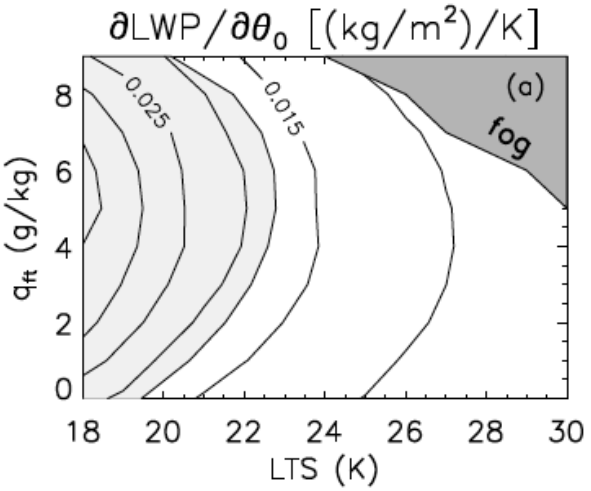
Opposing LWP responses, e.g. SST and free tropospheric temperature

Outlook/wish

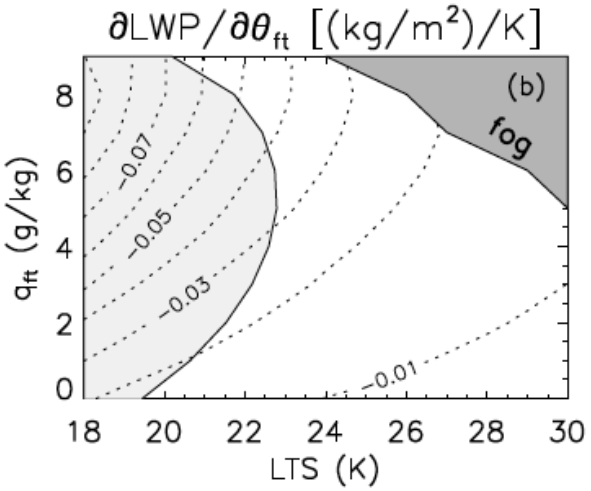
Test entrainment response due to a single change in SCM framework

Direct response (entrainment fixed)

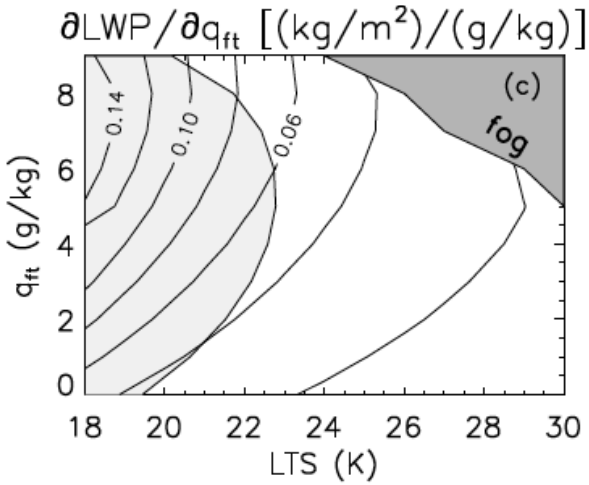
SST



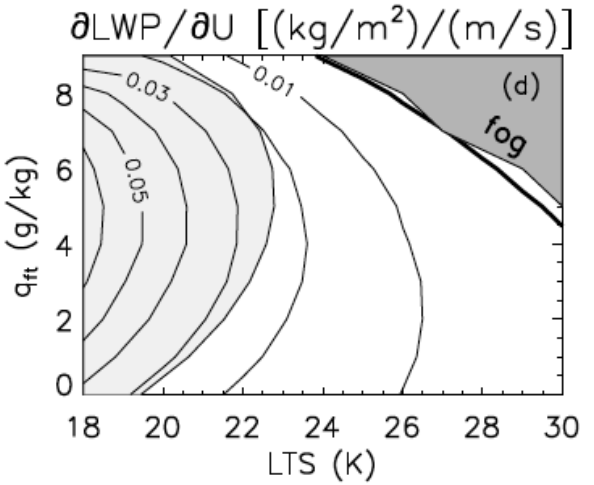
free tropospheric temperature



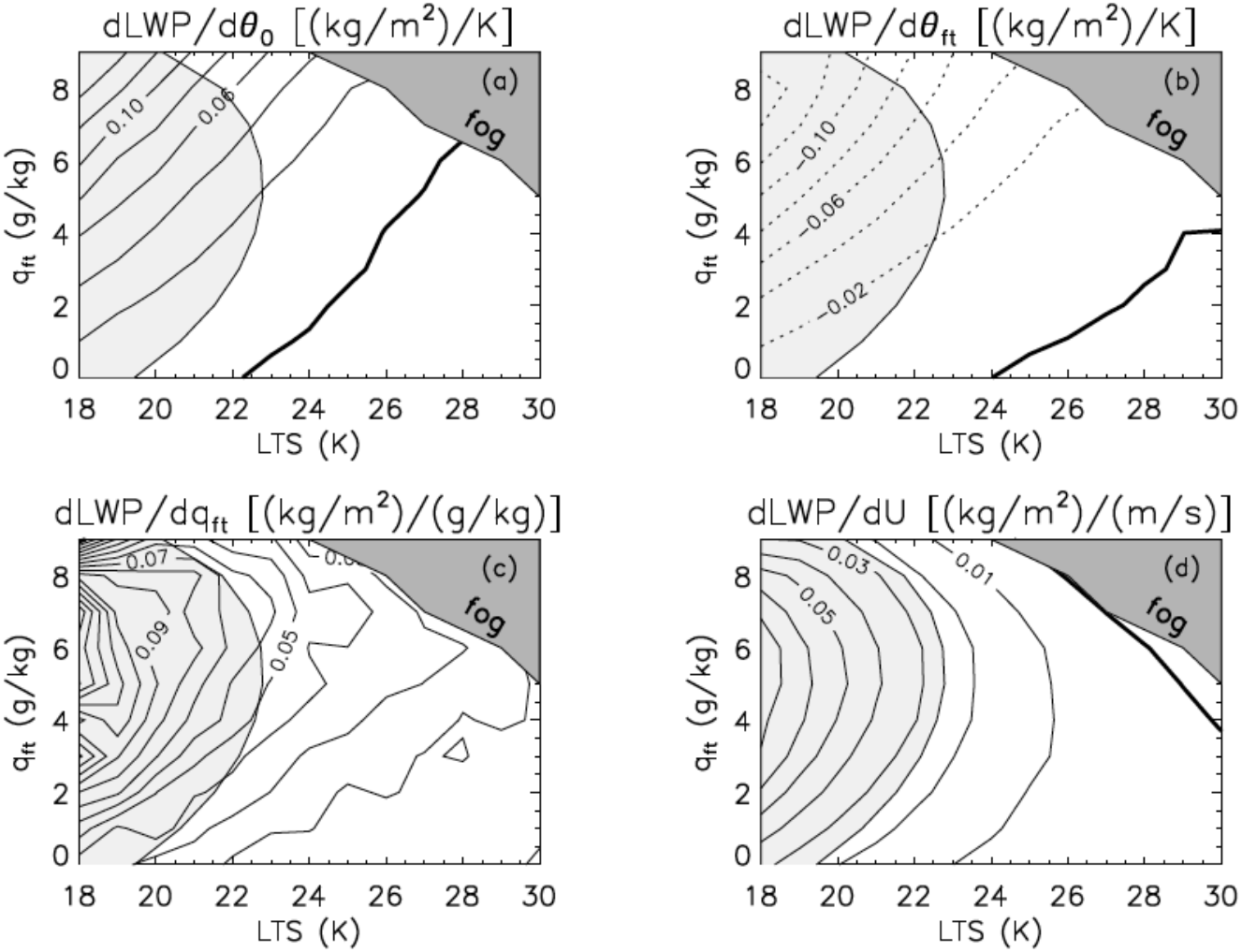
free tropospheric humidity



wind speed

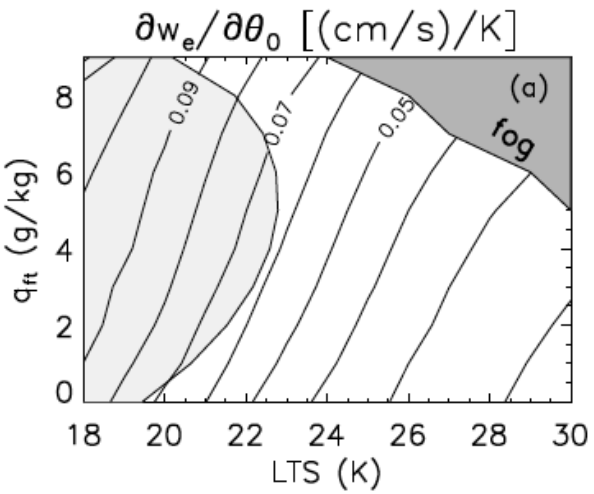


Total response (including entrainment response)

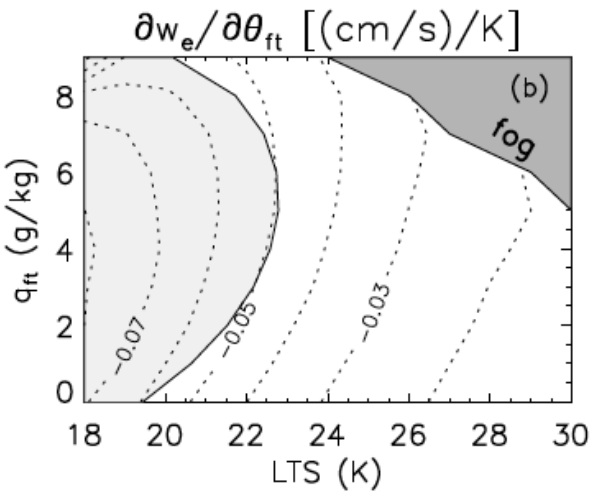


Total entrainment response (Nicholls & Turton)

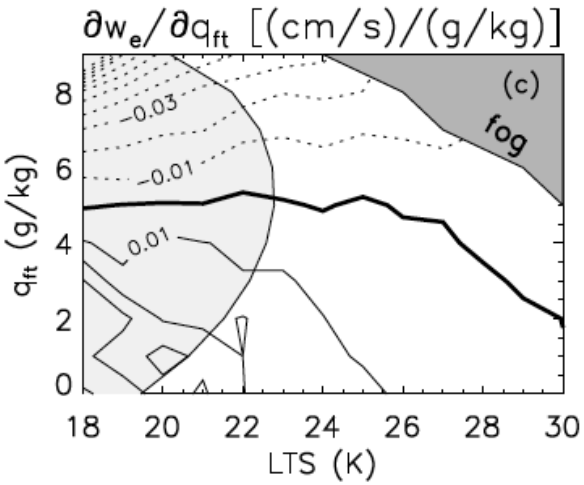
SST



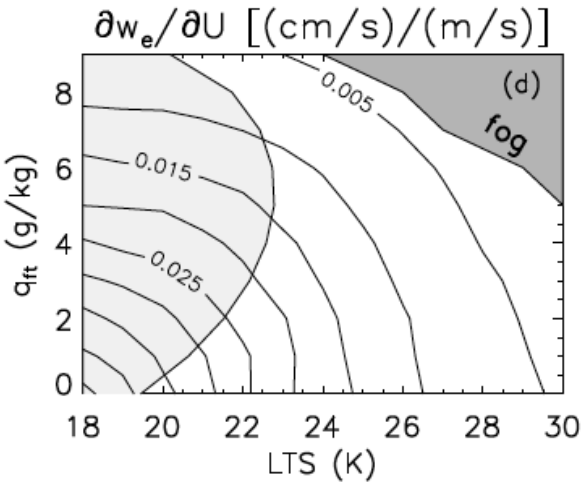
free tropospheric temperature



free tropospheric humidity



wind speed



Equilibrium State Solutions

$$\psi \in \{q_t, \theta_l\}$$

$$z_i \frac{\partial \psi_{ml}}{\partial t} = C_d U (\psi_0 - \psi_{ml}) + w_e (\psi|_{z_i+} - \psi_{ml}) - \Delta S_\psi \quad = 0$$

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}|_{z_i} \quad = 0$$

Entrainment rate w_e from Nicholls-Turton (1986)

$\Delta S_{qt} = 0$ - no drizzle

$\Delta S_{\theta l} = \Delta F_{rad}/\rho c_p$, $\Delta F_{rad} = 40$ Wm^{-2} - net radiative cooling