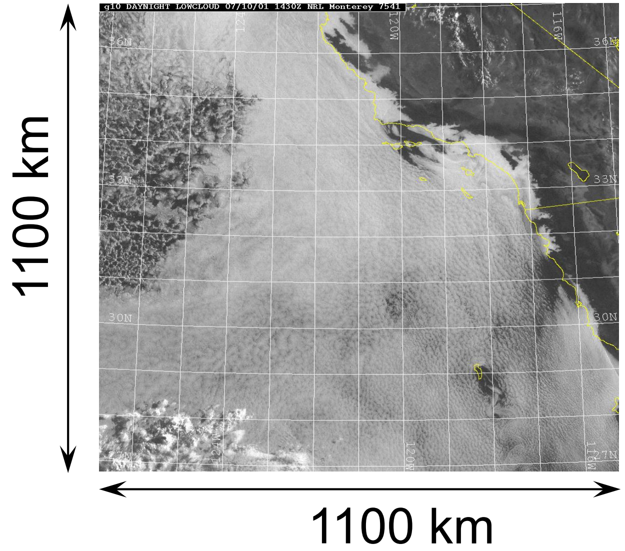
What controls the stratocumulus cloud amount?



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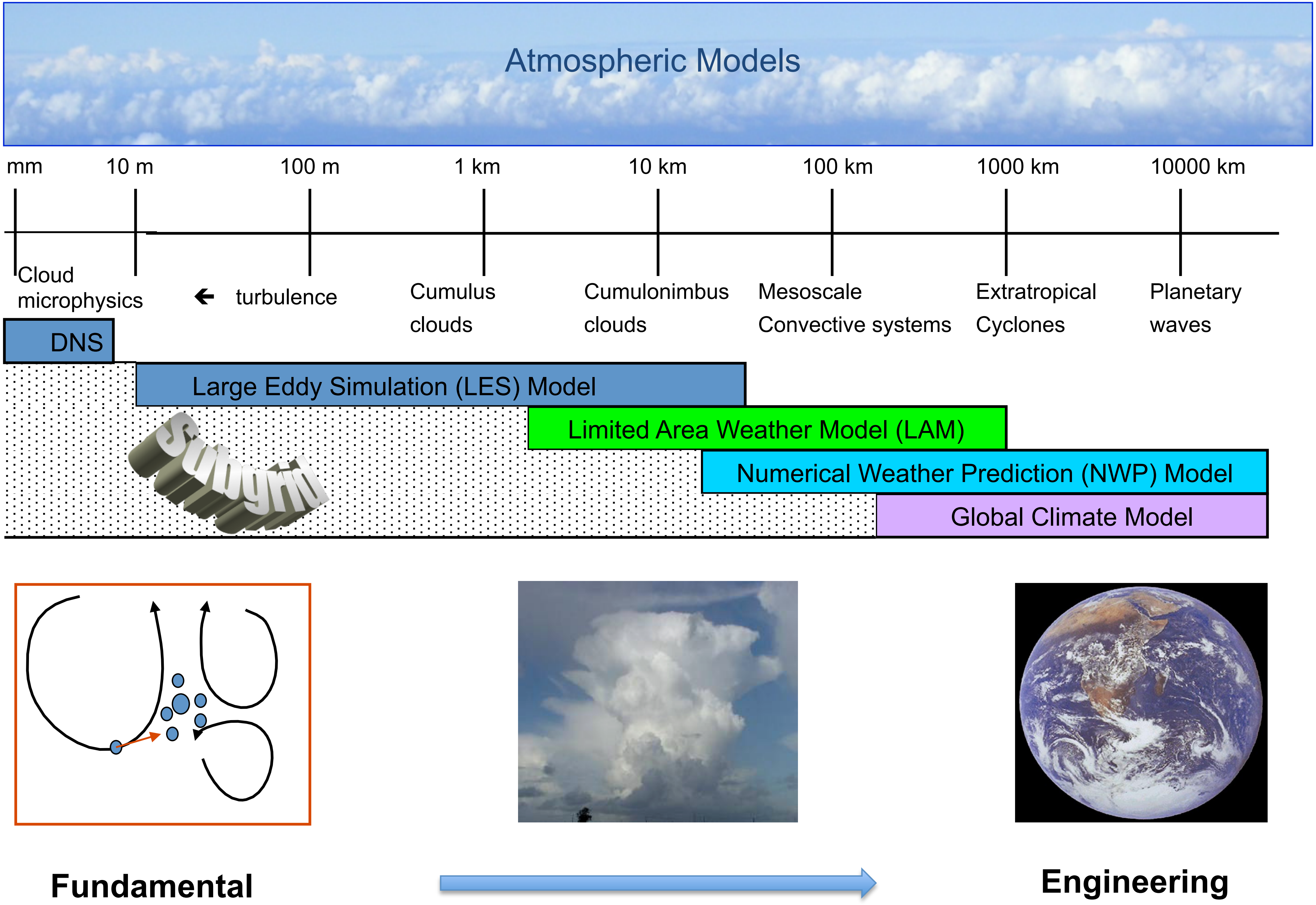
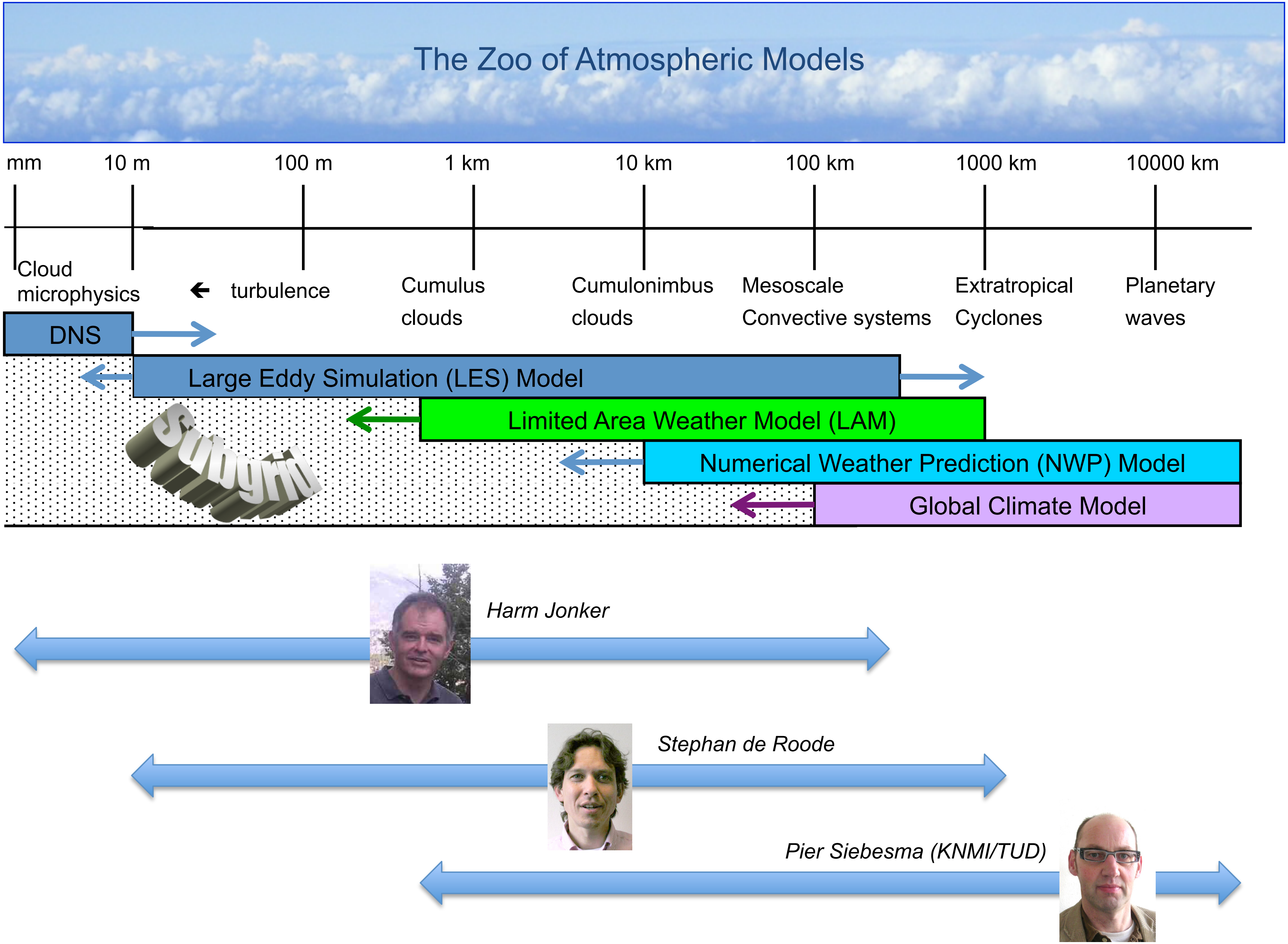
TU Delft
EUCLIPSE
Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



Atmospheric Models
mm
10 m
100 m
1 km
10 km
100 km
1000 km
10000 km
Cloud microphysics
turbulence
Cumulus clouds
Cumulonimbus clouds
Mesoscale Convective systems
Extratropical Cyclones
Planetary waves
DNS
Large Eddy Simulation (LES) Model
Limited Area Weather Model (LAM)
Numerical Weather Prediction (NWP) Model
Global Climate Model
Subgrid
Fundamental
Engineering


The Zoo of Atmospheric Models
mm
10 m
100 m
1 km
10 km
100 km
1000 km
10000 km
Cloud microphysics
turbulence
Cumulus clouds
Cumulonimbus clouds
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Numerical Weather Prediction (NWP) Model
Global Climate Model
Subgrid
Harm Jonker
Stephan de Roode
Pier Siebesma (KNMI/TUD)

NATURE GEOSCIENCE DOI: 10.1038/NGEO1580

Box 1 | Updated energy balance

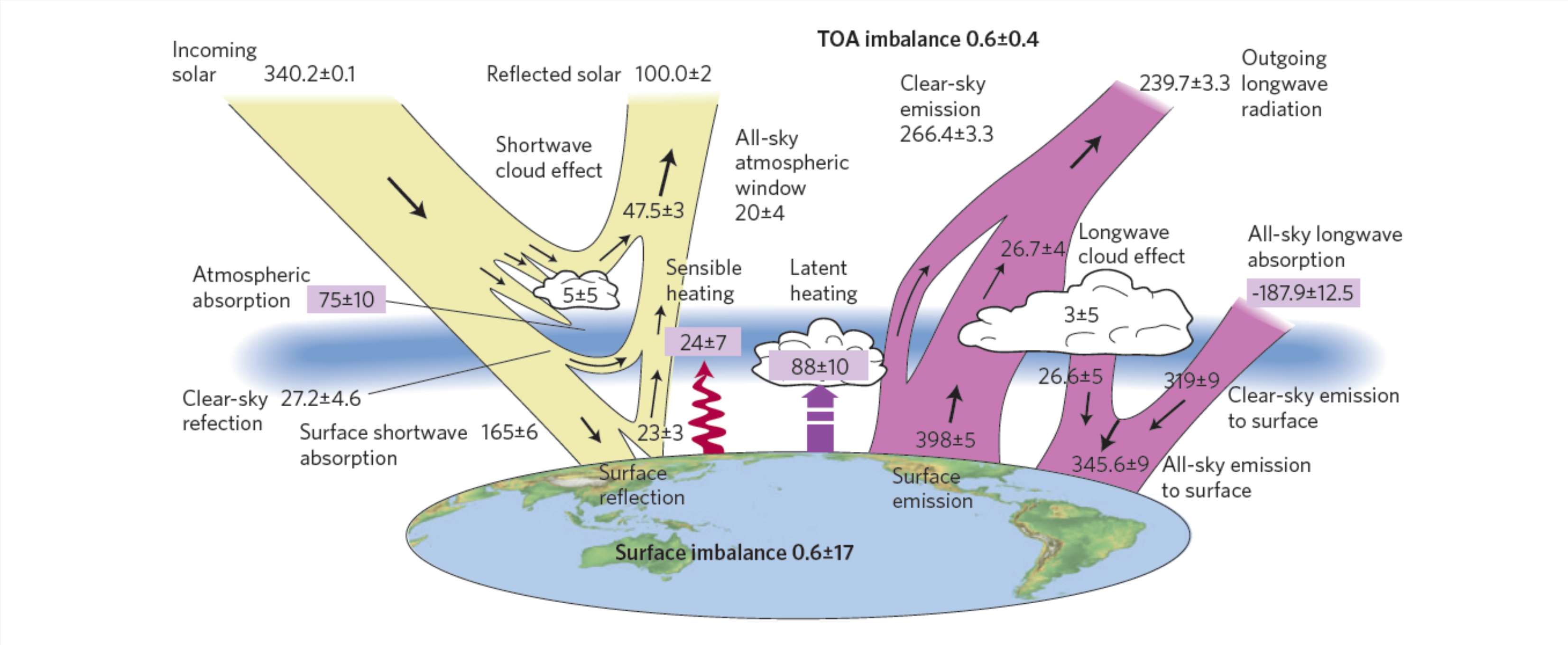
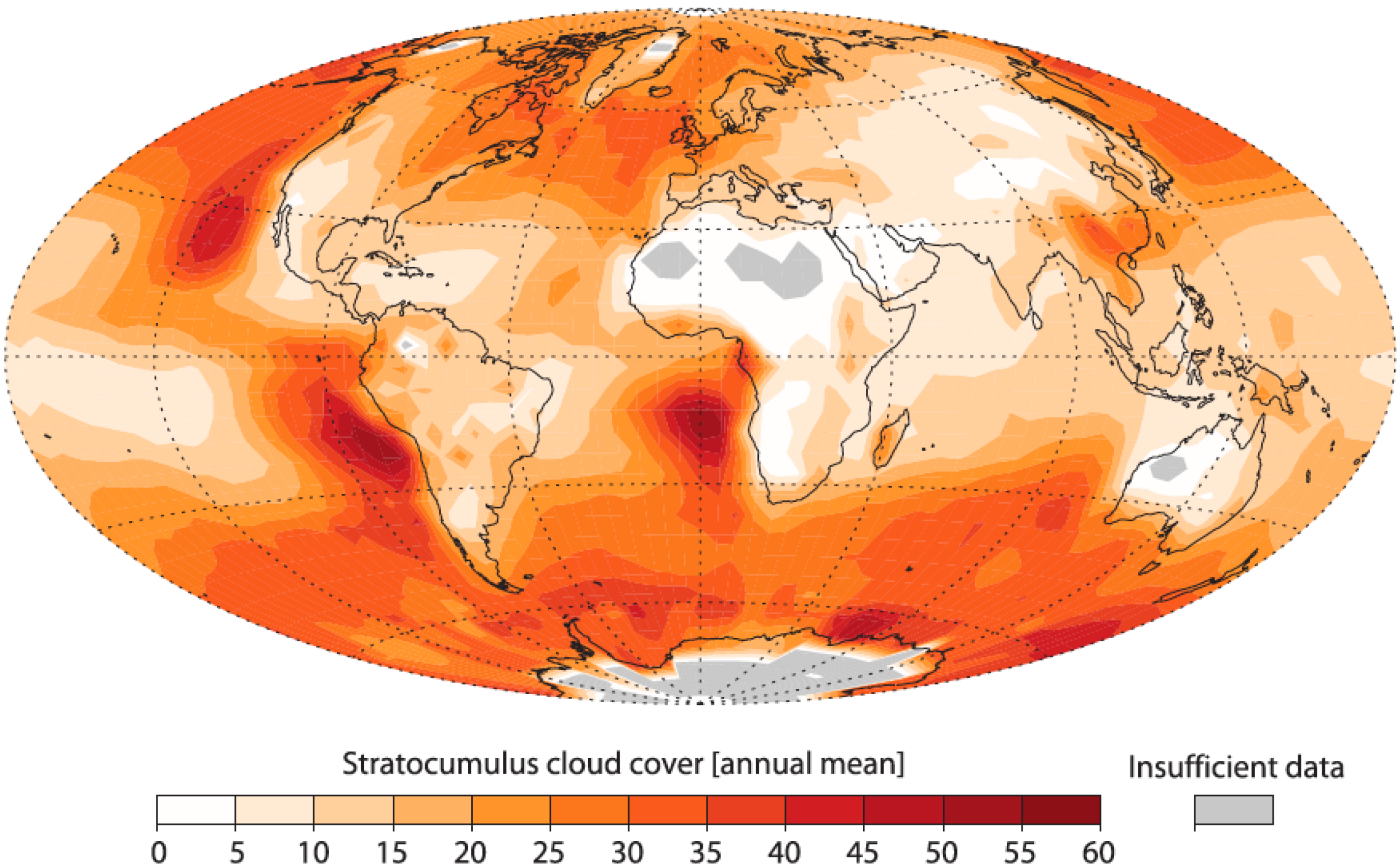


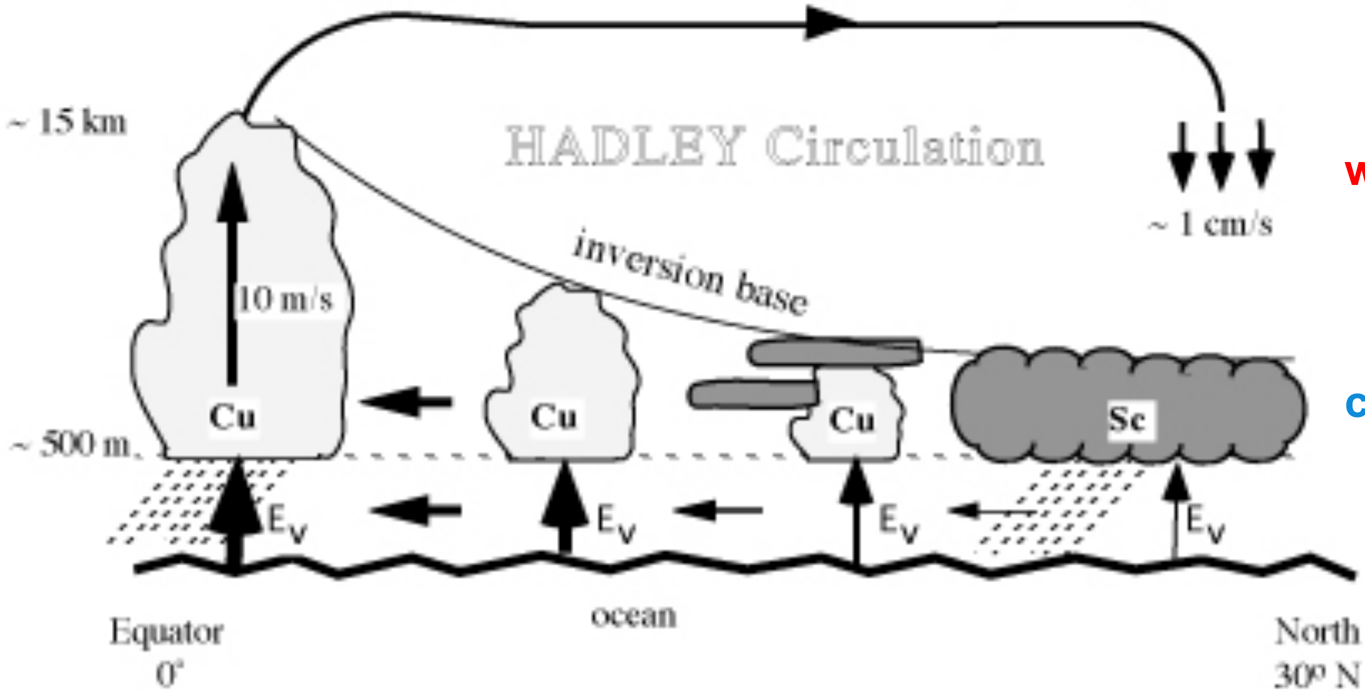
Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.

Stephens et al., 2012



adapted from Hahn and Warren (2007) by Wood (2012)

Clouds in the Hadley circulation



warm and dry

cold and moist

deep convection

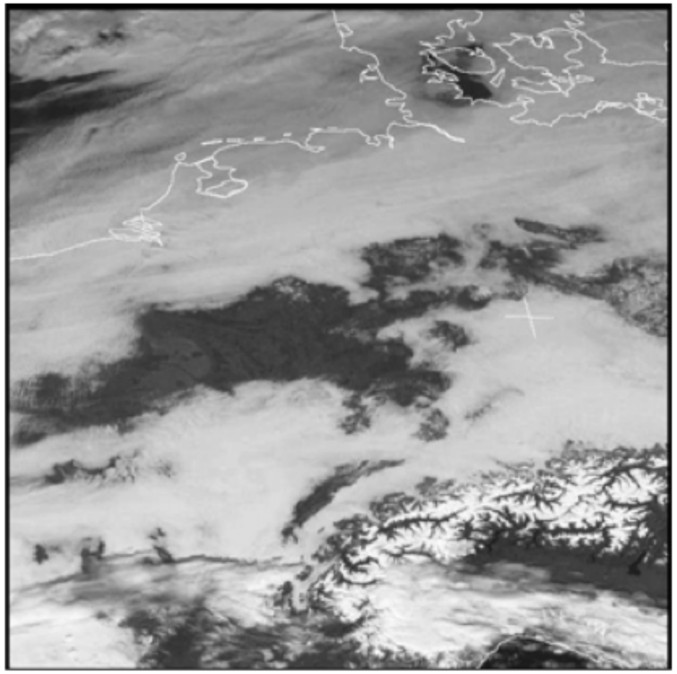
shallow cumulus

stratocumulus

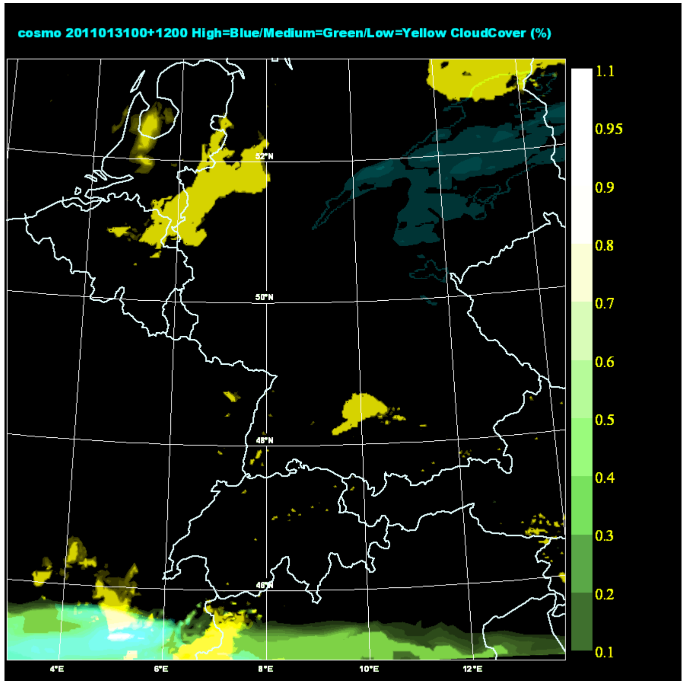
Stratocumulus and weather

Observed stratocumulus case, 31 January 2011, 12 UTC

satellite

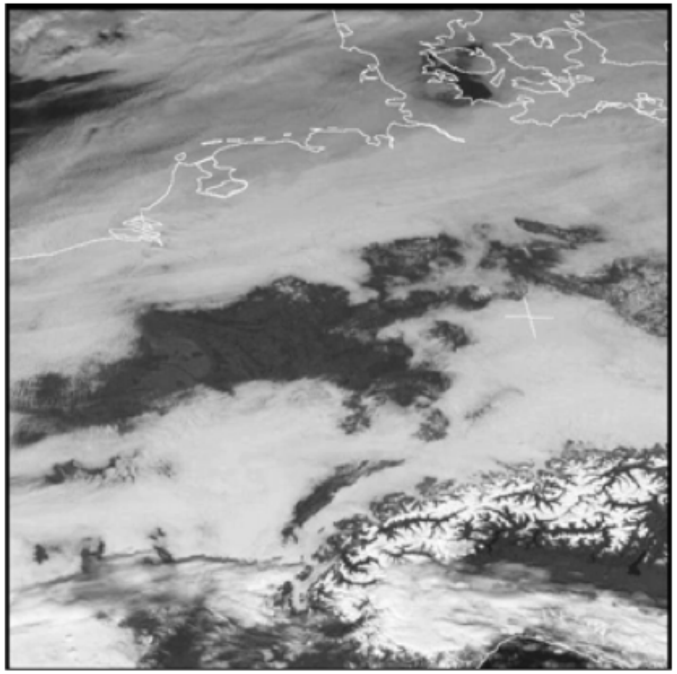


German weather forecast model COSMO

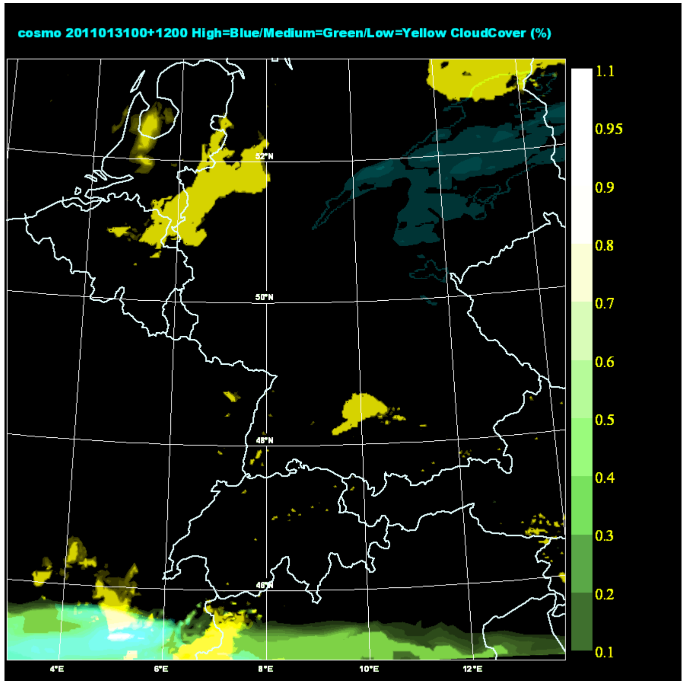


Observed stratocumulus case, 31 January 2011 12 UTC
Not predicted by DWD, ECMWF, KNMI, Meteo France.

satellite



German weather forecast model COSMO

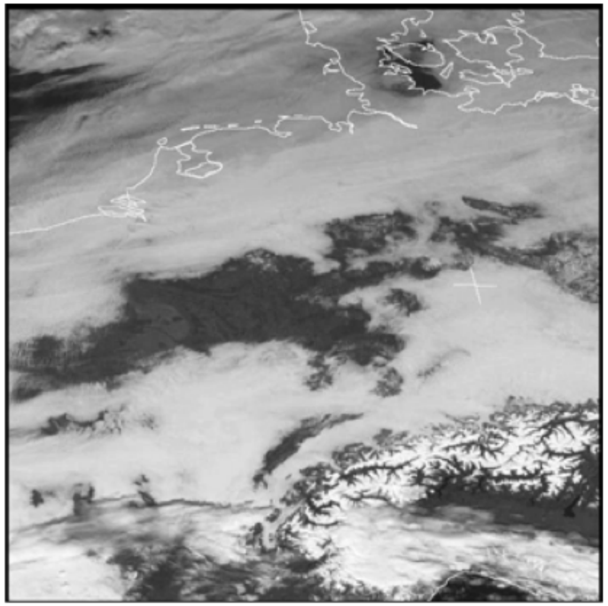


Sander Tijm (KNMI) in an email to DWD, ECMWF and Meteo France:

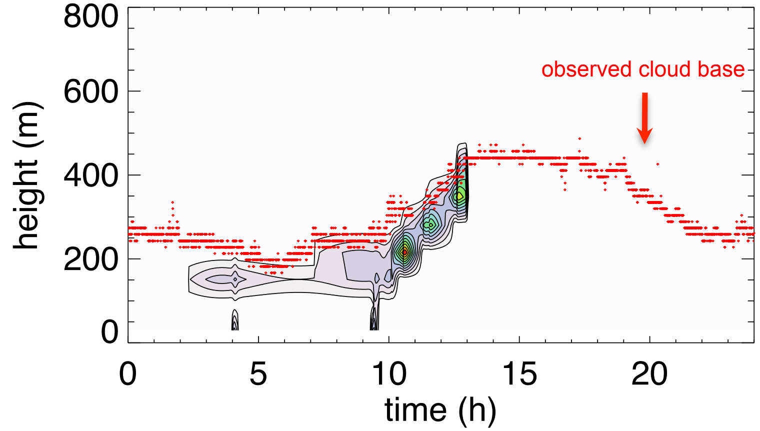
"The missed low clouds and fog have a large impact on the daily cycle of temperature and of course, the forecasters complain about this. In our case it probably also has a large impact on the possibility of freezing rain this afternoon in the southeastern part of the Netherlands, and of course it is also very important for aviation."

Large-Eddy model as a forecasting tool?

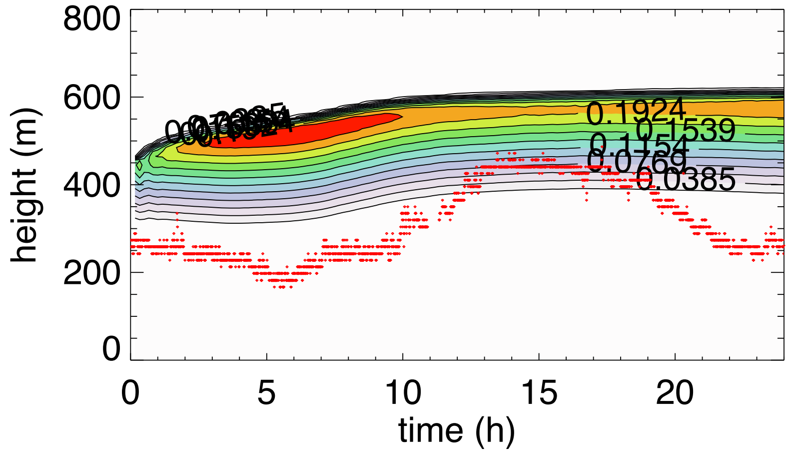
satellite



KNMI weather forecast model

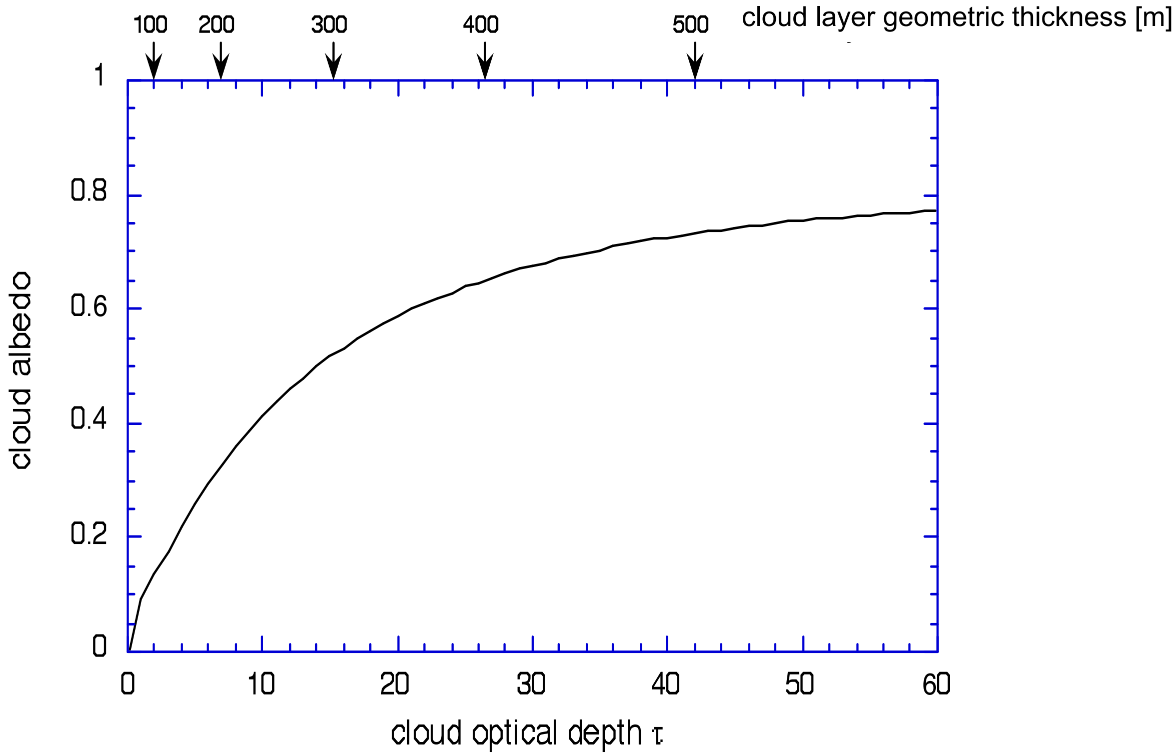


large-eddy simulation model

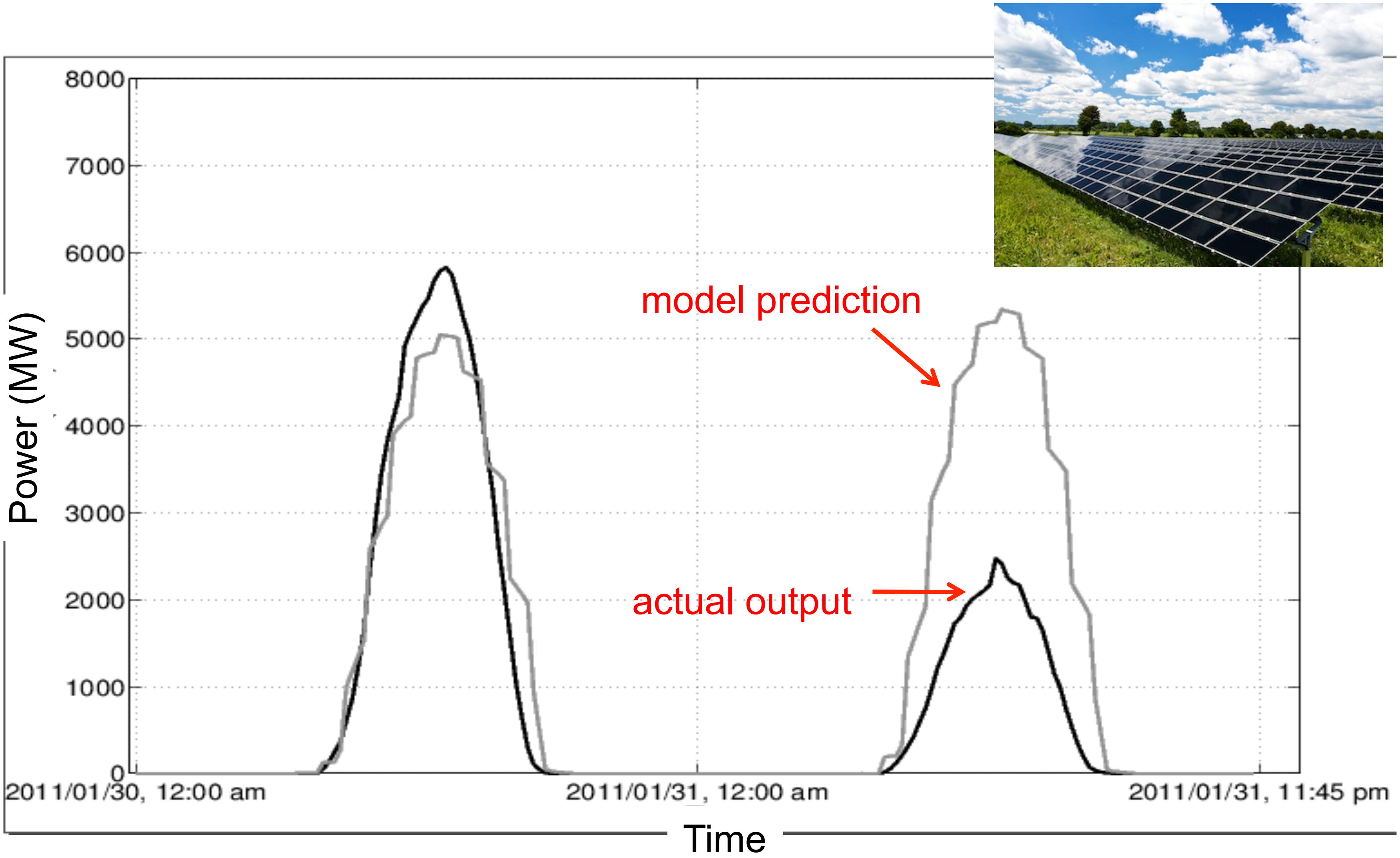


*Jacobs et al.,
2012 (KNMI report)*

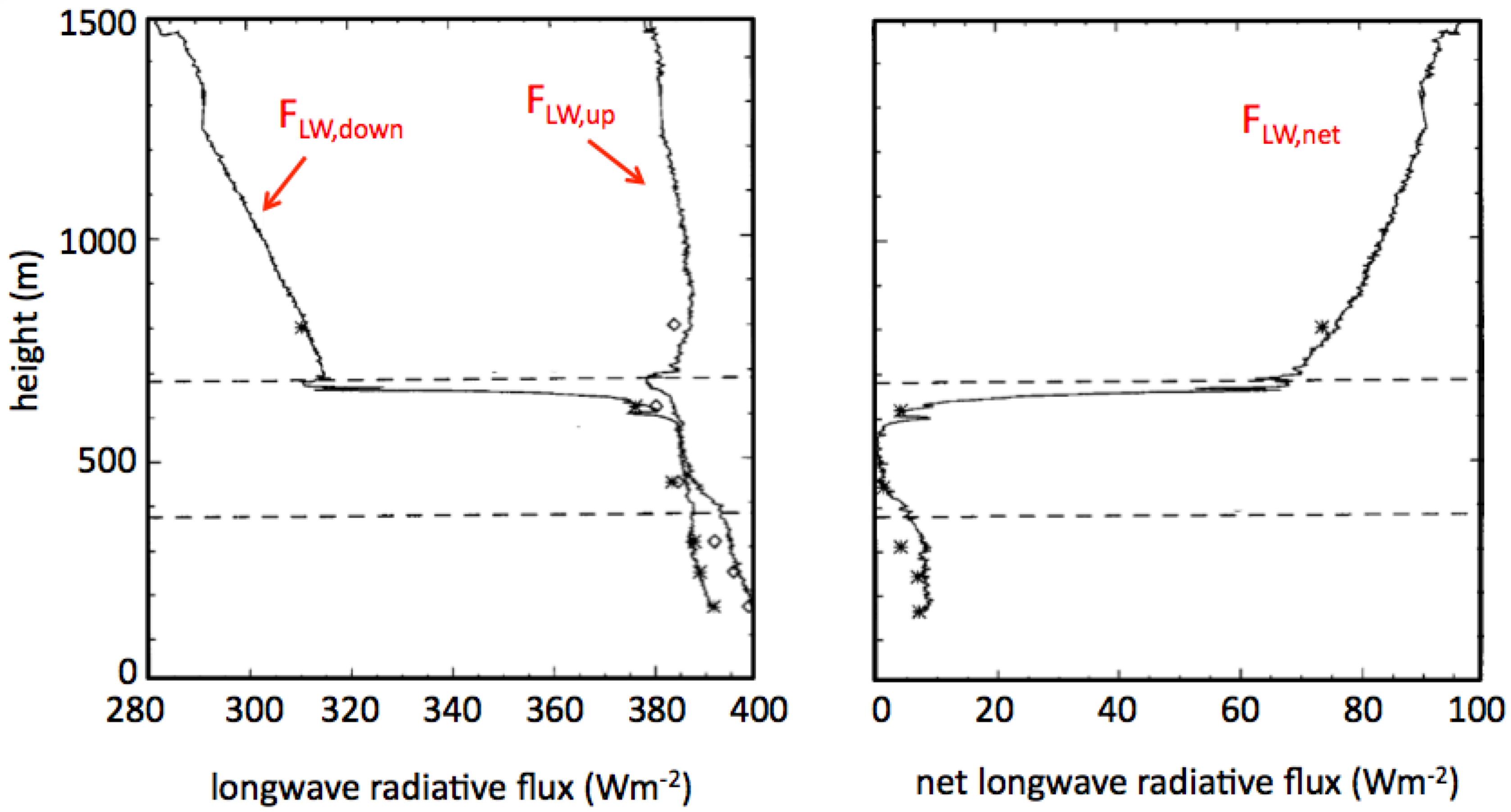
Stratocumulus albedo



Erroneous stratocumulus prediction: Consequences for expected solar radiation in Germany



Stratocumulus and longwave radiation



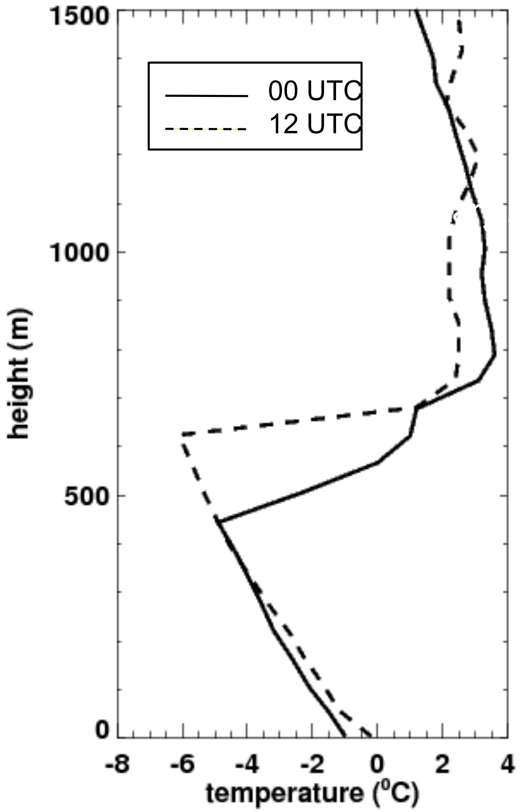
radiative cooling tendency at cloud top ~ -8 K/hr

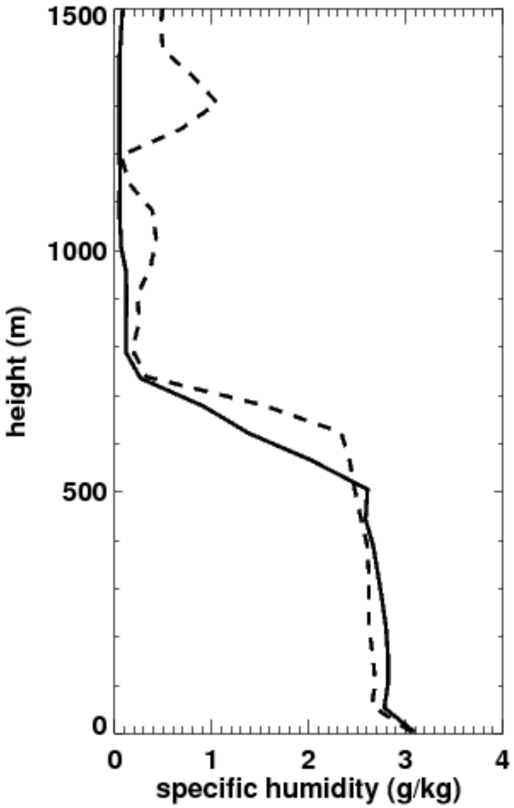
TU Delft

adapted from Duynkerke et al. (1995)

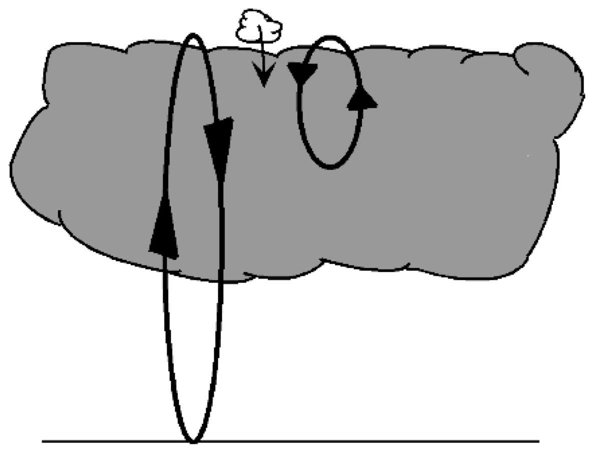
Radiosonde observations in stratocumulus,

De Bilt, 31 January 2011

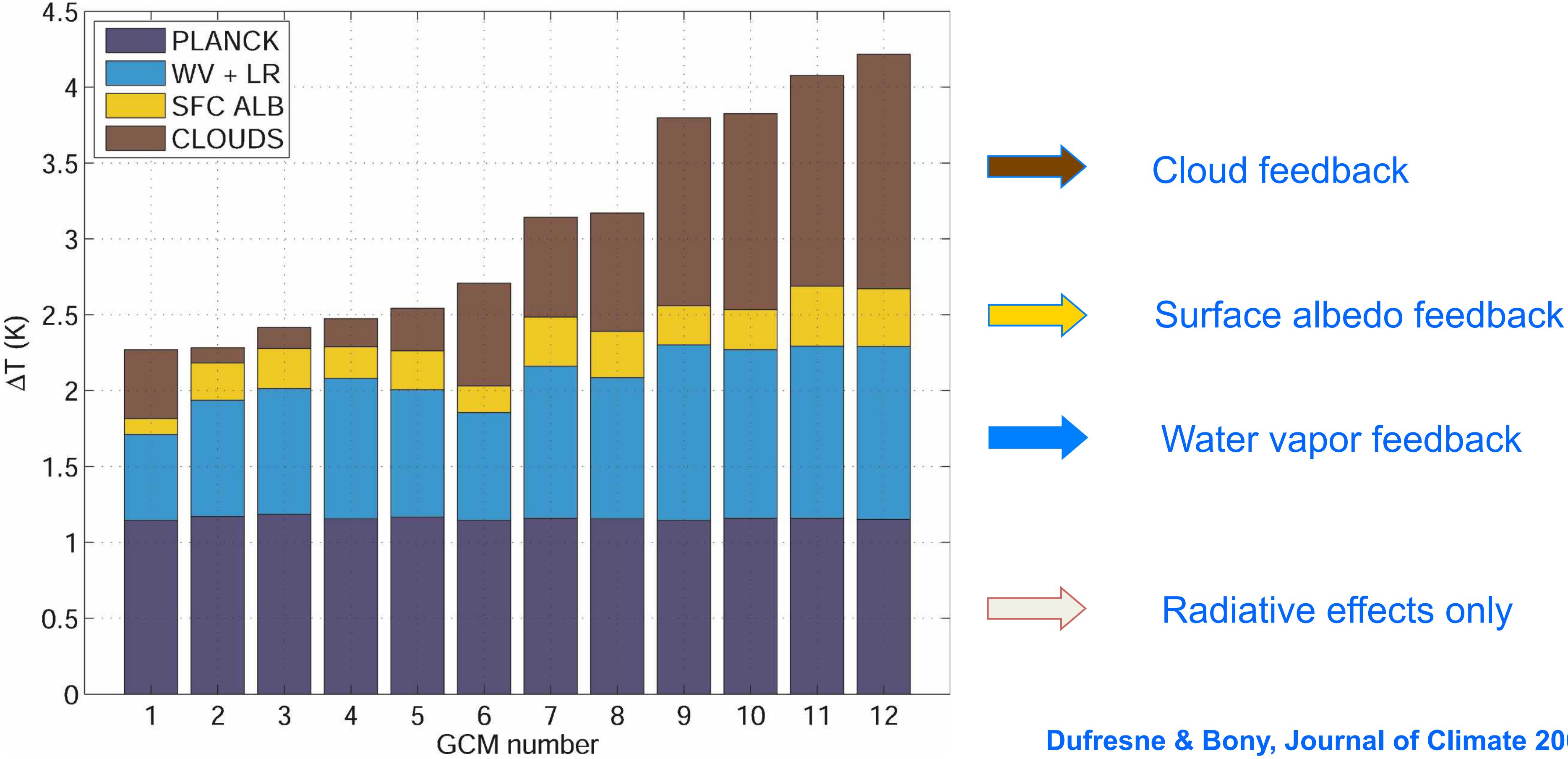




Entrainment of warm and dry air at cloud top

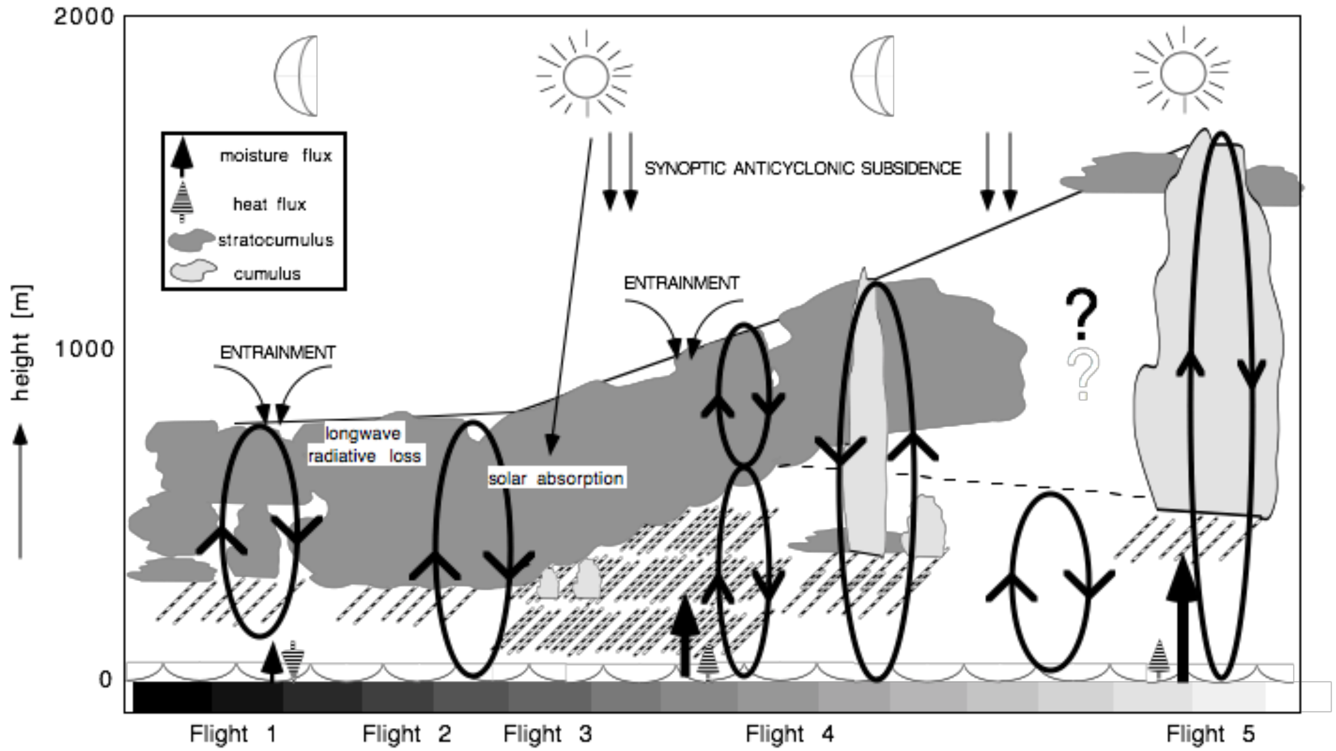


Feedback effects in a changing climate



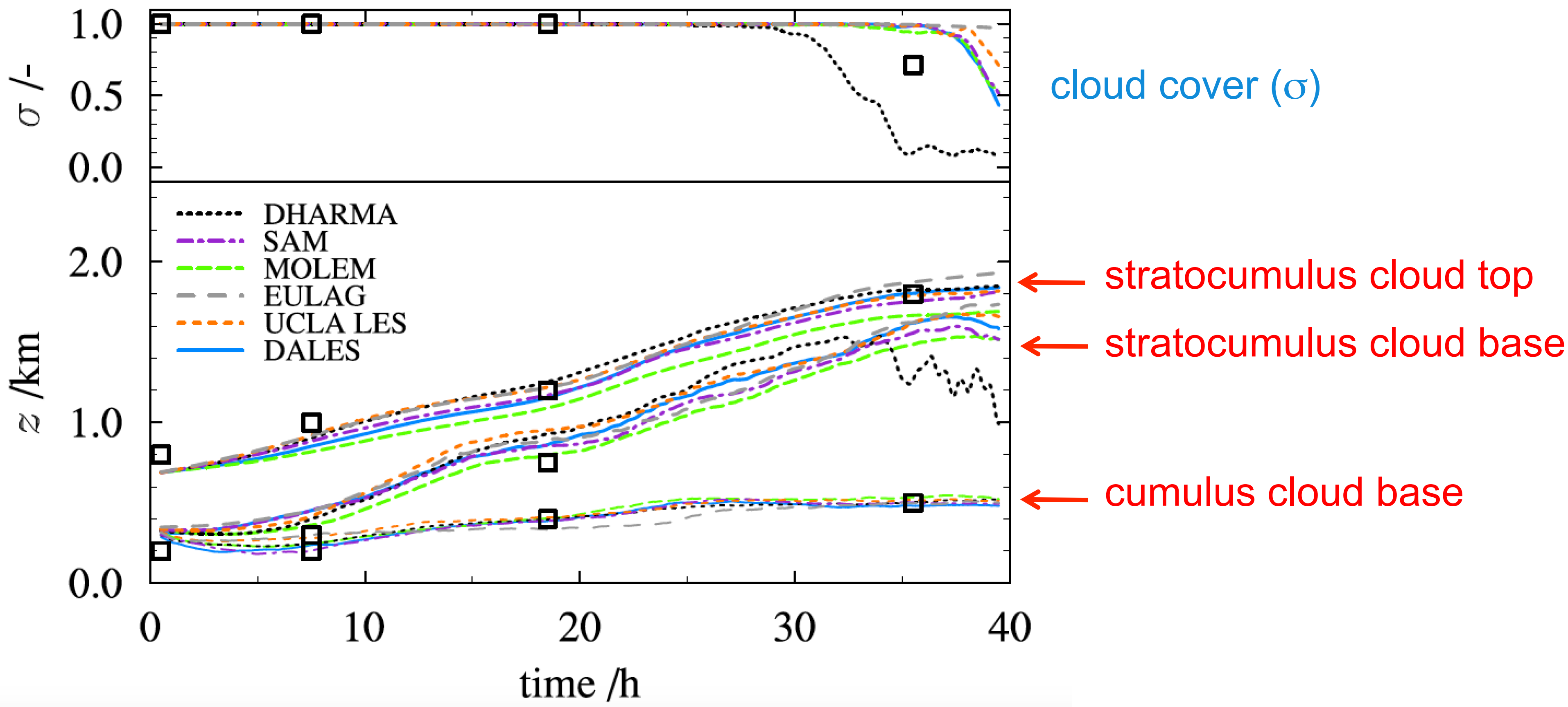
Dufresne & Bony, Journal of Climate 2008

simulating the ASTEX Lagrangian stratocumulus experiment



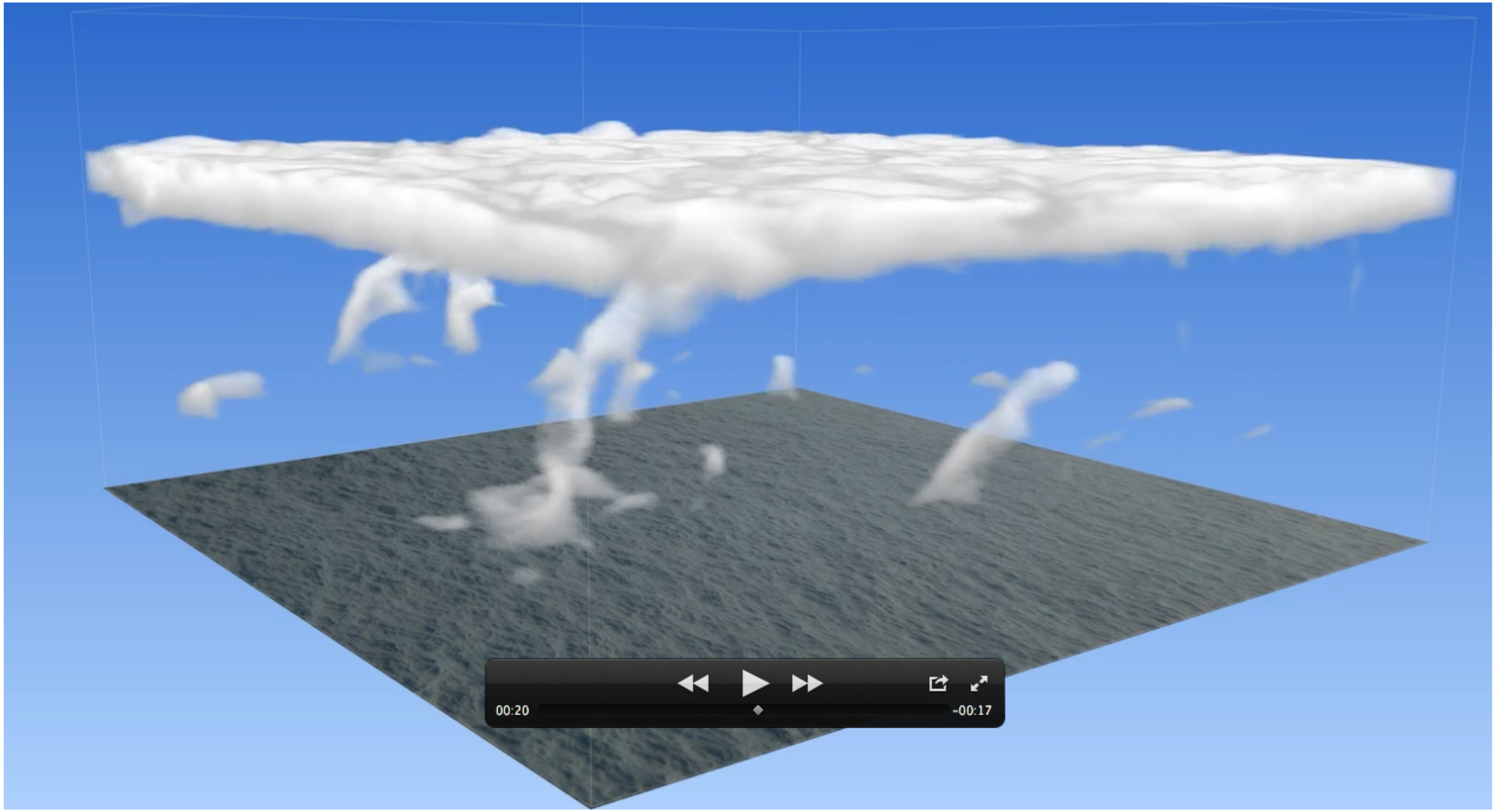
- Case set-up based on De Roode and Duynkerke (1997)
- 20 institutions participated in the model intercomparison case

LES results for the ASTEX case



Van der Dussen et al. (2013)

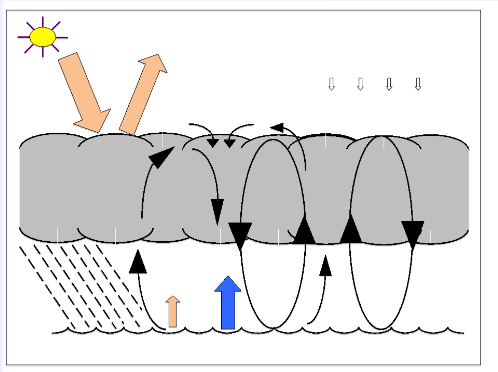
What did we learn from the Lagrangian transition?



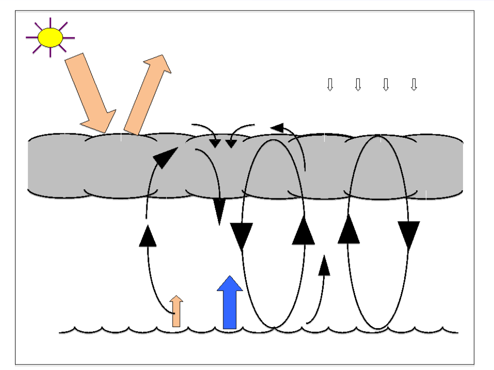
Movie by Johan van der Dussen

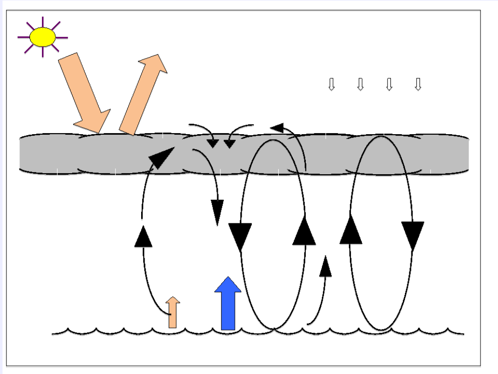
Present

Perturbed Future

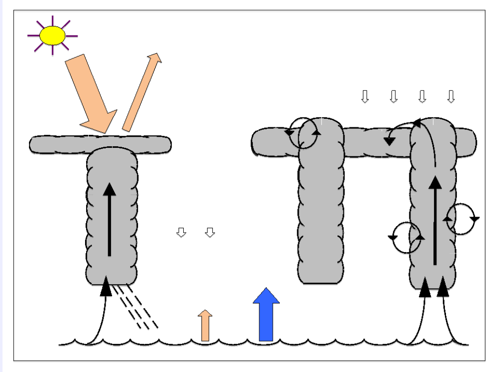


Neg. Feedback





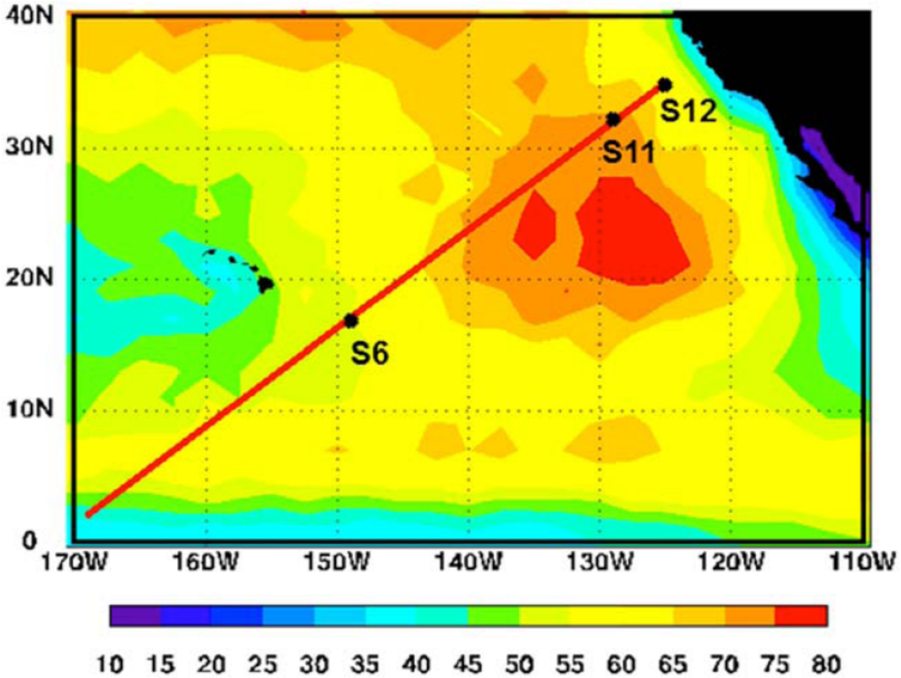
Pos. Feedback



Strong Pos. Feedback

CGILS experiment -
SCM & LES low cloud equilibrium solutions at three fixed locations

average summer low cloud amount



*** control case**

forcing from ERA Interim July 2003

forcing constant in time (no diurnal cycle)

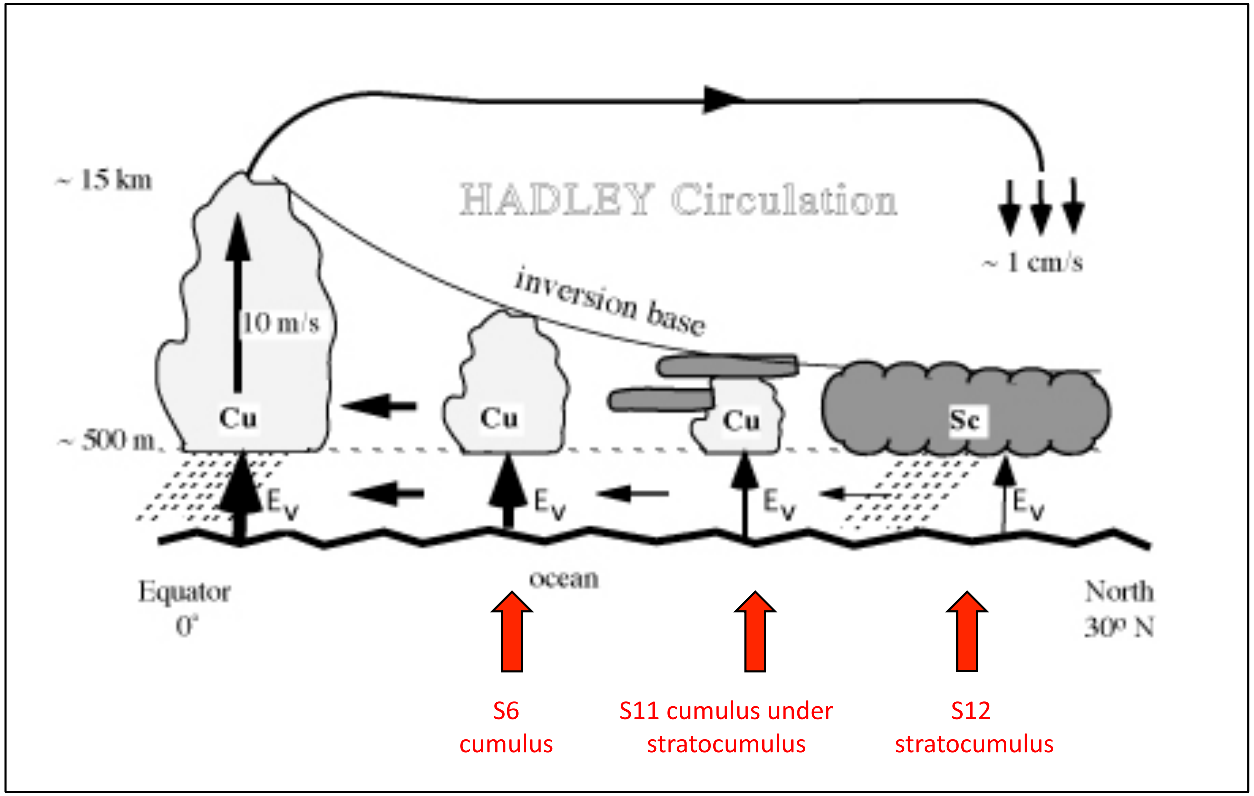
*** perturbed climate**

SST	+ 2K
$T_{\text{free trop}}$	+ 2K
$RH_{\text{free trop}}$	no change

Question: how will cloud amount change?

Zhang et al., 2013

The CGILS project *(Zhang et al. 2013)*



Equilibrium states are computed for three selected columns in the Hadley circulation

  * Single-column model (SCM) versions of climate models

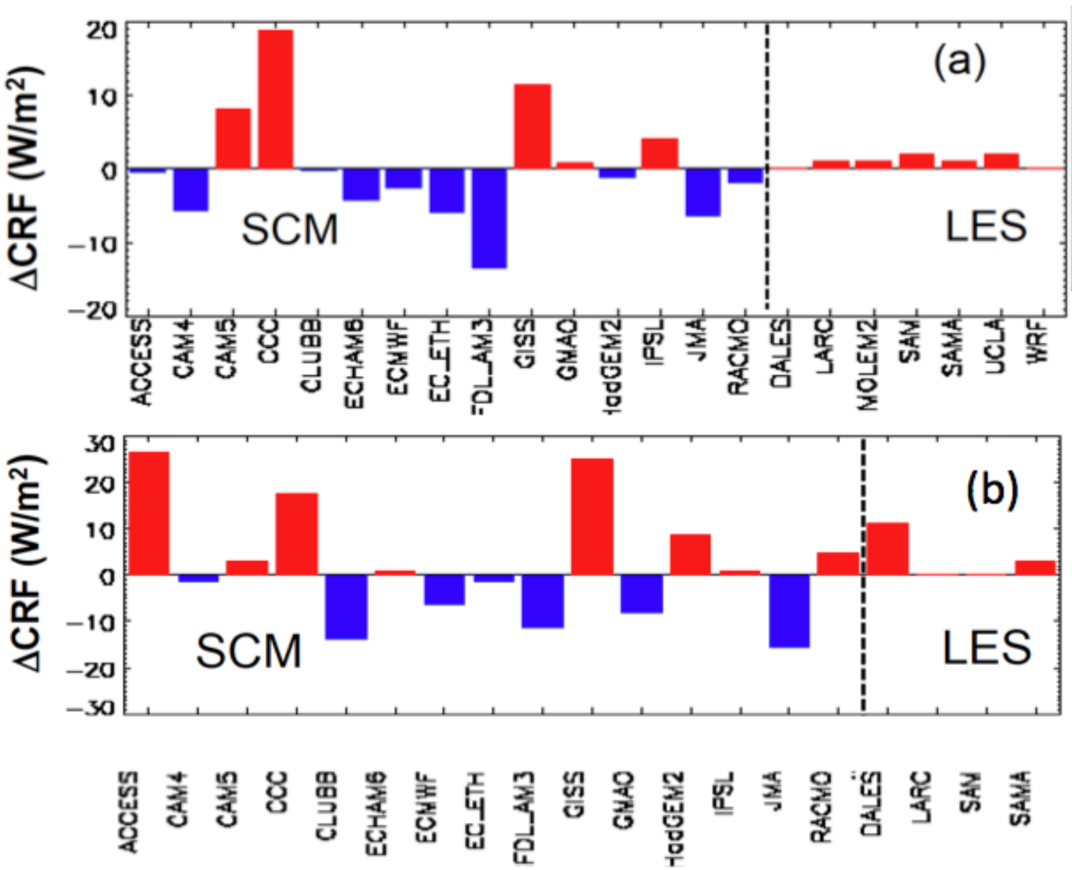
  * Large-eddy simulation (LES) models

- Run to steady state with diurnally-averaged insolation

Cloud Radiative Feedback (CRF) if the large-scale forcing is perturbed (higher sea surface temperature)

S12 stratocumulus

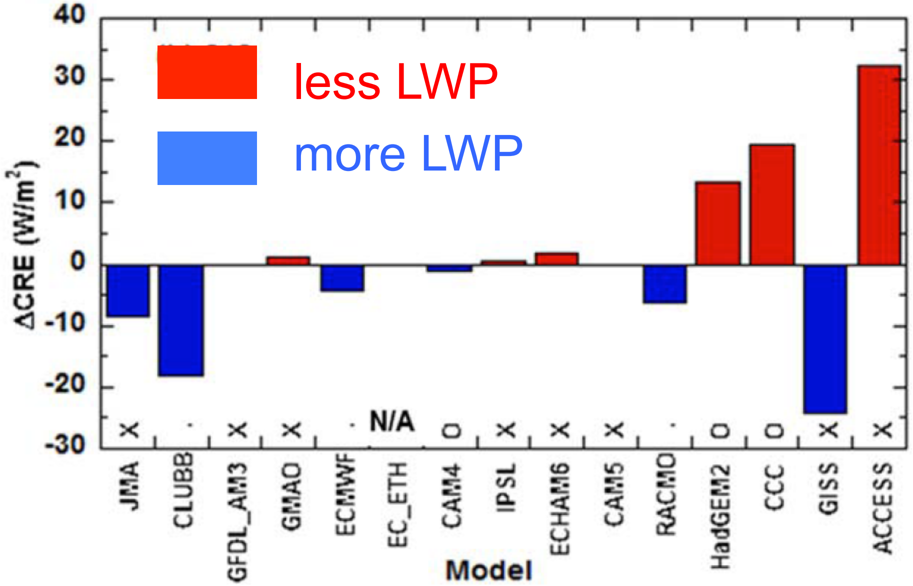
S11 cumulus under stratocumulus



red = positive feedback

blue= negative feedback

CGILS SCM results at stratocumulus location ("S12")

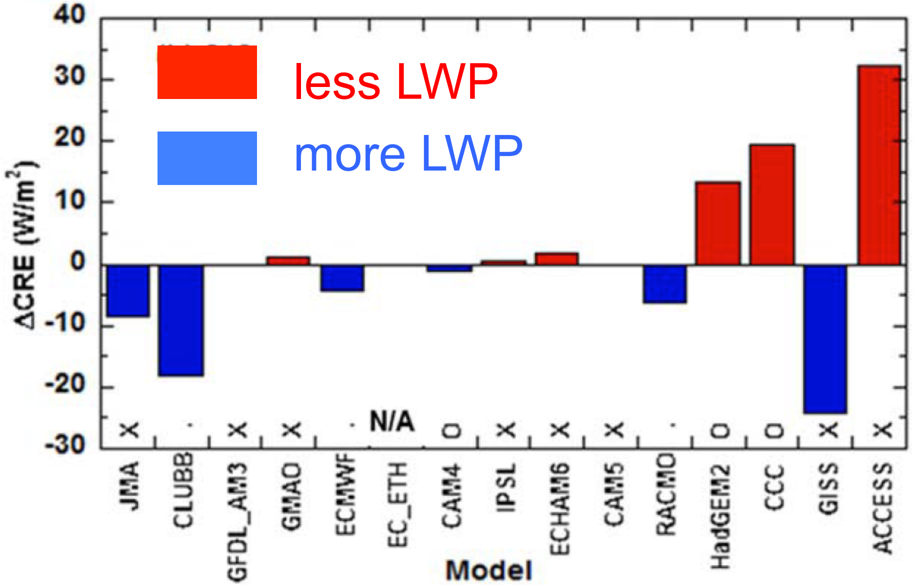


Zhang et al., 2013

Model_ID	SH	LH
ACCESS	13.8 (−5.8)	58.9 (−2.8)
CAM4	24.7 (−0.6)	48.3 (4.6)
CAMS	−6.0 (0.2)	2.9 (0.3)
CCC	26.6 (−3.6)	54.4 (13.1)
CLUBB	25.8 (−1.6)	64.7 (11.4)
ECHAM6	−22.8 (1.9)	62.2 (2.9)
ECMWF	10.1 (−3.7)	68.1 (15.4)
EC_ETH*	−27.9 (43.7)	1.5 (32.8)
GFDL_AM3	−4.8 (1.1)	18.9 (2.6)
GISS	11.3 (−0.5)	59.9 (10.7)
GMAO	1.3 (0.2)	35.5 (2.1)
HadGEM2	17.0 (−1.8)	61.2 (7.2)
IPSL	25.0 (−1.6)	66.4 (5.4)
JMA	27.0 (−0.4)	62.3 (4.9)
RACMO	20.2 (−3.5)	68.2 (11.9)

changes for perturbed climate

CGILS SCM results at stratocumulus location ("S12")



Zhang et al., 2013

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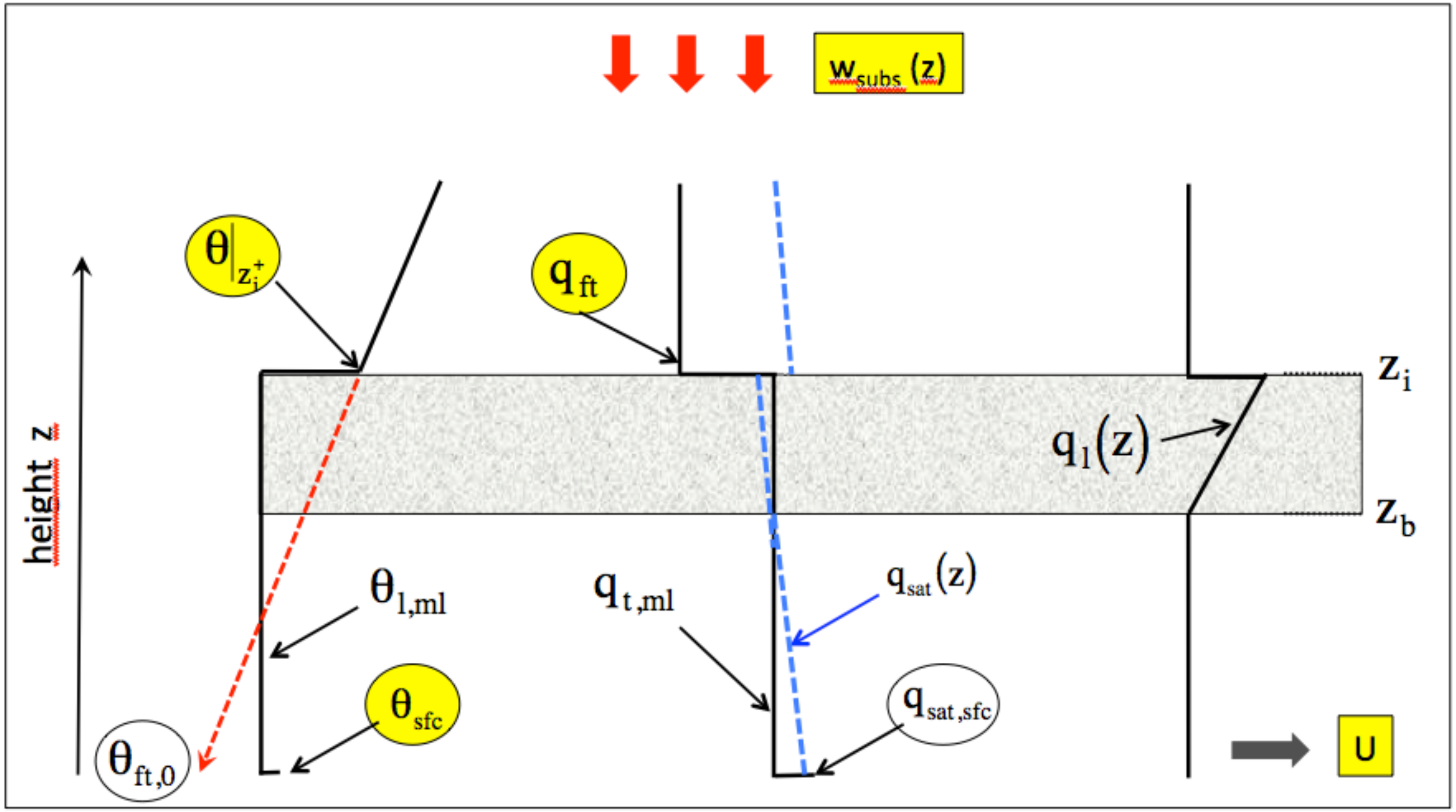
RACMO	20.2 (−3.5)	68.2 (11.9)

changes for perturbed climate

Perturbed climate in SCMs:

* LWP: both larger and smaller results
* Sensible heat flux: mainly smaller
* Latent heat flux: increase

Stratocumulus representation in a mixed layer model

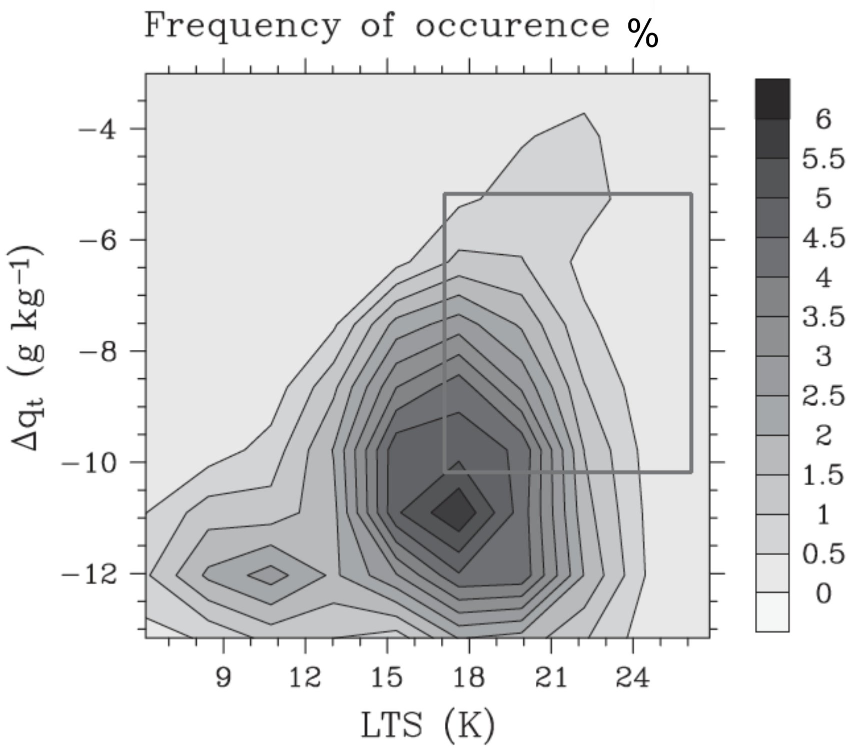


Example: how does stratocumulus respond to changes in the (SST)?

See De Roode et al. (2014, submitted)

Lower Tropospheric Stability and bulk humidity jumps (surface-3km)

ERA-Interim summer results for the NE Pacific Ocean



Gesso et al. (2013)

Control case set-up

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

Mixed-layer model equation and solutions

$$\cancel{z_\mathrm{i}\frac{\partial \psi_\mathrm{ml}}{\partial t}} = C_\mathrm{d} U(\psi_0 - \psi_\mathrm{ml}) + w_\mathrm{e}(\psi|_{z_\mathrm{i}^+} - \psi_\mathrm{ml}) - \Delta S_\psi$$

surface flux

entrainment flux

source term

steady state

Nicholls & Turton
entrainment
parameterization

net radiative cooling
no precipitation
no horizontal advection

Mixed-layer model equation and solutions

$$\cancel{z_\mathrm{i}\frac{\partial\psi_\mathrm{ml}}{\partial t}} = C_\mathrm{d}U(\psi_0 - \psi_\mathrm{ml}) + w_\mathrm{e}(\psi|_{z_\mathrm{i}^+} - \psi_\mathrm{ml}) - \Delta S_\psi$$

surface flux

entrainment flux

source term

steady state

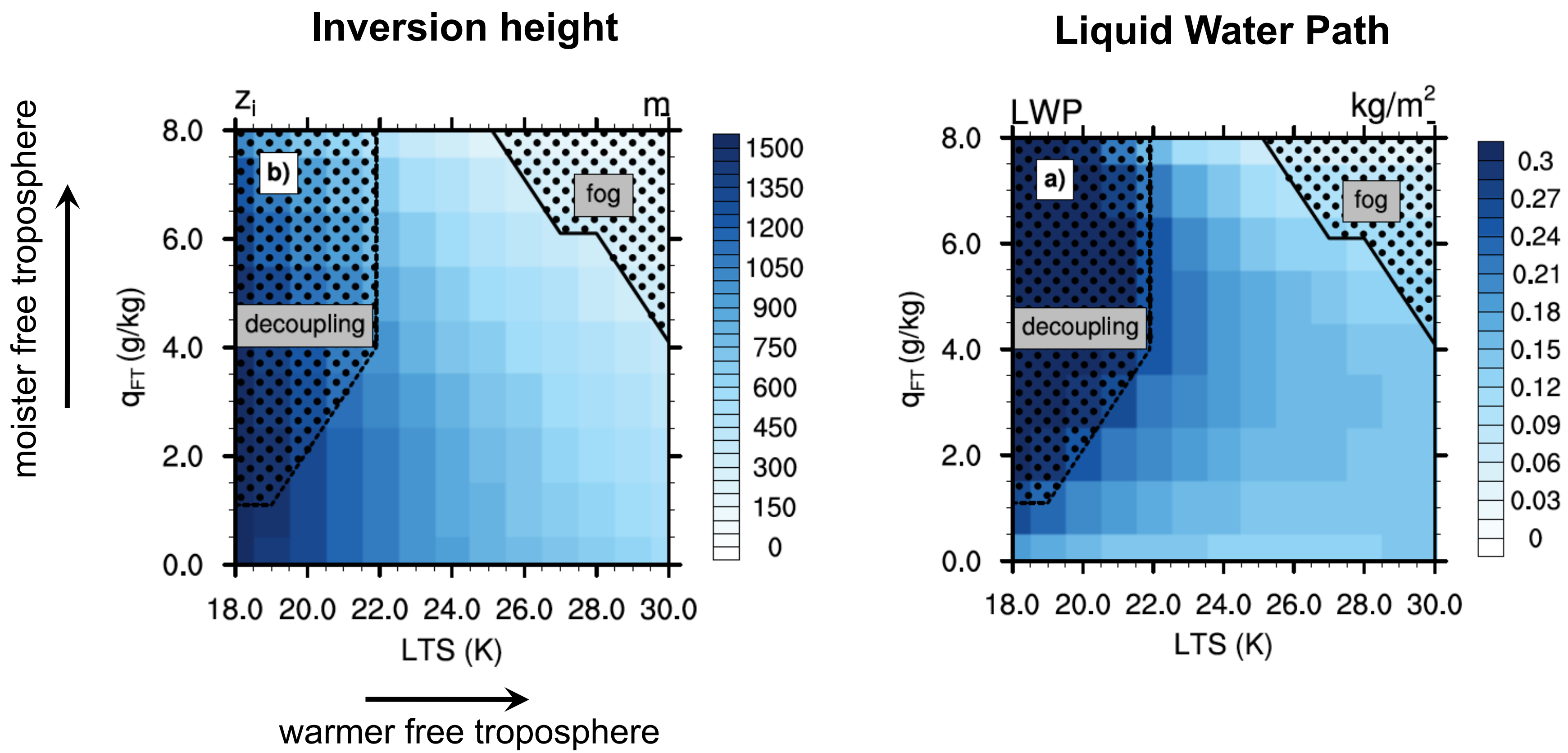
Nicholls & Turton entrainment parameterization

net radiative cooling
no precipitation
no horizontal advection

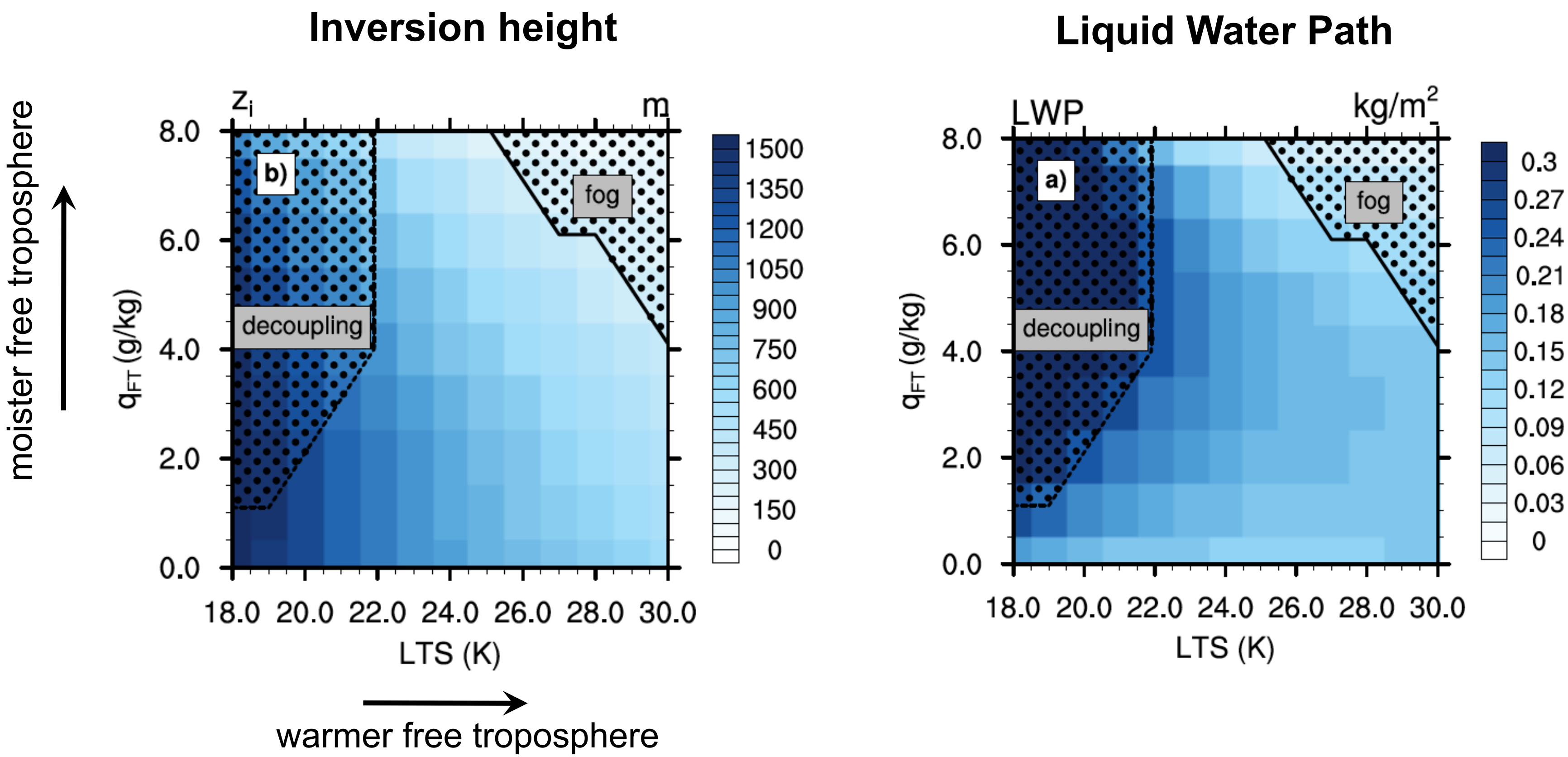
$$\theta_\mathrm{l,ml} = \theta_\mathrm{sfc} + \frac{w_\mathrm{e}(\theta_\mathrm{ft,0} + \gamma_\theta w_\mathrm{e}/D - \theta_\mathrm{sfc}) - \Delta F}{w_\mathrm{e} + C_\mathrm{d}U}$$

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

Control state results



Control state results



$$0 = C_d U\left(\theta_0 - \theta_{l,ml}\right) + w_e\left(\theta_{z_i^+} - \theta_{l,ml}\right) - \Delta F_{rad}$$

decoupled regime

small, negative

large, positive

What happens to the liquid water path if SST is increased?

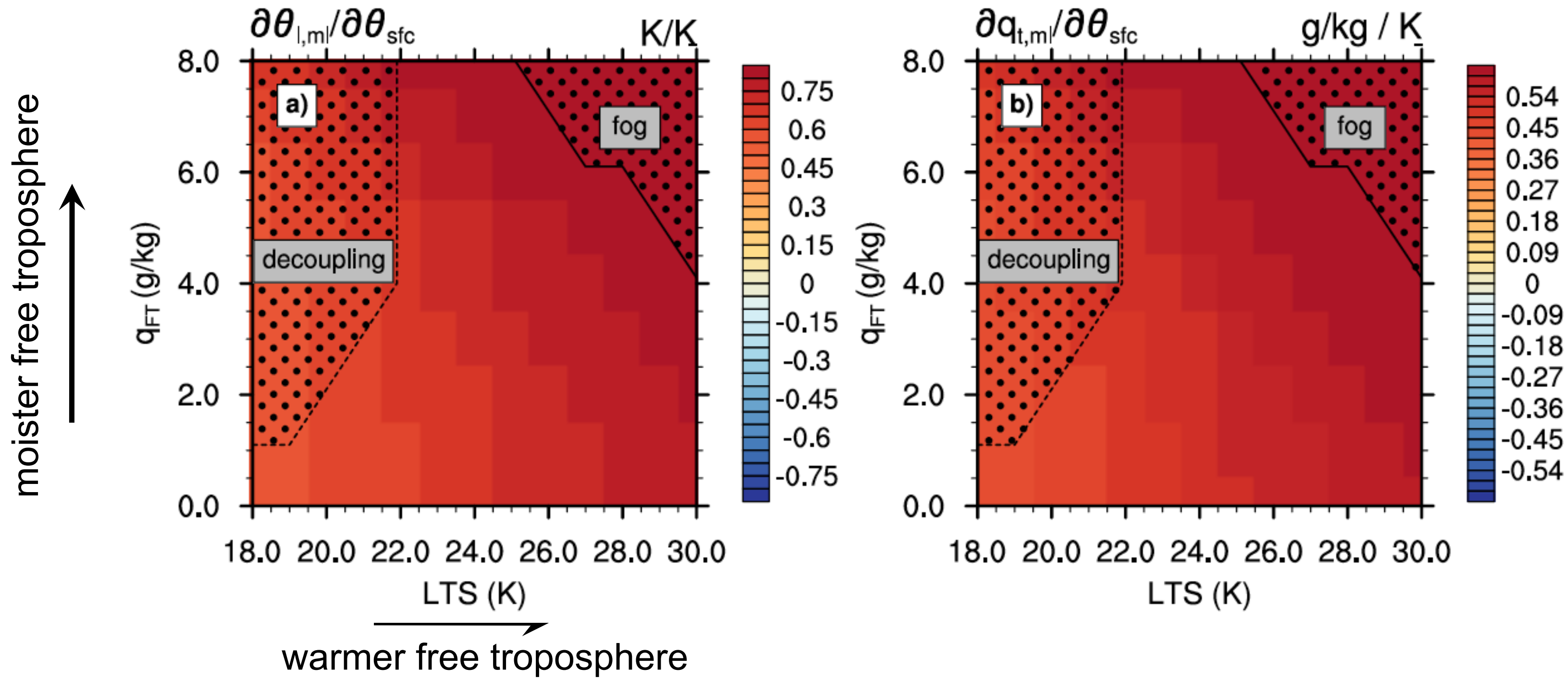
two possible scenarios

Scenario	Dominant effect in BL	LWP change
A.	warming	lower
B.	moistening	higher

Experiment 1: fix the entrainment rate to the control case
Experiment 2: allow entrainment to respond to perturbed forcing

Boundary layer thermodynamic response to increase in SST (θ_{sfc})

* entrainment fixed to control case value

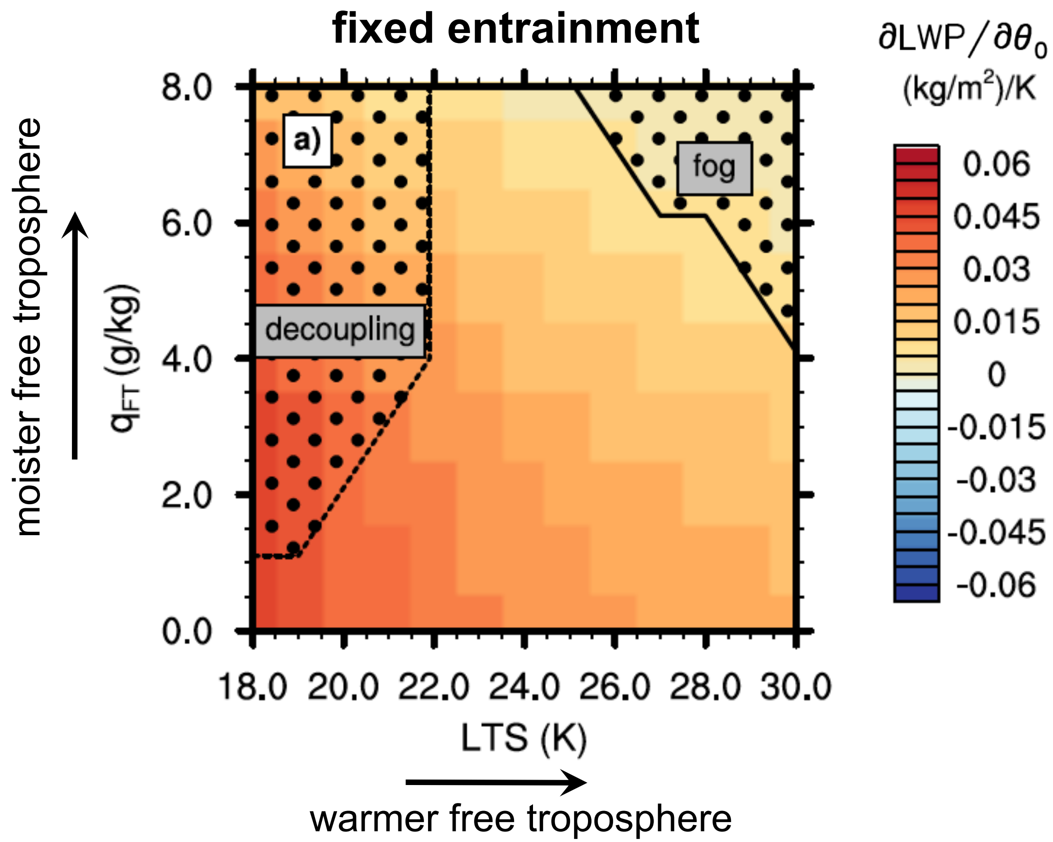


$$\frac{\partial \theta_{l,ml}}{\partial \theta_{sfc}} = \frac{C_d U}{w_e + C_d U} < 1$$ SHF increase

$$\frac{\partial q_{sat,sfc}}{\partial \theta_{sfc}} = 0.76 \quad g/kg/K$$ LHF increase

LWP response to increase in SST (θ_{sfc})

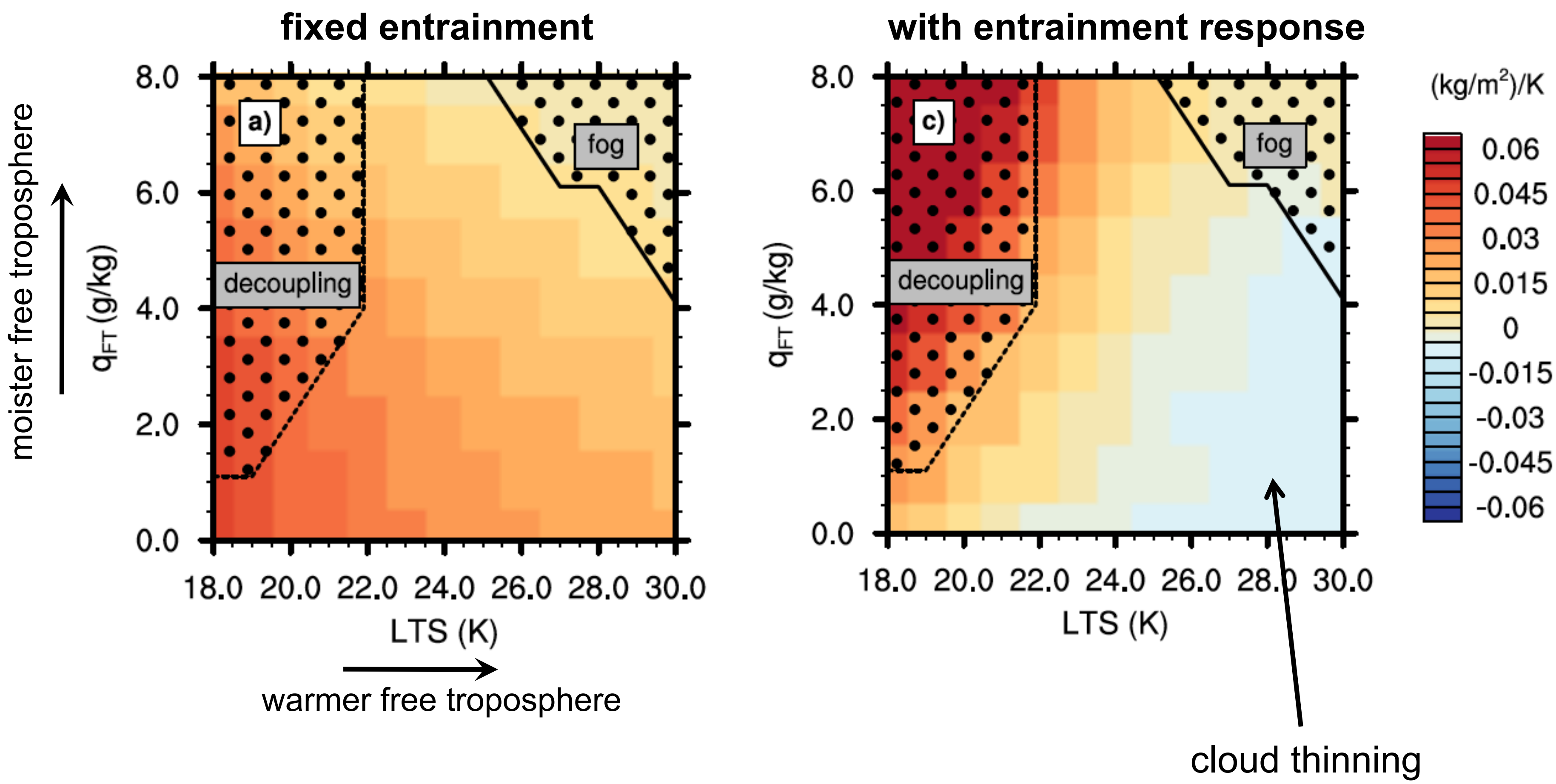
* entrainment fixed to control case value



moistening effect dominates,

more LWP

LWP response to increase in SST (θ_{sfc})

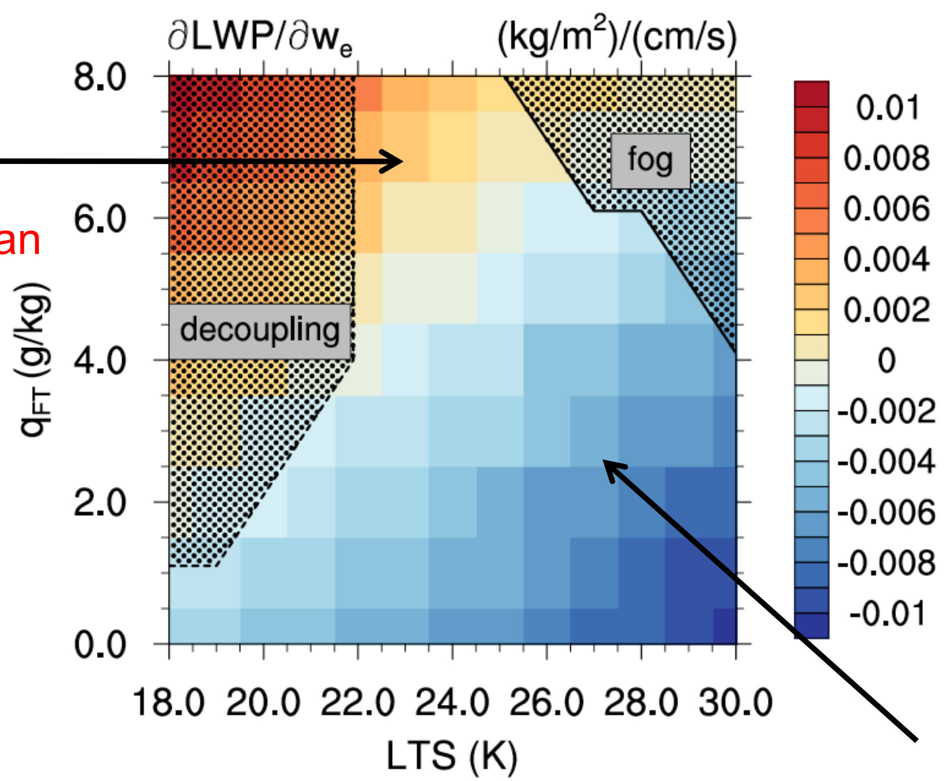


Total LWP response to a change in a cloud controlling factor φ_i

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

cloud thickening

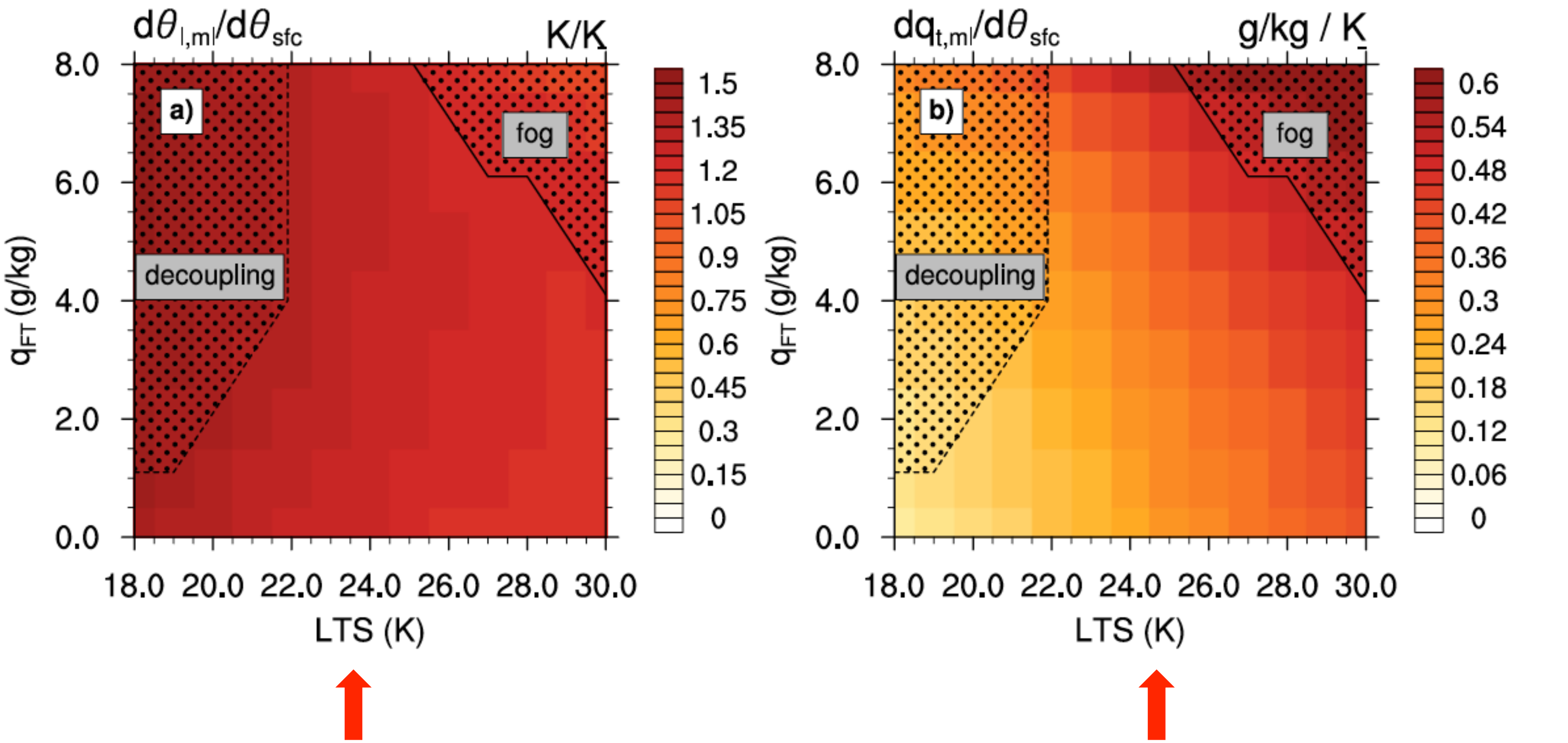
cloud top rises more than cloud base



cloud thinning

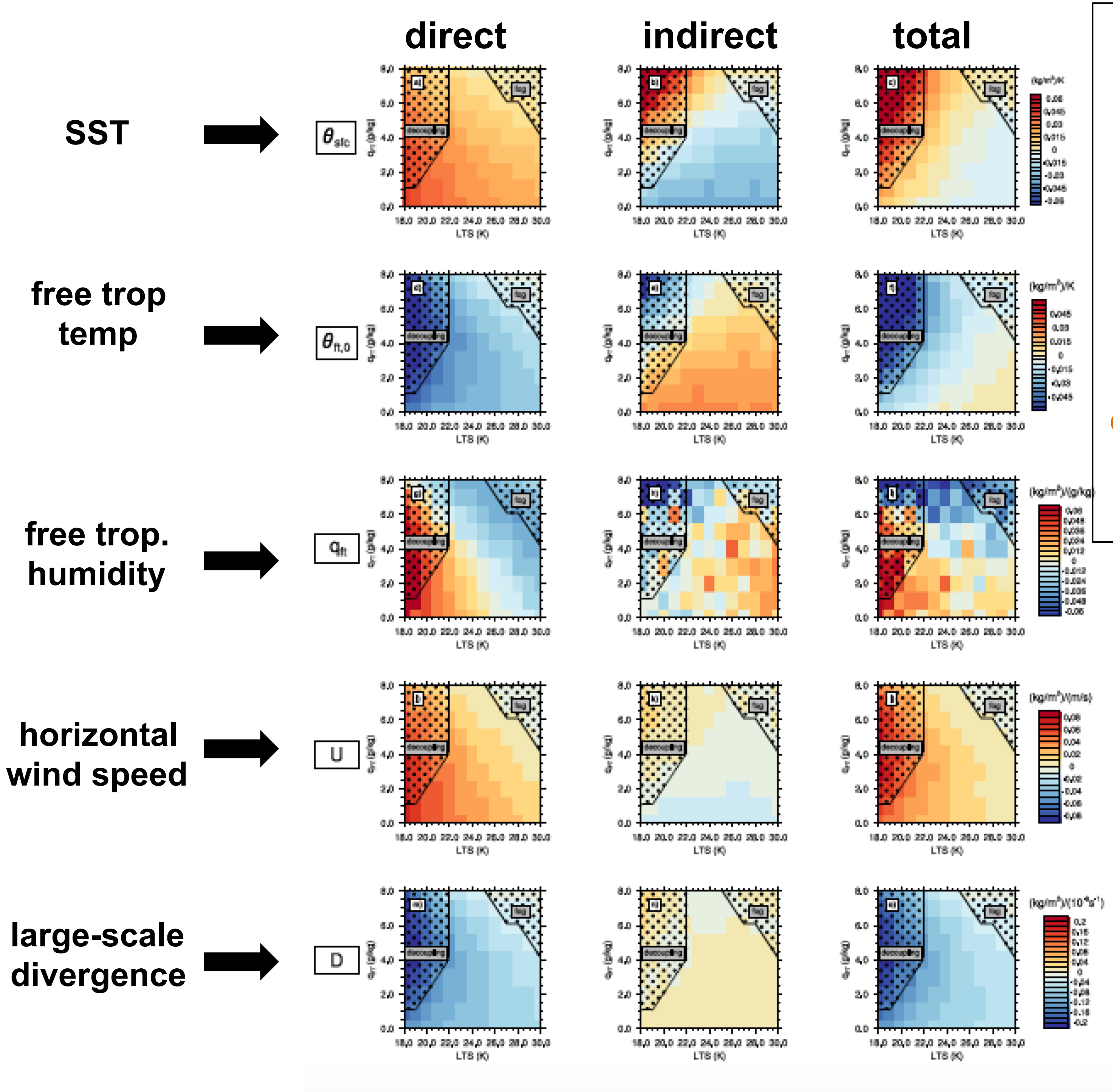
Boundary-layer and surface flux response to SST increase

(including entrainment response)



BL warms more than SST,
so **SHF will decrease**

BL moistening less than at surface,
so **LHF will increase**

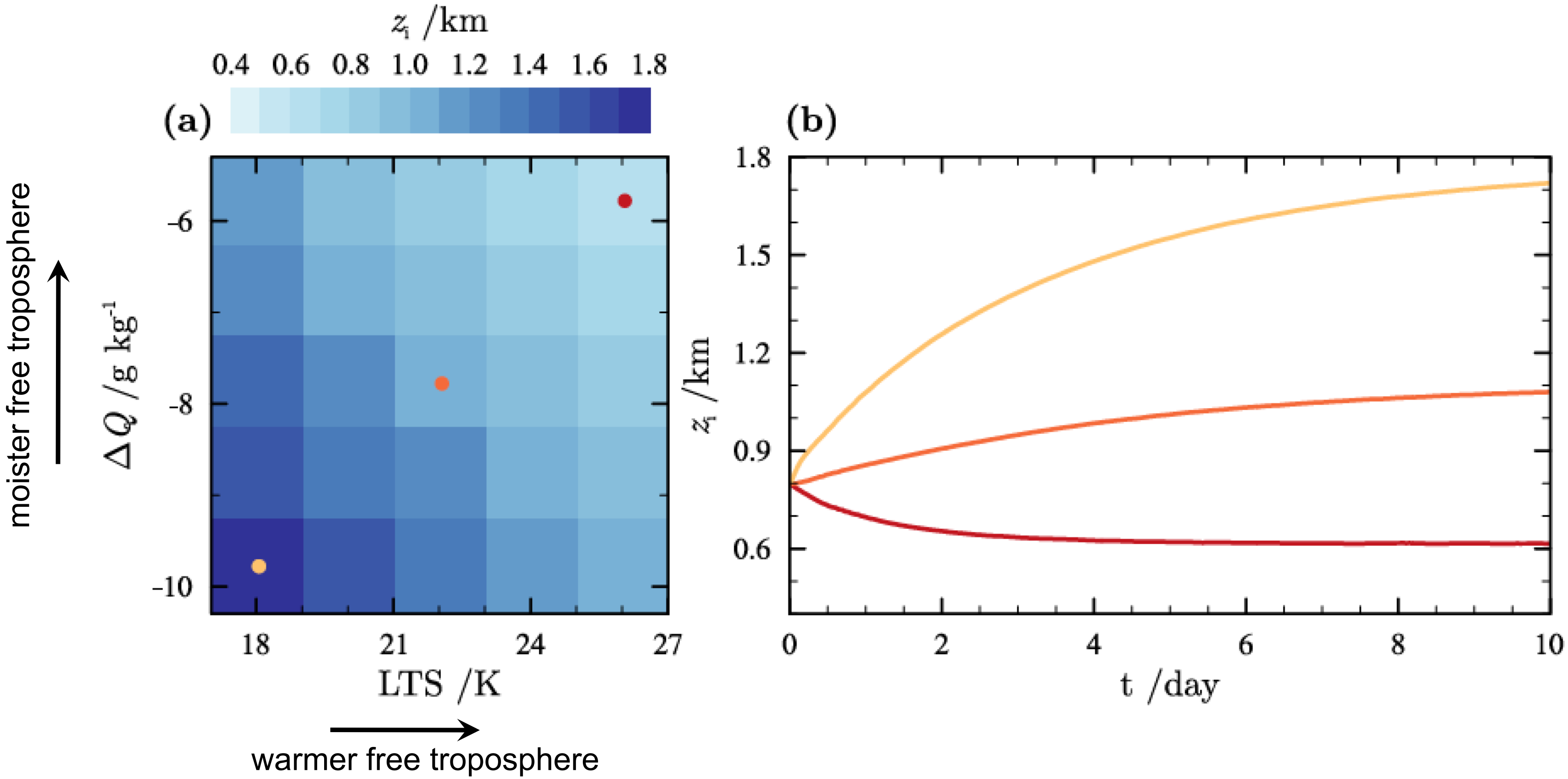


LWP change to an increase in a single forcing term

orange = more LWP

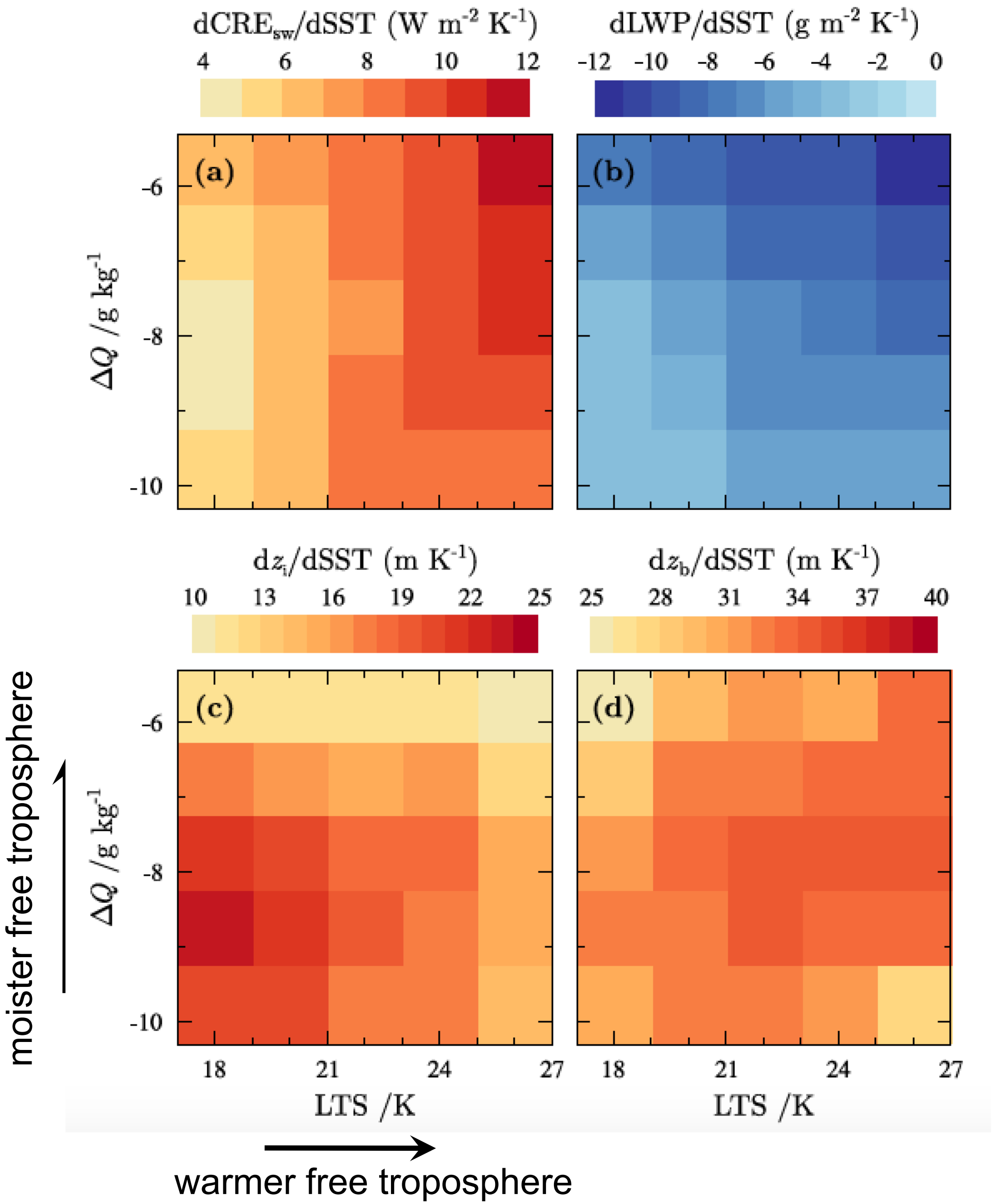
blue = less LWP

LES results



z_i /km
0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
(a)
-6
-8
-10
ΔQ /g kg^{-1}
18 21 24 27
LTS /K
moister free troposphere
warmer free troposphere
(b)
1.8
1.5
1.2
0.9
0.6
z_i /km
0 2 4 6 8 10
t /day

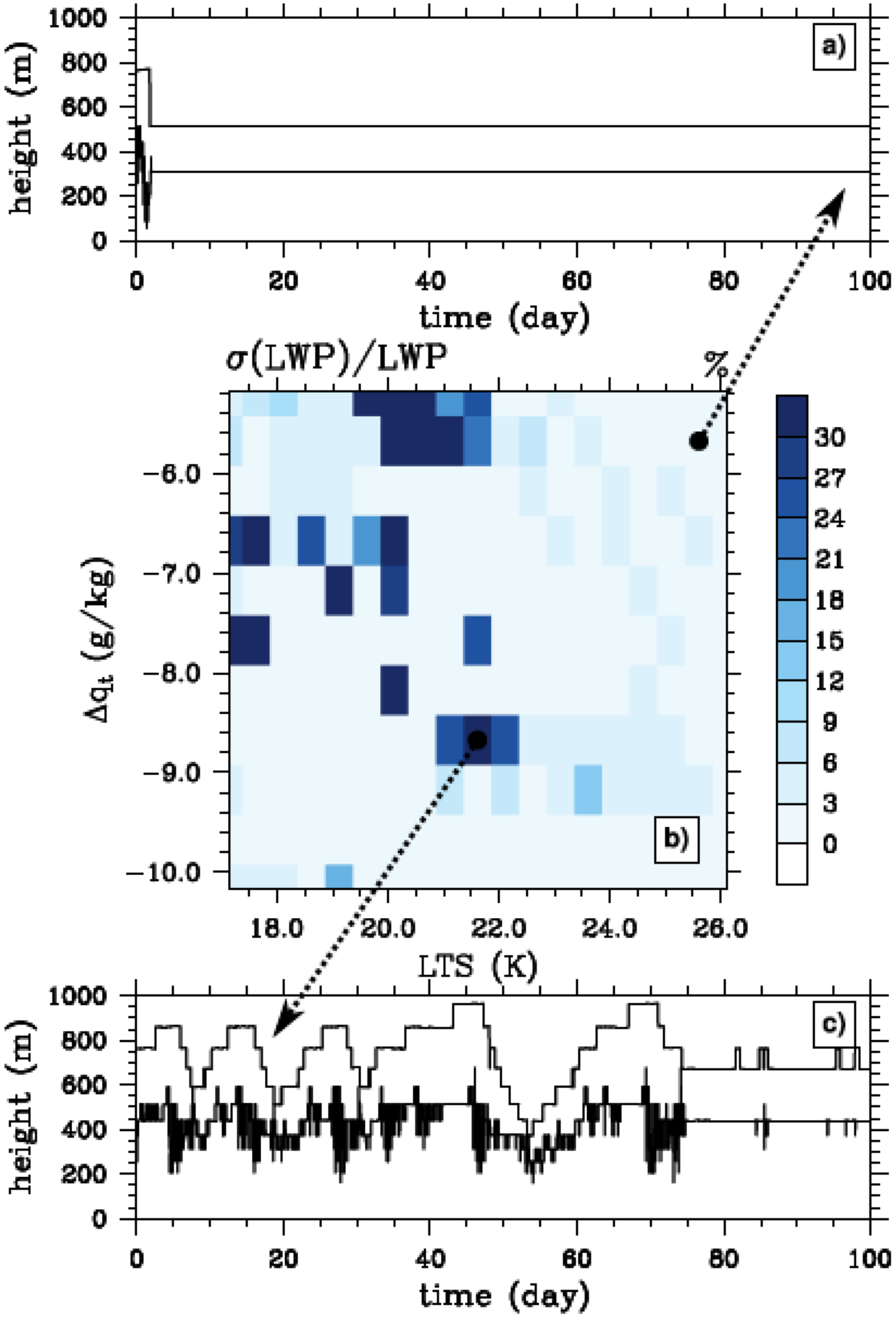
LES results indicate positive cloud feedback



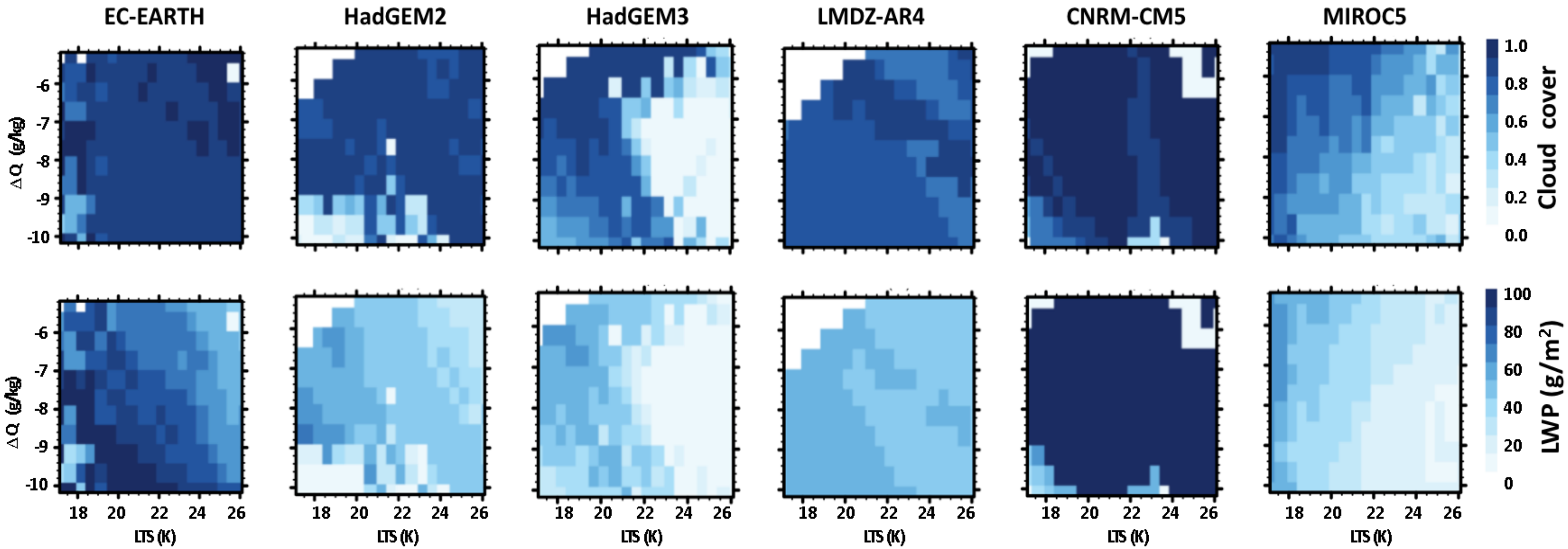
Single-Column Model version

KNMI climate model EC-EARTH

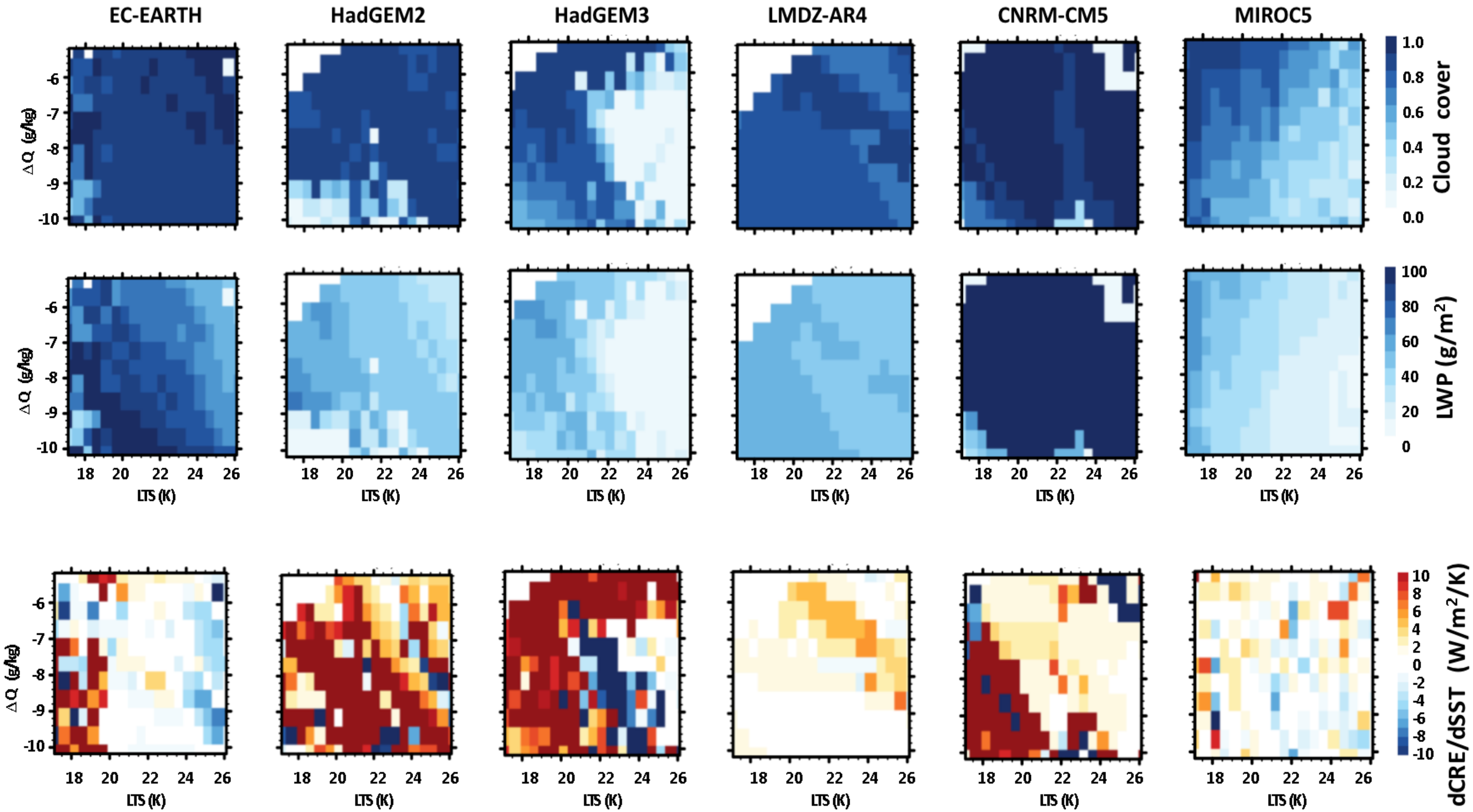
equilibrium is not always achieved



Reference experiments with the single column model versions



SCM results give a positive stratocumulus cloud feedback



Summary and Conclusions

- **Physics of stratocumulus**

  Small scale processes (longwave radiation, entrainment across thin inversion layer)

- **Weather forecast models**

  Have a coarse vertical resolution causing difficulties to capture small-scale processes

- **High-resolution large-eddy simulation models**

  Invaluable tool for studying dynamics of stratocumulus

  Ambition: Detailed weather prediction for wind and solar energy

- **Stratocumulus-cloud feedback to an idealized global warming scenario**

  Thinner clouds: positive feedback,

  but results sensitive to possible changes in forcing conditions (wind, subsidence)

References

Dal Gesso, S., J.J. van der Dussen, A.P. Siebesma, S. R. de Roode, I. A. Boutle, Y. Kamae, R. Roehrig, and J. Vial, 2014: A Single-Column Model intercomparison on the stratocumulus representation in present-day and future climate, submitted to *J. Adv. Model. Earth Syst.*

Van Der Dussen, J.J, S.R. de Roode, S. Dal Gesso, and A.P. Siebesma, 2014: An LES model study of the influence of the free troposphere on the stratocumulus response to a climate perturbation, submitted to *J. Adv. Model. Earth Syst.*

De Roode, S. R., A. P. Siebesma, S. Dal Gesso, H. J. J. Jonker, J. Schalkwijk, and J. Sival, 2014: A mixed-layer study of the stratocumulus response to changes in large-scale conditions. Revised version submitted to *J. Adv. Model. Earth Syst.*

Dal Gesso, S., A. P. Siebesma, and S. R. de Roode, 2014: Evaluation of low-cloud climate feedback through Single-Column Model equilibrium states. Online version published*, Q. J. R. Met. Soc.*

Dal Gesso, S., A. P. Siebesma, S. R. de Roode, and J. M. van Wessem, 2014: A mixed-layer model perspective on stratocumulus steady-states in a perturbed climate. *Q. J. R. Meteor. Soc., DOI:10.1002/qj.2282.*

Zhang, M. and 39 co-authors, 2013: CGILS: Results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models. *J. Adv. Model. Earth Sys*t., 5, doi:10.1002/2013MS000246.

van der Dussen, J. J. , S. R. de Roode, and A. P. Siebesma, 2014: Factors controlling rapid stratocumulus cloud thinning. *J. Atmos. Sci.,* 71, 655-664, doi: http://dx.doi.org/10.1175/JAS-D-13-0114.1.

van der Dussen, J. J. , S. R. de Roode, A. S. Ackerman, P. N. Blossey, C. S. Bretherton, M. J. Kurowski, A. P. Lock, R. A. J. Neggers, I. Sandu, and A. P. Siebesma, 2013: The GASS/EUCLIPSE Model Intercomparison of the Stratocumulus Transition as Observed During ASTEX: LES results. *J. Adv. Model. Earth Syst.,* 5, 1-17, doi:10.1002/jame.20033.

Blossey, P. N., C. S. Bretherton, M. Zhang, A. Cheng, S. Endo, T. Heus, Y. Liu, A. Lock, S. R. de Roode and K.-M. Xu, 2013: Marine low cloud sensitivity to an idealized climate change: The CGILS LES Intercomparison. *J. Adv. Model. Earth Syst*, 5, 1-25.