Climate sensitivity on an idealized land planet

Tobias Becker

Bjorn Stevens, Jürgen Bader

Max-Planck-Institute for Meteorology
IMPRS-ESM
Hamburg

Outline

Idea:

Study local influence of two surface properties on the land-ocean warming contrast:

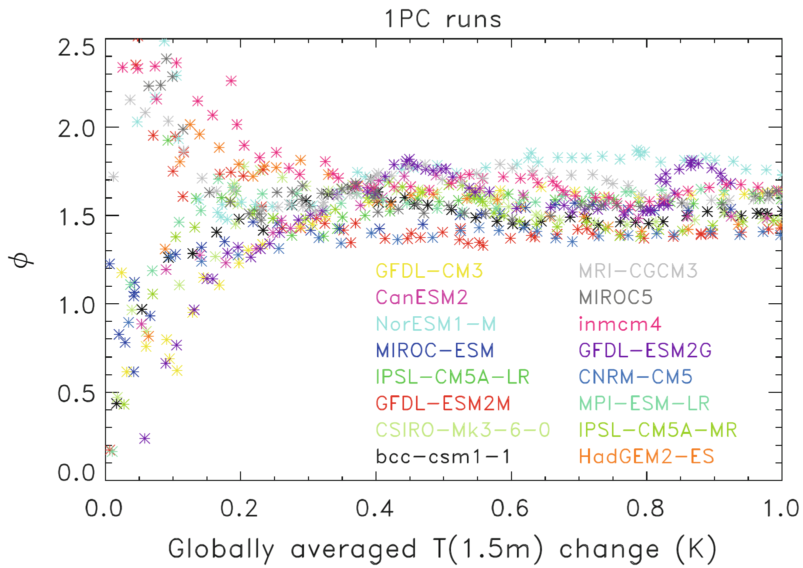
- Heat capacity
- Latent heat release

Key Questions:

- How does the surface-atmosphere interaction change?
- Is a land-ocean warming contrast reproducable?
- Which feedback mechanisms are involved?

Motivation

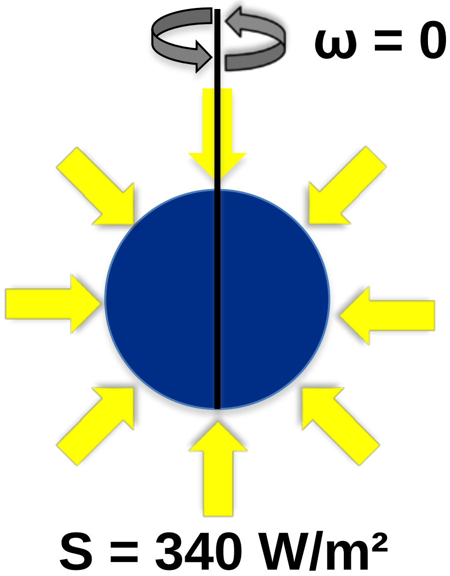
- Land-ocean warming ratio differs among CMIP5 models (ϕ = 1.4-1.8)

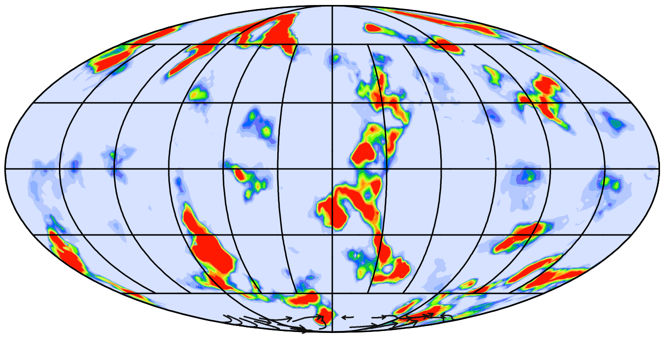


[Joshi et al., 2013]

- Understanding can be increased by studying local effects separated from large-scale effects
- Land and ocean can be studied separately by assuming that the temperatures at the longwave emission height are similar

Methods





Radiative-convective equilibrium
in ECHAM6 with

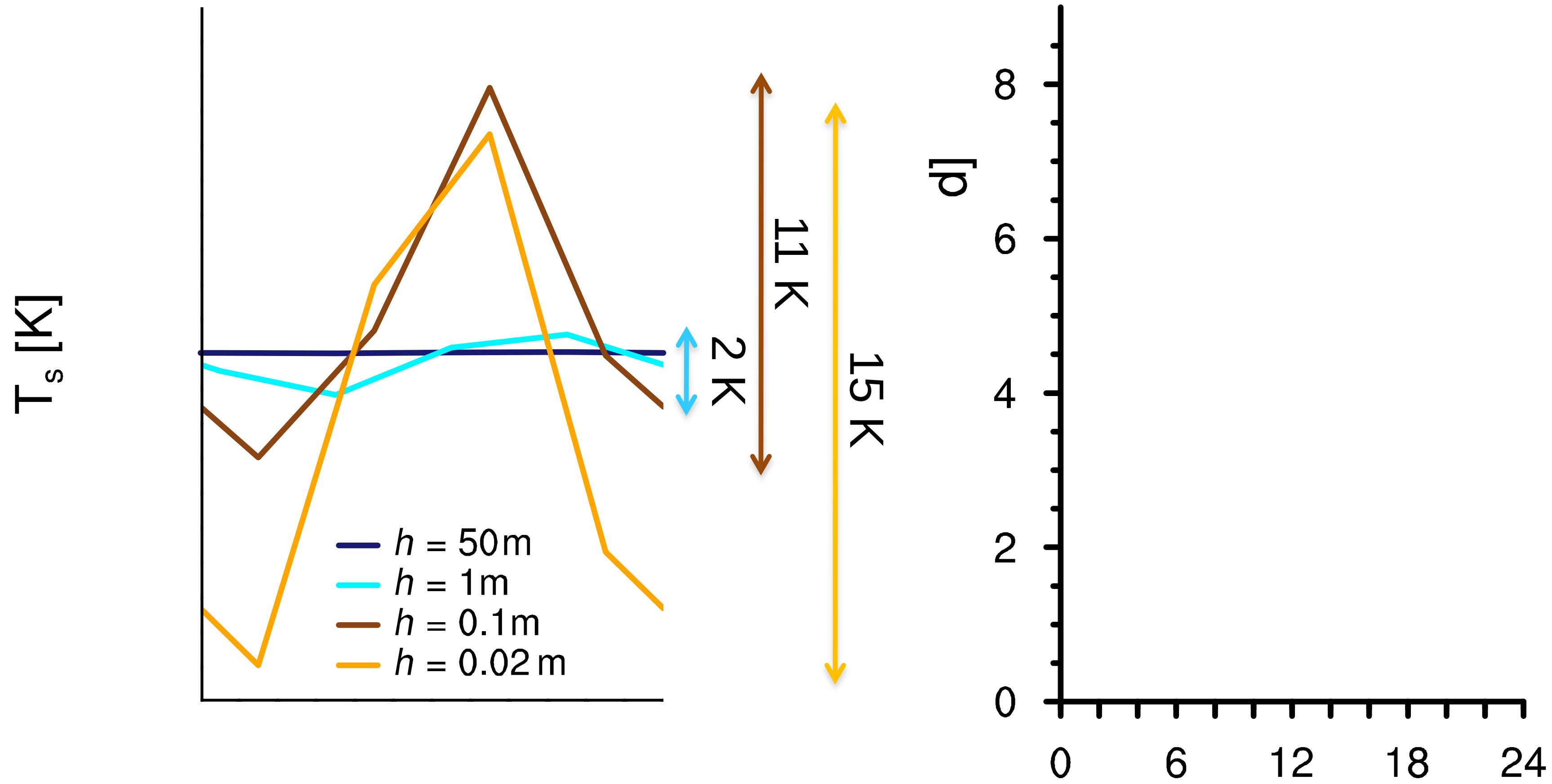
- No rotation
- No insolation gradients
- Perfectly conducting slab at surface
- Otherwise full suite of ECHAM6 physics

Transition to idealized land planet

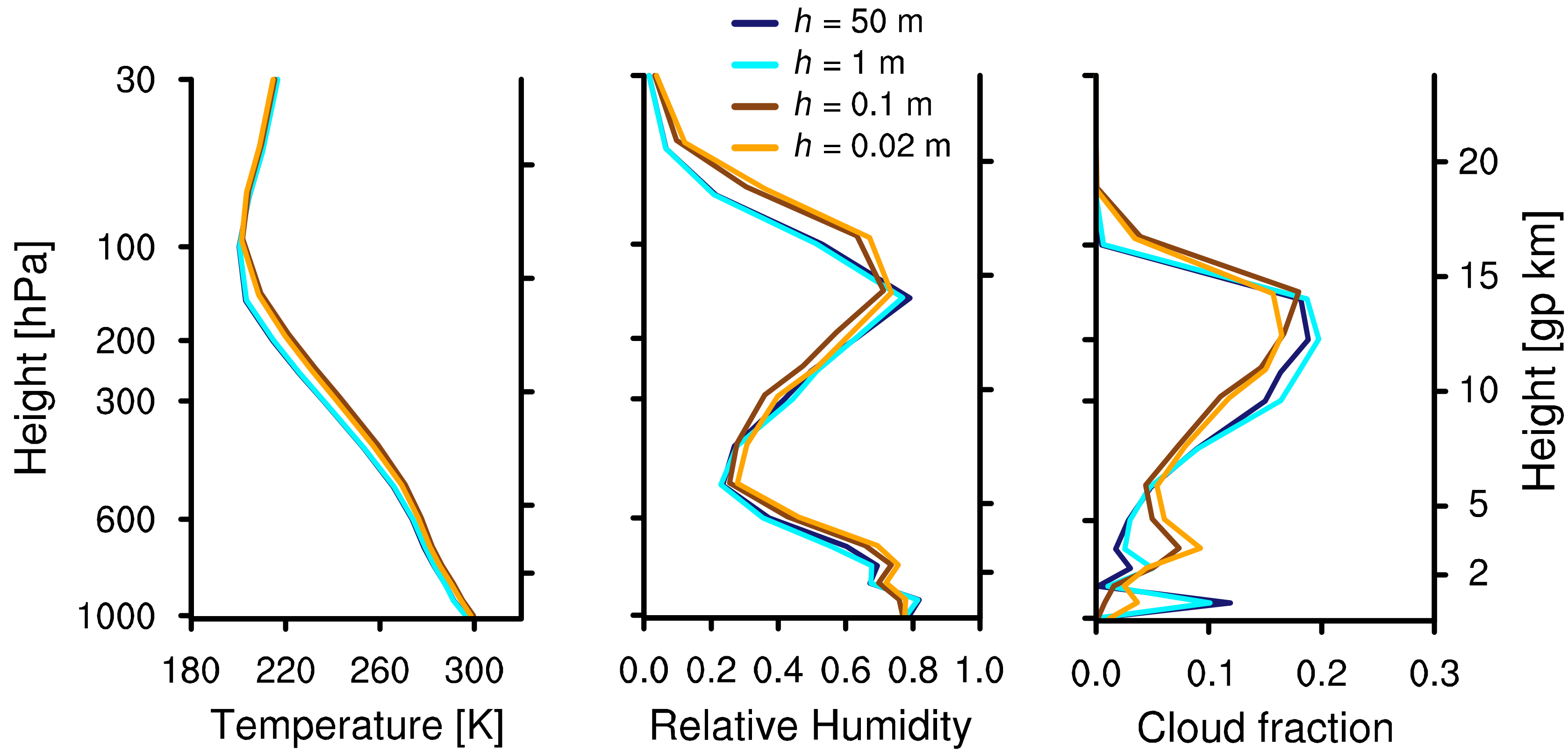
- Decrease of slab depth from 50 m to 0.02 m
- Decrease of surface latent heat flux

Influence of surface heat capacity

land-like diurnal cycle for slab depth $h \leq 0.1$ m



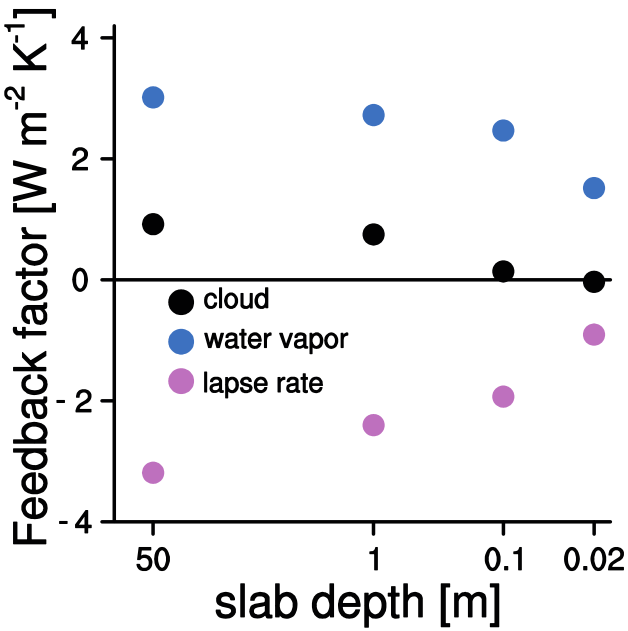
Atmosphere couples to $T_{s,\ diurnal\ max}$ rather than to $T_{s,\ diurnal\ mean}$ for slab depth *h* ≤ 0.1 m

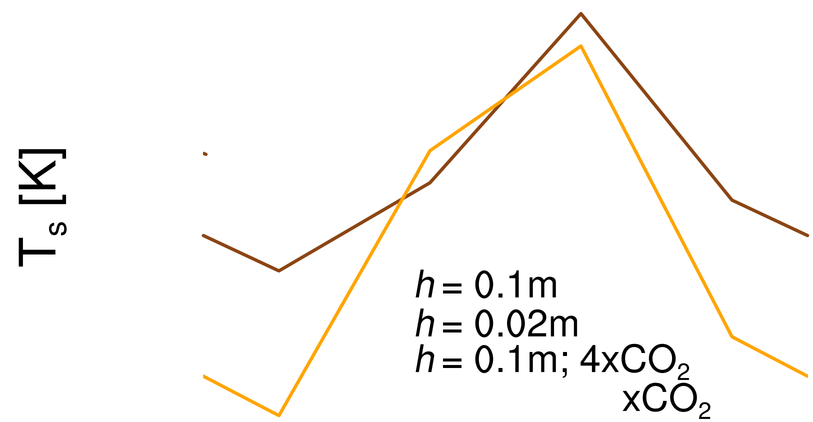


slab depth [m]	50	1	0.1	0.02
$T_{s,\ diurnal\ mean}$ [K]	300.1	299.8	301.3	298.6
$T_{s,\ diurnal\ max}$ [K]	300.1	300.6	307.7	306.3

Surface heat capacity only with small influence on climate sensitivity

slab depth [m]	50	1	0.1	0.02
Climate sensitivity [K]	2.2	2.4	1.6	2.4





Feedback factors decrease because atmosphere couples to $T_{s,\ \mathrm{diurnal\ max}}$, which increases to a lesser extent in a warming climate (rectification)

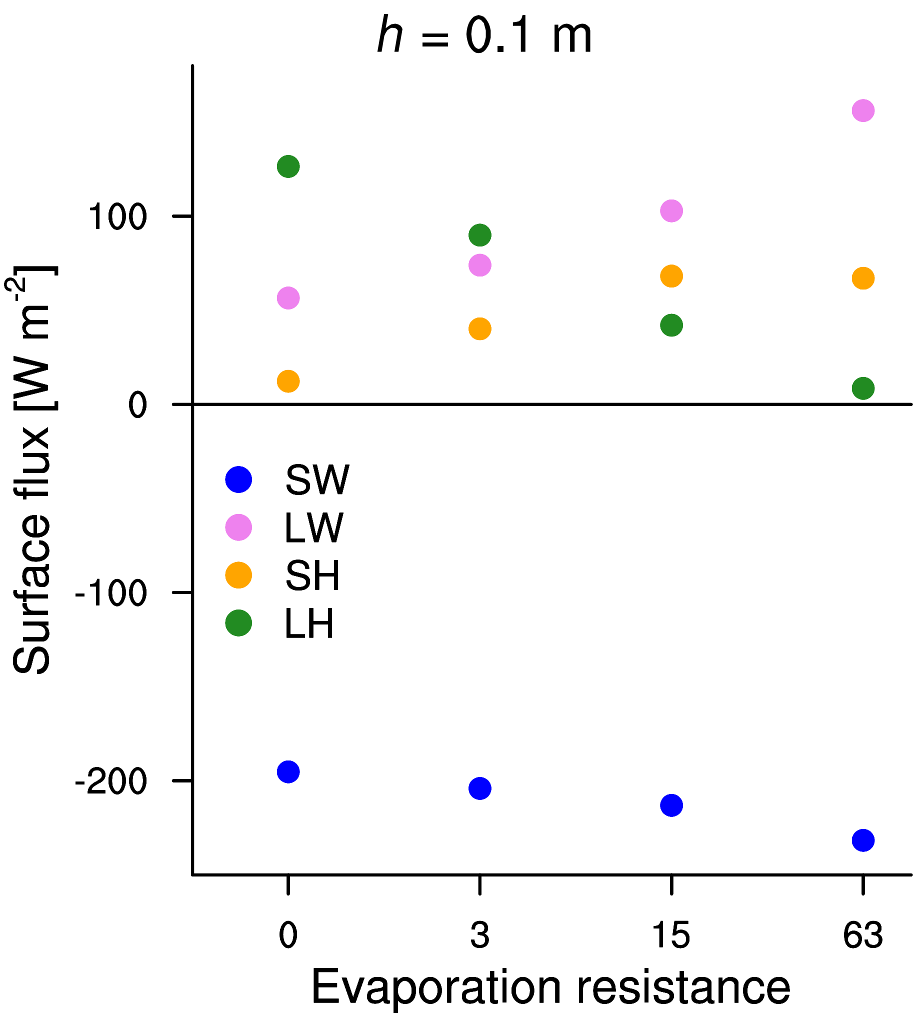
Reduction of surface latent heat flux – Introduction of evaporation resistance

- Bulk formula for turbulent latent heat flux: $\overline{w'q'} = -C_h |\vec{u}| \Delta q$
- ECHAM: Adaption of the turbulent heat-flux coefficient, C_h, if impact on evaporation:

$$C_{h,new} = \frac{1}{\frac{1}{C_h} + \frac{R}{\overline{C_h}}}$$

- Experiments with an evaporation resistance *R* of 0, 3, 15 and 63, both for a slab depth *h* of 50 m and 0.1 m

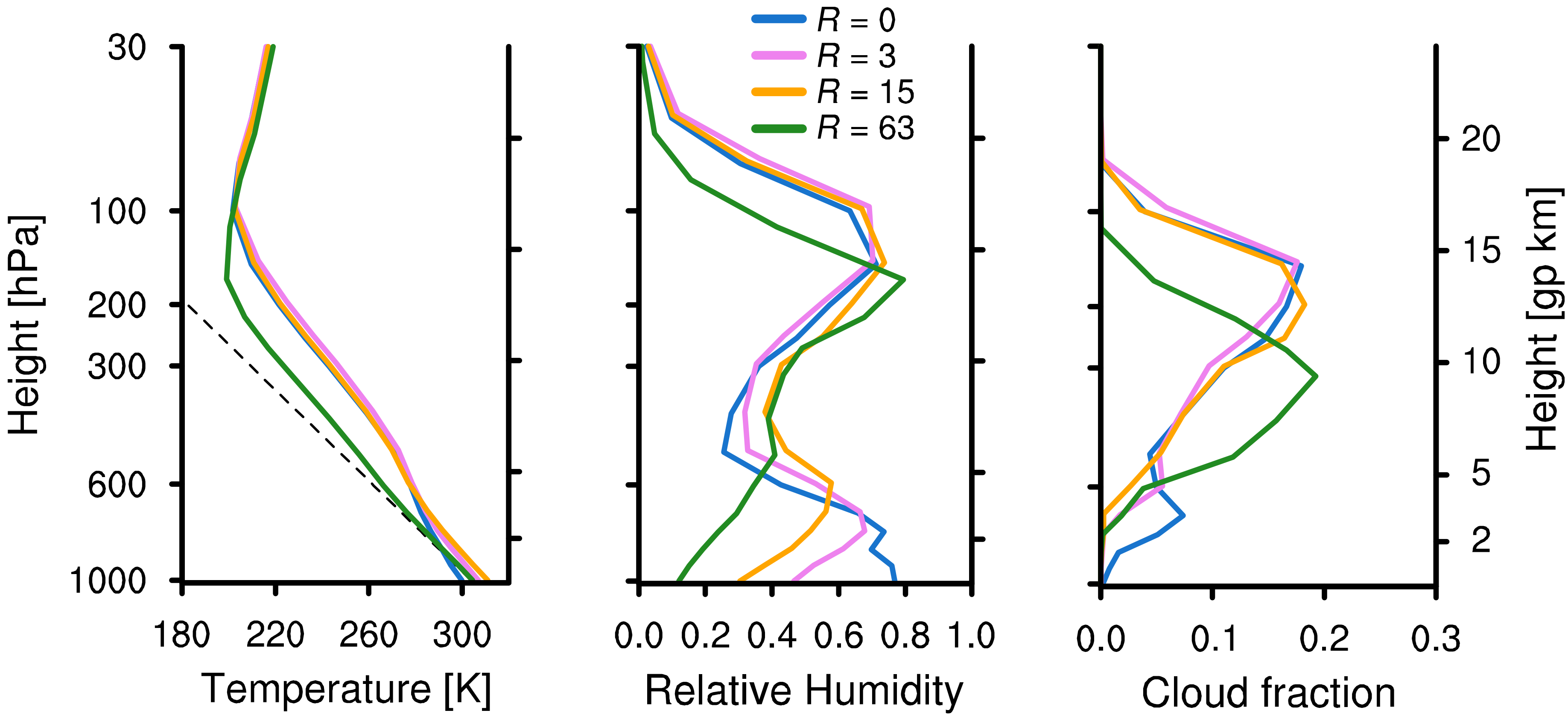
Reduction of LH flux is compensated primarily by LW, secondary by SH



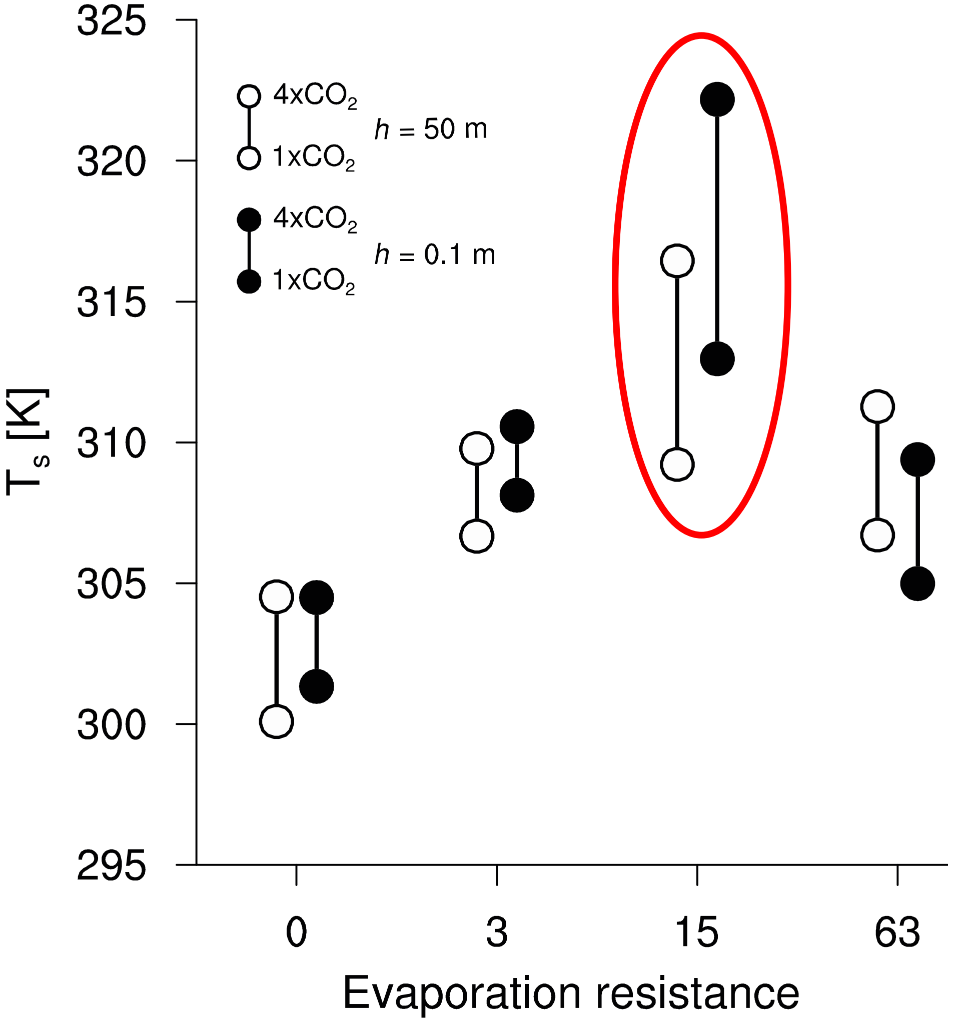
Bowen ratio (SH/LH) is about 1:2 in very humid tropical regions, with no upper limit in dry regions over land

➔ Bowen ratio land-like for ***R* ≥ 3**

Vertical profiles show bottom-up drying, lapse rate increase and reduction of cloud top height



Climate sensitivity maximizes under semiarid conditions

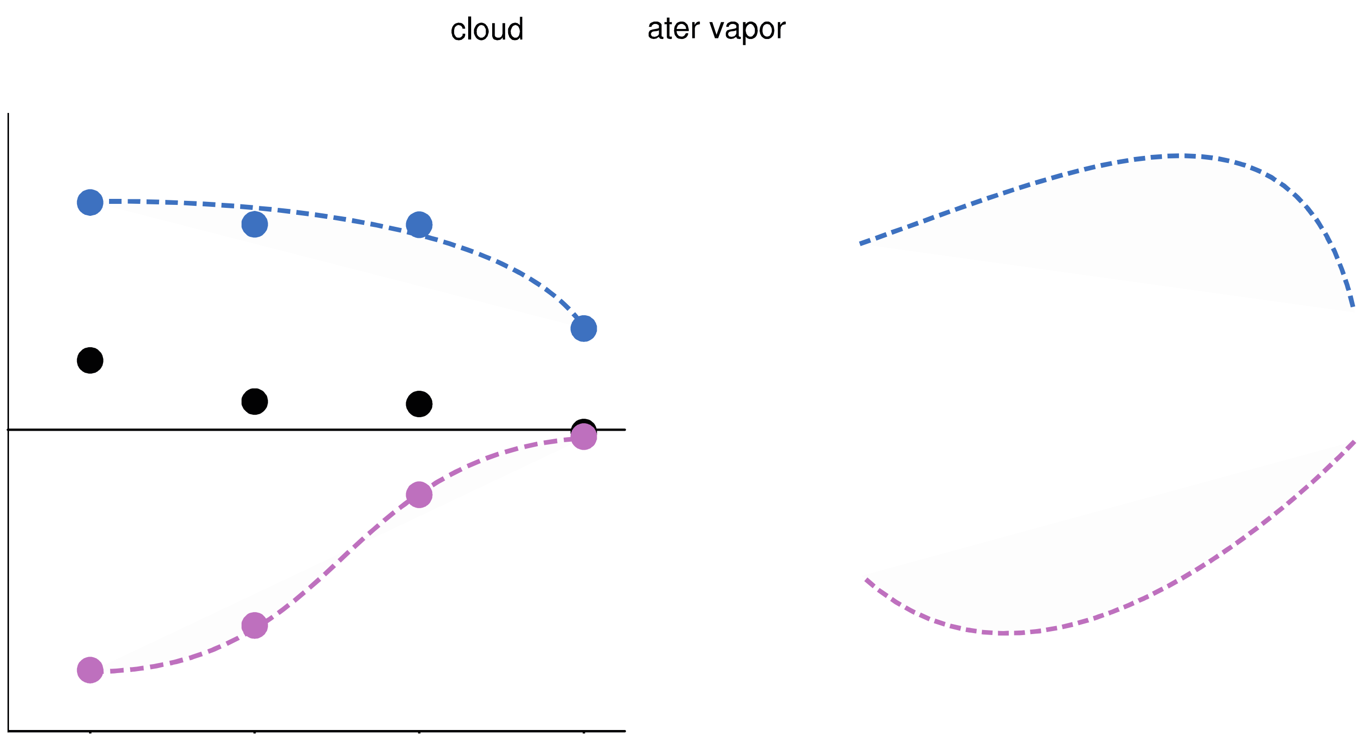


	Equilibrium climate sensitivity [K]	
	h = 50 m	*h* = 0.1 m
R = 0	2.2	1.6
R = 3	1.6	1.2
R = 15	3.7	4.6
R = 63	2.3	2.2

land-ocean warming ratio of $\phi = 1.7\text{-}2.1$

CMIP5: $\phi = 1.4\text{-}1.8$ [Joshi et al., 2013]

High climate sensitivity for *R* = 15: bottom-up drying exhausts lapse rate feedback more readily than water vapor feedback



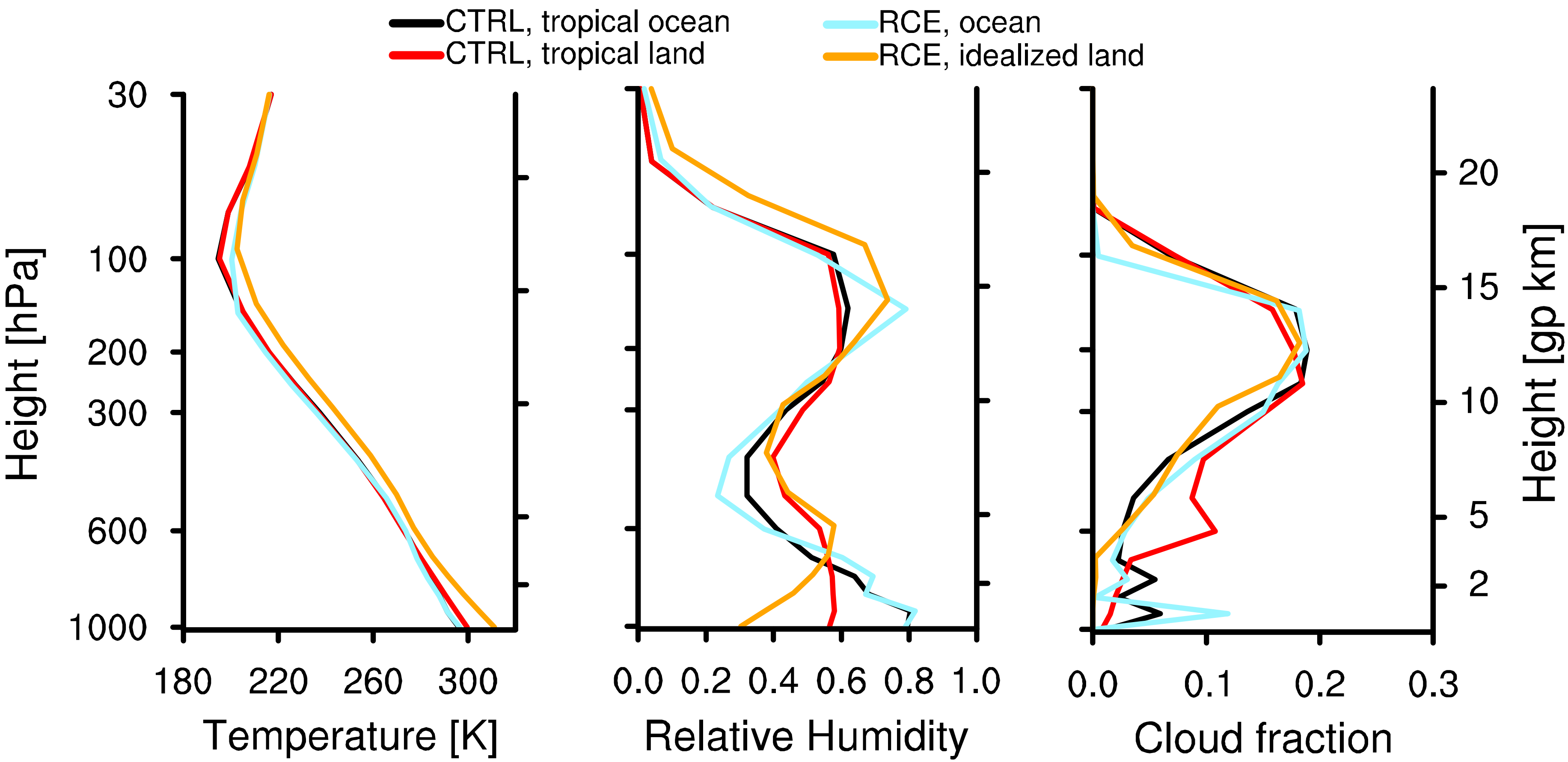
Answer of key questions

- **How does the surface-atmosphere interaction change?**
  - Pronounced diurnal cycle induces a decoupling of the free troposphere from the mean surface temperature
- **Is a land-ocean warming contrast reproducable?**
  - *Heat capacity*: of at most secondary importance
  - *Evaporation resistance*: capable to reproduce warming contrast under semiarid conditions
- **Which feedback mechanisms are involved?**
  - bottom-up drying exhausts lapse rate feedback more readily than water vapor feedback, inducing a high climate sensitivity

Paper will be submitted to JAMES soon:
Becker and Stevens, 2014: Climate and climate sensitivity to changing CO_2 on an idealized land planet

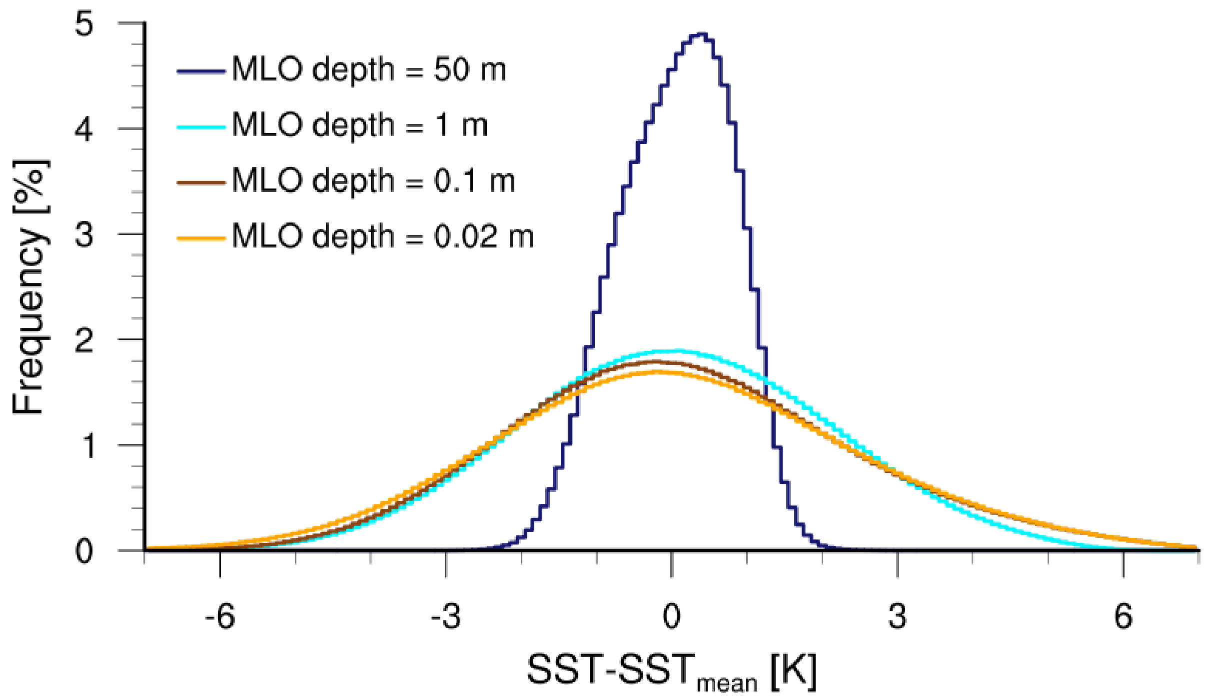
Additional slides

RCE profiles very similar to ECHAM6 climate over tropics



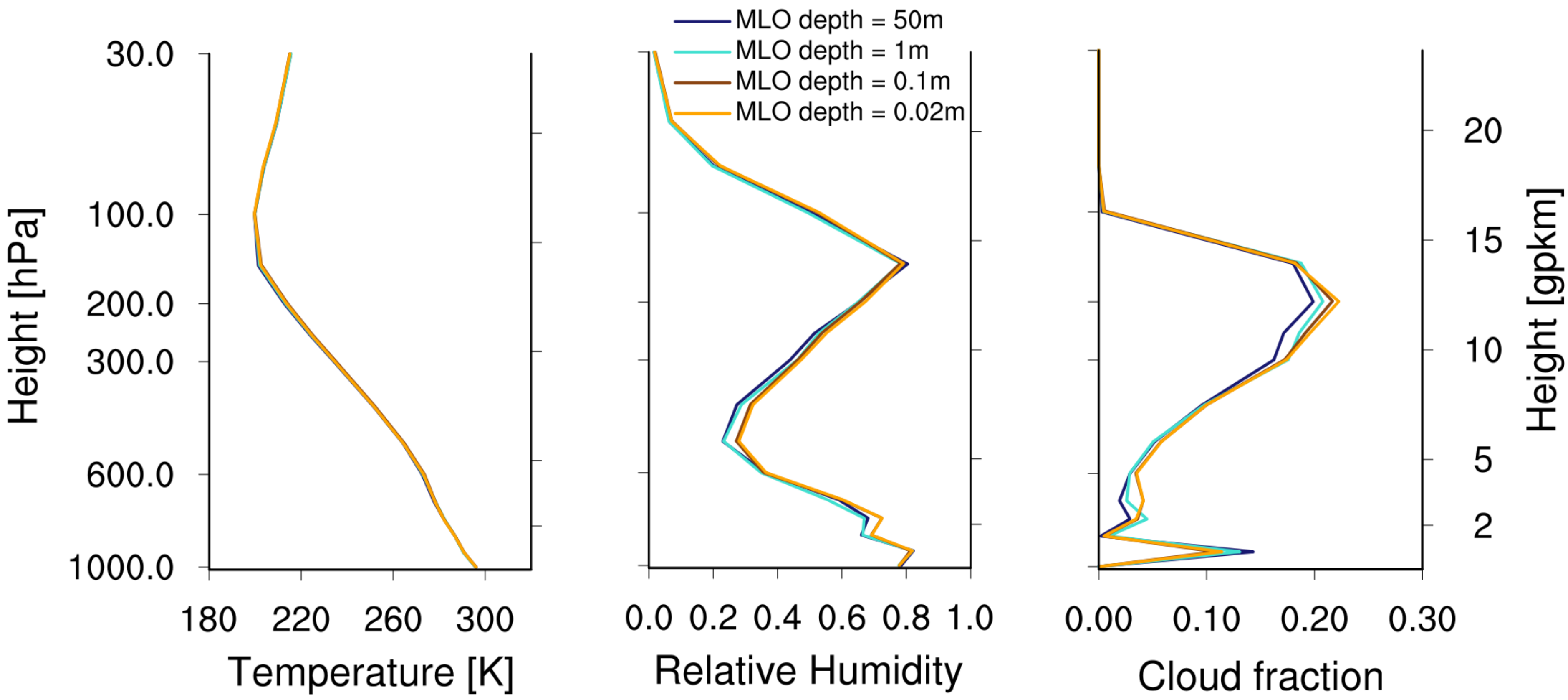
Surface coupling – without diurnal cycle

1m deep ocean is already fully coupled to atmosphere



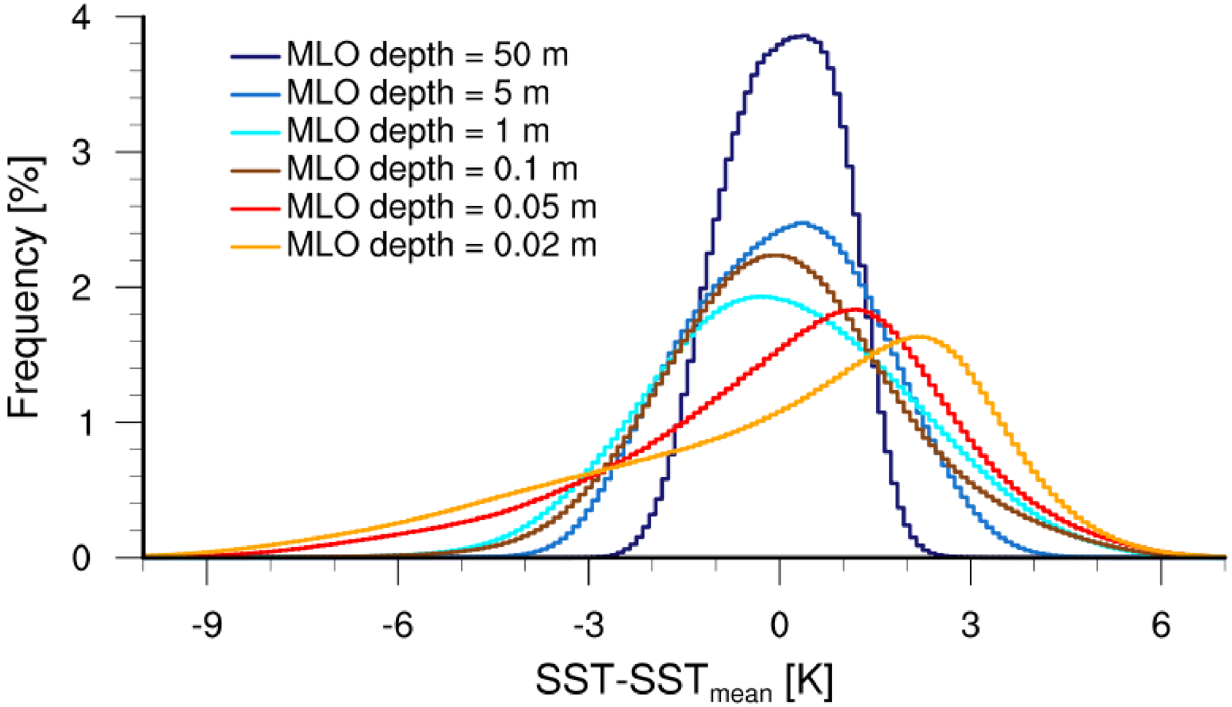
MLO depth	50 m	1 m	0.1 m	0.02 m
SST [K]	299.6	299.5	299.3	299.2
Precipitation [mm/d]	4.0	4.0	4.0	4.0

Vertical profiles are almost independent of surface coupling



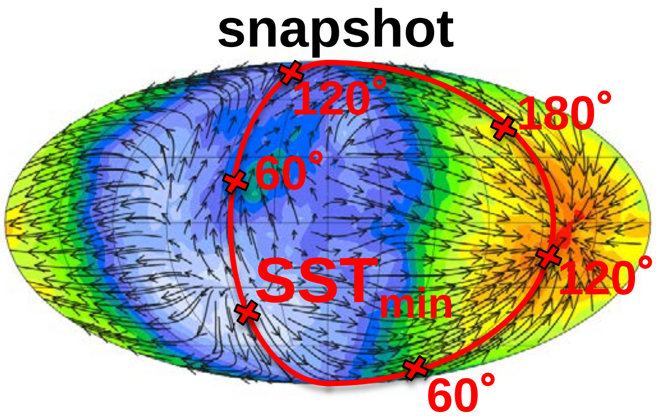
Diurnal cycle

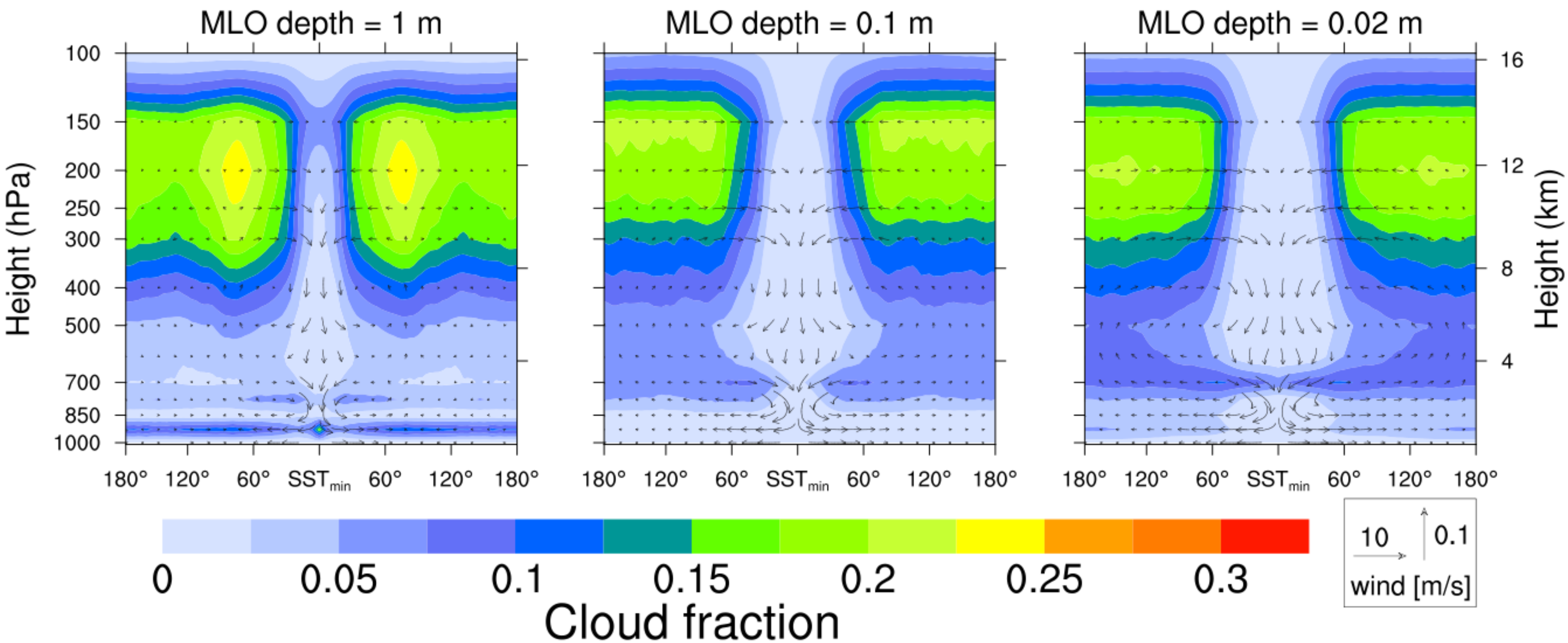
Variability of daily mean SSTs increases; negatively skewed for MLO depth ≤ 0.05 m



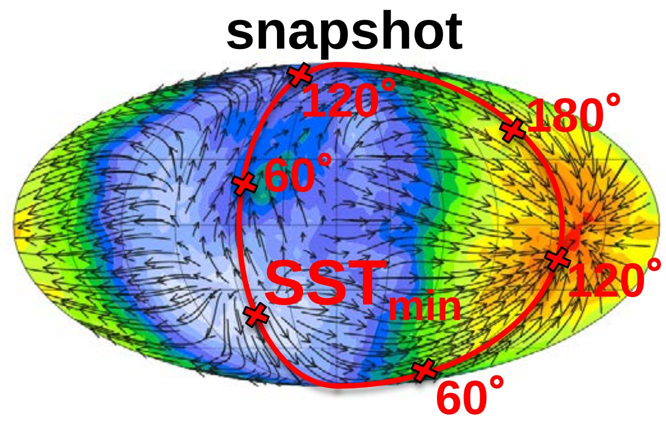
MLO depth	50 m	5 m	1 m	0.1 m	0.05 m	0.02 m
SST [K]	300.1	299.5	299.8	301.3	300.1	298.6
Precipitation [mm/d]	4.1	4.0	4.0	4.4	4.3	4.4

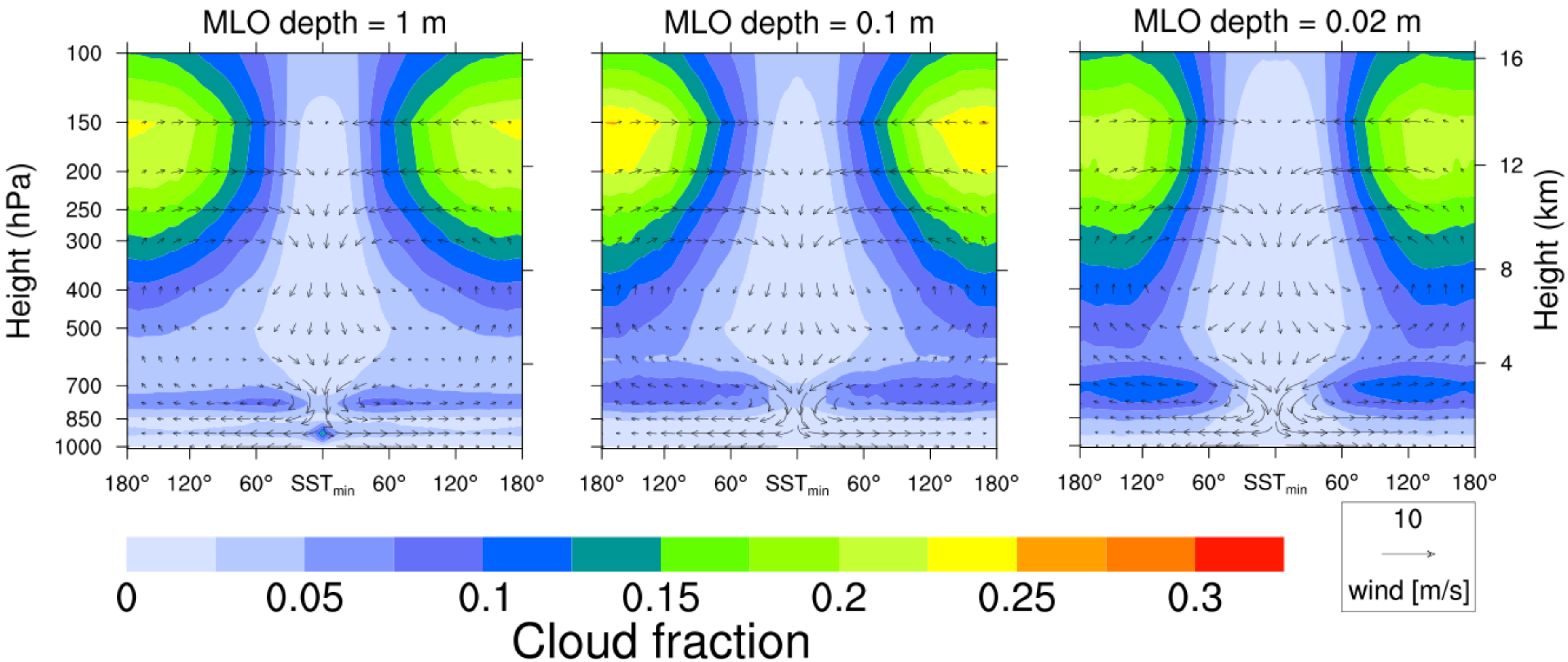
Vertical cross sections show 700 hPa cloud feedback for MLO depth = 0,02 m



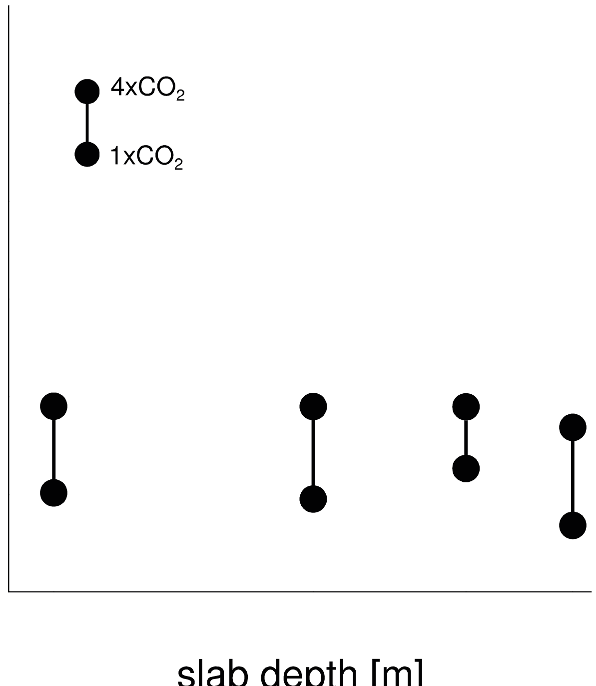


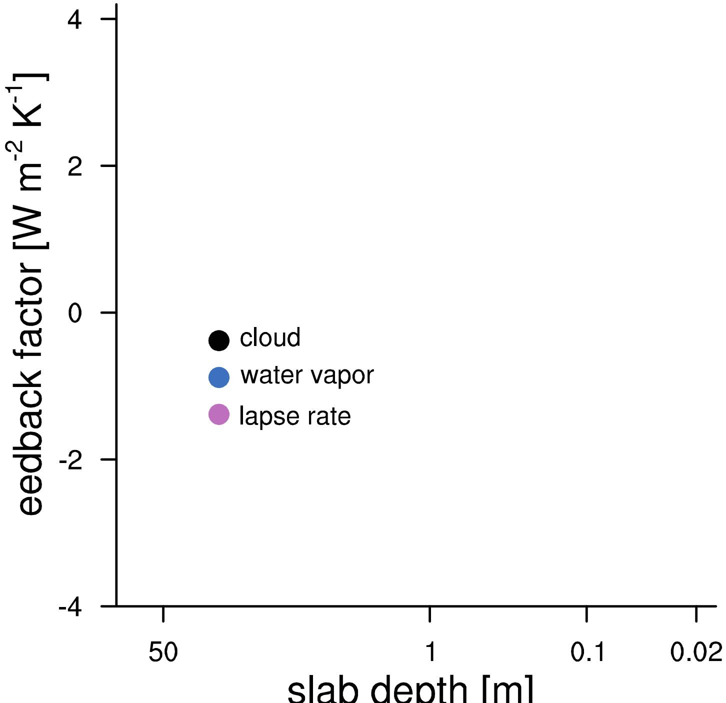
Vertical cross sections with quadrupled CO_2 concentrations





Influence of surface heat capacity on climate sensitivity

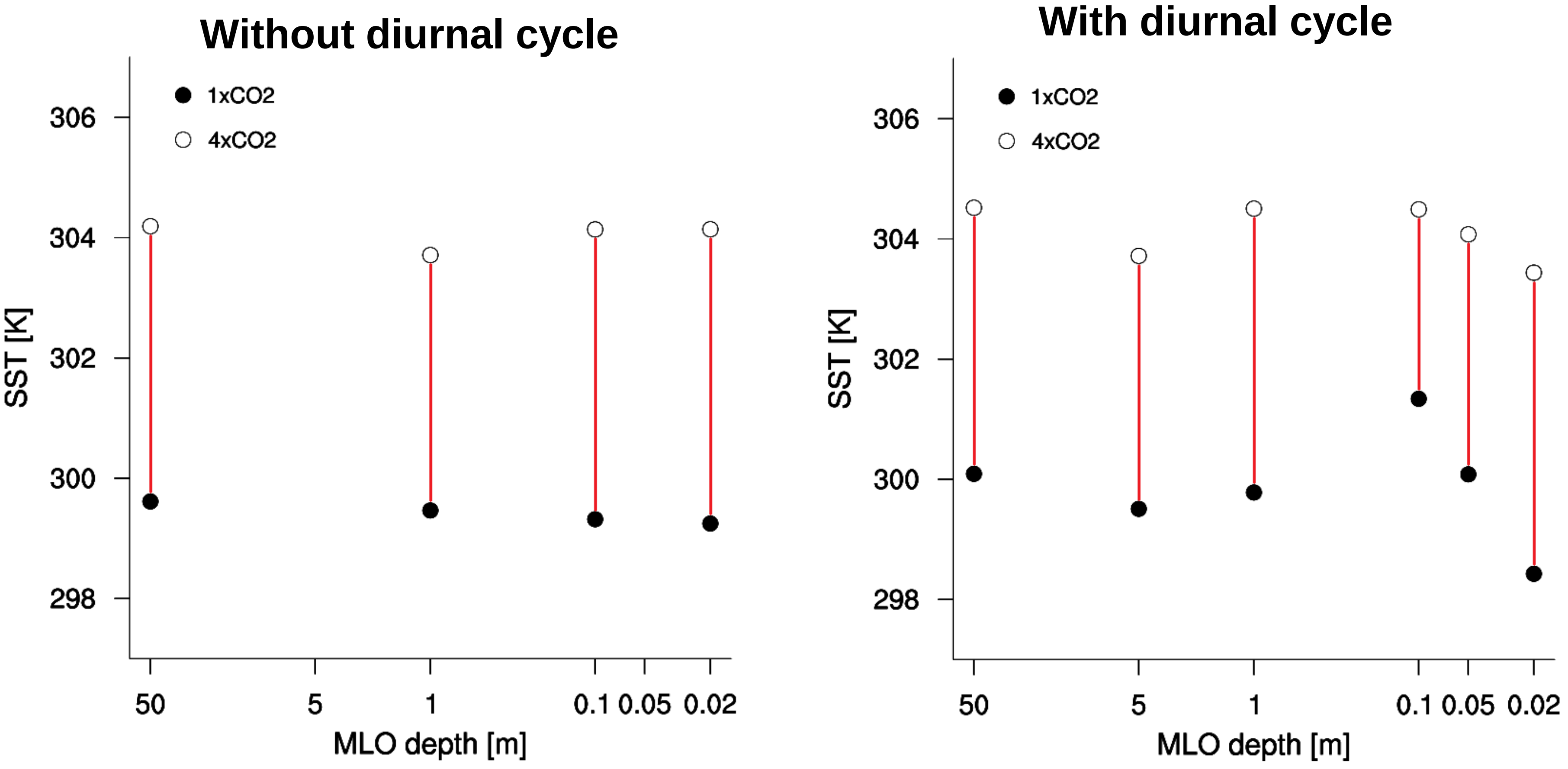




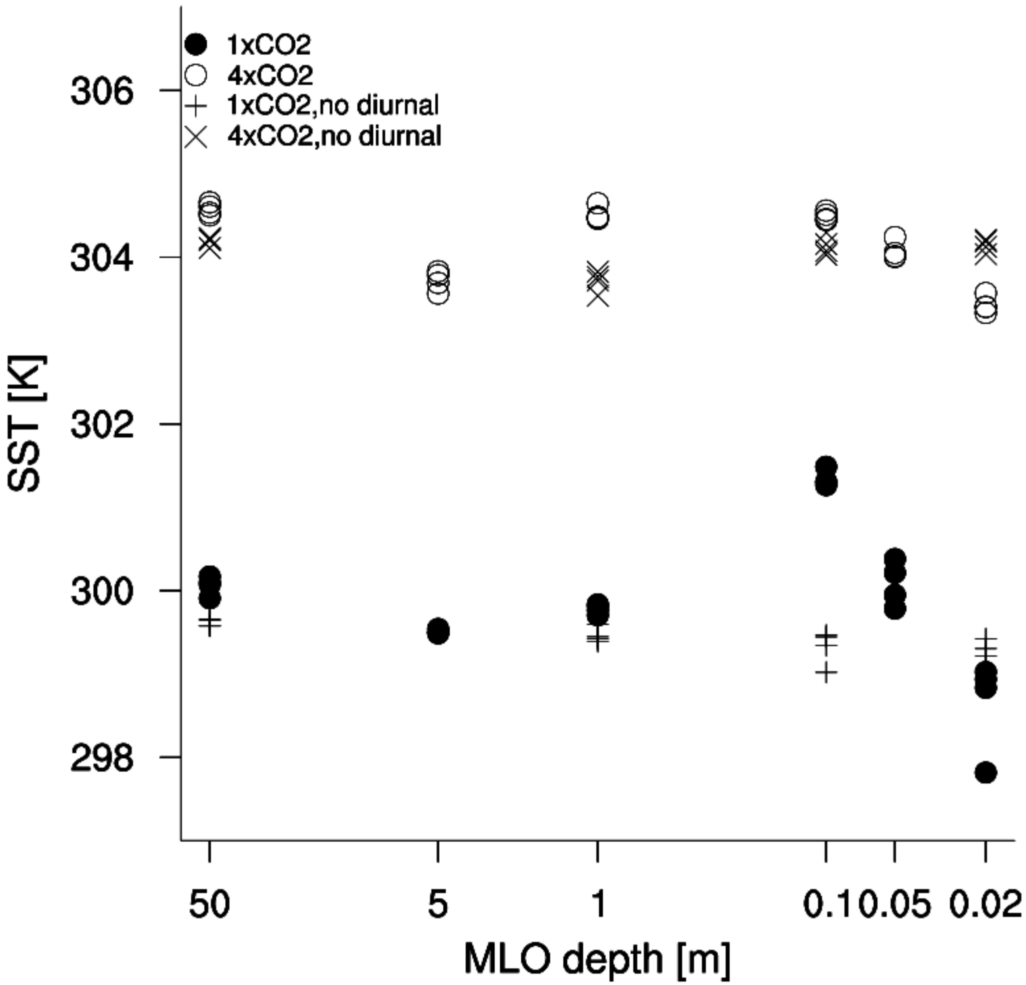
Though major impact on climate, heat capacity only with small influence on climate sensitivity

Atmosphere decouples from diurnal mean surface temperature, inducing a decrease of feedback factors

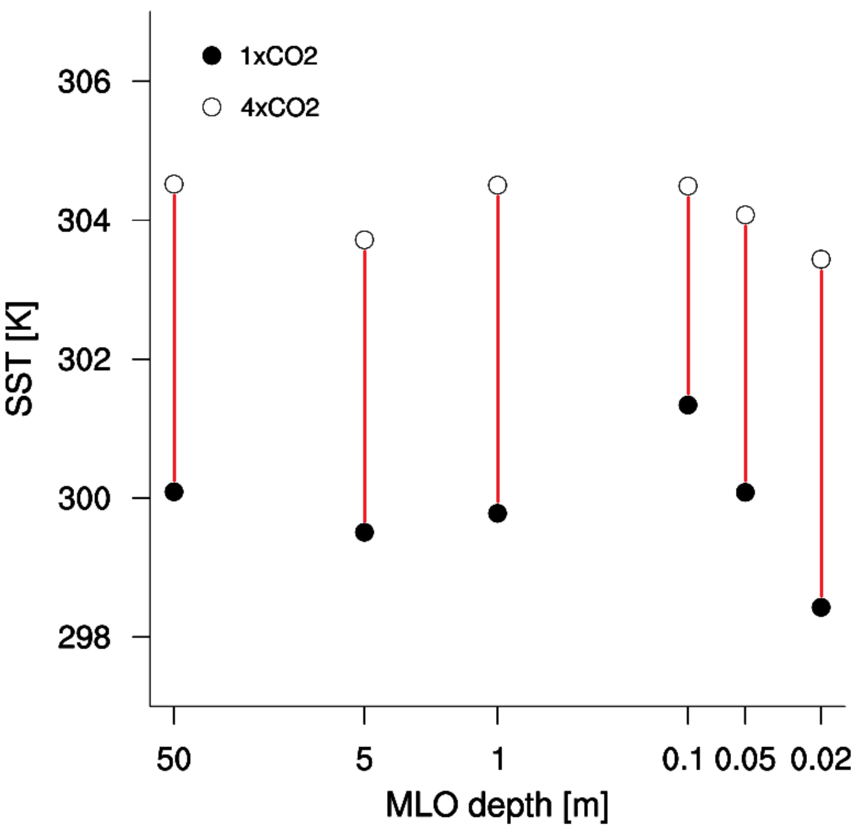
Climate sensitivity changes when diurnal SST amplitude starts influencing atmospheric processes

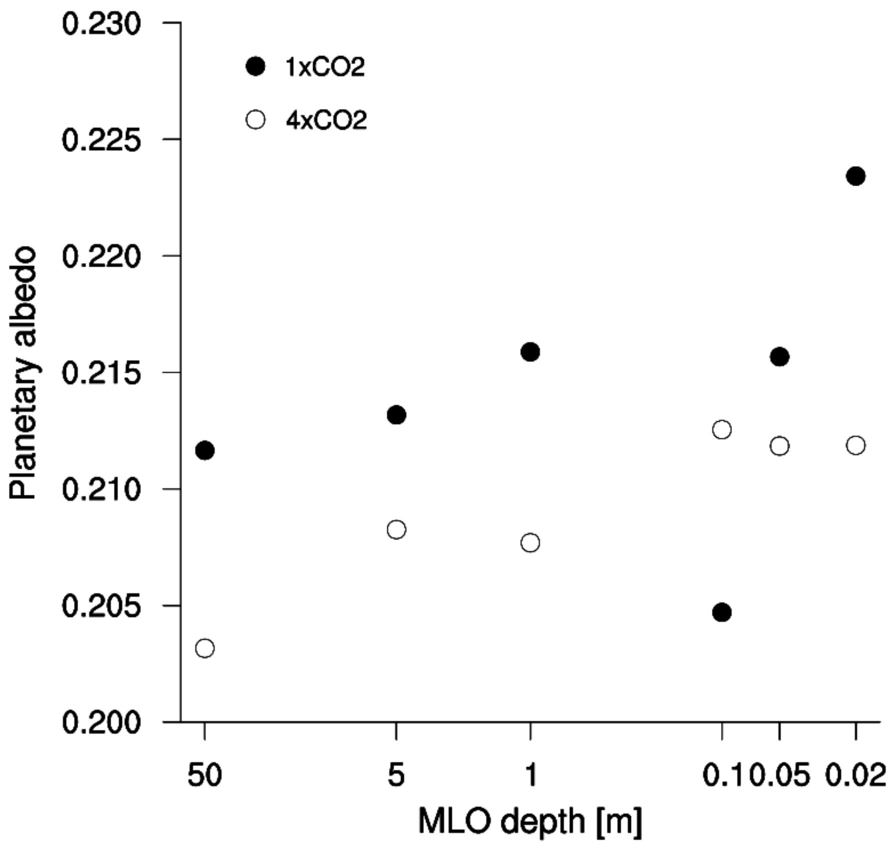


Global mean SSTs are significant

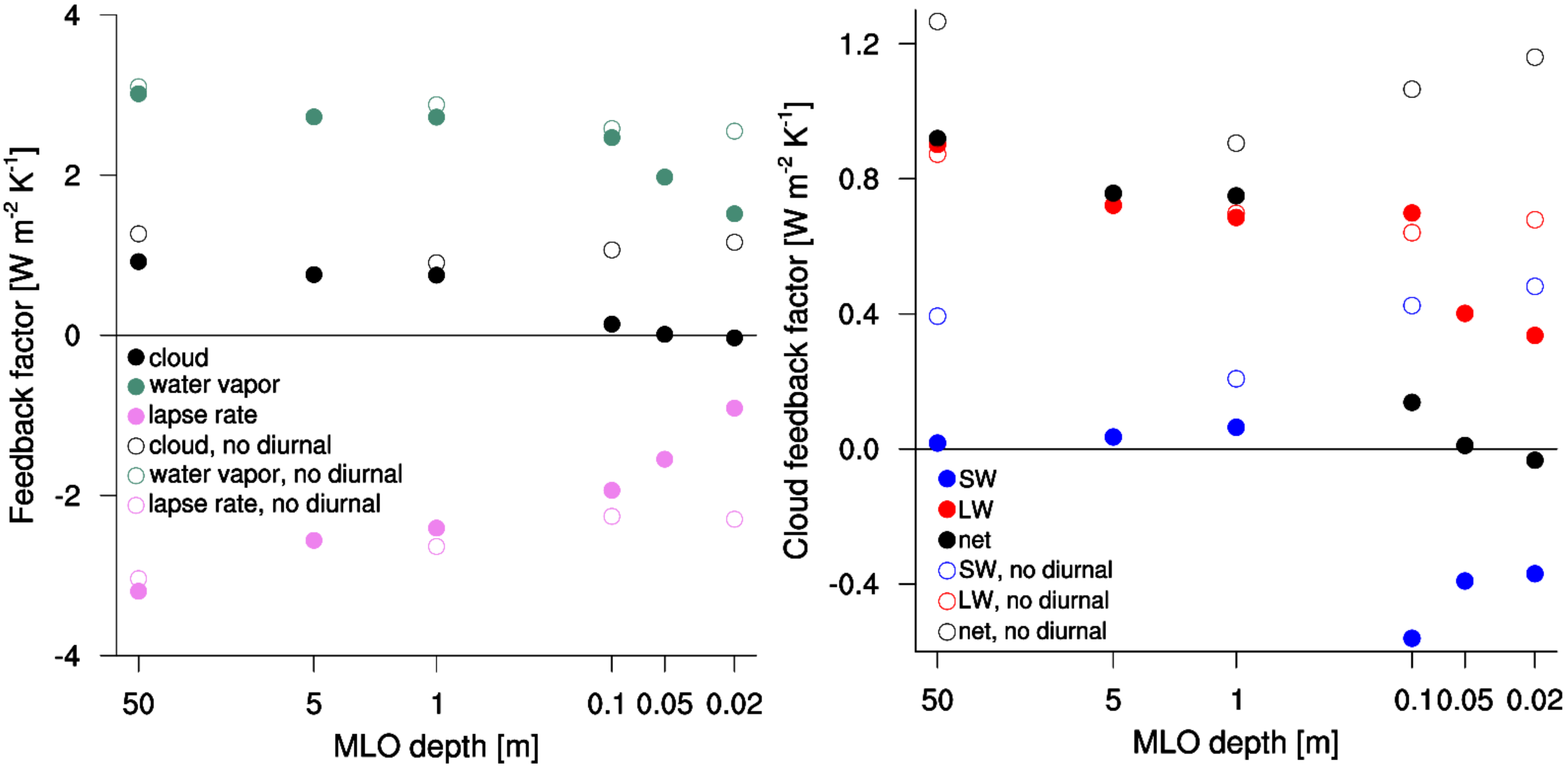


SST changes because planetary albedo changes

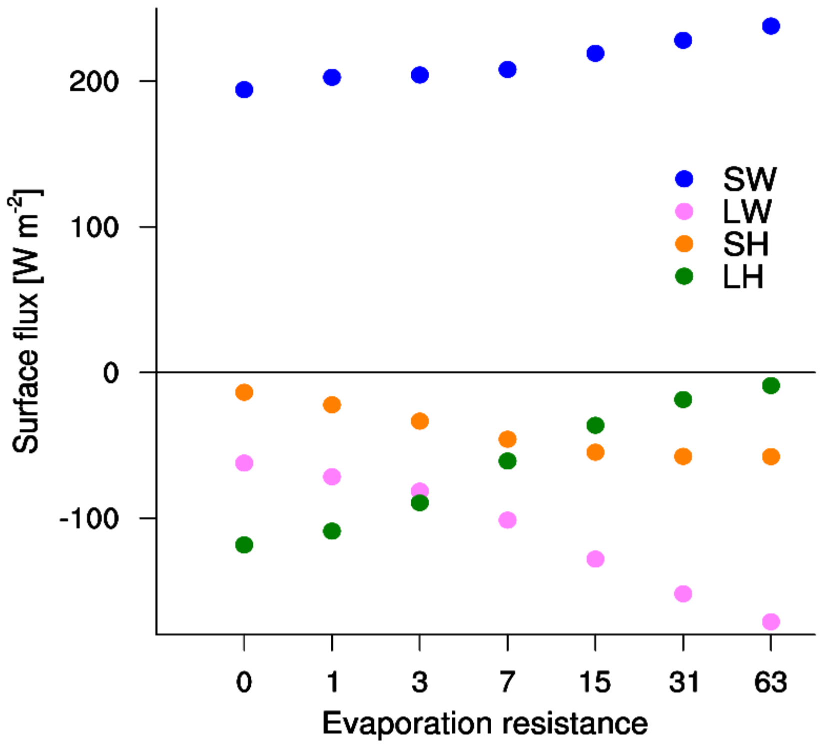


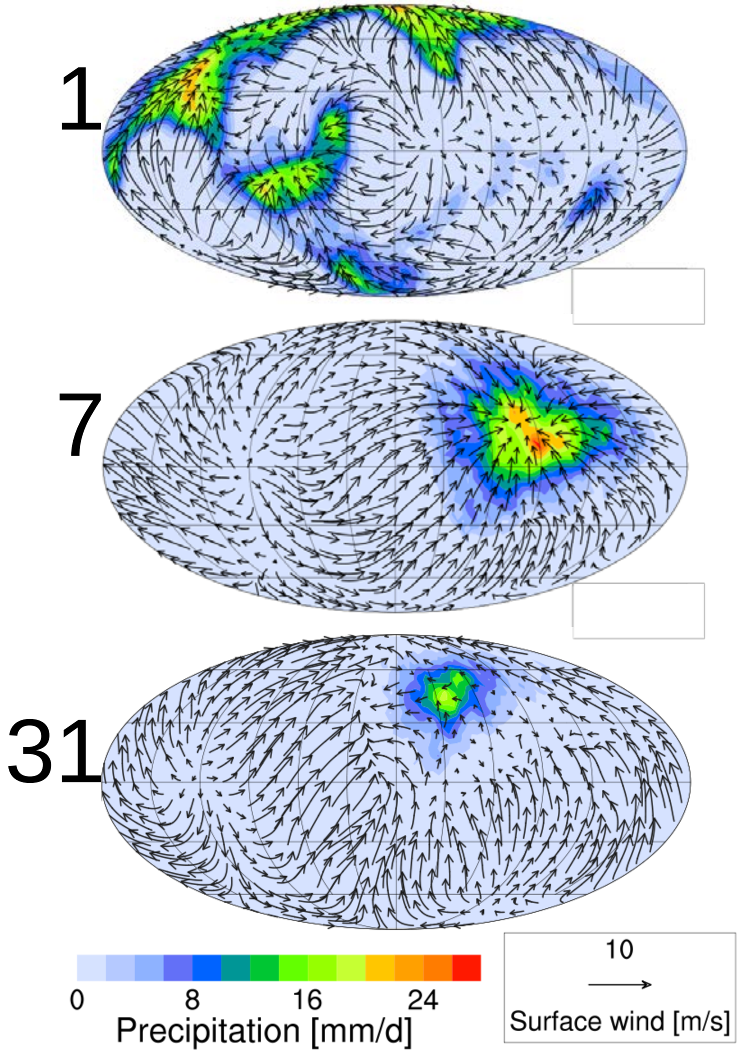


Feedback factors calculated with prp module



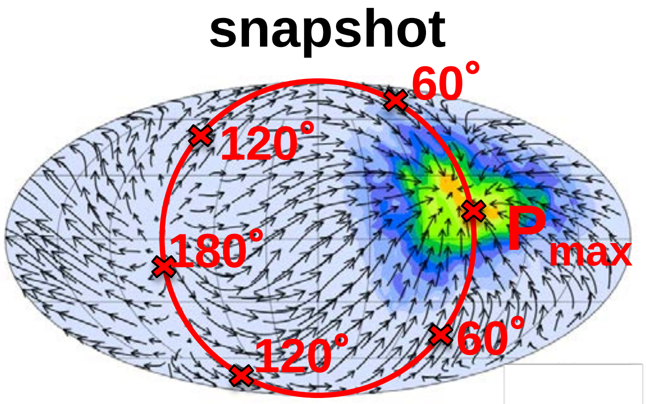
Reduction of LH flux is compensated primarily by LW, secondary by SH

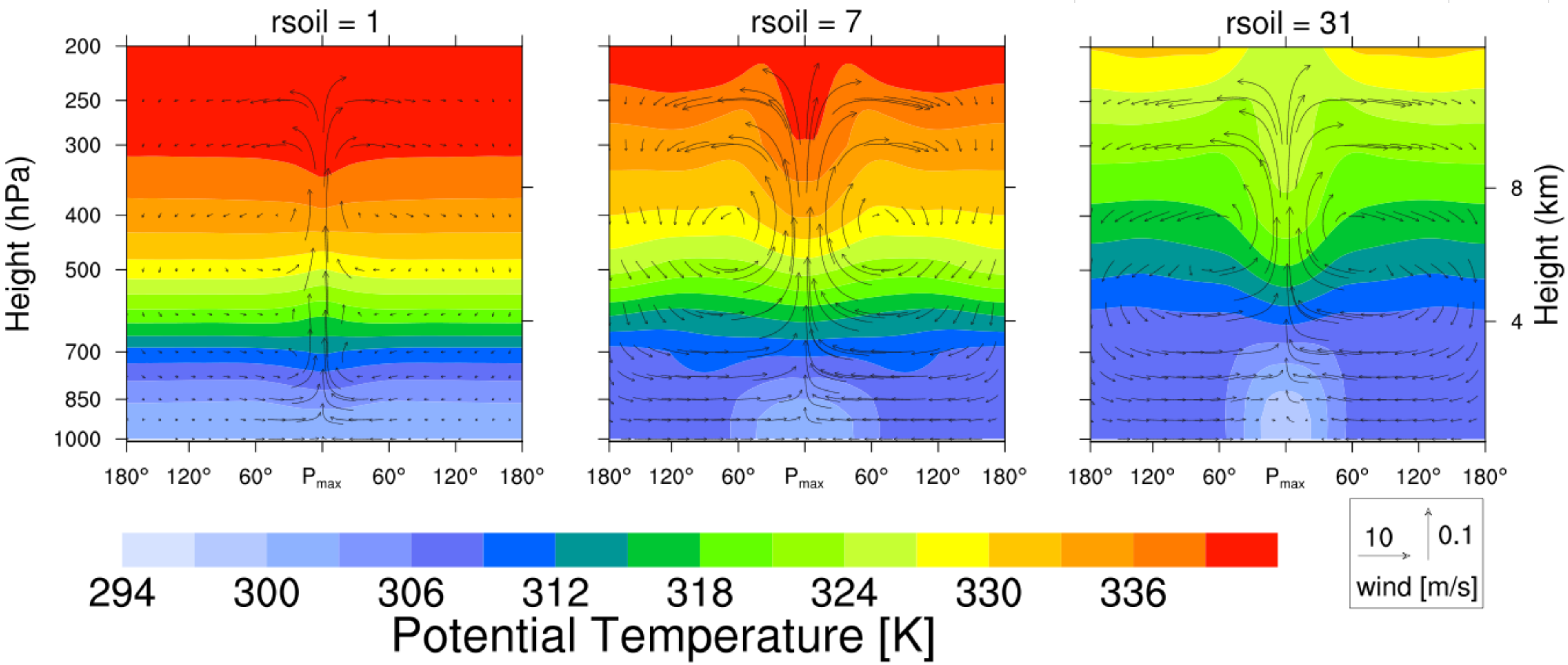




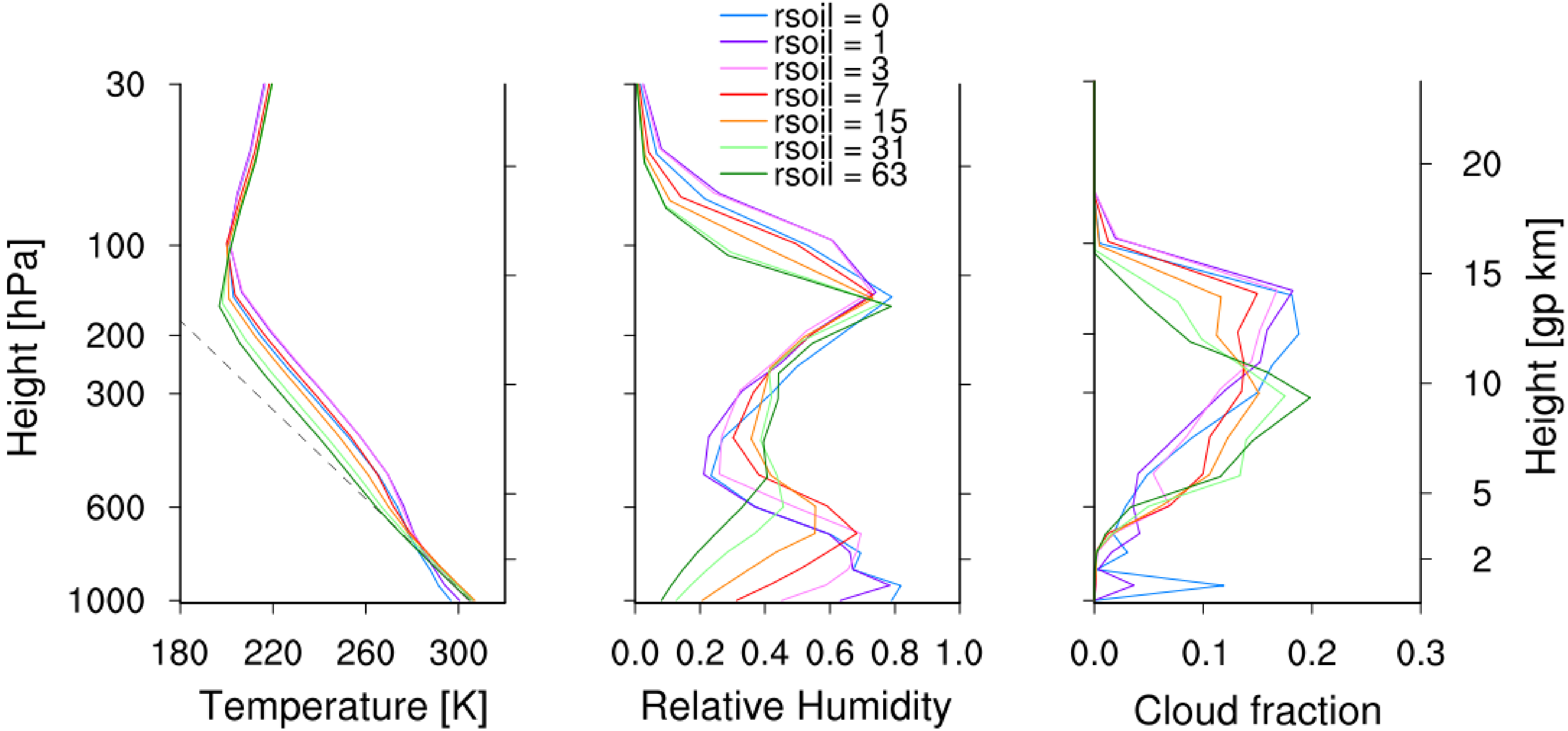
Evaporation resistance	0	1	3	7	15	31	63
Precipitation [mm/d]	4.1	3.8	3.1	2.1	1.3	0.6	0.3

Vertical cross sections centered at location of maximum precipitation

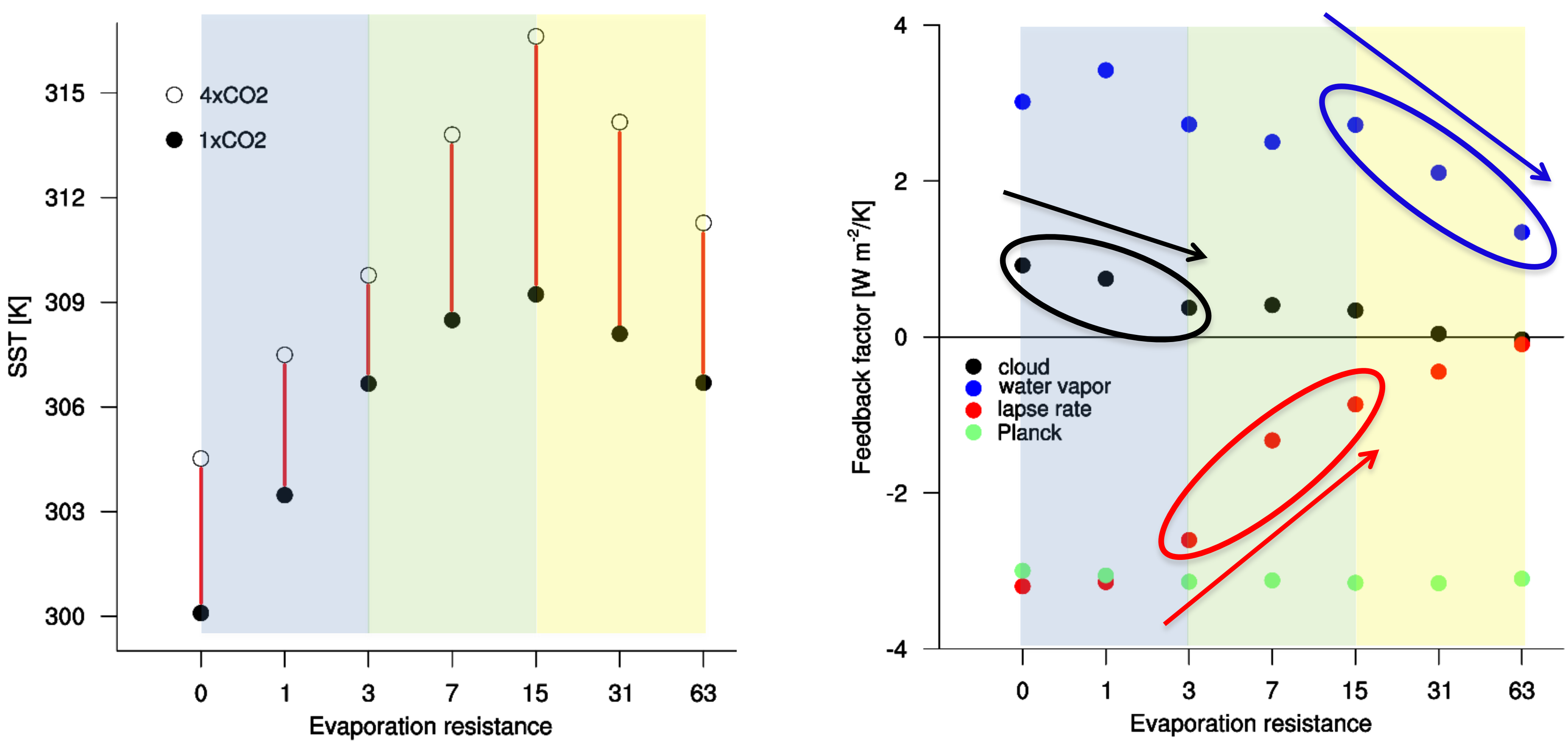




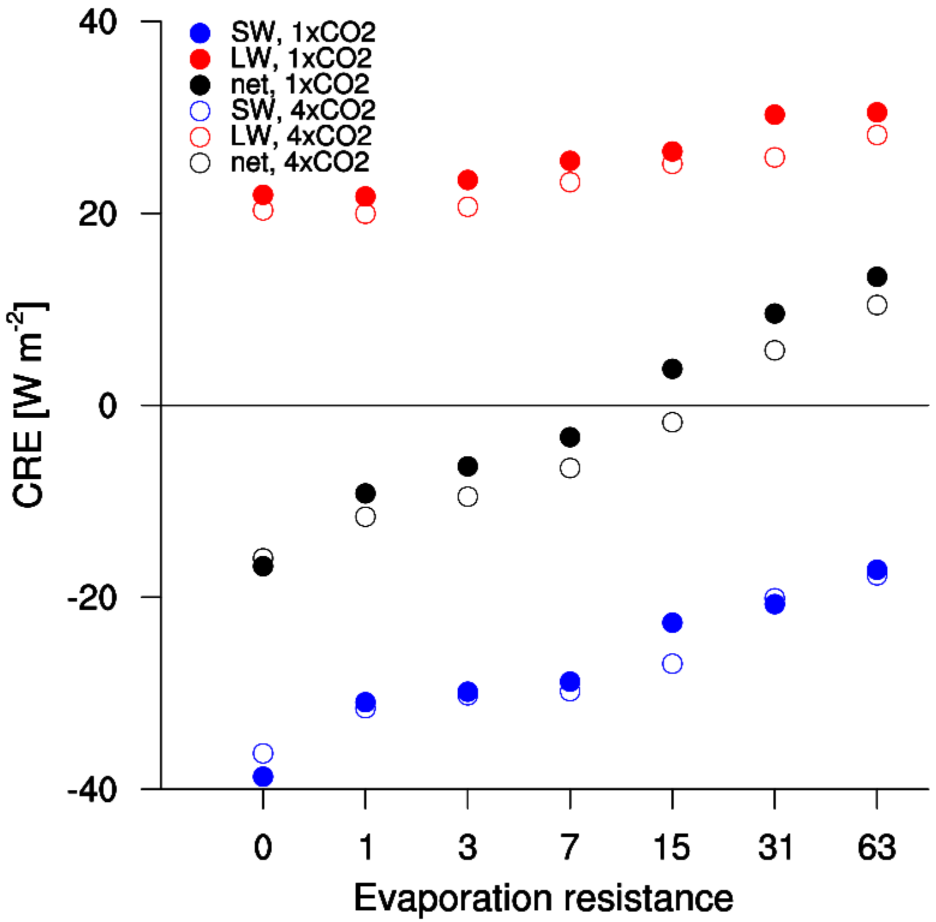
Vertical profiles show decrease of RH in low troposphere, lapse rate increase and reduction of cloud top height

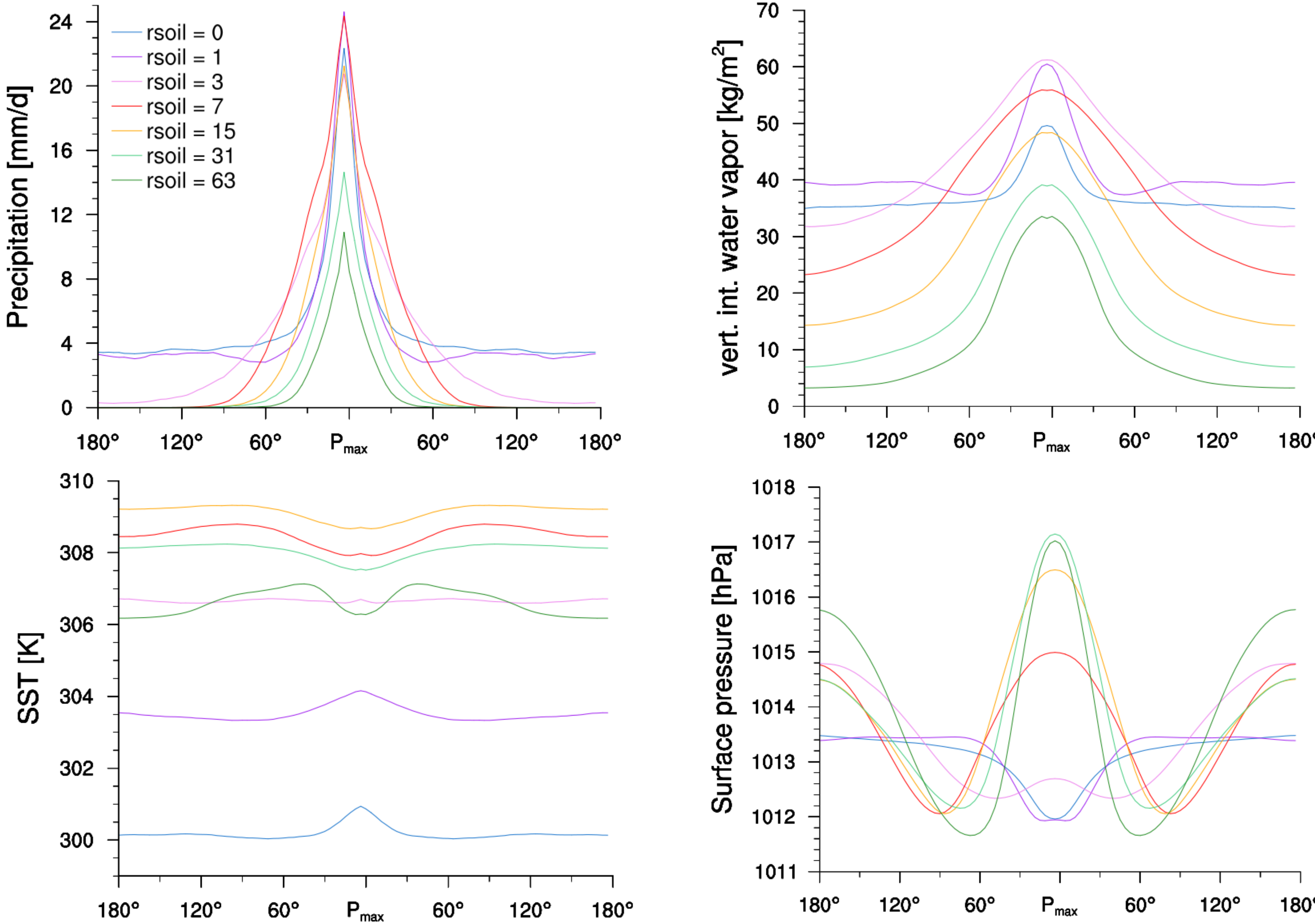


Evaporation resistance - climate sensitivity first decreases, then increases, then decreases again



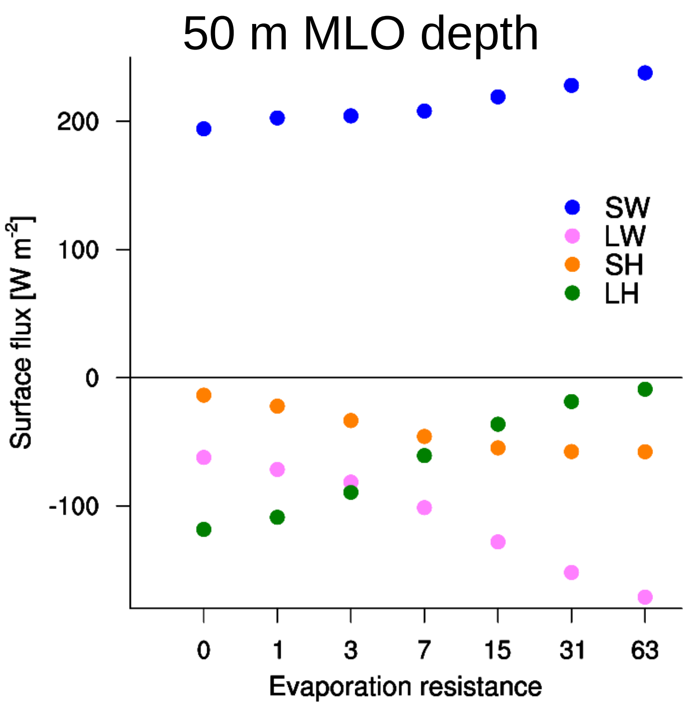
The decrease of CRE encourages self-aggregation

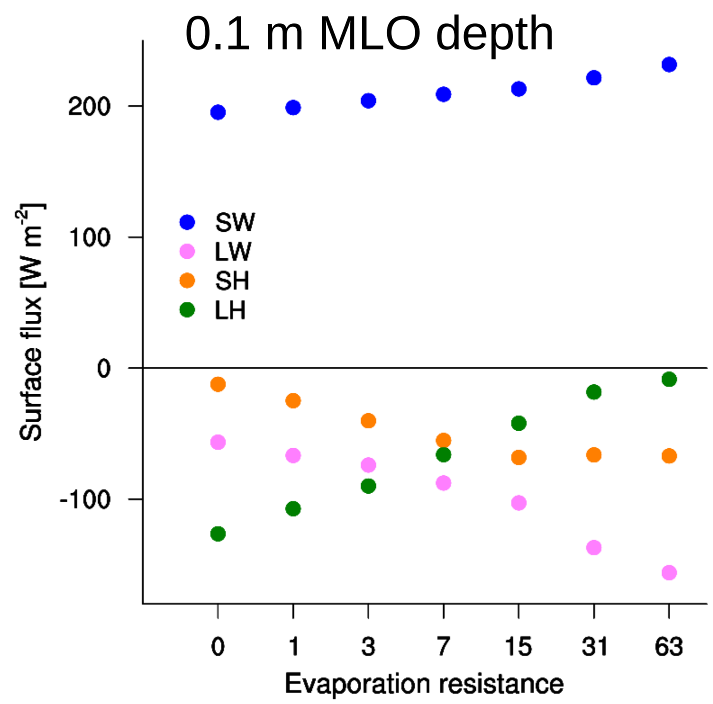



Precipitation [mm/d]
0
4
8
12
16
20
24
rsoil = 0
rsoil = 1
rsoil = 3
rsoil = 7
rsoil = 15
rsoil = 31
rsoil = 63
180°
120°
60°
Pmax
60°
120°
180°
vert. int. water vapor [kg/m2]
0
10
20
30
40
50
60
70
SST [K]
300
302
304
306
308
310
Surface pressure [hPa]
1011
1012
1013
1014
1015
1016
1017
1018

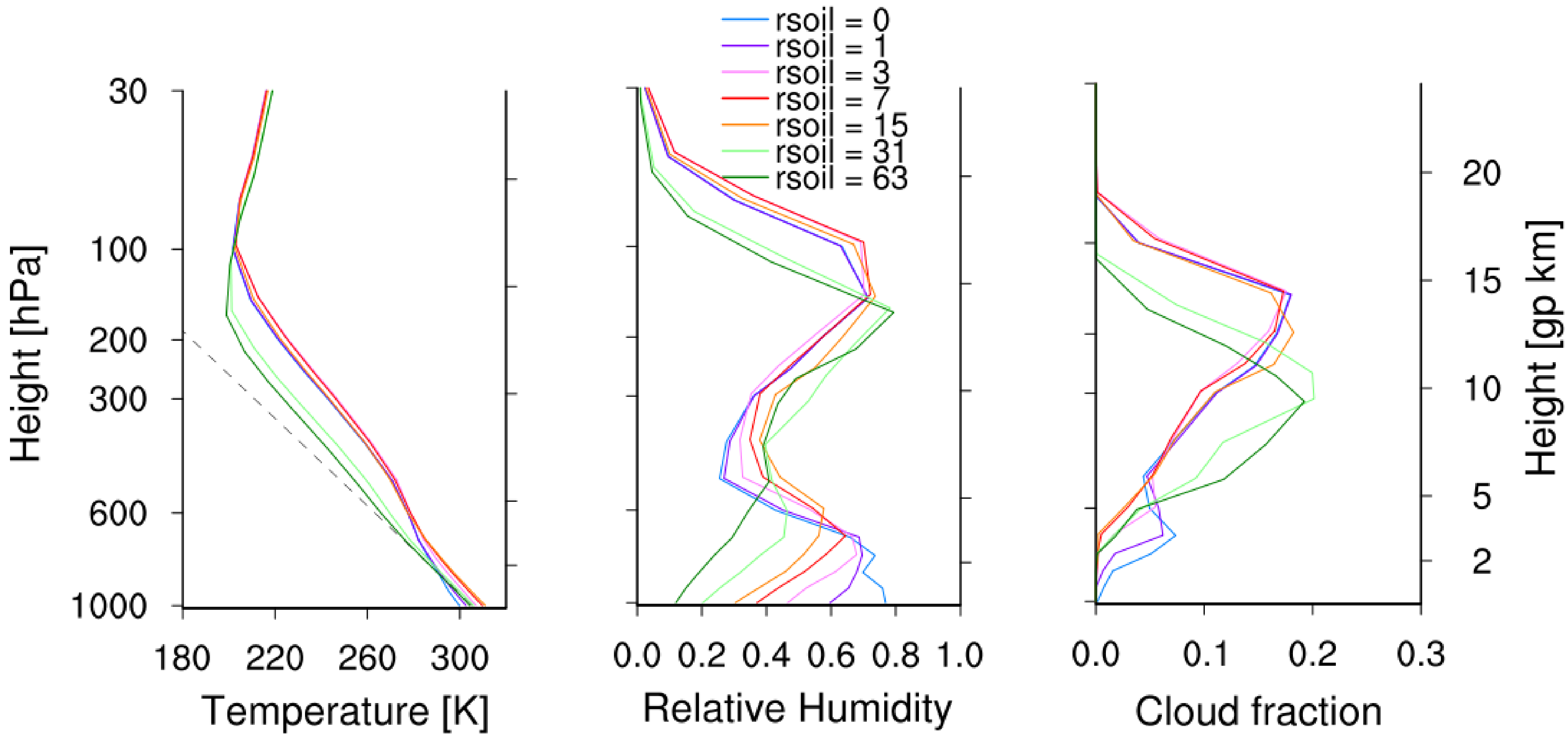
Combination of Effects

- 0.1 m MLO depth
- Evaporation Resistance 0, 1, 3, 7, 15, 31, 63

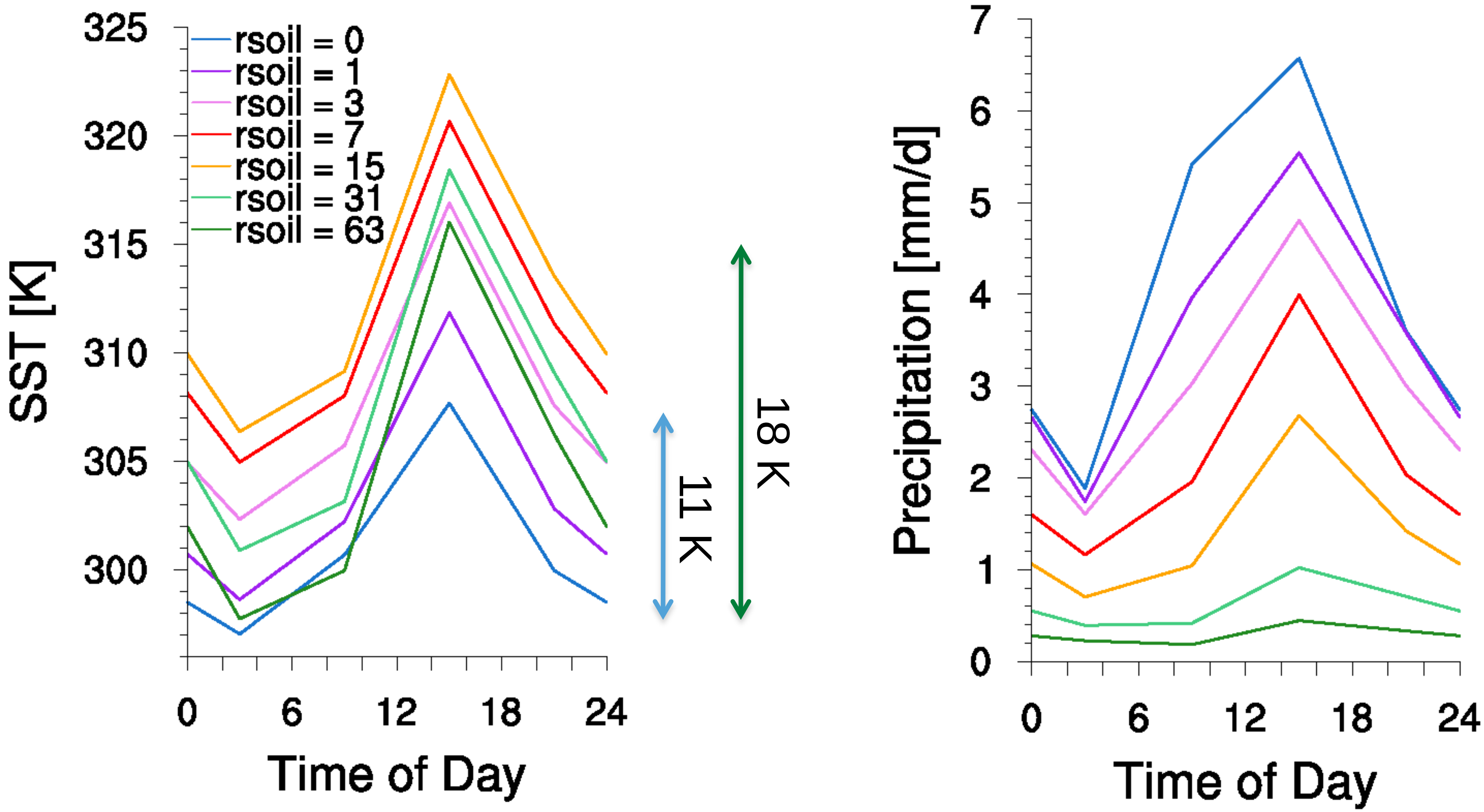




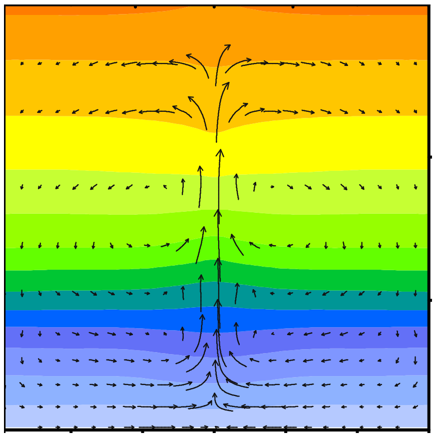
Similar tendencies of vertical profiles as before, with strong transition for rsoil > 15



SST amplitude increases while precipitation always peaks in the afternoon



R

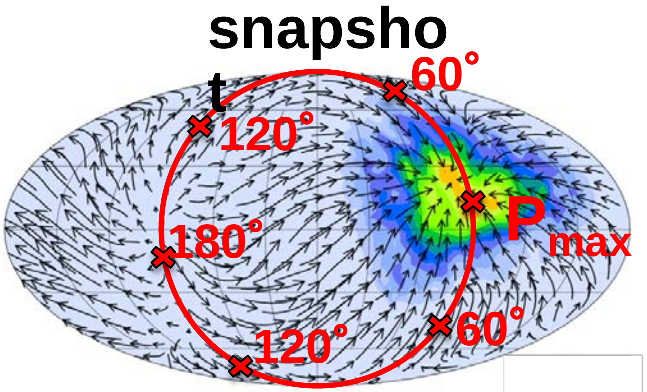


R

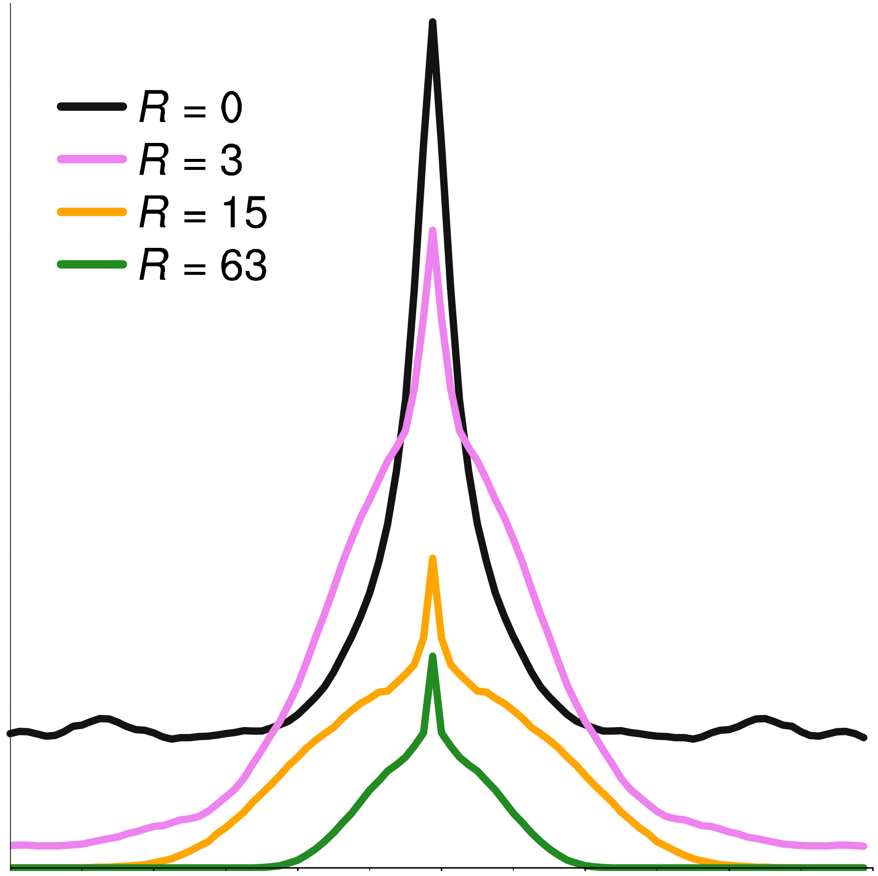
R

R

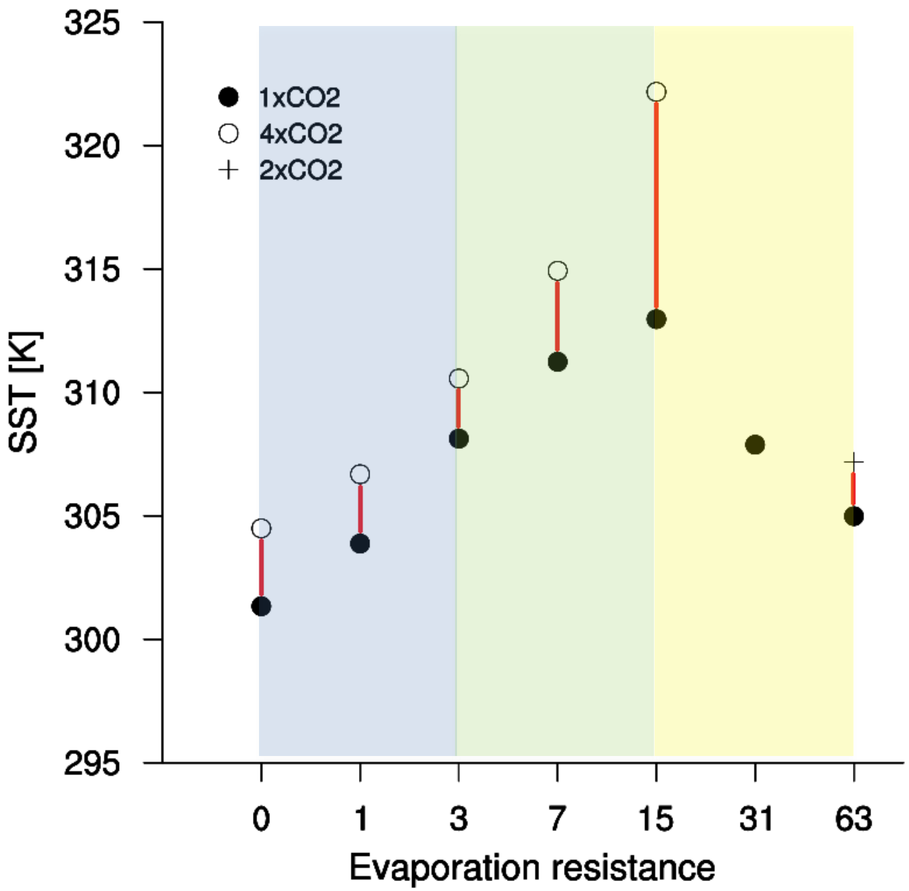
Vertical cross sections centered at location of maximum precipitation

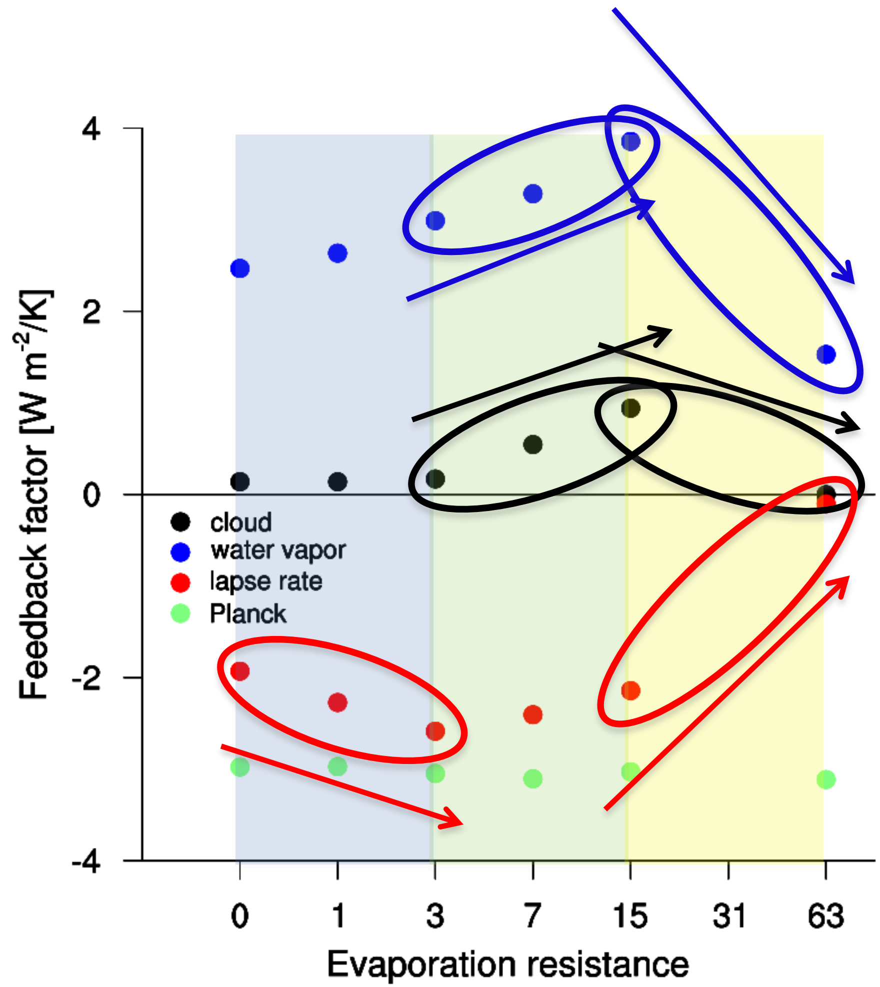


Convective aggregation for R ≥ 3



Similar tendencies for climate sensitivity as before, but dominant feedbacks change

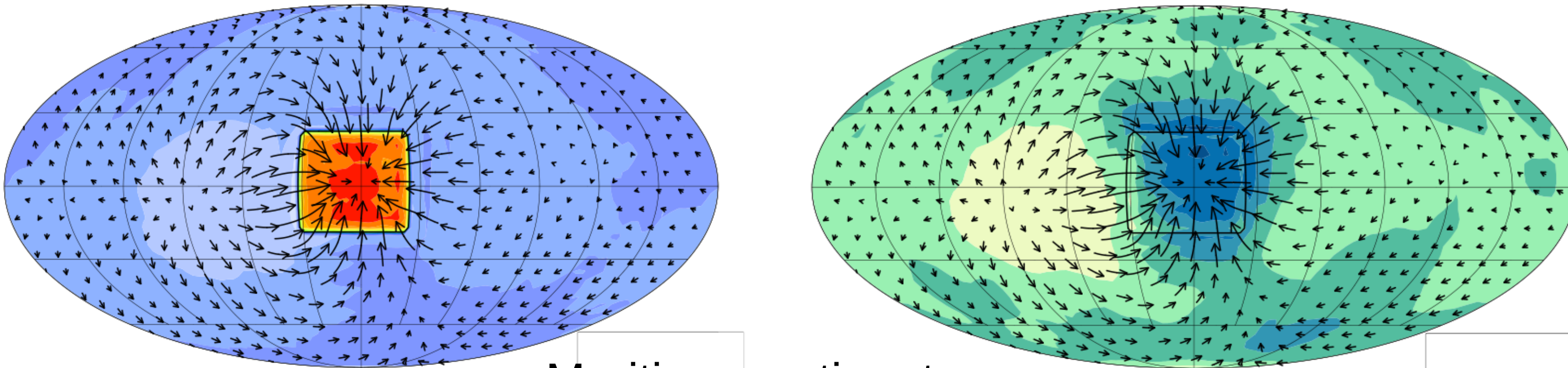




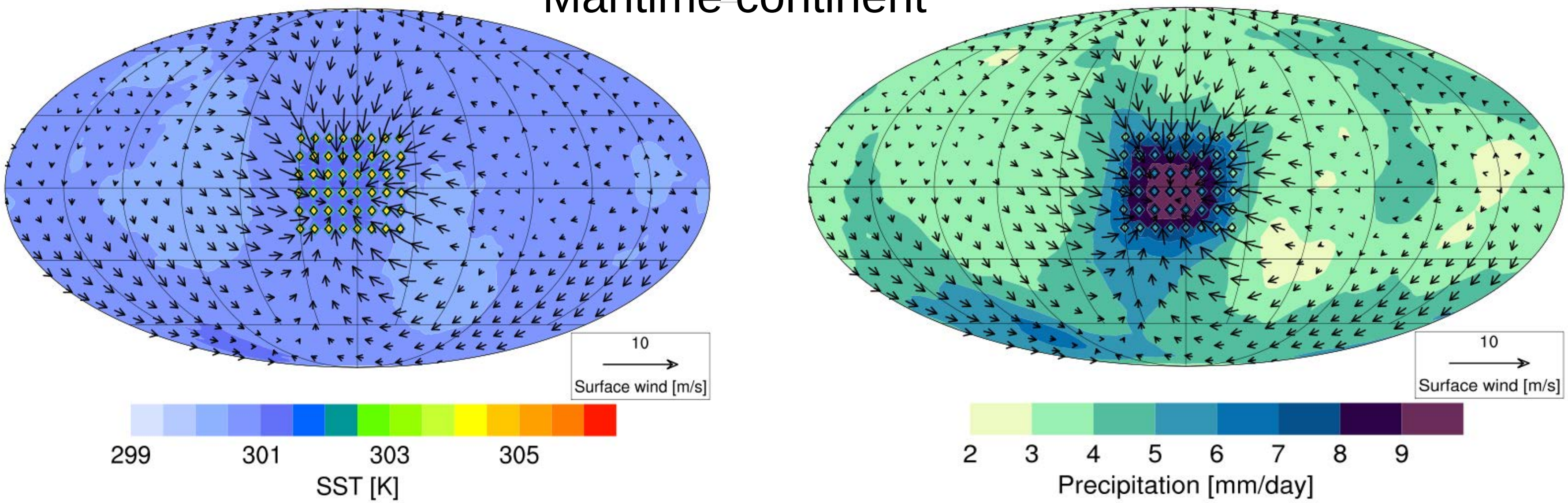
Idealized continents

MLO depth = 0.1 m
rsoil = 15

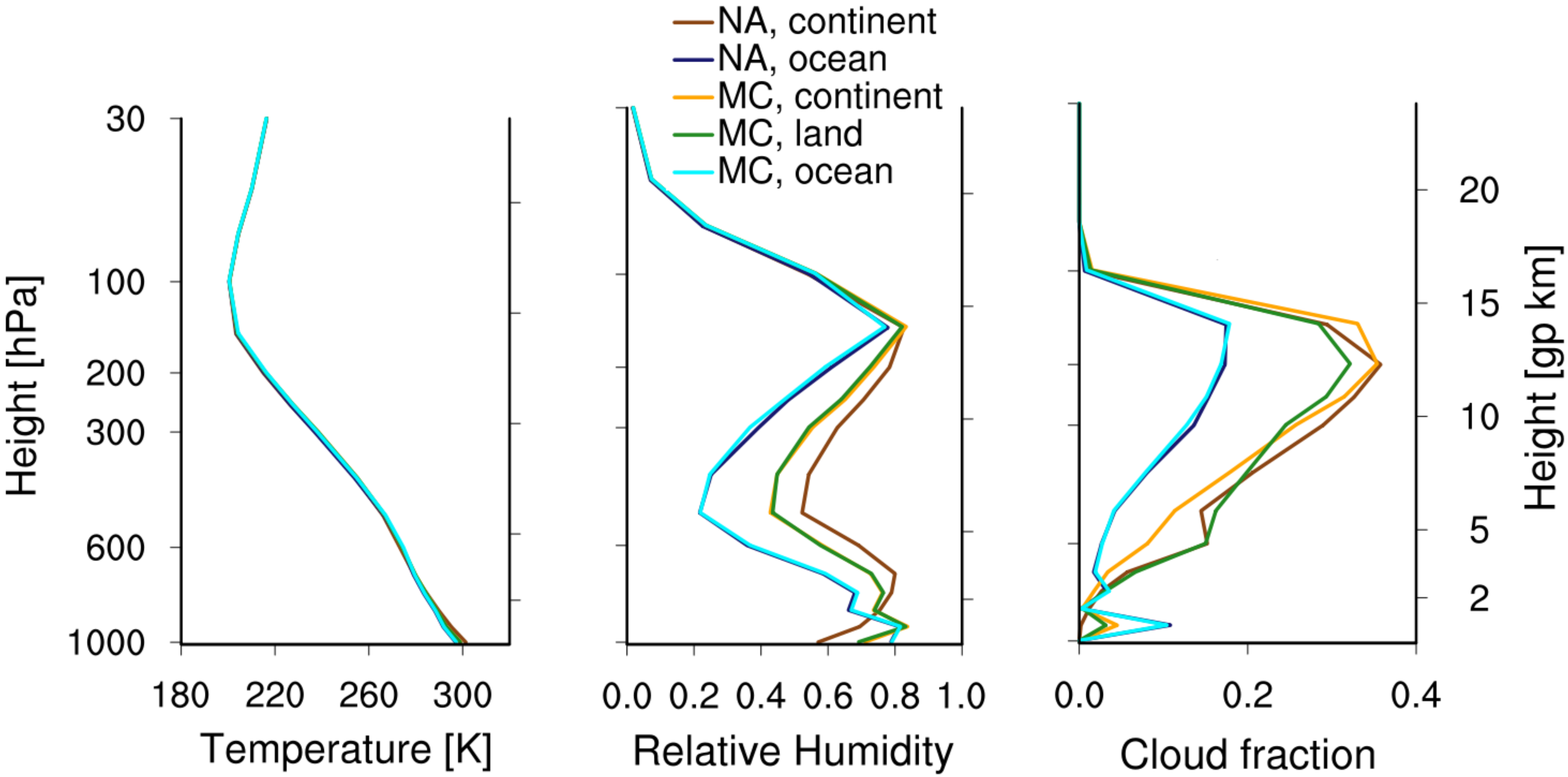
One continent – size of North Africa



Maritime continent



Temperature profiles very similar, though increased RH and more clouds over land



Summary

Influence of surface heat capacity

- If the slab depth is 10 cm or smaller, then the diurnal cycle of SST is strong enough to influence atmospheric processes
  - more convection
  - rectification
  - precipitation maximum moves from night to day
- One-off decrease of climate sensitivity due to boundary layer cloud dissipation

Influence of evaporation resistance

- Reduction of LH is compensated primarily by LW,
  but also by SH
- Climate sensitivity is highest (4.6 K) in a semiarid climate

- A change in heat capacity does not change main results