Stratocumulus steady states in a perturbed climate: a single-column model intercomparison study

S. Dal Gesso, A. P. Siebesma, S. de Roode
KNMI, Royal Netherlands Meteorological Institute
TUD, Delft University of Technology

1 Introduction and motivation

Marine stratocumulus (Scu) clouds strongly influence the radiative budget of the Earth. Predicting how both their geographical distribution and their physical properties would respond to climate change is still a fundamental open question. At the same time the subtle and complex interaction between atmospheric dynamics and convective, turbulent and radiative processes, from which Scu arise, is difficult to be captured by a general circulation model (GCM). For these reasons the Scu, together with cumulus clouds, are still the heart of the problem of climate feedback uncertainties, as claimed in Bony and Dufresne (2005).

Recently many efforts are put into identifying the causes of the large model spread for low-cloud climate feedback. In particular CGILS project is a Single-Column Model (SCM) and Large Eddy Simulation intercomparison study aimed to investigate this issue. The set-up includes three cases corresponding to three cloud regimes: coastal stratus (S12), Scu (S11) and cumulus (S6). The idealized large scale forcings and free-tropospheric conditions are based on selected locations along the GPCI transect. The models are forced to a steady state for the control set-up and the for perturbed large scale conditions, mimicking climate change. The response to this perturbation gives information on the feedback. On the one hand LESs agree well in the sign of the feedback, while SCM spread is still significant (Zhang and Bretherton, 2008, Zhang et al., 2013, ?).

The present framework is aimed to be a CGILS extension. In particular we generalize the Scu steady state response to climate change for different meteorological conditions. The scientific questions we want to address are the following:

1. What are the steady state solutions of a Scu-topped atmospheric boundary layer (ABL) for a wide range of different atmospheric conditions?

2. How are the steady state solutions affected by perturbations of large scale forcing?

2 Experimental set-up

2.1 Large scale forcings

The sea surface temperature (SST) is a typical value for Scu-topped region in the North-East Pacific. The large scale vertical velocity, $w(z)$, is chosen according to the following formula (Bellon and Stevens, 2012):

$$w(z) = w_0\left(1 - e^{-\frac{z}{z_w}}\right)$$

where w_0 is an asymptotic value and z_w is a typical length scale (for details see Table 1).

	CTL	PC
SST (K)	292.	294.
p_s (hPa)	1012.8	1012.8
w_0 (mm/s)	-3.5	-3.5
z_w (m)	500.	500.

Table 1: large scale forcings for both the control (CTL) and the perturbed climate (PC) case.

The incoming shortwave radiation at the top of atmosphere is kept constant and equal to the diurnally averaged value. This procedure mimics the absence of variation in time and space. Actually the model is run for 100 days in order to achieve the equilibrium and to collect enough statistics. The date, location and radiative forcing details, collected in Table 2, are the same as in CGILS S11.

LAT (N)	32.°
LON (W)	129.°
date	15 July 2003
TOA insolation (W/m^2)	471.5
Solar zenith angle	52
Daytime fraction	0.58
Eccentricity	0.967
Surface Albedo	0.07

Table 2: radiative forcings (Zhang and Bretherton, 2008)

2.2 Initial conditions

In this section we describe the initial thermodynamic profiles for a reference case that is generalized by varying the tropospheric conditions.

2.2.1 Reference simulation

The atmospheric initial thermodynamic profiles are defined as follows:

- **ABL**
  $z \leqslant 800m$ $\quad\theta_l = 289.5K \quad q_t = 10.7g/kg;$
- **free troposphere**
  $800m < z \leqslant 3000m \quad T = -6.5E-3 \cdot z + 303.1 \quad q_t = 5.7g/kg$
  $3000m < z \leqslant 15500m \quad T = -6.5E{-}3{\cdot}z{+}303.1 \quad q_t = q_t(3000m)\exp{(-\frac{z-3000}{1500})};$
- **tropopause**
  $15500m < z \leqslant 35000m \quad T = 0.002 \cdot z + 176.1 \quad q_t = 0g/kg;$
- **stratosphere**
  $z > 35000m \quad T = 239.5K \quad q_t = 0g/kg.$

The values in the ABL are chosen according to the following assumptions:

1. the atmospheric temperature at the surface is 1.5 K colder than SST;
2. the relative humidity, RH, at the surface is 80%.

The thermodynamic profiles in the free troposphere are defined in order to achieve an equilibrium in absence of horizontal advections. For the profiles in the tropopause and in the stratosphere, linear fits of CGILS thermodynamics profiles are considered as an idealization of realistic profiles in the North-Eastern Pacific.

In order to ensure that the free troposphere remains in equilibrium, nudging should be applied to all model levels above the highest model level below 3000 m. The nudging timescale should be equal (or shorter) than the model time step.

2.2.2 Generalization of the reference simulation: control case (CTL)

By systematically varying the inversion jumps (see Figure 1), we obtain a wide range of different meteorological free-tropospheric conditions. The following ranges of thermodynamic jumps are considered:

$$\Delta_I \theta_l \in [11., 20.]K$$

$$\Delta_I q_t \in [-7.5, -2.5] g/kg$$

They are modified by a step of 0.5 K and g/kg, respectively. In this way the region of the phase space dominated by Scu is well-mapped.

In order to have the same thermodynamic profiles in the tropopause and in the stratosphere, the height at which the troposphere becomes tropopause slightly changes from one simulation to the other.

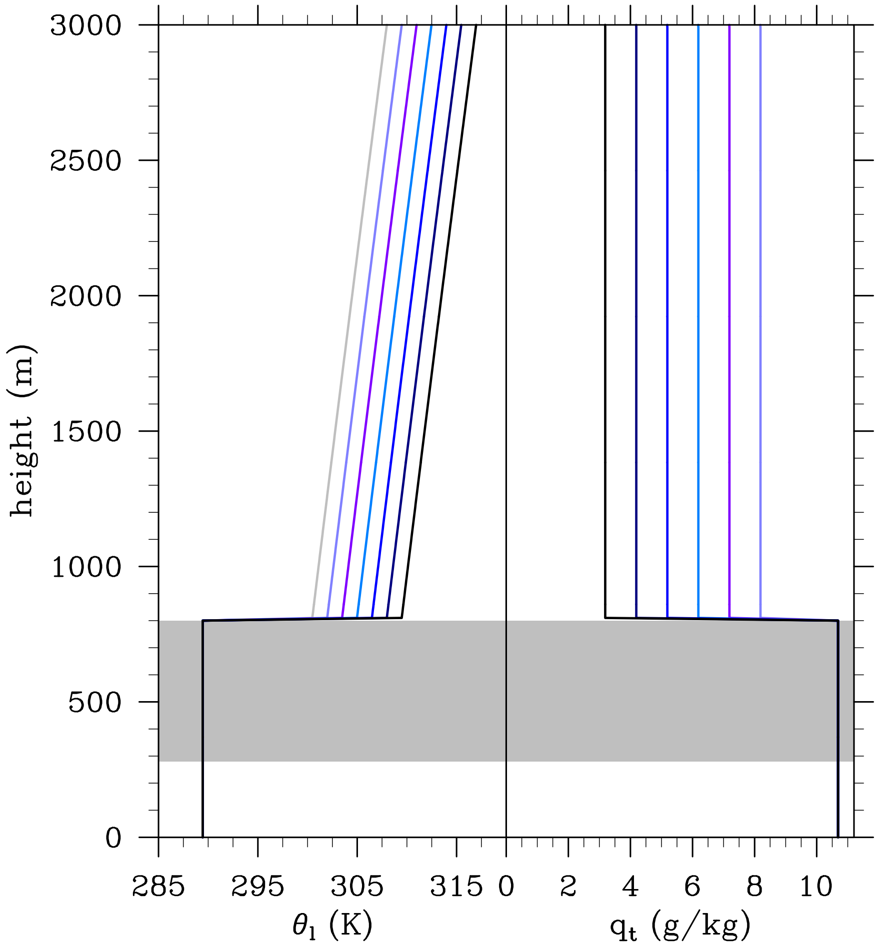

Figure 1: initial conditions of CTL case: some examples of liquid water potential temperature, θ_l, and total water content, q_t, profiles. The grey zone represents the cloud layer.

3 Climate perturbation

In the second set of experiments, called perturbed climate (PC), the large scale forcings are perturbed in order to mimic the future climate conditions. The details of the perturbation are collected in Table 1

3.1 Perturbed reference simulation

The atmospheric initial thermodynamic profiles are defined as follows:

- **ABL**
  $z \leqslant 800m$ $\theta_l = 291.4K$ $q_t = 12.g/kg$;
- **free troposphere**
  $800m < z \leqslant 3000m$ $T = -6.5E-3 \cdot z + 305.1$ $q_t = 6.4g/kg$;
  $3000m < z \leqslant 15700m$ $T = -6.5E{-}3{\cdot}z{+}305.1$ $q_t = q_t(3000m)\exp(-\frac{z-3000}{1500})$;
- **tropopause**
  $15700m < z \leqslant 35000m$ $T = 0.002 \cdot z + 176.1$ $q_t = 0g/kg$;
- **stratosphere**
  $z > 35000m$ $T = 239.5K$ $q_t = 0g/kg$.

The temperature and humidity in the ABL are calculated according to the same assumptions as in the reference case.
In the free troposphere the temperature profile is shifted by 2 K (as much as SST), thus the inversion jump corresponds to the reference one. While the total water content up to 3000 m is calculated so that the relative humidity (RH) at the top of the inversion is equal to the value in the reference case. As a consequence of the warming in the free troposphere the q_t stratification is different with respect to the reference case.
In the tropopause and stratosphere the profiles are not changed.

3.2 Perturbed climate case (PC)

To generalize the perturbed reference simulation we consider the same range of temperature jumps but we calculate the free-tropospheric values of q_t as explained before. The experiments are labelled using the phase-space coordinates (see next section for definitions) of the CTL simulations for the temperature they correspond to the actual ones while for the total water content the stratification is slightly stronger (see Figure 2).

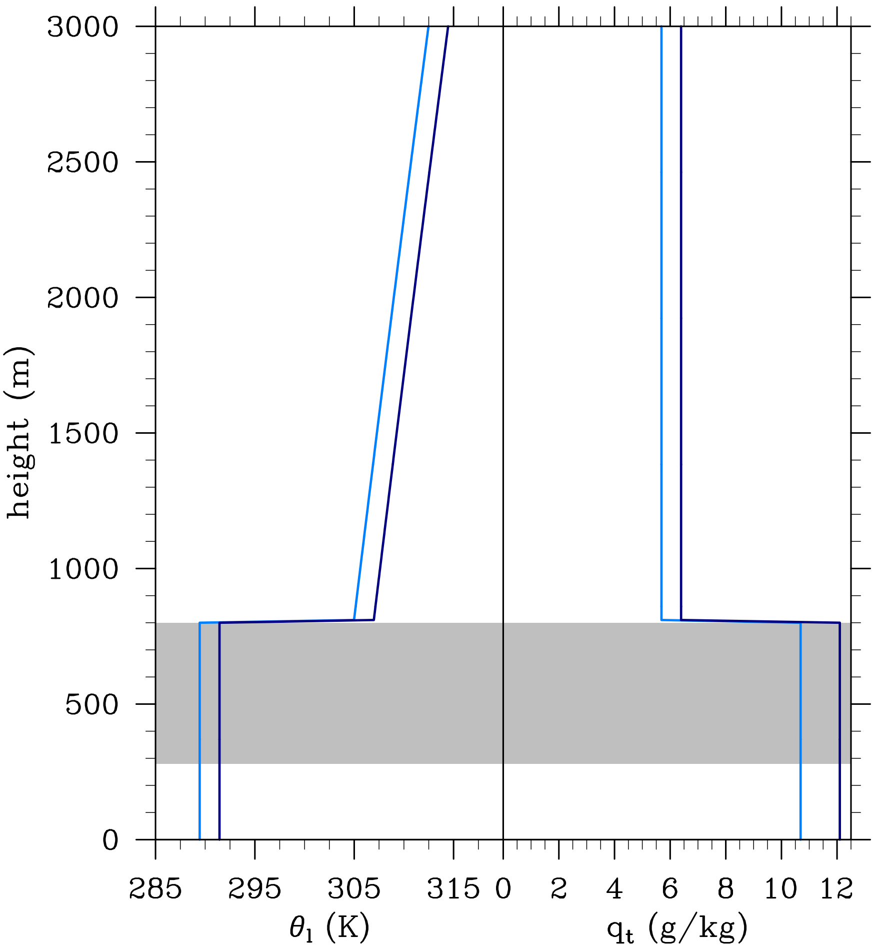

Figure 2: comparison between initial thermodynamic profiles of CTL (light blue) and PC case (dark blue): examples of liquid water potential temperature, θ_l, and total water content, q_t. The grey zone represents the cloud layer.

3.3 Stochastic forcing (SF)

Brient and Bony (2012) demonstrate that a single-column model can reproduce the cloud representation in a 3D GCM more realistically if a stochastic component is added to the Large scale forcing. To this purpose we define a additional stochastic term as:

$$w(t,z) = \overline{w}(z) + \overline{w}(z) \cdot X(t)$$

where X is a random number that varies between σ and $-\sigma$ with σ equal to 0.5. A new value of the subsidence is calculated every six hours. The previously described forcing is applied to both cases, i.e. CTL and PC, so that the feedback can be calculated with both steady and stochastic forcings.

4 Simulation instructions

4.1 General information

Deadline for submission: October 15, 2013.
Input files:

- CTL case: *SteadyStates_CTL_inpunt.nc*;
- PC case: *SteadyStates_PC_inpunt.nc*;
- stochastic forcing for CTL case: *SteadyStates_CTL_SF_inpunt.nc*;
- stochastic forcing for PC case: *SteadyStates_PC_SF_inpunt.nc*;

Simulation time: 100 days (for each simulation).
No diurnal cycle: as in CGILS we accept any method is more convenient for you as long as there is no diurnal variation in the SW heating.
Ozone concentration: not given in the input file as usually it is already prescribed in GCMs.
Submitted files: 3 files for each set of simulations so 12 files in total (further details in the next section)

4.2 Input files

File name for CTL case: **surname_in_CTL.nc**
File name for PC case: **surname_in_PC.nc**
File name for CTL case with stochastic forcing: **surname_in_CTL_SF.nc**
File name for PC case with stochastic forcing: **surname_in_PC_SF.nc**

The latter two files include only the stochastic forcing (i.e. large scale vertical velocity, w). All the other initial profiles are the same as in the standard case and can be found in the first two files.

5 Output requirement

The phase space is defined by the following quantities:

$$LTS = \theta_l(p = 700hPa) - \theta_{l\,surf} \qquad \Delta q_t = q_t(p = 700hPa) - q_{t\,surf}$$

where LTS is the lower tropospheric stability and Δq_t is the lower tropospheric humidity.

The dimensions of the outputs are:

1. $\Delta q_t(g/kg)$ [1]
2. $LTS(K)$
3. lev or lev1 (profiles only)

where lev and lev1 correspond to the number of full and half levels, respectively.

The outputs are a subset of CGILS requirements that needs to be collected in three NetCDF files. The first one gathers the initial conditions used by the modellers, this file is useful to check the consistency with the proposed set-up. The other two files are dedicated to the case results.
The results are calculated as six hourly averages over the last 80 days of simulation. Moreover the root mean squared (rms) of some variables is required to check the stationarity of the steady states (for each 6 hour interval).

[1] in the NetCDF file it must be called delta_qt

5.1 Initial conditions

File name for CTL case: **surname_in_CTL.nc**
File name for PC case: **surname_in_PC.nc**
File name for CTL case with stochastic forcing: **surname_in_CTL_SF.nc**
File name for PC case with stochastic forcing: **surname_in_PC_SF.nc**

Name	Unit	Dimensions	Description
SST	K	-	Sea Surface Temperature
ps	Pa	-	Surface Pressure
z_f	m	Δq_t ; LTS ; lev	Height at Full Levels
z_h	m	Δq_t ; LTS ; lev1	Height at Half Levels
p_f	Pa	Δq_t ; LTS ; lev	Pressure at Full Levels
p_h	Pa	Δq_t ; LTS ; lev1	Pressure at Half Levels
T	K	Δq_t ; LTS ; lev	Temperature
qv	g/kg	Δq_t ; LTS ; lev	Water Vapuor Mixing Ratio (q_v)
ql	g/kg	Δq_t ; LTS ; lev	Liquid Water Mixing Ratio (q_l)
cloud	-	Δq_t ; LTS ; lev	Cloud Fraction
u	m/s	Δq_t ; LTS ; lev	U-wind
v	m/s	Δq_t ; LTS ; lev	V-wind
w	m/s	Δq_t ; LTS ; lev	Subsidence

Table 3: phase space simulations: output for initial conditions file.

5.2 Scalars

File name for CTL case: **surname_scal_CTL.nc**
File name for PC case: **surname_scal_PC.nc**
File name for CTL case with stochastic forcing: **surname_scal_CTL_SF.nc**
File name for PC case with stochastic forcing: **surname_scal_PC_SF.nc**

Name	Unit	Dimensions	Description
cldtot	-	Δq_t ; LTS ; time	Total Cloud Cover
cldlow	-	Δq_t ; LTS ; time	Low-level Cloud Cover
tglwp	kg/m^2	Δq_t ; LTS ; time	Vertically-integrated Liquid Water
precw	kg/m^2	Δq_t ; LTS ; time	Precipitable Water
tsair	K	Δq_t ; LTS ; time	Surface Air Temperature
ps	hPa	Δq_t ; LTS ; time	Surface Pressure
prect	mm/day	Δq_t ; LTS ; time	Surface Total Precipitation Flux
sh	W/m^2	Δq_t ; LTS ; time	Surface Sensible Heat Flux
lh	W/m^2	Δq_t ; LTS ; time	Surface Latent Heat Flux
pblh	m	Δq_t ; LTS ; time	PBL Height
fsntc	W/m^2	Δq_t ; LTS ; time	TOA SW net downward clear-sky radiation
fsnt	W/m^2	Δq_t ; LTS ; time	TOA SW net downward total-sky radiation
flntc	W/m^2	Δq_t ; LTS ; time	TOA LW clear-sky upward radiation
flnt	W/m^2	Δq_t ; LTS ; time	TOA LW total-sky upward radiation
fsnsc	W/m^2	Δq_t ; LTS ; time	Surface SW net downward clear-sky radiation
fsns	W/m^2	Δq_t ; LTS ; time	Surface SW net downward total-sky radiation
flnsc	W/m^2	Δq_t ; LTS ; time	Surface LW net upward clear-sky radiation
flns	W/m^2	Δq_t ; LTS ; time	Surface LW net upward clear-sky radiation
rms_cldtot	-	Δq_t ; LTS ; time	RMS of Total Cloud Cover
rms_tglwp	kg/m^2	Δq_t ; LTS ; time	RMS of Vertically-integrated Liquid Water
rms_prect	mm/day	Δq_t ; LTS ; time	RMS of Surface Total Precipitation Flux
rms_sh	W/m^2	Δq_t ; LTS ; time	RMS of Surface Sensible Heat Flux
rms_lh	W/m^2	Δq_t ; LTS ; time	RMS of Surface Latent Heat Flux
rms_pblh	m	Δq_t ; LTS ; time	RMS of PBL Height

Table 4: phase space simulations: output for scalar file.

5.3 Profiles

File name for CTL case: **surname_prof_CTL.nc**
File name for PC case: **surname_prof_PC.nc**
File name for CTL case with stochastic forcing: **surname_prof_CTL_SF.nc**
File name for PC case with stochastic forcing: **surname_prof_PC_SF.nc**

Name	Unit of measurement	Dimensions	Description
z_f	m	Δq_t ; LTS ; time ; lev	Height at Full Levels
z_h	m	Δq_t ; LTS ; time ; lev1	Height at Half Levels
p_f	Pa	Δq_t ; LTS ; time ; lev	Pressure at Full Levels
p_h	Pa	Δq_t ; LTS ; time ; lev1	Pressure at Half Levels
T	K	Δq_t ; LTS ; time ; lev	Temperature
qv	g/kg	Δq_t ; LTS ; time ; lev	q_v
ql	g/kg	Δq_t ; LTS ; time ; lev	q_l
cloud	-	Δq_t ; LTS ; time ; lev	Cloud Fraction
u	m/s	Δq_t ; LTS ; time ; lev	U-wind
v	m/s	Δq_t ; LTS ; time ; lev	V-wind
prec	W/m^2	Δq_t ; LTS ; time ; lev1	Precipitation Flux
wthl	W/m^2	Δq_t ; LTS ; time ; lev1	Heat Flux
wqt	W/m^2	Δq_t ; LTS ; time ; lev1	Humidity Flux
wthv	W/m^2	Δq_t ; LTS ; time ; lev1	Buoyancy Flux
rms_T	K	Δq_t ; LTS ; time ; lev	RMS of Temperature
rms_qv	g/kg	Δq_t ; LTS ; time ; lev	RMS of q_v
rms_ql	g/kg	Δq_t ; LTS ; time ; lev	RMS of q_l
rms_cloud	-	Δq_t ; LTS ; time ; lev	RMS of Cloud Fraction
rms_u	m/s	Δq_t ; LTS ; time ; lev	RMS of U-wind
rms_v	m/s	Δq_t ; LTS ; time ; lev	RMS of V-wind
rms_prec	W/m^2	Δq_t ; LTS ; time ; lev1	RMS of Precipitation Flux

Table 5: phase space simulations: output for profile file.

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