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# Possible climate transitions from breakup of stratocumulus decks under greenhouse warming

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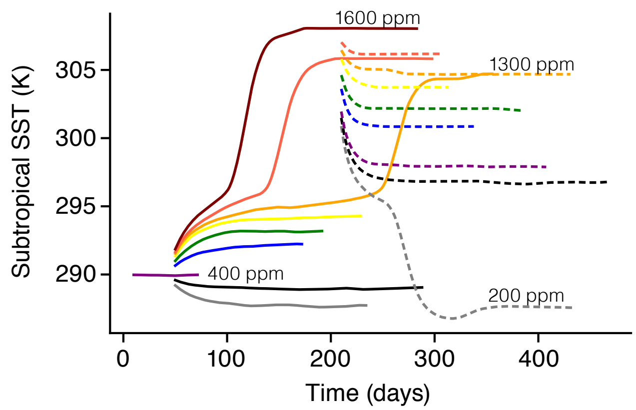
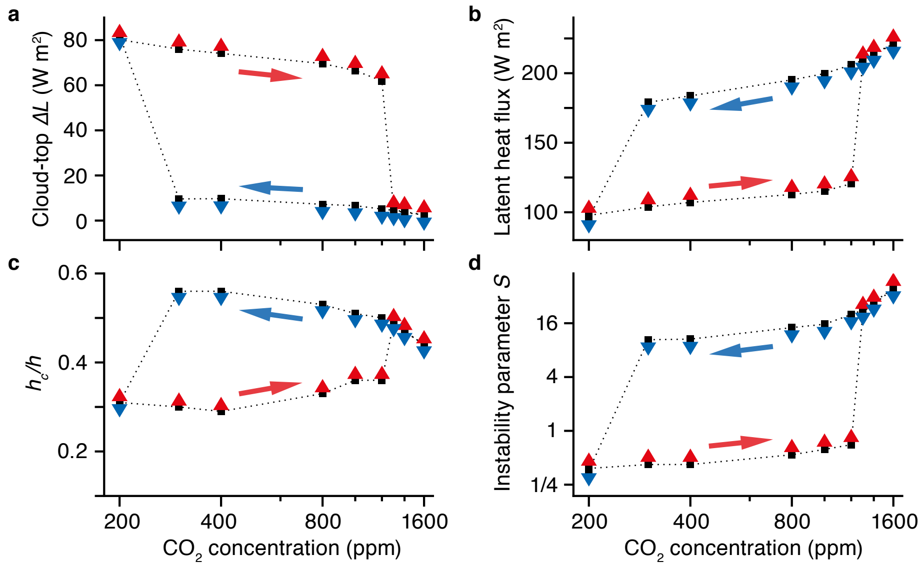
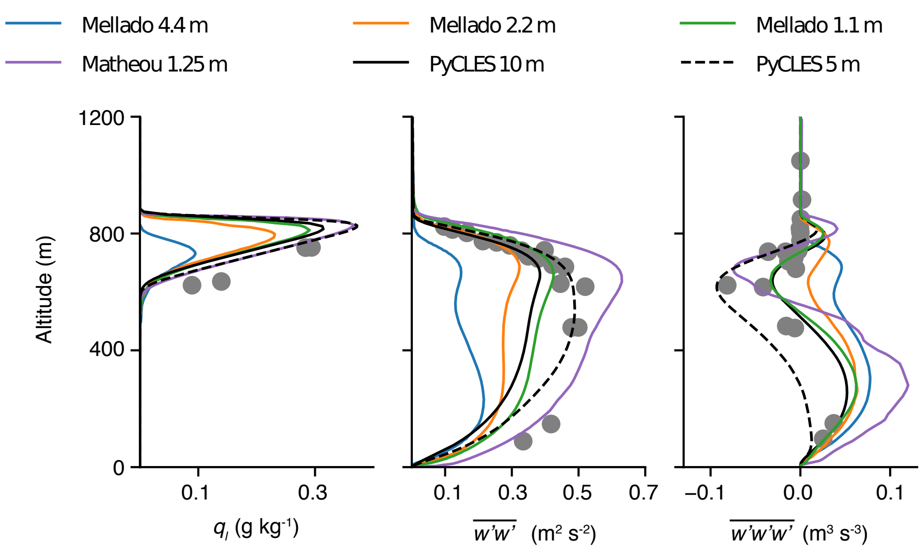


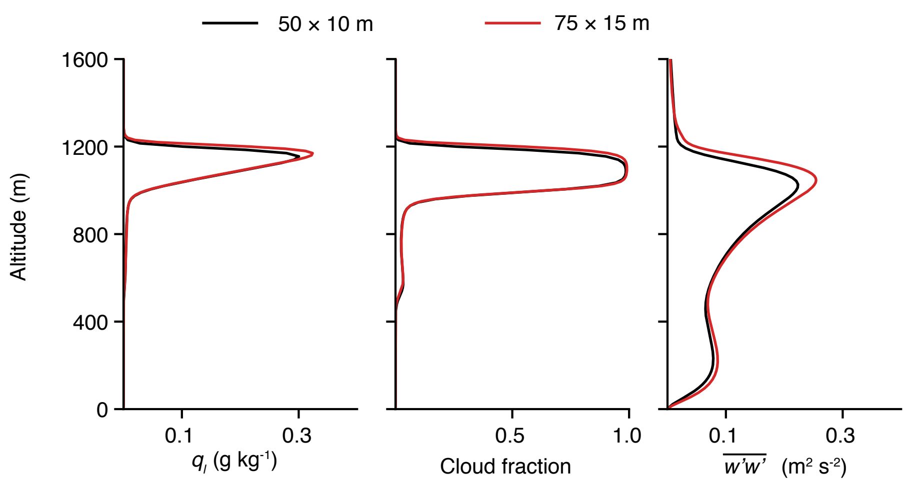

**Supplementary Fig. 1**: **Time evolution of SST in subtropical LES domain.** Shown are the subtropical SST in the standard simulations with fixed subsidence, as a function of simulated day. Solid lines for simulations started from 400 ppm $CO_2$; dashed lines for simulations started from 1600 ppm. Colors indicate atmospheric $CO_2$ concentration: 200, 300, 400, 800, 1000, 1200, 1300, 1400, and 1600 ppm. The small SST steps, e.g., around day 165 for the 1600 ppm simulation, arise because the tropical RCE calculation is updated only once the TOA radiative flux imbalance deviates from its target value by more than a threshold value of $0.2\ \mathrm{W\ m^{-2}}$ (Methods).




**Supplementary Fig. 2**: **Factors controlling stability of stratocumulus decks in simulations with fixed large-scale subsidence.** (**a**) Longwave radiative cooling of cloud tops ($\Delta L$), computed as the difference between net cloudy-sky longwave fluxes at cloud top and 150 m below cloud-top. (**b**) Latent heat flux (LHF) at the surface. (**c**) Fraction of boundary layer occupied by cloud ($h_c/h$). (**d**) Instability parameter $S = (\mathrm{LHF}/\Delta L) \times (h_c/h)$, on a logarithmic axis. As in Fig. 3, red upward arrows indicate simulations started from 400 ppm $CO_2$; blue downward arrows indicate simulations started from 1600 ppm. The cloud base height is determined as the height where the horizontally averaged cloud fraction first exceeds 5%. (The lateral moisture export in our simulations strengthens as the climate warms. Because some of this lateral moisture export occurs in the subcloud layer, it reduces the latent heating that can be realized in the cloud layer from that implied by the surface latent heat fluxes. However, taking this subcloud layer export into account does not substantially change the results here.)




**Supplementary Fig. 3**: **Comparison of simulations of the DYCOMS stratocumulus benchmark.** Liquid water specific humidity ($q_l$), vertical velocity variance ($\overline{w'w'}$), and the third cumulant of vertical velocity ($\overline{w'w'w'}$) in LES and DNS of the DyCOMS-II RF01 benchmark[4], which is qualitatively similar to our baseline case. Simulations with PyCLES at $50\ \mathrm{m} \times 10\ \mathrm{m}$ and $35\ \mathrm{m} \times 5\ \mathrm{m}$ resolution (solid and dashed black lines; profiles averaged between $t = 2$ h and $4$ h after initialization) compare favorably with observations (circles)[43]. They also compare favorably with LES by Matheou[44] (labeled with grid resolution; profiles are snapshots at $t = 2$ h) and with DNS by Mellado et al.[45] on higher-resolution isotropic grids (likewise labeled with grid resolution; profiles averaged between $t = 3.4$–$4.1$ h). For the LES by Matheou, liquid water mixing ratio is plotted in place of the specific humidity $q_l$, but the two are practically indistinguishable in this plot.




**Supplementary Fig. 4**: **Effect of grid resolution on simulated cloud properties.** Liquid water specific humidity ($q_l$), cloud fraction, and vertical velocity variance ($\overline{w'w'}$) in fixed-subsidence simulations with 400 ppm $CO_2$. The black line is the baseline simulation with 50 m horizontal and 10 m vertical resolution; the red line is a simulation with coarsened resolution of $75 \times 10$ m. The simulation setup in both cases is the same, except that the subtropical ocean heat uptake in the coarser-resolution simulation is increased slightly to $\mathrm{OHU} = 3\ \mathrm{W\ m^{-2}}$, to compensate for small changes in radiative energy fluxes at the surface.

**Supplementary Movie**

Movie S1: **Time evolution of the stratocumulus instability.** The shading shows the liquid water path in the subtropical LES domain in the 1300 ppm simulation between days 255 and 275, which is during the time of the stratocumulus breakup (Fig. **1**). Blue for zero LWP, and the colorscale saturates white at a LWP of $300\ \mu\mathrm{m}$. The time series at the bottom show the cloud fraction (blue) and SST (red) in the LES domain. The breakup of the stratocumulus clouds is more rapid than it would be in nature because of the unrealistically small thermal inertia of the underlying slab ocean.