Stratocumulus cloud top radiative cooling and cloud base updraft speeds

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Motivation

- Doppler radar, microwave radiometer, and lidar measurements enable the retrieval of cloud condensation nucleus (CCN) properties in the stratocumulus-capped marine boundary layer (Feingold et al., 1998). The retrieval utilizes the relationship between the cloud drop number concentration, cloud base updraft speed $w^{\uparrow}_b$, and the cloud base CCN spectrum.
- An empirical relationship between stratocumulus cloud-integrated radiative heating + cooling ("cloud-top radiative cooling", CTRC) and $w^{\uparrow}_b$ (Zheng et al., 2016) enables
  - the use of satellite-derived cloud parameters to determining the CCN concentration below clouds using satellite observations of cloud radiation,
  - and the parameterization of cloud base updraft speed in climate models to improve the representation of aerosol-cloud interactions.
- We investigate the relationship of CTRC and cloud base updraft speed $w^{\uparrow}_b$ in a stratocumulus cloud using a large eddy simulation.

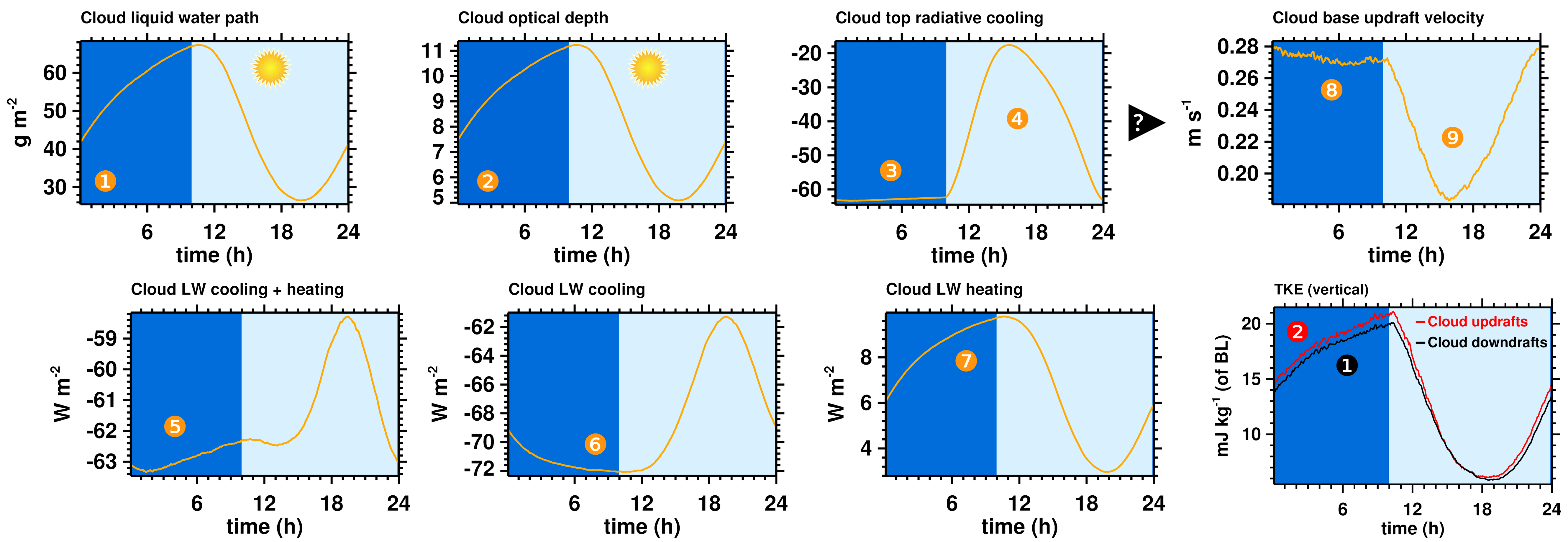
Methods

- Large eddy simulations (LES) of a shallow, non-drizzling stratocumulus (CGILS S12, Blossey et al., JAMES, 2013, Kazil et al., JAMES 2017) with the System for Atmospheric Modeling SAM (Khairoutdinov and Randall, JAS, 2003)
  - 10-day periodic diurnal cucle simulations approaching a quasi-steady state, last day is analyzed
  - 38.4 km domain size, horizontal periodic boundary conditions
  - dx = 50 m, dz = 10 m, dt = 1 s
  - Feingold 2-moment bin-emulating cloud microphysics
  - RRTM radiative transfer model
  - Constant free tropospheric temperature and water vapor
  - Constant aerosol concentration 100 mg^{-1}
- Radiative fluxes are analyzed with offline radiative transfer calculations applied to domain mean profiles of the LES:
  - LibRadtran with the DISORT solver

Why does cloud base heating increase from sunset to sunrise?

From sunset to sunrise, the boundary layer

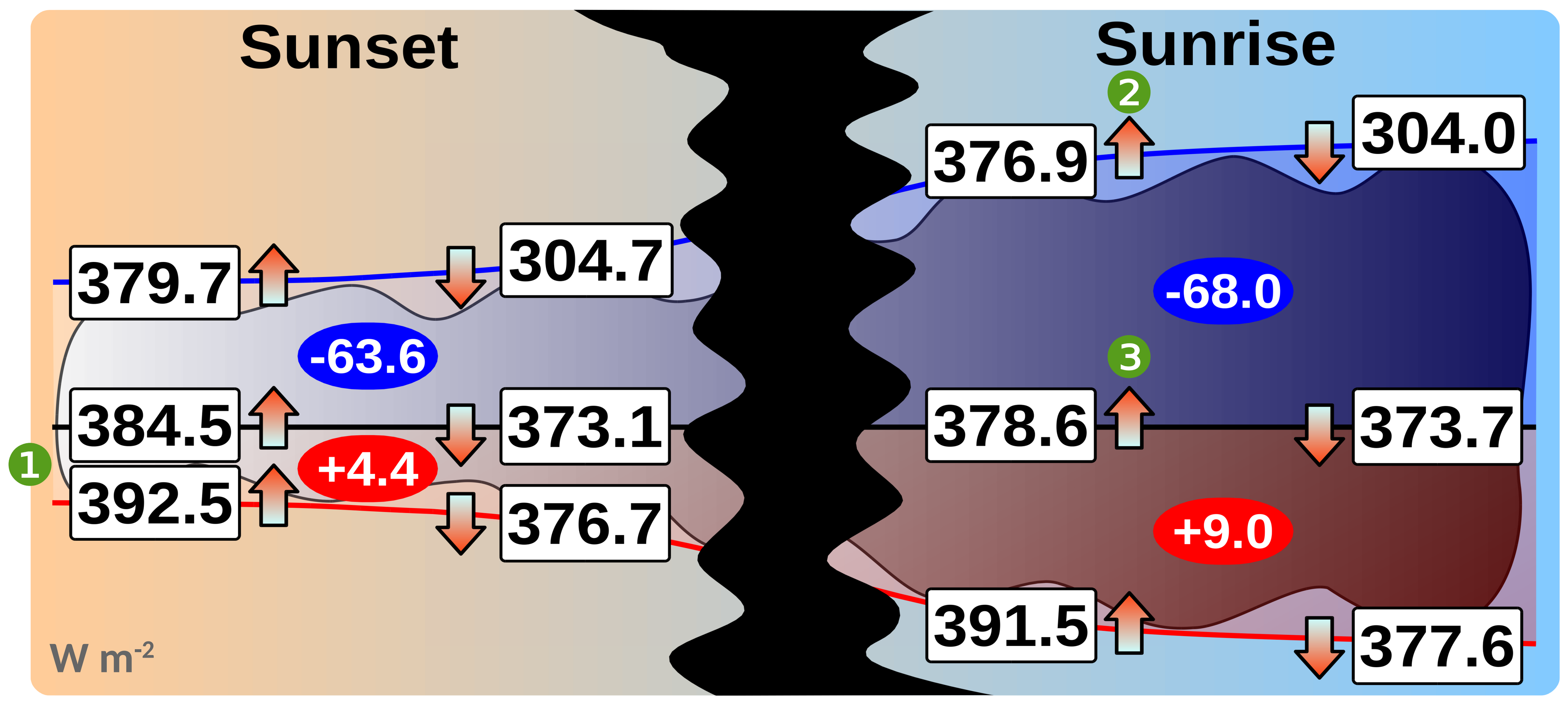
1. Cools (due to the absence of insolation).
2. Dries (due to inversion rise and entrainment).
3. Forms a thicker cloud (due to boundary layer cooling).
4. The result is enhanced cloud top cooling and cloud base heating.
5. Running the radiative transfer code DISORT using SAM sunset temperature (T) and water vapor (q_v) with SAM sunrise cloud water (q_c) produces the enhanced cloud base heating.

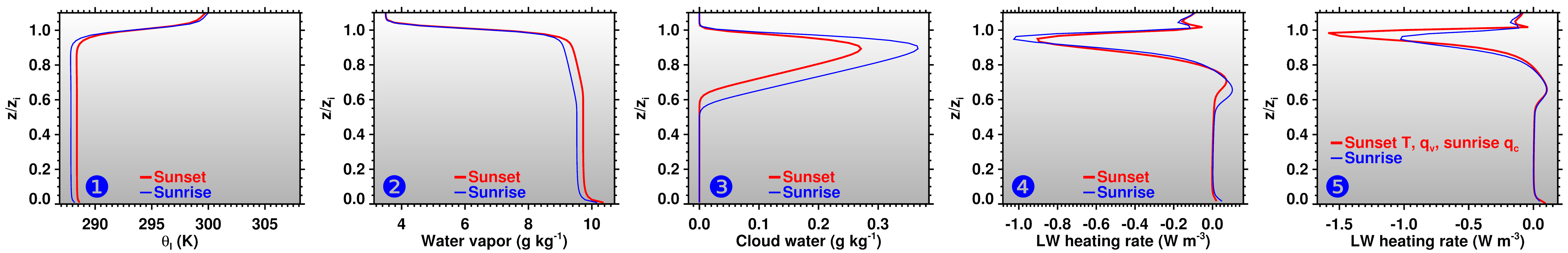


Cloud top cooling and cloud base heating (long-wave)

1. Cloud base heating is caused mainly by absorption of upwelling radiation from the sub-cloud layer/ocean surface.
2. Upwelling LW from cloud top at sunrise is reduced relative to sunset because the boundary layer is cooler.
3. Stronger sunrise cooling in the "upper" cloud layer relative to sunset is due to a reduced flux from the "lower" cloud layer to the "upper" cloud layer.

- The overall cloud LW forcing of the boundary layer is reduced at sunrise (-59 W m^{-2}) relative to sunset (-59.2 W m^{-2}) because of increased cloud base heating.
- (A difference between LW radiative fluxes produced by RRTM in SAM and DISORT applied to SAM output of ~ 4 W m^{-2} needs to be resolved.)





Results

- Cloud liquid water path (1) and cloud optical depth (2) grow starting in the afternoon and over the course of the night.
- CTRC falls over the course of the night (3), despite the concurrent increase in liquid water path (1).
- Daytime CTRC (4) is suppressed due to short-wave heating.
- Reduction in nighttime net long-wave cooling (5) arises from:
  - Nighttime saturation of gross LW cooling (6)
  - Nighttime increase in gross LW heating (7)
- Cloud base updraft velocity $w^{\uparrow}_b$ drops between sunset and sunrise (8), then faster towards noon, and recovers by sunset (9).
- Time of day determines the relationship of $w^{\uparrow}_b$ and cloud-integrated radiative heating/cooling:

Daytime (4,9):

- Stronger CTRC is associated with stronger $w^{\uparrow}_b$: r = - 0.99
- $w^{\uparrow}_b$ (cm s^{-1}) = -4.8*CTRC(W m^{-2}) + 72

Nighttime (3,8):

- Stronger CTRC is associated with stronger $w^{\uparrow}_b$: r = - 0.68
- $w^{\uparrow}_b$ (cm s^{-1}) = -6.8*CTRC(W m^{-2}) - 44

However:

- Nighttime turbulence kinetic energy TKE of in-cloud downdrafts (1) and $w^{\uparrow}_b$ (8) are anticorrelated.
- ▸ Therefore, nighttime evolution of $w^{\uparrow}_b$ is not determined by CTRC.

Furthermore:

- Nighttime CTRC falls (4) but TKE of in-cloud updrafts (2) and downdrafts (1) grows.
- ▸ Therefore, nighttime strengthening of cloud turbulence in general, and of in-cloud updrafts and downdrafts in particular is driven by latent heating/cooling, rather than the action of CTRC.

Conclusions

Stratocumulus cloud-integrated radiative heating + cooling ("cloud-top radiative cooling", CTRC) and cloud base updraft speed $w^{\uparrow}_b$:

- Are well correlated as determined in observations (Zheng et al., 2016).

However:

- Linear regressions give different functional relationships of CTRC and $w^{\uparrow}_b$ for daytime and nighttime.
- The correlation of CTRC and $w^{\uparrow}_b$ is not causal at night.

Therefore: Empirical relationships of CTRC and $w^{\uparrow}_b$ ...

- should not be constructed using nighttime observations,
- should not be used to parameterize nighttime $w^{\uparrow}_b$.

Furthermore:

- In optically thick, non-precipitating Sc, with constant free tropospheric temperature and moisture profiles, turbulence increases overnight by the action of latent heating and cooling, rather than from LW cooling.

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