Cloud-top Turbulence and Radiative Flux Retrievals in Entraining Stratocumulus Clouds

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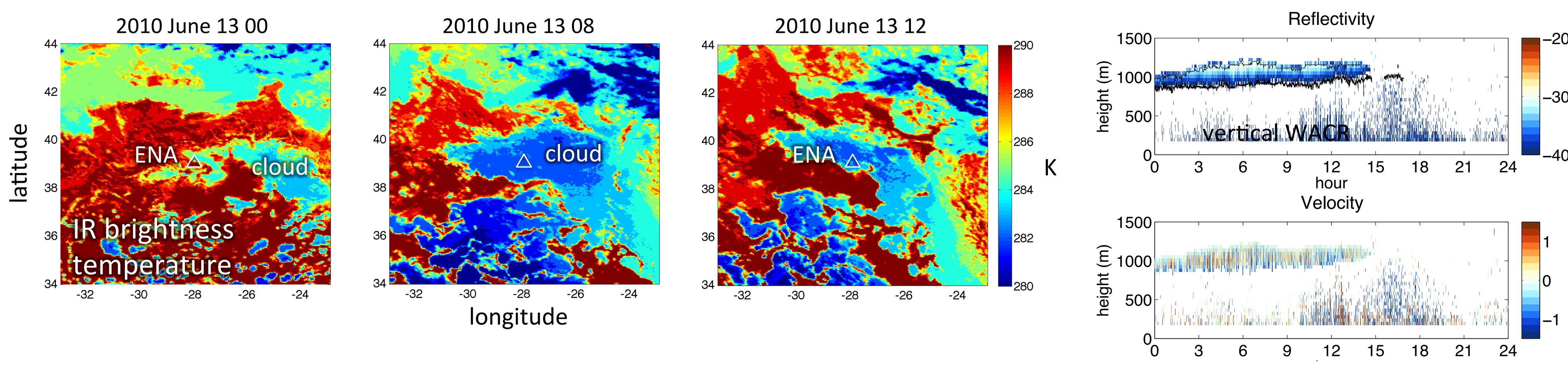
Introduction

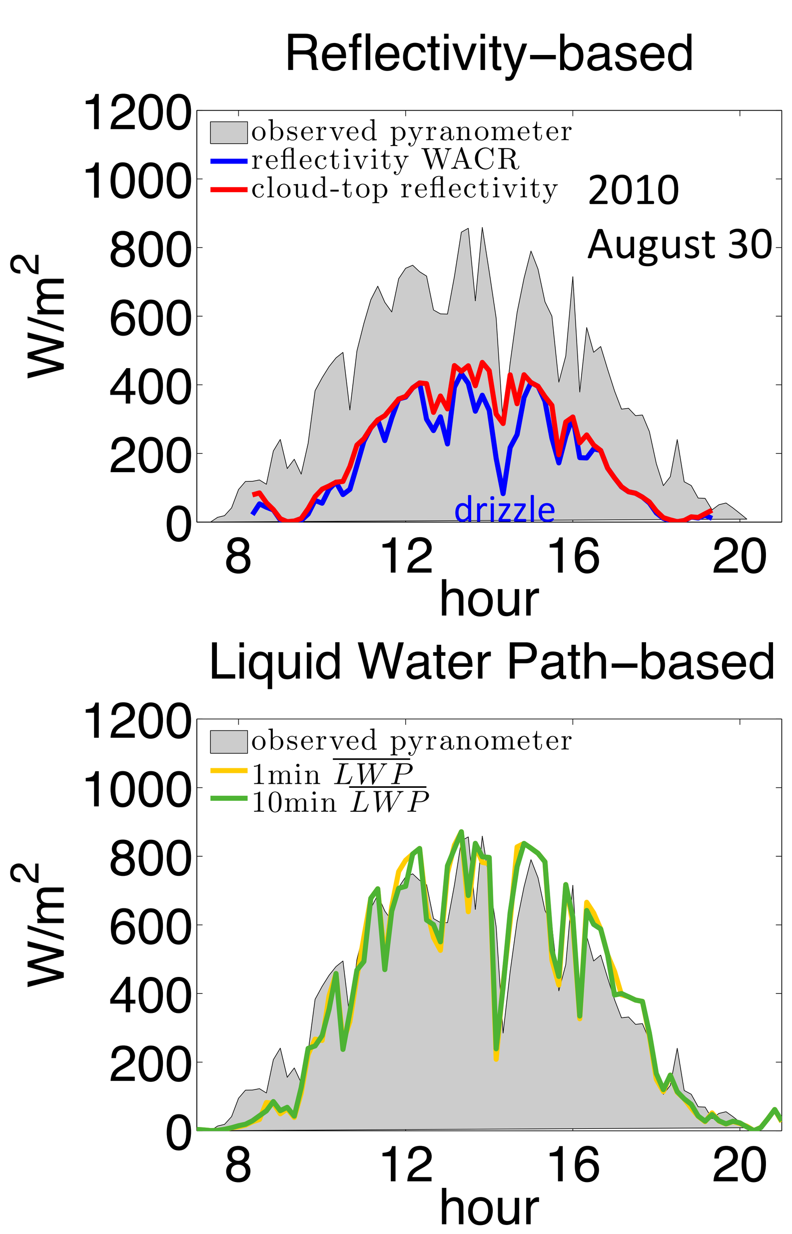
Marine low clouds have an important radiative cooling effect on the climate. Models have difficulty simulating low clouds and their radiative effect is a leading source of uncertainty for climate projections. Turbulent entrainment of warm dry air at cloud top sustains the cloud height, yet reduces boundary layer humidity.

We examine the relationship between cloud-top turbulence and radiative divergence in two relatively long-lived stratocumulus clouds (2010 June 13 and 16) over the Eastern North Atlantic site at Graciosa, Azores. The Doppler W-band ARM Cloud Radar (WACR) measures hydrometeor vertical velocities of clouds and rain. Near cloud top, cloud droplet velocities are nearly equal to the air velocity. Turbulence is slightly intermittent on 10-minute timescales, yet below cloud top, divergence of turbulent buoyancy flux inferred from the turbulent kinetic energy dissipation nearly balances the cooling from radiative divergence.

2010 June 13 Graciosa ARM ENA site case



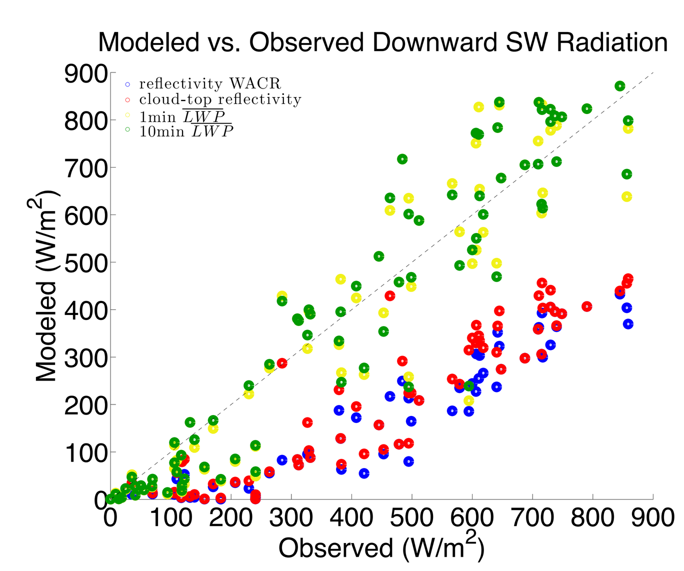
1. Evaluate and refine radiative transfer simulation



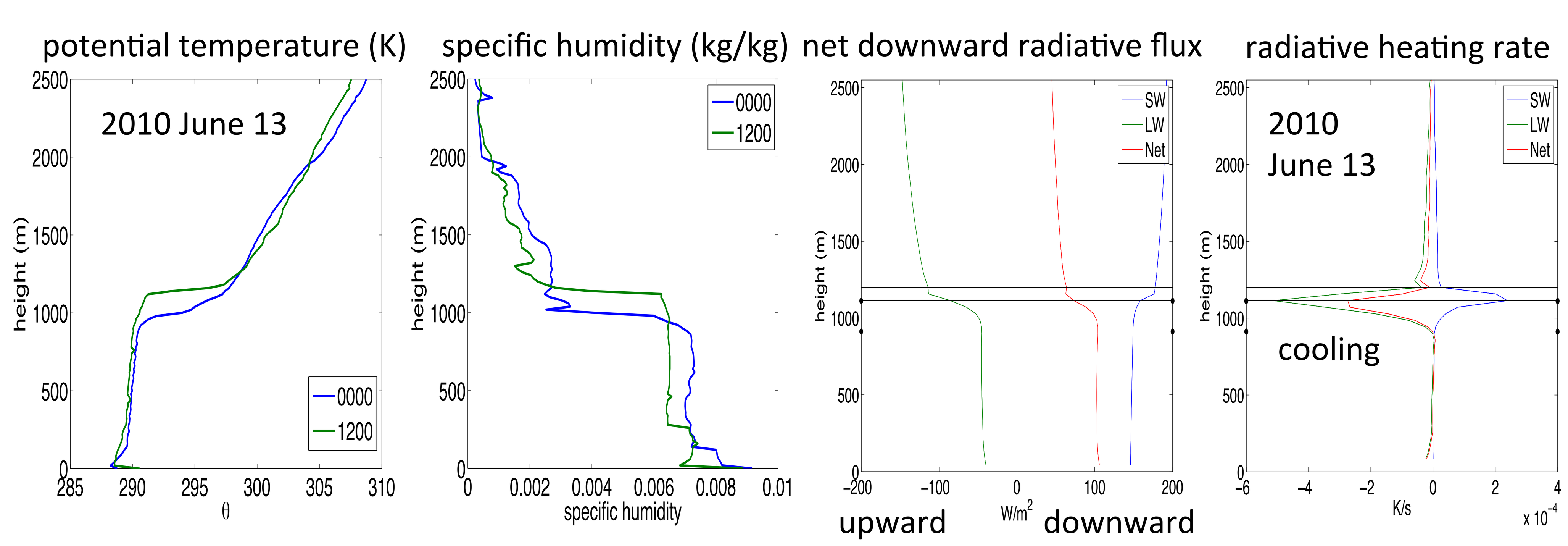
Simulate radiative flux profiles with Rapid Radiative Transfer Model (RRTM):

- for radiosonde T, q_v;
- for clear-sky and low cloud based on thickest ARSCL cloud.
- Liquid water (LWC) from WACR reflectivity (above left) or triangular profile inferred from LWP (lower left).
- Effective radius r_e from N_c=74 cm^{-3}, lognormal width σ=0.35 (Miles et al. 2000).

LWC from LWP improves surface solar flux simulation.

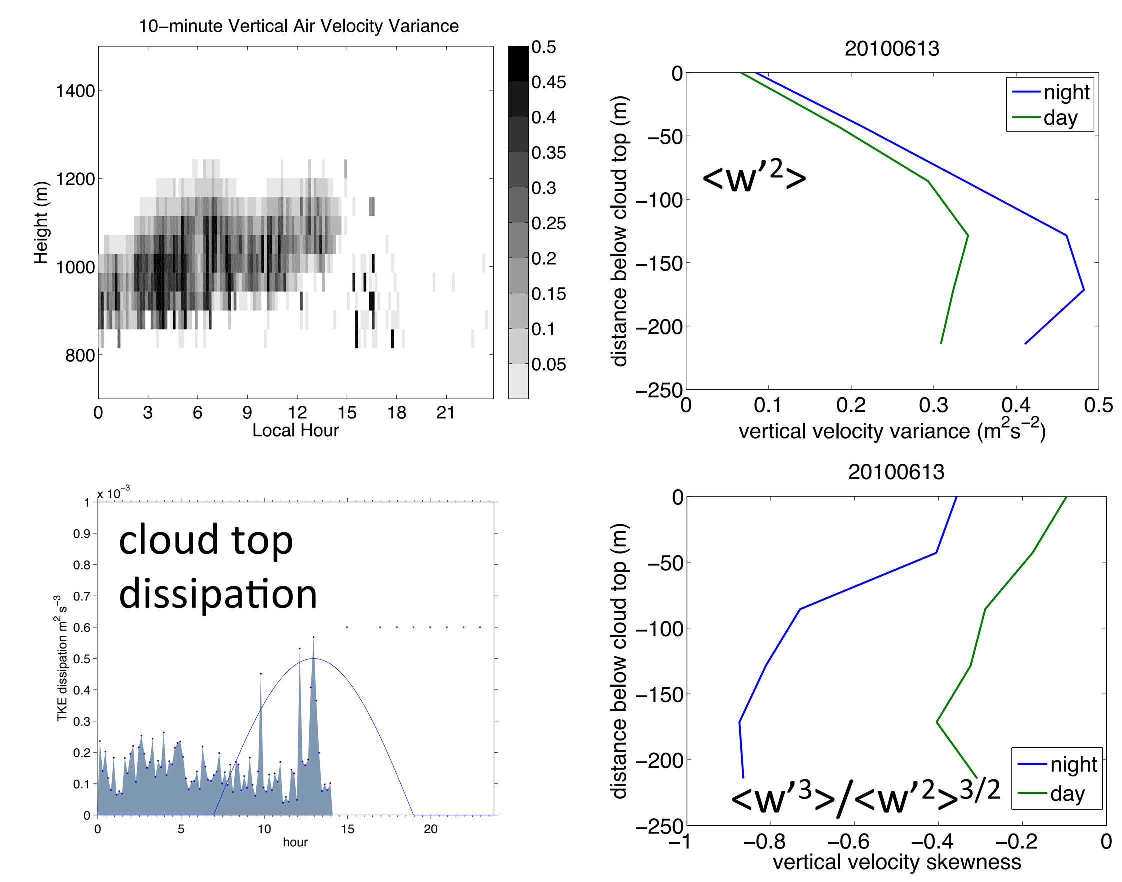


2. Simulate radiative profiles using best cloud retrieval



3. Estimate cloud-top turbulence and TKE dissipation

2010 June 13



Vertical velocity variance <w'²> (upper left) and skewness are evaluated every 10 minutes. Their average profiles relative to cloud top on 2010 June 13 (neighboring panels at right) have an entrainment interface layer with weak turbulence at cloud top. Variance increases and skewness becomes more negative 100-200 m into the cloud. Variance and skewness weaken during the day due to solar warming compensating the longwave cooling.

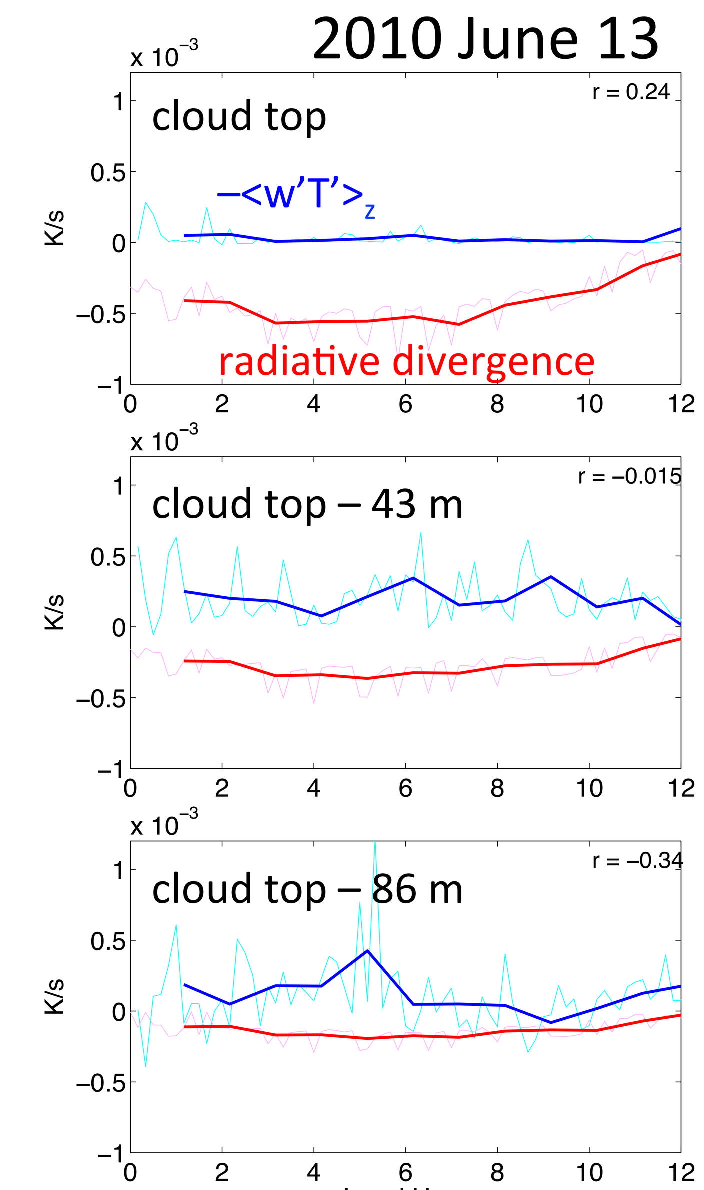
TKE dissipation ε is estimated every 10 minutes from the inertial range of the spectrum $S(f)$ of w' from WACR Doppler cloud radar near cloud top:

$$\epsilon = \frac{2\pi}{U}\left(\frac{3}{4C_\kappa}\overline{f^{5/3}S(f)}\right)^{3/2}$$

4. Compare TKE dissipation and radiative flux divergence

Dissipation is a proxy for buoyancy flux, assuming buoyancy production balances TKE dissipation. In addition, buoyancy flux divergence balances radiative flux divergence for steady temperature, neglecting condensation. These terms are shown at right. Simplification of the heat and TKE budget equations are shown below.

- At cloud top, turbulent heat flux vanishes and strong radiative cooling is unbalanced. Cooling air at the inversion base contributes to non-turbulent "radiative entrainment".
- A positive heat flux at cloud top would match the positive net radiative heat flux in the inversion, but perhaps negative heat flux at cloud top, due to entrainment of warm inversion air into the cloud, cancels any such positive turbulent heat flux.
- 40-90 m below cloud top, radiative cooling is balanced on average by positive turbulent heat flux divergence.
- The radiative cooling and turbulent heat flux divergence both decrease by a factor of ~3 from 43 to 86 m into the cloud.
- There is some intermittency in the turbulent buoyancy flux divergence estimated from the dissipation.



turbulent kinetic energy (TKE) equation $\quad e = \overline{u_i' u_i'}/2 = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2$

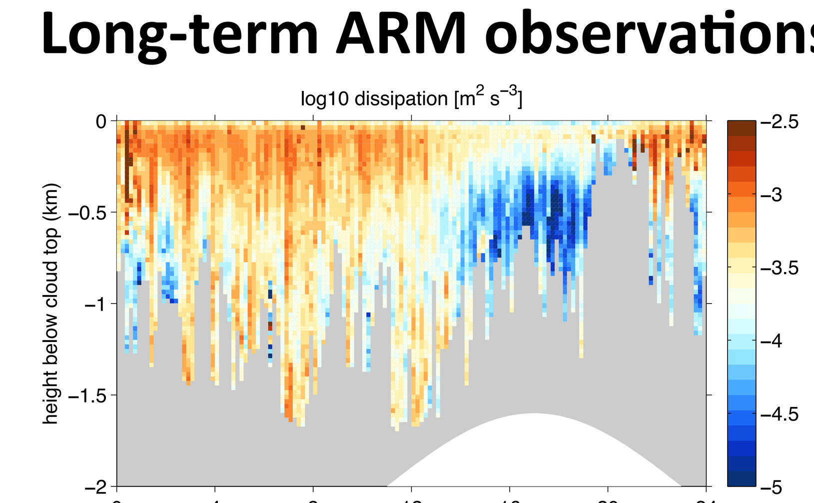
$$\frac{\partial e}{\partial t} = g\frac{\overline{w'T_v'}}{\overline{T_v}} - \overline{u_i'w'}\frac{\partial \overline{u_i}}{\partial z} - \frac{\partial \overline{w'u_i'u_i'}}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon \qquad 0 = \frac{g}{\overline{T}}\overline{w'T'} - \epsilon$$

temperature equation

$$\rho c_p \frac{dT}{dt} = -\frac{\partial}{\partial z}\left((\rho c_p)^{-1}F_{\mathrm{rad}} + \overline{w'T'}\right) - L\left(\frac{\partial q_v}{\partial t}\right)_{\mathrm{cond}} \qquad 0 = -\frac{\partial}{\partial z}\left((\rho c_p)^{-1}F_{\mathrm{rad}} + \frac{\overline{T}}{g}\epsilon\right)$$

simplifies to

Long-term ARM observations and the prospect of very stationary clouds



A shorter deployment of a W-band Doppler cloud radar in VOCALS sampled persistent stratocumulus clouds with a regular diurnal cycle over the southeastern tropical Pacific. Diurnal composite of dissipation over 19 days shows growing turbulence below the entrainment interface layer at cloud top, decreasing turbulence and decoupling 500 m below cloud top during daylight, and rapid resumption of strong turbulent mixing in the late afternoon. The MAGIC transects may sample similar clouds with the WACR.