Latent heat release dependence on mass flux in trade wind shallow cumulus clouds

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PRESENTED AT:

AGU FALL MEETING
Online Everywhere | 1–17 December 2020

STUDY DESIGN

OBJECTIVE

The accurate formulation of sub-grid scale (SGS) latent heat release (LHR) is important for improving NWP model forecasts and is the main focus of our modeling study.

Specifically we investigate the dependencies between condensation/evaporation rate (latent heat release) and thermodynamical parameters of trade wind cumulus convective clouds

APPROACH

The research is ba on the LES model initialized with daa from the RICO field project. The simulations provide dynamically balanced 3D datasets necessary for obtaining statistically robust correlation dependencies. The analysis is facilitated by stratifying clouds by cloud top, cloud maturity and precipitation capacity.

MODEL SETUP

Our LES model (SAMBM) employs the dynamical core of the System for Atmospheric Modeling (SAM, Khairoutdinov and Randall 2003, JAS) and the Bulk Microphysics (BM, Kogan 2013, JAS) fine-tuned for shallow Cu convection. The observations from the RICO field campaign (van Zanten et al 2011, JAMES) were used for initializing LES simulations conducted in a rather large 50.0×50.0×4 km3 domain (500×500×100 grid points).

DATASET

Over the course of the simulation from 8 to 32 hours, we selected 2031 clouds that were collected every 30 minutes. Our previous research has shown that the "brute force" statistical approach to relate phase transition rates (or latent hear release - LHR) to the dynamical parameters cannot succeed because of the complexity of the cloud system that consists of clouds at various stages of their development.

Therefore. the dataset was sorted out by cloud top height and divided into four groups G1-G4, each of which condenses approximately equal amount of water vapor per second. The groups G1-G2 represent clouds mostly at the growing stage, while groups G3-G4, on the contrary, contain mature and decaying clouds.

CLOUD OVERALL PARAMETERS

CLOUD AND PHASE TRANSITION RATE PARAMETERS

Fig. 1 shows mean and standard deviation of selected physical and precipitation cloud parameters in each group. G1 clouds are the most numerous; they are also the smallest with cloud tops varying in the range from 1.34 to 2.3 km. Their mean projected surface area is on average less than 2 km2 and mean volume is less than 1 km3.

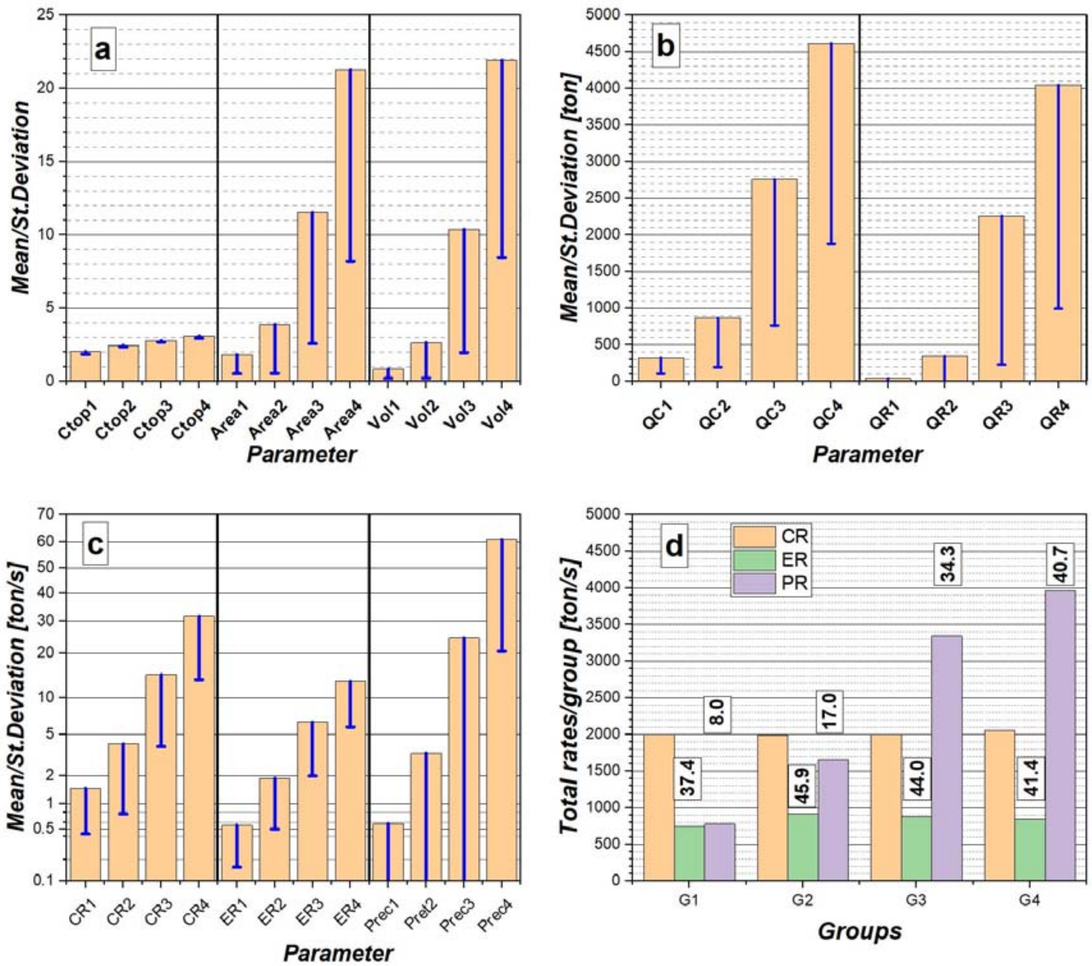


Fig. 1. Mean and standard deviation of cloud physical parameters in each of the four groups. a) cloud top, surface area, volume (Ctop, Area, Vol - in km, km2, km3, respectively); b), cloud and rain water content (QC, QR – tons); c) per cloud condensation/evaporation and precipitation rate (PR - integrated over the cloud surface area) in ton/s; d) total CR/ER/PR integrated over the group (ton/s). Numbers over the ER and PR columns are explained in the text.

The linear increase only by 300 m in cloud height from G2 to G3, and further to G4 is accompanied by an exponential increase in cloud area and volume (Fig. 1a), as well as cloud and rain water (Fig 1b).

Cloud water content increase seems to be lagging behind the increase in cloud volume, e.g., nearly nine-fold increase in cloud volume from G2 to G4 results only in five-fold increase in cloud water content, but in more than eleven times increase in rain water content. This does not indicate, however, that larger

clouds condense less effectively; it simply reflects the acceleration of rain formation as clouds grow larger. Note, however, large variations of all parameters shown by blue line segments in Fig 1.

Mean condensation/evaporation rates (CR/ER) are more in line with the increase in volume (Fig. 1c, notice probability scale on the y-axis). It is also notable that the majority of clouds in groups G1 and G2 are at a growing stage, as their condensation rates are larger than the precipitation rates (PR), while the opposite is true for larger clouds in G3-G4.

Even larger, exponential increase is prominent when mean precipitation rates are analyzed. For example, mean precipitation rates (PR) for clouds in G1 are very small, only 0.58 mm/hr. Clouds in G2 are three time bigger in volume, but their PR are 5.8 times larger. The clouds in G3 have about 3.8 times larger volumes compared to G2 clouds, but their PR increase more than 7.2 times. Even more dramatic differences is noticeable for G4 clouds. Compared to G2, their mean volumes are 8.6 times larger, but mean PR are larger 18 times

While Figs 1a-c show mean cloud parameters in each group, the Fig. 1d shows integral contribution of these parameters, i.e. they are integrated over the whole group. Each group, by design, contributes approximately equal amount of condensation. The fraction of evaporation to condensation rates (ER/CR) is on average about 40%. The exact percentages for each group are shown above the ER green columns in Fig 1d; they are smaller for G1 and G4 clouds, while larger for G2-G3 clouds. Evidently, G1 clouds predominantly grow, therefore evaporation is lagging behind condensation, while G2-G3 clouds are mature and have already a well-formed quasi-stable dynamical updraft/downdraft structure where both condensation and evaporation are balanced. Larger rain water content in G4 clouds contribute more to precipitation and somewhat less to evaporation which may explain the reduced fraction of evaporation in G4 compared to G3 clouds.

The precipitation in G4 is quite large which is clear from the numbers over the PR columns (Fig. 1d). These numbers denote percentages of precipitation in each group relative to the total precipitation from all groups. G4 and G3 together account for three quarter of total precipitation; G1 and G2 clouds contribute, respectively 8 and 17%. Notably, these groups precipitate less than condense, i.e., they are still growing, while G3 and especially G4 clouds precipitate about 70 and 100% more than condense, that is, they are losing water and, therefore, at the stage of decay.

PRECIPITATION EFFICIENCY

CLOUD PRECIPITATION EFFICIENCY

The ratio of precipitation to condensation rates can be considered as an indicator of cloud "precipitation efficiency" (PE=PR/CR). As Fig. 2 shows, in G1 and G2 groups about 88 and 77% of clouds, respectively, have PE<1, meaning that these clouds are mostly growing, i.e., they precipitate less than condense. The opposite is true for G3-G4 groups where in most clouds precipitation rates are larger than condensation rates. In the G3 group 60% and in the G4 group 80% of clouds have PE>1, meaning that these groups have considerable and. in G4 predominant, portion of clouds that are past their matue stage and in the process of decay.

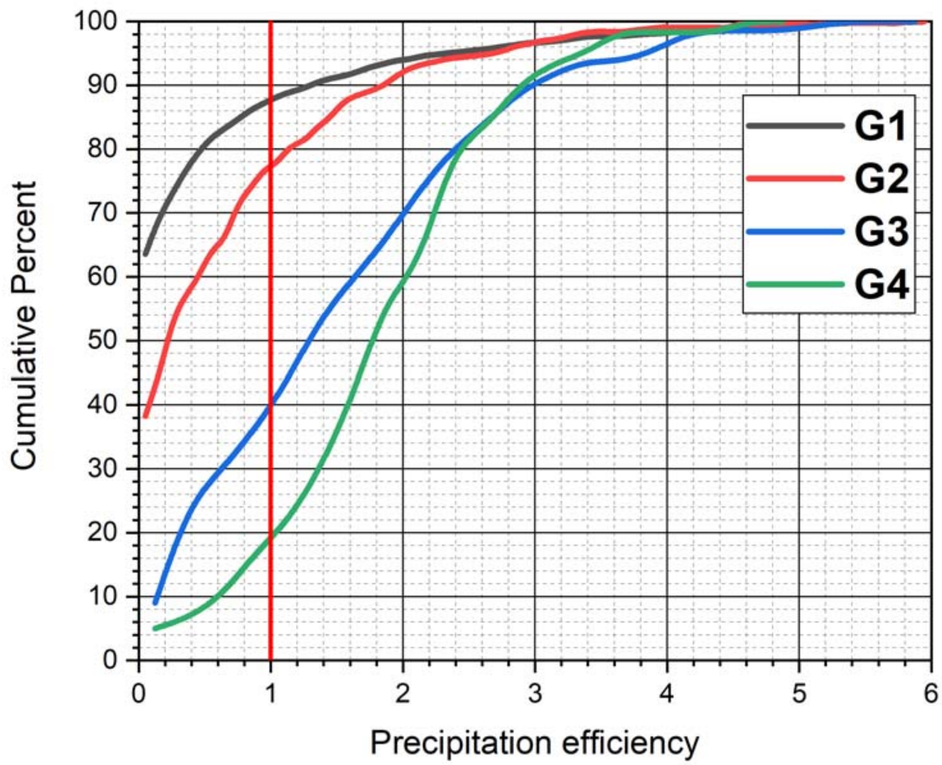


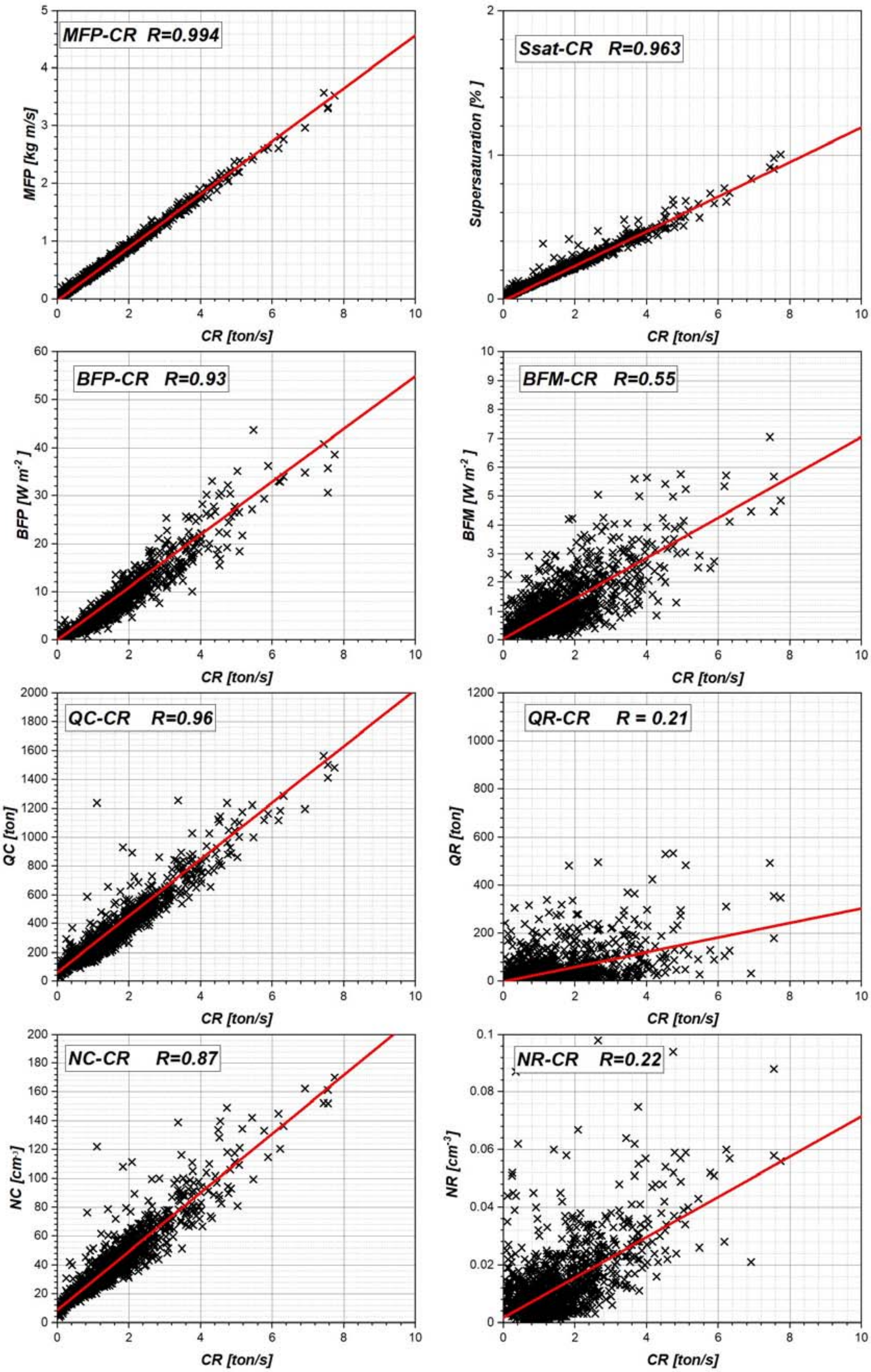
Fig. 2. Cumulative distribution of precipitation efficiency (PE) in each of the four cloud groups.

LATENT HEAT - MASS FLUX CORRELATION

PHASE TRANSITION RATE DEPENDENCE ON CLOUD PARAMETERS

The main focus of the study is to identify correlations between LHR which is directly related to phase transition rates (CR/ER) and parameters that define cloud thermodynamical properties. In this study we focused on the total parameters, i.e, parameters that are integrated over the whole cloud volume. The latter include: up (Plus) and down (Minus) mass flux (MFP and MFM - defined as air density ρ times vertical velocity: ρW), cloud and rain water content (QC and QR), cloud and rain drop concentration (NC and NR), positive and negative supersaturation (ss), up and down buoyancy flux BFP and BFM (defined as $c_p\rho\theta'W$. where c_p is the specific heat of air and θ' is the virtual temperature perturbation). As the integral variables are integrated over the whole cloud, and the size of the cloud volume is measured in billions of cubic meters, it is convenient to normalize the integral variables by a unit volume $V_0 = 10^9$ cubic meters = 1 cubic kilometer.

Fig. 3 shows correlation between condensation rate (CR) and some of the major parameters for clouds in group G1. Almost perfect correlation exists between condensation rate and upward (plus) mass flux (MFP). Correlation between CR and upward (plus) buoyancy (BFP) is also strong, but less than with MFP. Similar strong correlation exists with cloud water an drop concentration (QC and NC). As one my expect, the correlation between condensation and downward fluxes, as well as rain parameters is weaker.



MFP-CR R=0.994
MFP [kg m/s]
CR [ton/s]
Ssat-CR R=0.963
Supersaturation [%]
CR [ton/s]
BFP-CR R=0.93
BFP [W m-2]
CR [ton/s]
BFM-CR R=0.55
BFM [W m-2]
CR [ton/s]
QC-CR R=0.96
QC [ton]
CR [ton/s]
QR-CR R = 0.21
QR [ton]
CR [ton/s]
NC-CR R=0.87
NC [cm-3]
CR [ton/s]
NR-CR R=0.22
NR [cm-3]
CR [ton/s]

Fig 3. Scatter plots of parameters referred to in plot legends versus condensation rate (CR). Group G1

Analysis of other cloud groups reveal similar conclusions: the strongest correlation is between CR and MFP. Surprisingly the evaporation rates (ER) have also similar stronger correlation with upward mass flux than with downward mass flux. As a matter of fact, all four groups have the about the same coefficients of proportionality between CR and MFP and between ER and MFP.

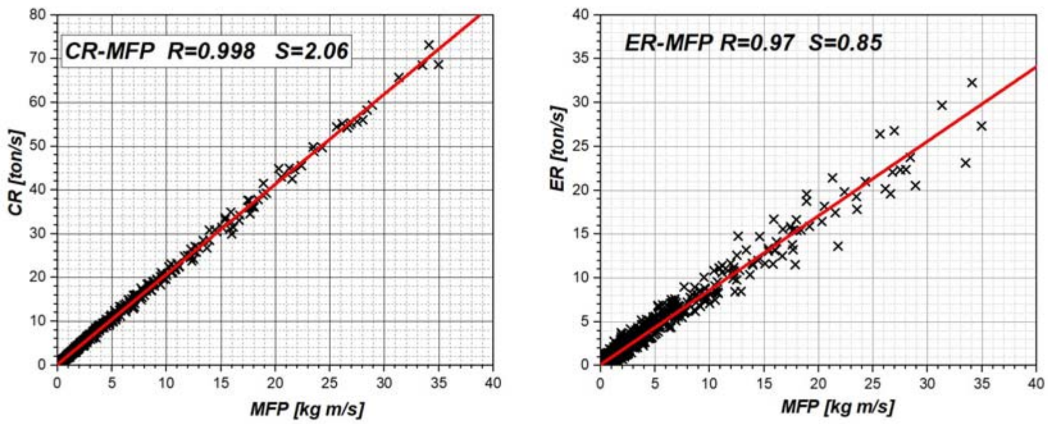


Fig 4. Scatter plots of condensation/evaporation rates (CR/ER) as a function of upward mass flux (MFP) for clouds in all groups. R is the correlation coefficient; S is the slope of the linear fit.

The scatter plot in Fig. 4 illustrates this fact which can be expressed as a relationship between phase transition rate (TR) and upward mass flux:

TR = α MFP (1)

where α = 2.06 for for qv > qvs (condensation) and α = -0.85 for qv < qvs (evaporation), qv and qvs are the water vapor and saturation water vapor content. Obviously, using the specific latent heat constant, one can directly relate formulation (1) to the energy released in phase transitions.

MAJOR FINDINGS

Results from our numerical modeling study of shallow cumulus clouds reveal nearly perfect correlation between integral condensation/evaporation rate (iatent hear release) and integral upward mass flux. This strong correlation suggests possible direction for parameterization development of vertically dependent SGS latent heat release.

ABSTRACT

We performed LES simulation of tropical cumulus clouds initialized with soundings from the RICO field project (vanZanten et al. 2011, JAMES). Our analysis concentrated on thermodynamic characteristics of convective clouds, specifically on relationships between the condensation/evaporation rates and cloud micro-physical and dynamical parameters. Such relationships are important for developing parameterizations of the sub-grid latent heat release on the grid size typical for a mesoscale model.

The simulation was conducted using an integration domain of 50km; about 2000 clouds were selected for analysis over the course of the 28 hour simulation. The condensation/evaporation rates were analyzed by stratifying the clouds by their size (cloud top). The analyzed parameters included, among others, integral mass and buoyancy flux, cloud and rain water, supersaturation.

The results of the analysis revealed rather remarkable relationships between integral latent heat released in a cloud and some of its integral dynamical parameters. These relationships may form the basis for parameterization development.