Buoyancy-precipitation coupling in the life cycle of tropical mesoscale convective systems

Wei-Ming Tsai, Fiaz Ahmed, J. David Neelin

Department of atmospheric and oceanic sciences, University of California, Los Angeles

Overview

U.S. DEPARTMENT OF ENERGY **Regional & Global Model Analysis**

Our project aims to bridge the gap between phenomenon-based diagnostics—involving the identification of leading atmospheric features associated with weather phenomena including low pressure systems (LPS), mesoscale convective systems (MCS), frontal systems (FT), and atmospheric rivers (AR)—and other leading diagnostic approaches: (1) spatiotemporal statistics of precipitation; (2) process-oriented diagnostics for the coupling of precipitation to its large-scale environment. The present study focuses on the process-oriented sector for tropical MCSs as a start for coordinating feature-environment catalogues, data encompassing both features and their surrounding environments, that can be broadly leveraged.

Here we start with a prototype of the feature-environment catalogue for tropical MCSs and demonstrate compatible analyses of process-oriented diagnostics. MCSs account for nearly half of the total tropical precipitation, playing an essential role in the tropical hydroclimate. However, MCS initiation and the thermodynamic states associated with their life cycle remain unclear, which creates a challenging for evaluating representation of MCS processes in global high-resolution models. A measure of lower-tropospheric buoyancy that accounts for a combination of instability and entrainment has provided baseline empirical buoyancy-precipitation relationships for deep convection. Here we characterize such relationships during the evolution of MCSs, to set an observational benchmark for MCS-related thermodynamics.

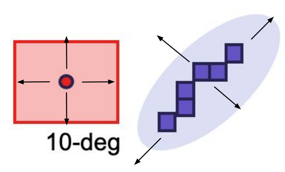
1. Toward feature-environment diagnostics on the process level

❑ A framework of characterizing atmospheric features and associated environments

The success of tracking/identifying algorithms for a variety of atmospheric features is promising for investigating relationships between the detected features and associated environments

→ The overarching goal is to design catalogues of features and environmental variables and to provide encompassed products from observations and climate models for process-oriented diagnostics

- **Things to be coordinated for extracting feature-associated environment in the framework**
  - feature type: centroid (e.g., LPS, tropical cyclone), bounded 2-D mask (MCS, AR, FT)
  - environment window type: a fixed feature-relative domain (e.g., a lat-lon box about centroid) or a dilation approach to cover the associated environment (grid points surrounding the feature)

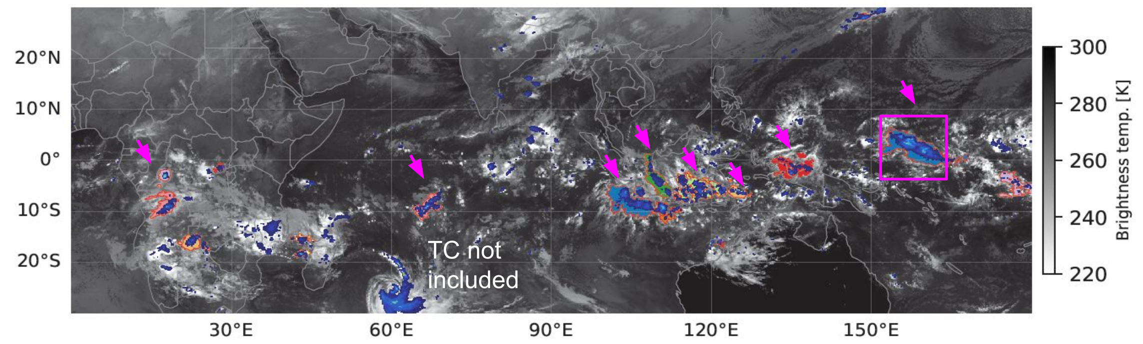


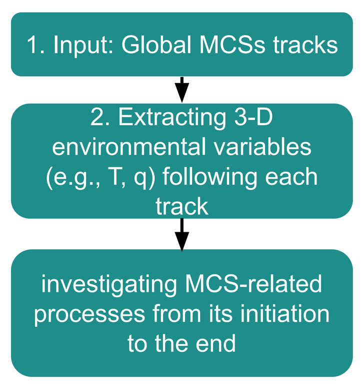
- **Coordinating output standards of feature-environment catalogues**
  - feature information: e.g., geolocation, time, binary mask of bounded features
  - common environmental variables: e.g., T, q, u, v, w, precipitation, etc, most appropriate for process-level studies of each feature

❑ A subset of feature-environment catalogues: observational MCSs as example

- impactful to the tropical hydroclimate and extreme precipitation
- as a challenging start because of the large number of features (e.g., compared to LPS, AR), for data size estimation and data structure planning of feature-environment catalogues
- coordinating potential parallels in MCS-environment studies in approaches to relating MCSs and associated environments

MCSs: red contour + shading color; GPM-IMERG precipitation (jet color shading)

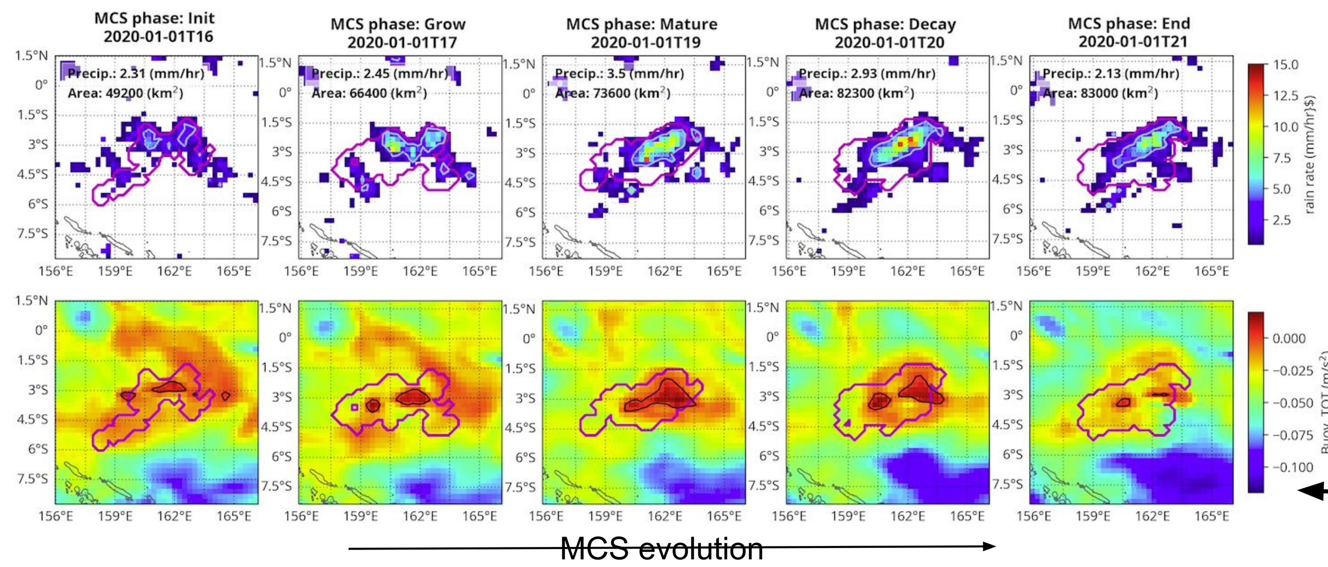




1. **FLEXTRKR global MCS tracks** (Feng et al., 2021; 2023)
   - A 20-year satellite-based data using GPM-IMERG precipitation and MERGE-IR brightness temperature
   - provides hourly information of MCS characteristics, such as duration, precipitation rate, cloud size, etc.

2. **ERA5 reanalysis**
   - Resolution: 0.25-degree in lat/lon, 32 pressure levels, hourly
   - Provides atmospheric variables, including temperature, specific humidity, surface pressure, etc.

- **Selective MCS tracks in the analysis of the present work**
  - Tropical MCSs developing within 30S-30N (excluding tropical cyclones identified as MCSs)
  - Excluding tracks related to merging of pre-existing MCSs for clarity of the MCS life cycle
  - Using a fixed 10 x 10 degree looking window centered at the MCS centroid along the track



- **Determining MCS stages:** Initial, Grow, Mature, Decay, End
- Mature stage: defined as the time at the peak of total precipitation
- The growing and decaying stages: defined as the intermediate times

2. Investigating the buoyancy-precipitation relationship

❑ Low-tropospheric buoyancy measure B_L:

- expressed by the layer-averaged equivalent potential temperature components following Ahmed and Neelin (2018)
- describe the instability and saturation of the low-troposphere that affect convective processes

$$B_L = \frac{g}{\bar{\kappa}_L \theta_{e0}} \left[\underbrace{w_B \left(\frac{\theta_{eB} - \theta^*_{eL}}{\theta^*_{eL}} \right) \theta_{e0}}_{\mathrm{CAPE_L}\ (B_{L,CAPE})} - \underbrace{w_L \left(\frac{\theta^*_{eL} - \theta_{eL}}{\theta^*_{eL}} \right) \theta_{e0}}_{\mathrm{SUBSAT_L}\ (B_{L,SUBSAT})} \right]$$

B: boundary layer (100 hPa above sfc.)
L: low-troposphere (900-500 hPa)
asterisk symbol: saturated
K_L: const. = 3
θ_{e0}: reference temperature = 340 K
W_B/W_L: the layer weights

CAPE: instability source
SUBSAT: dilution effect from entrainment

❑ Conditionally averaged precipitation for non-MCS and MCS

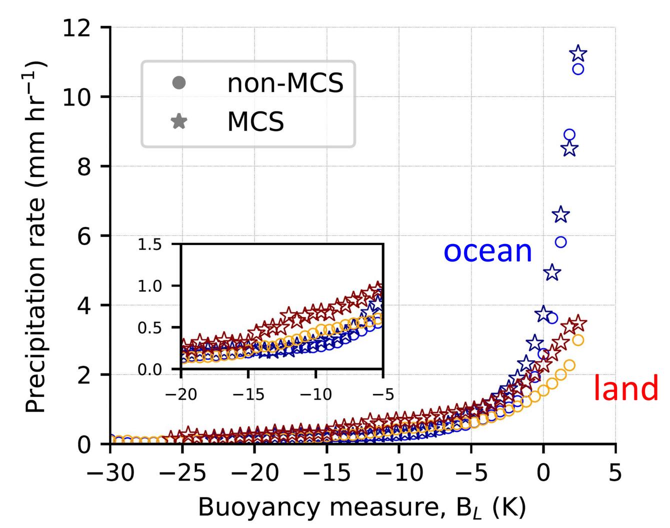


Figure. Conditionally averaged precipitation binned by the low-tropospheric buoyancy measure BL for non-MCSs and MCSs over oceans (blue) and land (red and orange).

- Pick-up of precipitation as B_L approaches less negative values for non-MCSs and MCSs
- More manifest differences in rain rates and the pick-up values between non-MCSs and MCSs over land, compared to oceans

❑ Contributions to rainfall from individual MCS stages

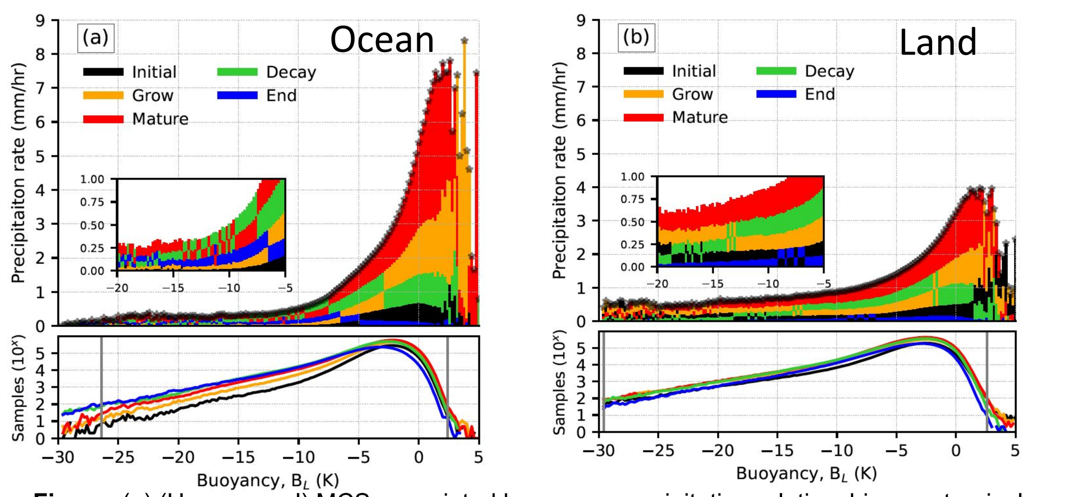


Figure. (a) (Upper panel) MCS-associated buoyancy-precipitation relationship over tropical oceans. The asterisk is the conditional precipitation rate binned by B_L. Stacked colored bars at each bin are the precipitation contributed from the defined MCS stages, ordered by the relative magnitudes, with the bin width of 0.2 K. (Lower panel) The number of samples in different MCS stages in a log10 scale (10^x). The vertical lines enclose bins with samples > 100. (b) for land.

- Nearly no contribution from the initial stage for B_L lower than ~ -10K
- In high B_L regimes (e.g., > -5K), a major contribution to conditional rainfall comes from the growing and mature stages.
- Contribution from the decaying stage becomes greater over the lower BL regimes (e.g., < -5K)
- Shifts in the B_L distributions: towards high B_L as MCSs grow
- Similarity in MCSs over oceans and land.

Acknowledgements: supported by Department of Energy Earth & Environmental Systems Modeling, Regional & Global Model Analysis Program DE-SC0023244 and DE-SC0023519 and National Oceanographic & Atmospheric Administration Climate Program Office, Modeling, Analysis and Prediction Program NA21OAR4310354

3. Evolution of buoyancy components in the MCS life cycle

As precipitation shows a life cycle during MCS events, the buoyancy components at different MCS life stages should reflect conditions that favor and disfavor the development of MCSs

❑ Characterizing MCS-related thermodynamics on the CAPE-SUBSAT diagram

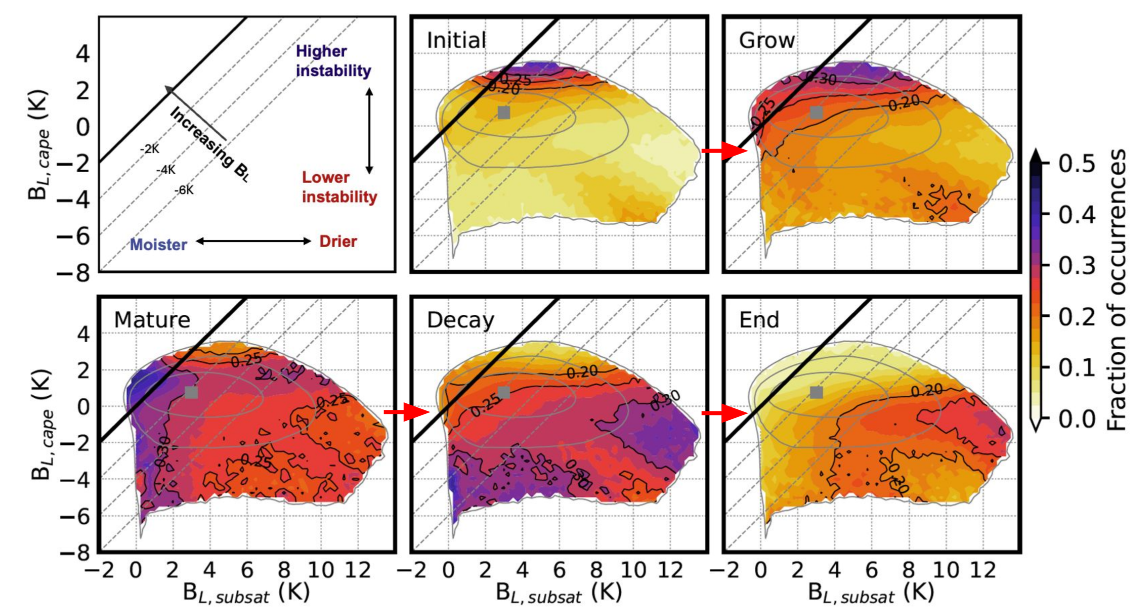


Figure. Fraction of occurrences associated with identified life stages for MCS over both land and oceans: Initial, Grow, Mature, Decay, and End. Values at a given grid across 5 MCS stages sum to 1. The black contours indicate the joint histogram of samples throughout all MCS stages, starting from 2 to 5 in the log10 scale. The slant lines are constant B_L with an interval of 2 K (solid = 0 K). The gray square indicates the mode of the joint histogram, identical in each panel. Bins with a sample number < 100 are neglected and the bin width is 0.25 K for both axes.

- Shown as a fraction of occurrences for the given stage, e.g., occurrences of high $B_{L,CAPE}$ tend to be in the initial stage
- A clear change in the buoyancy components along the life cycle:
  - initialized with higher CAPE but moderate SUBSAT
  - more occurrences over greater B_L and higher saturation in the growing stage
  - almost saturated conditions tend to be in the mature stage with a broad range of $B_{L,CAPE}$
  - lower $B_{L,CAPE}$ and higher $B_{L,SUBSAT}$ associated with the decay and end stages

❑ Conditional precipitation on the CAPE-SUBSAT diagram

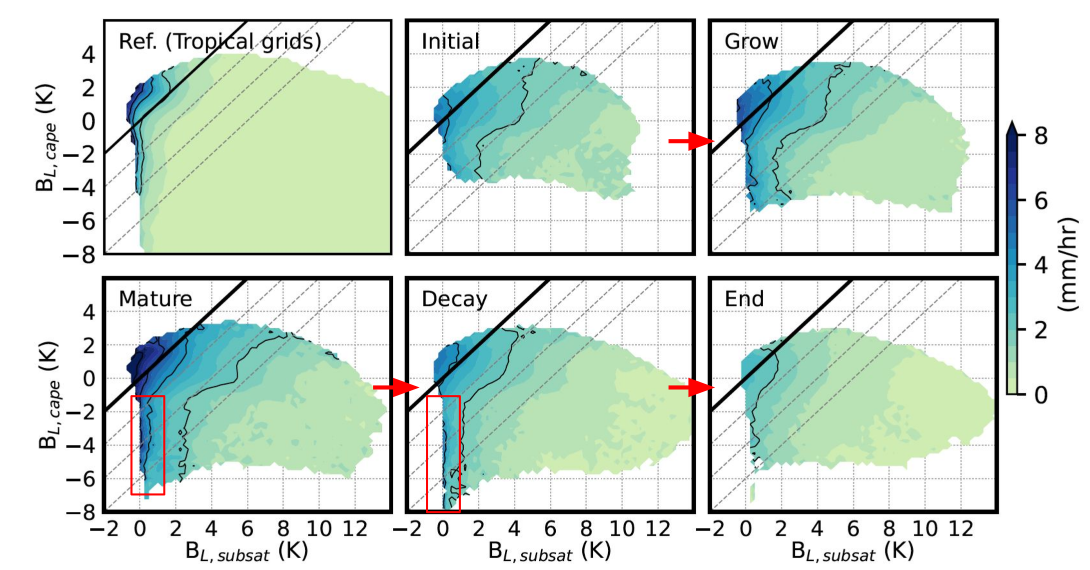


Figure. Condition precipitation binned by BL,cape and BL,subsat for different MCS life stages. A reference for all tropical grids is shown at upper left corner. Pixels with the sample number less than 200 are masked out. Black contours reinforce selected color bar values starting from 2 mm/hr with an interval of 2.

- Precipitation shows MCS stage-dependence, suggesting changing microphysics and dynamics during the life cycle
- Intense conditional avg. precipitation over regimes of low $B_{L,CAPE}$, $B_{L,SUBSAT}$ ~ 0 likely reflect the growth of stratiform rain

Summary

- This work introduces a proposed feature-environment catalogue for tropical MCSs as an example of process-oriented analysis on relating key factors to features and associated precipitation.
- The initialization of tropical MCSs and associated precipitation are related to the low-tropospheric buoyancy measure.
- The growing and mature stage of evolving MCSs exhibits high buoyancy values and has considerable contribution of precipitation to the buoyancy-precipitation conditional statistics. The decaying stage, in contrast,
- The CAPE-SUBSAT buoyancy diagram demonstrates the evolution of the MCS life cycle as a function of buoyancy contributions by conditional instability and lower free tropospheric moisture.
- The difference between MCS stages in the CAPE-SUBSAT conditional precipitation suggests the overall time dependence of the precipitation process associated with microphysics and dynamics in MCS evolution.

References: Ahmed and Neelin 2018, http://doi.org/10.1175/JAS-D-17-0333.1; Feng et al. 2021, doi.org/10.1029/2020JD034202; Feng et al. 2023, doi.org/10.5194/gmd-16-2753-2023;