Variability in surface meteorological variables and surface fluxes over the tropical Indian Ocean during the CINDY2011/DYNAMO campaign
— Observation by R/V *Mirai* —

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Introduction & Summary

Variability in air-sea heat flux exchange is considered to be important for dynamics of tropical intraseasonal variability. **This study examines influence of cumulus convection on surface meteorological variables and the fluxes over the tropical Indian Ocean** observed by Research Vessel (R/V) *Mirai* during the CINDY2011/DYNAMO campaign conducted in October–November of 2011. Characteristics of observed convection by a Doppler Radar installed on R/V *Mirai* before and after October 12 were quite different from each other. In the former period, four mesoscale convective systems (MCSs) produced most of precipitation. On the other hand, sub-MCS scale convective systems dominated in the latter period.

The four MCS events induced considerable variability in the surface variables and fluxes. Sensible heat flux (SHF) was increased by ~30 [W m^{-2}] during the passage of the MCS, due to both increase in air–sea temperature difference and increase in surface wind. On the other hand, latent heat flux (LHF) was increased by ~140 [W m^{-2}] not only during the passage but also after the passage of the MCS, due solely to the increase in the surface wind.

Composite analysis of 28 sub-MCS events after October 12 revealed that changes in the surface wind speed and air–sea temperature and humidity differences are qualitatively similar to results in previous studies. LHF increase was found only during convective active phase, while SHF increase was observed during the active period as well as subsequent recovery phase.

Data and method

Observation of R/V *Mirai*

- Staying at 8°S, 80.5°E during the period Sep. 30 – Oct. 24 & Oct. 30 – Nov. 28 (~52 days).
- **Surface meteorological observations**
  Horizontal wind, temperature, humidity, downwelling SW & LW, in-take SST at a 5-m depth, gauge rainfall
  10-minute resolution
- Surface sensible & latent heat fluxes are estimated using COARE3.0 algorithm (Fairall et al. 2003).
- **Reflectivity of C-band Doppler Radar**
  CAPPI at 2km height, 1-km horizontal resolution, 10-minute intervals.

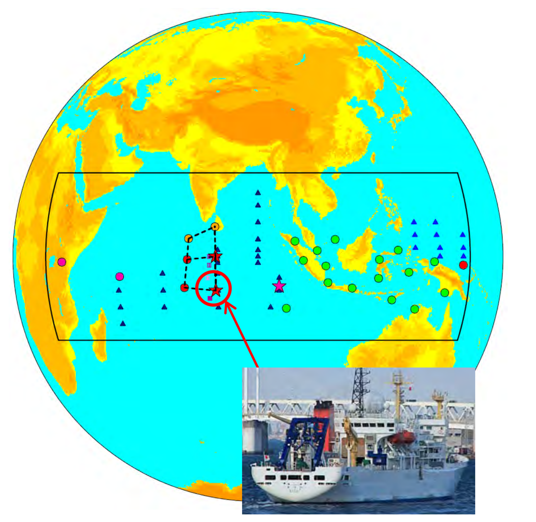

Figure 1. CINDY2011/DYNAMO observation network. The red circle indicate location of R/V *Mirai*.

Overall characteristics of observed convection

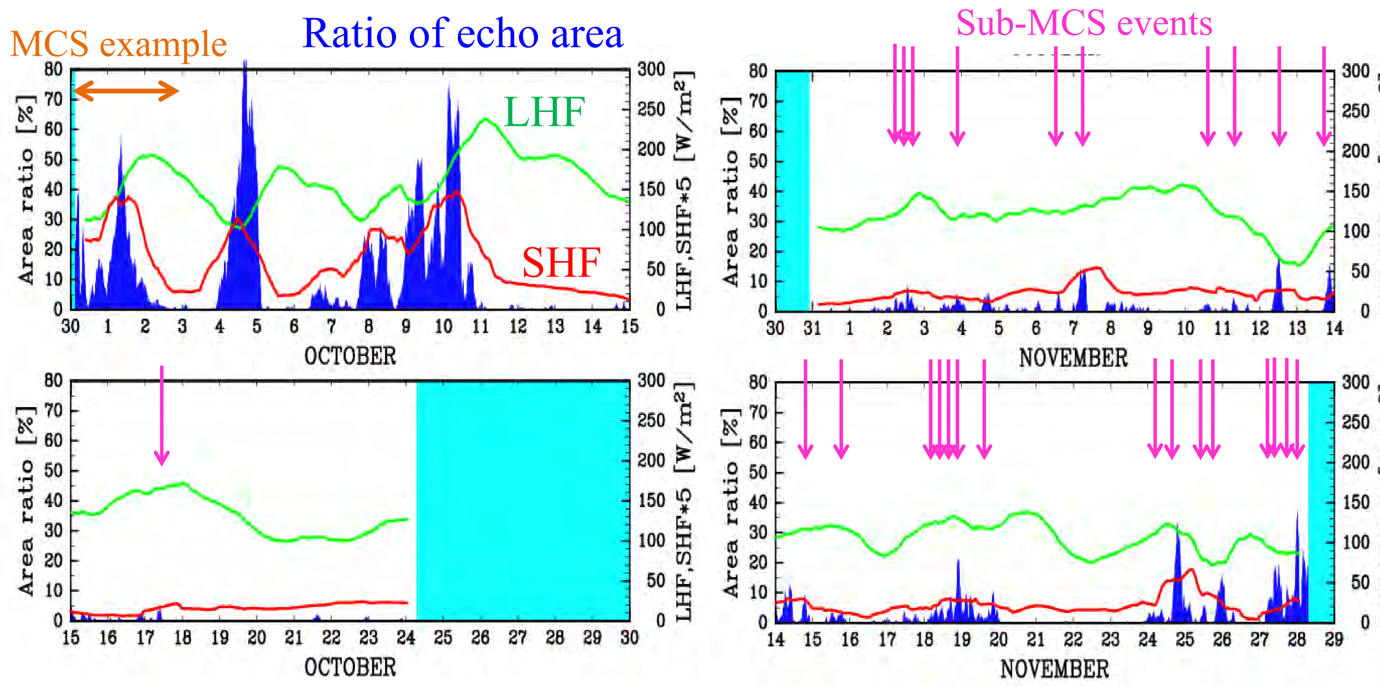

Figure 2. Time series (1-day running mean) of (red) sensible and (green) latent heat fluxes estimated by the COARE3.0 algorithm using surface meteorological observations at R/V *Mirai*, and ratio [%] of echo area over 15 dBZ to the observation area with 50km range. Note that the sensible heat flux is quintupled. A brown arrow indicates MCS example, while purple arrows indicate sub-MCS events.

- Southeasterly surface wind was dominated over 2 month.
- Before Oct. 12: Four mesoscale convective system (MCS) events caused considerable fluctuation in daily-mean surface heat fluxes.
- After Oct. 12: Dominated by sub-MCS-scale convective systems.

Table 1. Mean and standard deviation of surface meteorological variables over the entire observation period.

Variable	Mean	Std. dev.
Sensible heat flux (SHF) [W m^{-2}]	6.6	8.0
Latent heat flux (LHF) [W m^{-2}]	129.4	39.1
Air–sea temperature difference (ΔT) [K]	1.0	0.8
Air–sea humidity difference (Δq) [g kg^{-1}]	6.6	0.9
Wind speed [m s^{-1}]	6.4	2.0
Zonal wind [m s^{-1}]	−5.4	2.1
Meridional wind [m s^{-1}]	2.6	2.3

Case study of Oct. 1 MCS event

Before October 12, four MCSs passed over R/V *Mirai*.

A typical example occurred on October 1:

- The MCS-scale convection with a broad area of stratiform rainfall came from the south.
- Just before the arrival of the MCS (4:30Z 1 Oct.), surface temperature decreased sharply by about 2 K, and recorded a minimum at 10:00Z.
- Surface wind speed increased twice (5 → 10 m s^{-1}), and strong winds were observed till Oct. 3.
- **Increases in surface fluxes** associated with the MCS passage:

	Amount	Timing of the increase	Cause
SHF	+30 W m^{-2}	**During** the passage	$\overline{U}\Delta T'$ & $U'\overline{\Delta T}$
LHF	+140 W m^{-2}	**During and after** the passage	$U'\overline{\Delta q}$

Such characteristics were also observed for MCSs events in October 4, 8, and 9–10 (see Fig. 2).

Decomposition of SHF and LHF anomalies using bulk aerodynamic formula:

$$SHF' = \rho C_p C(\overline{U}\Delta T' + U'\overline{\Delta T} + \overline{U'\Delta T'})$$
$$LHF' = \rho L C(\overline{U}\Delta q' + U'\overline{\Delta q} + \overline{U'\Delta q'})$$

ρ: atmospheric density, C_p: the specific heat at constant pressure,
L: the latent heat of vaporization, C: a constant (= 1.05 × 10^{-3}),
U: surface wind speed, ΔT: air-sea temperature difference,
Δq: air-sea specific humidity difference
$\overline{(\cdot)}$: average between 00:00Z Sep 30 – 04:00Z Oct 1 (pre-MCS condition)
$(\cdot)'$: anomaly w.r.t. pre-MCS condition.

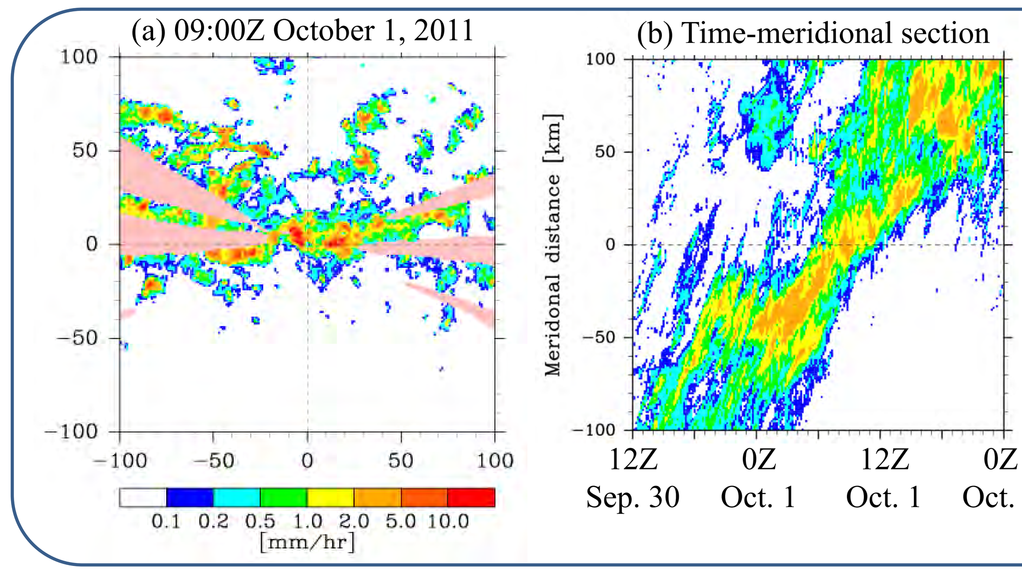

Figure 3. Rainfall estimated from radar reflectivity (Z) at 2-km height. (a) Snapshot on 09:00Z Oct. 1. (b) Time-meridional cross section averaged zonally from −100km to +100km.

Z-R relationship:
Z = 138 R$^{1.45}$ for convective rain
Z = 386 R$^{1.31}$ for stratiform rain

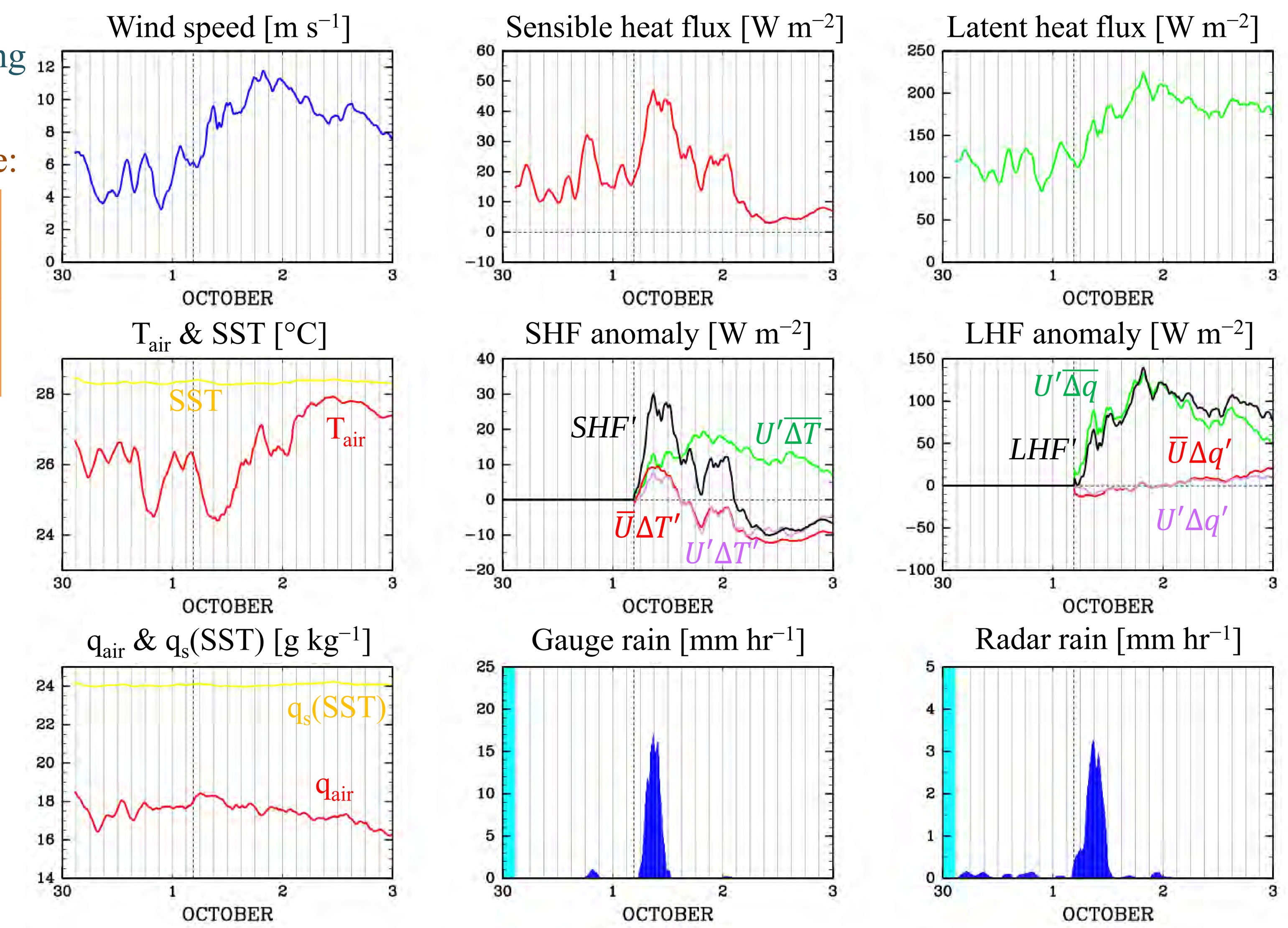

Figure 4. Time series (2-hr running mean) of surface meteorological variables, heat fluxes, decomposition of flux anomaly, and radar rainfall averaged with 10 km range.

Composite analysis of 28 sub-MCS events

Twenty-eight (28) events are detected by identifying sharp atmospheric temperature (T_{air}) drop (using Saxen and Rutledge (1998) for reference).

Each event comprises the following four phases:

Preconvective	1-hr period just before the T_{air} drop
Convectively active	From the T_{air} drop until minimum T_{air} Mean duration: 1.1 hrs Divided into two sub-phases (0.55-hr length)
Recovery	From the minimum T_{air} until when 2-hr mean T_{air} starts to decrease. Mean duration: 3.4 hrs Divided into four sub-phases (0.85-hr length)
Postrecovery	1-hr period just after the recovery phase

Results of composite analysis:

- Rainfall and increase in the surface wind (by ~1 m s^{-1}) are observed almost only during the convectively active phase.
- Atmospheric temperature in the first half of the recovery phase is still lower than that in the preconvective phase.
- **Increases in surface fluxes**:

	Amount	Timing of the increase	Cause
SHF	+14 W m^{-2}	Convectively active phase and the first half of recovery phase	$\overline{U}\Delta T'$
LHF	+20 W m^{-2}	Convectively active phase only	$U'\overline{\Delta q}$

These characteristics are qualitatively similar to previous results (e.g. Saxen and Rutledge, 1998), although magnitude of LHF anomaly is considerably smaller.

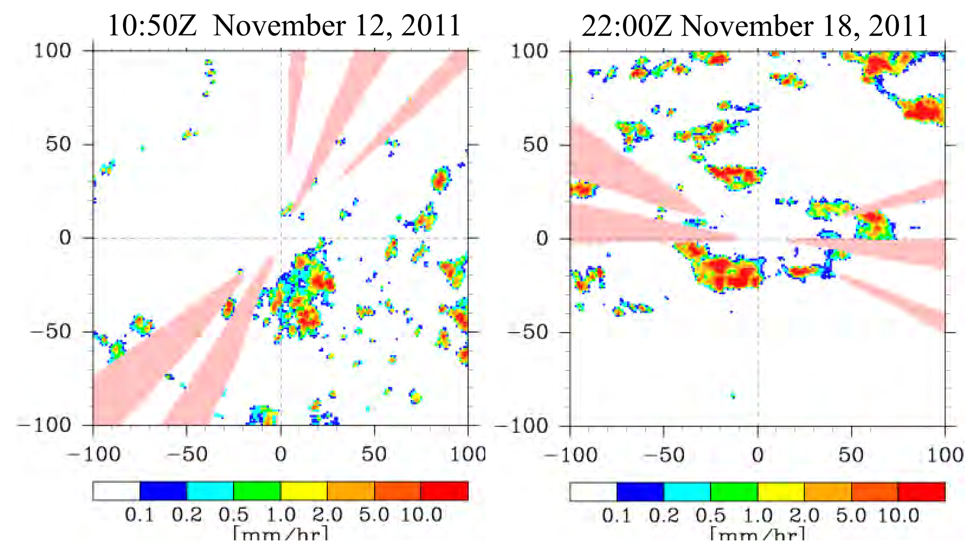

Figure 5. Snapshots of rainfall estimated from radar reflectivity at 2-km height. They are examples of sub-MCS events.

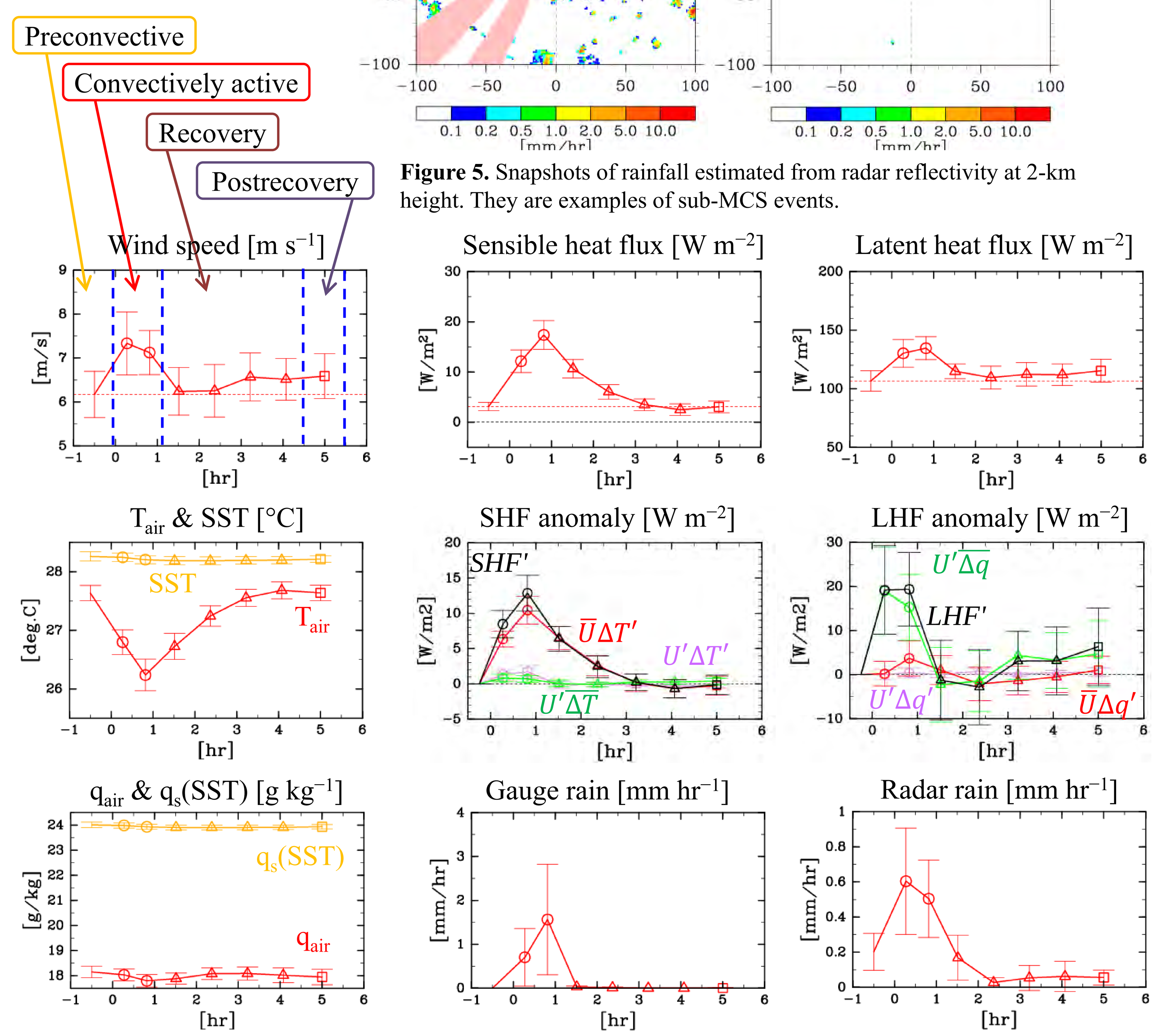

Figure 6. Composite of surface meteorological variables, heat fluxes, decomposition of flux anomaly (w.r.t. preconvective phase), and radar rainfall averaged with 10 km range for 28 sub-MCS events. Circles, triangles, and squares indicate convectively active, recovery and postrecovery phases. Error bars indicate 90% interval estimation.