Attribution Analysis of Lake Latent and Sensible Heat Enhancement during Cold Outbreak Events

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1 Introduction

- As the important parts of lake energy balance, latent heat flux (*LE*) and sensible heat flux (*H*) have a vital impact on biophysical and biochemical processes.
- Cold outbreak events are major weather events in cold seasons. The variabilities in cold outbreak activities play an important role in promoting *H* and *LE*.
- But the study on the effects of cold outbreak events intensities and major driving factor of *LE* and *H* has been reported rarely.

1. Do different intensities of cold outbreak events have different effects on *LE* and *H*?

2. Which is the most important driving factor for the variations of *LE* and *H* in the cold outbreak events?

2.Data and Methods

2.1 Observation sites

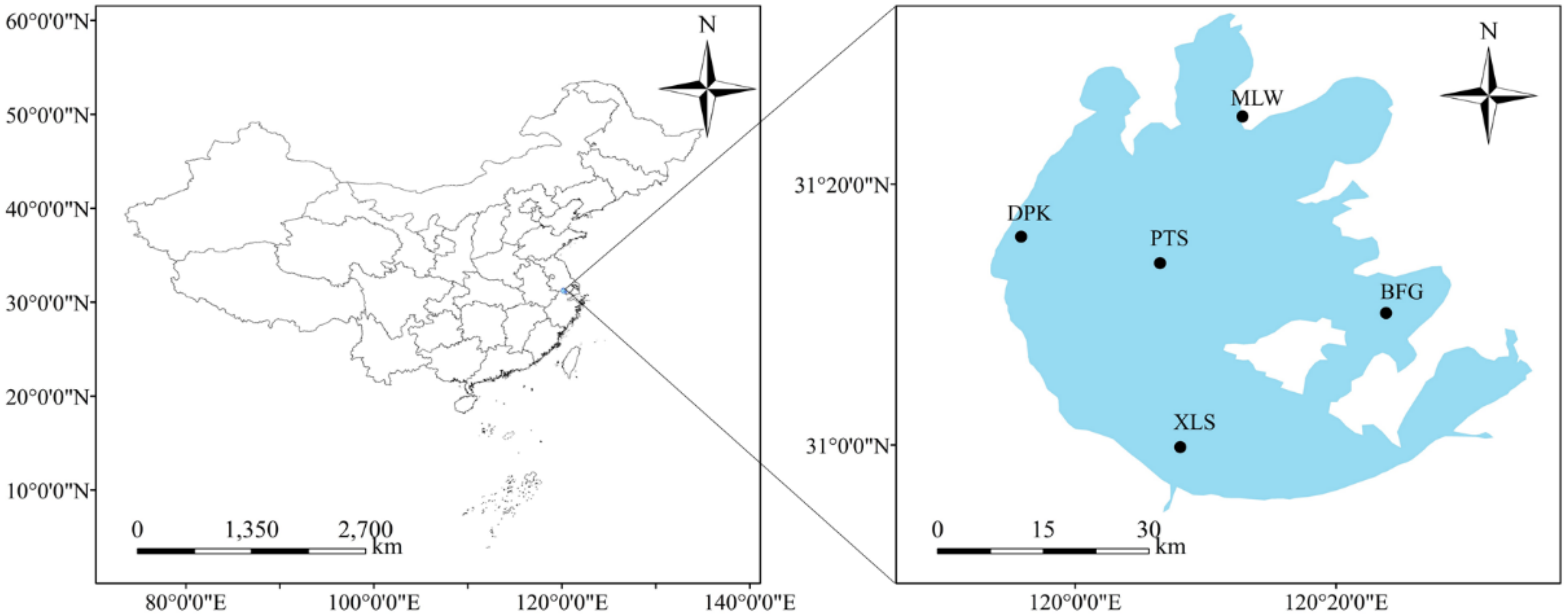

Figure 1. The locations of observation sites.

2.2 Data

- Taihu Eddy Flux Network: flux data (LE and H), meteorological data (T_a, e_a, u, P), radiation components ($K_{\downarrow}$, $K_{\uparrow}$, $L_{\downarrow}$, $L_{\uparrow}$) at BFG.
- Dongshan site (31.0799°N,120.4346°E, No.58358): daily minimum temperature.
- Time series: cold seasons (from November to March, $\bar{T}$<15℃) from 2012 to 2017.

2.3 Cold outbreak events definition

Table 1. Classification criterions for different cold outbreak events

	Daily minimum temperature	Detemperature rate within 24h	Detemperature rate within 48h	Detemperature rate within 72h
Cold wave(CW)	≤4℃	≥8℃	≥10℃	≥12℃
Strong cold outburst(SCO)	≤8℃	——	≥8℃	——
Moderate cold outburst(MCO)	——	——	6℃≤ΔT<8℃	——

(Grading of cold air, 2006)

2.4 P-T model

$$LE = \frac{s}{s+\gamma}(Rn - G) + \frac{\gamma}{s+\gamma} LE_A$$

$$LE = \alpha \frac{s}{s+\gamma}(Rn - G)$$

When it's advection free, α=1.26

$$LE + H = Rn - G$$

$$\beta = \frac{H}{LE}$$

$$\alpha = \frac{s+\gamma}{s(1+\beta)}$$

2.5 Decompositions of H

$$H = \rho_a c_p u C_H (T_s - T_a)$$

$$\Delta H = H_1 - H_2$$

$$= \rho_a c_p \left(u_1 C_{H_1} \Delta T_1\right) - \rho_a c_p (u_2 C_{H_2} \Delta T_2)$$

$$= \rho_a c_p \left((u_2 + \Delta u)(C_{H_2} + \Delta C_H)(\Delta T_2 + \Delta T)\right) - \rho_a c_p \left(u_2 C_{H_2} \Delta T_2\right)$$

$$= \rho_a c_p (u_2 \Delta C_H \Delta T_2 + \Delta u C_{H_2} \Delta T_2 + u_2 C_{H_2} \Delta T +$$

ΔC_H | Δu | $\Delta(T_s - T_a)$

$$\Delta u \Delta C_H \Delta T_2 + u_2 \Delta C_H \Delta T + \Delta u C_{H_2} \Delta T + \Delta u \Delta C_H \Delta T)$$

1 | 2 | 3 | 4

2.6 Decompositions of LE

Method 1

$$LE = \rho_a \lambda u C_E (q_s - q_a) \qquad q = \frac{\varepsilon e}{P}$$

$$LE = \epsilon \rho_a \lambda u C_E (e^*{}_\mathrm{a} - e_a + \Delta \mathrm{e})/\mathrm{P} \qquad s = \frac{\Delta e}{\Delta T} \qquad D = e^*{}_\mathrm{a} - e_a$$

$$LE = \epsilon \rho_a \lambda u C_E (D - s\Delta \mathrm{T})/P$$

$$\Delta LE = LE_1 - LE_2$$

$$= \frac{\lambda \varepsilon}{p}\left(u_1 C_{E_1}(D_1 + s\Delta T_1\right) - \frac{\lambda \varepsilon}{p}(u_2 C_{E_2}(D_2 + s\Delta T_2)$$

$$= \frac{\lambda \varepsilon}{p}\Big((u_2 + \Delta u)\big(C_{E_2} + \Delta C_E\big)[(D_2 + \Delta D) + s(\Delta T_2 + \Delta T)]\Big) - \frac{\lambda \varepsilon}{p}(u_2 C_{E_2}(D_2 + s\Delta T_2)$$

$$= \frac{\lambda \varepsilon}{p}[\underbrace{u_2 \Delta C_E (D_2 + s\Delta T_2)}_{\Delta C_\mathrm{E}} + \underbrace{\Delta u C_{E_2}(D_2 + s\Delta T_2)}_{\Delta u} + \underbrace{u_2 C_{E_2} s\Delta T}_{\Delta(T_s - T_a)} + \underbrace{u_2 C_{E_2} \Delta D}_{\Delta \mathrm{D}} +$$

$$\underbrace{\Delta u \Delta C_E (D_2 + s\Delta T_2)}_{1} + \underbrace{u_2 \Delta C_E (\Delta D + s\Delta T)}_{2} + \underbrace{\Delta u \Delta C_E (\Delta D + s\Delta T)}_{3} + \underbrace{\Delta u C_{E_2}(\Delta D + s\Delta T)}_{4}]$$

Method 2

$$LE = \lambda C_E \rho_a u(q_s - q_a)$$

$$LE = \lambda C_E \rho_a u[q^* (T_a + \Delta T) - RH q^*(T_a)] \qquad q^* = q_0 e^{\alpha T}$$

$$LE = \lambda C_E \rho_a u q_0 \left[e^{\alpha(T_a + \Delta T)} - RH e^{\alpha T_a} \right]$$

$$LE' = \frac{\delta LE}{\delta C_\mathrm{E}} {C_E}' + \frac{\delta LE}{\delta u} u' + \frac{\delta LE}{\delta \Delta T} \Delta T' + \frac{\delta LE}{\delta RH} RH' + \frac{\delta LE}{\delta T_a} {T_a}'$$

$$\frac{\delta LE}{\delta C_\mathrm{E}} {C_E}' = \lambda u q_0 \left[e^{\alpha(T_a+\Delta T)} - RH e^{\alpha T_a}\right] {C_E}'$$

ΔC_E

$$\frac{\delta LE}{\delta u} u' = \lambda C_E q_0 \left[e^{\alpha(T_a+\Delta T)} - RH e^{\alpha T_a}\right] u'$$

Δu

$$\frac{\delta LE}{\delta \Delta T} \Delta T' = \lambda C_E u q_0 \alpha e^{\alpha(T_a+\Delta T)} \Delta T'$$

$\Delta(T_s - T_a)$

$$\frac{\delta LE}{\delta RH} RH' = -\lambda C_E u q_0 e^{\alpha T_a} RH'$$

ΔRH

$$\frac{\delta LE}{\delta T_a} {T_a}' = \lambda C_E u q_0 \alpha \left[e^{\alpha(T_a+\Delta T)} - RH e^{\alpha T_a}\right] {T_a}'$$

ΔT_a

3 Results

3.1 Occurrences of cold outbreak events during the observation period

Table 2. Statistical results of different cold events from 2012 to 2017

	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017
Times of CW	0	0	1	2	1
Times of SCO	5	2	1	1	2
Times of MCO	10	5	7	7	4
Total number of times	15	7	9	10	7
Total percentage	26%	12%	14%	19%	11%

3.2 Changes in various parameters during cold outbreak events

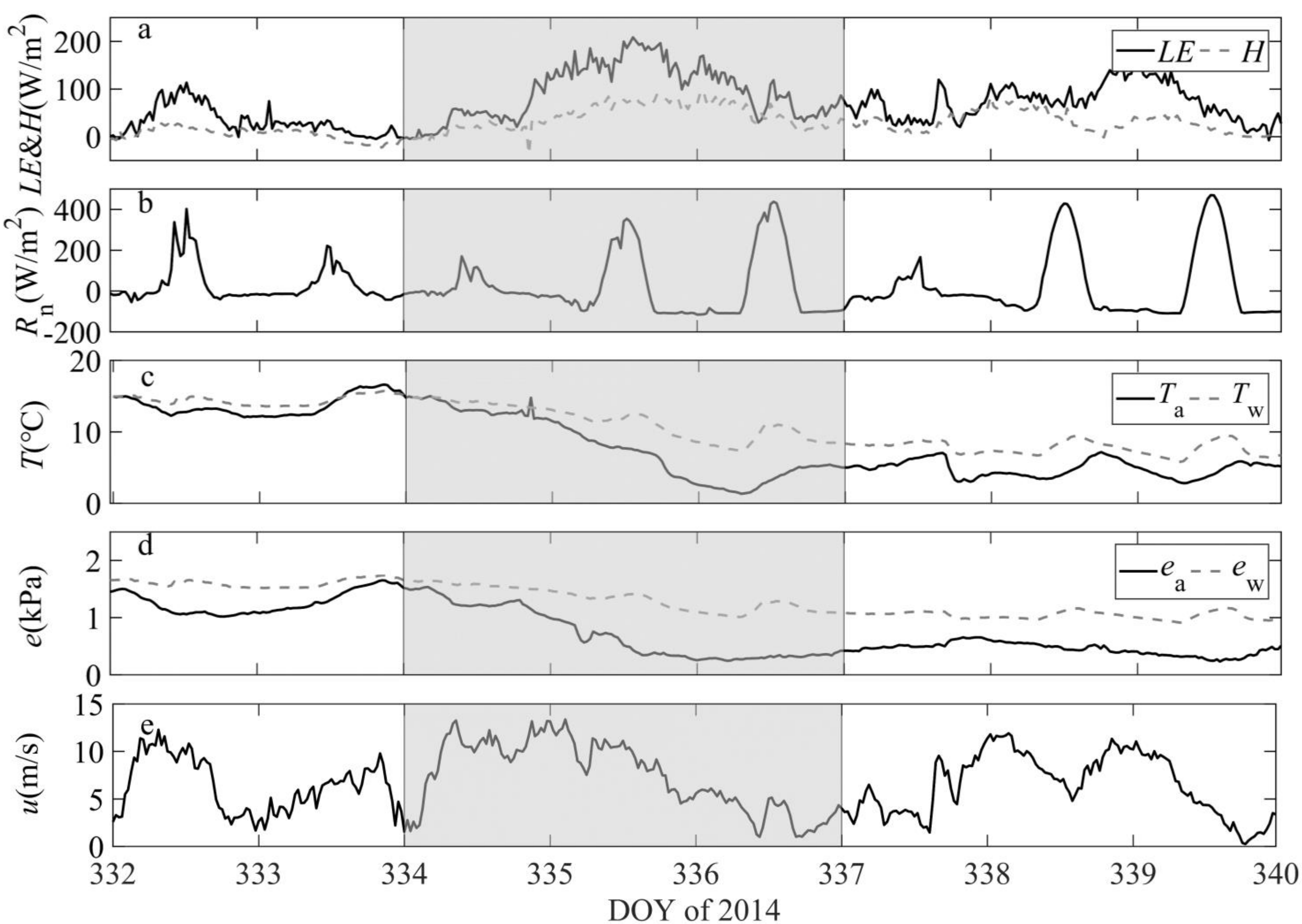

Figure 2. Time series of parameters during a SCO in 2014.
(Shadow area represents the period of SCO)

3.3 Comparisons among different cold outbreak events

Table 3. Meteorological factors and radiation of different cold events

	CW	SCO	MCO	No cold
T_a (°C)	6.9	6.3	7.8	8.6
e_a (kPa)	0.79	0.69	0.73	0.85
RH (%)	72.7	67.9	65.9	73.8
u (m/s)	7.7	6.0	5.6	4.2
R_n (W/m^2)	20.8	47.3	37.6	50.3

3.3 Comparisons among different cold outbreak events

Table 4. *LE* and *H* of different cold events

	CW	SCO	MCO	No cold
H (W/m^2)	44.4	25.9	18.8	4.3
LE (W/m^2)	93.9	49.7	64.1	23.4
Days	14	31	79	632
Total percentage of *H*	11%	14.3%	26.4%	48.3%
Total percentage of *LE*	5.8%	6.8%	22.3%	65.1%

About 50%

About 35%

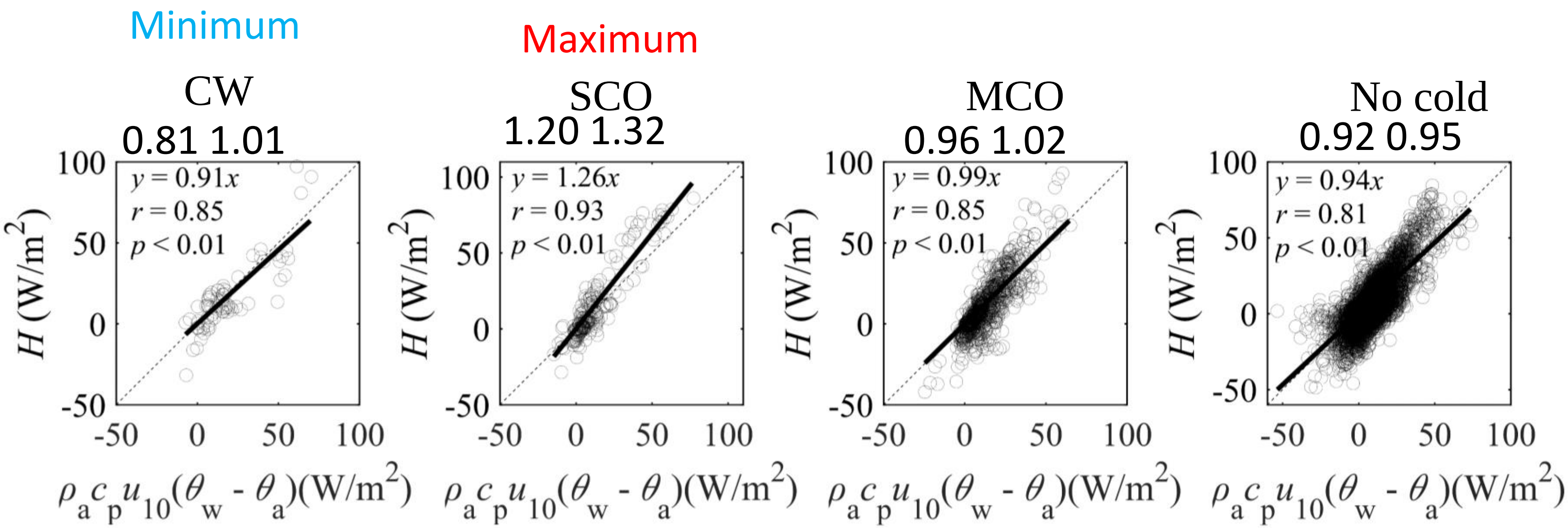

Figure 3. Comparisons of transform coefficient of *H* among different cold outbreak events

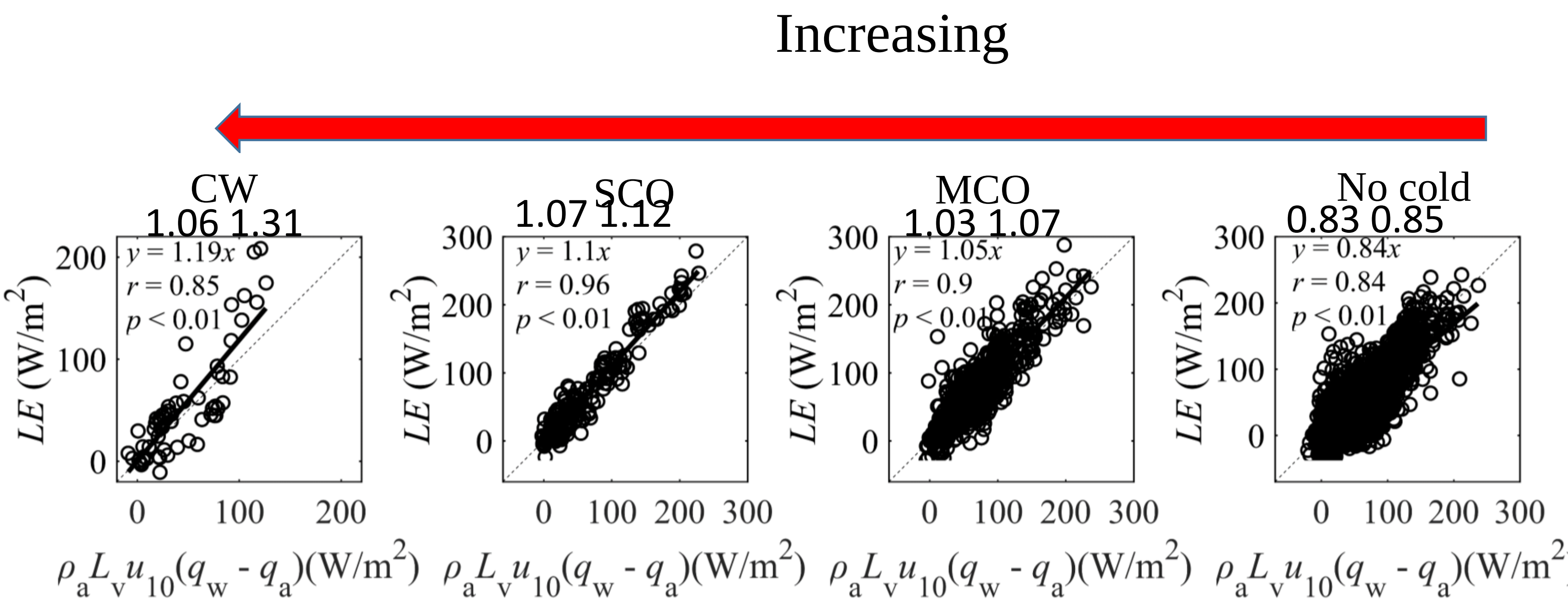

Figure 4. Comparisons of transform coefficient of *LE* among different cold outbreak events

Table 5. Comparisons of α and β among different cold events

	CW	SCO	MCO	No cold
α	1.45	1.37	1.53	1.58
β	0.37	0.47	0.26	0.19

When it's advection free, α=1.26

$$\alpha = \frac{\Delta + \gamma}{\Delta(1 + \beta)} \qquad \beta = \frac{H}{LE}$$

3.4 The decomposition results of H and LE

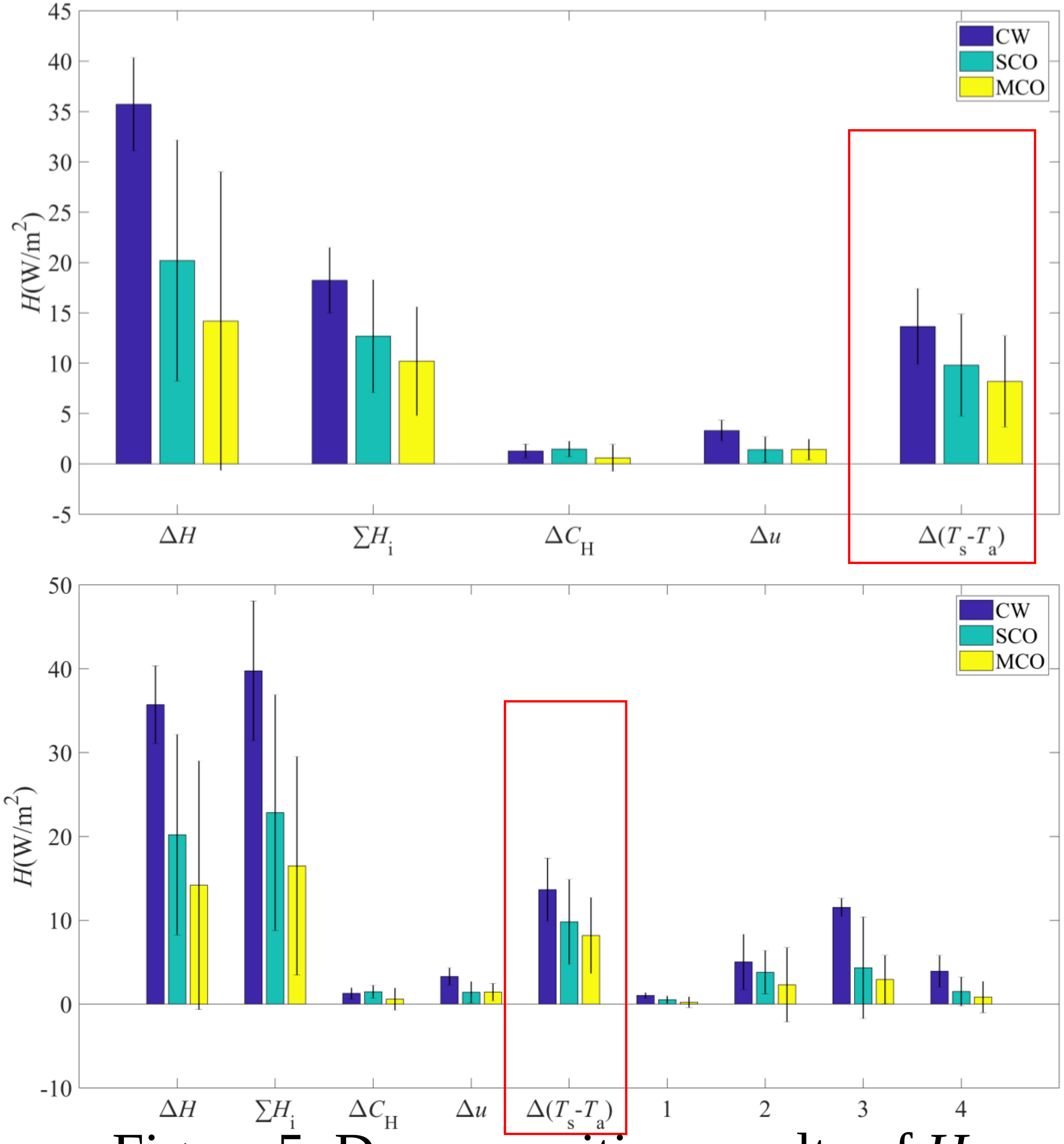

Figure 5. Decomposition results of H.

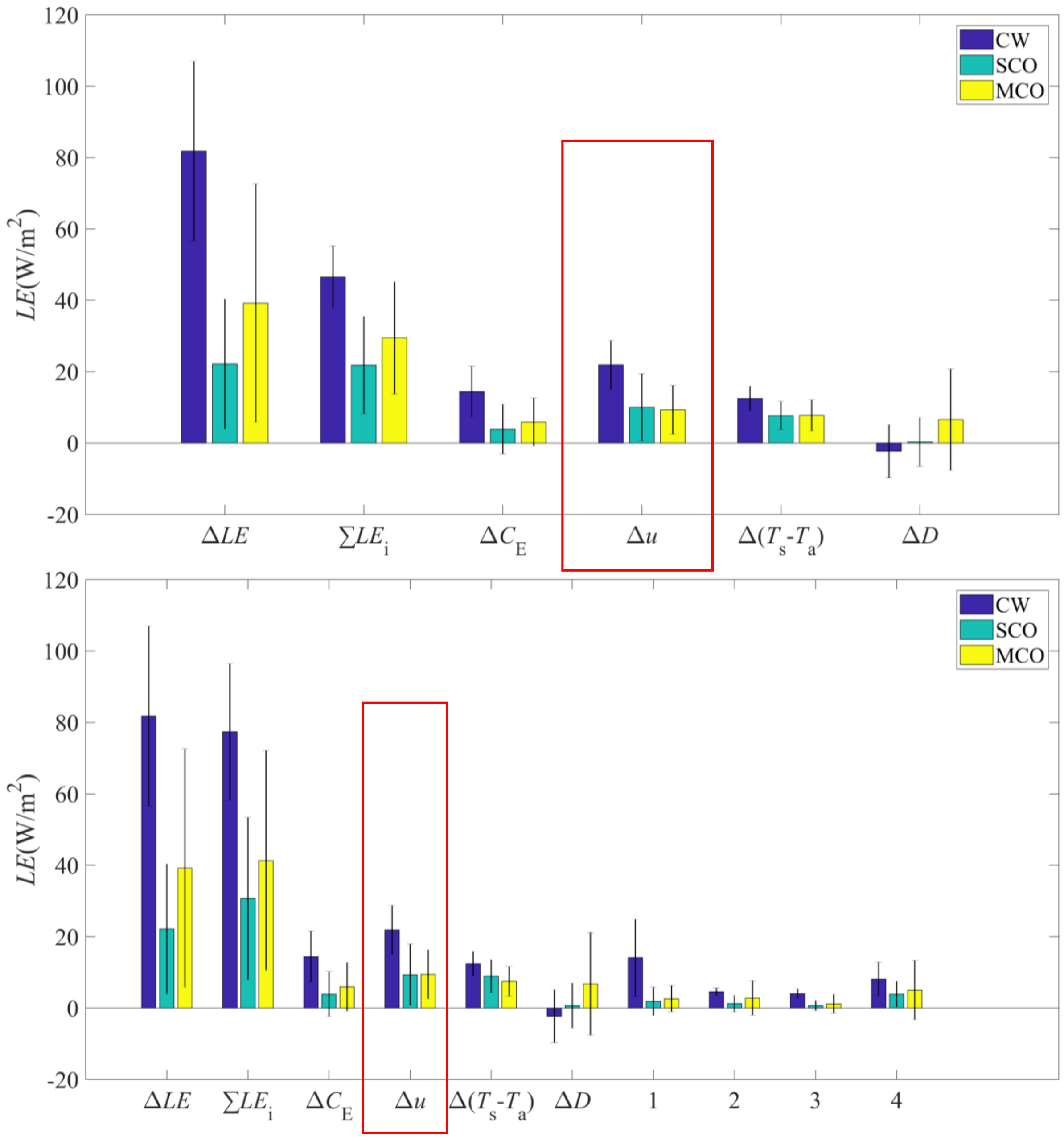

Figure 6. Decomposition results of *LE* based on method 1.

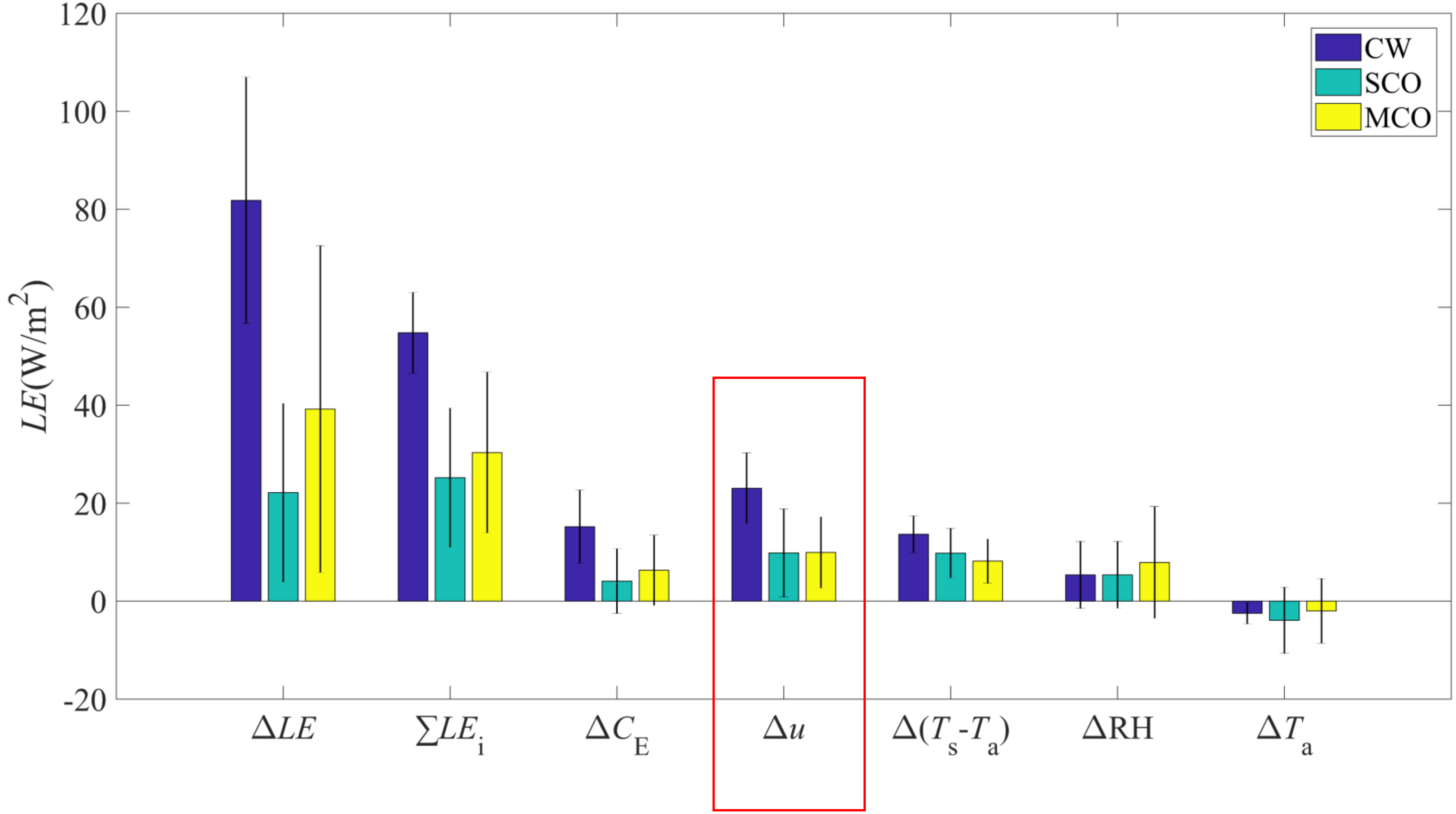

Figure 7. Decomposition results of *LE* based on method 2.

4 Conclusions

- In the warmer future, there'll be fewer cold events (SCO, MCO), but CW doesn't show a decreasing trend.
- *LE* and *H* increase significantly during cold events, especially for the period of CW (up to 4 and 9 times for *LE* and *H*, respectively).
- Temperature gradient contributes directly 35%~48% for ΔH. Wind speed has a major contribution for ΔLE, up to 30%.

Thank you for your attention