Budget Analyses of Precipitation and Energetics Associated with Torrential Rainfall Events over Zhejiang, Fujian and Jiangxi

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Abstract

Four cases of heavy rainfall over Zhejiang, Fujian and Jiangxi during mid-June are simulated by the two-dimensional (2D) cloud-resolving model using the large-scale forcing data derived from the 6-hourly ERA-Interim data set. The simulations are used to conduct budget analysis of precipitation and energetics associated with the development of torrential rainfall. Surface rainfall is dominated by water vapor convergence (Q_WVF) in water vapor related surface rainfall budget and heat divergence (S_HF) in thermally related surface rain budget. The high linear correlation coefficients between water vapor related precipitation efficiency (PEWV) and heat related precipitation efficiency (PEH) stem from the statistical similarities between Q_WVF and S_HF. The diurnal variations of surface rainfall correspond to the upward motions. An energy conversion efficiency is defined as the ratio of perturbation kinetic-energy to convective available potential energy to measure how efficiently the secondary circulations develop under the consumption of the convective available potential energy. The diurnal variations of energy conversion efficiency generally are in phase with the rainfall, indicating importance of interaction between dynamics and water vapor in build-up of rainfall peaks.

1. Introduction

Rainfall is a key component in understanding atmospheric circulations and hydrological cycles of the Earth system. Ding et al. (2006) summarized the rainy season in China generally begins with the onset of the summer monsoon in the South China Sea then ends with its withdrawal. It is widely recognized that a heavy-rain band moves northward from South China to eastern China with the northward advance of summer east-Asian monsoon (Gao and Xu 2001; Dong and Zhao 2004). Chen and Yu (1988) and Sampé and Xie (2010) argued that low-level westerly jet is important to the development of meiyu rainfall. Matsumoto et al. (1971) and Ninomiya (2000) revealed that meiyu frontal rainfalls reach their maxima at the south of the upper level jet stream. The development of eddies near the front zone are also related to the cold incursion in the upper levels and convergence in the lower levels (Ni and Zhou 2004). Zhai et al. (2014) found a relationship between rainfall peak and moisture convergence in a meiyu event during mid-June in 2011.

East Asian rainy season starts from April-June over Southern China (pre-summer heavy rainfall) and over Jiang-Huai areas during June–July (meiyu torrential rainfall) (Ding and Chen 2005). Many studies argued that this rain band jumps suddenly into Yangtze River Valley from south China (Wang and Fan 1999; Ding and Wang 2008). However, Huang et al. (2016) found an intensive rainfall center over Zhejiang-Fujian-Jiangxi region (ZFJ; see Fig. 1 in this study) when the rain band moves northward into Yangtze River Valley from south China in mid-June (pentad 33–34), filling the gap between pre-summer rainy season over south China and meiyu torrential rainfall. According to the official statistics, heavy rain during this period causes landslides and floods, leading to sever economic losses and casualties in this region. The rainfall in most part of ZFJ over 200 mm during 12 June to 15 June in 1998 (Jiang and Ni 2003). The surge in river systems due to persistent heavy rain caused 103 deaths and economic losses over 1,700 million dollars in June 1998. In June 2010, the daily rainfall of over 100 mm led to landslides, floods and power outages over southern Jiangxi. Hence, quantitative analysis and accurate forecasting for the heavy rain events over ZFJ are very important for governmental decision making for the disaster prevention.

Compared to studies of meiyu torrential rainfall, heavy rain events over ZFJ during mid-June have been seldom studied. Shen and Zhu (2007) analyzed a heavy rain event in 2005 over ZFJ using MM5. Zhang et al. (2012) analyzed the large-scale circulation of the heavy rain events over ZFJ in June 2011.

The objective of this study is to analyze the torrential rainfall events in ZFJ from the view of surface rainfall budget, precipitation efficiency and energy conversion. Four rainfall cases are simulated by a two-dimensional cloud-resolving model and the simulations are validated with the observational data and used for the analysis of rainfall in ZFJ. The model setups and large-scale forcing data are briefly discussed in the next section. The results are presented in Section 3. A summary will be given in Section 4.

2. Model setups and large-scale forcing data

The two-dimensional (2D) cloud-resolving model used in this study is developed by Soong and Ogura (1980), Soong and Tao (1980), Tao and Simpson (1993), and Sui et al. (1994, 1998) then modified by Li et al. (1999). The non-hydrostatic model with an...
The domain simulated is the region of ZFJ (26°N–29°N, 116°E–121°E; Fig. 1). Observed data of daily precipitation amount is provided by China International Ground Exchange Station, which is assessable at http://cdc.nmic.cn/ including information of quality control. The large-scale forcing data were linearly interpolated into the 12-s interval and imposed horizontally uniformly in the entire model domain at each time step.

The simulated rain rates generally follow the observed rain rates (right panel in Fig. 2). The root mean square differences in rain rate between simulations and observations show 23.2%, 24.9%, 31.1% and 26.7% of standard deviation in 1994, 1998, 2000 and 2002, respectively. The phrases of simulation and observation generally match each other. Thus, the model simulations basically capture the observed evolution of surface precipitation.

3. Results

From Appendix, the water vapor related surface rainfall budget can be written as

$$P_s = Q_{WVT} + Q_{WVF} + Q_{WVE} + Q_{CM}$$  \hspace{1cm} (1a)

Here, the surface rain rate ($P_s$) is determined by local atmospheric drying ($Q_{WVT}$), water vapor convergence ($Q_{WVF}$), water vapor evaporation ($Q_{WVE}$), and hydrometeor loss/convergence ($Q_{CM}$). The model domain mean of $Q_{CM}$ denotes hydrometeor change because hydrometeor convergence/divergence vanishes as a result of lateral periodic boundaries.

Thermally related surface rainfall budget can be expressed by

$$P_s = S_{HT} + S_{HR} + S_{HS} + S_{LH} + S_{RAD} + Q_{CM}$$  \hspace{1cm} (1b)

Here, the surface rain rate ($P_s$) is determined by local atmospheric warming ($S_{HT}$), latent heat divergence ($S_{HR}$), heat divergence ($S_{HS}$), surface sensible heat ($S_{LH}$), latent heat due to ice-related progress ($S_{LH}$), and radiative cooling ($S_{RAD}$).

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**Fig. 2.** Left column: Temporal and vertical distribution of vertical velocity (hPa/hr) over Zhejiang-Fujian-Jiangxi (ZFJ; 26°N–29°N, 116°E–121°E) in (a1) 1994, (b1) 1998, (c1) 2000, (d1) 2002. Right column: Times series of observed surface rain rate (solid line) over ZFJ and simulated in the 2D cloud-resolving model (dashed) with the forcing from ECMWF in (a2) 1994, (b2) 1998, (c2) 2000, (d2) 2002.
heating ($S_{RAD} < 0$), and hydrometeor loss/convergence ($Q_{CM} > 0$) or hydrometeor gain/divergence ($Q_{CM} < 0$). $S_{HIFT}$ is significantly smaller than other terms (see Appendix) and we thus will not discuss it in this study.

The model domain mean surface rainfall budgets in 4 cases are shown in Fig. 3 (water vapor related budget) and Fig. 4 (thermally related budget). The four rainfall cases reveal that the mean rainfall corresponds mainly to the mean water vapor convergence ($Q_{WVT} > 0$) in 2000, whereas PEWV in 1998, whereas PEWV is larger than PEH in the other three years because $S_{IM}$ contributes more to precipitation source in 1998 than in 1994 and 2002, displaying larger scattered distributions than water vapor convergence versus heat divergence.

Precipitation is intimately associated with secondary circulations, which can be measured by perturbation kinetic energy ($K'$). The source of $K'$ can be convective available potential energy (CAPE), which is calculated in pseudo-adiabatic process following Li et al. (2002). Thus, efficiency of potential energy conversion (EPEC) can be written as,

$$EPEC = \frac{K'}{[CAPE]}$$

where,

$$K' = \frac{(w')^2 + (w^y)^2}{2}$$

$$[0] = \int_{Z_a}^{Z_b} \rho(z) dz$$

when $F > 0$, whereas $H(F) = 0$ when $F \leq 0$.

The relationship between water vapor related precipitation efficiency ($PEWV$) and thermally related precipitation efficiency ($PEH$) is shown in Fig. 5a. Statistically, PEH nearly equals to PEWV in 1998, whereas PEWV is larger than PEH in the other three years because $S_{IM}$ contributes more to precipitation source comparing with $Q_{WVF}$ (Fig. 5b). The high linear correlation coefficients between PEWV and PEH are 0.84 for 1994, 0.97 for 1998, 0.96 for 2000 and 0.86 for 2002. The high linear correlation coefficients between PEWV and PEH stem from the statistical similarities between $Q_{WVF}$ and $S_{IM}$ in 4 cases (Fig. 5b). Figure 5c shows that the other rainfall sources excluding $Q_{WVF}$ and $S_{IM}$ contribute more to precipitation source in 2000 and 1998 than in 1994 and 2002, displaying larger scattered distributions than water vapor convergence versus heat divergence.

Precipitation efficiencies are defined as

$$PEWV = \frac{P_i}{\sum_{i=1}^{n} H(Q_i)Q_i}$$

$$PEH = \frac{P_i}{\sum_{i=1}^{n} H(S_i)S_i + H(Q_{CM})Q_{CM}}$$

In these equations, $Q_i = (Q_{WVT}, Q_{WVF}, Q_{WVE}, Q_{CM}); S_i = (S_{HT}, S_{IM}, S_{HIFT}, S_{HIFT}, S_{RAD}); H$ is the Heaviside function, $H(F) = 1$ when $F > 0$, whereas $H(F) = 0$ when $F \leq 0$.

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Fig. 5. (a) PEWV versus PEH, (b) resource of PEWV versus resource of PEH, and (c) resource in PEH except water vapor convergence/divergence (QWVF) versus resource in PEWV except heat divergence/convergence (SHF). Blue triangle stands for 1994, green square stands for 1998, yellow circle stands for 2000, and red diamond stands for 2002; lines in (a) are regression equations of PEH and PEWV; lines in (b) are regression equations of resource of PEH and resource of PEWV; where blue line for 1994, green line for 1998, yellow line for 2000, red line for 2002.

Fig. 6. Time series of surface rain rate (blue line) on the left axis, water vapor related surface precipitation efficiency (PEWV; red line and red label), and efficiency of potential energy conversion (EPEC; black line and black label) on the right label over Zhejiang-Fujian-Jiangxi (ZFJ; 26°N–29°N, 116°E–121°E) in (a) 1994, (b) 1998, (c) 2000, and (d) 2002.

In Eq. (3a), u and w are zonal and vertical components of wind, respectively; overbar stands for model domain mean; prime stands for a perturbation from model domain mean; Zb and Zt stand for the heights of the top and the bottom of the model atmosphere. The EPEC ranges generally from 0 to 10% with occasions of over 20–30% (Fig. 6), which is consistent with the efficiency of atmospheric thermodynamic engine in tropical natural convection of 10% estimated by Rennó and Ingersoll (1996). The EPEC of over 30% on 19 June 2000 may result from prevailed downward motions before upward motions were restored. The downward motions reduce atmospheric water vapor and thus CAPE. The restored upward motions increase K′ significantly, while they do not produce large precipitation in a dry atmosphere.

Considering the similarity of PEWV and PEH, we only discuss PEWV in the latter sections. Figure 6 shows the evolution of P, PEWV and EPEC in the 4 cases. On the onset stage of the rainfall events, PEWV and EPEC increases as P increases on 8–9 June 1994, 12–14 June 1998, 4–5 and 18–19 June 2000, 10–11 and 13–14 June 2002. In this stage, the secondary circulations grow rapidly when CAPE is consumed. As a result, EPEC increases rapidly.

On the mature stage of the rainfall events, PEWV stays high. For instance, PEWV sustains over 95% on 13–18 and 20–23 June 1994, 16–26 June 1998, 8–12 June 2000, 14–17 and 20–24 June 2002. In this stage, the CAPE brought by the vapor influx offsets the consumption of K′.

We also notice some abnormal EPECs. The EPEC on 19 June 1994 increases to 5% while P and PEWV decrease. The downward motions occur below 800 hPa (Fig. 2a1), which leads to atmospheric drying and reduces CAPE. The dry atmosphere reduces precipitation as well as its efficiency, while it increases EPEC.

Figure 7 shows the diurnal variations of P, rainfall source (sum of local atmospheric drying, water vapor convergence, surface evaporation and hydrometeor loss), PEWV and EPEC and the imposed large-scale vertical velocity in the 4 cases. As the trend of energy conversion in rainy period is opposite to rain-free period, main rainy parts of the simulations of 2000 and 2002 are analyzed in this section. The diurnal cycle of rainfall generally corresponds to that of large-scale upward motions. PEWV does not show strong diurnal signals in 1994, 1998 and 2002, while it reveals a strong diurnal cycle in 2000. The diurnal variation of P is consistent with the satellite observations with a peak in the afternoon (Chen et al. 2012).

Both rainfall and its source increase in the morning and reaches peak in the afternoon, which causes less regular diurnal variation of PEWV. But the diurnal variation of rainfall is intimately associated with EPEC because the rainfall is dynamically controlled by growth of the secondary circulations. We also notice the shifting of P and EPEC during 1400–2000 Local Standard Time (LST) in Fig. 7c1. In 2000, the K′ reaches its maximum around 1800 LST after the rainfall peak at 1400 LST 9 June. The rainfall is little despite the large EPEC because rainfall source decays ahead.

Actually, a rainfall event cannot develop without enough rainfall source or the active secondary circulations. Weak water vapor convergence with high EPEC produces little rainfall. But this process can be very efficient, such as the early morning in 2002. If the rainfall source develops ahead of EPEC, the addition of rainfall is minimal, causing the change of PE. The fluctuation of PEWV mainly stems from the phrase difference between EPEC.
and rainfall source. There are four asynchronous scenes: rainfall source develops ahead of EPEC; the source stays large when EPEC starts to decay; EPEC develops ahead of rainfall source; EPEC stays large when EPEC starts to decay. The first two scenes show the decrease of PEWV, whereas the latter two show the relatively large PEWV.

When rainfall source increases before EPEC does, the water vapor from the influx could not be consumed for the production of rainfall. For instance, $P_S$ is maintained small because of the low-level EPEC, while rainfall source increases during 0600–0800 LST in 1994. PEWV restarts to increase when EPEC grows after 0800 LST as rainfall source keeping increasing. The same scene happens during 0800–1000 LST in 2002. With a decrease in EPEC during 0500–0700 LST, the diurnal variation of PE in 2000 tells similar scenario. When EPEC decays before rainfall source does, PEWV drops significantly during 1200–1500 LST in 1994. The same scenario occurs during 1400–1900 LST in 2002 and 1300–1500 LST in 1998. These two kinds of asynchrony produce a tiny addition even a decrease of $P_S$, while rainfall source increases largely, which leads to a sudden decrease of PEWV during this period.

When EPEC develops ahead of rainfall source, the addition of rainfall is ignorable despite the high PE and the increasing PEWV, as mentioned previously during the early morning in 2002. When rainfall source decays before EPEC does during 1400–2000 LST in 2000, PEWV sustains high while $P_S$ reduces. With these two kinds of asynchrony, high PEWV can be maintained because the active secondary circulations can consume nearly all the water vapor supply for the production of rainfall.

On the other hand, $P_S$ and PEWV augment significantly when rainfall source and EPEC grow synchronously from 0800 LST or so until noon (e.g. from 0800 LST to 1200 LST in 1994, 0700 LST to 1300 LST in 1998, 0800 LST to 1300 LST in 2000). During this period, rainfall source increases rapidly and the growing secondary circulation is strong enough to transport the water vapor into rainfall. Thus, $P_S$ increases with increasing PE.

From the view of rainfall budget, high PEWV means nearly all the terms in the rainfall budget contribute to the production of rainfall. And the decrease in PEWV is related with hydrometeor divergence and local atmospheric moistening. The significant decrease in water vapor convergence also causes the significant decrease in PEWV. Local atmospheric drying, water vapor convergence and hydrometeor convergence decrease when EPEC and rainfall source reduce synchronously.

### 4. Summary

The budgets of water vapor, heat and energie associated with torrential rainfall events during mid June in the four strong rainfall years (1994, 1998, 2000 and 2002) are investigated by analyzing simulation data from the two-dimensional cloud-resolving model. The mean rainfall is largely associated with the mean water vapor convergence in water vapor related surface rainfall budget and heat divergence in thermally related surface rain budget for all the rainfall events. The additional rainfall corresponds to local atmospheric drying in water vapor related surface rainfall budget and to local atmospheric warming in thermally related surface rainfall budget in 1994, 1998 and 2000. In contrast, the water vapor convergence and heat divergence are respectively used to moisten and cool local atmosphere in 2002, which decreases rainfall.

The precipitation efficiencies defined in water vapor related surface rainfall budget (PEWV) and defined in thermally related surface rainfall budget (PEH) in 1998 are similar, whereas PEWV is larger than PEH because heat divergence ($S_{HF}$) contributes more to precipitation source compared to water vapor convergence ($Q_{WVF}$) in the other years. The statistical analysis with daily simulation data reveals the high linear correlation between PEWV and PEH, steming from the strong statistical similarities between $Q_{WVF}$ and $S_{HF}$.
Perturbation kinetic energy (K'¢) is used to represent the diurnal variation of rainfall. Unlike PEWV, EPEC reveals strong diurnal signals. The diurnal variation of rainfall is associated with those of PEWV and EPEC. The diurnal variation of rainfall sustains high. EPEC is relatively stable during this period because both rainfall and rainfall source reveal strong diurnal cycles, while it shows a diurnal cycle in 2000. Unlike PEWV, EPEC reveals strong diurnal signals. The peaks of EPEC are in phase with rainfall in 1998 and 2002, but the peaks of EPEC lag the rainfall in 1994 and 2000 probably because the growth of the secondary circulations with the consumption of water vapor by rainfall peak fails to build up the peak of rainfall sources.

### Acknowledgements

The authors thank the comments from the Editor Prof. Kazuaki Yasunaga and the two anonymous reviewers and the support from the Training Center of Atmospheric Sciences of Zhejiang University. This work was supported by National Natural Science Foundation of China (41775040).

Edited by: K. Yasunaga

### Supplements

Supplement Appendix and Table S1 are attached.

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Manuscript received 1 September 2018, accepted 28 October 2018