The EASM, unlike other tropical monsoons, is characterized by mixed tropical and mid-latitude influences with frontal systems and jet stream effects (Ding and Chan, 2005; Molnar et al., 2010). Previous studies have emphasized land-sea thermal contrast and heating over the Tibetan Plateau (TP) as primary drivers of the EASM (e.g., Chou et al., 2001; Wu et al., 2007), with the subtropical westerly jet possibly advecting downstream warm air originating over and south of the TP and sustaining rainfall in the EASM region (Sampe and Xie, 2010).

Quantitative studies of regional hydrological budgets can be performed by considering the vertically integrated DSE and moisture equations in pressure coordinates,

$$c_p\langle\partial_t T\rangle + c_p\langle\boldsymbol{v}\cdot\nabla T\rangle + \langle\omega\partial_p s\rangle = \langle Q_c\rangle + S^{net} + R^{net} + SH, \tag{1}$$

$$L_v\langle\partial_t q\rangle + L_v\langle\boldsymbol{v}\cdot\nabla q\rangle + L_v\langle\omega\partial_p q\rangle = \langle Q_q\rangle + LH, \tag{2}$$

where T is temperature, q is specific humidity, s is dry static energy (c_pT+gz, z is geopotential height and g is gravitational acceleration) and $\langle\cdot\rangle$ indicates a vertical mass integral (i.e., $\int \cdot dp/g$). The vertically integrated change of internal energy and work done by the atmosphere is balanced by the energy fluxes at the boundaries of the atmospheric column, that is, the net shortwave radiation S^{net}, the net longwave radiation R^{net} and the sensible heat SH, and the latent heating Q_c. The vertically integrated change of moisture in the atmospheric column is balanced by the evaporation LH/L_v and precipitation $-\langle Q_q\rangle/L_v$, where LH is the surface latent heat flux, Q_q is moistening and L_v is latent heat of vaporization. The sum of convective heating and moistening must be zero in the atmospheric column because precipitation $P = -\langle Q_q\rangle/L_v = \langle Q_c\rangle/L_v$, so that by summing Eqs. 1 and 2, one obtains the MSE equation:

$$\langle\overline{\frac{\partial E}{\partial t}}\rangle = \overline{F^{net}} - \langle\overline{\boldsymbol{v}\cdot\nabla E}\rangle - \langle\overline{\omega\frac{\partial h}{\partial p}}\rangle, \tag{3}$$

with moist enthalpy $E = c_pT + L_vq$, moist static energy $h = E + qz$ and net energy flux through the top and bottom of the atmospheric column $F^{net} = S^{net} + R^{net} + SH + LH$. The horizontal advection term, as discussed in details in (Chen and Bordoni, 2014), can be further decomposed into stationary and transient eddy fluxes:

$$\langle\overline{\mathbf{v}\cdot\nabla E}\rangle = \langle[\overline{\mathbf{v}}]\cdot[\overline{\nabla E}]\rangle + \langle[\overline{\mathbf{v}}]\cdot\overline{\nabla E^{*}}\rangle + \langle\overline{\mathbf{v}^{*}}\cdot[\overline{\nabla E}]\rangle + \langle\overline{\mathbf{v}^{*}}\cdot\overline{\nabla E^{*}}\rangle + \langle\overline{\mathbf{v}'\cdot\nabla E'}\rangle. \tag{4}$$

The first term on the right side is the zonal-mean energy advection by the zonal-mean flow; the second term is the advection of the stationary eddy energy by the zonal-mean flow; the third term is the advection of the zonal-mean energy by the stationary eddy velocity; the fourth term is the advection of the stationary eddy energy by the stationary eddy velocity; the fifth term is the advection of the transient eddy energy by the transient eddies. Conventionally, $(\cdot)'$ and $(\cdot)^*$ denote deviations from the time $\overline{(\cdot)}$ and zonal $[\cdot]$ mean, respectively. These stationary and transient eddy fluxes provide insights into the regional hydrological pattern associated with zonal asymmetries.

We study the dynamics of the EASM with an comprehensive approach that makes use of satellite observations, reanalysis and model simulations. Observations include GPCP daily data and Obs4MIPs standard outputs (http://obs4mips.llnl.gov:8080/wiki/) project hosted

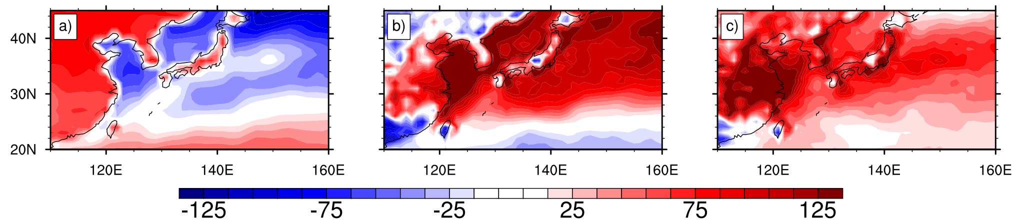

Figure 1: Vertically integrated MSE budget. Net energy flux into the atmospheric column $\overline{F^{net}}$ (left), vertical integral of horizontal moist enthalpy advection $-\langle\overline{\boldsymbol{v}\cdot\nabla E}\rangle$ (middle) and vertical integral of vertical MSE advection $-\langle\overline{\omega\frac{\partial h}{\partial p}}\rangle$ (right) for the MB season. Contours are in W m^{-2}.

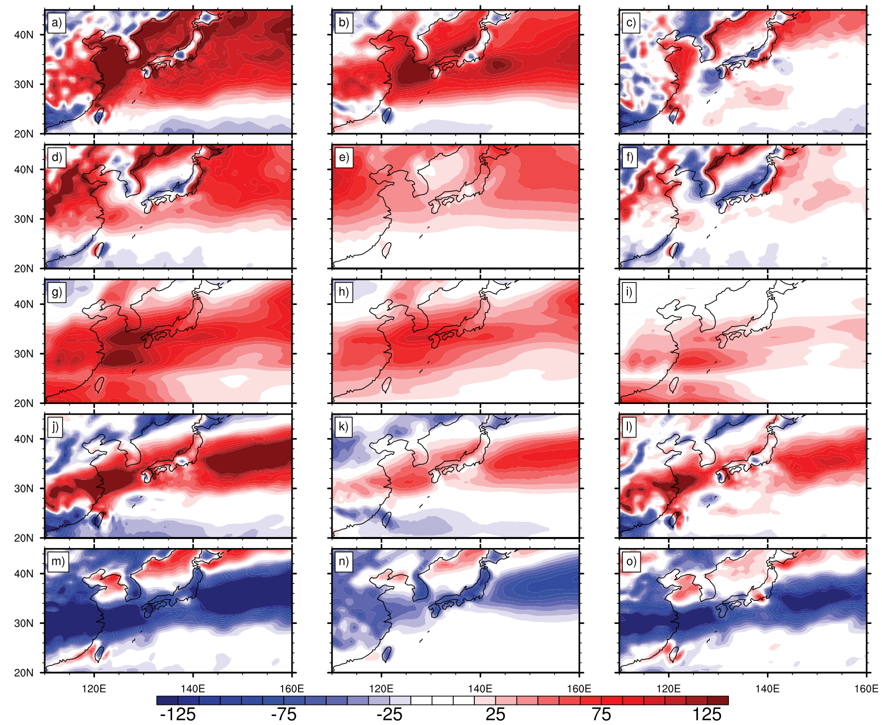

Figure 2: Eddy decomposition of the vertical integral of the horizontal moist enthalpy advection $-\langle\overline{\boldsymbol{v}\cdot\nabla E}\rangle$ (left), the horizontal dry enthalpy advection $-\langle\overline{c_p\boldsymbol{v}\cdot\nabla T}\rangle$ (middle) and the latent energy advection $-\langle\overline{L_v\boldsymbol{v}\cdot\nabla q}\rangle$ (right) during the MB season. Rows indicate the total advection $-\langle\overline{\boldsymbol{v}\cdot\nabla(\cdot)}\rangle$ (first), the advection of the stationary eddy energy by the zonal-mean flow $-\langle[\overline{\boldsymbol{v}}]\overline{\nabla(\cdot)}^*\rangle$ (second), the advection of the zonal-mean energy by the stationary eddy velocity $-\langle\overline{\boldsymbol{v}}^*[\overline{\nabla(\cdot)}]\rangle$ (third), the advection of the stationary eddy energy by the stationary eddy velocity, or pure stationary eddy $-\langle\overline{\boldsymbol{v}}^*\overline{\nabla(\cdot)}^*\rangle$ (fourth) and the advection of the transient eddy energy by the transient eddy velocity $-\langle\overline{\boldsymbol{v}'\cdot\nabla(\cdot)'}\rangle$ (fifth). Contours are in W m^{-2}.

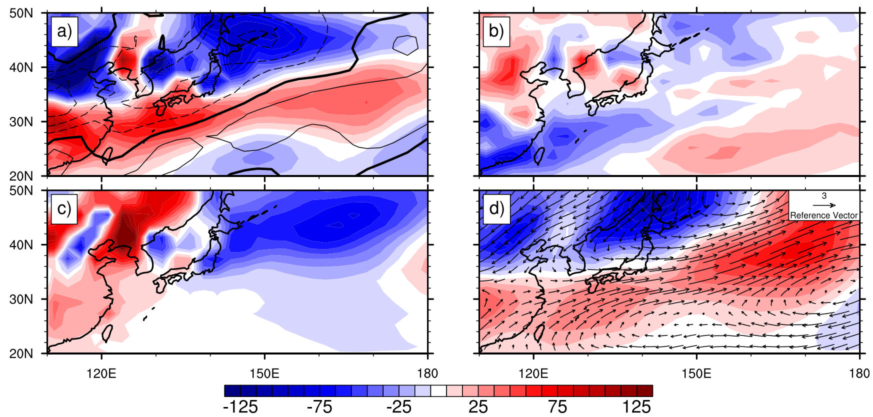

Figure 3: Anomalies (TP - noTP experiments) in horizontal dry enthalpy advection $-\langle \overline{c_p \boldsymbol{v} \cdot \nabla T} \rangle$ (color contours) and vertically integrated (normalized, not mass-weighted) meridional stationary eddy velocity divergence $\langle \overline{\partial_y v^*} \rangle$ (line contours, contour interval 10^{-6} s^{-1}) (a), latent energy advection $-\langle \overline{L_v \boldsymbol{v} \cdot \nabla q} \rangle$ (b), the advection of the stationary eddy dry enthalpy by the zonal-mean flow $-\langle c_p [\overline{\boldsymbol{v}}] \cdot \overline{\nabla T^*} \rangle$ (c), the advection of the zonal-mean dry enthalpy by the stationary eddy velocity $-\langle c_p \overline{\boldsymbol{v}^*} \cdot [\overline{\nabla T}] \rangle$ (color contours) and vertically integrated (normalized, not mass-weighted) stationary eddy wind fields (vectors) with reference vector 3 m s^{-1} (d).

on the Earth System Grid Federation (http://esgf.org). Reanalysis data are primarily obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim products. Numerical simulations are performed with the AM2.1 AGCM developed at the Geophysical Fluid Dynamics Lab (GFDL, Anderson et al. 2004), in which two different model integrations are performed with different topography over Asia, one where full topography at present-day height is retained (control) and one where the TP and Himalaya mountains are removed (experiment). The following text brief summarizes the findings in Chen and Bordoni (2014).

Using the MSE budget (Eq. 3), we find that positive horizontal moist enthalpy advection, and primarily dry enthalpy advection, sustains the MB rainfall band in a region of otherwise negative net energy input into the atmosphere column (Fig. 1). Both $\overline{F^{net}}$ and horizontal moist enthalpy advection are important in sustaining the rainfall in the Meiyu region; however, in the Baiu region and northwestern Pacific, energy input into the atmosphere is negative, and the horizontal moist enthalpy advection alone sustains the rainfall. Given that the horizontal moist enthalpy advection plays an essential role in positioning the stationary MB rainfall band, heuristically we expect the stationary eddy fluxes to be the dominant terms in the horizontal moist enthalpy advection. By using Eq. 4, stationary eddy fluxes due to zonal thermal gradient $\partial_x \overline{T^*}$ and the meridional stationary eddy velocity $\overline{v^*}$ are shown to be dominant in creating the pattern of total dry enthalpy advection in the MB region (Fig. 2).

Numerical simulations with and without the TP are designed to explore how the presence of the TP modifies the MSE and moisture budgets, and, hence, influences the EASM. The presence of the TP is shown to affect significantly the formation of the EASM through changes in the meridional stationary eddy velocity $\overline{v^*}$ as well as its meridional gradient $\partial_y \overline{v^*}$, while changes in the meridional thermal gradient due to zonal asymmetries $\partial_x \overline{T^*}$ have a lesser impact and are confined to the near downstream of the TP (Fig. 3). This result is different from that of Sampe and Xie (2010) in that the meridional temperature advection by the meridional stationary eddy velocity, rather than the zonal temperature advection from the TP, is shown to be the primary contribution to the energetics of the MB fronts.

The moisture budget, directly relating the net precipitation to the moisture flux convergence, is also examined to better quantify the contribution to the rainfall intensity by evaporation and circulation (moisture advection and/or wind convergence). It is found that the largest contribution to the moisture flux convergence sustaining the MB rainfall arises from stationary eddy convergence $-\overline{\nabla \cdot \mathbf{v}^*}$, which is consistent with the other findings.

Novel results emerging from this study include:

- Positive horizontal moist enthalpy advection, and primarily dry enthalpy advection, sustains the MB rainfall band in a region of otherwise negative net energy input into the atmosphere;
- The zonal thermal gradient due to zonal asymmetries $\partial_x \overline{T^*}$ and the meridional stationary eddy velocity $\overline{v^*}$ are the dominant stationary terms creating the pattern of total dry enthalpy advection in the MB region;
- The largest contribution to the moisture flux convergence sustaining the MB rainfall arises from stationary eddy convergence $-\overline{\nabla \cdot \boldsymbol{v}^*}$;
- The numerical experiments with and without the TP show that the TP primarily influences the formation of the MB front through changes in the meridional stationary eddy velocity $\overline{v^*}$ as well as its meridional gradient $\partial_y \overline{v^*}$. Changes in the meridional thermal gradient due to zonal asymmetries $\partial_x \overline{T^*}$ have a lesser impact and are confined to the near downstream of the TP.

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