Zonal Structure of anomalies in tropical atmospheric energy budgets

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1. Introduction
The variability of the vertically integrated tropical energy budget is evaluated, employing third-generation reanalyses European Re-Analysis Interim (ERA-I), Climate Forecast System Reanalysis (CFSR) and Modern Era Retrospective-analysis for Research and Applications (MERRA). The divergence of total energy (TEDIV), latent heat (VIMD) and dry static energy (DSEDIV) transport can be computed from eqs. (1) and (2) (all symbols have their usual meaning). Results only make sense when the mass budget of the realanalyses is balanced.

\[
\text{TEDIV} = \left\langle \nabla \cdot \mathbf{F}_{\text{total}} \right\rangle = \text{Rad}_{\text{tot}} - F_S - \frac{\partial (\mathbf{q}^c)}{\partial t}
\]

\[
\text{VIMD} = \left\langle \nabla \cdot \mathbf{F}_{\text{latent}} \right\rangle = -L \cdot P - L \cdot E - L \cdot \frac{\partial (\mathbf{q}^c)}{\partial t}
\]

Divergences averaged over the tropical belt (20N-20S) and thus tropical total energy export show only small variation (±4%) which is on the order of the uncertainty of the obtained values (Mayer and Haimberger, 2012). In contrast, the tropical energy budgets show a pronounced zonal anomaly structure associated with El Niño-Southern Oscillation (ENSO) which is investigated in this work.

2. Longitude-time variability
Anomalies on the order of up to ±15Wm⁻² in TEDIV and up to ±30Wm⁻² in DSEDIV and VIMD can be seen in Fig. 1. DSEDIV and VIMD show a quadrupole anomaly structure with extreme values over the Indic Ocean, Indo-Pacific Warm Pool, Eastern Pacific and the Atlantic. During warm ENSO phases, DSEDIV (which is closely related to diabatic heating processes) exhibits positive anomalies over the Eastern Pacific and Indic Ocean, while VIMD anomalies have the opposite sign. Thus, VIMD anomalies indicate changes of atmospheric circulation, leading to changes in diabatic heating. TEDIV tends to show a dipole structure with one extreme value over the Indo-Pacific Warm Pool and one over the Eastern Pacific. As RadTOA generally shows weak variations, positive TEDIV anomalies relate to stronger than normal surface fluxes, i.e. when the atmosphere is gaining energy from the ocean.

The effects of known temporal inhomogeneities related to assimilation of SSM/I radiances have been reduced by using split climatologies (1979-1991, 1992-2002, 2003-) in all figures. Without the splitting, the described patterns are noticeably more noisy but clearly visible in ERA-I and also the other two reanalyses (not shown).

3. Composites
Anomaly composites of tropical VIMD for the three strongest El Niños after 1978 (1982/83, 1986/87, 1997/98) show a region of stronger than normal moisture convergence over the Indo-Pacific Warm Pool, around 18 months before the peak of the event. This anomaly gradually propagates to the Eastern Pacific where it diminishes at 90E around 12 months after the El Niño (Fig. 2). Analogous plots for DSEDIV show a mirrored image, but even stronger, as there is additional contribution from stronger than normal radiative flux convergence (not shown). TEDIV shows this transition to a much smaller extent. Results from all three employed reanalyses agree remarkably well.

4. EOF analysis
Fig. 3. EOF 1 (describing 27% of total variability) and 2 (16%) of ERA-I VIMD, multiplied by standard deviation of respective PCs (signs chosen for warm ENSO events).

EOF 1 (Fig. 3) clearly depicts the quadrupole structure as seen from Fig. 1. PC 1 is correlated 0.95 at lag 0 with Niño 3.4 index. Thus, EOF 1 clearly depicts the atmospheric VIMD response to mature ENSO events. EOF 2 shows a transition state with strongest moisture convergence near the dateline. PC 2 is correlated -0.78 at lag -3 with Trans-Niño-Index (TNI). EOF 2 thus describes the VIMD response to a central Pacific warming event (“El Niño Modoki”). Tropical VIMD anomaly series reconstructed from EOF 1 and 2 (Fig. 4) exhibits the basic structures already seen in Fig. 1.

5. Conclusions/Outlook
* Energy budget anomalies in the Tropics show remarkable zonal structures related to ENSO extreme phases quadrupole for DSEDIV and VIMD, dipole for TEDIV.
* DSEDIV and VIMD exhibit propagating anomaly patterns during the transition between ENSO extreme phases, i.e. seamless transition from La Niña to El Niño and vice versa.
* Composites for the strongest warm events confirm this picture.
* EOF analysis of tropical VIMD reveals one Canonical El Niño pattern (EOF 1) and one “El Niño Modoki” pattern (EOF 2).
* EOF 2 describes a transition phase (e.g. ahead of the big 82/83 and 97/98 Niños) but also a stationary “El Niño Modoki” state (e.g. early 2000s).
* PC 2 leading TNI suggest atmospheric circulation changes to be drivers for central Pacific SST anomalies.
* Need to extend analysis backward with reanalyses reaching back beyond the satellite era (JRA-55, ERA-Clim pilot reanalyses, …)


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