Interannual Variations in Atmospheric Energy and Moisture Budgets

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Goal

• Analyze interannual variations in atmospheric energy and moisture budgets from reanalysis & observation-based datasets during past 12 years.

• Stratify data according to large-scale domains corresponding to ascending and descending branches of Hadley Circulation.

• How do interannual variations in atmospheric radiation, precipitation, sensible heat and dry static energy divergence co-vary in different circulation regimes?
Data Used

- ERA-Interim monthly reanalysis data


- GPCP V2.2 precipitation
Dry Static Energy Budget

- On annual mean time-scale:

\[ R_a + LP + S = H \]

\[ R_a = \text{net atmospheric radiation (} = R_{toa} - R_{sfc} \) \]
\[ P = \text{precipitation rate} \]
\[ L = \text{Latent heat of vaporization} \]
\[ S = \text{Surface sensible heat flux} \]
\[ H = \text{Vertical integral of divergence of dry static and kinetic energy.} \]

\[ H = \nabla \cdot \frac{1}{g} \int_0^{ps} (s + k) v dp \]

where \( s = c_p T + gz \) is the dry static energy and \( k \) is kinetic energy.
**Moist Static Energy Budget**

\[ Ra + LE + S = M \]

- \( R_a \) = Net atmospheric radiation (=\( R_{\text{toa}} - R_{\text{sfc}} \))
- \( E \) = Evaporation rate
- \( L \) = Latent heat of vaporization
- \( S \) = Surface sensible heat flux
- \( M \) = Vertical integral of divergence of moist static and kinetic energy.

\[ M = \nabla \cdot \frac{1}{g} \int_0^{p_s} (h + k) \mathbf{v} dp \]

where \( h = s + Lq \) is the moist static energy and \( k \) is kinetic energy.
Moisture Budget

- From difference between DSE and MSE budgets:

\[ L(P - E) = H - M = -\nabla \cdot \frac{1}{g} \int_0^{p_s} (Lq)v \, dp \]
• Evaluate time variation in ATM energy budget within 3 branches of Hadley Circulation.
• The averaging domains change with season (follow large-scale circulation).
Annual cycle of Latitudinal Boundaries of 3 Branches of Hadley Circulation

SH and NH Stream Function Strength at 650 hPa
Dry Static Energy Budget
(March 2000 – February 2010; ERA-Interim)

Change in Dry Static Energy Budget
(Dec07-Nov11 minus Mar00-Feb04; ERA-Interim)

- Increase in precipitation everywhere, especially ascending branch.
- Large increase in H in ascending branch; large decrease in H in descending branches.
  => Increase in circulation strength?
Relationship with Hadley Circulation Strength

Anomalies in Stream Fn Gradient and H (ERA-Interim)

Stream Function Gradient Anomaly ($10^{10}$ kg s$^{-1}$ per deg)

- SH Desc
- Asc
- NH Desc

Year: 2000 to 2012

Anomaly in H (Wm$^{-2}$)
Increase Circulation Strength:
- Increase DSE divergence in ascending branch
- Increase DSE convergence in descending branches

DSE Divergence vs Strength of Hadley Circulation

SH
Slope = -78.31
r² = 0.5

NH
Slope = -72.59
r² = 0.4

Asc
Slope = 89.82
r² = 0.5

Stream Fv Gradient Anomaly ($10^{10}$ kg s⁻¹ deg lat⁻¹)
Moisture Budget
(March 2000 – February 2010; ERA-Interim)

Moisture Budget: \( L(P - E) = H - M \)

- Asc Branc: LP > LE => Moisture Convergence (H-M > 0)
- Desc Branches: LE > LP => Moisture Divergence (H-M < 0)

Change in Moisture
(Dec07-Nov11 minus Mar00-Feb04; ERA-Interim)

- Increase in LP not balanced by increase in LE and/or moisture convergence/divergence.
- Large imbalance in moisture budget during latter portion of record.
Observations (CERES+GPCP) show no significant change in H (circulation strength) during past decade.

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- Near zero $\Delta H$ in ascending branch due to balance between LP and H throughout record.

- Large increase in convergence of DSE ($H < 0$) in subsidence branches reduces $\Delta H$ during latter part of record.
While atmospheric energy imbalance becomes smaller during latter part of the record, moisture imbalance gets larger due to precipitation increase.
Summary

• Atmospheric energy budget:
  - Asc Branc: Latent heating > Radiative cooling => Divergence of DSE (H > 0).
  - Desc Branches: Radiative cooling > Latent heating => Convergence of DSE (H < 0).

• H correlated with strength of Hadley circulation (r ~ 0.7).

• ERA-Interim shows marked increase in precipitation after 2009, especially in ascending branch of Hadley circulation.
  - This is accompanied by large increase in H in ascending branch & large decrease in descending branch.

⇒ Increase in circulation strength?

• H determined as residual (Ra+LP+S) from observations (CERES, GPCP) does not show a significant change during CERES period.

• ERA-I record also shows huge temporal swings in ATM energy & moisture imbalances, which depend upon circulation regime.

• Suggests there are spurious drifts in P and H in ERA-I (input changes?).