Temporal variability of atmospheric column energy balance residual

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Current status of satellite based surface energy balance residual in Wm$^{-2}$

Surface: $344-398-23-75+189-22=15$ Wm$^{-2}$ (depending on data sets used)
Ocean heating rate: 0.53 to 0.75 Wm$^{-2}$ (Lyman et al. 2010 Nature)
  0.4 - 0.6 Wm$^{-2}$ in 0 to 2000 m layer (Roemmich et al. 2015)
  0.64+0.44 Wm$^{-2}$ for the entire column (Llovel et al. 2014)
Objective of this study

• To find where large energy balance residuals exist.
• To examine regional residuals with newer versions of data products.
  • Top-of-atmosphere and surface radiation products (EBAF-TOA and –surface) were revised from Edition 2.8 to Edition 4.0
  • Precipitation data product (Global Precipitation Climatology Project) was revised from Version 2.2 to 2.3.
  • Dynamical energy transport computed from ERA-Interim is revised.
  • Seaflux data product was extended through December 2016.
• How do the energy balance residual vary temporally and spatially?
• What is needed to reduce the residual.
Testing atmospheric energy balance using observations
Data source (March 2000 through Dec. 2016)

• Atmospheric net irradiance: EBAF-TOA and EBAF-surface (Ed 4.0, Loeb et al. 2018; Kato et al. 2018 )
• Precipitation: GPCP (V2.3, Huffman et al. 1997; Adler et al. 2012 )
• Divergence of dry static energy: ERAI.DSEDIV (Fasullo et al. 2018 )
• Divergence of kinetic energy: ERAI.KEDIV
• Divergence of latent energy: ERAI.LEDIV
• Total energy tendency: ERAI.TETEN
• Latent energy tendency: ERAI.LETEN
Regions with a large energy imbalance

Atmospheric energy balance (Trenberth and Stepaniak 2003)

\[-\left[ \frac{\partial (K_E + S_H + \Phi_s + L_E)}{\partial t} \right] - (R_T - R_s) + H_s + LE + \nabla_p \cdot (F_k + F_{DE} + F_{LE}) \right] = 0\]

Latent heat release by water

\[-\left[ \frac{\partial L_E}{\partial t} + LP + LE + \nabla_p \cdot F_{LE} \right] = 0\]

- Kinetic energy + dry static energy tendency
- Kinetic energy divergence
+ atmospheric net irradiance
+ precipitation × (latent heat of vaporization)
- Surface sensible heat flux (positive downward)

Dry static energy = sensible heat flux + potential energy
Neglecting water phase change (the error in the global mean is about 0.8 Wm$^{-2}$)
Extra terms due to water mass transfer (Mayer et al. 2017)

\[
\frac{1}{g} \frac{\partial}{\partial t} \int_0^{\rho_s} \left( c_p T + \Phi_s + k \right) dp + \frac{1}{g} \nabla_p \cdot \int_0^{\rho_s} \mathbf{u} \left( c_p T + \Phi + k \right) dp = \left( R_{TOA} - R_{sfc} \right) + LP - F_{SH} + c_w T_s E - c_w T_p P
\]

Where
\( c_w \): Specific heat capacity of water
\( L \): Latent heat of vaporization
\( T_s \): Surface skin temperature
\( T_p \): Temperature of rain droplets/snow
\( E \): Mass flux of water vapor
\( P \): Mass flux of rain/snow

\( c_w T_s E \) and \( c_w T_p P \) are internal energy transferred by wager vapor and precipitation
Regions with large \( P \) are usually associated with smaller \( E \)
Regions with small \( P \) are usually associated with larger \( E \)
Even when \( T_s = T_p \), regionally, these terms can be significant
Internal energy flux associated with water mass exchange

\[ c_w T_s E \quad T_s: \text{skin temperature} \]

\[ c_w T_p P \quad T_p: 750 \text{ hPa temperature} \]
Net energy exchange

\[ c_w(T_s E - T_p P) \]

Weak sensitivity to Tp
Global maps of residual

- Precipitation is too small
- Divergence is too large
- Radiative cooling is too large

\[ \varepsilon = -\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s} (c_p T + \Phi_S + k)dp - \frac{1}{g} \nabla_p \cdot \int_0^{p_s} \mathbf{U}(c_p T + \Phi + k)dp + (R_{TOA} - R_{Sfc}) + LP - F_{SH} \]
Global map of residual with energy flux with mass transfer

\[ \mathcal{E} = -\frac{1}{g} \frac{\partial}{\partial t} \int_0^{p_s} \left( c_p T + \Phi_s + k \right) dp - \frac{1}{g} \nabla_p \cdot \left( \int_0^{p_s} \mathbf{U} \left( c_p T + \Phi + k \right) dp + (R_{TOA} - R_{Sfc}) + LP - F_{SH} + c_w(T_s E - T_p P) \right) \]

- Negative area
- Precipitation is too small
- Divergence is too large
- Radiative cooling is too large
Time series of residual

![Graph showing time series of residual with two lines representing different latitude ranges: 30°N-30°S (red) and 60°N-60°S (blue). The x-axis represents time (Year) from 2001 to 2015, and the y-axis represents residual (Wm⁻²).]
Anomaly time series of energy budget balance residual

No significant trend in the time series of atmospheric energy budget residual averaged between 30°N to 30°S
Summary and future

• Revised atmospheric energy balance
  • Included internal energy transport associated with water mass transport
• Larger negative residuals appear over regions with heavy precipitation
• Positive residuals appear over stratocumulus regions
• Needs further consistency check with dry static energy divergence
• Investigate relationship with regional number of deep convective cloud occurrence
Surface downward irradiance validation

Downward Shortwave irradiance

Downward longwave irradiance