Temporal variability of atmospheric column energy balance residual

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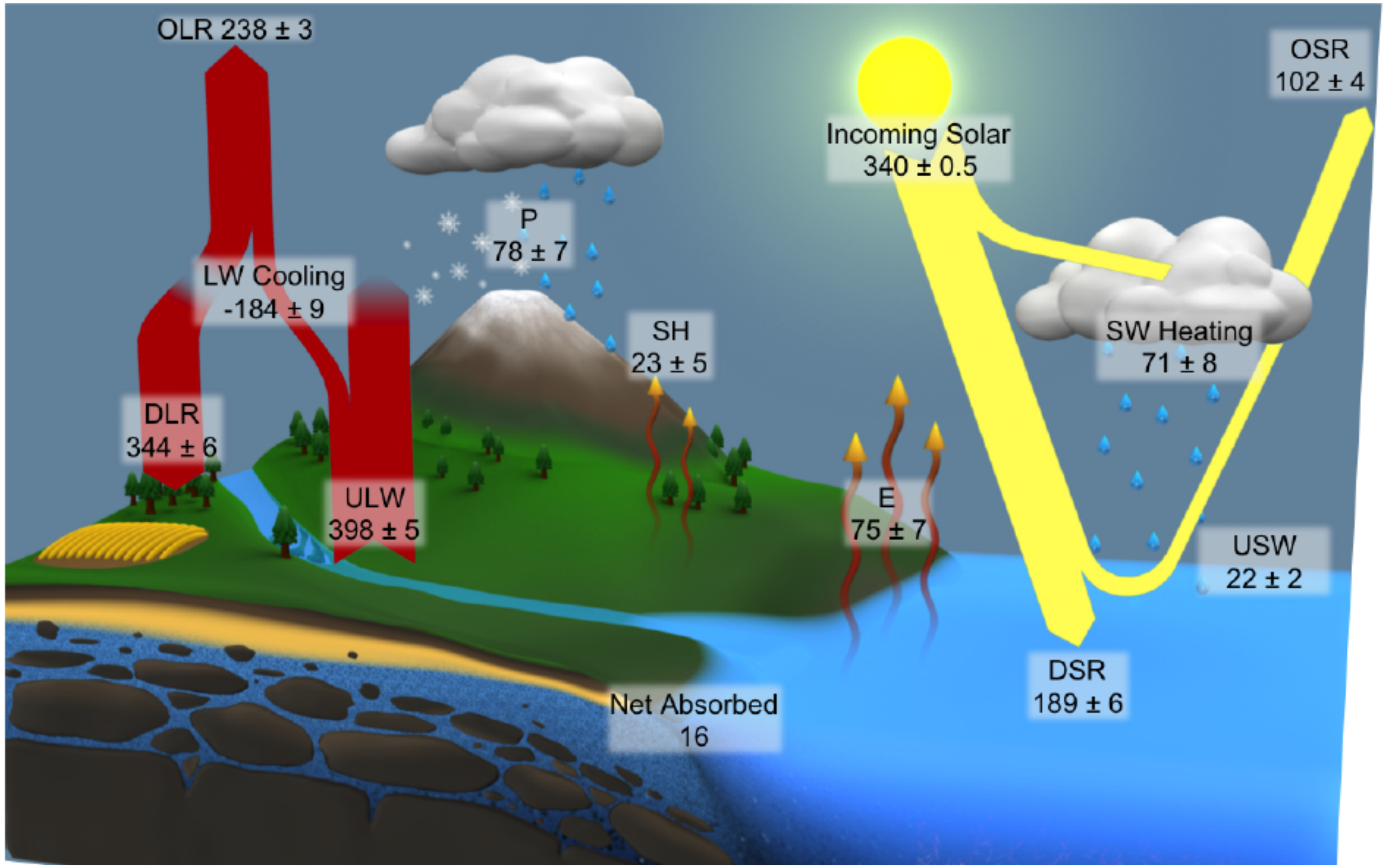
Current status of satellite based surface energy balance residual in Wm^{-2}



L'Ecuyer et al. 2015 (J. Climate)

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)
- Surface sensible and latent heat flux: SeaFlux (Jan 2000 through Dec. 2016, Clayson and Bogdanoff 2014).
- 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

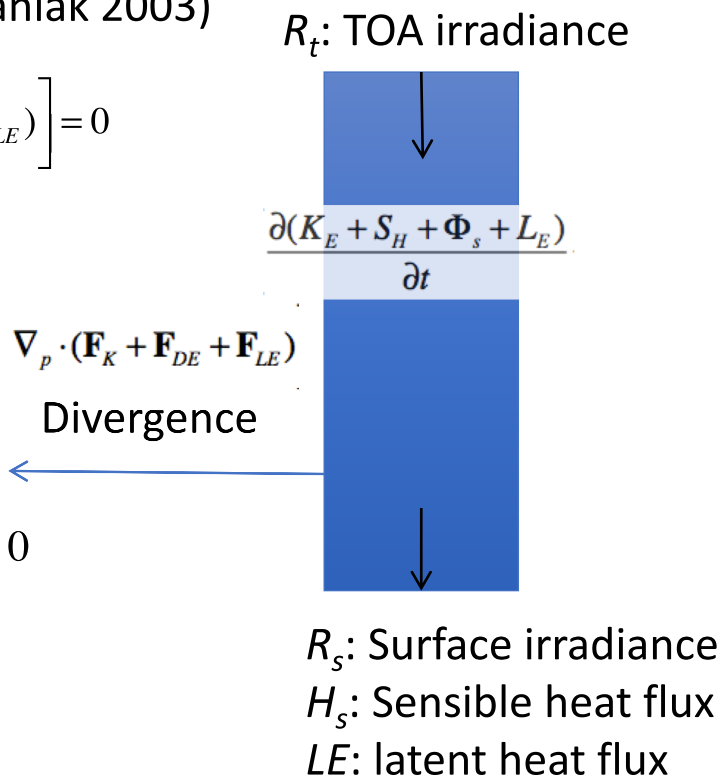
Atmospheric energy balance (Trenberth and Stepaniak 2003)

$$-\left[\frac{\partial(K_E+S_H+\Phi_s+L_E)}{\partial t}-(R_T-R_s)+H_s+LE+\nabla_p\cdot(\mathbf{F}_K+\mathbf{F}_{DE}+\mathbf{F}_{LE})\right]=0$$

Latent heat release by water

$$-\left[\frac{\partial L_E}{\partial t}+LP+LE+\nabla_p\cdot\mathbf{F}_{LE}\right]=0$$

$$-\frac{\partial(K_E+S_H+\Phi_s)}{\partial t}-\nabla_p\cdot(\mathbf{F}_K+\mathbf{F}_{DE})+(R_T-R_s)+LP-H_s=0$$



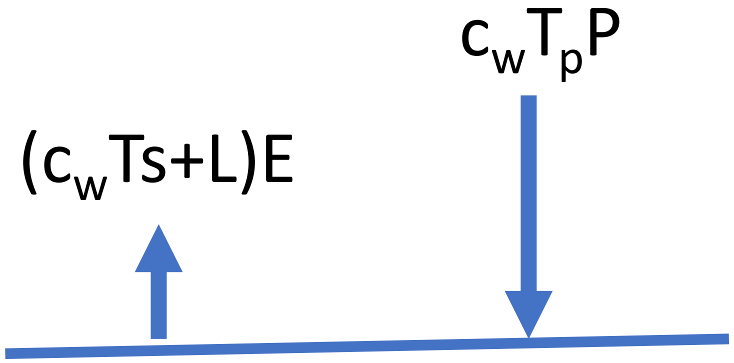
- Kinetic energy + dry static energy tendency
- Kinetic energy divergence
+ atmospheric net irradiance
+ precipitation × (latent heat of vaporization)
- Surface sensible heat flux (positive downward)

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)

$$\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}\left(c_pT+\Phi_s+k\right)dp+\frac{1}{g}\nabla_p\cdot\int_0^{p_s}\mathbf{U}\left(c_pT+\Phi+k\right)dp=(R_{TOA}-R_{sfc})+LP-F_{SH}+\boldsymbol{c_wT_sE}-\boldsymbol{c_wT_pP}$$

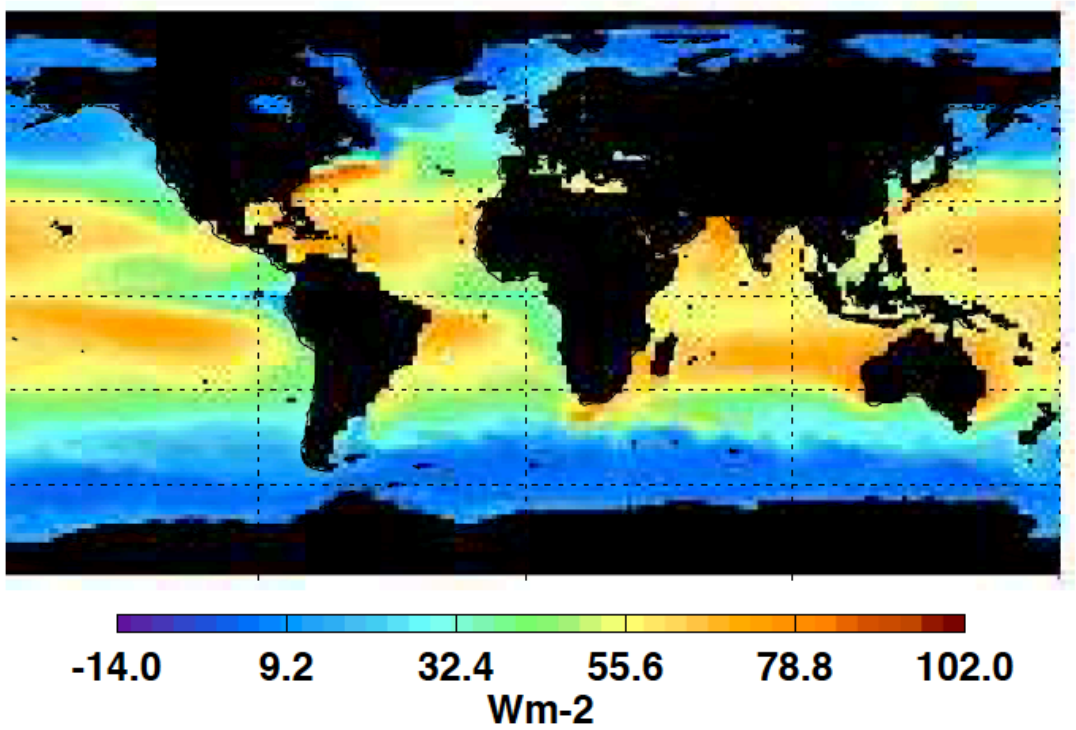
Where
c_w: Specific heat capacity of water
L: Latent heat of vaporization
T_s: Surface skin temperature
T_p: Temperature of rain droplets/snow
E: Mass flux of water vapor
P: Mass flux of rain/snow



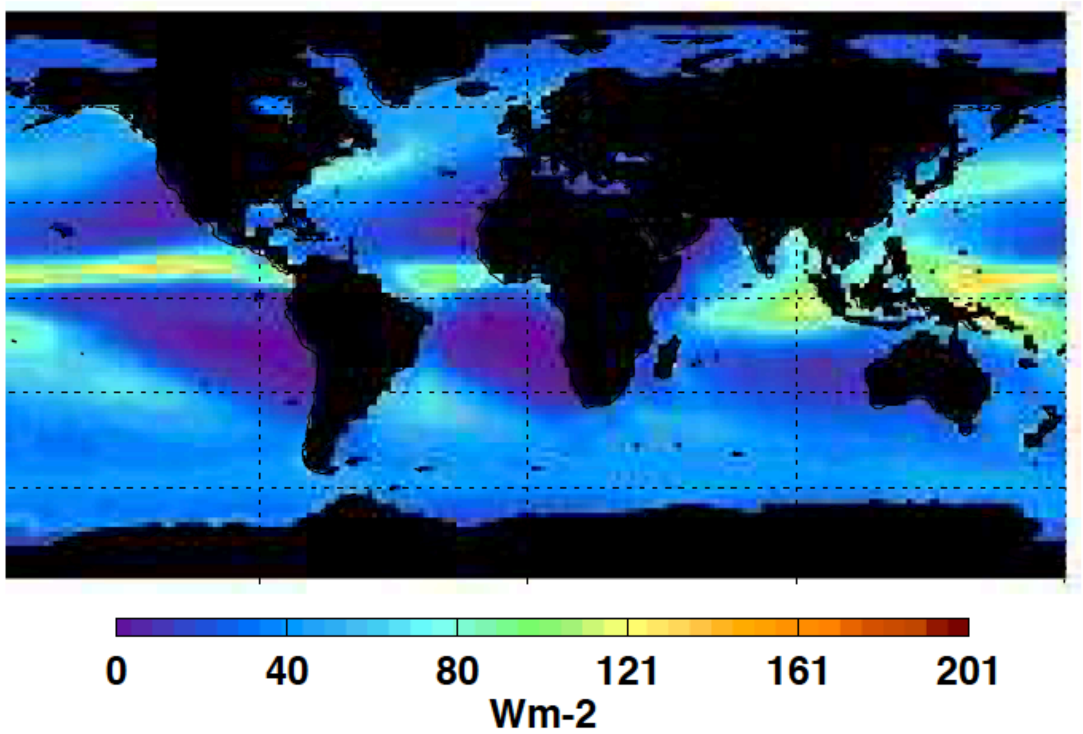
c_wT_sE and c_wT_pP are internal energy transferred by wager vapor and precipitation
Regions with large P are usually associated with smaller E
Regions with small P are usually associated with larger E
Even when Ts = Tp, regionally, these terms can be significant

Internal energy flux associated with water mass exchange

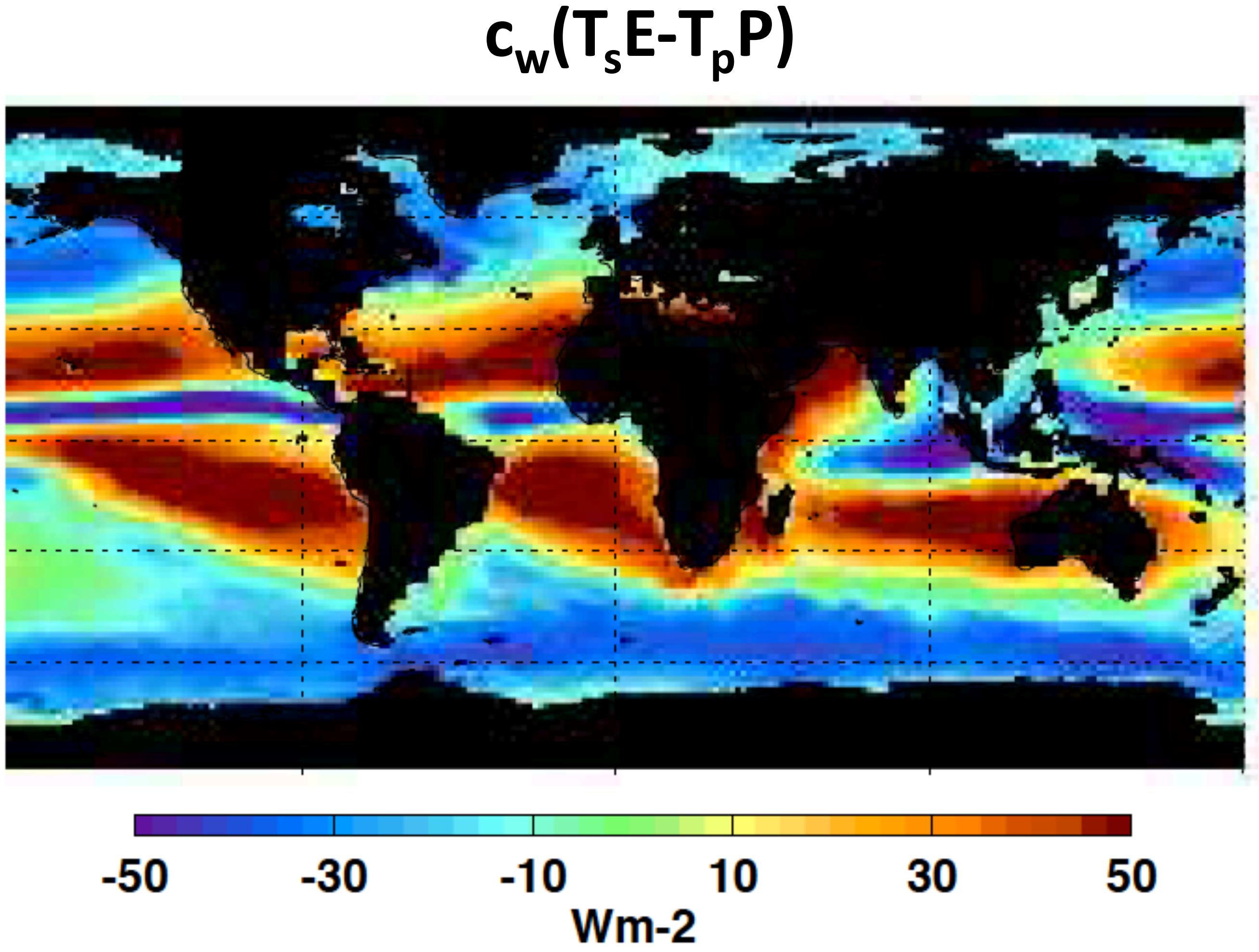
$c_w T_s E$ T_s: skin temperature



$c_w T_p P$ T_p: 750 hPa temperature

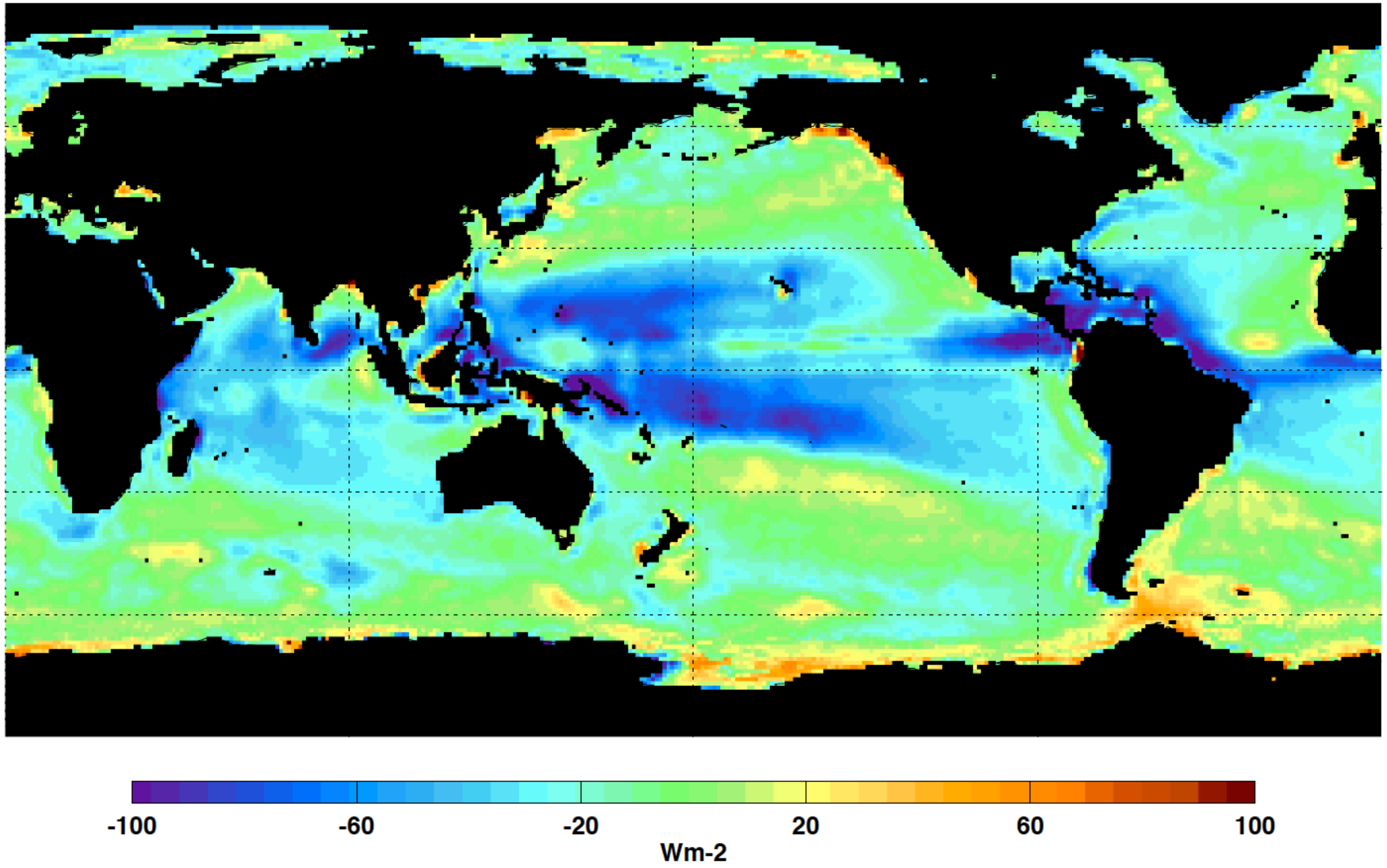


Net energy exchange



Weak sensitivity to Tp

Global maps of residual

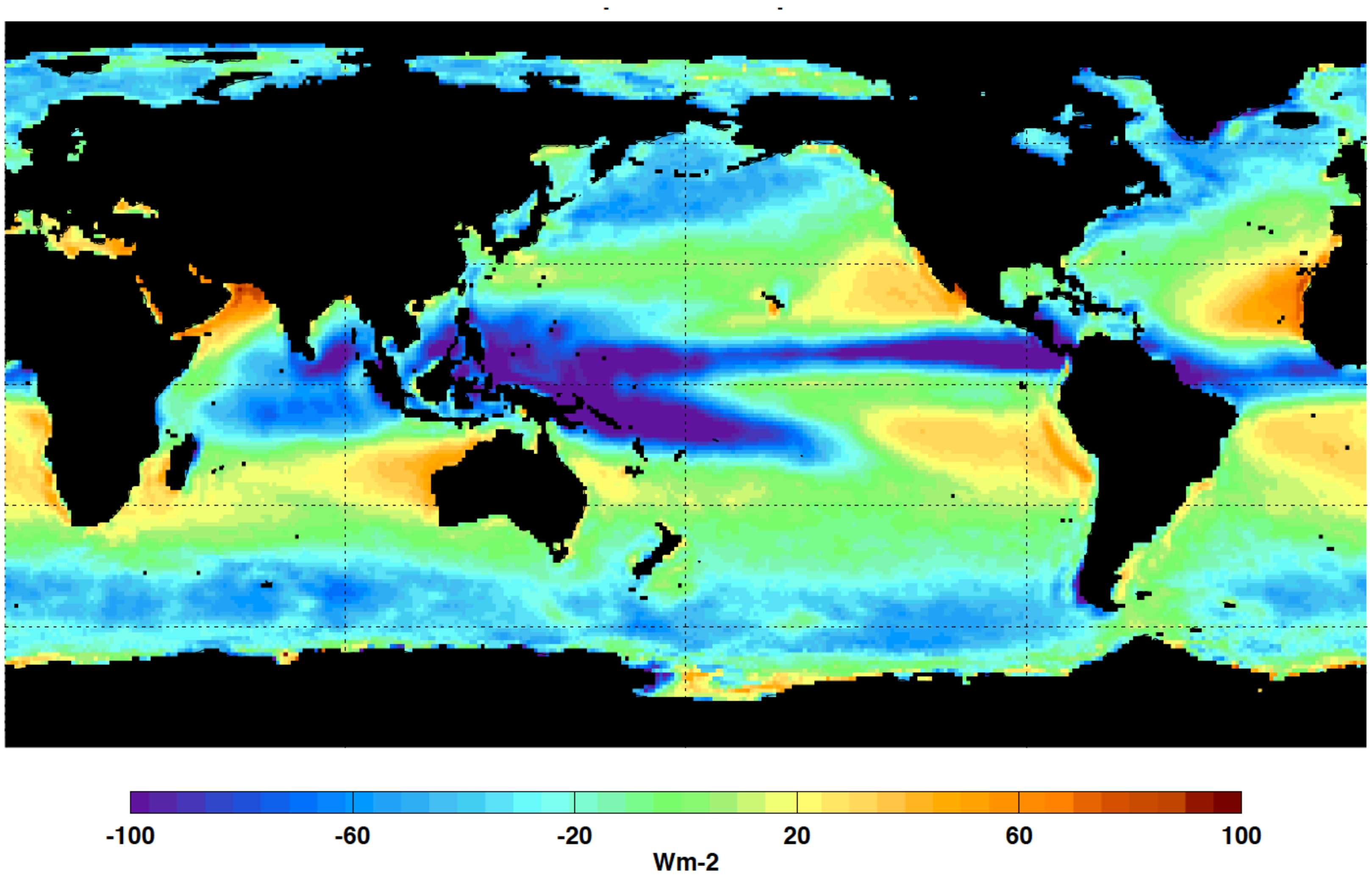


Negative area

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

$$\mathcal{E} = -\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}\left(c_pT + \Phi_s + k\right)dp - \frac{1}{g}\nabla_p \cdot \int_0^{p_s}\mathbf{U}\left(c_pT + \Phi + k\right)dp + (R_{TOA} - R_{sfc}) + LP - F_{SH}$$

Global map of residual with energy flux with mass transfer

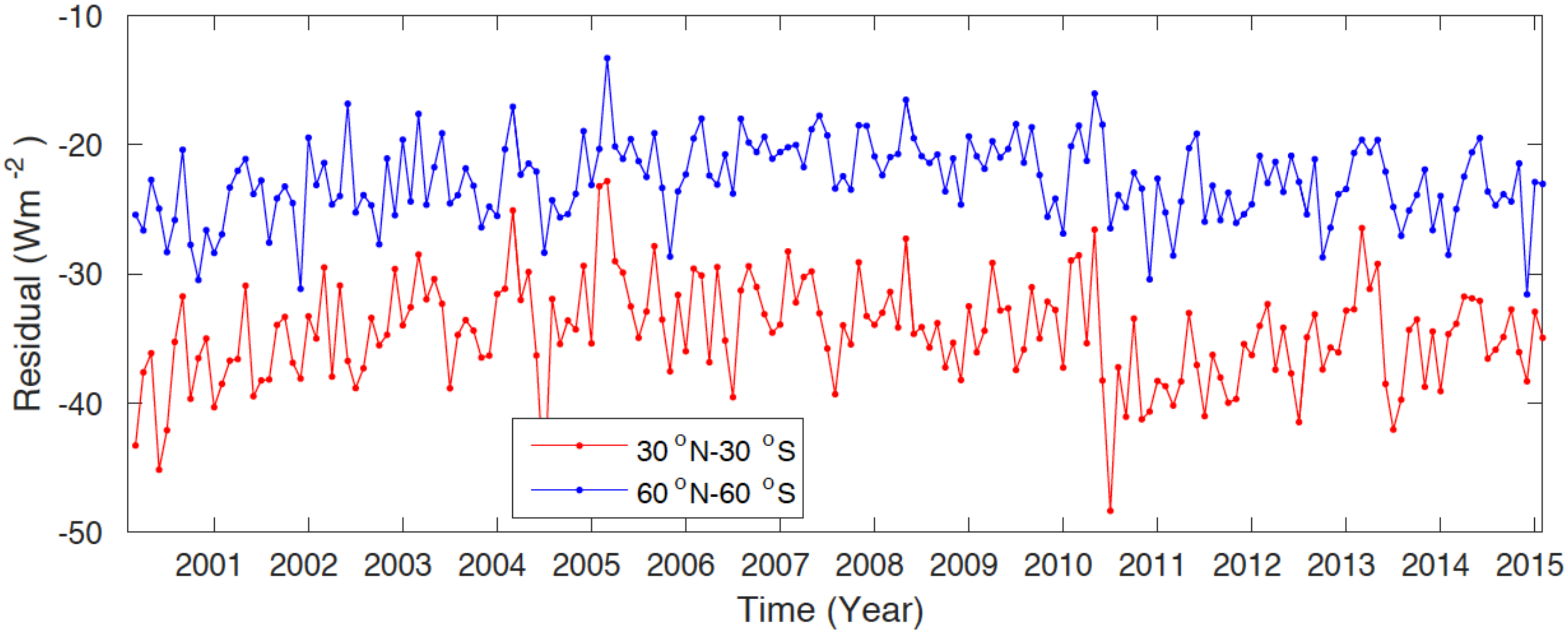


Negative area

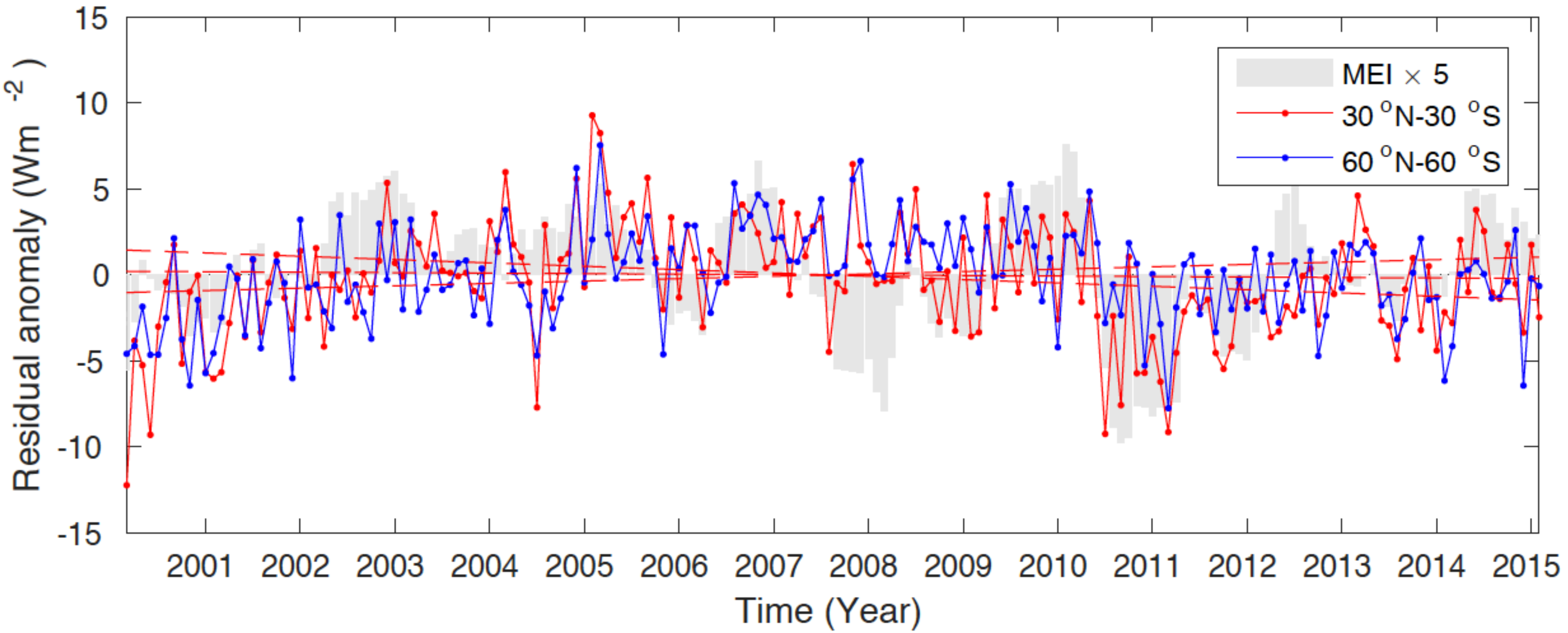
- Precipitation is too small
- Divergence is too large
- Radiative cooling is too large

$$\mathcal{E} = -\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}\left(c_pT + \Phi_s + k\right)dp - \frac{1}{g}\nabla_p \cdot \int_0^{p_s}\mathbf{U}\left(c_pT + \Phi + k\right)dp + \left(R_{TOA} - R_{sfc}\right) + LP - F_{SH} + c_w\left(T_sE - T_pP\right)$$

Time series of residual



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