

Toward reducing surface and atmospheric energy balance residual

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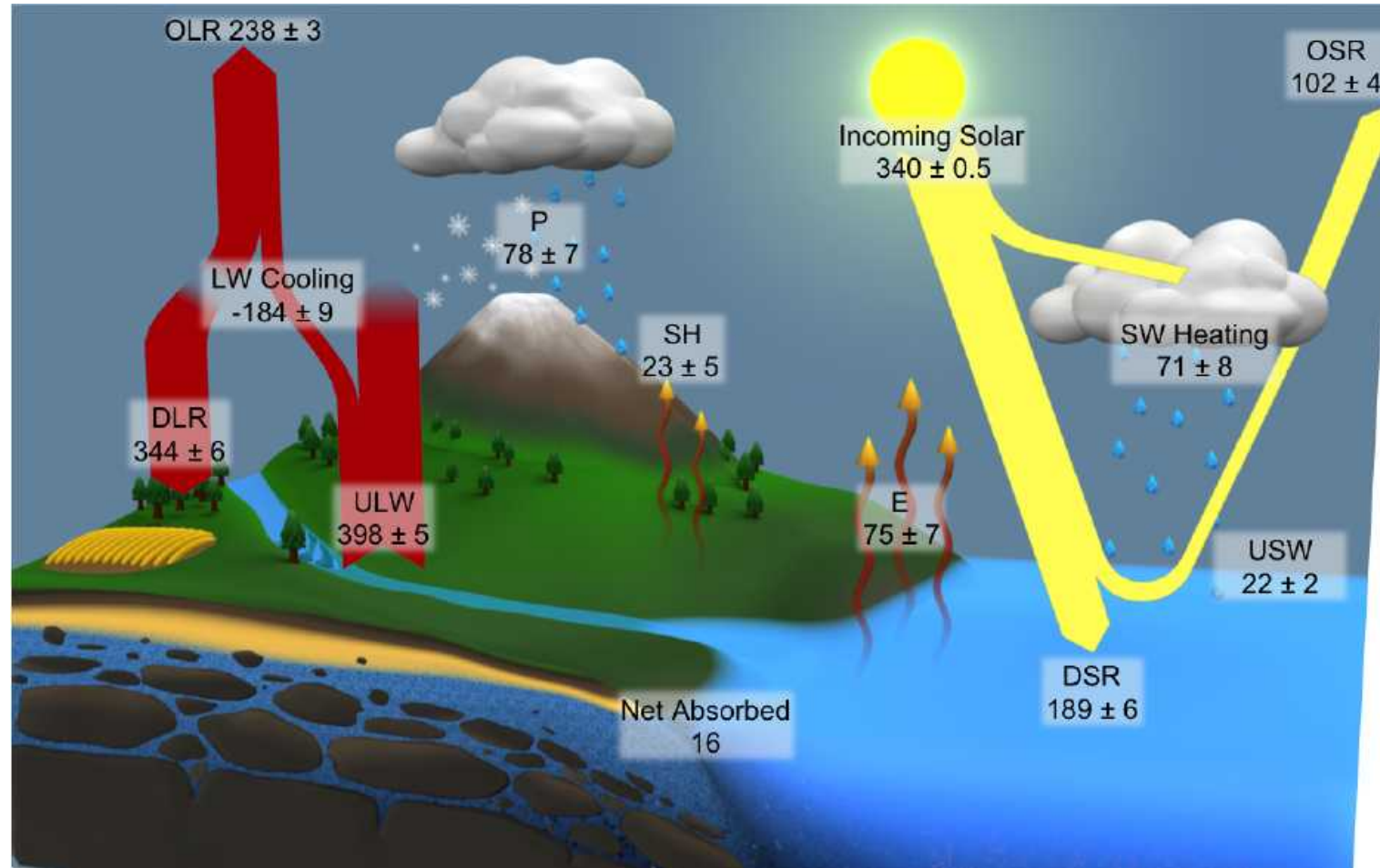
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Intro and outline of this talk

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



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

Surface: $344 - 398 - 23 - 75 + 189 - 22 = 15 \text{ Wm}^{-2}$ (depending on data sets used)

Ocean heating rate: 0.53 to 0.75 Wm^{-2} (Lyman et al. 2010 Nature)

$0.4 - 0.6 \text{ Wm}^{-2}$ in 0 to 2000 m layer (Roemmich et al. 2015)

$0.64 \pm 0.44 \text{ Wm}^{-2}$ for the entire column (Llovel et al. 2014)

Regions with a large energy residual

Atmospheric energy balance (Trenberth and Stepaniak 2003)

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

Water mass balance

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

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

- 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)

R_t : TOA irradiance

$$\frac{\partial(K_E + S_H + \Phi_s + L_E)}{\partial t}$$

$\nabla_p \cdot (\mathbf{F}_K + \mathbf{F}_{DE} + \mathbf{F}_{LE})$
Divergence



R_s : Surface irradiance

H_s : Sensible heat flux

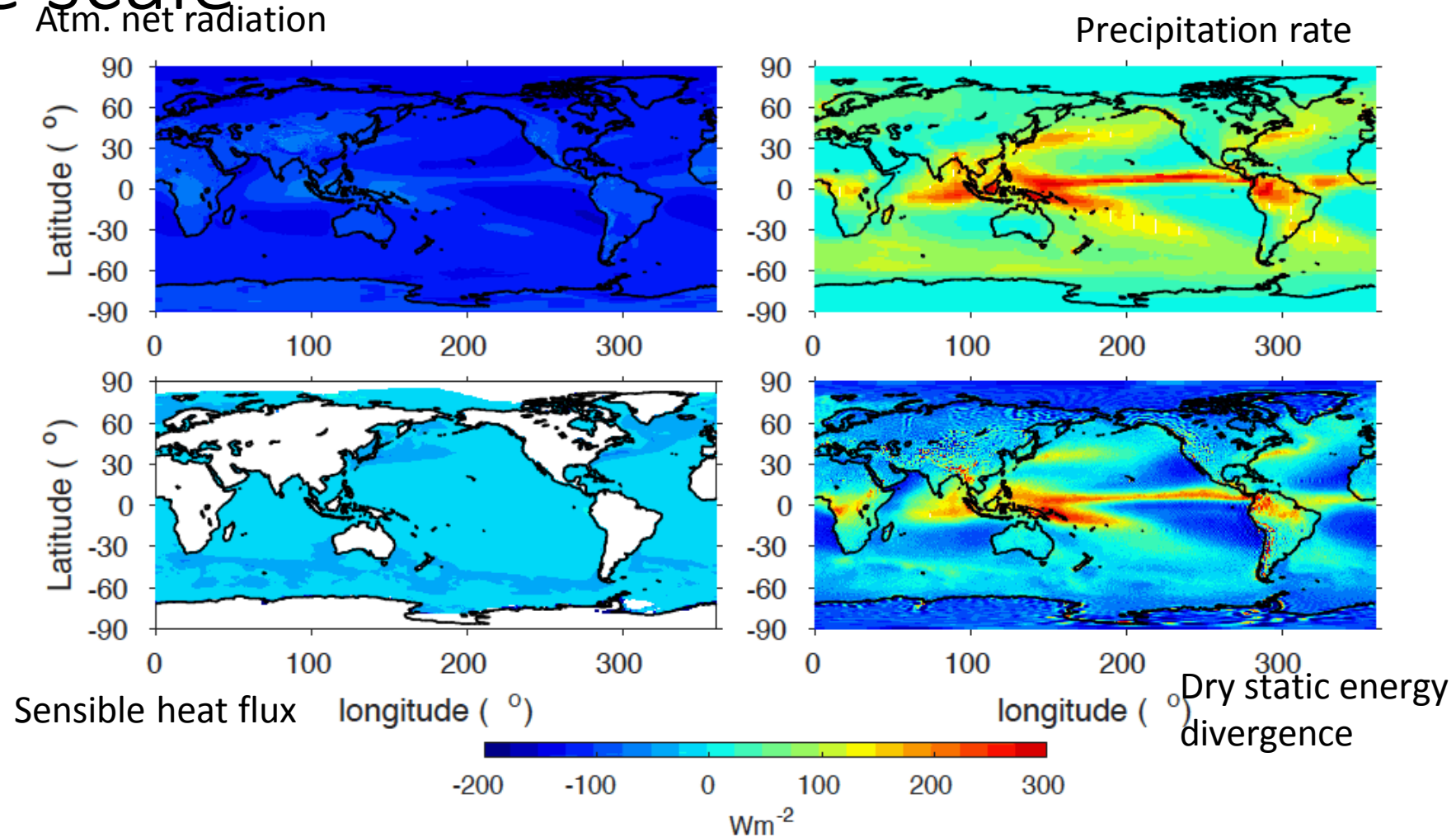
LE : latent heat flux

Testing atmospheric energy balance using observations

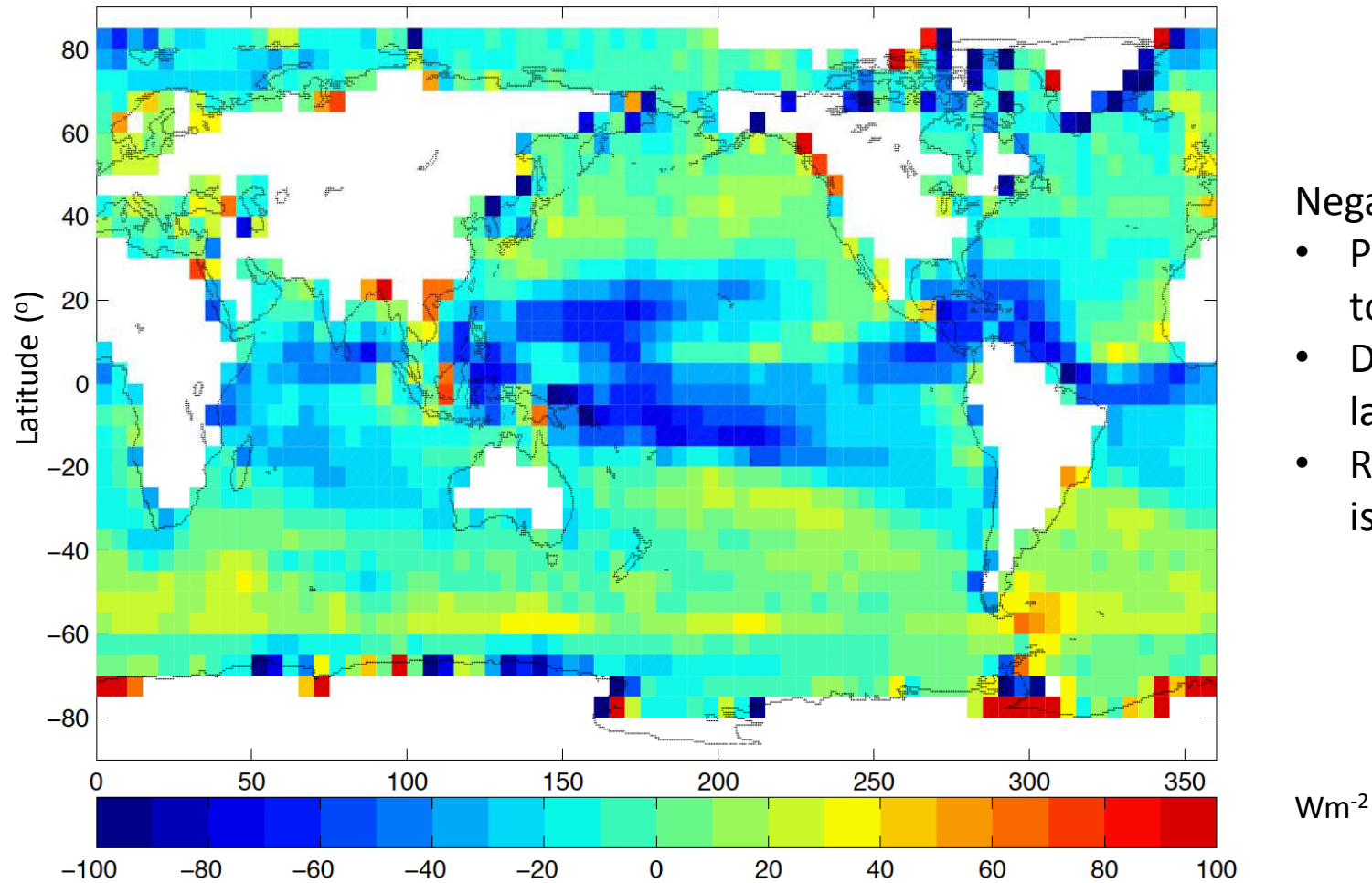
Data source (March 2000 through Feb. 2010)

- Atmospheric net irradiance: EBAF-TOA and EBAF-surface (Ed 2.8, Loeb et al. 2009, 2012; Kato et al. 2013)
- Precipitation: GPCP (V2.2, Huffman et al. 1997; Adler et al. 2012)
- Surface sensible and latent heat flux: SeaFlux (Jan 2000 through Dec. 2007, Clayson and Bogdanoff 2014).
- Divergence of dry static energy: ERAI.DSEDIV (Trenberth et al. 2011)
- Divergence of kinetic energy: ERAI.KEDIV
- Divergence of latent energy: ERAI.LEDIV
- Total energy tendency: ERAI.TETEN
- Latent energy tendency: ERAI.LETEN

Annual mean energy components on the same scale



Sum of all energy terms for the atmospheric column in Wm^{-2} (10 year average)



Negative area

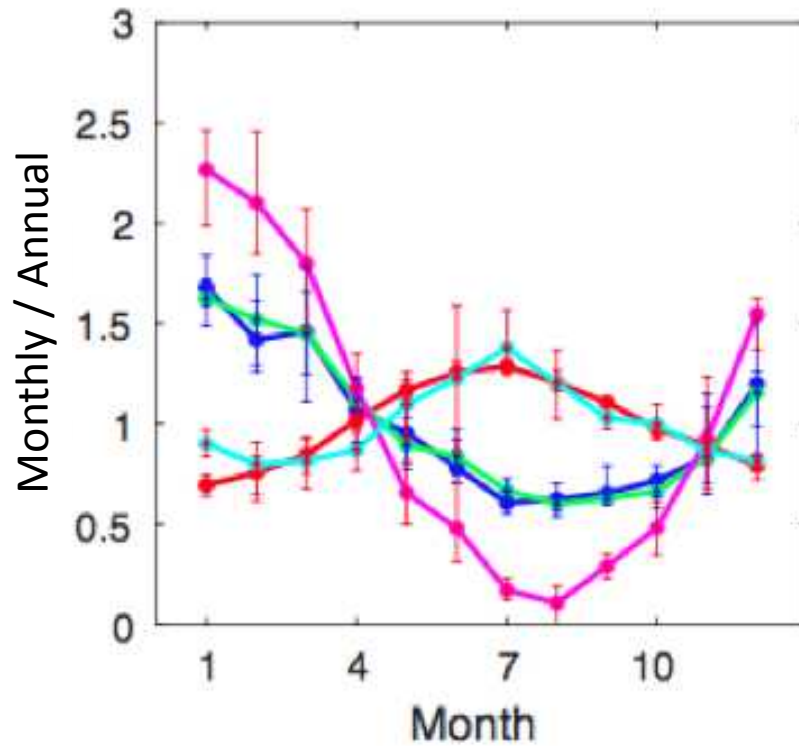
- Precipitation is too small
- Divergence is too large
- Radiative cooling is too large

-Dry static and Kinetic energy tendency - divergence of dry static energy
 -divergence of kinetic energy + atmospheric net irradiance + precipitation - surface
 sensible heat flux (positive downward)

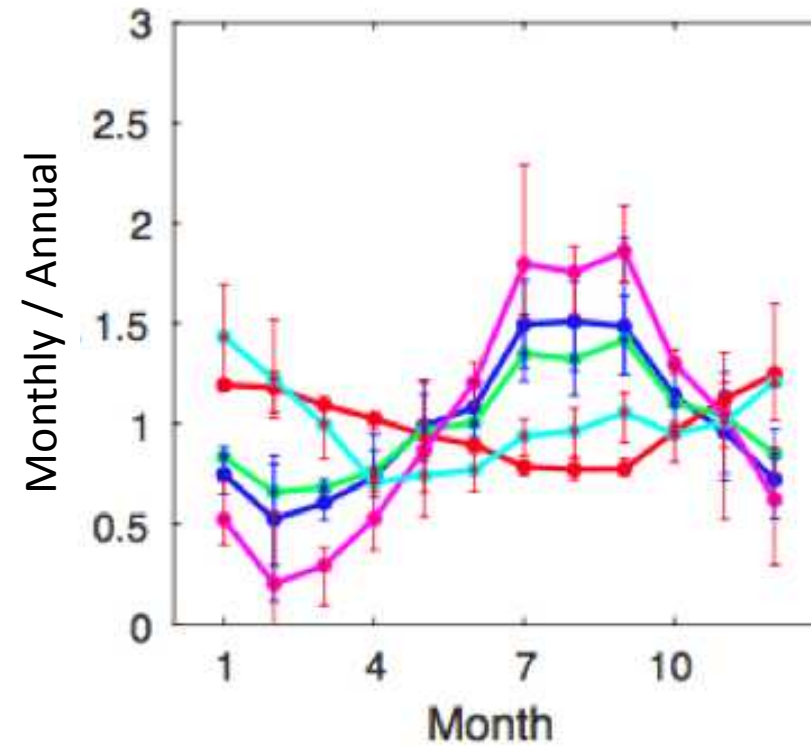
$$-\frac{\partial(K_E + S_H + \Phi_s)}{\partial t} - \nabla_p \cdot (\mathbf{F}_K + \mathbf{F}_{DE}) + (R_T - R_s) + LP - H_s = 0$$

Seasonal variability of energy flux components

Southern western Pacific (0° to 25°S; 105°E to 180°E)



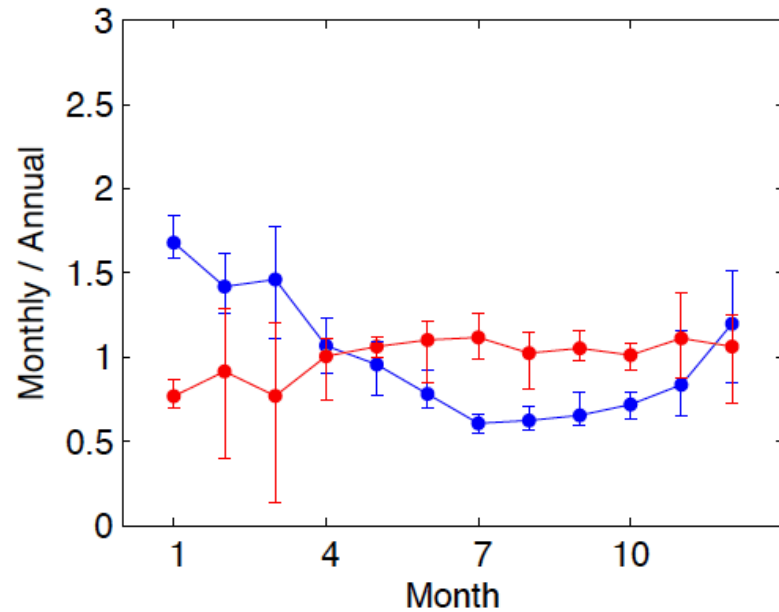
Northern western Pacific (0° to 25°N; 105°E to 180°E)



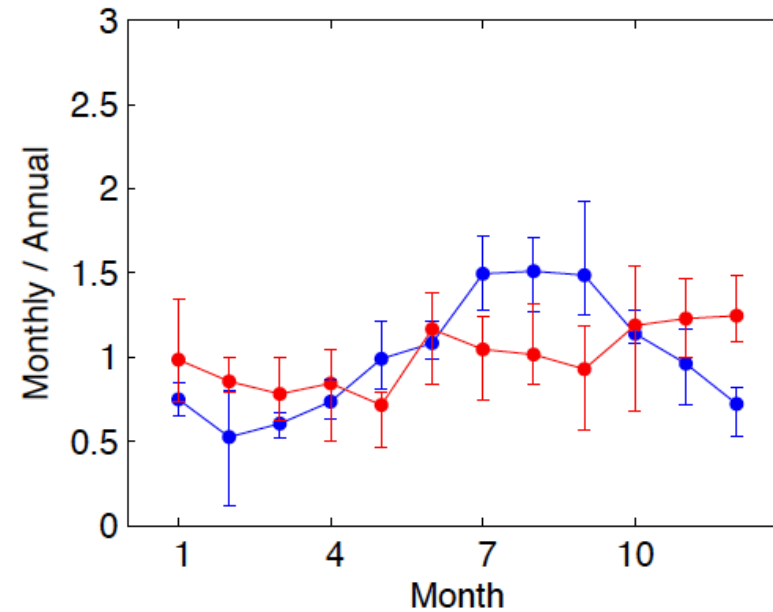
- Number of deep convective cloud objects
- Atmospheric radiative cooling
- Precipitation
- Divergence of dry static energy
- Sensible heat flux

Seasonal variability of atmospheric energy balance residual vs. deep convective clouds

Southern western Pacific (0° to 25°S; 105°E to 180°E)



Northern western Pacific (0° to 25°N; 105°E to 180°E)

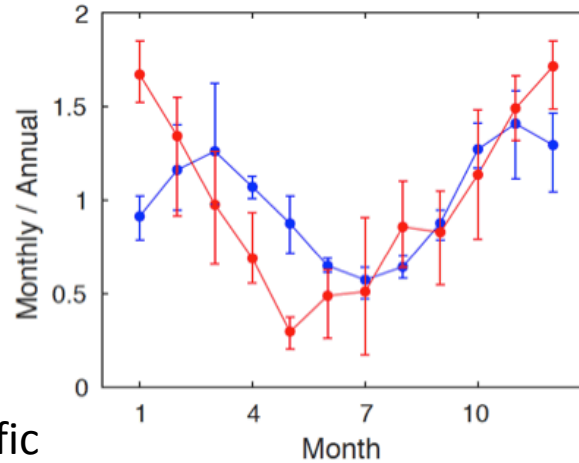


Blue: number of deep convective cloud objects

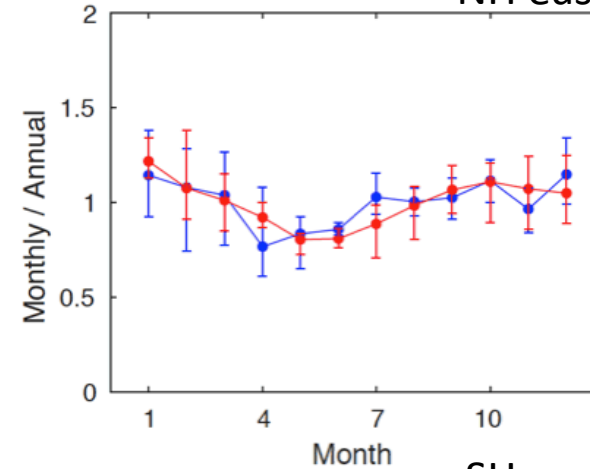
Red: Atmospheric energy balance residual + surface sensible heat flux

Atmospheric energy balance residual vs. shallow cumulus clouds

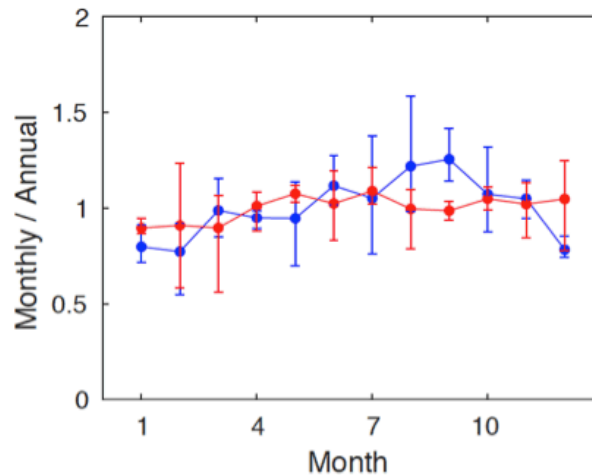
NH western Pacific



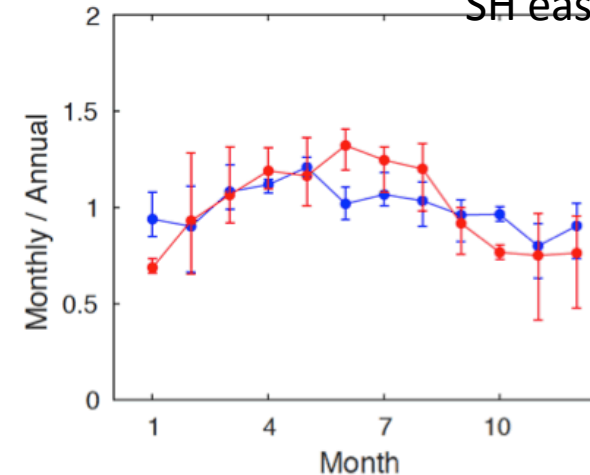
NH eastern pacific



SH western pacific



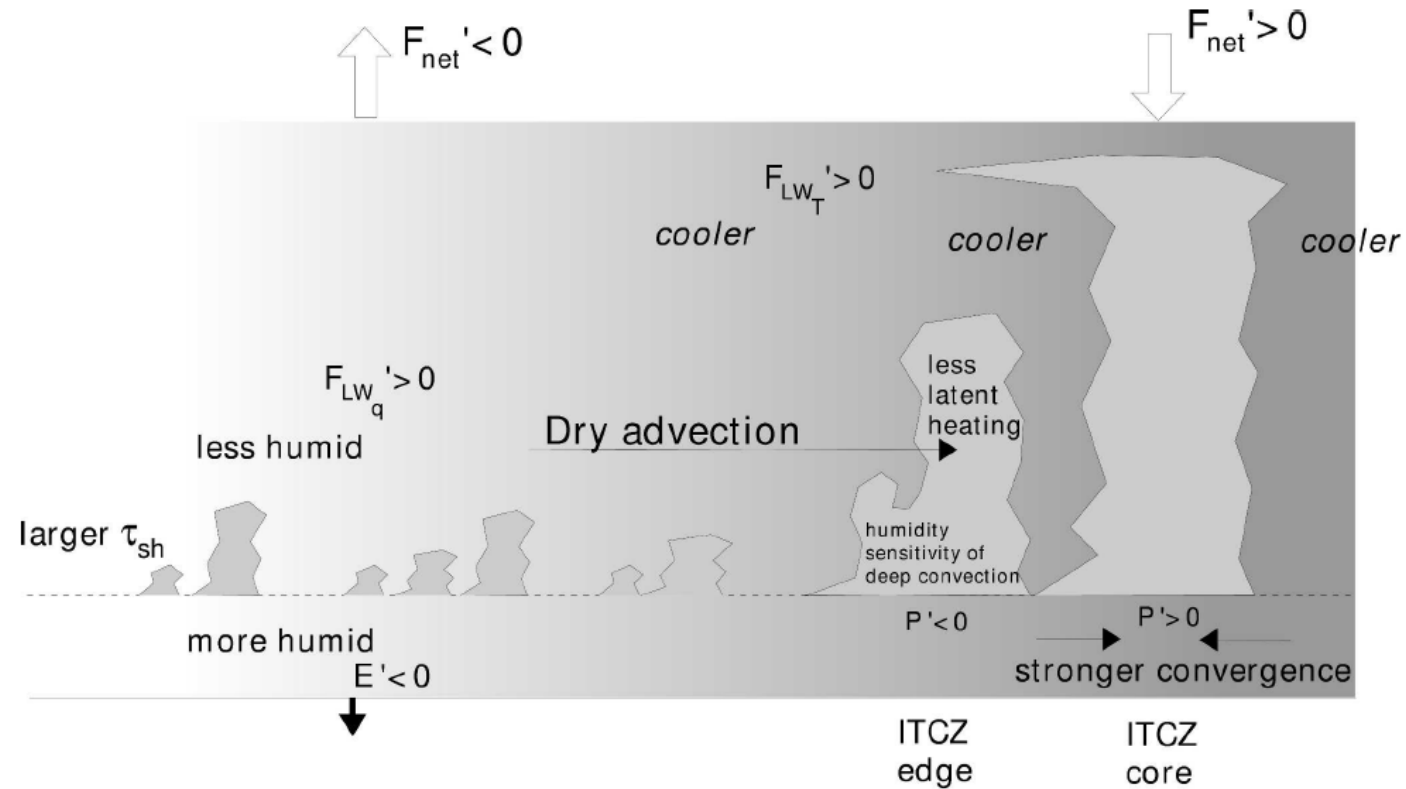
SH eastern pacific



Blue: number of shallow cumulus cloud objects

Red: Atmospheric energy balance residual + surface sensible heat flux

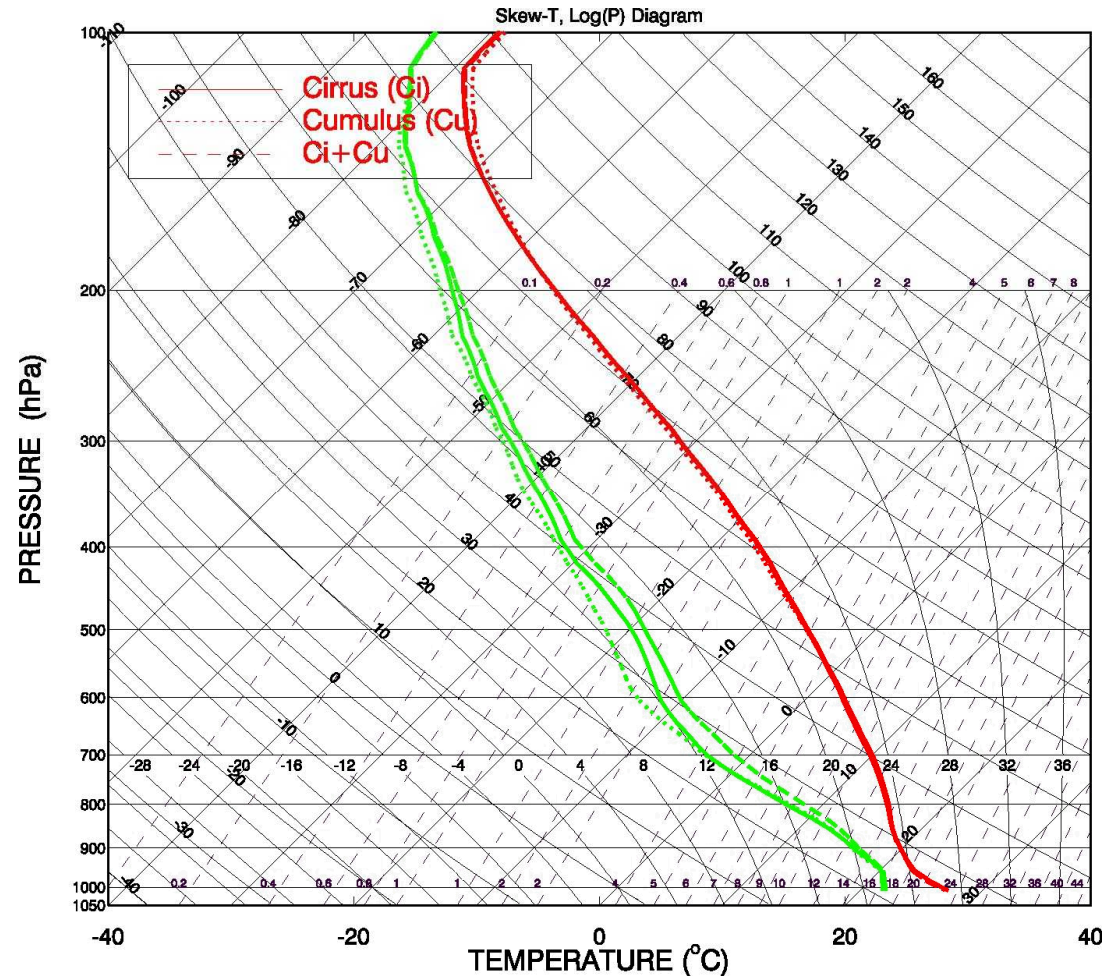
Proposed relationship between shallow cumulus and precipitation by deep convective clouds



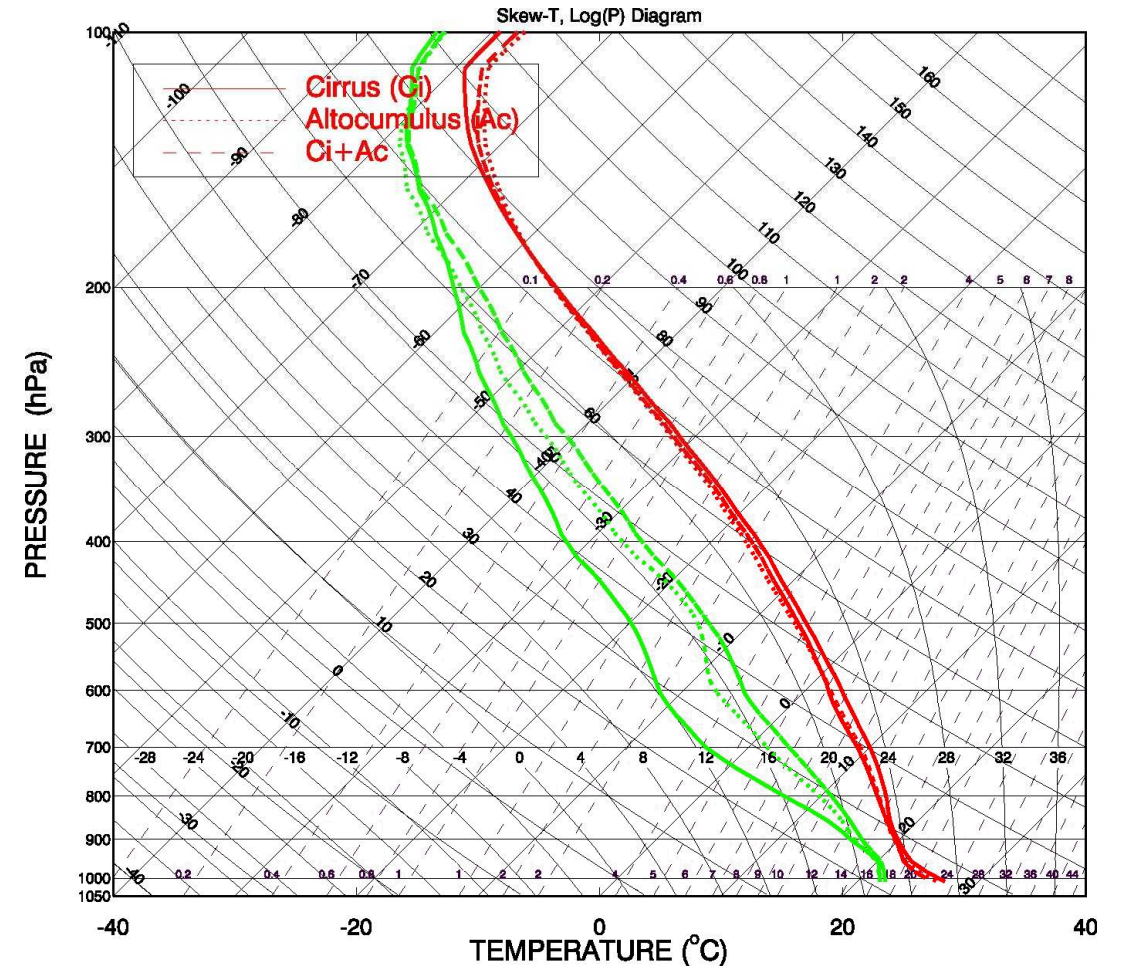
More humid boundary layer $\rightarrow$ more shallow cumulus $\rightarrow$ dryer free troposphere $\rightarrow$ narrower ITCZ
 $\rightarrow$ stronger precipitation by deep convective clouds

Atmospheric profiles (cloud type determined by CloudSat)

Presence of Cumulus clouds



Presence of altocumulus clouds



Free troposphere is dryer when cumuli are present

Humidity in Free troposphere

- Free troposphere is dryer when more cumulus clouds are present
- When free troposphere is moist, altocumulus tends to form, sometimes overlap with cirrus clouds
- Because of moist free troposphere, cirrus and altocumulus tends to overlap, more often than random overlap assumption predicts
- High correlation between energy balance residual and number of shallow cumulus cloud object seems to indicate that energy balance residual is associated with dryer free troposphere

Summary and conclusions

- Surface energy budget residual 10 to 15 Wm^{-2}
- Regional atmospheric column energy imbalance exists over tropical ocean
 - Values and even the sign of energy balance residual vary spatially and temporally
 - Regions with large negatives over western pacific tend to coincide with areas with large deep convective cloud objects (> 300 km) and shallow convective clouds occupy a large area (> 300 km).
- Energy budget residual temporally correlated with the number of shallow cumulus cloud objects
- Upper troposphere is dryer when shallow cumuli are present than the upper troposphere with the presence of alto cumuli