

1. Introduction and Motivation

- The 24-hour cycle of solar insolation drives diurnal cycles in Earth system processes critical to climate: radiation, convection, turbulence, and cloud processes.
- The presence of robust diurnal cycles fundamentally changes the time mean top-of-atmosphere (TOA) energy budget by altering the planetary albedo and greenhouse effect—relative to a system with the same diurnal mean clouds properties but invariant with local time.
- Therefore, there is a need to understand the diurnal cycle contributions to the TOA energy budget in both observations and climate models.

Numerical models have difficulty reproducing the timing of the observed climatological diurnal cycles (Yang and Slingo 2001; Bechtold et al. 2004; Itterly and Taylor 2014)

2. TOA flux diurnal cycle errors in models

- The variability in the TOA flux diurnal cycle is quantified using a RMSE metric, Eq. (1) normalized by Eq. (2)

$$RMSE_{Var,model} = \sqrt{\frac{1}{N} \sum_{h=1}^N (Var_{model}(h) - Var_{CERES}(h))^2} \quad (1) \quad \sigma_{Var,DC} = \sqrt{\frac{1}{N} \sum_{h=1}^N (Var_{CERES}(h))^2} \quad (2)$$

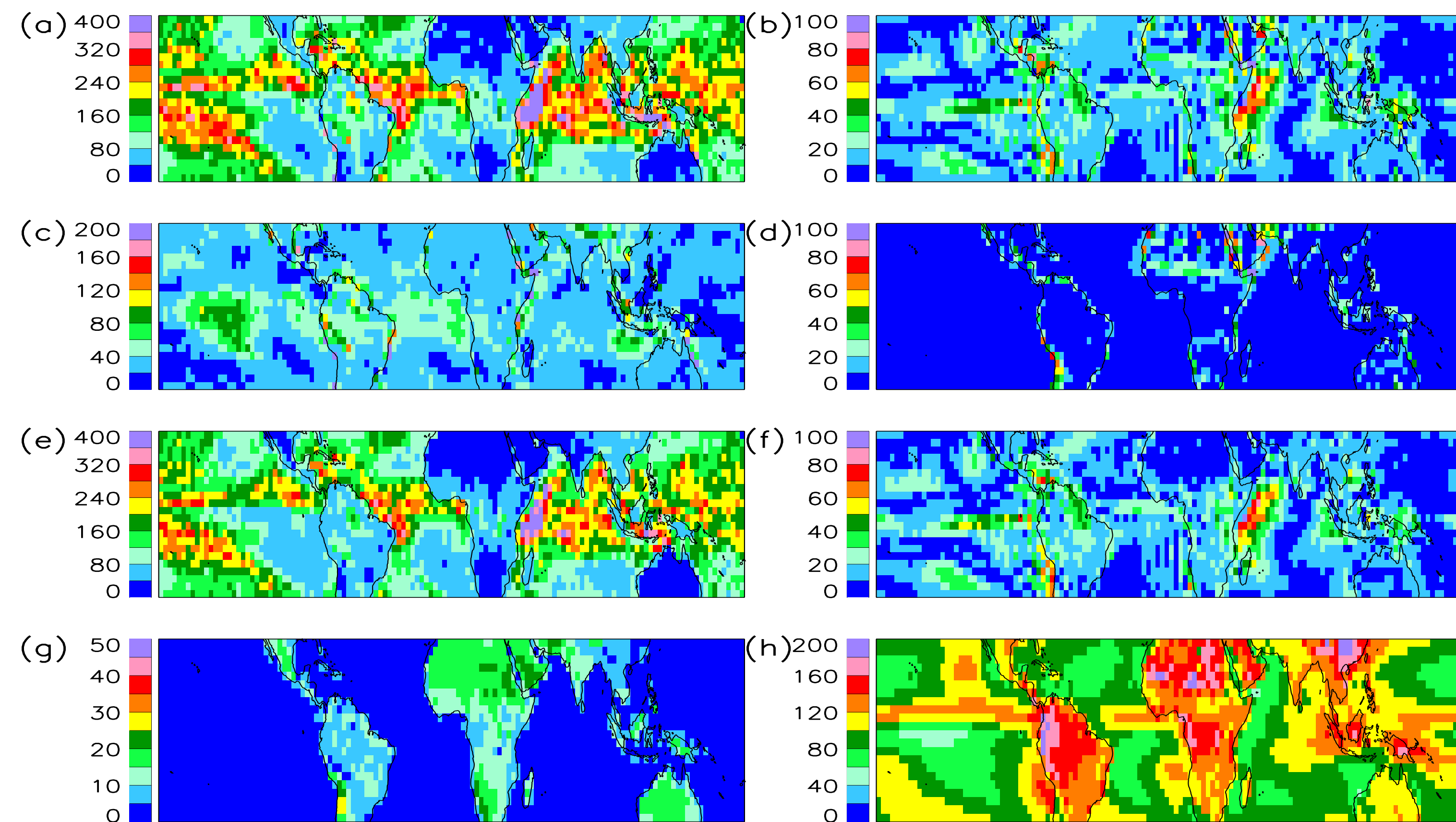


Figure above shows the climatological-annual CanAM4 diurnal cycle NRMSE (units: %) against CERES SYN Ed3a: (a) NRMSE_{OLR}, (b) NRMSE_{RSW}, (c) NRMSE_{OLR_{CL}}, (d) NRMSE_{RSW_{CL}}, (e) NRMSE_{LWCF}, (f) NRMSE_{SWCF}, (g) $\sigma_{OLR,DC}$ and (h) $\sigma_{RSW,DC}$.

The largest errors in LW TOA flux 3-hourly composites occur over land and ocean in regions of frequent convection. NRMSE_{LWCF} is the dominant contributor to NRMSE_{OLR} in land and ocean convective regions. NRMSE_{OLR_{CL}} is the dominant contributor to NRMSE_{OLR} in land nonconvective regions.

The largest errors in SW TOA flux 3-hourly composites occur over land convective and ocean non convective regions. NRMSE_{SWCF} is the dominant contributor to NRMSE_{RSW} in nearly all regions. NRMSE_{RSW_{CL}} values are small over the land and ocean.

5. How do diurnal cycle errors contribute to time mean state TOA energy budget?

- The cloud diurnal cycle contributions to the time mean TOA energy budget are defined as the difference between two calculations of the TOA flux: (1) diurnally varying clouds and (2) diurnally constant clouds (Bergman and Salby 1997).

Answer:

Errors in the cloud diurnal cycle do not significantly influence the time mean OLR—error contributions are less than $\pm 1 \text{ W m}^{-2}$. Errors in the cloud diurnal cycle, however, can significantly influence the time mean RSW—error contributions range from $+16$ to -8 W m^{-2} .

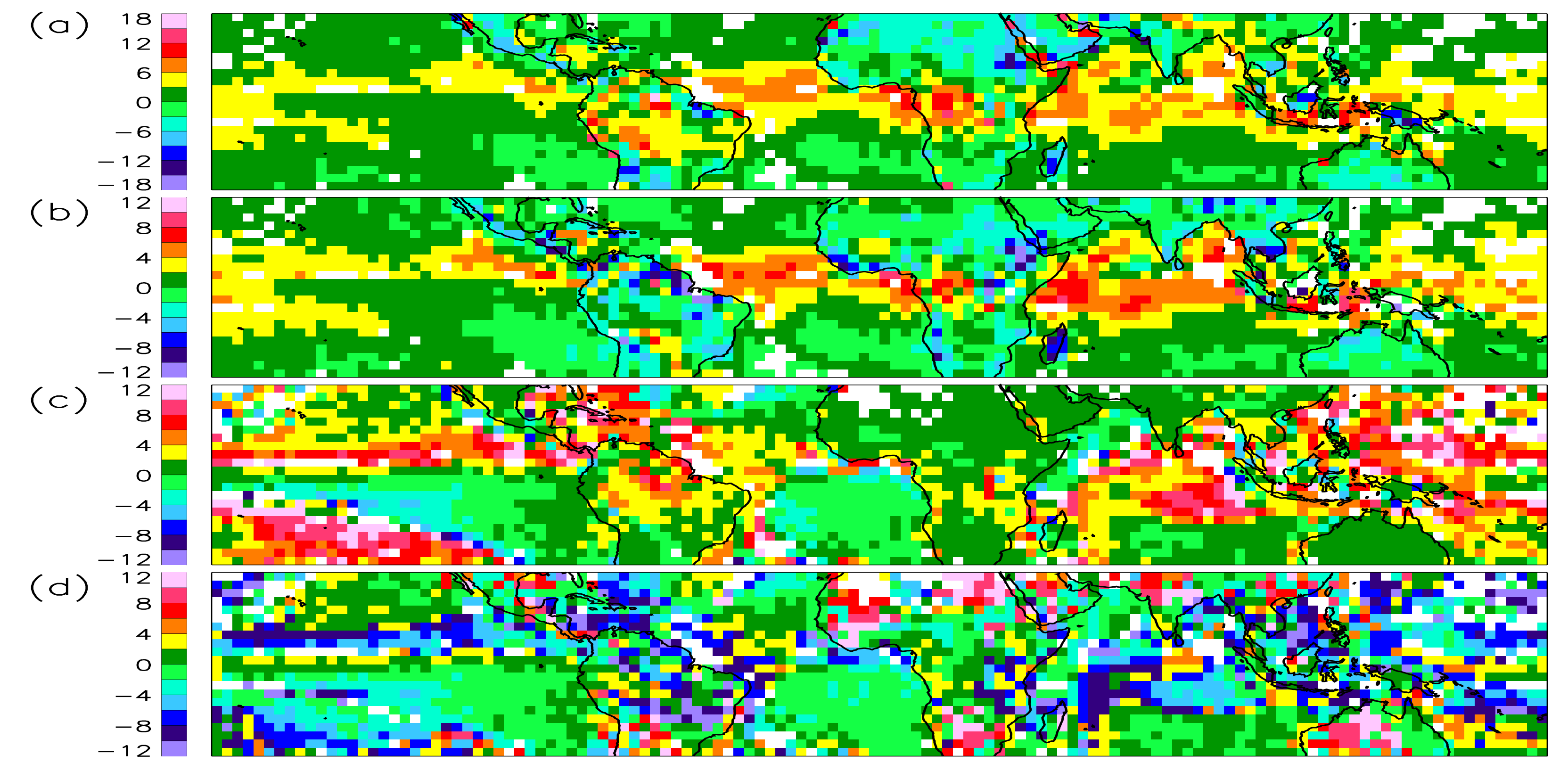
6. Conclusions

- It is important to understand the diurnal cycle contributions to the TOA energy budget for observations and models.
- Diurnally forced propagating convection (e.g., Maritime continent) are not simulated by CanAM4
- The impact of the diurnal cycle on the time mean TOA energy budget as observed by CERES is $1\text{-}3 \text{ W m}^{-2}$ and $5\text{-}25 \text{ W m}^{-2}$ for the time mean TOA longwave and shortwave fluxes, respectively.
- Regional differences between CanAM4 and CERES are $\pm 1 \text{ W m}^{-2}$ and $+8$ to -16 W m^{-2} in LW and SW fluxes, respectively.
- Despite cloud diurnal cycle biases contributing as much 25-30% to regional RSW time mean biases—e.g., over central South America—the regional time mean TOA energy budget biases are to first order determined by the model's ability to simulate the correct regional distribution of cloud type.

3. Which diurnal cycle characteristics contribute to diurnal cycle errors?

Answer:

- (1) CanAM4 produces an OLR diurnal cycle that is too weak over land region.
- (2) Diurnal cycle phase errors are large in land convective regions indicating that the transition from shallow to deep convection happens too slowly in CanAM4.
- (3) The diurnally forced propagating convection does not occur in CanAM4.



The figure above shows differences between the CanAM4 and CERES climatological-annual first diurnal cycle harmonic amplitude and phase: (a) $A_{OLR,CanAM4} - A_{OLR,CERES}$, (b) $A_{LWCF,CanAM4} - A_{LWCF,CERES}$, (c) $P_{OLR,CanAM4} - P_{OLR,CERES}$, (d) $P_{LWCF,CanAM4} - P_{LWCF,CERES}$.

4. Diurnal Cycle Evolution Histograms

- Diurnal evolution histograms are created by taking the difference between the probability distribution function (PDF) for each 3-hour interval and the 24-hour (daily) PDF (Morcrette 1991; Yang and Slingo 2001; Taylor 2012)

Figure on the left show climatological-annual diurnal evolution histograms over central South America, central Africa, Peruvian/Chilean MSc, and over regions of the Indian Ocean. Contours represent the percent difference between the 3-hourly and daily PDFs. The x-axis is LST.

The diurnal cycle evolution histograms demonstrate

- (1) the transition from shallow to deep convection occurs slowly in CanAM4,
- (2) missing diurnally forced propagating convection causes errors diurnal cycle over the Indian Ocean,
- (3) and diurnal cycle errors are attributed to CanAM4 simulating the geographic distribution of cloud types incorrectly.

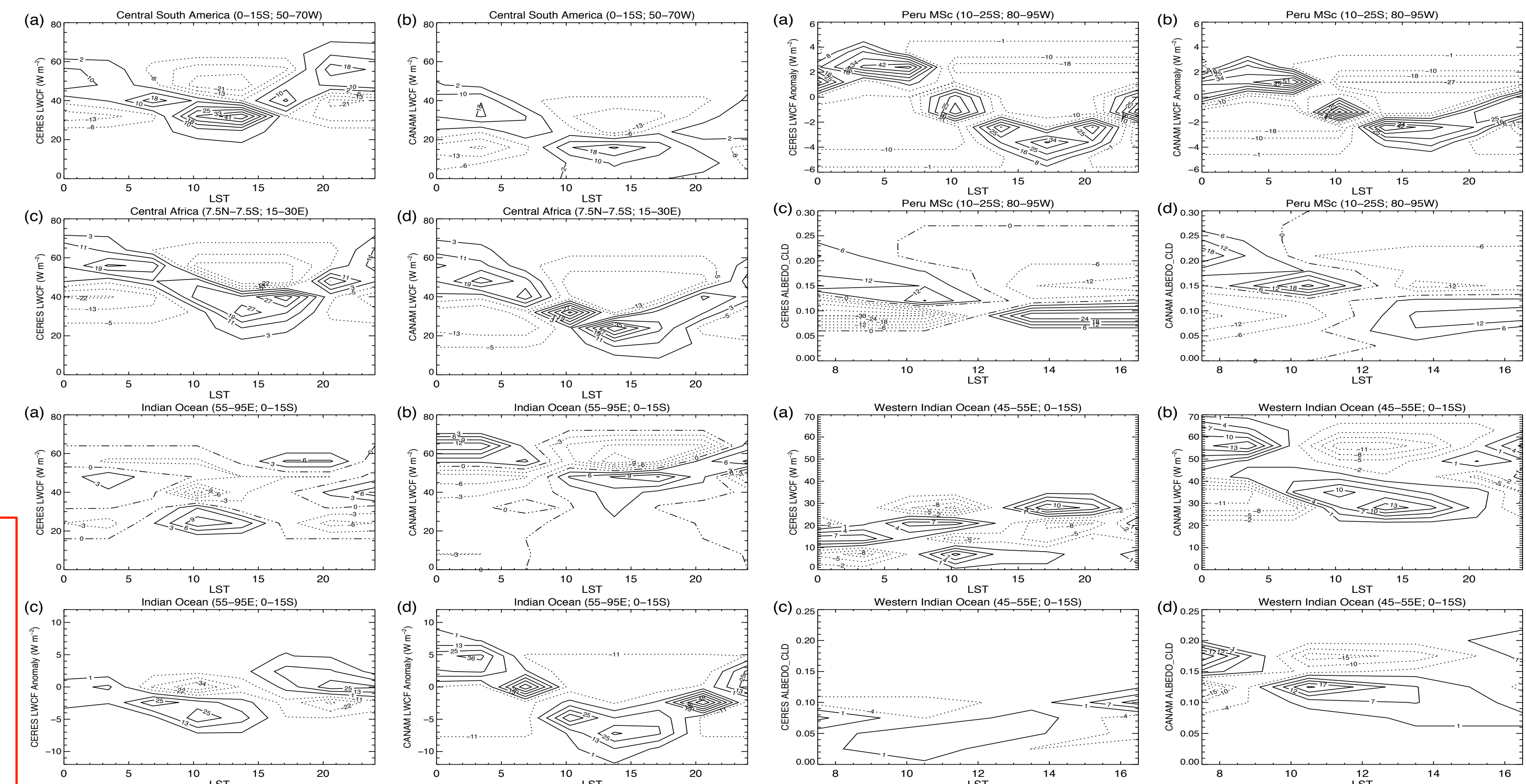


Figure below summarizes the CanAM4 (left column) RSW and (right column) OLR mean state differences attributed to diurnally varying and diurnally constant contributions: (a) CanAM4 minus CERES difference, (b) CanAM4 minus CERES difference, (c) CanAM4 minus CERES OLR_{DC} difference, (d) CanAM4 minus CERES RSW_{DC} difference, (e) CanAM4 minus CERES OLR_{DC} difference, (f) CanAM4 minus CERES RSW_{DC} difference.

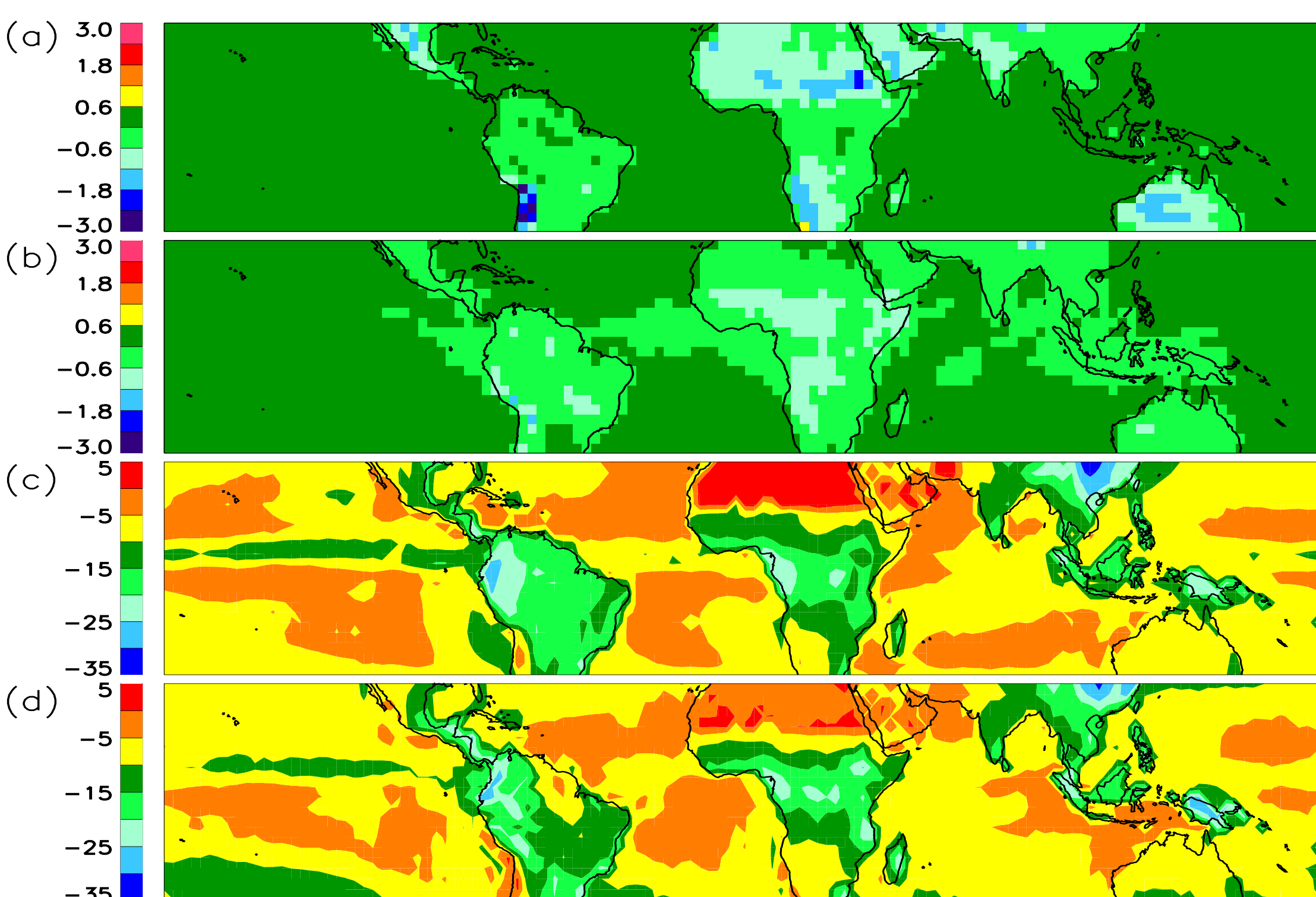
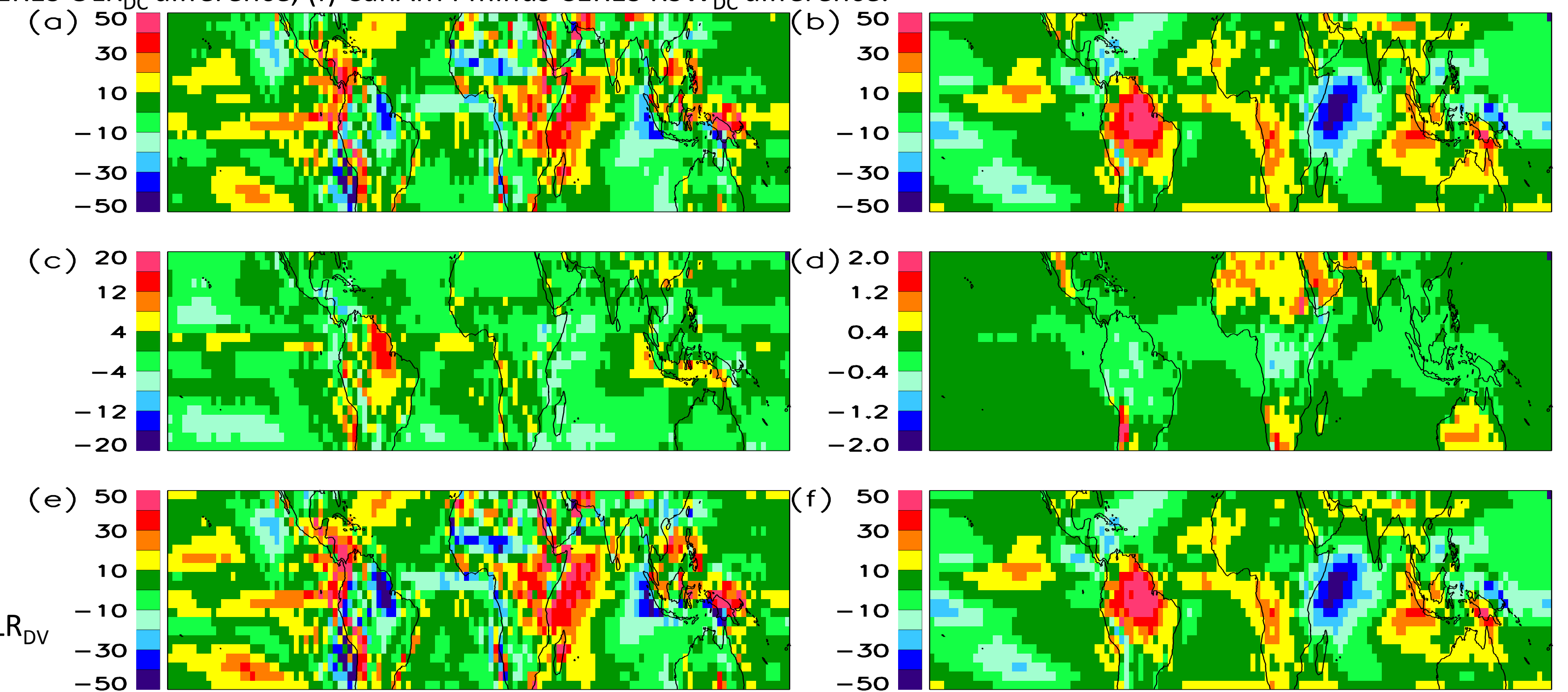


Figure above shows a Tropical contour plot of the CERES observed and CanAM4 simulated cloud diurnal cycle on the time mean TOA energy budget: (a) CERES OLR_{DV}, (b) CanAM4 OLR_{DV}, (c) CERES RSW_{DV}, and (d) CanAM4 RSW_{DV}.