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**Observed Modulation of the Tropical Radiation Budget by Deep Convective Organization and Lower-Tropospheric Stability**

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Observed modulation of the tropical radiation budget
by deep convective organization
and lower-tropospheric stability

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Key Points:

• The interannual variability of deep convective organization in the tropics is investigated using satellite observations.

• An enhanced organization of deep convection is associated with a drier troposphere, fewer high clouds and a radiative cooling of the tropics.

• Convective organization and lower-tropospheric stability exert equal and complementary modulations of the tropical radiation budget.

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Abstract

This study analyses the observed interannual variability of the tropical radiation budget, and shows that variations of the lower-tropospheric stability and of the spatial organization of deep convection both strongly contribute to this variability. Satellite observations show that on average over the tropical belt, when deep convection is more aggregated, the free troposphere is drier, the deep-convective cloud coverage is less extensive, and the emission of heat to space is increased; an enhanced aggregation of deep convection is thus associated with a radiative cooling of the tropics. An increase of the tropical-mean lower-tropospheric stability is also associated with a radiative cooling of the tropics, primarily because it is associated with more marine low clouds and an enhanced reflection of solar radiation, although the drier free-tropospheric humidity also contributes to the cooling. Convective aggregation and lower-tropospheric stability exhibit some correlation, but the anti-correlation between convective aggregation and the tropical-mean radiation budget is largely independent of lower-tropospheric stability variations. Together, the observed relationships between convective organization and lower-tropospheric stability with relative humidity and clouds account for more than sixty percent of the interannual variance of the tropical radiation budget, with roughly equal contributions from convective organization and stability variations. Satellite observations thus support the suggestion from modeling studies that the spatial organization of deep convection substantially influences the radiative balance of the Earth. It emphasizes the importance of understanding the factors that control convective organization and lower-tropospheric stability variations, and the need to monitor their changes as the climate warms.

Plain Language Summary

Interannual anomalies of the tropically-averaged radiative balance determine the year-to-year variations of the tropical climate. The stability of the lower atmosphere has been shown to influence this balance because it promotes the formation of low-level clouds and the reflection of solar radiation to space. Modelling studies have suggested that the spatial distribution of deep convection, especially the degree of clustering of deep clouds, could also impact humidity and cloud coverage, and thus the radiative balance of the Earth system. However, the relationships between cloud clustering, humidity, and the radiation budget have never been observed at the scale of the tropics. By analysing long
time series of satellite observations, we show that interannual variations of lower-atmospheric
stability and convective clustering are both strongly correlated with variations of the ra-
diative cooling of the tropics, and that their contributions to the modulation of the ra-
diation budget are complementary and equally important. These observational results
thus confirm modeling inferences, and emphasize that to predict the future of our cli-
mate, it will be necessary to determine how the stability and the clustering of deep con-
vection will change with warming.

1 Introduction

How well do we understand the factors that modulate the tropical radiation bud-
get? This understanding has long been recognized as a path towards interpreting the long-
term stability of tropical temperatures over the past million years (Herbert et al., 2010),
and estimating the sensitivity of the climate system to current and future increases of
greenhouse gases in the atmosphere (Pierrehumbert, 1995). Observations and climate
models suggest that the Earth’s radiation budget is significantly influenced by changes
in lower-tropospheric stability (Ceppi & Gregory, 2017). Indeed, an enhanced stability
is associated with a strengthening of the inversion at the top of the marine boundary layer
(Klein & Hartmann, 1993; Wood & Bretherton, 2006), which reduces the mixing across
the inversion and helps trap moisture at low levels. This favors the formation of low-level
clouds, and thus the cooling of climate through the enhanced reflection of solar radia-

More recently, modeling studies have hypothesized that variations in the spatial
organization of deep convection could also influence the radiation balance of the Earth
(Khairoutdinov & Emanuel, 2010; Mauritsen & Stevens, 2015): idealized experiments
have shown that when a randomly-organized convection spontaneously organizes into
dry and moist patches, on average the atmosphere becomes drier, clearer and more ef-
ficient at emitting heat to space (Bretherton et al., 2005; Wing & Emanuel, 2014; Emanuel
et al., 2014; Wing et al., 2017). The analysis of satellite observations has confirmed that
for given conditions of large-scale circulation and surface temperature at the regional scale,
situations associated with an enhanced convective aggregation are associated with de-
creased humidity, decreased upper-level cloudiness, increased outgoing longwave radi-
ation (OLR) and decreased planetary albedo (Tobin et al., 2012; Tobin et al., 2013; Stein
et al., 2017; Holloway et al., 2017). However, it is unknown whether these relationships
still hold in the presence of natural variations of sea surface temperatures (SSTs) and large-scale atmospheric circulations. It also remains an open issue as to whether the radiative influence of changes in convective aggregation is significant compared to that of other well-established controlling factors such as the lower-tropospheric stability.

In this study, we address these questions by analyzing observed variations of convective organization, tropospheric stability and top-of atmosphere (TOA) radiation budget over the tropical belt (30°S - 30°N) at the interannual time scale. First, we characterize the variability of the spatial organization of deep convection across the tropics, and we show that interannual variations of convective organization strongly correlate with variations of tropospheric humidity and TOA radiation. Then we show that convective organization and lower-tropospheric stability both exhibit strong anti-correlations to net radiation, through complementary influences. The relative influences of convective organization and stability on the tropical-mean radiation budget are further quantified and analyzed through radiative computations, and the implications of these results for climate feedbacks are discussed.

2 Data and Method

2.1 Convective organization index

To characterize the spatial organization of deep convection across the tropics, we use 3-hourly, intercalibrated and gridded infrared brightness temperature data $T_b$ derived from geostationary satellites, a dataset known as the GridSat-B1 dataset (Knapp et al., 2011). $T_b$ data are mapped on an equal-angle grid of 0.07° degree. The GridSat infrared calibration uncertainty is less than 0.5 K for each satellite, and the temporal uncertainty is less than 0.1 K decade$^{-1}$. We use data over the 30°S-30°N latitude belt during the Jan 1990 to Dec 2017 period.

First, we detect the areas of the tropics covered by deep convection. For this purpose, for each 3-hourly snapshot distribution of $T_b$ data we apply a smoothing of the $T_b$ field at 0.7 x 0.7 degrees (10 x 10 GridSat pixels) to remove isolated convective pixels. Then we consider all the pixels having a $T_b$ value lower than 240 K as being associated with deep convection, and within each area of 0.21 x 0.21 degrees (3 x 3 GridSat pixels), the deep convective pixel (if any) having the lowest $T_b$ value is considered as a deep convective centroid. The deep convective points detected through this 'local minimum'
method effectively detect organized convective features such as squall lines inferred from
ground-based radar observations (see Supplementary Material Figure S1).

A close examination of the data reveals that some 3-hourly GridSat images exhibit
an anomalously high number of undefined data (due for instance to the absence of a geo-
stationary satellite), some anomalously low $T_b$ values, or some spatial discontinuity near
the edge of the satellite field of view due to the alternate use of nadirmost and second
nadirmost satellite observations. To ensure a good homogeneity of the data over the whole
tropical belt at any given time, we exclude the 3-hourly data for which more than 1%
of the tropics are covered by undefined data, or for which the total number of deep con-
vective centroids exceeds the long-term mean by more than two standard deviations. It
represents 6% of all images over the 1990-2017 period, and less than 5% over the 2001-
2017 period.

Then, we characterize the spatial organization of the deepest convective entities
across the tropical belt ($30^\circ$S-$30^\circ$N). For this purpose we use the $I_{org}$ index, that had
been originally introduced to characterize the degree of convective aggregation in cloud-
resolving simulations (Tompkins & Semie, 2017). This index compares the cumulative
density function of the nearest-neighbor distances among deep convective centroids (NNCDF)
to that expected for a random distribution of the same number of convective centroids.
In the case of a random distribution associated with a Poisson process, the NNCDF is
given by a Weibull distribution (Weger et al., 1992). Values of $I_{org}$ significantly larger
than 0.5 correspond to a clustered distribution, and the higher the value of $I_{org}$, the more
aggregated the deep convective entities. The interannual anomalies of deep convective
aggregation ($\Delta I$) are given from the monthly averages of 3-hourly $I_{org}$ values, deseason-
alized and the linear trend removed. Their time evolution is shown in Figure 1a.

To test the robustness of our characterization of the convective clustering, we al-
ternatively calculated $I_{org}$ using a different definition of convective centroids: instead of
defining them as the local minima of $T_b$ within a 0.21 x 0.21 degree domain, we apply
a clustering algorithm to the $T_b$ field (deep convection still corresponding to the pixels
where $T_b$ is lower than 240 K, and a convective cluster is defined as an area made up
of adjacent convective pixels). $I_{org}$ is then calculated from the nearest neighbor distance
between the deep convective clusters. The main difference with the previous method is
that only one centroid corresponds to each cluster of deep convection irrespective of the
cluster size, significantly reducing the number of deep convective centroids in areas where deep convective clusters are large. Although the method of local minima is thought to better characterize the aggregation of deep convection than this clustering method, the interannual time series of $I_{org}$ computed with the two methods are highly correlated ($R = 0.9$) and, as will be shown below, the main conclusions of this study are similar for both methods.

### 2.2 Lower-tropospheric stability

Previous studies, e.g. Ceppi and Gregory (2017), have shown that the Earth’s radiation budget is correlated to changes in lower-tropospheric stability (LTS) and estimated inversion strength (EIS). Those are defined as $LTS = \theta_{700} - \theta_{1000}$, where $\theta_{700}$ and $\theta_{1000}$ are potential temperatures at 700 and 1000 hPa levels (Klein & Hartmann, 1993), and $EIS = LTS - \Gamma_{850}^n(z_{700} - LCL)$ where $\Gamma_{850}^n$ is the moist-adiabatic potential temperature gradient at 850 hPa, $z_{700}$ is the height of the 700 hPa level, and $LCL$ is the height of the lifting condensation level assuming a surface relative humidity of 80% (Wood & Bretherton, 2006).
To estimate these quantities, we use monthly ERA interim reanalyses at a spatial resolution of 0.75° in longitude and latitude (Dee et al., 2011). We compute EIS over each ocean region and compute the tropical-mean EIS as the spatial average over all tropical oceans (30°S-30°N). The time evolution of deseasonalized and detrended anomalies of EIS (ΔE) is shown in Figure 1b.

2.3 Radiative kernels

We use the radiative kernel technique to decompose the top-of-atmosphere radiative flux anomalies into contributions from changes in temperature, water vapor, surface albedo and clouds (Soden & Held, 2006). To do so, we use anomalies of monthly-mean temperature and water vapor profiles from 2003 to 2014 from the Atmospheric Infrared Sounder (Aumann et al., 2003) Version 6 Level 3 product. Anomalies in surface albedo and cloud radiative effects are calculated using CERES-EBAF radiative fluxes for the same period of record. All anomalies are calculated relative to the mean of the first five years of data and the timeseries are deseasonalized and detrended.

To convert changes in the non-cloud variables to a radiative response, we multiply each timeseries of anomalies by radiative kernels derived from CloudSat/CALIPSO observations (Kramer et al., 2019). Following common practice, we separately diagnose radiative responses due to uniform temperature change (Planck effect) and due to departures from the uniform temperature change (lapse rate response). Furthermore, since convective aggregation is associated with variability in mid- and upper-tropospheric relative humidity (e.g., Holloway et al., 2017) it is appropriate to decompose the water vapor radiative response into contributions from fixed and changing relative humidity. Following similar decompositions by Soden et al. (2008) and Held and Shell (2012), the fixed relative humidity radiative response is calculated by multiplying the water vapor radiative kernel by the total temperature change. We add this term to the lapse rate radiative response. The radiative response due to relative humidity changes is calculated by differencing the total water vapor and fixed relative humidity radiative responses. Due to nonlinear radiative responses to overlapping clouds, there is no radiative kernel specific to cloud perturbations in this methodology. Cloud radiative responses are therefore diagnosed from changes in cloud radiative effects corrected for cloud masking using the kernel-derived, non-cloud radiative responses. Soden et al. (2008) outlines this approach in greater detail.
Figure 2. (a) Observed NNCDF (nearest-neighbor distances cumulative distribution function) of deep convective centroids across the tropical belt (solid line) compared to the NNCDF that would be theoretically expected for a random distribution of the same number of convective centroids (dashed line). (b) Relationship between the observed and Poisson NNCDFs (the $I_{org}$ index corresponds to the area under the solid curve). (c) Probability distribution function of the nearest-neighbor distances among the observed deep convective centroids over the tropical belt. The distributions shown here are averaged over the 2001-2017 period, but qualitatively similar distributions are obtained when considering individual 3-hourly images (examples of instantaneous distributions are given in Supplementary Material, Figure. S2).

3 Variability of deep convective organization

The computation of the $I_{org}$ index for each 3-hourly image of the GridSat dataset shows that, at the scale of the whole tropics ($30^\circ$S-$30^\circ$N) and on average over the period 1990-2017, the distribution of deep convection is highly ‘clustered’ (the mean $I_{org}$ value is 0.82), i.e. the deep convective centroids are closer to each other than would be predicted for a random distribution of the same number of centroids (Figure 2a-b).

The organization index computed over the $30^\circ$S-$30^\circ$N, $20^\circ$S-$20^\circ$N or $15^\circ$S-$15^\circ$N latitude bands (referred to as $I_{org}$, $I_{org}^{20}$ and $I_{org}^{15}$, respectively) are highly correlated to each other ($R=0.92$ between $I_{org}$ and $I_{org}^{20}$, and $R=0.85$ between $I_{org}$ and $I_{org}^{15}$). Therefore, although deep convection can sometimes happen at subtropical latitudes as a result of tropical waves activity or extra-tropical intrusions, the time variations of $I_{org}$ computed over $30^\circ$S-$30^\circ$N are dominated by the variations of convective organization that occur at equatorial latitudes.
Across the tropical belt, deep convection exhibits multiple spatial scales of organization, ranging from the planetary scale to the mesoscale. As $I_{org}$ is a metric of spatial organization integrated across these multiple scales, one may wonder whether its variations are dominated by particular spatial scales. The $I_{org}$ index is based on the distribution of nearest-neighbor distances across the tropics. The probability distribution function of nearest-neighbor distances shows that 98% of these distances are shorter than 200 km (Figure 2c). Therefore, although $I_{org}$ characterizes the spatial organization of deep convection over a large range of scales, in practice most of the variability of the deep convective organization captured by $I_{org}$ arises from the mesoscale or, to be precise, from what (Orlanski, 1975) calls the meso-$\beta$ (20 km to 200 km) scale.

The spatial organization of deep convection observed during 1990-2017 varies on a range of timescales. A spectral analysis of 3-hourly data shows that diurnal, annual and semi-annual variations constitute the dominant modes of variability (not shown). Those modes of variability forced by the diurnal and seasonal variations of the insolation are removed when $I_{org}$ is averaged over the day and the mean seasonal cycle of the daily-mean values is subtracted. The time series of the diurnally-averaged and deseasonalized $I_{org}$ then exhibits prominent modes of variability at intra-seasonal and inter-annual time scales (Figure 3). Part of the intra-seasonal variability relates to Madden-Julian Oscillations (Madden & Julian, 1994), whose timescale is around 30-60 days, and part of the inter-annual variability relates to the El-Niño Southern Oscillation, which is

**Figure 3.** Power spectrum of daily-mean, deseasonalized data of the deep convective organization index $I_{org}$ computed within 30°S-30°N over the 1990-2017 period.
dominated by the 3-7 year timescale (Rasmusson & Carpenter, 1982; Radel et al., 2016). Note that these tropical phenomena are known to modulate the spatial distribution of deep convection at the planetary scale. The fact that $I_{org}$ is based on nearest-neighbor distances smaller than 200 km (Figure 2c) suggests therefore that $I_{org}$ reflects these planetary-scale modes of variability primarily through their impact on the mesoscale organization of convection that is embedded within the large-scale envelopes of deep convection. Note that $I_{org}$ anomalies are poorly correlated to anomalies of the tropical-mean SST, and they are only moderately correlated to the Southern Oscillation Index defined as the sea level pressure difference between Tahiti and Darwin (Supplementary Material Table S3).

In the rest of this paper, we will focus on monthly deseasonalized and detrended anomalies of $I_{org}$ computed within 30°S-30°N, and of several atmospheric and radiative properties averaged over the same tropical belt. Although these monthly anomalies may include some intra-seasonal variations (a significant part of the $I_{org}$ variance occurs around the 50 day timescale, Figure 3), for the sake of simplicity, we will refer to these anomalies as 'interannual anomalies'.

4 Convective Organization, Water Vapor and Radiation

How does convective organization relate to tropospheric humidity? Figure 4 shows that interannual variations of the tropical-mean mid-tropospheric relative humidity inferred from microwave satellite observations over the 1999-2014 period (Chung et al., 2013) are strongly anti-correlated (R = -0.63) with $I_{org}$ variations: as convective aggregation is stronger, the mid-troposphere (300-700 hPa) is drier on average over the tropics.

Several factors can contribute to this anti-correlation. Cloud-resolving models suggesting that drier atmospheres can inhibit the development of deep convection (Tompkins, 2001), mean drying could be associated with a contraction of the convective areas, and depending on how the drying is manifested spatially, could influence the organization of deep convection. Dry anomalies in the free troposphere can also help trigger convective self-aggregation (Emanuel et al., 2014). In turn, the clustering of convection enhances the precipitation efficiency of convective systems (Tobin et al., 2012; Bao & Sherwood, 2019), promoting the drying of the atmosphere. While causal relationships are difficult to unravel from observations, the anti-correlation between convective aggregation and large-scale tropospheric humidity found in modeling studies (Bretherton et al., 2005; Wing
Figure 4. Relationship between monthly interannual anomalies of the tropically-averaged mid-tropospheric relative humidity (MTH) derived from microwave satellite observations and $I_{org}$ interannual anomalies. Each marker corresponds to one month of the 2001-2014 period. Also reported is the linear regression line across all points.

The regional pattern of humidity changes associated with aggregation variations is investigated by regressing the local interannual anomalies of mid-tropospheric water vapor onto $I_{org}$ anomalies (Figure 5a): an increase of the organization of deep convection is associated with large areas of drying in equatorial regions and in the subtropics. A glaring exception is the western Pacific warm pool which, on the contrary, is associated with an enhanced convective activity and a moistening of the troposphere when $I_{org}$ increases. Upper-tropospheric water vapor data show similar results (not shown).

The Clouds and Earth’s Radiant Energy Systems Energy Balanced and Filled (CERES-EBAF, Edition 4.0) observations (Loeb et al., 2018) make it possible to investigate the impact of this drying on monthly radiative fluxes at TOA. The drying associated with the enhanced organization of convection is associated with an enhanced emission of clear-sky longwave (LW) radiation to space (due to the lower effective emission height of infrared radiation), a reduced absorption of clear-sky shortwave (SW) radiation by water vapor molecules, and then an enhanced net clear-sky cooling at TOA. This is true on
Figure 5. Linear regression onto $I_{org}$ anomalies of regional (a) MTH interannual anomalies and (b) clear-sky net radiation anomalies ($\partial MTH/\partial I$ and $\partial NCS/\partial I$). Results are reported where the regional relationship is statistically significant ($p$-value lower than 0.05).
Table 1. Linear correlation coefficients of the different components of the net radiation budget ($N$, with $N = N_{cs} + CRE$, where $N_{cs} = N_{cs,tw} + N_{cs,sw}$; $N_{cs,tw} = -\text{OLR}_{cs}$ and $CRE = CRE_{tw} + CRE_{sw}$, $CS$ referring to as "clear-sky" and CRE "cloud-radiative effect") and of the mid-tropospheric relative humidity (MTH) with the deep convective organization index $I_{org}$ and the lower-tropospheric stability EIS. All quantities are tropical averages ($30^\circ$-$30^\circ$N). Coefficients in brackets are not statistically significant (p-value larger than 0.05).

|     | $N_{cs}$ | CRE | $N_{lw}$ | $N_{sw}$ | $N_{cs,tw}$ | $N_{cs,sw}$ | CRE$_{lw}$ | CRE$_{sw}$ | MTH  |
|-----|---------|-----|----------|----------|-------------|-------------|------------|------------|-------|
| $I_{org}$ | -0.65  | -0.54 | -0.43    | -0.53    | -0.22       | -0.47       | -0.33      | -0.39      | (-0.13)      | -0.63 |
| EIS     | -0.66  | -0.44 | -0.55    | -0.36    | -0.41       | (-0.10)     | -0.41      | -0.41      | -0.56 |

average over the tropics ($R = -0.54$, Table 1), and locally when clear-sky net radiation anomalies are regressed onto $I_{org}$ anomalies (Figure 5b).

The radiative cooling associated with interannual anomalies of deep convective organization does not occur only in clear-sky, but also in all-sky conditions (Table 1). The tropically-averaged net radiation budget $N$ is anti-correlated with $I_{org}$ variations ($R = -0.65$, Figure 6a), mostly through its LW component. It partly results from the drying of the atmosphere and its impact on clear-sky radiation, but also from the reduced LW cloud radiative effects (CRE$_{lw}$, the difference between TOA clear-sky and all-sky outgoing radiative fluxes). It is explained by the fact that an increase of convective organization is associated with a reduced area of deep convection and, as shown by cloud observations from the spaceborne lidar CALIPSO (Chepfer et al., 2010), with a reduced high-level cloud amount (Supplementary Material Figure S3 and Table S1).

5 Convective Organization vs Lower-Tropospheric Stability

As $I_{org}$, EIS exhibits variability over the 1990-2017 period (Figure 1b), and monthly interannual anomalies of EIS are strongly anti-correlated with $N$ anomalies ($R = -0.66$, Figure 6b, Table 1). Cloud observations show that this occurs mostly through the cloudy component of $N$, and more specifically through the albedo effect of clouds (CRE$_{sw}$) which strengthens when EIS, and thus low-level clouds, increase (Supplementary Material, Table S1). However, as will be discussed later, we also note a negative correlation between anomalies of clear-sky OLR and EIS, as strong as that between clear-sky OLR and $I_{org}$. 
In contrast, the tropical-mean SST is only weakly correlated with $N$ variations ($R = -0.16$), and it does not exhibit any significant correlation to $I_{org}$ and EIS variations.

The occurrence of El-Niño/La-Niña events is also found to have a minor effect on the relationships described here (Supplementary Material, Table S2). Therefore, although these events modulate $I_{org}$ and EIS, they don’t seem to affect the relationships between $I_{org}$ (or EIS) and clouds or humidity in a specific way.

![Figure 6](image)

**Figure 6.** Monthly interannual anomalies of the observed tropically-averaged Earth radiation budget $\Delta N$ vs anomalies of (a) the organization index of deep convection $\Delta I$ or (b) EIS averaged over tropical ocean $\Delta E$. (c) $\Delta N$ anomalies (in color) stratified by $\Delta I$ and $\Delta E$. Each point corresponds to one month of the 2001-2017 period (all anomalies are deseasonalized and detrended).

The tropical-mean radiation budget thus exhibits strong anti-correlations with both EIS and the organization of deep convection ($R = -0.66$ and $-0.65$, respectively), each explaining about 40% of its interannual variance. $I_{org}$ and EIS are positively correlated to each other ($R = 0.37$ during 2001-2017), but they correlate to the radiation budget through different ways, with $I_{org}$ primarily affecting the clear-sky component and EIS primarily the cloudy component (Table 1). This suggests that $I_{org}$ and EIS exert complementary influences on $N$. This is confirmed by Figure 6c, which shows how $N$ anomalies ($\Delta N$) relate to $I_{org}$ and EIS anomalies ($\Delta I$ and $\Delta E$, respectively). Negative $\Delta N$ tend to be associated with both positive $\Delta I$ and positive $\Delta E$, but the anticorrelation between $\Delta I$ and $\Delta N$ remains for a given $\Delta E$, and the anticorrelation between $\Delta E$ and $\Delta N$ remains for a given $\Delta I$. This is consistent with the partial correlations $(\partial N/\partial I_{org})_{EIS}$ and $(\partial N/\partial EIS)_{I_{org}}$, which are equal to -0.58 and -0.60, respectively.
Figure 7. (a) Time series of monthly interannual anomalies of the tropically-averaged Earth radiation budget $\Delta N$ derived from CERES satellite observations (thick solid line) and reconstituted (dashed line) from $\Delta I_{org}$ and $\Delta EIS$ through linear multiple regression ($\Delta N = \alpha \Delta I_{org} + \beta \Delta EIS$). (b) Time series of the tropical-mean $\Delta N$ observed from CERES (thick solid line) and reconstructed from kernel radiative calculations (thin solid line). Also reported are the radiative contributions due to $I_{org}$ anomalies (in red) and to EIS anomalies (in blue) inferred from kernel calculations. On both time series, a 5-month running mean has been applied.

Given the complementary influences of $I_{org}$ and EIS on $N$, we assess the ability of $\Delta I$ and $\Delta E$ to predict $\Delta N$. A linear multiple regression calculation shows that the simple model $\Delta N = \alpha \Delta I + \beta \Delta E$ with ($\alpha$, $\beta$) = (-111.41, -3.14) explains more than 60% of the interannual variance of $N$ (Figure 7a, $R = 0.79$, $R^2 = 0.62$), i.e. much more than what is explained (about 40%) either by $\Delta I$ or by $\Delta E$ individually. The multiplication of $\alpha$ and $\beta$ by the variances of $\Delta I$ and $\Delta E$ over the 2001-2017 period ($\sigma_I = 4.3 \times 10^{-3}$ and $\sigma_E = 0.16$ K) is informative about the relative influence of $I_{org}$ and EIS vari-
ations on $N$ variations. As $\alpha \sigma_I = -0.48$ and $\beta \sigma_E = -0.50$, the influences of $I_{org}$ and EIS on $N$ variations appear to be of similar order of magnitude.

6 Decomposition of radiative anomalies

By using radiative kernels (section 2.3), the total TOA flux anomalies can be decomposed into contributions from changes in temperature, water vapor, surface albedo and clouds:

$$\Delta N = \sum_{x=T,RH,A,C} K_x \Delta x + \Delta N_C = \sum_{x=T,RH,A,C} \Delta N_x$$

(1)

In this expression, $K_x$ is the radiative kernel associated with temperature ($T$), relative humidity ($RH$) or surface albedo ($A$) variations, and $\Delta N_C$ is the contribution of cloud changes to $\Delta N$, computed as the change in cloud-radiative effect corrected for cloud masking. This decomposition is applied regionally for each month, and each component of the decomposition is then regressed against the monthly time series of $I_{org}$ and EIS interannual anomalies (Table 2), so that equation (1) can be rewritten as:

$$\Delta N = \sum_{x=T,RH,A,C} \left( \frac{\partial N_x}{\partial I} \Delta I + \frac{\partial N_x}{\partial E} \Delta E \right) = \Delta N_I + \Delta N_E$$

(2)

where $\Delta N_I$ and $\Delta N_E$ represent the $I_{org}$ and EIS contributions to $\Delta N$, respectively.

The $N$ anomalies reconstructed from kernel calculations using equation (2) is shown on Figure 7b together with the $\Delta N$ actually observed and the radiative contributions of convective organization and lower-tropospheric static stability to these anomalies. The observed and reconstructed $\Delta N$ exhibit the same good agreement ($R = 0.79$) as seen in Figure 7a. Although the EIS contribution dominates $\Delta N$ during ENSO years, most of the time $I_{org}$ and EIS contributions are of same order of magnitude.

The radiative responses to $I_{org}$ and EIS are mainly driven by variations in relative humidity and cloudiness (Table 2). $\Delta N_I$ arises as much from changes in relative humidity as from changes in LW cloud-radiative effects, while $\Delta N_E$ arises primarily from SW cloud-radiative effects, with an additional contribution from relative humidity variations.

More surprisingly, relative humidity changes appear to contribute to $\Delta N$ almost as much through $I_{org}$ variations (-0.20 Wm$^{-2}$) as through EIS variations (-0.15 Wm$^{-2}$). Similarities are also found when considering the zonally-averaged vertical distribution of $\Delta N_{RH}$ regressed onto $I_{org}$ or EIS variations (Figure 8). As discussed earlier, an increase in convective organization or in EIS is associated with a drying of the free tro-
Table 2. Contributions of changes in temperature (uniform and lapse rate variations), surface albedo, relative humidity and clouds (± the 1-99% confidence interval) to the tropical-mean radiative responses to $I_{org}$ and EIS. To facilitate the comparison between the different sensitivities, the sensitivities to $I_{org}$ and EIS have been multiplied by the interannual standard deviation of $I_{org}$ or EIS ($\sigma_I = 4.3 \times 10^{-3}$ and $\sigma_E = 0.16$ K, respectively). The values in bold are statistically significant (p-value lower than 0.01). Also reported are correlation coefficients (R) between $N_x$ and $I_{org}$ or EIS.

| $x$                              | $\frac{\partial N_x}{\partial I_{org}}\sigma_I$ [W m$^{-2}$] | $\frac{\partial N_x}{\partial E}$ [W m$^{-2}$] | R($N_x$, $I_{org}$) | R($N_x$, E) |
|----------------------------------|-------------------------------------------------------------|-------------------------------------------------|---------------------|-------------|
| Δtemperature (uniform, constant RH) | -0.04 ± 0.13                                                 | -0.12 ± 0.12                                    | -0.06               | -0.21       |
| Δtemperature (lapse rate, constant RH) | -0.09 ± 0.10                                                 | -0.07 ± 0.09                                    | -0.20               | -0.17       |
| Δsurface albedo                  | 0 ± 0.02                                                     | 0 ± 0.02                                        | 0                   | 0           |
| Δrelative humidity               | **-0.20 ± 0.07**                                             | **-0.15 ± 0.06**                                | **-0.54**           | **-0.45**   |
| Δcloud (LW)                      | **-0.18 ± 0.10**                                             | **-0.03 ± 0.09**                                | **-0.37**           | -0.07       |
| Δcloud (SW)                      | -0.15 ± 0.16                                                 | **-0.32 ± 0.13**                                | -0.20               | **-0.47**   |

posphere over most of the tropical belt (Table 1) and leads to a net radiative cooling at TOA. Figure 8 shows that this radiative cooling stems from the drying of the free troposphere over its whole depth, mostly in equatorial regions in the case of $I_{org}$ variations, and mostly in subtropical regions in the case of EIS variations.

7 Summary and Discussion

This study shows that interannual variations of the tropical radiation budget can be explained to a large extent by the radiative influences of variations in the lower-tropospheric stability and in the spatial organization of deep convection. Both influences are equally strong, and despite a modest correlation between convective organization and lower-tropospheric stability, these influences are largely independent of each other. They are also complementary because they operate on different components of the radiation budget: the clustering of deep convection affects TOA radiation mostly through its influence on clear-sky radiation and LW CRE, which relate to variations of free-tropospheric relative humidity and high-level clouds, respectively. On the other hand, lower-tropospheric sta-
Figure 8. Sensitivity to (a) $I_{org}$ and (b) EIS variations of the radiative response to changes in relative humidity at each atmospheric level calculated through the kernel approach, multiplied by the interannual standard deviation of $I_{org}$ or EIS ($\sigma_I = 4.3 \cdot 10^{-3}$ and $\sigma_E = 0.16$ K, respectively). Units: W.m$^2$. (thickness hPa)$^{-1}$ where ”thickness (hPa)” refers to the pressure thickness of each layer. The tropically-averaged, vertical integrals of each panel correspond to the relative humidity contributions $\frac{\partial N_{RH}}{\partial I} \sigma_I$ and $\frac{\partial N_{RH}}{\partial E} \sigma_E$ (in W.m$^{-2}$, reported in Table 2), respectively.

Given the strong influence of convective organization and stability on the tropical radiation budget, it will be important to understand what drives their variations in present and future climates. One potential influencing factor in variations of $I_{org}$ and/or EIS is the tropical large-scale overturning circulation. However, $I_{org}$ and EIS anomalies turn out to be not, or poorly, correlated to basic metrics of this circulation, such as the mean subsidence fraction (the fractional area of the tropics covered by large-scale downward motions), the mean large-scale subsiding motion or the mean circulation strength (as diagnosed by Bony et al. (2013) using large-scale vertical velocity data from ERA interim reanalyses).

Previous research has shown that on decadal and longer time scales, EIS depends on the spatial pattern of surface temperatures, especially on the temperature difference
between warm convective areas and the rest of the tropics (Qu et al., 2015; Zhou et al., 2016; Ceppi & Gregory, 2017). At the interannual time scale, we do note a tendency of EIS to increase with this temperature difference, but it explains only a few percent of the interannual variance of EIS. On the other hand, we note a strong anti-correlation between EIS and relative humidity in the free-troposphere (Table 1). This magnitude of anti-correlation does not exist between EIS and the area and/or strength of large-scale subsidence in the tropics. Therefore, we suggest that it arises rather from a radiative coupling: dry anomalies in the free troposphere enhance the radiative cooling at the top of the moist boundary-layer of subtropical regions, which strengthens the inversion at the top of the boundary layer and thus EIS. By inhibiting the vertical development of convective clouds, a stronger EIS prevents the free troposphere from being moistened by the detrainment of shallow or deeper congestus clouds, thus reinforcing the anti-correlation between MTH and EIS.

Since periods of enhanced convective organization are associated with dry anomalies in the mid and upper troposphere (Figure 5), they are likely to induce a positive correlation between convective organization and EIS anomalies. Indeed, the regression of regional EIS anomalies onto $I_{org}$ anomalies shows a clear enhancement of EIS on both sides of equatorial regions when convective organization is stronger (Figure 9). This is consistent with the positive correlation between $I_{org}$ and the tropical-mean EIS ($R = 0.37$).

![Figure 9](image-url)

**Figure 9.** Regional EIS anomalies regressed onto $I_{org}$ interannual anomalies during 2001-2017. Results are reported where the relationship is significant (p-value lower than 0.05).
The factors that control the spatial organization of deep convection across the tropics constitute an area of active research. Modeling studies suggest that the aggregation of deep convection strongly depends on atmospheric radiative processes (Muller & Held, 2012; Wing & Emanuel, 2014; Muller & Bony, 2015; Holloway & Woolnough, 2016), and on the spatial distribution of surface temperatures (Coppin & Bony, 2018). It may also be sensitive to the mean surface temperature (see Wing et al. (2017) for a review), although idealized simulations of the tropical atmosphere do not provide consistent results on that matter. Some studies suggest that convective aggregation increases under global warming (Coppin & Bony, 2015; Pendergrass et al., 2016), but others suggest that conclusions regarding the sensitivity of convective organization to warming depend on the metric used to quantify the organization, and on the range of warming considered (Cronin & Wing, 2017). The present analysis of interannual variations is not more conclusive in that regard, as the correlation between convective organization and the tropical-mean surface temperature is insignificant (Supplementary Material Table S2). On the other hand, convective organization might be more sensitive to changes in regional SST patterns (Coppin & Bony, 2018). Preliminary investigations suggest that $I_{org}$ and EIS correlate to different SST patterns (Supplementary Material Figure S5). Future investigations should thus determine how much the radiative influence of SST patterns, which partly results from the influence of the SST distribution on EIS (Zhou et al., 2016), also stems from the influence of SST patterns on the organization of deep convection.

However, in addition to being potentially affected by slowly-varying boundary conditions such as SST changes, the spatial organization of deep convection may also be affected by purely internal atmospheric variability. For instance, $I_{org}$ exhibits some variability at timescales characteristics of the Madden-Julian Oscillation (Figure 3), which has been suggested to be a manifestation of an instability driven by cloud-radiation feedbacks (Emanuel et al., 2014; Arnold & Randall, 2015; Khairoutdinov & Emanuel, 2018). This is in contrast with the lower-tropospheric stability which does also exhibit variability at interannual timescales but not at the intra-seasonal timescale. Therefore, while $I_{org}$ and EIS might both be sensitive to slow changes in the ocean-atmosphere system, $I_{org}$ presumably results as well from short-term processes and interactions within the atmosphere.

Although the issue of whether and how convective organization and EIS will change in the future remains unsettled, this observational study suggests that their changes at
decadal or longer time scales might matter for the radiation balance of the Earth, wa-

ter vapor and cloud feedbacks and thus climate sensitivity. It stresses the importance

of testing the ability of numerical models of the climate system to reproduce the observed

relationships analyzed in this study. It also emphasizes the need to better understand

physically the factors that control convective organization and lower-tropospheric sta-

bility, and the need to monitor their changes as the climate warms.

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Radiative Fluxes and Clouds dataset (Edition 4A,

doi:10.5067/TERRA+AQUA/CERES/EBAF-TOA_L3B004.0) is made available

by the CERES group from the NASA Langley Research Center. CALIPSO-GOCCP data

are available from http://climserv.ipsl.polytechnique.fr/cfmip-obs/Calipso_goccp.html.

The Southern Oscillation Index (SOI) is available from https://www.cpc.ncep.noaa.gov/data/indices/soi.

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