How tropical convection couples high moist static energy over land and ocean

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Key Points:

- The utility of quasi-equilibrium and weak temperature gradient theories (QE-WTG) can be demonstrated by a rainfall-weighting method.
- Observed convection occurs at very similar subcloud moist static energy across all latitudes in the inner tropics as a result of QE-WTG.
- The highest moist static energy values are tightly coupled over land and ocean, while the lower values are free to differ.

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Abstract

We show that in the tropics, tropical atmospheric dynamics force the subcloud moist static energy (MSE) over land and ocean to be very similar in, and only in, regions of deep convection. Using observed rainfall as a proxy for convection and reanalysis data to calculate MSE, we show that subcloud MSE in the non-convective regions may differ substantially between land and ocean but is uniform across latitudes in convective regions even on a daily timescale. This result holds also in CMIP5 model simulations of past cold and future warm climates. Furthermore, the distribution of rainfall amount in subcloud MSE is very similar over land and ocean with the peak at 343 J/g and a half width at half maximum of 3 J/g. As a result, the annual-maximum subcloud MSE at each location over land and ocean is subject to a common upper bound set by the convective regions.

Plain Language Summary

An extremely idealized picture of the tropical atmospheric dynamics is that deep convection sets a horizontally uniform free tropospheric troposphere profile. Here, we show that despite the idealization, this simple picture is very useful in explaining the observations; Convection occurs at very similar spatially uniform subcloud MSE regardless of over land or ocean.

1 Introduction

The tropics show, even at equal latitudes and despite a relatively uniform annual mean insolation, a large variety of local climates ranging from regions with highest rainfall globally to deserts. Given the paramount importance of rainfall over land for ecosystems and humans, the processes governing its distribution and how it may change in the future are focus of intense efforts both in terms of improved process representations in numerical climate models, and development of theories to interpret observations and model results (e.g., Lintner & Chiang, 2005; Seneviratne et al., 2013; Pendergrass et al., 2017; Byrne & O'Gorman, 2015). Understanding climate over land inevitably requires understanding its connection to the oceans. A fundamental difference between land and ocean is that over land, evapotranspiration is constrained by available moisture and, as a consequence, sensible heat flux plays a larger role over land than ocean. An important corollary of this surface energy budget consideration that is robustly observed in global climate model simulations is that the surface temperature response to radiative forcing is larger over land than ocean (Manabe et al., 1991).

The limited evaporation over land not only affects the partitioning between sensible and latent heat flux, but also leads to different temperature lapse rates in the lower layers of the troposphere over land and ocean. Joshi et al. (2008) note that in model calculations there exists a level sufficiently high up in the troposphere where temperature change in response to forcing is similar over land and ocean, and the larger surface temperature response over land then is consistent with the different changes in lapse rates over land and ocean. Byrne and O'Gorman (2013a) formulate this effect in terms of the equality of equivalent potential temperature averaged over land and ocean as a result of weak temperature gradients in the free troposphere and convective quasi-equilibrium, which is largely supported by simulations with idealized climate models. However, they also notice that this equality breaks down in realistic climate models (Byrne & O'Gorman, 2013b), and the changes in the mean surface equivalent potential temperature, rather than the mean equivalent potential temperatures themselves, are more similar over land and ocean (Byrne & O'Gorman, 2013b; Byrne & O'Gorman, 2018).

In the following, we present observation and model results to provide a more precise picture how tropical atmospheric dynamics couple the moist static static (MSE; equivalent to the equivalent potential temperature used in (Byrne & O'Gorman, 2013a, 2013b)) of air near the surface over land and ocean to the free atmosphere. We show that the subcloud MSE where convection occurs is roughly constant with latitude in the inner tropics (about 20°S-20°N) and very similar over land and ocean, which may not be expected in light of the well-documented land-ocean contrast of tropical convection (Robinson et al., 2011; Matsui et al., 2016). Notably, this similarity holds across all latitudes of the inner tropics even on a daily timescale. As a result, the connection in subcloud MSE over land and ocean is only established in the highest MSE values that compose the convective regions.

2 Data and Method

2.1 Subcloud MSE

Subcloud MSE is computed using ERA-Interim 6-hourly reanalysis data on 0.75°x0.75° grid and pressure levels (Dee et al., 2011). Moist static energy h is calculated following the definition

$$h = c_p T + gz + Lq, \tag{1}$$

where c_p is the heat capacity of air, T is temperature, g is gravitational acceleration, z is height, L is the latent heat of water, and q is the mixing ratio of water vapor. Standard values used in climate models and reanalysis data are adopted here, namely $c_p = 1005\,\mathrm{J/kg}$, $L = 2.5 \times 10^6\,\mathrm{J/kg}$ and $g = 9.8\,\mathrm{m/s^2}$. The subcloud layer is the portion of the boundary layer extending from the surface to the average altitude of the base of clouds (American Meteorological Society, 2012). Here, we calculate the lifting condensation level on 6-hourly time frequency. Subcloud MSE is then the average MSE either within the layer between the ground and the LCL when the LCL is within the boundary layer, or within the boundary layer when the LCL is higher than the boundary-layer top (no-cloud case). The 6-hourly subcloud MSE is averaged to a daily timescale to match the time resolution of the rainfall observation.

2.2 Convective subcloud MSE

The convective (subcloud) MSE is calculated by weighting the subcloud MSE in each grid box with the corresponding rainfall received, i.e., rainfall intensity multiplied by the area of the grid box, following the rainfall-weighting method in Flannaghan et al. (2014); Fueglistaler et al. (2015):

$$\text{Convective subcloud MSE} = \frac{\sum_i P_i h_i}{\sum_i P_i} \tag{2}$$

Daily rainfall observations from Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2007) from 2001 to 2014 of 0.25°x0.25° resolution are interpolated to the ERA-Interim grid conserving total precipitation fluxes. The convective (subcloud) MSE can be loosely interpreted as the subcloud MSE weighted by the mass flux transported from the subcloud layer to the free atmosphere by deep convection, as convective mass flux scales roughly linearly with rainfall (Raymond et al., 2015). The resolution of the data used here (order 100 km) does not allow distinguishing between convective rain (1-10 km) and stratiform rain (∼100 km) (Houze, 1997), which may introduce some ambiguity in the determination of convective MSE. For the convective MSE as a function of latitude, the subcloud MSE in each latitude band is first calculated on a yearly basis before averaged over the chosen period and hence is not influenced by trends or interannual variability in total tropical rainfall.

3 Results

3.1 The MSE threshold for convection – A zeroth-order picture

The tropical atmosphere can be seen as consisting of a boundary layer with diverse temperature, humidity, and topography (the three components of MSE) and a free troposphere that is comparatively homogenous. Deep convection transports boundary layer air upward into the free atmosphere. Once the free atmosphere is filled with buoyant air originating from the warm and humid boundary layer, it suppresses upward motion in the colder regions, establishing a threshold for convection. More quantitatively, the constraint from atmospheric dynamics can be expressed as a combination of convective quasi-equilibrium (QE) and weak temperature gradient (WTG) (Byrne & O'Gorman, 2013a), subsequently referred to as QE-WTG. Strict quasi-equilibrium assumes that convection maintains the subcloud MSE equal to the saturated MSE aloft in the free atmosphere (e.g., Arakawa & Schubert, 1974; Emanuel, 2007) (The saturated MSE only strongly depends on the air temperature). Weak temperature gradient states that the free atmosphere cannot sustain substantial horizontal temperature gradients due to the smallness of the Coriolis parameter in the tropics (e.g., Charney, 1963; A. H. Sobel & Bretherton, 2000). Consequently, at the limit of strict quasi-equilibrium and zero temperature gradient, simultaneously convecting regions, regardless of over land or ocean, should have the same subcloud MSE which we refer to as the MSE threshold for convection. While previous studies (Byrne & O'Gorman, 2013a, 2013b; Byrne & O'Gorman, 2018) evaluate the QE-WTG picture with the large-scale mean MSE over land and ocean, we argue that QE-WTG should be evaluated only in the regions where deep convection couples the MSE in the subcloud layer to the free atmosphere and does not apply to the regions where the sublcoud MSE is too low to reach the threshold for convection. Leveraging the aforementioned rainfall-weighting method, we are able show that QE-WTG apply to each latitude in the observations, even on a daily timescale, and there is a clear breakdown of the theoretical picture around 20° in both hemispheres.

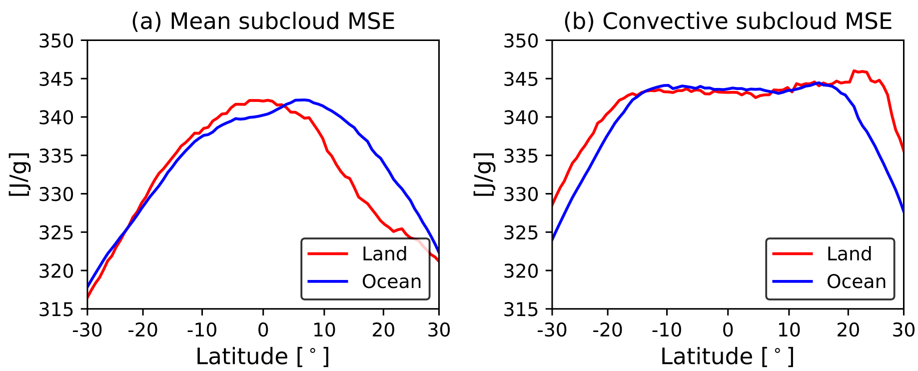

Figure 1. Zonal-mean (a) and convective (b) subcloud moist static energy (MSE) over land (red) and ocean (blue). Subcloud MSE is derived from ERA-Interim and rainfall is from TRMM. Daily data from 2001 to 2014 are used. The convective subcloud MSE is determined by weighting the subcloud MSE at each longitude with the corresponding rainfall within each latitudinal band of 0.75° wide.

The zonal-mean subcloud MSE (Fig. 1(a)) peaks around the equator reflecting the annual-mean solar forcing, whereas the convective subcloud MSE (Fig. 1(b)) is roughly uniform throughout the inner tropics and very similar between land and ocean, reflecting the weak horizontal temperature gradients in the free atmosphere. The sharp drop-off at about 20° in both hemispheres indicates where the Coriolis effect is no longer negligible and QE-WTG breaks down. As a result, rainfall in the subtropics can occur either at very low subcloud MSE when induced by the extratropical eddies (Funatsu & Waugh, 2008) or at very high subcloud MSE during the South Asian monsoon which creates the peak in the convective MSE around 25°N over land (Boos & Kuang, 2010). The contrast between the mean and the convective subcloud MSE resolves the aforementioned inconsistency between the strict QE-WTG theory and the realistic simulations mentioned in (Byrne & O'Gorman, 2013b); Convection only occurs in the part of the domain where the subcloud MSE is high enough to reach the tropically uniform MSE threshold of about 343 J/g shown in Fig. 1(b), and in the part of the domain that is not convecting subcloud MSE is not coupled to the free atmosphere and therefore can differ between land and ocean.

A more stringent test examines how effectively QE-WTG works on a daily basis. Fig. 2 shows the seasonal evolution of the zonal-mean subcloud MSE in the convective

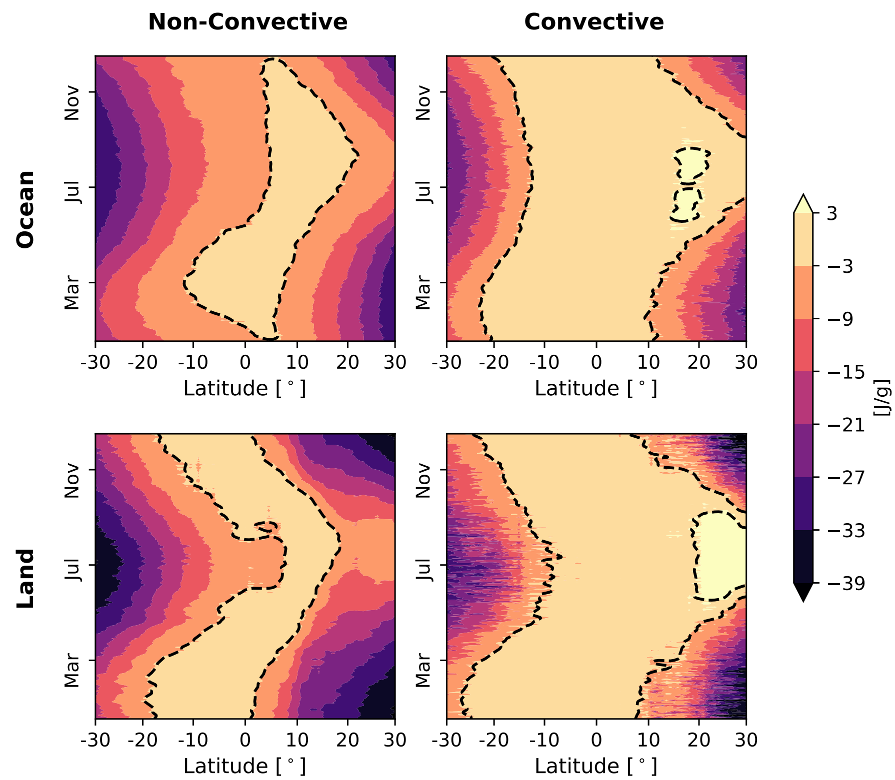

Figure 2. The mean subcloud moist static energy (MSE) as a function of latitude and day of year in the non-convective and convective regions over ocean and land. Daily data are used from ERA-Interim and TRMM between 2001 and 2014. Convective and non-convective regions are identified with a rainfall threshold of 6 mm/day. The dashed contour lines indicate the subcloud MSE within $\pm 3\,\mathrm{J/g}$ relative to a common reference value (see text).

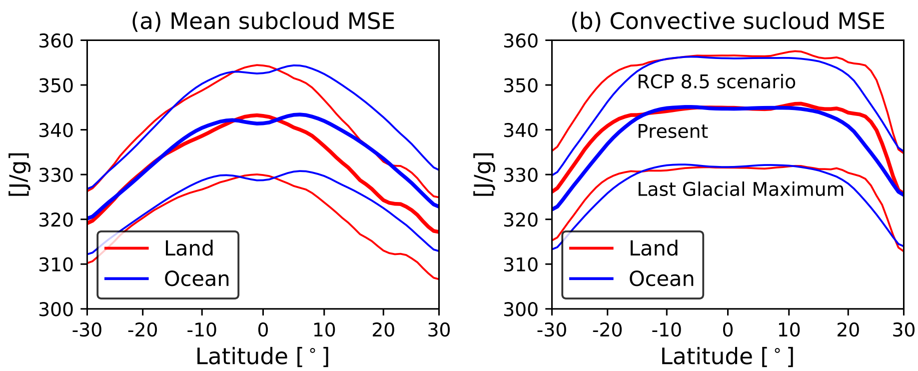

Figure 3. Zonal-mean (a) and convective (b) subcloud moist static energy (MSE) for model simulations. The multi-model mean of monthly data from CMIP5 models (See Table S1) are shown. Three experiments are shown from bottom to top: the Last Glacial Maximum, the period from 1979 to 2005 in the simulation of current climate (labeled "Present"), and the last 20 years of the 21st century in the global warming simulation (labeled "RCP 8.5 scenario").

regions (left column) and non-convective regions (right column) over land (lower row) and ocean (upper row). Here the convective MSE is defined as the mean subcloud MSE where the rain rate is above 6 mm/day (A. Sobel et al., 2002) and *vice versa* for the non-convective MSE. The results are not sensitive to the choice of a rainfall threshold from 2 mm/day to 20 mm/day (Figs. S1, S2). This method is different from the rainfall-weighting method used in Fig. 1 but yields similar convective MSE values, essentially because rainfall anywhere in the inner tropics occurs at very similar subcloud MSE. To facilitate the comparison, a reference value for each day of year, calculated as the mean subcloud MSE in the convective regions over equatorial (5°S-5°N) ocean, is subtracted. Even on a single day of year, the convective MSE is still uniform over a broad range in latitude, though this latitudinal range has seasonality (Fig. 2, right column). The seasonal evolution of the non-convective MSE has more prominent land-ocean contrast than the convective MSE (indicated by the shapes of the dashed black contours), supporting the concept that only the subcloud MSE in the convective regions over land and ocean are tied to the uniform temperature in the free atmosphere.

The physics involved in the QE-WTG mechanism does not rely on the mean climatic state, therefore QE-WTG is expected to hold in all climates. Global climate models from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al.,

2012) that correctly reproduce the observed uniform convective MSE in the simulations of the present climate (Fig. S3 and Table S1) also show a uniform convective MSE in the projections of a much warmer climate under the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario (Fig. 3). Model simulations of the much colder Last Glacial Maximum also show a uniform convective MSE over both land and ocean. Therefore, Fig. 3 demonstrates the validity of QE-WTG in a wide range of climates.

3.2 Finite width of the MSE threshold for convection – A first-order correction

The latitudinal uniformity of the convective subcloud MSE in the inner tropics and its similarity between land and ocean (Fig. 1, 2) provide observational support for the zeroth-order picture. However, it is well established that factors such as the mid-tropospheric humidity (Emanuel, 2019; Brown & Zhang, 1997), convective inhibition (Mapes, 2000), low-level convergence (Lindzen & Nigam, 1987; Back & Bretherton, 2009), and stationary or transient equatorial waves (Gill, 1980; Kiladis et al., 2009) all affect the triggering of convection. How can these complicating factors by reconciled with the simple picture of a uniform MSE threshold for convection?

The convective MSE threshold shown in Fig. 1(b) is a weighted mean over a range of subcloud MSE values rather than a single MSE value. Fig. 4(a) shows the total amount of rainfall that falls into each subcloud MSE bin of a width of 0.2 J/g. This rainfall distribution can be roughly regarded as the convective mass flux distribution as a function of subcloud MSE. If QE-WTG were strict, this distribution would be a Dirac function at the highest subcloud MSE. In the observed climate, however, the majority of rainfall occurs around 343 J/g–the value is comparable to the convective MSE (Fig. 1(a))–with a Half Width at Half Maximum (HWHM) of 3 J/g. The half width of 3 J/g then encapsulates the previously mentioned factors that affect the local triggering of convection. This width is narrow compared to the entire range of the tropical subcloud MSE of about 60 J/g. Remarkably, the shape of the rainfall distribution as a function of subcloud MSE is also similar between land and ocean, a result not predicted by the theoretical limit of QE-WTG.

The tails of the rainfall distribution at very high subcloud MSE above 350 J/g and low subcloud MSE below 336 J/g are somewhat different for land and ocean, due to the

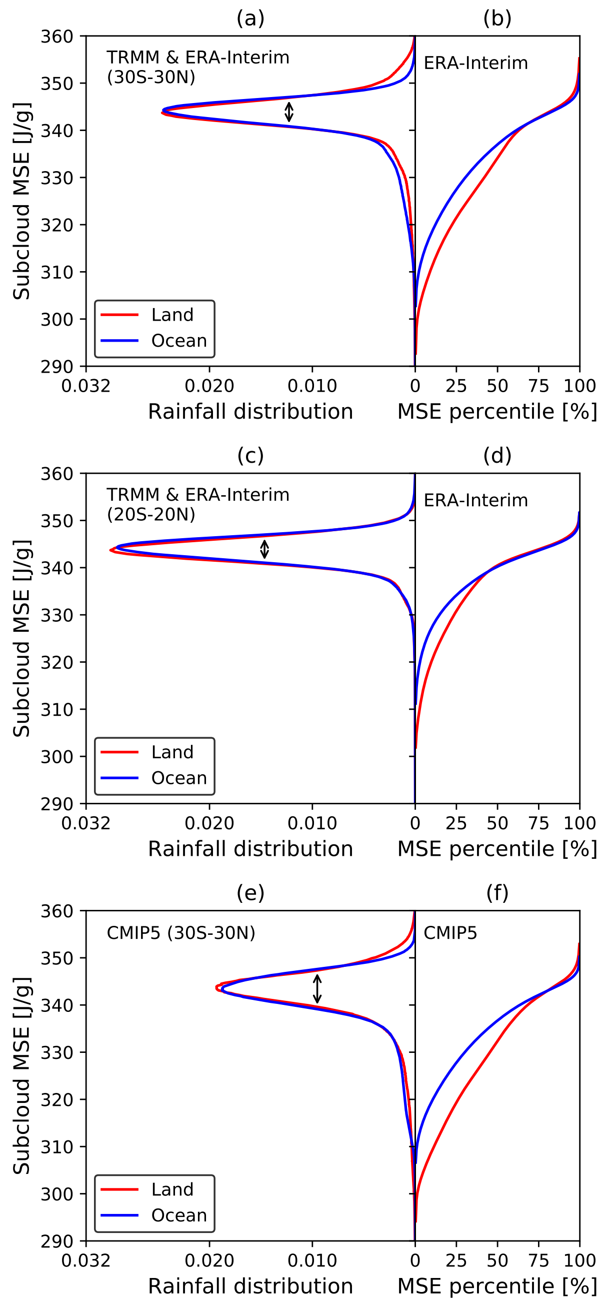

Figure 4. Rainfall distribution as a function of subcloud MSE (left panels) and the corresponding percentiles of subcloud MSE (right panels). (a) and (b) show rainfall from TRMM and subcloud MSE from ERA-Interim between 30°S and 30°N. (c) and (d) are the same as (a) and (b) but with data between 20°S and 20°N. (e) and (f) are the same as (a) and (b) but is the multi-model mean of monthly output from CMIP5 models in the coupled simulation from 1979 to 2005 (Table S1). The double arrows indicate where the HWHM is evaluated.

break-down of QE-WTG in the subtropics. When the latitudinal range is restricted to 20°S-20°N (Fig. 4(c)), the tails disappear and a convective mode centered at 343 J/g emerges which is almost identical over land and ocean.

Fig. 4(e) is the same as Fig. 4(a) but for the CMIP5 multi-model mean. The width of the MSE threshold is wider than that in the observations, because it is an average of models with slightly different mean states. In fact, the half width for an individual CMIP5 model is also 3 J/g on average.

To put the magnitude of the width into context, we compare it with typical MSE changes due to departure from the strict QE-WTG: Observed convective available potential energy (CAPE) varies between 0 and 4 J/g (Williams & Renno, 1993; Gettelman et al., 2002) and the free tropospheric temperature varies by order 1 K horizontally (e.g. Fueglistaler et al., 2009) which translates to about 2 J/g of subcloud MSE. It is thus not obvious which factor contributes more given the similar amplitudes. We also notice that the width is not strongly dependent on the time frequency (daily or monthly) of data.

Figs. 4(b,d,f) show the corresponding percentiles of subcloud MSE sorted in ascending order and averaged in equal-area bins. Fig. 4(b) reiterates that only the highest subcloud MSE values between 30°S and 30°N are coupled over land and ocean while the low subcloud MSE values are free to differ – the upper 30% of subcloud MSE has almost identical distribution over land and ocean while the lower 70% of the subcloud MSE over ocean is systematically higher than that over land. In addition, Figs. 4(b,d) highlight an interesting aspect of the Earth's tropical climate: The convective area fraction is approximately equal over land and ocean.

4 Conclusion and outlook

We show that a simple theoretical picture of the tropical atmosphere based on the convective quasi-equilibrium and the weak-temperature-gradient assumptions (QE-WTG) can effectively explain the observations. In accordance with QE-WTG, the convective subcloud MSE is roughly constant with latitude between 20°S and 20°N on a daily timescale in the observed current climate and in the simulated past and future climates. The utility of QE-WTG is manifested in its capability of reconciling the land-ocean contrast. The vastly different land and ocean surfaces share almost identical convective subcloud MSE, distribution of highest subcloud MSE values, and precipitation distribution as a function of subcloud MSE. Whereas the role of subcloud MSE forcing the free troposphere has been well appreciated in tropical convection, we demonstrate that the horizontally uniform free tropospheric temperature forces the highest subcloud MSE values to be similar over land and ocean, which is an interesting aspect of convection in the tropics. These results fill the gap between the idealized, conceptual understanding of the tropical atmospheric dynamics and the real world consisting of diverse regional climates.

An important implication of our results is that the maximum subcloud MSE at a given location, either over land or over ocean, is subject to a common upper bound set by the convective regions. As moist static energy is related to heat stress metrics (Fischer & Knutti, 2013; Sherwood & Huber, 2010; Byrne & O'Gorman, 2013b) and as is pointed out in Byrne and O'Gorman (2013b) that the mean heat stress over land is controlled by the ocean, our results suggest that atmospheric dynamics may also control heat stress extremes in the tropics.

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Supporting Information for "How tropical convection couples high moist static energy over land and ocean"

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Text S1. Land mask

Coastal regions and islands are known to have substantial amounts of rainfall. The horizontal resolution of data used in this work implies ambiguity regarding the separation into land and ocean which could damp the differences between the calculated convective MSE over land and ocean. We therefore employ a strict criterion to eliminate the grid boxes that are not overwhelmingly land or ocean. A grid box is classified as ocean if the land area fraction is less than 5%, and is classified as land if the land area fraction is more than 95%. The remaining "coastal" grid cells taking up about 5% of area of the entire tropics are discarded in this analysis. For ERA-Interim, the land cover type data (MCD12C1) on $0.05° \times 0.05°$ grid from Moderate Resolution Imaging Spectroradiometer data (Friedl & Sulla-Menashe, 2015) is used to calculate the fraction of land in each box of the reanalysis grid. For CMIP5 models, the land area fraction provided by the modeling centers is used.

Text S2. Convective subcloud moist static energy (MSE) in CMIP5 models.

A simplified procedure for the calculation of the subcloud MSE is used for the CMIP5 model output where less detailed boundary layer information is available. The reduced vertical resolution of the CMIP5 model output to the standard pressure levels (1000, 925, 850 hPa ...) precludes the same accuracy as with the reanalysis data in the determination of the lifting condensation level (LCL). In addition, most models do not extrapolate data over land to the 1000 hPa level. We thus use a simplified procedure to estimate the subcloud MSE in the CMIP5 models: We use the 925 hPa as the generic upper boundary of the subcloud layer following Williams, Pierrehumbert, and Huber (2009); Williams and Pierrehumbert (2017). For models that report all the required data on the near-surface level (temperature, specific humidity, orography) and the 925 hPa pressure level (temperature, specific humidity, geopotential height), subcloud MSE is the average of the near-surface MSE and the 925-hPa MSE; For models that do not report all the required data on the near-surface level but report extrapolated information on the 1000 hPa over land, subcloud MSE is the average of the MSE on 1000 and 925 hPa pressure levels. This calculation is based on monthly mean data. To estimate the error introduced by the simplification, we apply this simplified procedure to the monthly mean ERA-Interim and TRMM data and find that the convective MSE is still similar over land and ocean on monthly timescale.

Fig. S3 shows the convective MSE over land vs. over ocean calculated with the simplified calculation for the CMIP5 models. Most models produce very similar convective subcloud MSE over land and ocean, but there are a few strong outliers. The multi-model mean values shown in Figs. 3 and 4 only include those models (SI Appendix, Table S1) that reasonably reproduce the observation in the Historical experiment and have a difference in the convective subcloud MSE between land and ocean of less than 2 J/g. For the multi-model mean, all the zonal-mean quantities are first calculated on the models' native grids and then interpolated onto a common 1° meridional grid.

References

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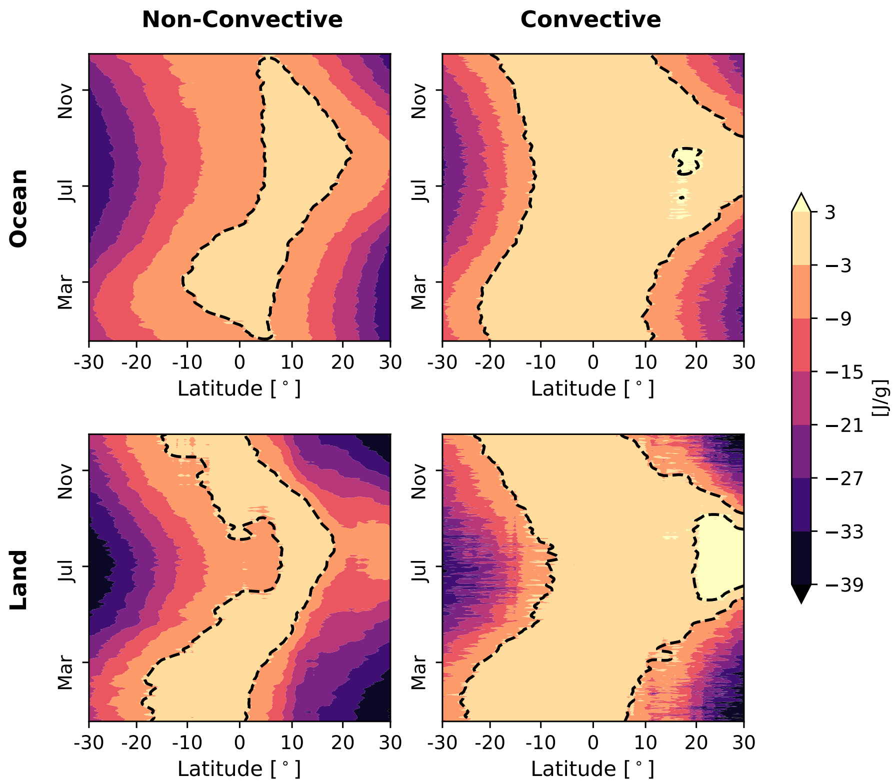

Figure S1. The mean subcloud moist static energy (MSE) as a function of latitude and day of year in the non-convective and convective regions over land and ocean. Convective and non-convective regions are identified with a rainfall threshold of 2 mm/day.

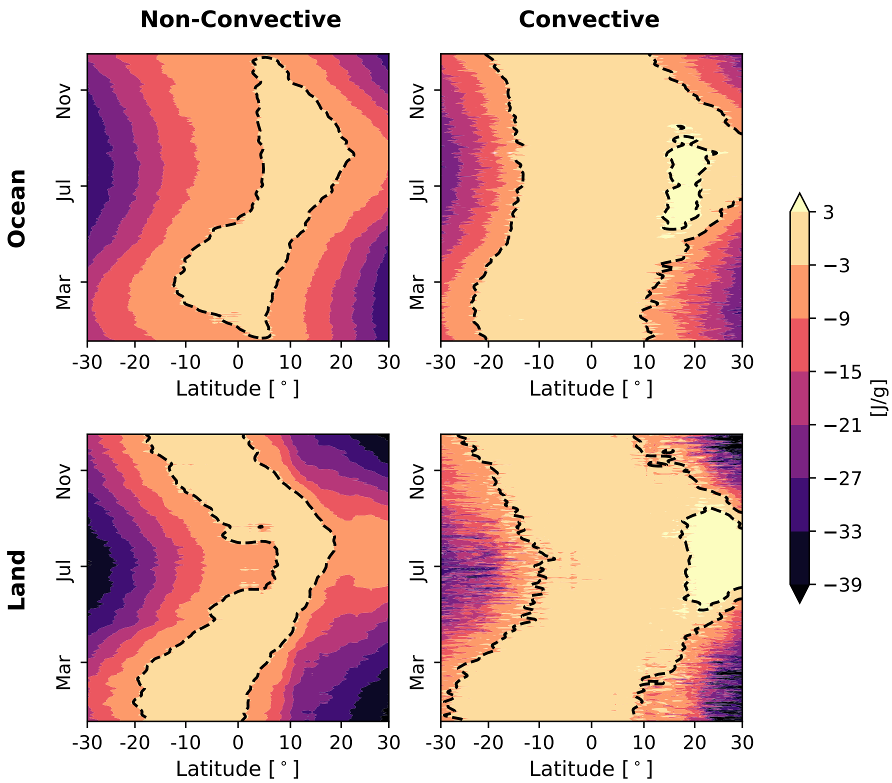

Figure S2. The mean subcloud moist static energy (MSE) as a function of latitude and day of year in the non-convective and convective regions over land and ocean. Convective and non-convective regions are identified with a rainfall threshold of 20 mm/day.

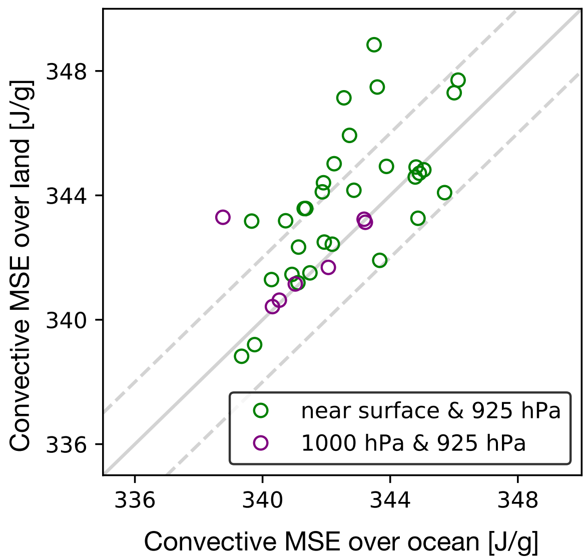

Figure S3. Convective subcloud MSE over land and ocean for CMIP5 models during the period from year 1979 to 2005 in the Historical experiment. Green circles are models where atmospheric near-surface data are available and subcloud MSE is calculated with the near-surface and the 925hPa level data. Purple circles are models that do not report complete near-surface data but report data over land at 1000 hPa and subcloud MSE is calculated with the 1000 hPa level and 925 hPa level data. The multi-model means shown includes only models that approximately reproduce the observation and have less than 2 J/g difference (dashed lines) between land and ocean (Table S1).

Table S1. Table of CMIP5 models used. ✓and ✗indicates whether a model is shown or not, while blank indicates a model that does not report complete information (See Text S2). "S" or "L" indicates the subcloud MSE is calculated with near-surface data or 1000 hPa data (See Text S2).

Model Name	Method	Historical	RCP 8.5	LGM	Institute ID
ACCESS1-0	S	✗	✗		CSIRO-BOM
ACCESS1-3	S	✗	✗		CSIRO-BOM
BCC-CSM1.1	S	✓	✓		BCC
CCSM4	S	✓	✓	✓	NCAR
CESM1-BGC	S	✓	✓		NSF-DOE-NCAR
CESM1-CAM5	S	✓	✓		NSF-DOE-NCAR
CESM1-FASTCHEM	S	✓			NSF-DOE-NCAR
CESM1-WACCM	S	✓			NSF-DOE-NCAR
CMCC-CESM	L	✓	✓		CMCC
CMCC-CM	L	✓	✓		CMCC
CMCC-CMS	L	✓	✓		CMCC
CNRM-CM5	S	✓	✓	✓	CNRM-CERFACS
CNRM-CM5-2	S	✓			CNRM-CERFACS
CSIRO-Mk3-6-0	S	✓	✓		CSIRO-QCCCE
CanESM2	S	✓	✓		CCCMA
GFDL-CM3	S	✓	✓		NOAA GFDL
GFDL-ESM2G	S	✗	✗		NOAA GFDL
GFDL-ESM2M	S	✗	✗		NOAA GFDL
GISS-E2-H	S	✗	✗		NASA GISS
GISS-E2-R	S	✗	✗		NASA GISS
HadGEM2-AO	S	✓	✓		NIMR/KMA
HadGEM2-CC	S	✓	✓		MOHC
HadGEM2-ES	S	✓	✓		MOHC
INM-CM4	L	✗			INM
IPSL-CM5A-LR	S	✗	✗	✓	IPSL
IPSL-CM5A-MR	S	✗	✗		IPSL
IPSL-CM5B-LR	S	✓	✓		IPSL
MIROC-ESM	S	✗	✗	✓	MIROC
MIROC-ESM-CHEM	S	✗	✗		MIROC
MIROC4h	S	✓			MIROC
MIROC5	S	✗	✗		MIROC
MPI-ESM-LR	L	✓	✓		MPI-M
MPI-ESM-MR	L	✓	✓		MPI-M
MPI-ESM-P	L	✓		✓	MPI-M
MRI-CGCM3	S	✓	✓	✓	MRI
MRI-ESM1	S	✓	✓		MRI
NorESM1-M	S	✓	✓		NCC
NorESM1-ME	S	✓			NCC