

What drives the Mesoamerican Midsummer Drought? Insights from the moist static energy budget

Jorge Luis Garcia-Franco

`jorge.garcia-franco@physics.ox.ac.uk`

Universidad Nacional Autonoma de Mexico <https://orcid.org/0000-0002-0396-9744>

Robin Chadwick

Met Office

Spencer Hill

CUNY City College: The City College of New York

Kuniaki Inoue

Goddard Institute for Space Studies

Kevin Schwarzwald

Columbia University

Arianna Varuolo-Clarke

Dartmouth College

Research Article

Keywords: Midsummer drought, Central America, Mexico, moist static energy budget, seasonal cycle of precipitation, Caribbean Low-Level Jet

Posted Date: October 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11132449/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

What drives the Mesoamerican Midsummer Drought? Insights from the moist static energy budget

Jorge L. García-Franco^{1,2,3*}, Robin Chadwick^{4,5}, Spencer Hill⁶, Kuniaki Inoue⁷,
Kevin Schwarzhald^{2,8}, Arianna Varuolo-Clarke⁹

^{1*} Escuela Nacional de Ciencias de la Tierra, Universidad Nacional Autónoma de
México, Mexico City, Mexico .

² Lamont-Doherty Earth Observatory, Columbia University, New York, USA .

³ Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, United
Kingdom .

⁴ Met Office Hadley Centre, Exeter, United Kingdom .

⁵ University of Exeter, Exeter, United Kingdom .

⁶ The City College of New York, New York, New York, USA .

⁷ NASA Goddard Institute for Space Studies, New York, New York, USA .

⁸ Columbia Climate School, Columbia University, New York, New York, USA .

⁹ Department of Geography, Dartmouth College, Hanover, New Hampshire, USA .

Abstract

The Midsummer Drought (MSD) is a robust feature of the seasonal cycle of rainfall across Mesoamerica, but the mechanisms that drive it remain uncertain. Here we use the column moist static energy (MSE) budget in two reanalyses (ERA5 and JRA-3Q) to test, within a single framework, the two leading hypotheses for the MSD: an increase in large-scale stability, and enhanced horizontal drying associated with the Caribbean Low-Level Jet. Column-integrated MSE tracks precipitation variability closely in both space and time, supporting its use as a diagnostic. We find that the troposphere remains unstable to convection throughout the rainy season, so the MSD is not well explained by a change in dry static stability. Horizontal MSE export does increase into the MSD, driven by the zonal advection of moisture in the lower troposphere and consistent with the low-level jet hypothesis, but this increase is modest and is largely offset by a concurrent increase in surface turbulent fluxes over land. At the same time, the vertical structure of the ascent changes, with weaker mid-level ascent exporting less MSE from the column. The seasonal cycle of rainfall therefore emerges from the combination of these processes: a change in the efficiency with which the circulation ventilates the column, together with the evolving balance between horizontal MSE export and surface turbulent flux input. Under this balance the column gains MSE during the MSD even as precipitation is suppressed, which may contribute to the recovery into the second precipitation peak.

Keywords: Midsummer drought, Central America, Mexico, moist static energy budget, seasonal cycle of precipitation, Caribbean Low-Level Jet

1 Introduction

In southern Mexico and northwestern Central America, the seasonal cycle of precipitation features a summer rainy season (May–October) with a pronounced reduction in rainfall during midsummer (July–August) (Mosiño and García 1966; Perdigón-Morales et al. 2018). This period is commonly referred to as the Midsummer Drought (MSD) and is also known locally as the “canícula” or “veranillo” (Mosiño and García 1966; Magaña et al. 1999; Dillely 1996). MSD-related rainfall variations are large

enough to have long shaped agricultural practices in the region (Corral 2012; Baez-Gonzalez et al. 2018). Consequently, local farmers are highly vulnerable to changes in MSD characteristics arising from anthropogenic forcing or natural variability (Hellin et al. 2017; Maurer et al. 2017; Ley et al. 2023).

The societal relevance of the MSD motivates continued efforts to understand the physical mechanisms that shape the seasonal cycle of rainfall in this region. A better understanding of its mechanisms could help improve its prediction across timescales (García-Franco et al. 2025; Zermeno-Díaz and Ray 2025) or interpret our diagnosis of severe droughts in general (Anderson et al. 2023; Hidalgo et al. 2025). Although extensive research has examined and advanced our understanding of proposed mechanisms for the Mesoamerican MSD (e.g., Mosiño and García 1966; Small et al. 2007; Herrera et al. 2015; Maldonado et al. 2016; Zhao and Du 2026), fundamental questions remain about the processes that set its amplitude and modulate its variability (García-Franco et al. 2023).

A methodology that has not yet been used to better understand the MSD is the moist static energy (MSE) budget framework. MSE is a state variable that combines gravitational potential energy, sensible heat, and latent heat, and is approximately conserved following air parcels under moist-adiabatic processes (Neelin and Su 2005; Back and Bretherton 2006; Ma et al. 2019). The MSE budget framework was developed to connect tropical circulations with moist convection (Neelin and Held 1987; Adames Corraliza and Mayta 2023).

The MSE budget has therefore been applied in tropical weather and climate research to understand phenomena, interpret mechanisms and validate models. For instance, several studies have used this framework to characterize monsoons (Bordoni and Schneider 2008; Hill 2019), including their response to forcing (Hill et al. 2017; Smyth and Ming 2020; Chadwick et al. 2026) and their seasonal evolution (Ma et al. 2019), as well as tropical cyclones (e.g., Wing et al. 2019), El Niño–Southern Oscillation (Annamalai 2020) and its teleconnections (Neelin and Su 2005), the seasonal cycle of rainfall (Schwarzwalld et al. 2023), and the Madden–Julian Oscillation (Inoue and Back 2015).

Out of the several existing hypotheses to explain the MSD (see García-Franco et al. 2023, for a detailed review), there are two hypotheses that could be examined using the MSE budget framework. First, several studies (Mapes et al. 2005; Gamble et al. 2008; Rauscher et al. 2008) suggest that the North Atlantic Subtropical High pressure system and its seasonal cycle forces regional-scale descent over Central America and southern Mexico during the MSD through large-scale stability (Wang 2007) or wind shear (Angeles et al. 2010). Other studies have instead suggested that the horizontal advection of moisture, modulated by the Caribbean Low-Level Jet (CLLJ), is the leading factor causing the MSD (see e.g. Herrera et al. 2015; Hidalgo et al. 2015; Maldonado et al. 2016). The CLLJ strength and direction have been shown to modulate the moisture transport across various spatiotemporal scales (Martinez et al. 2019; Perdigón-Morales et al. 2021). Therefore, this hypothesis suggests that the CLLJ strengthening creates an anomalous moisture divergence signal in the Eastern Pacific, west of Guatemala, which cause the relative decrease in precipitation, or the MSD onset (MSDO).

However, it remains unclear whether either mechanism adequately explains the timing and amplitude of the MSD. The proposed hypotheses have largely been developed independently, and there has been relatively little effort to diagnose and compare their predictions within a common framework (García-Franco et al. 2023). In this context, the MSE budget provides a useful framework for evaluating the leading-order processes associated with the MSD in a unified way. For example, MSE-based measures of large-scale stability have proven useful in other tropical regions (Varuolo-Clarke et al. 2019; Schwarzwalld et al. 2023), while decomposing the relative roles of horizontal and vertical MSE advection (Hill et al. 2017; Chadwick et al. 2026) offer a comprehensive way to assess the moisture-transport hypothesis associated with the CLLJ.

Here, we use the column MSE budget diagnosed in two reanalysis datasets to test these hypotheses and to determine whether the MSD is better explained by changes in large-scale stability, by horizontal drying, or by their combined effects on the subseasonal MSE balance.

2 Data and methods

2.1 Reanalysis and precipitation data

This study uses two reanalysis datasets, from the European Centre for Medium-Range Weather Forecasts (ECMWF) we use Reanalysis v5 (fifth generation) known as ERA5 (Hersbach et al. 2020) and the Japanese Reanalysis for Three Quarters of a Century (JRA-3Q) developed by the Japan Meteorological Agency (JMA) (Kosaka et al. 2024). For both reanalyses, the fields used were zonal and meridional

Table 1 Observational data used in this study.

Dataset	Variable	Source data	Period
TRMM	precipitation	Satellite (gauge-adjusted)	1999-2019
CMORPH CRT	precipitation	Satellite (gauge-adjusted and bias corrected)	1999-2024
GPCP	precipitation	Satellite + gauge analysis over land	1998-2023
CHIRPS	precipitation	Station and satellite	1981-2024
ERA5	u, v, q, sp , SH , $\langle Q_r \rangle$, LH , T , z , ω	Reanalysis	1981-2024
JRA3Q	u, v, q, sp , SH , $\langle Q_r \rangle$, LH , T , z , ω	Reanalysis	1981-2024

wind velocity (v), temperature, specific humidity, geopotential and vertical velocity, in addition to sensible (SH) and latent (LH) heat fluxes, and column radiative heating (Q_r). The period of 1979-2024 was used for both datasets.

ERA5 data was downloaded at a $0.75 \times 0.75^\circ$ resolution and daily frequency at all 29 levels in the troposphere (up to 100 hPa). In the case of JRA3Q, the data was downloaded as daily-means at a 1.25° resolution. From both reanalysis, the variables downloaded at pressure levels were the zonal (u) and meridional (v) components of the wind as well as the vertical velocity (ω), air temperature (T), geopotential height (z) and specific humidity (q). In addition, surface fields such as sea-level pressure (sp) and surface heat fluxes, both sensible (SH) and latent (LH) were downloaded.

For precipitation we use estimates from four different satellite-based products. These products are: (1) the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA; 3B42 v7.0; Huffman et al. 2007), available from 1998 until 2019 (Huffman 2016); (2) the Climate Prediction Center morphing technique (CMORPH; 1999-2023; Xie et al. 2017; NOAA CDR Program 2022); (3) the Global Precipitation Climatology Project (GPCP v1.3; 1998-2022; Huffman et al. 2001; Adler et al. 2016) and (4) the Climate Hazards group Infrared Precipitation with Stations (CHIRPS v2; 1981-2024; Funk et al. 2015) dataset. The original resolutions of these datasets are 0.25° for TRMM and CMORPH, 0.05° for CHIRPS and 1° for GPCP.

All the precipitation datasets were regridded to a common 1° grid. In addition, in throughout most of this study, see e.g., Figure 1, precipitation results are shown using the average across all four datasets. See table 1 for a summary of the data used in this study.

2.2 MSE budget calculation

The MSE, also denoted as h is given by:

$$h = Lq + C_p T + gz = Lq + s \quad (1)$$

where C_p is the heat capacity at constant pressure, T is the air temperature, L is the latent heat of vaporization, q is the specific humidity and s is the dry static energy.

The vertically integrated budget in pressure coordinates is frequently written (e.g. Back and Bretherton 2006; Inoue and Back 2015; Annamalai 2020) as:

$$\left\langle \frac{dh}{dt} \right\rangle = - \left\langle \vec{u} \cdot \nabla_p h \right\rangle - \left\langle \omega \frac{\partial h}{\partial p} \right\rangle + D, \quad (2)$$

where $\langle \cdot \rangle$ denotes a mass-weighted vertical integral in pressure coordinates from the local surface pressure $p_s(x, y, t)$ down to the top of the integration layer $p_t = 100$ hPa,

$$\langle A \rangle \equiv \frac{1}{g} \int_{p_t}^{p_s} A dp. \quad (3)$$

The value of a field A at the surface is obtained by linear interpolation in p between the two levels that bracket p_s .

The term D denotes the diabatic forcing term of MSE which is given by the surface fluxes and the radiative heating of the column:

$$D = LH + SH + \langle LW \rangle + \langle SW \rangle = SF + \langle Q_r \rangle \quad (4)$$

where SH and LH are the surface turbulent sensible and latent heat fluxes, respectively, adding up to total surface heat fluxes (SF). The heating rate term, in both ERA5 and JRA3Q, was inferred

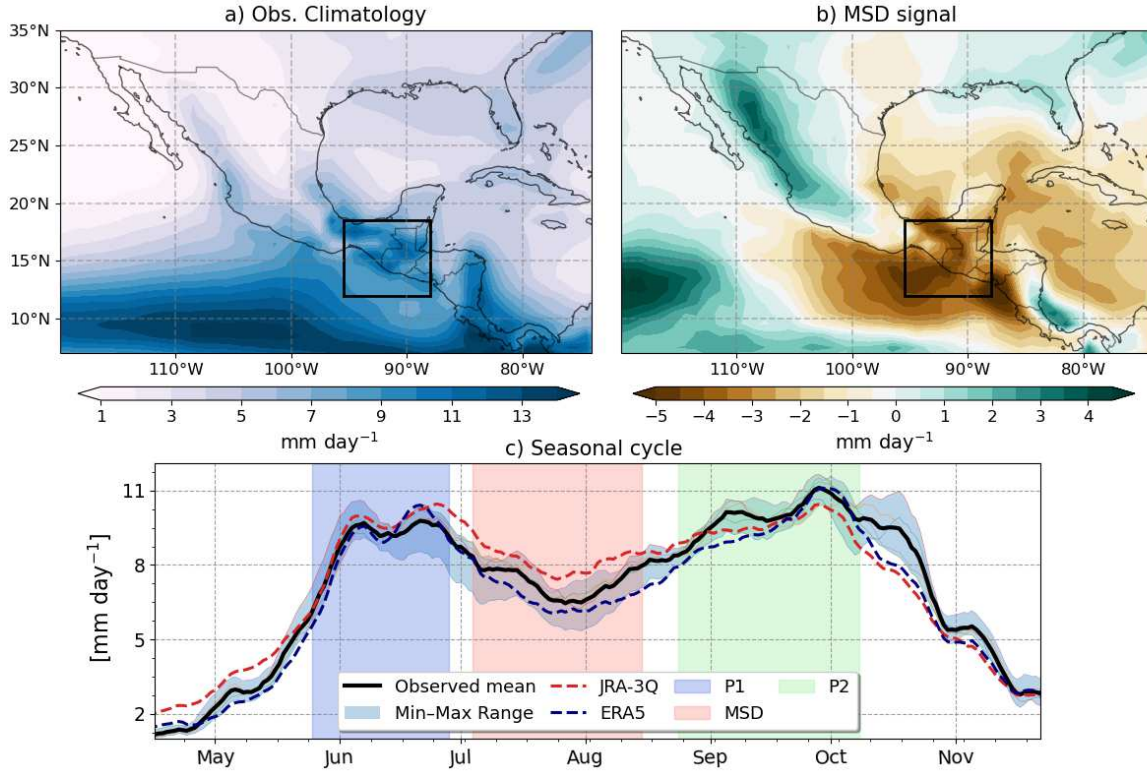


Fig. 1 a) Observed precipitation climatology during the rainy season from the observed blend. b) The MSD signal defined as the difference between the two peaks of precipitation minus the MSD period. c) Seasonal cycle of precipitation (area-averaged over the region denoted in a)) in observed and reanalysis datasets.

from the total net flux of radiation from the surface and at the top of atmosphere, as in previous studies (Kiranmayi and Maloney 2011; Fan and Dommenget 2021). LW and SW are the longwave and shortwave column-integrated heating rates, respectively which added up give the total column heating $\langle Q_r \rangle$.

In addition to the MSE budget diagnostics, we compute a measure of subcloud buoyancy defined as the difference between the surface MSE and the saturated MSE at a representative free-tropospheric level,

$$B = h_s - h^*(p_{ft}), \quad (5)$$

where h_s is the MSE evaluated at the surface and $h^*(p_{ft})$ is the saturation MSE at pressure level p_{ft} , typically in the free troposphere. This metric provides a measure of convective instability: when $B > 0$, a surface parcel possesses sufficient energy to saturate the free troposphere, favoring deep convection, while a larger B indicates a more unstable column (Cook and Seager 2013; Williams and Pierrehumbert 2017; Schwarzwald et al. 2023).

We evaluate h^* at $p_{ft} = 650$ hPa, rather than the more commonly used 700 hPa, to account for the complex topography of the study region. High terrain over southern Mexico and Guatemala means that lower free-tropospheric levels can intersect the orography in parts of the domain. At 650 hPa, we are consistently above the surface. In addition to the buoyancy metric B , we compute two forms of gross moist stability (GMS), denoted by Γ ; see the Supplementary Information for details.

2.3 Determining the timing of the MSD

There are several methods to determine the dates when the MSD begins (MSDO) and ends (MSDE) on daily to monthly timescales (Zhao and Zhang 2021; Maurer et al. 2022). In this study, we use the wavelet transform method proposed in García-Franco et al. (2021). This method uses a precipitation time-series, either area-averaged or at the grid scale, that is then filtered by the convolution of the Haar wavelet at different temporal scales, leading a resulting time-series of wavelet transform coefficients. These coefficients represent the relative change of precipitation averaged over the temporal scales chosen such that the rainy season onset, for example, is defined as the date of the maximum of the sum

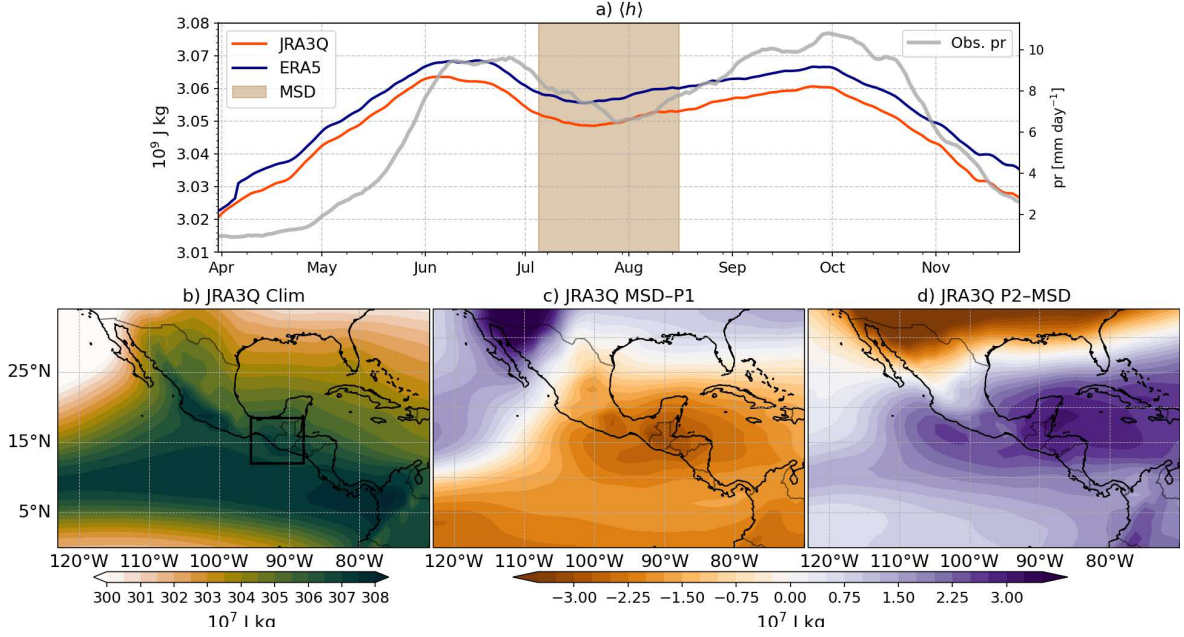


Fig. 2 a) Seasonal cycle of column-integrated MSE ($\langle h \rangle$ in J kg^{-1}) and precipitation, b) rainy season (May 16-Oct 25) climatology of $\langle h \rangle$ in JRA3Q. Also shown are the differences in $\langle h \rangle$ between c) MSD-P1 and d) P2-MSD periods. The seasonal cycle in a) was computed over the area-mean values in the box illustrated by panel b.

of these coefficients, which means that onset is the date where the maximum increase of precipitation is diagnosed. Similarly, the retreat is diagnosed as the date of the minimum value of this sum.

Based on the wavelet transform method and the determination of the dates of rainy season onset, retreat and MSDO and MSDE, we split the rainy season into three different stages: the first peak of precipitation (P1), the MSD and the second peak of precipitation (P2). These periods are illustrated in Figure 1. In addition, we also use the definition of rainy season, as the period between onset and retreat for each year, to conduct several analyses. This rainy season starts on average on May 16 and ends on October 25 (García-Franco et al. 2025).

3 Results

We begin by assessing whether the MSE budget framework captures the observed spatial and temporal variability of the MSD well enough to serve as a useful diagnostic tool. We then use this framework to examine two leading explanations for the MSD: changes in large-scale stability and changes in horizontal MSE advection. Finally, we synthesize these results using the column-process framework to evaluate whether the seasonal evolution of the MSE budget provides a more coherent interpretation of the MSD than any hypothesis considered in isolation.

3.1 The MSE budget across the MSD stages

To explore the spatial and temporal variability of the integrated MSE, and diagnose whether this diagnostic is related to precipitation variability we focus on a region (shown in Figure 2a) where the MSD signal has been shown to be large (García-Franco et al. 2021).

Figure 2 shows the spatial and temporal variability of $\langle h \rangle$, comparing both reanalysis datasets. The column-integrated MSE ($\langle h \rangle$) exhibits a bimodal seasonal cycle, with peaks that align with the peaks of precipitation and a local minima that occurs approximately a week before the MSD precipitation minimum. Both reanalyses generally agree on the magnitude, spatial distribution and seasonality of $\langle h \rangle$.

The spatial pattern of the JJAS mean $\langle h \rangle$ (Fig. 2b) shows higher values over the ocean, maximizing over the position of the ITCZ. Over land, the maximum values of integrated MSE are found along the western Mexican coast. Between the MSD and the first peak (P1), the $\langle h \rangle$ decreases significantly across Mesoamerica, including the Caribbean and the easternmost Pacific oceans. During the second peak (P2), the $\langle h \rangle$ increases again, with a corresponding decrease of the variable over the Mexico-USA border regions, depicting the end of summer. The spatial pattern of the $\langle h \rangle$ signal, associated with

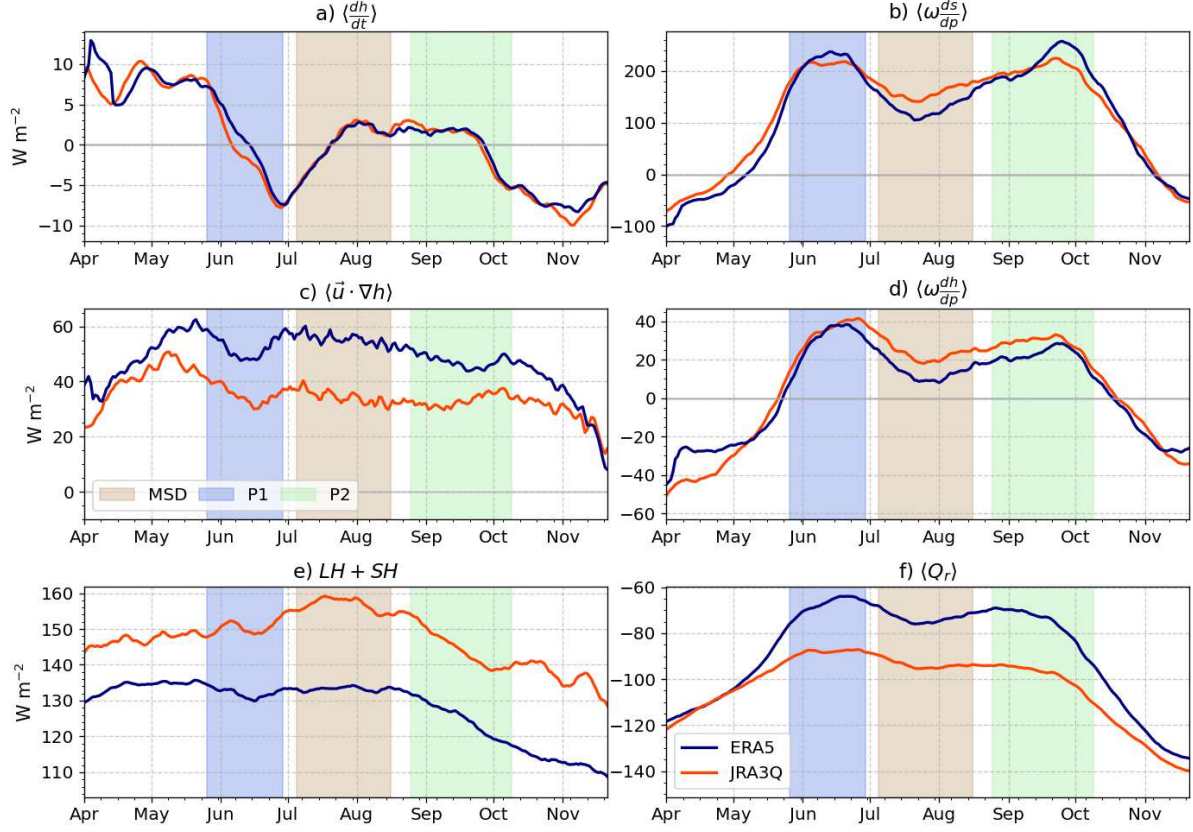


Fig. 3 Seasonal cycle of the a) time tendency of column-integrated MSE ($\langle h \rangle$ in J kg^{-1}), b) vertical advection of dry static energy, c) horizontal and d) vertical advection of MSE, e) total turbulent fluxes and f) radiative heating ($\langle Q_r \rangle$)

the MSD, is wider than the precipitation signal. However, the signal in $\langle h \rangle$ maximizes in the study region, similar to the MSD signal that has been shown for other variables such as outgoing-longwave radiation, specific humidity and moisture convergence (García-Franco et al. 2023; Zhao et al. 2020).

In short, Figures 2 and S1 shows that composite mean column-integrated MSE maximizes throughout the region during the two peak precipitation periods and noticeably decreases throughout Mesoamerica during the MSD. This result implies that the seasonal cycle of $\langle h \rangle$ resembles the seasonal cycle of precipitation.

To further diagnose the nature of the relationship between column-integrated MSE and precipitation, Figure S2 show that there are significant positive correlations between $\langle h \rangle$ and precipitation [mm day^{-1}] on both interannual and daily timescales. Although a modest relationship on interannual timescales, this result suggests that years with higher MSE are generally years with more precipitation. On daily timescales, there is a higher and significant positive correlation ($r = 0.58$) between the variables that maximizes at lag 0 days. This means the relationship between the variables is synchronous and highlights that day-to-day variability in column integrated MSE is associated with precipitation, consistent with previous studies (Inoue et al. 2021; Schwarzwald et al. 2023).

Next, explore the seasonal cycle of the MSE budget terms (eq. 2) in Figure 3, i.e., the time tendency of column-integrated MSE ($\langle h \rangle$) and the vertical advection of dry static energy ($\langle \omega \frac{\partial s}{\partial p} \rangle$), a proxy of the strength of the circulation (Inoue et al. 2021). The $\langle h \rangle$ term (a) show that column MSE increases prior to the onset of the rainy season, and during the first days of the rainy season. However, this term decreases through the first peak of precipitation leading to minima found around the beginning of the MSD. During the MSD, the term becomes positive again, increasing column MSE.

The vertical advection of dry, and moist (panels b,d) static energy shows a clear two-peak structure with the peaks and minima coinciding with the peaks of precipitation and the MSD, highlighting the link between the circulation strength and the precipitation rates. The horizontal advection (c) shows an increase during the rainy season peaking during the MSD, but with no clear bimodal structure. The radiative heating terms (panel f) reflect how cloud radiative effects, both on longwave and shortwave interact with the seasonal march of insolation as well as convective activity (García-Franco et al. 2023). These results show that column cooling increases during the MSD, due to both the decrease in the

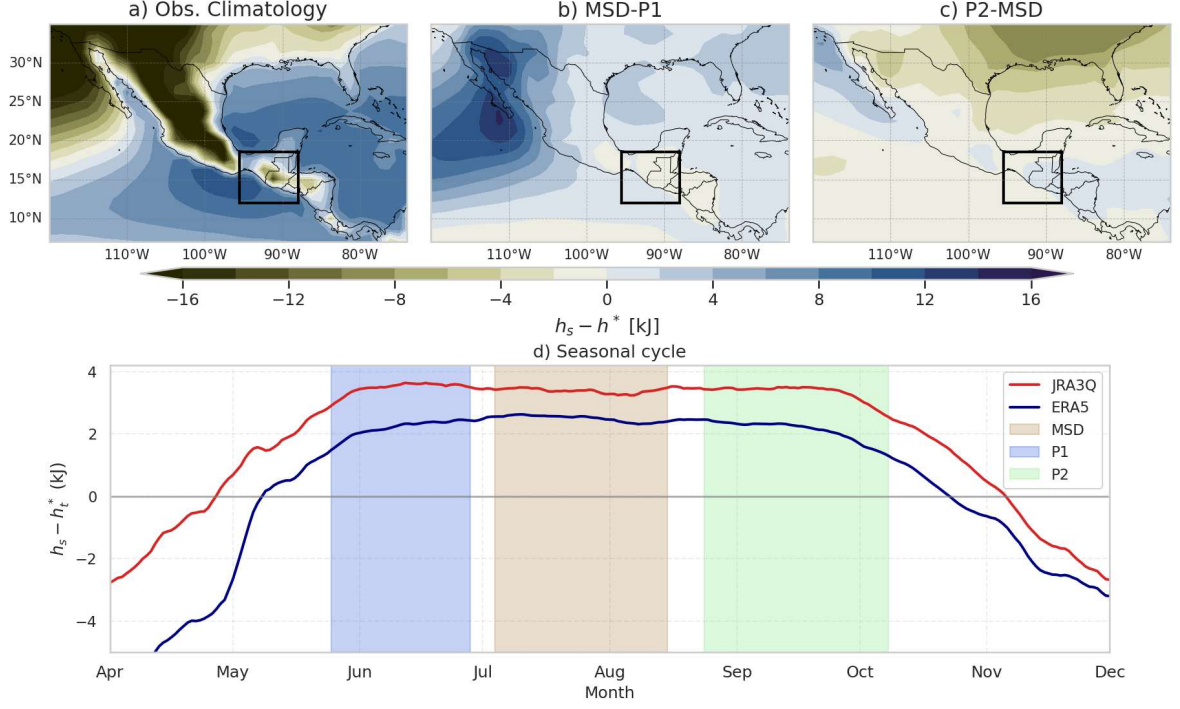


Fig. 4 Composite-mean stability ($h_s - h^*$) averaged over the MSD box for the a) climatological rainy season mean and the differences between b) MSD-P1 and c) P2-MSD. The seasonal cycle of $h_s - h^*$ is shown in d).

LW CRE but also the reduction in incoming solar radiation due to the declination angle (Karnauskas et al. 2013).

Overall, the figure shows that the seasonal cycle of the budget terms appears temporally related to the MSD precipitation signal, but the specific roles of these terms in shaping the precipitation variability. Both reanalysis datasets agree well in most budget terms with each other, except for the surface turbulent fluxes, which are higher in JRA3Q compared to ERA5. Similarly, the radiative net cooling and horizontal advection terms are higher in ERA5 relative to JRA3Q, indicating compensating processes leading to a similar source term.

This section showed that the spatial and temporal variability of column-integrated MSE follows closely the temporal and spatial behaviour of precipitation in the MSD region. In particular, column-integrated MSE increases during the peaks of precipitation over the broad Intra-Americas Seas region, and decreases during the MSD. The vertical advection terms, which are highly dominated by ω and therefore a measure of the strength of the circulation are also weaker during the MSD and stronger during the peaks of precipitation. Overall, the MSE budget seems a suitable tool to explore the mechanisms that underpin the MSD.

3.2 The large-scale stability hypothesis

This section examines the large-scale stability hypothesis which argues that regional forcing from the North Atlantic High creates anomalous subsidence during the MSD. First, we analyse the spatial and temporal variability of the bouyancy metric defined as the difference between the surface MSE and the saturated MSE at the 650 hPa level ($h_s - h^*$) (Fig. 4).

During the rainy season there is region-wide instability ($h_s - h^* > 0$) over the ocean surrounding the study region. However, there seems to be little variation in this stability metric in the MSD region throughout the rainy season. After the onset of the rainy season, the atmosphere becomes unstable but there is relatively little change in the magnitude of B during the MSD. This lack of a change in this stability metric could be because B is only a measure of undilute parcel buoyancy, such that this metric does not consider any differences in convective stability associated with entrainment of dry environmental air. In other words, this does not consider the saturation deficit in the midtroposphere because it may be plausible that while temperature remains constant in the free troposphere, the specific humidity does not, and drier environmental air may be detrimental to convective activity.

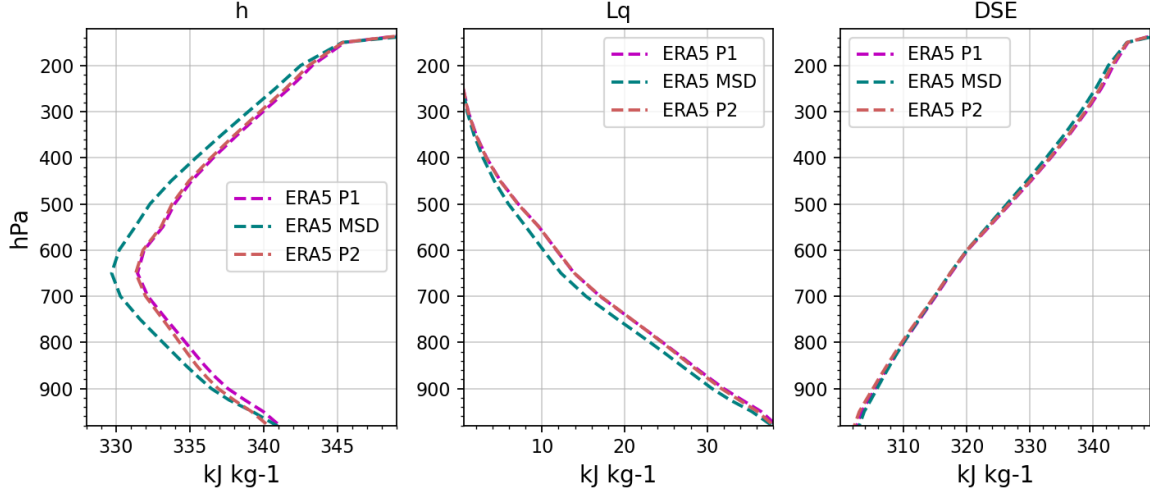


Fig. 5 Composite-mean profiles, averaged over the MSD region, of a) MSE or h , b) Lq and c) dry static energy for ERA5 data. The profiles are also binned for their stage in the rainy season (P1, MSD and P2).

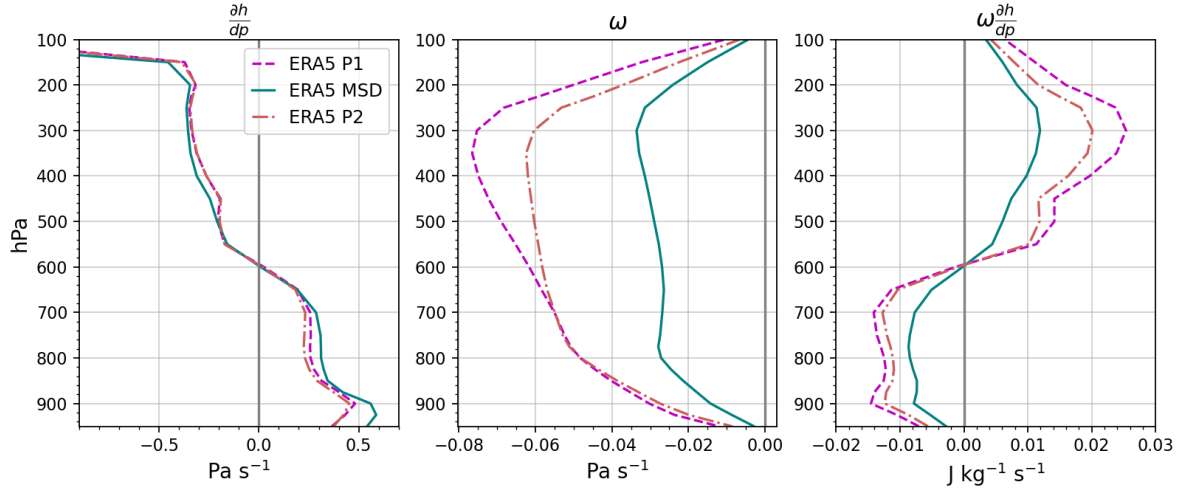


Fig. 6 Composite-mean profiles, averaged over the MSD region, of the a) vertical MSE gradient $\frac{\partial h}{\partial p}$, b) the vertical velocity ω and c) the vertical advection term $\omega \frac{\partial h}{\partial p}$ for ERA5 data. The profiles are also binned for their stage in the rainy season (P1, MSD and P2).

To better characterize the vertical structure of MSE and its seasonal cycle, Figure 5 shows the composite mean profiles of MSE split into the s and the Lq term. The profiles show a decrease in mid-tropospheric MSE during the MSD associated with a decrease in humidity. However, DSE seems unchanged, which means that the dry static stability does not vary with the different stages of the rainy season. In other words, the temperature profile remains relatively unchanged throughout the rainy season. The profiles of Lq demonstrate that while the measure of $h_s - h^* > 0$ changes little within the season, the 500-800 hPa layer dries.

These results, combined, may mean that if humidity decreases in the midtroposphere but temperature stays the same, the environment is further away from saturation. Since the dry static energy profile remains largely unchanged throughout the rainy season, the reduction in mid-tropospheric MSE during the MSD can be attributed to a decrease in the latent energy term Lq . When humidity decreases while temperature remains constant, the environment moves further from saturation. The subcloud buoyancy remains approximately constant, indicating that surface-based instability is maintained but that the drier free troposphere might act to suppress deep convection through enhanced entrainment dilution of rising parcels (Morrison et al. 2021).

The composite vertical profiles of the vertical advection terms (Fig. 6) clarify the nature of this change. The vertical MSE gradient $\partial h/\partial p$ is nearly identical across P1, MSD and P2, confirming that the thermodynamic structure of the column varies little through the rainy season, consistent with previous studies (Inoue and Back 2015; Bui et al. 2016). The vertical velocity, in contrast, changes in both magnitude and shape. During P1 and P2, ascent peaks in the mid-troposphere, around 300–400 hPa, whereas during the MSD the profile is both weaker and more bottom-confined, with the largest relative reduction occurring between 300 and 600 hPa. Because $\partial h/\partial p$ is essentially unchanged, the vertical MSE export term $\omega\partial h/\partial p$ inherits this change directly: the deep export through the 250–550 hPa layer largely disappears during the MSD, while the low-level import in the 600–900 hPa layer is maintained. This is a change in the vertical structure of the overturning circulation, not only a uniform weakening of ω .

These results are consistent with the relationship between free-tropospheric humidity and convective activity, whereby a drier environment inhibits precipitation even in the presence of sufficient surface buoyancy (Bretherton et al. 2004; Holloway and Neelin 2009). Similarly, the vertical and temporal variability of the vertical advection of MSE (Fig. 6) shows that the vertical gradient of h ($\frac{\partial h}{\partial p}$) varies little within the rainy season and most of the vertical advection changes are due to the variations of ω , consistent with previous studies (Inoue and Back 2015; Bui et al. 2016).

Overall, this section has aimed to diagnose the large-scale stability hypothesis, with little evidence found to support it. Rather than a change in dry static stability, our results point to two other changes during the MSD: a drying of the midtroposphere, which moves the environment further from saturation, and a change in the vertical structure of the ascent, which becomes shallower and less effective at exporting MSE from the column. Neither is a stability change in the classical sense, and both suggest that the MSD is better characterized by how the circulation ventilates the column than by whether convection is permitted at all.

3.3 The horizontal advection hypothesis

Previous horizontal moisture-budget studies have suggested that the CLLJ plays an important role in modulating regional moisture transport and precipitation during the MSD (Durán-Quesada et al. 2017; Martinez et al. 2019). Here, we examine whether the horizontal advection of MSE exhibits changes consistent with this hypothesis. In particular, we evaluate the seasonal evolution of the horizontal advection of Lq , its magnitude relative to vertical MSE advection, and the extent to which the total horizontal advection is controlled by its dry versus moist contributions and by its zonal versus meridional components.

Figure 7 shows the seasonal cycle of the horizontal advection of MSE, including the decomposition of the total horizontal advection into its contribution by the dry and Lq terms and zonal and meridional components. The horizontal advection of MSE is positive throughout the rainy season and is dominated by the moisture term Lq . In contrast, the contribution from the dry static energy advection is relatively low, especially in ERA5, and varies little throughout the rainy season. The advection of Lq increases only very slightly around the onset of the MSD, more so in ERA5 than in JRA3Q, consistent with the lack of noticeable subseasonal changes in the full term $\langle \vec{u} \cdot \nabla h \rangle$.

The decomposition of the horizontal advection of MSE into zonal and meridional components (Figs. 7d-e) provides a clearer picture into the variations of the total term. These results illustrate how the zonal and meridional components mirror each other over the rainy season. While the meridional term ($V\frac{\partial h}{\partial y}$) decreases after the onset of the rainy season, turning negative during June, the zonal component increases sharply during the first peak of precipitation reaching a maximum value around the time of the onset of the MSD. The decomposition results show that the very slight increase (+5–8 W m^{-2}) in MSE horizontal advection around the MSDO date is mostly due to the zonal advection of moisture increasing, which is consistent with the CLLJ hypothesis. However, this increase in the zonal component is mirrored by a decrease in the meridional component which leads to a net small change in $\langle \vec{u} \cdot \nabla h \rangle$. In addition, this column integrated estimate of the horizontal advection term does not decrease noticeably after the MSD end, suggesting that this column estimate is not clearly related to the MSD precipitation variations.

To provide further context into the vertically-integrated quantities shown before, Figure 8 shows the vertical profiles of the MSE horizontal advection terms, averaged over the MSD region. The horizontal advection of MSE is positive throughout most of the troposphere in all periods of the rainy season. During the MSD, the horizontal advection in the 800–600 hPa layer increases substantially, nearly doubling the values found during the wetter P1 and P2 periods. This increase in the MSE horizontal

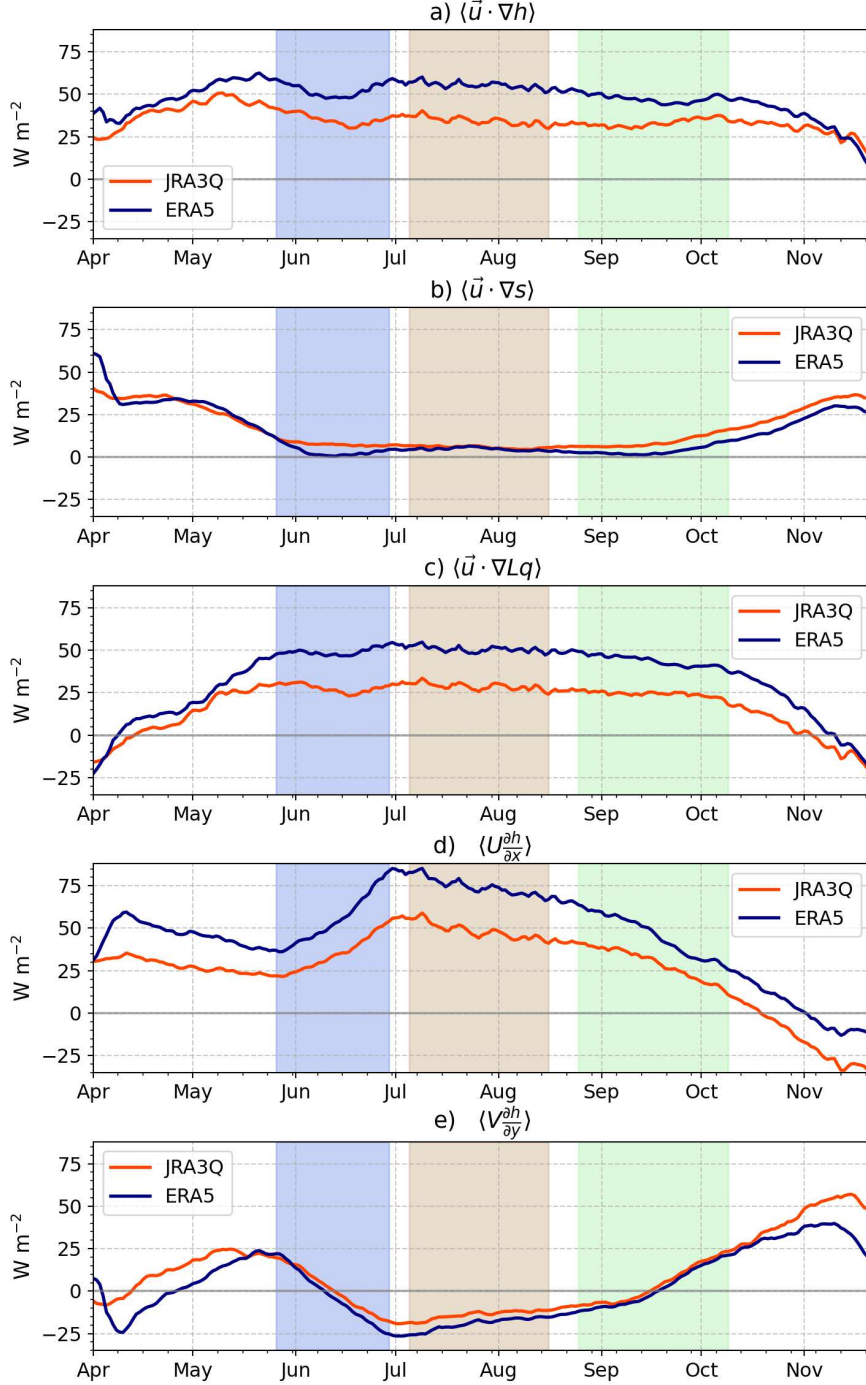


Fig. 7 As in Figure 2, but for the vertically-integrated, area-averaged, horizontal advection terms, including a) $\langle \vec{u} \cdot \nabla h \rangle$, b) the DSE horizontal advection and the moist part only $\langle \vec{u} \cdot \nabla Lq \rangle$. The seasonal cycle of the d) zonal and e) meridional components of the MSE are shown.

advection in the lower troposphere during the MSD arises mostly from an increase in the zonal component of the advection term, despite a negative, yet smaller opposite, contribution by the meridional term throughout the 850-400 hPa layer. In other words, a net increase in horizontal MSE advection is diagnosed in the lower troposphere as the result of the sum of the positive zonal component and negative meridional component contributions.

Furthermore, Figure 9 shows spatial maps of the vertically integrated horizontal MSE advection $\langle \vec{u} \cdot \nabla h \rangle$ as well as the term $\vec{u} \cdot \nabla h$ calculated at the 700 hPa level. During the rainy season, broadly, the continental region is characterized by positive MSE horizontal advection. However, $\langle \vec{u} \cdot \nabla h \rangle$ varies across the stages of the rainy season, increasing over the Yucatan Peninsula and Central America during the MSD, while decreasing over the oceanic region of the Gulf of Tehuantepec [95.2°W, 15.6°N] associated with the gap winds (Romero-Centeno et al. 2007).

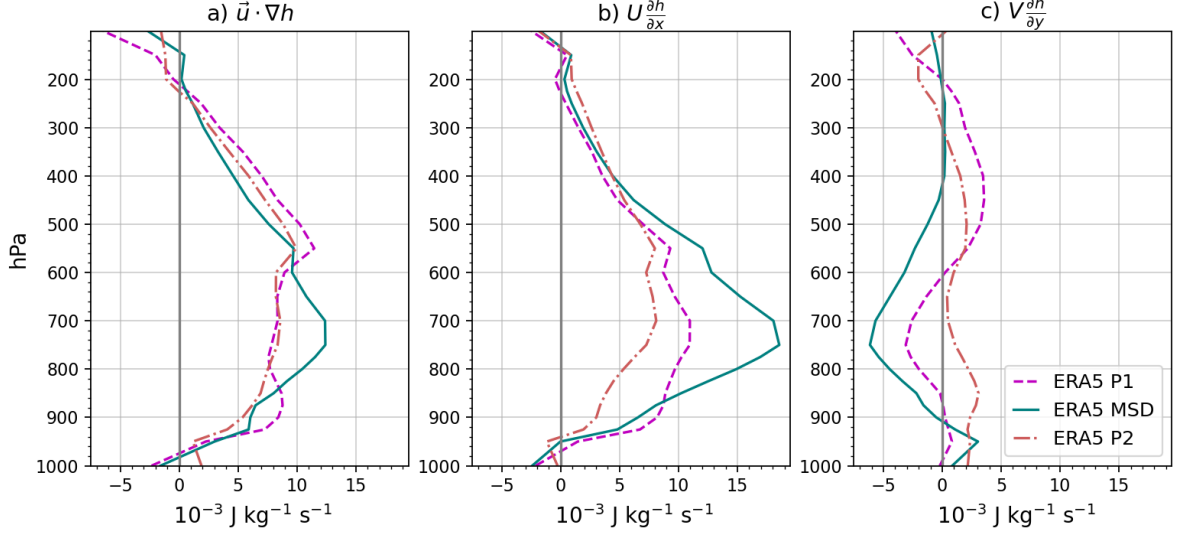


Fig. 8 As in Figure 5, but for the horizontal advection of MSE split into the a) total $\vec{u} \cdot \nabla h$, and b) the zonal $U \frac{\partial h}{\partial x}$ and c) meridional components $V \frac{\partial h}{\partial y}$.

This compensation between the positive MSD-P1 differences over the eastern, continental portion of the MSD region and the negative differences over the western, oceanic portion likely explains why the changes in the area-averaged term are relatively small. The land and ocean signals therefore need to be considered separately: over land, the MSD exhibits a clear increase in $\langle \vec{u} \cdot \nabla h \rangle$, drying the column, and this increase reverses into P2. We return to this land-only signal in Section 3.4, where we show that it is largely offset by a concurrent increase in surface turbulent fluxes. The drying signal over land is diagnosed in the 600-850 hPa layer, consistent with the vertical domain of influence of the CLLJ (Amador 2008; Hidalgo et al. 2015; Martinez et al. 2019). Whether the jet itself controls the timing of this drying is, however, less clear and is further explored in Section 3.4.

At 700 hPa (Fig. 9b, d), the easterly flow from the Caribbean changes considerably between P1 and MSD, perhaps explaining a big part of the increase in the MSE horizontal advection. In other words, the increase in the MSE horizontal advection in the study region during the MSD appears related to an increase in the zonal flow stemming from the CLLJ in the Caribbean Sea. However, it may be that changes in the advection are also contributed by changes in the gradient of MSE. At lower levels, such as 850 hPa (Fig. S3) the results are similar, except that changes in the zonal wind are stronger at lower levels, consistent with previous studies showing how the CLLJ magnitude and variability maximizes in the lowermost troposphere (950-to-850 hPa) (Hidalgo et al. 2015; Martinez et al. 2019).

The changes between the MSD and rainy season peaks in the $\langle \vec{u} \cdot \nabla h \rangle$ could be due to either changes in the winds, changes in the spatial gradient of MSE or both. To decompose the horizontal advection term for these two terms, we compute the difference between two stages (1 and 2), or MSD-P1 or P2-MSD as $\Delta(\cdot) = (\cdot)_2 - (\cdot)_1$. We assume an *exact* symmetric decomposition as follows:

$$\Delta(\vec{u} \cdot \nabla h) = \underbrace{\vec{u} \cdot \Delta(\nabla h)}_{\text{gradient contribution}} + \underbrace{\Delta \vec{u} \cdot \nabla h}_{\text{wind contribution}}, \quad (6)$$

albeit a numerical residual, which is found to be small ≈ 0 .

Figure 10 shows the contribution to changes the horizontal MSE advection between periods, where we find that $\langle \vec{u} \cdot \nabla h \rangle$ is influenced by both wind and gradient changes. In the MSD-P1 differences, the increase of MSE advection in the continental portion of the MSD shows a larger contribution by the winds but the contribution by changes in the MSE gradient is also positive and non negligible. The gradient contributions appear to be more relevant than the wind contributions over the easternmost Pacific Ocean. In the P2-MSD differences, the negative differences over land in the total horizontal MSE advection are also mostly contributed by the wind changes, but there are relevant contributions from changes in the MSE gradient.

Lag-lead composites (Fig. S4) show that precipitation sharply decreases (leads -4 to +4) when the MSD is starting (MSD Onset) which is associated with a sharp and nearly synchronous increase in the horizontal MSE advection, driven mostly by the zonal and humidity components. The opposite is

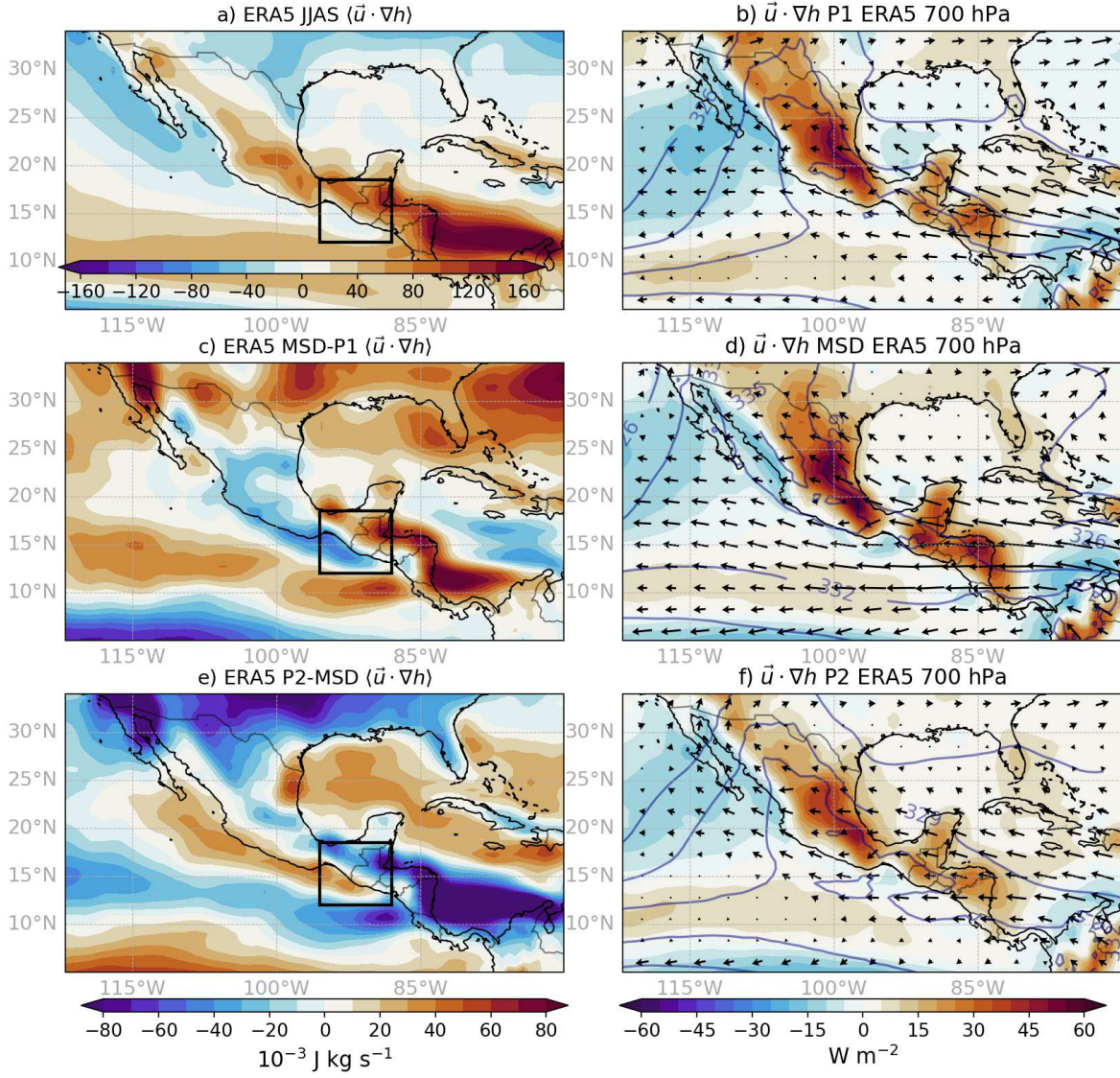


Fig. 9 Composites of (left) vertically integrated horizontal MSE advection $\langle \vec{u} \cdot \nabla h \rangle$ in ERA5. The rainy season climatological values are shown in panel a (see inset colorbar), whereas panels c,e) show temporal differences between stages of the rainy season (MSD-P1 and P2-MSD, respectively). Also shown (panels b, d and f) are composites of 700-hPa horizontal advection of MSE $\vec{u} \cdot \nabla h$ for ERA5 depicting the mean values over each stage of the rainy season. The vectors show the wind speed and direction, whereas the blue contour lines show the absolute values of MSE [10^3 kJ] at the same 700-hPa level.

found during the end of the MSE (MSDE) indicating that the zonal component of the MSE advection is largely correlated with the precipitation changes at the specific dates where the MSE begins and ends.

Overall, horizontal MSE advection increases modestly into the MSD and this change is driven primarily by the zonal moisture-advection component in the lower troposphere, broadly consistent with the CLLJ hypothesis. However, its seasonal amplitude is small and its evolution does not fully mirror the precipitation increase after the MSD, into the second peak of precipitation, suggesting that horizontal advection alone is insufficient to explain the full MSD cycle, specially during the second part of the rainy season.

3.4 The land column MSE balance during the MSD

The previous sections show that neither changes in large-scale stability nor horizontal MSE advection alone fully explain the seasonal evolution of the MSD. In this section, we focus on land grid cells within the MSD region because the role of surface turbulent fluxes may differ over land and ocean. Over ocean, turbulent surface fluxes may be tightly coupled to convection through wind-induced surface exchange and convective gustiness (Emanuel 2007). Over land, latent and sensible heat fluxes are

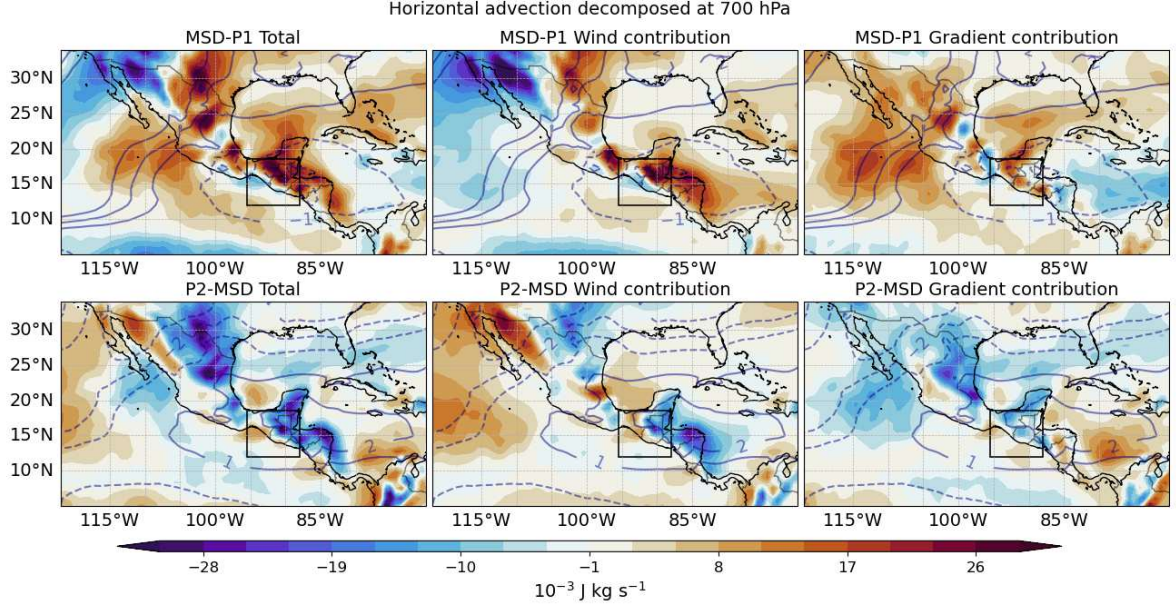


Fig. 10 Composite-mean differences at 700 hPa between rainy periods and the MSD in the average horizontal advection of (left) MSE $\bar{u} \cdot \nabla h$. The total term is decomposed into differences arising from the changes in the winds Δu (middle) or from changes in the gradient of MSE $\Delta \nabla h$

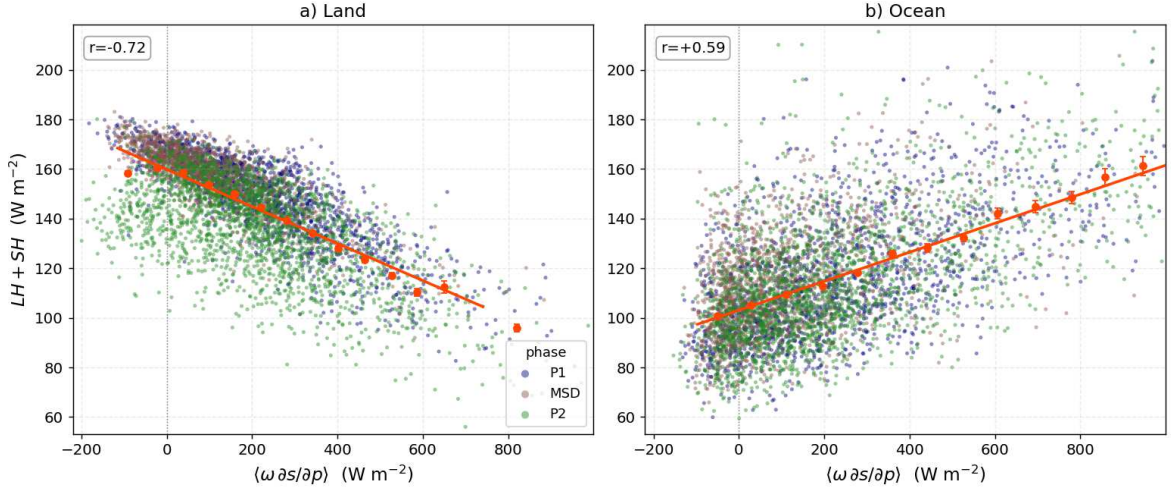


Fig. 11 Scatter plot of the coupling between surface fluxes and convection on daily timescales. Daily mean surface fluxes are plotted against convective strength $\langle \omega \partial s / \partial p \rangle$ over a) land and b) ocean grid points within the MSD region, for ERA5.

instead constrained by soil moisture and temperature, vegetation, land-surface state, etc. (Miralles et al. 2025).

For this reason, here we investigate first whether surface turbulent fluxes act as an external forcing on the land column, or whether they form part of the internally coupled convective response. Then, the MSE budget over land only is examined to diagnose how this change in the column process combines with the horizontal export and the surface turbulent fluxes over land.

Figure 11 compares the relationship between surface fluxes and convective strength over land and ocean. Over the ocean, Inoue et al. (2021) show that surface fluxes are intertwined with convection through the wind-induced circulation associated with convection and the subsequent air-sea flux exchange, in a positive feedback. This is supported by the positive correlation found here ($r = +0.59$): the stronger the convection, the larger the surface fluxes. Over land, they posited that the inclusion of this term in the column process may no longer be valid because surface fluxes could be decoupled from convection. We instead find that surface fluxes over land in the MSD region are, if anything, more strongly coupled to convective strength ($r = -0.72$), but with the opposite sign.

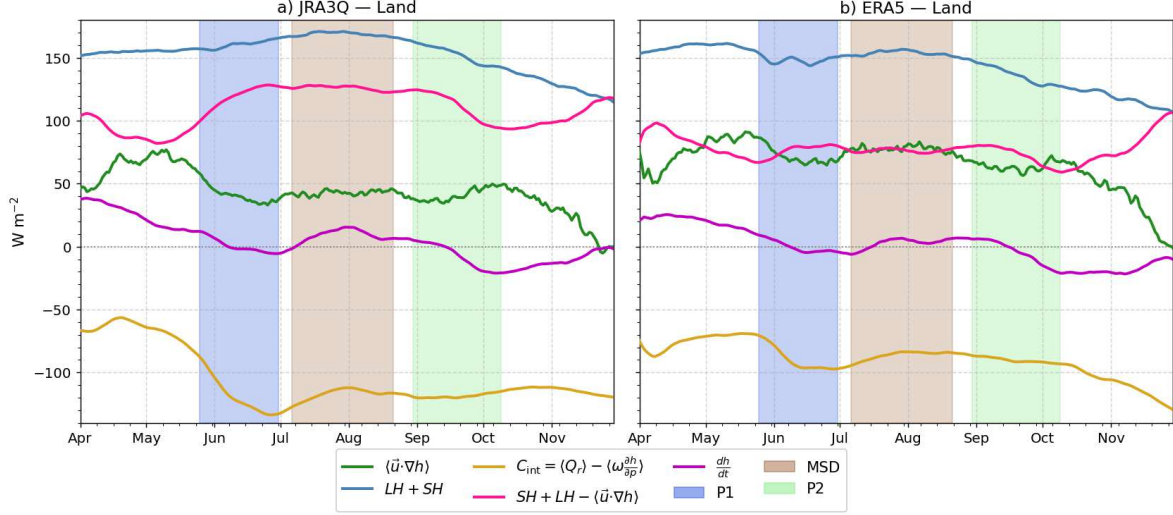


Fig. 12 Seasonal cycle of the column MSE budget terms over land within the MSD region, for (a) JRA3Q and (b) ERA5: the internally coupled column process C_{int} , the horizontal advection $\langle \vec{u} \cdot \nabla h \rangle$, the surface turbulent fluxes $LE + SH$, and the resulting MSE tendency. For ERA5 the rainy-season mean of the tendency, -12.9 W m^{-2} , which reflects the non-closure of the offline budget, is removed; JRA3Q is shown unadjusted. Shading marks the first peak (P1, blue), the midsummer drought (brown), and the second peak (P2, green).

This result suggests that stronger convection is associated with weaker surface fluxes, plausibly because cloud radiative effects shape the surface energy balance. This is in agreement with previous results showing an increase in incoming shortwave radiation at the surface during the MSD, associated with a reduction in convective cloud (García-Franco et al. 2023). The implication for the budget is that over land the surface flux response damps convection rather than amplifying it, so grouping the surface fluxes together with the radiative and vertical advective terms, as is appropriate over ocean, may not be justified here.

Starting from the column-integrated MSE budget (Equation 2), we define, for the land portion of the MSD region, the internally coupled column process as

$$C_{\text{int}} \equiv \langle Q_r \rangle - \left\langle \omega \frac{\partial h}{\partial p} \right\rangle, \quad (7)$$

which collects the terms associated with the convecting column itself: radiative heating or cooling, and the vertical MSE export by the overturning circulation. The budget can then be written as

$$\frac{\partial \langle h \rangle}{\partial t} \simeq C_{\text{int}} + LE + SH - \langle \vec{u} \cdot \nabla h \rangle, \quad (8)$$

where the horizontal MSE export $\langle \vec{u} \cdot \nabla h \rangle$ is the only term treated as external to the column. Surface fluxes are kept as a separate term rather than folded into C_{int} . The column gains MSE when the column process and the surface flux input together exceed the horizontal export, and loses MSE otherwise. This rearrangement of the budget should be read as an energetic consistency condition for convective amplification or decay and not as an independent predictor of the MSE tendency.

The seasonal evolution of the budget terms differs somewhat when averaged over land only, compared with the all-grid-point estimate of Section 3.3 (Fig. 12). Both the horizontal advection and the surface fluxes increase into the MSD, and because they enter equation 8 with opposite sign, their contributions largely offset one another, leaving the net drying by these two terms approximately unchanged through the MSD.

The term that does change is the column process, which reaches a local minimum near the end of the P1 period, at the MSD onset (MSDO). This minimum reflects the change in the vertical structure of the ascent diagnosed in Section 3.2: as the profile becomes weaker and more bottom-heavy (Fig. 6), the circulation exports less MSE from the column even though the diabatic input changes comparatively little. The normalized vertical export, measured through the gross moist stability, falls accordingly, peaking during P1 and decreasing into and during the MSD, decreasing further in P2 (Fig. S5).

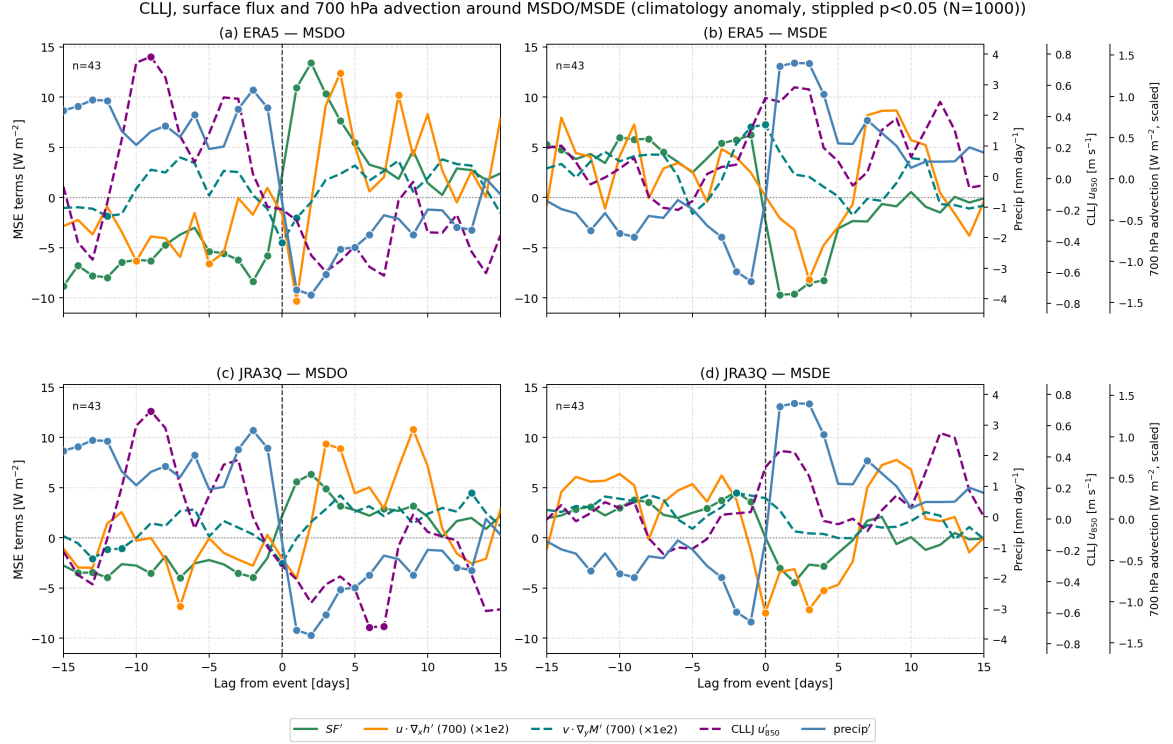


Fig. 13 Lag lead anomaly composites averaged over land grid points with respect to each year's dates of a-c) MSDO and b-d) MSDE for both reanalysis datasets. Plotted are the composites of surface fluxes (SF') the horizontal and meridional components of the horizontal advection, an index for the CLLJ at 850 hPa and precipitation. Significant anomalies to the 95% confidence level are denoted through a dot.

The resulting tendency shows a clear MSE-depleting period at the end of P1, a positive MSE-recharging period during the MSD, and a renewed decay after P2 associated with increased horizontal drying and reduced surface fluxes. The MSD is therefore not a period of column drying. Based on these results one could argue that the MSD is instead a period during which the column recharges while precipitation remains suppressed, and this recharge is what subsequently permits the second precipitation peak.

In Figure 13, the lag lead composites investigate more closely how these terms vary when selected around specific dates of MSDO and MSDE, for each individual year, then composited together. The results show a clear signal by precipitation sharply decreasing around the MSDO and the MSDE, as demonstrated in previous studies using the wavelet transform method (García-Franco et al. 2023). However, the meridional and zonal advection terms vary little and are rarely significant anomalies. Surface fluxes are anomalously lower than normal before the MSDO and quickly increase after the MSDO. Around the MSDE, an opposite behaviour characterized by higher than normal anomalies at negative leads are followed by negative anomalies after the end of the MSD.

The CLLJ index at 850 hPa appears to change very little, and no change is significant around these dates, confirming recent results (García-Franco et al. 2023; Zhao and Du 2026) indicating that a simple CLLJ index does not correlate well with the dates of the MSD. When considering how the column process and the external forcing, i.e., the balance of surface fluxes versus horizontal drying, results also show that only the column process changes significantly around the dates of MSDO and MSDE (Fig. S6).

No single term dominates the seasonal evolution of the land column MSE budget. The MSD emerges from the combination of a shallower, less efficient overturning circulation and a near-cancelling pair of horizontal export and surface flux changes. The two reanalyses agree on the sign of the seasonal change in every individual term, but differ in magnitude, most notably in the horizontal advection. Because the tendency is estimated as a difference between terms of comparable size, these differences are amplified in the residual, and the two datasets are therefore best compared through the timing of the tendency changes rather than their absolute values.

4 Discussion and conclusions

This study used the column MSE budget in two reanalysis datasets to reassess two commonly invoked explanations for the bimodal seasonal cycle of precipitation known as the Midsummer Drought (MSD). These hypotheses posed two arguments suggesting that the precipitation variability can be explained by a midsummer increase in large-scale stability and/or an enhancement of horizontal drying linked to the CLLJ. The main advance of this work is the evidence that the seasonal evolution of the MSD can be coherently interpreted within a column MSE framework and that perhaps through this lens the MSD can be understood compared to a paradigm with a single dominant mechanism. In the MSE budget framework, the MSD appears as the outcome of a seasonally evolving balance between diabatic MSE sources and the export of MSE by the large-scale circulation.

This analysis provides limited support for a simple large-scale stability explanation of the MSD. The buoyancy metric based on $h_s - h^*$ shows that the region remains broadly unstable throughout the rainy season, with only weak subseasonal variations. This suggests that the midsummer reduction in rainfall is not well explained by a marked increase in subcloud buoyancy inhibition or dry static stability. Instead, the vertical profiles show a clear reduction in midtropospheric humidity during the MSD, while dry static energy changes little.

In addition, the shape of the ω profile changes from top-heavy during both rainy periods to shallower and more bottom-confined during the MSD (Fig. 6), indicating a reduction in the efficiency with which the circulation exports MSE from the column (Inoue and Back 2017). The MSD is therefore better characterized by a drier free troposphere and a less efficient overturning circulation than by an increase in dry static stability.

The horizontal-advection results support, partially, the CLLJ hypothesis. Horizontal MSE advection is positive throughout the rainy season and is dominated by its moisture component, while the contribution from dry static energy advection remains comparatively small. Around the onset of the MSD, the total horizontal advection increases modestly, driven mainly by an enhancement of the zonal component in the lower troposphere, broadly consistent with previous work linking the CLLJ to anomalous moisture transport. However, this increase is limited in magnitude and does not fully reverse after the MSD ends, indicating that horizontal advection alone is insufficient to explain the full seasonal evolution of rainfall. In this sense, the horizontal circulation appears to contribute to the timing and maintenance of the MSD, but not to provide a complete explanation by itself.

Restricting the budget to land grid points clarifies how these terms combine. Over land, surface turbulent fluxes are strongly coupled to convective strength, but with the opposite sign to that found over ocean: stronger convection is associated with weaker fluxes, consistent with a cloud-shading control on the surface energy balance. The oceanic grouping of surface fluxes with the convection-coupled column process is therefore not appropriate over land. Both the horizontal MSE export and the surface fluxes increase into the MSD and, entering the budget with opposite sign, largely offset one another, so the net drying by these two terms changes little through the MSD. The term that does change is the column process, which reaches a local minimum near the MSD onset as the ascent profile weakens and shallows. The resulting tendency is negative through the end of P1, positive during the MSD itself, and negative again after P2. The MSD is thus, according to our results, not purely a period of column drying but one in which the column recharges while precipitation remains suppressed, which is what subsequently permits the second precipitation peak.

The lag composites reinforce the limited role of the horizontal circulation in setting MSD timing. Neither the zonal and meridional advection components nor a CLLJ index at 850 hPa shows significant anomalies around the MSD onset or end dates, confirming other studies (García-Franco et al. 2023). Whatever sets the timing of the MSD transitions is therefore not captured by a simple CLLJ index, or a more sophisticated decomposed circulation budget, even though the horizontal export does contribute to the seasonal-mean drying.

There are several important caveats and limitations to this study. Although ERA5 and JRA3Q agree on most of the qualitative results presented here, they differ in the magnitude of individual budget terms, most notably in the partitioning of the diabatic source term between surface turbulent fluxes and column radiative heating. This indicates that the broad seasonal balance is robust, but that caution is warranted when interpreting the absolute magnitude of the component terms. In addition, the MSE budget was computed offline from archived reanalysis variables rather than from native model tendency terms, so the budget does not close exactly. The residual likely reflects a combination of temporal averaging, interpolation, vertical discretization, and differences between archived diagnostics and the underlying model calculations. Accordingly, the results are most robust as a framework for

interpreting the relative seasonal evolution and covariability of the budget terms (Inoue et al. 2024), rather than as an exact quantitative closure of the full column MSE budget.

Overall, this study suggests that the MSD is better understood as a seasonally evolving energetic balance than as the consequence of either an increase in large-scale stability or an increase in horizontal drying alone. Neither classical hypothesis is supported in its simple form: dry static stability changes little, and the horizontal export increases too modestly, and with too little correspondence to the MSD dates, to account for the full seasonal cycle. What the MSE budget adds is a change in how the circulation ventilates the column. The overturning becomes shallower and less efficient at exporting MSE during midsummer, and because the surface flux and horizontal export changes largely cancel, the column recharges during the MSD even as precipitation is suppressed. This framework does not identify what ultimately sets the timing of the circulation change, which remains an open question, but it offers a more unified and physically consistent account of the maintenance and recovery of the MSD than the classical hypotheses considered separately.

Declarations

Funding. This study was supported by the SECIHTI Ciencia de Frontera program under project CBF-I-4.

Competing interests. The authors declare no competing interests.

Author contributions. J.L.G.-F. conceived the study, performed the analysis, and wrote the initial manuscript. RC contributed to design of the study. All authors contributed to the interpretation of the results and to the review and editing of the manuscript.

Data availability. All datasets used in this study are publicly available. ERA5 data are available from the Copernicus Climate Data Store, and JRA-3Q data are available from the Japan Meteorological Agency.

Supplementary information. Supplementary Information provides additional details on the gross moist stability calculations and includes Supplementary Figs. S1–S6.

Acknowledgements. The authors would like to thank Simona Bordoni and David Adams for their feedback on earlier versions of this work.

References

- Adames Corraliza, A.F., Mayta, V.C.: On the Accuracy of the Moist Static Energy Budget When Applied to Large-Scale Tropical Motions. *Journal of the Atmospheric Sciences* **80**(10), 2365–2376 (2023) <https://doi.org/10.1175/JAS-D-23-0005.1> . Accessed 2023-11-28
- Angeles, M.E., González, J.E., Ramírez-Beltrán, N.D., Tepley, C.A., Comarazamy, D.E.: Origins of the Caribbean rainfall bimodal behavior. *Journal of Geophysical Research: Atmospheres* **115**(D11) (2010)
- Amador, J.A.: The intra-Americas sea low-level jet: Overview and future research. *Annals of the New York Academy of Sciences* **1146**(1), 153–188 (2008)
- Anderson, T.G., McKinnon, K.A., Pons, D., Anchukaitis, K.J.: How Exceptional Was the 2015–2019 Central American Drought? *Geophysical Research Letters* **50**(21), 2023–105391 (2023) <https://doi.org/10.1029/2023GL105391> . Accessed 2023-11-28
- Annamalai, H.: ENSO precipitation anomalies along the equatorial Pacific: Moist static energy framework diagnostics. *Journal of Climate* **33**(21), 9103–9127 (2020)
- Adler, R., Wang, J.-J., Sapiiano, M., Huffman, G., Chiu, L., Xie, P.P., Ferraro, R., Schneider, U., Becker, A., Bolvin, D., Nelkin, E., Gu, G., NOAA CDR Program: Global Precipitation Climatology Project (GPCP) Climate Data Record (CDR), Version 2.3 (Monthly). NOAA National Centers for Environmental Information. Type: dataset (2016). <https://doi.org/10.7289/V56971M6> . <https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00979> Accessed 2022-08-15

- Back, L., Bretherton, C.: Geographic variability in the export of moist static energy and vertical motion profiles in the tropical Pacific. *Geophysical research letters* **33**(17) (2006)
- Baez-Gonzalez, A., Kiniry, J., Meki, M., Williams, J., Alvarez Silva, M., Ramos Gonzalez, J., Magallanes Estala, A.: Potential impact of future climate change on sugarcane under dryland conditions in Mexico. *Journal of Agronomy and Crop Science* **204**(5), 515–528 (2018)
- Bretherton, C.S., Peters, M.E., Back, L.E.: Relationships between water vapor path and precipitation over the tropical oceans. *Journal of climate* **17**(7), 1517–1528 (2004)
- Bordoni, S., Schneider, T.: Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience* **1**(8), 515–519 (2008)
- Bui, H.X., Yu, J.-Y., Chou, C.: Impacts of vertical structure of large-scale vertical motion in tropical climate: Moist static energy framework. *Journal of the Atmospheric Sciences* **73**(11), 4427–4437 (2016)
- Chadwick, R., Good, P., Garcia-Franco, J.L., Alves, L.M., Hart, N., Zilli, M.T., Douville, H., Saint-Lu, M., Medeiros, B.: Processes controlling the South American monsoon response to climate change. *Journal of Climate* **39**(1), 261–280 (2026)
- Corral, A.L.: El impacto de la canícula en poblaciones agrícolas de Tepeaca, siglo XVI. *Itinerarios* **15**, 261–278 (2012)
- Cook, B.I., Seager, R.: The response of the North American Monsoon to increased greenhouse gas forcing: NA MONSOON AND GHG WARMING. *Journal of Geophysical Research: Atmospheres* **118**(4), 1690–1699 (2013) <https://doi.org/10.1002/jgrd.50111> . Accessed 2023-08-17
- Dilley, M.: Synoptic controls on precipitation in the Valley of Oaxaca, Mexico. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **16**(9), 1019–1031 (1996)
- Durán-Quesada, A.M., Gimeno, L., Amador, J.: Role of moisture transport for Central American precipitation. *Earth System Dynamics* **8**(1), 147–161 (2017) <https://doi.org/10.5194/esd-8-147-2017>
- Emanuel, K.: Quasi-equilibrium dynamics of the tropical atmosphere. *The Global Circulation of the Atmosphere* **186**, 218 (2007)
- Fan, C.-S., Dommenges, D.: A diagnostic model for the large-scale tropical circulation based on moist static energy balance. *Climate Dynamics* **57**(11-12), 3159–3181 (2021) <https://doi.org/10.1007/s00382-021-05861-2> . Accessed 2023-12-19
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J.: The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data* **2**, 150066 (2015)
- García-Franco, J.L., Chadwick, R., Gray, L., Osprey, S., Adams, D.K.: Revisiting mechanisms of the mesoamerican midsummer drought. *Climate Dynamics* **60**(1-2), 549–569 (2023)
- García-Franco, J., Jaramillo, A., Dominguez, C., Tippet, M., Muñoz, Á.: Subseasonal prediction of the rainy season and the midsummer drought in Mesoamerica. *Journal of Geophysical Research: Atmospheres* **130**(20), 2025–044023 (2025)
- García-Franco, J.L., Osprey, S., Gray, L.J.: A wavelet transform method to determine monsoon onset and retreat from precipitation time-series. *International Journal of Climatology* **41**(11), 5295–5317 (2021) <https://doi.org/10.1002/joc.7130> <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/joc.7130>
- Gamble, D.W., Parnell, D.B., Curtis, S.: Spatial variability of the Caribbean mid-summer drought and relation to North Atlantic high circulation. *International Journal of Climatology* **28**(3), 343–350 (2008)

Huffman, G.J., Adler, R.F., Morrissey, M.M., Bolvin, D.T., Curtis, S., Joyce, R., McGavock, B., Susskind, J.: Global precipitation at one-degree daily resolution from multisatellite observations. *Journal of hydrometeorology* **2**(1), 36–50 (2001)

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N.: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**(730), 1999–2049 (2020) <https://doi.org/10.1002/qj.3803> <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.3803>

Huffman, G.J., Bolvin, D.T., Nelkin, E.J., Wolff, D.B., Adler, R.F., Gu, G., Hong, Y., Bowman, K.P., Stocker, E.F.: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. *Journal of Hydrometeorology* **8**(1), 38–55 (2007) <https://doi.org/10.1175/JHM560.1> . Accessed 2022-08-15

Hidalgo, H., Chou-Chen, S., McKinnon, K., Pascale, S., Quesada-Chacón, D., Alfaro, E., Bautista-Solís, P., Pérez-Briceño, P., Diaz, H., Maldonado, T., *et al.*: Detection and attribution of trends of meteorological extremes in central america. *Climatic Change* **178**(5), 95 (2025)

Hellin, J., Cox, R., López-Ridaaura, S.: Maize Diversity, Market Access, and Poverty Reduction in the Western Highlands of Guatemala. *Mountain Research and Development* **37**(2), 188–197 (2017) <https://doi.org/10.1659/MRD-JOURNAL-D-16-00065.1>

Hidalgo, H.G., Durán-Quesada, A.M., Amador, J.A., Alfaro, E.J.: The caribbean low-level jet, the inter-tropical convergence zone and precipitation patterns in the intra-americas sea: a proposed dynamical mechanism. *Geografiska Annaler: Series A, Physical Geography* **97**(1), 41–59 (2015) <https://doi.org/10.1111/geoa.12085> <https://doi.org/10.1111/geoa.12085>

Hill, S.A.: Theories for past and future monsoon rainfall changes. *Current Climate Change Reports* **5**(3), 160–171 (2019)

Herrera, E., Magaña, V., Caetano, E.: Air–sea interactions and dynamical processes associated with the midsummer drought. *International Journal of Climatology* **35**(7), 1569–1578 (2015)

Hill, S.A., Ming, Y., Held, I.M., Zhao, M.: A Moist Static Energy Budget–Based Analysis of the Sahel Rainfall Response to Uniform Oceanic Warming. *Journal of Climate* **30**(15), 5637–5660 (2017) <https://doi.org/10.1175/JCLI-D-16-0785.1> . Accessed 2023-11-28

Holloway, C.E., Neelin, J.D.: Moisture vertical structure, column water vapor, and tropical deep convection. *Journal of the atmospheric sciences* **66**(6), 1665–1683 (2009)

Huffman, G.J.: The transition in multi-satellite products from trmm to gpm (tmpa to imerg). Algorithm Information Document. Available online: https://docserver.gesdisc.eosdis.nasa.gov/public/project/GPM/TMPA-to-IMERG_transition.pdf (accessed on 2 November 2021) (2016)

Inoue, K., Back, L.E.: Gross moist stability assessment during TOGA COARE: Various interpretations of gross moist stability. *Journal of Atmospheric Sciences* **72**(11), 4148–4166 (2015)

Inoue, K., Back, L.E.: Gross Moist Stability Analysis: Assessment of Satellite-Based Products in the GMS Plane. *Journal of the Atmospheric Sciences* **74**(6), 1819–1837 (2017) <https://doi.org/10.1175/JAS-D-16-0218.1> . Accessed 2023-11-28

Inoue, K., Biasutti, M., Fridlind, A.M.: Evidence that Horizontal Moisture Advection Regulates the Ubiquitous Amplification of Rainfall Variability over Tropical Oceans. *Journal of the Atmospheric Sciences* **78**(2), 529–547 (2021) <https://doi.org/10.1175/JAS-D-20-0201.1> . Accessed 2023-11-28

Inoue, K., Kelley, M., Fridlind, A.M., Biasutti, M., Elsaesser, G.S.: Accurate column moist static energy budget in climate models. part 1: Conservation equation formulation, methodology, and primary

633 results demonstrated using giss modele3. arXiv preprint arXiv:2407.13855 (2024)

634 Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., Harada, M., Goto,
635 N., Chiba, J., Miyaoka, K., *et al.*: The jra-3q reanalysis. *Journal of the Meteorological Society of*
636 *Japan. Ser. II* **102**(1), 49–109 (2024)

637 Kiranmayi, L., Maloney, E.D.: Intraseasonal moist static energy budget in reanalysis data: Intraseasonal
638 mse budget in NCEP and ERA. *Journal of Geophysical Research: Atmospheres* **116**(D21) (2011)
639 <https://doi.org/10.1029/2011JD016031> . Accessed 2023-12-19

640 Karnauskas, K.B., Seager, R., Giannini, A., Busalacchi, A.J.: A simple mechanism for the climatological
641 midsummer drought along the Pacific coast of Central America. *Atmósfera* **26**, 261–281 (2013)

642 Ley, D., Bolaños, T.G., Castaneda, A., Hidalgo, H.G., Pignot, P.O.G., Fernández, R., Alfaro, E.J.,
643 Castellanos, E.J.: Central america urgently needs to reduce the growing adaptation gap to climate
644 change. *Frontiers in Climate* **5**, 1215062 (2023)

645 Magaña, V., Amador, J.A., Medina, S.: The midsummer drought over Mexico and Central America.
646 *Journal of Climate* **12**, 1577–1588 (1999)

647 Mosiño, A., García, E.: Evaluación de la sequía intraestival en la República Mexicana. In: *Proc. Conf.*
648 *Reg. Latinoamericana Unión Geogr. Int*, vol. 3, pp. 500–516 (1966)

649 Martinez, C., Goddard, L., Kushnir, Y., Ting, M.: Seasonal climatology and dynamical mechanisms
650 of rainfall in the caribbean. *Climate dynamics* **53**(1-2), 825–846 (2019)

651 Mapes, B.E., Liu, P., Buenning, N.: Indian monsoon onset and the Americas midsummer drought:
652 Out-of-equilibrium responses to smooth seasonal forcing. *Journal of Climate* **18**(7), 1109–1115 (2005)

653 Morrison, H., Peters, J.M., Sherwood, S.C.: Comparing growth rates of simulated moist and dry
654 convective thermals. *Journal of the Atmospheric Sciences* **78**(3), 797–816 (2021)

655 Maldonado, T., Rutgersson, A., Amador, J., Alfaro, E., Claremar, B.: Variability of the caribbean
656 low-level jet during boreal winter: large-scale forcings. *International Journal of Climatology* **36**,
657 1954–1969 (2016)

658 Maurer, E.P., Roby, N., Stewart-Frey, I.T., Bacon, C.M.: Projected twenty-first-century changes in the
659 central american mid-summer drought using statistically downscaled climate projections. *Regional*
660 *Environmental Change* **17**, 2421–2432 (2017)

661 Maurer, E.P., Stewart, I.T., Joseph, K., Hidalgo, H.G.: The mesoamerican mid-summer drought: the
662 impact of its definition on occurrences and recent changes. *Hydrology and Earth System Sciences*
663 **26**(5), 1425–1437 (2022)

664 Ma, D., Sobel, A.H., Kuang, Z., Singh, M.S., Nie, J.: A moist entropy budget view of the South Asian
665 summer monsoon onset. *Geophysical Research Letters* **46**(8), 4476–4484 (2019)

666 Miralles, D.G., Arellano, J., McVicar, T.R., Mahecha, M.D.: Vegetation–climate feedbacks across
667 scales. *Annals of the New York Academy of Sciences* **1544**(1), 27–41 (2025)

668 Neelin, J.D., Held, I.M.: Modeling tropical convergence based on the moist static energy budget.
669 *Monthly Weather Review* **115**(1), 3–12 (1987)

670 NOAA CDR Program: NOAA Climate Data Record (CDR) of CPC Morphing Technique (CMORPH)
671 High Resolution Global Precipitation Estimates, Version 1. NOAA National Centers for Environ-
672 mental Information. Type: dataset (2022). <https://doi.org/10.25921/W9VA-Q159> . <https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00948> Accessed 2022-08-15
673

674 Neelin, J.D., Su, H.: Moist teleconnection mechanisms for the tropical South American and Atlantic
675 sector. *Journal of Climate* **18**(18), 3928–3950 (2005)

- 676 Perdigón-Morales, J., Romero-Centeno, R., Ordoñez, P., Nieto, R., Gimeno, L., Barrett, B.S.: Influence
677 of the madden-julian oscillation on moisture transport by the caribbean low level jet during the
678 midsummer drought in mexico. *Atmospheric Research* **248**, 105243 (2021)
- 679 Perdigón-Morales, J., Romero-Centeno, R., Ordóñez, P., Barrett, B.S.: The midsummer drought
680 in Mexico: perspectives on duration and intensity from the CHIRPS precipitation database.
681 *International Journal of Climatology* **38**, 2174–2186 (2018)
- 682 Romero-Centeno, R., Zavala-Hidalgo, J., Raga, G.: Midsummer gap winds and low-level circulation
683 over the eastern tropical pacific. *Journal of Climate* **20**(15), 3768–3784 (2007)
- 684 Rauscher, S.A., Giorgi, F., Diffenbaugh, N.S., Seth, A.: Extension and intensification of the Meso-
685 American mid-summer drought in the twenty-first century. *Climate Dynamics* **31**, 551–571 (2008)
- 686 Small, R.J.O., De Szoeki, S.P., Xie, S.-P.: The Central American midsummer drought: Regional aspects
687 and large-scale forcing. *Journal of Climate* **20**(19), 4853–4873 (2007)
- 688 Smyth, J.E., Ming, Y.: Characterizing drying in the South American monsoon onset season with the
689 moist static energy budget. *Journal of Climate* **33**(22), 9735–9748 (2020)
- 690 Schwarzwald, K., Seager, R., Ting, M., Giannini, A.: Large-Scale Stability and the Greater Horn of
691 Africa Long and Short Rains. *Journal of Climate* **36**(20), 7297–7317 (2023) <https://doi.org/10.1175/JCLI-D-23-0126.1> . Accessed 2023-11-28
- 693 Varuolo-Clarke, A.M., Reed, K.A., Medeiros, B.: Characterizing the north american monsoon in the
694 community atmosphere model: Sensitivity to resolution and topography. *Journal of Climate* **32**(23),
695 8355–8372 (2019)
- 696 Wang, C.: Variability of the caribbean low-level jet and its relations to climate. *Climate dynamics*
697 **29**(4), 411–422 (2007)
- 698 Wing, A.A., Camargo, S.J., Sobel, A.H., Kim, D., Moon, Y., Murakami, H., Reed, K.A., Vecchi,
699 G.A., Wehner, M.F., Zarzycki, C., *et al.*: Moist static energy budget analysis of tropical cyclone
700 intensification in high-resolution climate models. *Journal of Climate* **32**(18), 6071–6095 (2019)
- 701 Williams, I.N., Pierrehumbert, R.T.: Observational evidence against strongly stabilizing tropical cloud
702 feedbacks **44**(3), 1503–1510 (2017) <https://doi.org/10.1002/2016GL072202> . Accessed 2023-12-29
- 703 Xie, P., Joyce, R., Wu, S., Yoo, S.-H., Yarosh, Y., Sun, F., Lin, R.: Reprocessed, Bias-Corrected
704 CMORPH Global High-Resolution Precipitation Estimates from 1998. *Journal of Hydrometeorology*
705 **18**(6), 1617–1641 (2017) <https://doi.org/10.1175/JHM-D-16-0168.1> . Accessed 2022-08-15
- 706 Zhao, Z., Du, Y.: Diversity of mesoamerican midsummer drought. *Climate Dynamics* **64**(8), 360 (2026)
- 707 Zermeno-Díaz, D.M., Ray, P.: Improvements in the seasonal prediction of the mid-summer drought
708 based on the north american multimodel ensemble. *International Journal of Climatology* **45**(6), 8798
709 (2025)
- 710 Zhao, Z., Holbrook, N.J., Oliver, E.C., Ballesteros, D., Vargas-Hernandez, J.M.: Characteristic atmo-
711 spheric states during mid-summer droughts over Central America and Mexico. *Climate Dynamics*,
712 1–21 (2020)
- 713 Zhao, Z., Zhang, X.: Evaluation of methods to detect and quantify the bimodal precipitation over
714 Central America and Mexico. *International Journal of Climatology* **41**, 897–911 (2021)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SIMSDMSEclimDyn.pdf](#)