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Future Mediterranean drying: The role of stationary eddies

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Abstract

We investigate changes in the Mediterranean hydroclimate using historical simulations and future projections from ten models participating in phase 6 of the Coupled Model Intercomparison Project (CMIP6) through the lens of the atmospheric moisture budget. By the end of the 21st century, the multi-model mean projects a substantial decrease in annual-mean net precipitation ($\boldsymbol{P-E}$) over the Mediterranean Sea and surrounding land. This primarily arises from increased moisture flux divergence by the time-mean flow, while changes in transient eddies make a smaller and more spatially heterogeneous contribution. Decomposing the time mean flow into contributions from the zonal mean and stationary eddies reveals that much of the annual-mean response is associated with changes in stationary eddies, rather than with the zonal-mean overturning circulation. The dominant stationary-eddy drying tendency arises from increased moisture divergence by the zonally anomalous circulation acting on zonal-mean moisture and is associated with enhanced zonally anomalous descent over the Mediterranean. This tendency is partially compensated by changes in the pure stationary-eddy

term, reflecting the coupling between zonally anomalous circulation and moisture. Both thermodynamic and circulation changes contribute to the projected drying, although their relative importance varies seasonally: circulation changes play a more prominent role in the localized winter response, whereas thermodynamic changes make a larger contribution to summertime time-mean drying. Our results highlight the importance of zonally asymmetric circulation changes, alongside thermodynamic changes, in shaping the magnitude and spatial structure of future Mediterranean hydroclimate change.

Keywords: Mediterranean aridity, Climate change, Atmospheric Circulations, Stationary eddies

Plain Language Summary

The Mediterranean region is expected to become drier as the climate warms, with important consequences for its already limited water resources. We use climate model projections to investigate the atmospheric processes responsible for this drying. We find that changes in large-scale regional circulation patterns play an important role in transporting moisture away from the Mediterranean. In particular, changes in atmospheric circulations that vary with longitude across the region contribute more strongly to the projected drying than changes in the globally averaged meridional circulation. The balance between circulation and warming-related effects also varies with season: circulation changes are more important for some of the localized drying in winter, while the direct effects of a warmer, moister atmosphere make a larger contribution in summer. These results show that understanding future Mediterranean drying requires considering not only how atmospheric moisture increases with warming, but also how regional atmospheric circulation patterns change.

1 Introduction

The world's Mediterranean-type climate regions, including California, southwestern Australia, Chile, the southern tip of South Africa, and the Mediterranean region itself (Alessandri et al., 2014; Seager et al., 2024), are transitional zones between the subtropics and the lower midlatitudes (Seager et al., 2019; D'Agostino and Lionello, 2020). Mediterranean climates are generally characterized by moderate, wet winters and hot, dry summers.

In the Mediterranean region, midlatitude winter storms that provide moisture flux convergence (Giorgi and Lionello, 2008; Seager et al., 2014a; D'Agostino and Lionello, 2020) sustain cold-season precipitation, which is generally in the form of rainfall except at high altitudes (Şahin et al., 2015; Seager et al., 2019). In the summer, the Mediterranean climate is governed by well-known large-scale circulation patterns. The western edge of the basin, consistent with other Mediterranean-type regions, is primarily influenced by the eastern flank of the North Atlantic subtropical high (Rodwell and Hoskins, 2001; Simpson et al., 2015a). Pronounced atmospheric descent over the central and eastern regions is, however, driven by the monsoon-desert mechanism

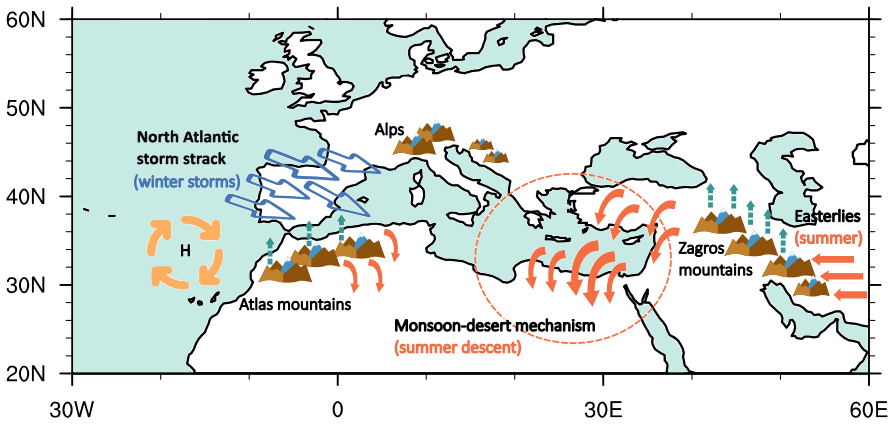


Fig. 1 Schematic of the Mediterranean region, its complex orography, and the mechanisms involved in shaping its annual mean hydrological cycle, including winter storms in the western Mediterranean that provide moisture convergence and wintertime precipitation, and the remotely forced monsoon-desert mechanism encompassing the eastern and central Mediterranean, resulting in enhanced summertime descent.

(Tyrlis et al., 2013; Rodwell and Hoskins, 1996, 2001; Cherchi et al., 2014; Wills and Schneider, 2015; Tootoonchi et al., 2025): diabatic heating and deep convection associated with the South Asian monsoon trigger a Rossby wave response characterized by a region of downward motion to the west of the monsoon heating (Rodwell and Hoskins, 1996; Simpson et al., 2015a). The complex topography of the Middle East (Simpson et al., 2015a) and northwestern Africa (Rodwell and Hoskins, 1996) further localizes and intensifies the descent, anchoring it over the Mediterranean basin. The resulting highly stable atmospheric conditions lead to clear skies and to the region's characteristic summertime aridity (Simpson et al., 2015a; Tuel and Eltahir, 2020; Tuel et al., 2021).

Together, the influence of the North Atlantic subtropical high, remotely forced descent associated with the South Asian monsoon, and the anchoring effect of regional orography (see schematic in Fig. 1), create a distinct climatic regime that distinguishes the Mediterranean from other Mediterranean-type climate regions (Rodwell and Hoskins, 1996; Simpson et al., 2015b; Flaounas et al., 2022). The combination of midlatitude storm influence in winter and strong zonally asymmetric descent in summer makes the regional hydrological cycle particularly sensitive to changes in atmospheric circulation.

With global warming, the Earth's water cycle is expected to undergo significant changes (Allen and Ingram, 2002; Chou and Neelin, 2004; Held and Soden, 2006; Giorgi and Lionello, 2008; Chou et al., 2009), leading to profound environmental, societal, and

economic impacts (Flaounas et al., 2022; Calvin et al., 2023). A useful first-order expectation for the hydroclimate response follows from thermodynamics: as atmospheric moisture increases with warming, existing patterns of moisture convergence and divergence tend to strengthen, producing the familiar tendency for wet regions to become wetter and dry regions drier (Held and Soden, 2006; Stephens and Ellis, 2008; Byrne and O'Gorman, 2015). This "wet-get-wetter and dry-get-drier" response in net precipitation (precipitation minus evaporation, $P - E$) follows from the Clausius-Clapeyron relation under the assumption of constant relative humidity and unchanged circulation (Held and Soden, 2006; Stephens and Ellis, 2008; Chou et al., 2009). Because this scaling assumes that moisture transport is dominated by the time-mean circulation (Chou et al., 2009; Chadwick et al., 2013; Seager et al., 2014a,b; Byrne and O'Gorman, 2015) and neglects circulation changes and eddy-driven moisture transport, deviations from this response are expected at the regional scale (Roderick et al., 2014; Byrne and O'Gorman, 2015; He and Soden, 2016; Zappa et al., 2020; Elbaum et al., 2022).

The Mediterranean region is a clear example: previous studies have shown that the thermodynamic response cannot fully explain the Mediterranean drying (He and Soden, 2016; Brogli et al., 2019; Tuel and Eltahir, 2020), and that other mechanisms, primarily dynamical in nature, significantly contribute to its aridification (Seager et al., 2014a,b; Zappa et al., 2015, 2020; D'Agostino and Lionello, 2020). Identifying which components of the atmospheric circulation produce this dynamical response is thus central to understanding the magnitude and regional structure of projected Mediterranean drying.

One proposed dynamical driver is the global expansion of the Hadley cell and accompanying shifts in midlatitude storm tracks (e.g., Staten et al., 2020; Giorgi et al., 2019). While the Mediterranean's subtropical location makes it highly sensitive to these planetary-scale shifts (Mariotti et al., 2002; Giorgi and Lionello, 2008; D'Agostino et al., 2020), zonally symmetric frameworks alone have proven insufficient to explain the magnitude and spatial structure of projected drying. A growing body of work instead points to changes in zonally asymmetric circulations, namely stationary waves, as important contributors to Mediterranean climate change (Simpson et al., 2014, 2015b,c; Tuel et al., 2021; Seager et al., 2019).

This perspective is particularly relevant in light of the climatological moisture budget. By decomposing the ERA5 moisture budget into zonal mean, stationary eddy, and transient eddy components, we have recently demonstrated that zonally anomalous descent and low-level divergence associated with stationary eddies exert a first-order control on climatological net precipitation patterns over the Mediterranean (Tootoonchi et al., 2025). In particular, much of the time-mean moisture divergence over the region is associated with stationary eddies rather than with the zonal-mean overturning circulation. This raises a natural question for climate projections: do changes in these same zonally asymmetric circulations also dominate the future response of the Mediterranean hydrological cycle?

Previous moisture-budget studies have established that increased moisture divergence by the time-mean flow is a major contributor to projected Mediterranean drying in both winter and summer (Seager et al., 2014a). They have also shown that future $(P - E)$ changes can be separated into a comparatively well-understood

thermodynamic contribution associated with increasing atmospheric moisture and a more uncertain dynamical contribution associated with circulation changes (Held and Soden, 2006; Seager et al., 2010, 2014a; Byrne and O'Gorman, 2015; Wills et al., 2016; Elbaum et al., 2022). However, the time-mean circulation itself contains dynamically distinct components. In particular, in these studies changes in the zonal-mean circulation and in stationary eddies are generally combined or inferred indirectly, making their respective contributions to projected Mediterranean drying difficult to quantify.

Here, we address this gap by extending the climatological moisture-budget framework of Tootoonchi et al. (2025) to CMIP6 projections. We examine changes by the end of the 21st century (2081–2100) relative to the 1995–2014 historical period under the SSP5-8.5 scenario. Our goal is to determine the thermodynamic and dynamical contributions to projected Mediterranean ($P - E$) changes and, within the dynamical response, to distinguish the roles of the zonal-mean circulation, stationary eddies, and transient eddies. We further investigate the circulation and moisture changes underlying the stationary-eddy response. Finally, we examine how these mechanisms vary between winter and summer, providing a physical interpretation of both the annual-mean and seasonal hydroclimate response.

The rest of the paper is organized as follows: Section 2 describes the CMIP6 models and moisture-budget framework. Section 3 presents the projected annual-mean changes and explores their physical drivers. Section 4 contrasts the mechanisms operating in winter and summer. Section 5 summarizes the main results and discusses the implications for the already limited water resources in the region.

2 Methods

2.1 Models

We use ten state-of-the-art Global Climate Models (GCMs) from the CMIP6 archive retrieved through the Copernicus Climate Data Store (see Table 1). We compare the last twenty years of historical simulations (1995–2014) with future projections at the end of the 21st century (2081–2100) under the high-emission SSP5-8.5 Shared Socioeconomic Pathway. This "business-as-usual" scenario assumes rapid economic development and continued intense exploitation of fossil fuels (Eyring et al., 2016; O'Neill et al., 2017). For each model, the global moisture budget and its components are computed using monthly data on eleven pressure levels (1000 925 850 700 600 500 300 250 200 100 50 hPa) before computing the multi-model ensemble mean. Results shown below are robust to different choices of vertical levels (see also Tootoonchi et al. 2025). Notably, the selected models span the full range of Equilibrium Climate Sensitivity (ECS), encompassing high-ECS models, such as CanESM5, and low-ECS models, such as NorESM2 (Zelinka et al., 2020; Lovato et al., 2022).

While our analyses are performed globally, we focus on the extended Mediterranean region (10°W–40°E, 30°N–50°N) following the domain definition of Tootoonchi et al. (2025). To facilitate a consistent inter-model comparison, outputs from all CMIP6 models are regridded to a common $1^\circ \times 1^\circ$ grid. In all figures, we show the multi-model mean, with stippling indicating regions where at least 7 out of 10 models agree on the sign of the change.

Table 1 CMIP6 models used here with the modeling center and horizontal resolution

No.	Model	Host Institution	Resolution
1	CanESM5-CanOE	Canadian Centre for Climate Modelling and Analysis (CCCma), Canada	2.8° × 2.8°
2	CESM2	National Centre for Atmospheric Research, USA	0.94° × 1.25°
3	CMCC-CM2-SR5	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	0.94° × 1.25°
4	CMCC-ESM2	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	0.94° × 1.25°
5	CNRM-ESM2-1	Centre National de Recherches Meteorologiques, France	1.4° × 1.4°
6	EC-Earth3-Veg-LR	EC-Earth European Modelling Consortium, Europe	1.125° × 1.125°
7	GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL), USA	1.25° × 1°
8	MIROC6	Climate Modelling Consortium, Japan	1.406° × 1.406°
9	MPI-ESM1-2-LR	Max Planck Institute for Meteorology (MPI-M), Germany	1.87° × 1.87°
10	NorESM2-MM	NorESM Climate modeling Consortium, Norway	0.9° × 1.25°

2.2 Anomalous moisture budget

To quantify how different circulation components and physical drivers contribute to projected net precipitation ($P - E$) changes, we decompose the anomalous moisture budget following the framework detailed in Seager et al. (2014a) and Tootoonchi et al. (2025). Briefly, our starting point is the climatological moisture budget in pressure coordinates:

$$\overline{P} - \overline{E} = -\nabla \cdot \langle \overline{\mathbf{u}}\overline{q} \rangle \tag{1}$$

where $\langle \cdot \rangle$ indicates a mass-weighted vertical integral, ∇ is the nabla operator, $\overline{(\cdot)}$ is the time mean, $\mathbf{u}$ is the horizontal wind vector $\mathbf{u} = (u, v)$, and q is specific humidity.

Defining anomalies δ as the difference between the last 20 years of the 21st century (2081–2100) and the last 20 years of the historical period (1995–2014), the anomalous moisture budget is

$$\delta(\overline{P} - \overline{E}) = -\delta(\nabla \cdot \langle \overline{\mathbf{u}}\overline{q} \rangle) \tag{2}$$

2.2.1 Mean flow and eddy contributions

Our first objective is to isolate the role of zonally asymmetric processes, which are critical in the Mediterranean but often obscured in global-scale studies. Following Seager et al. (2014a), Wills and Schneider (2015), and D'Agostino and Lionello (2020), we first apply a Reynolds decomposition to partition the moisture flux convergence (MFC) into contributions from the time-mean flow (denoted by overbars) and transient eddies (denoted by primes):

$$\delta(\overline{P} - \overline{E}) = -\delta(\nabla \cdot \langle \overline{\mathbf{u}}\,\overline{q} + \overline{\mathbf{u}'q'} \rangle) \tag{3}$$

To explicitly expose the influence of stationary waves, we further decompose the time mean flow into contributions by the zonal mean ($\overline{[\,\cdot\,]}$) and by stationary eddies ($\overline{(\,\cdot\,)^*}$), such that $\overline{(\,\cdot\,)} = \overline{[\,\cdot\,]} + \overline{(\,\cdot\,)^*}$ (Chen and Bordoni, 2014; Wills and Schneider, 2015; Tootoonchi et al., 2025), to obtain:

$$\delta(\overline{P} - \overline{E}) = -\delta(\nabla \cdot \langle [\overline{\mathbf{u}}][\overline{q}] \rangle) - \delta(\nabla \cdot \langle \overline{\mathbf{u}}^*\overline{q}^* + [\overline{\mathbf{u}}]\overline{q}^* + \mathbf{u}^*[\overline{q}] \rangle) - \delta(\nabla \cdot \langle \overline{\mathbf{u}'q'} \rangle) \tag{4}$$

This relates changes in net precipitation to: 1) changes in the zonal-mean circulation associated with the Hadley cell in the lower latitudes; 2) changes in the sum of all components involving stationary eddies, hereafter referred to as the total stationary eddies $\overline{\mathbf{u}}^\dagger\overline{q}^\dagger \equiv \overline{\mathbf{u}}^*\overline{q}^* + [\overline{\mathbf{u}}]\overline{q}^* + \overline{\mathbf{u}}^*[\overline{q}]$; and 3) changes in the transient eddies. Importantly, the stationary eddy term includes cross-interactions between eddies and the zonal mean, which we have previously shown to play a first-order role in Mediterranean climatological net precipitation (e.g., Tootoonchi et al., 2025). All terms in Eq. 4 are computed explicitly, with the exception of the transient eddy term, $\delta(\nabla \cdot \langle \overline{\mathbf{u}'q'} \rangle)$, which is implicitly computed as the residual:

$$\delta(\nabla \cdot \langle \overline{\mathbf{u}'q'} \rangle) = -\delta(\overline{P} - \overline{E}) - \delta(\nabla \cdot \langle [\overline{\mathbf{u}}][\overline{q}] \rangle) - \delta(\nabla \cdot \langle \overline{\mathbf{u}}^\dagger\overline{q}^\dagger \rangle) \tag{5}$$

2.2.2 Convergence and advection contributions

To analyze the spatial character of net precipitation changes, we also distinguish between changes driven by local wind convergence and by moisture advection. To do this, by taking the nabla operator inside the vertical integral, the time-mean flow change is expanded as:

$$\delta(\overline{P}-\overline{E}) = \underbrace{-\delta(\langle\overline{q}\nabla\cdot\overline{\mathbf{u}}\rangle)}_{\delta Div}\ \underbrace{-\delta(\langle\bar{\mathbf{u}}\cdot\nabla\bar{q}\rangle)}_{\delta Adv}\ \underbrace{-\delta(\nabla.\langle\overline{\mathbf{u}'q'}\rangle)}_{\delta Eddy} - \delta\overline{S}, \tag{6}$$

thus relating changes in $P-E$ to changes in moisture divergence (δDiv), moisture advection (δAdv), and the inferred eddy term ($\delta Eddy$). While previous studies have primarily focused on the wind divergence term (e.g., Seager et al., 2010, 2014a), we explicitly evaluate the advective term (δAdv), which might be particularly relevant for the Mediterranean region, given its complex topography and the influence of the monsoon-desert teleconnection. Note that by taking the nabla operator inside the vertical integral, an additional surface term ($\delta\overline{S}$) appears, due to near-surface fluxes moving along surface pressure gradients (Wills and Schneider, 2015; Seager et al., 2010).

Similar to D'Agostino et al. (2020), we calculate this term implicitly as the difference between changes in the time mean flow and changes in the terms related to advection and divergence,

$$\delta\overline{S} \approx \delta(\nabla\cdot\langle\overline{\mathbf{u}}\,\overline{q}\rangle) - \delta(\langle\overline{q}\nabla\cdot\overline{\mathbf{u}}\rangle) - \delta(\langle\overline{\mathbf{u}}\nabla\overline{q}\rangle) \tag{7}$$

This surface term is found to play a negligible contribution to $\delta(\overline{P}-\overline{E})$ (not shown) and is hereafter neglected.

To further isolate the role of stationary eddies within these spatial components, we similarly break down the total stationary eddy term in horizontal convergence and advection contributions:

$$\delta(\nabla\cdot\langle\overline{\mathbf{u}}^*\overline{q}^*+[\overline{\mathbf{u}}][\overline{q}]^*+\overline{\mathbf{u}}^*[\overline{q}]\rangle) = \delta\langle(\overline{q}^*\nabla\cdot\overline{\mathbf{u}}^*+\overline{\mathbf{u}}^*\cdot\nabla\overline{q}^*)+(\overline{q}^*\nabla\cdot[\overline{\mathbf{u}}]+[\overline{\mathbf{u}}]\cdot\nabla\overline{q}^*)+([\overline{q}]\nabla\cdot\overline{\mathbf{u}}^*+\overline{\mathbf{u}}^*\cdot\nabla[\overline{q}])\rangle+\delta\overline{S}^* \tag{8}$$

where $\delta\overline{S}^*$ on the right-hand side is the additional surface-pressure gradient term arising from taking the nabla operator inside the vertical integral (Seager and Henderson, 2013; Seager et al., 2014a; Wills and Schneider, 2015). As before, this term is computed as a residual and found to be negligible.

2.2.3 Thermodynamic and dynamic components

To separate the thermodynamic effects due to warming from those associated with circulation changes, we follow Seager et al. (2014a) and partition the moisture divergence into thermodynamic (δTh) and dynamic (δDy) contributions:

$$\delta(\overline{P}-\overline{E}) = \underbrace{-\langle(\nabla\cdot\overline{\mathbf{u}})\delta\overline{q}\rangle}_{\delta Th}\ \underbrace{-\langle\delta(\nabla\cdot\overline{\mathbf{u}})\overline{q}\rangle}_{\delta Dy} - \delta(\langle\overline{\mathbf{u}}\cdot\nabla\overline{q}\rangle) - \delta(\nabla.\langle\overline{\mathbf{u}'q'}\rangle) - \delta\overline{S} \tag{9}$$

The δTh term represents the expected "pure" thermodynamic response to increased specific humidity under the assumption of fixed circulation and relative humidity, following the Clausius-Clapeyron relation (Held and Soden, 2006; Byrne and O'Gorman, 2015). δDy captures the response due to circulation changes with unchanged moisture. Notice how we do not decompose either the moisture advection term (third term on the right-hand side of Eq. 9 or the eddy term (fourth term) into thermodynamic and dynamic contributions. This is in fact not possible for the latter, considering it is computed implicitly as the residual of the perturbed moisture budget (Eq. 5). The nonlinear term, involving the covariance between moisture and circulation anomalies, has been argued to be negligible in previous studies (Seager et al., 2010, 2014a) and is hence neglected here.

2.2.4 Sector averages

Finally, to assess the relative contributions of the different moisture-budget components to projected $P - E$ changes as a function of latitude, we compute their zonal sector means over the Mediterranean:

$$\{\delta(\overline{P} - \overline{E})\} = -\{\delta(\nabla \cdot \langle[\overline{\mathbf{u}}][\overline{q}]\rangle)\} - \{\delta(\nabla \cdot \langle\overline{\mathbf{u}}^{\dagger}\overline{q}^{\dagger}\rangle)\} - \{\delta(\nabla \cdot \langle\overline{\mathbf{u}'q'}\rangle)\} \tag{10}$$

$$= -\{\langle\delta(\overline{q}\nabla.\overline{\mathbf{u}})\rangle\} - \{\langle\delta(\overline{\mathbf{u}}\nabla\overline{q})\rangle\} - \{\delta(\nabla.\langle\overline{\mathbf{u}'q'}\rangle)\} - \{\delta S\} \tag{11}$$

$$= -\{\langle(\delta\overline{q})\nabla.\overline{\mathbf{u}}\rangle\} - \{\langle\delta(\nabla.\overline{\mathbf{u}})\overline{q}\rangle\} - \{\langle\delta(\overline{\mathbf{u}}\nabla\overline{q})\rangle\} - \{\delta(\nabla.\langle\overline{\mathbf{u}'q'}\rangle)\} - \{\delta\overline{S}\} \tag{12}$$

where $\{\cdot\}$ denotes an average in longitude over the broad Mediterranean region (10°W–40°E).

3 Projected annual mean changes

The primary objective of this study is to evaluate Mediterranean hydroclimate change by the end of the 21st century using state-of-the-art CMIP6 models. Following our previous work, which established ERA5 as a reliable reference for this region (Tootoonchi et al., 2025), we first assess the ability of the CMIP6 ensemble of the selected models to reproduce the climatological moisture budget. As detailed in the Supplementary Material S1, the models accurately capture the annual mean climatology of the hydrological cycle for the 1995–2014 reference period. While some localized biases exist with respect to ERA5 (see Figs. S1-S3), the CMIP6 ensemble mean effectively represents large-scale features, justifying its use for evaluating future hydroclimate shifts.

Under the SSP5-8.5 scenario, annual and region mean net precipitation is projected to decrease significantly across the Mediterranean by the end of the 21st century (2081–2100) relative to the reference period (1995–2014) (Fig. 2). Despite some inter-model spread (light-brown shading), all ten CMIP6 models unanimously project a negative $P - E$ anomaly, highlighting the robustness of the drying signal across the ensemble.

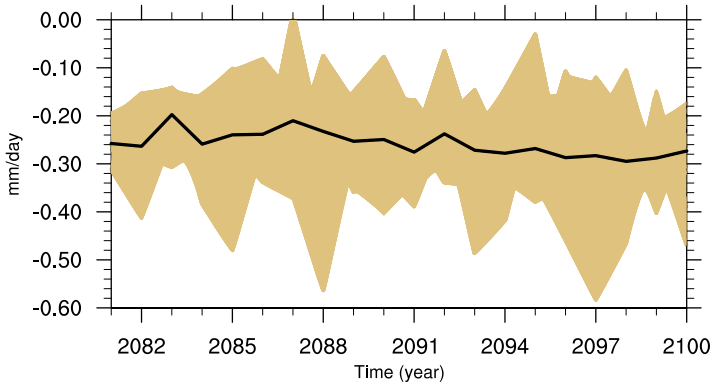


Fig. 2 Net precipitation anomalies across the Mediterranean region in the 2081–2100 period with respect to the 1995–2014 reference period from our ten selected CMIP6 models (see Table 1) shown in terms of the multi-model mean (black curve) and the multi-model spread (light brown shading).

3.1 Sector averages

Before looking at spatial maps, it is instructive to first assess sector-mean changes as a function of latitude for the 2081–2100 period relative to the 1995–2014 reference period (Fig. 3). Consistent with previous work (Seager et al., 2014a, 2024), the CMIP6 multi-model mean projects a robust drying (negative $\delta(P-E)$, black solid line in Fig. 3a) across all latitudes, with a broad peak near 37°N. This drying is primarily driven by changes in the time-mean flow ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}\,\overline{q}\rangle)$, light blue solid line), while the transient eddy contribution ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}'q'}\rangle)$, green solid line) is smaller and varies in sign, reinforcing the drying signal of the time-mean flow only between around 37 and 41°N and poleward of 44°N.

Following Eq. 4, time-mean flow changes can be further decomposed into contributions from the stationary eddies ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{\dagger}\overline{q}^{\dagger}\rangle)$, maroon solid line) and the mean meridional circulation ($-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}][\overline{q}]\rangle)$, yellow solid line). This decomposition reveals that both the magnitude and latitudinal dependence of the time-mean flow changes are primarily explained by the total stationary eddy term, with the mean meridional circulation exerting a non-negligible drying tendency only at lower latitudes. The total stationary eddy contribution, in turn, primarily arises from the zonally anomalous circulation term ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}[\overline{q}]\rangle)$, red dashed line), which causes enhanced moisture flux divergence and drying across all latitudes within the region. This drying tendency is partially offset by the moistening tendency associated with the pure stationary eddy term ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}\overline{q}^{*}\rangle)$, red dotted line). Interestingly, changes in the transport of zonally anomalous moisture by the zonally symmetric circulation ($-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}]\overline{q}^{*}\rangle)$, red dash-dotted line) have only limited impacts on the region's zonal sector-mean hydrological cycle, causing weak moistening tendencies in the higher and lower latitudes and weak drying in the central parts of the region.

This analysis, while focused on the sector mean, already shows how hydroclimatic changes in the Mediterranean region are not caused by the mean meridional circulation

associated with the expansion of the Hadley cell but by changes in stationary eddies, which are also the dominant term in shaping the climatological MFC across the region (Tootoonchi et al., 2025).

Fig. 3b complements the analysis in Fig. 3a by decomposing changes in the time-mean flow into contributions from changes in moisture divergence, $-\langle\delta(\overline{q}\nabla\cdot\overline{\mathbf{u}})\rangle$, and advection, $-\langle\delta(\overline{\mathbf{u}}\cdot\nabla\overline{q})\rangle$, with the former being approximated separately by changes in specific humidity and in mean circulation (see Eqs. 6 and 9).

As discussed in Section 2.2.3, this decomposition results in the additional surface pressure change term, $\delta\overline{S}$, which we calculate as the residual of the perturbation budget (see Eq. 7) and find negligible (not shown). Changes in moisture advection ($-\langle\delta(\overline{\mathbf{u}}\cdot\nabla\overline{q})\rangle$, cyan solid line) cause moderate moistening at all latitudes, which is more than counterbalanced by increased drying due to the divergence term ($-\langle\delta(\overline{q}\nabla\cdot\overline{\mathbf{u}})\rangle$, brown solid line) arising from changes in specific humidity (δTh, light-brown dotted line) and circulation (δDy, light-brown dash-dotted line). As expected, in the absence of circulation changes, the thermodynamic term, $-\{\langle(\delta\overline{q})\nabla\cdot\overline{\mathbf{u}}\rangle\}$, causes an increase in moisture divergence (convergence) where the mean flow is divergent (convergent) in the base climate. This "dry-get-drier" pattern at all latitudes within the region appears evident when comparing the thermodynamic term in Fig. 3b against the climatological time-mean flow depicted in Fig. S1b (blue line) in the supplementary material. The contribution from dynamical changes ($-\{\langle\delta(\nabla\cdot\overline{\mathbf{u}})\overline{q}\rangle\}$, light-brown dash-dotted line) is, however, far from negligible. In fact, it contributes substantially to the region's hydroclimate change, causing a drying tendency in the annual and sector mean hydrological cycle at all latitudes within the Mediterranean region.

3.2 Spatial patterns

The spatial patterns of annually averaged projected changes in all terms discussed above are shown in Figs. 4 and 5. Unsurprisingly, net precipitation is projected to decrease significantly across the Mediterranean region, particularly over northern land areas and the sea itself (Fig. 4a). The time-mean flow, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}}\,\overline{q}\rangle)$, contributes significantly to the region's drying due to increased moisture flux divergence (Fig. 4b). Clear exceptions are the Iberian Peninsula, northwestern Africa, southern Türkiye, and, to some extent, the eastern Alps and southeastern Europe.

Changes in the mean meridional circulation, $-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}][\overline{q}]\rangle)$, are small (Fig. 4c). Therefore, changes in the time-mean flow are driven primarily by changes in total stationary eddies ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{\dagger}\overline{q}^{\dagger}\rangle)$, Fig. 4d). In agreement with the sector-mean results (Fig.3a), stationary eddy changes arise mainly due to increased divergence of mean moisture by the zonally anomalous circulation ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}[\overline{q}]\rangle)$, Fig. 4f), which is partially compensated for by increased moistening due to the pure stationary eddies ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}\overline{q}^{*}\rangle)$, Fig. 4e). There is an opposing behavior over the Iberian Peninsula and northwestern Africa, where the moistening tendency due to the zonally anomalous circulation term (Fig. 4f) is partially (but not fully) offset by the drying tendency due to pure stationary eddies (Fig. 4e). The transport of zonally anomalous moisture by the zonal mean circulation ($-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}]\overline{q}^{*}\rangle)$, Fig. 4g) is projected to cause mild moistening over the Mediterranean Sea and northeastern land regions surrounding the sea and mild drying over northwestern land regions, over Morocco, and eastern Mediterranean

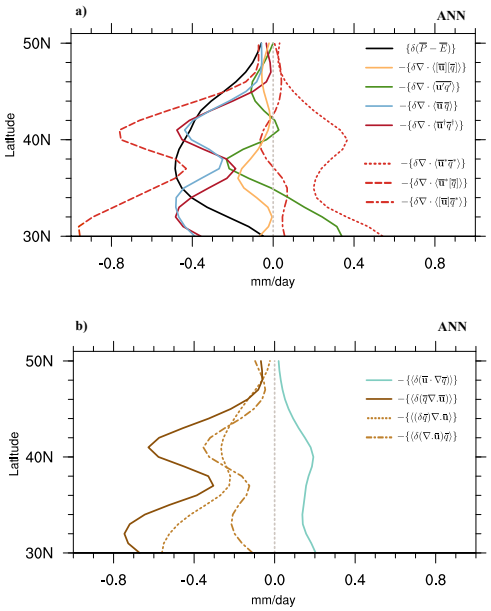


Fig. 3 Contributions from different circulations to changes in the annual (ANN) and sector-mean Mediterranean hydroclimate in the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model mean. Each curve is smoothed in the latitudinal direction using a 3-point running average filter.

land areas, including Türkiye and the Levant. Notice how this term, which was found to be nearly negligible in the zonal sector mean (Fig.3a), plays non-trivial contributions at the regional scale. Overall, a comparison of the three constituent terms of the total stationary eddies (Fig.4, panels e, f, and g) reveals that the amplified drying induced by the total stationary eddies is predominantly driven by changes in the transport of mean moisture by the zonally anomalous circulation term (panel f).

Transient eddies, $-\delta(\nabla \cdot \langle \overline{\mathbf{u}'q'} \rangle)$, contribute to the overall annual-mean drying by inducing increased moisture flux divergence over the Mediterranean Sea, the Adriatic Sea, the northern Iberian Peninsula, northwestern Africa, France, and the Alps. Moderate moistening is seen over some localized areas over the southern Iberian Peninsula, northern Türkiye, and the eastern Mediterranean land regions (Fig. 4h). As we will show in the following, this annually averaged signal arises from differing responses in the solstice seasons.

The decomposition of the time mean MFC in moisture advection and convergence terms, as well as thermodynamic and dynamic contributions, is shown in Fig. 5. Changes in advection, $-\langle \delta(\overline{\mathbf{u}} \cdot \nabla \overline{q}) \rangle$, result in moderate moistening over the entire Mediterranean domain, with the exception of the Iberian Peninsula and northwestern Africa (Fig. 5a). This is more than offset by changes in moisture divergence ($-\langle \delta(\overline{q} \nabla \cdot \overline{\mathbf{u}}) \rangle$, Fig. 5b), which causes increased drying over the Mediterranean Sea and the surrounding land regions, except over the Iberian Peninsula, northwestern

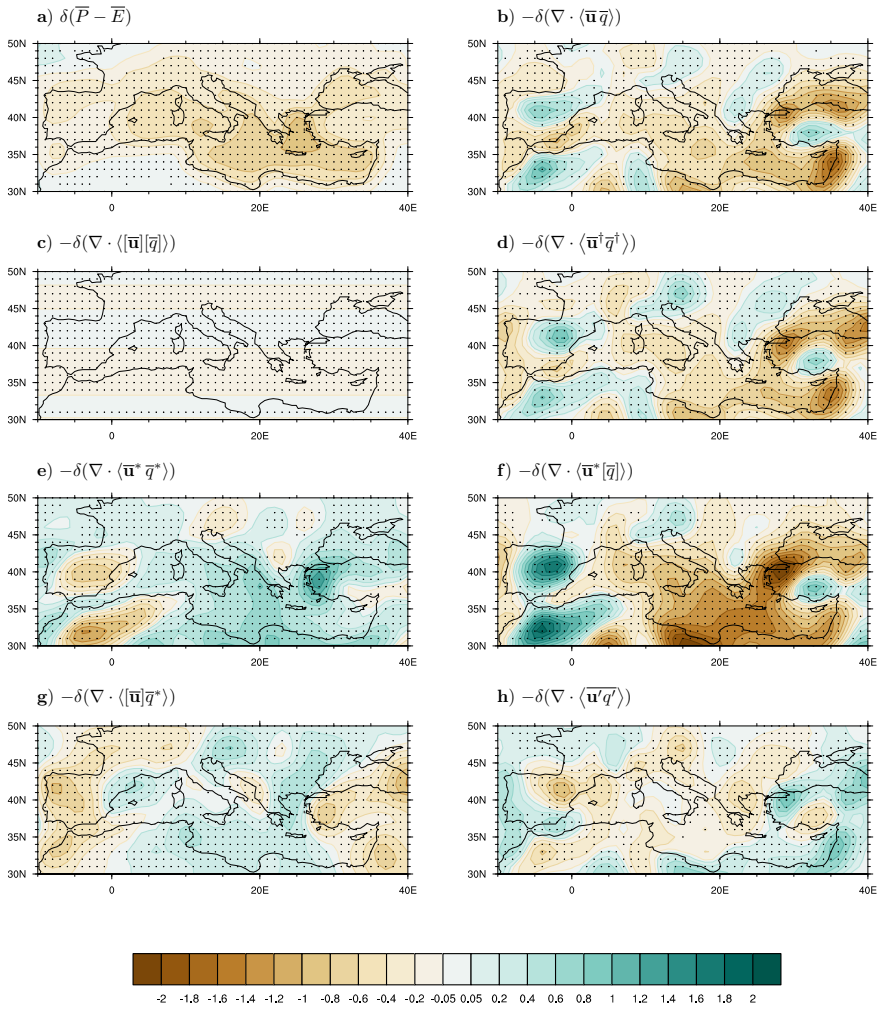


Fig. 4 Contributions from changes in the moisture budget components for the 2081–2100 period with respect to the 1995–2014 reference period in the annual mean (ANN): Changes in (a) $P-E$, (b) time-mean flow, (c) zonal-mean flow, (d) stationary eddies, (e) pure stationary eddies, (f) zonally anomalous circulation, (g) zonally anomalous water vapor, and (h) transient eddies. All fields have been smoothed using a 3×3 point smoothing filter. Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

Africa, and southern Türkiye. This enhanced drying (Fig. 5b) arises from both thermodynamic and dynamic changes (Fig. 5c and d, respectively). The thermodynamic term, $-\langle(\delta\overline{q})\nabla\cdot\overline{\mathbf{u}}\rangle$, is easier to understand: it depicts an amplified pattern of the climatological time mean flow, resulting in a negative $P-E$ tendency across the Mediterranean region, except northwestern Africa, where the time mean flow causes MFC in the climatology (Fig. S2b). Dynamical changes, $-\langle\delta(\nabla\cdot\overline{\mathbf{u}})\overline{q}\rangle$, arising from changes in the mean circulation, are far from negligible and contribute substantially

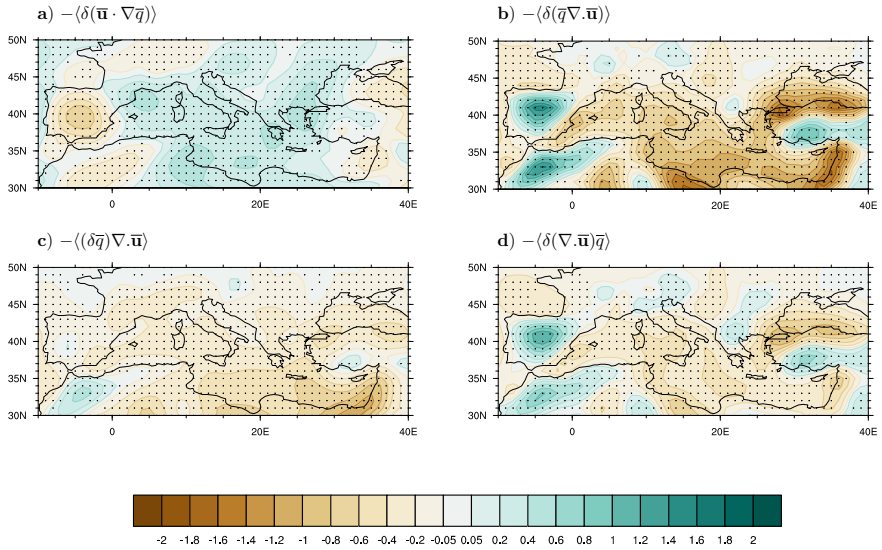


Fig. 5 Changes in moisture (a) advection and (b) convergence and its approximation by the (c) thermodynamic and (d) dynamic contributions by the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model mean for the annual mean (ANN). Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

to the enhanced moisture flux divergence across the Mediterranean (Fig. 5d). These changes reinforce the thermodynamic tendency of increased drying over the Mediterranean Sea, southern Italy, the Balkans, northern Türkiye, the Black Sea and result in increased moistening over the Iberian Peninsula, northwestern Africa, and southern Türkiye.

In sum, circulation changes are just as important as, if not more important than, thermodynamic changes for the spatial and temporal $P - E$ response across the Mediterranean region, in agreement with previous work (e.g.; Seager et al., 2014a, 2019; Tuel and Eltahir, 2020; Tuel et al., 2021). By explicitly quantifying the contribution of stationary eddies to the time-mean MFC, we further show how these dynamical changes are primarily driven by zonally anomalous circulations rather than the mean overturning.

3.3 Drivers of changes in stationary eddies

The results above show that projected changes in the annual- and time-mean flow are primarily associated with stationary eddies and, in particular, with increased moisture flux divergence by the zonally anomalous circulation acting on zonal-mean moisture ($\delta(-\nabla\cdot\langle\overline{\mathbf{u}}^*[\overline{q}]\rangle)$, Fig.4f). This drying tendency is partially offset by the pure stationary eddy term ($\delta(-\nabla\cdot\langle\overline{\mathbf{u}}^*\overline{q}^*\rangle)$, Fig.4e). A similar compensation characterizes the climatological moisture budget (Tootoonchi et al., 2025) and arises because the zonally anomalous subsidence not only drives moisture divergence but also maintains the negative (dry) zonally anomalous moisture field over the basin. Here, we investigate

how these circulation and moisture fields respond to warming and give rise to the projected changes in the stationary eddy moisture flux divergence.

Circulation changes are illustrated by the 500-hPa vertical pressure velocity, which provides a useful proxy for changes in large-scale vertical motion and associated low-level convergence and divergence (Fig. 6c,d). Note how in these panels, we show changes in the negative vertical pressure velocity; positive (negative) values indicate an increase (decrease) in ascending motion. The CMIP6 ensemble projects enhanced zonally anomalous descent ($\delta(-\overline{\omega}^*_{850})$) across a broad portion of the Mediterranean, including the central Mediterranean Sea, central and southern Italy, Corsica, western Türkiye, southeastern Europe, and northeastern Africa. Importantly, the strongest anomalous descent is centered over the central Mediterranean, rather than over the southeastern Mediterranean, where climatological stationary-wave descent is strongest (see Fig. 6 in Tootoonchi et al., 2025). In contrast, changes in the zonal-mean vertical motion ($\delta(-[\overline{\omega}]_{850})$) are weak across the Mediterranean (Fig. 6d), consistent with the comparatively small contribution of the zonal-mean circulation to the annual-mean moisture-budget response (Figs. 3a and 4c). An alternative diagnosis based on the local meridional overturning circulation (see AppendixA) shows modest anomalous descent over the central-eastern Mediterranean (Fig. A1). However, its magnitude is small compared with the total change in descending motion over the region (Fig. 6c), indicating that changes in the local meridional overturning account for only a fraction of the zonally asymmetric projected descent. Most of this change therefore appears to be associated with the stationary circulation rather than with the local manifestation of the meridional overturning circulation.

The impact of this circulation response on moisture transport depends on both the increase in background moisture and changes in its zonally asymmetric distribution. Zonal-mean low-level specific humidity, ($\delta[\overline{q}]_{850}$), increases throughout the Mediterranean as the atmosphere warms (Fig. 6b), whereas ($\delta\overline{q}^*_{850}$) is predominantly negative over the basin (Fig. 6c). The enhanced zonally anomalous descent and associated horizontal divergence, therefore, act on an increasingly moist background atmosphere, contributing to the strong drying tendency associated with ($\delta(-\nabla\cdot\langle\overline{\mathbf{u}}^*[\overline{q}]\rangle)$). At the same time, changes in the zonally anomalous circulation are accompanied by changes in zonally anomalous moisture ($\delta\overline{q}^*_{850}$), resulting in an opposing contribution from the pure stationary eddy term. This compensation is analogous to that found in the climatological moisture budget (Tootoonchi et al., 2025), where anomalous descent and divergence over the Mediterranean are associated with negative moisture anomalies that reduce the effective moisture export by the stationary circulation.

The decomposition of the stationary terms into horizontal-advection and wind-divergence contributions further clarifies this response (Fig. 7 left and right, respectively). Increased moisture divergence is a major contributor to the drying associated with the zonally anomalous circulation acting on zonal-mean moisture (Fig. 7d), consistent with the enhanced anomalous descent identified above. In contrast, changes involving zonally anomalous moisture depend strongly on horizontal advection. In particular, changes in the transport of $\overline{q}^*$ by the zonal-mean circulation, ($\delta(-\nabla\cdot\langle[\overline{\mathbf{u}}]\overline{q}^*\rangle)$), arise almost entirely through its advective component (Fig. 7e,f), while horizontal

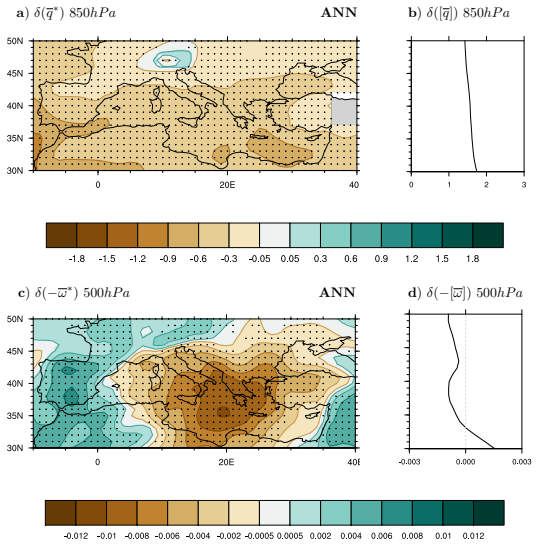


Fig. 6 Changes in specific humidity (in $\mathrm{g\,kg^{-1}}$) and vertical (pressure) velocity (in $\mathrm{Pa\ s^{-1}}$) by the 2081–2100 period with respect to the 1995–2014 reference period in the annual mean (ANN) from the CMIP6 multi-model mean: changes in low-level (850 hPa) a) zonally anomalous specific humidity and b) zonal mean specific humidity, and changes in mid-tropospheric (500 hPa) c) zonally anomalous vertical velocity and d) zonal mean vertical velocity. Stippling indicates where more than 7 models agree on the sign of change.

advection is also at least as important as wind divergence for changes in the pure stationary eddy term (Fig. 7a,b). Thus, changes in zonally anomalous moisture primarily modify the stationary-eddy response through horizontal moisture advection, whereas the dominant drying contribution is closely tied to changes in the zonally asymmetric circulation and associated divergence.

Overall, these results show that the projected stationary eddy contribution to Mediterranean drying is not simply an amplification of the climatological moisture-budget pattern by increasing atmospheric moisture. It also involves substantial changes in the regional zonally asymmetric circulation, characterized by enhanced descent and moisture divergence over the Mediterranean. The resulting drying is partially compensated by changes in zonally anomalous moisture and its advection.

4 Solstice season changes

The annual-mean response discussed above masks substantial seasonal differences in both the magnitude and the mechanisms of Mediterranean hydroclimate change. We therefore contrast winter (December–February, DJF) and summer (June–August, JJA), when the regional hydrological cycle is governed by distinct dynamical regimes. Results from the shoulder seasons, spring (March–May, MAM) and autumn (September–November, SON), are available in the supplementary material (Figs. S4–S7).

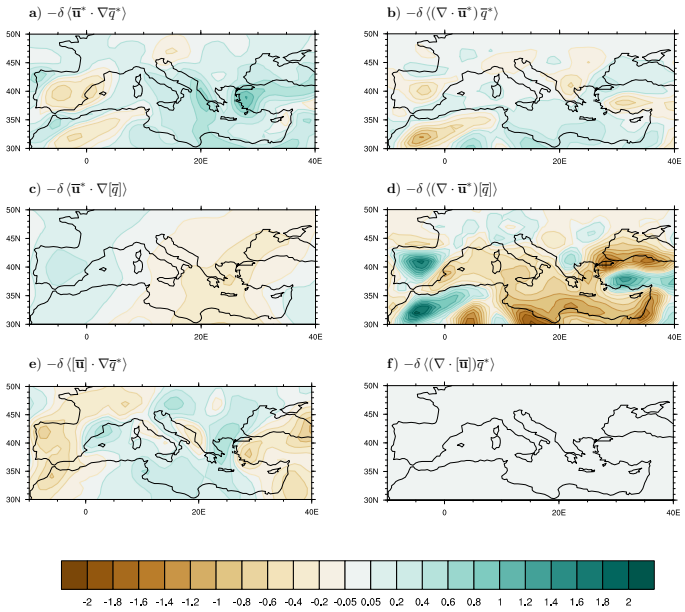


Fig. 7 Contributions from changes in advection (left) and wind divergence (right) to changes in the total stationary eddy MFC within the Mediterranean region by the 2081–2100 period with respect to the 1995–2014 period in the annual mean (ANN) from the CMIP6 model-model mean: changes in (a,b) pure stationary eddies, (c,d) zonally anomalous circulation term, and (e,f) zonally anomalous water vapor term. Units are millimeters per day

In winter, $P-E$ decreases across most of the Mediterranean south of ~ 44°N (Fig. 8a), with the strongest drying over the southeastern Mediterranean Sea. Both the time-mean flow, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}}\,\overline{q}\rangle)$, and transient eddies, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}'q'}\rangle)$, contribute to the drying response over the ocean, while featuring a more varied and opposing pattern over land regions (Fig. 8b,h). Unlike in the annual mean, changes in the zonal mean circulation, $-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}][\overline{q}]\rangle)$, are non-negligible and contribute to drying over the southern Mediterranean between 30°N and 36°N (Fig. 8c). This zonally symmetric response, however, cannot account for the more localized drying over the central and eastern Mediterranean, which is primarily associated with stationary eddies ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^\dagger\overline{q}^\dagger\rangle)$, Fig. 8d). As in the annual mean, their dominant drying contributions arise from increased moisture divergence by the zonally anomalous circulation acting on zonal-mean moisture ($-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^*[\overline{q}]\rangle)$, Fig. 8f), coincident with enhanced zonally anomalous descent over the region (not shown).

The decomposition for the DJF response into divergence and advection contributions, as well as dynamic and thermodynamic components, further highlights the importance of circulation changes. Moisture advection provides a modest moistening tendency (Fig. 9a), which is more than offset by increased drying due to the wind divergence term (Fig. 9b), especially in the eastern Mediterranean. Both thermodynamic ($-\langle(\delta\overline{q})\nabla\cdot\overline{\mathbf{u}}\rangle$, Fig. 9c) and dynamic ($-\langle\delta(\nabla\cdot\overline{\mathbf{u}})\overline{q}\rangle$, Fig. 9d) changes contribute to

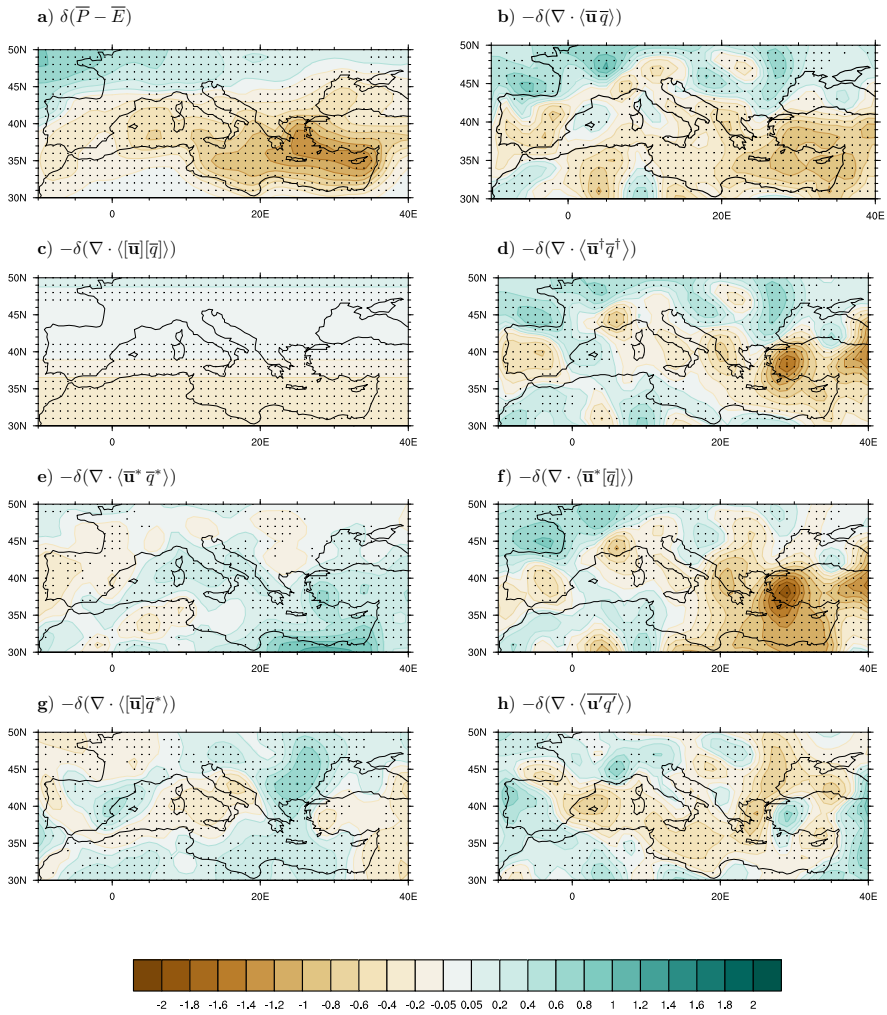


Fig. 8 Changes in the moisture budget components by the 2081–2100 period with respect to the 1995–2014 reference period for winter (DJF): Changes in (a) $P-E$, (b) time-mean flow, (c) zonal-mean flow, (d) stationary eddies, (e) pure stationary eddies, (f) zonally anomalous circulation, (g) zonally anomalous water vapor, and (h) transient eddies. Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

this enhanced divergence, with the former (latter) exerting a more localized response over the western (eastern) Mediterranean region.

The summer response is substantially different. The projected decrease in $P-E$ is weaker but widespread (Fig. 10a). Importantly, this relatively weak response does not reflect a muted response to warming, but instead results from strong and spatially varied tendencies by the time-mean flow, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}}\,\overline{q}\rangle)$, and transient eddies, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}'q'}\rangle)$, that largely oppose one another (Fig. 10b,h). As in the annual mean, changes in the time-mean flow arise primarily from changes in the total stationary eddies

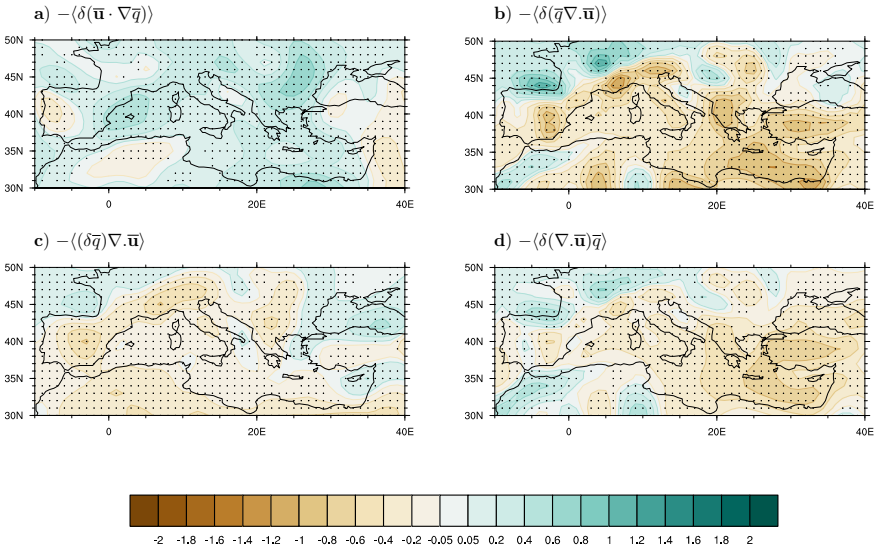


Fig. 9 Contributions from changes in (a) moisture advection, (b) wind convergence and its components due to the (c) thermodynamic and (d) dynamic responses by the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model ensemble mean for winter (DJF). Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

$(-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{\dagger}\overline{q}^{\dagger}\rangle)$, Fig. 10d), while the contribution by the mean meridional circulation, $-\delta(\nabla\cdot\langle[\overline{\mathbf{u}}][\overline{q}]\rangle)$, remains small (Fig. 10c). The stationary eddy response again reflects substantial compensation between the zonally anomalous circulation,$-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}[\overline{q}]\rangle)$, and the pure stationary eddy, $-\delta(\nabla\cdot\langle\overline{\mathbf{u}}^{*}\overline{q}^{*}\rangle)$, terms (Fig. 10f,e).

The mechanisms driving the JJA response also differ from those operating in winter. Moisture advection $(-\langle\delta(\overline{\mathbf{u}}\cdot\nabla\overline{q})\rangle$, Fig. 11a) generally opposes the drying tendency caused by wind divergence $(-\langle\delta(\overline{q}\nabla\cdot\overline{\mathbf{u}})\rangle$, Fig. 11b). Unlike winter, however, the increased divergence is primarily thermodynamic $(-\langle(\delta\overline{q})\nabla\cdot\overline{\mathbf{u}}\rangle$, Fig. 11c). Dynamical changes in wind divergence,$-\langle\delta(\nabla\cdot\overline{\mathbf{u}})\overline{q}\rangle$, are more spatially heterogeneous, producing localized drying and moistening tendencies rather than a coherent contribution to Mediterranean aridification (Fig. 11d).

The different dynamical contributions in winter and summer are interesting in light of previous work on the seasonal sensitivity of Mediterranean circulation to surface forcing. Using targeted regional-model experiments, Tuel et al. (2021) found that the circulation response to relative Mediterranean SST cooling is much stronger in winter than in summer. They attributed this contrast to lower near-surface static stability and the absence of strong remotely forced descent in winter, which allow the surface thermal anomaly to extend into the lower troposphere, whereas strong static stability and monsoon-forced descent confine the response near the surface in summer. While we do not explicitly investigate surface thermal forcing here, these results provide useful context for the seasonal differences in circulation changes identified in our analysis.

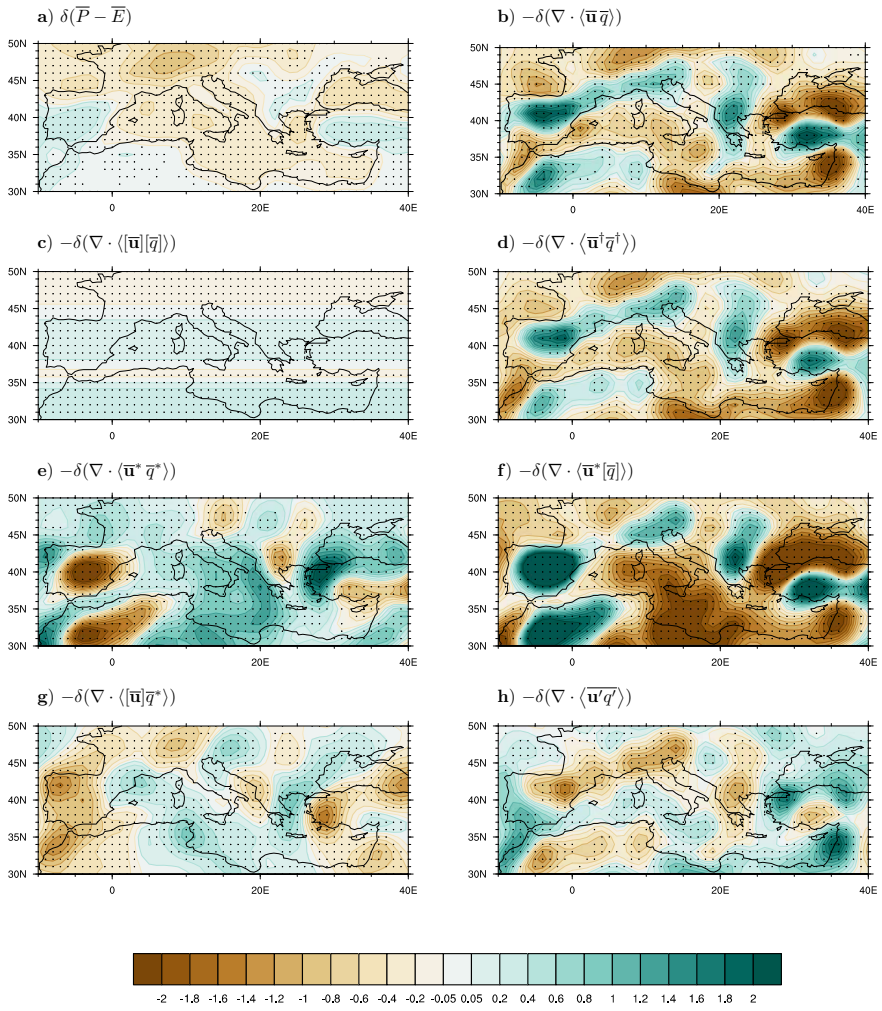


Fig. 10 Changes in the moisture budget components by the 2081–2100 period with respect to the 1995–2014 reference period in summer (JJA): Changes in (a) $P-E$, (b) time-mean flow, (c) zonal-mean flow, (d) stationary eddies, (e) pure stationary eddies, (f) zonally anomalous circulation, (g) zonally anomalous water vapor, and (h) transient eddies. Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

To summarize, the annual mean response reflects differences in the relative contributions of different processes in winter and summer. Circulation changes appear to play a more prominent role in the more localized winter drying, through changes in zonally anomalous moisture flux divergence, while thermodynamic changes make a more important contribution to the summertime drying. In summer, compensation between time-mean and transient-eddy tendencies also contribute to the relatively

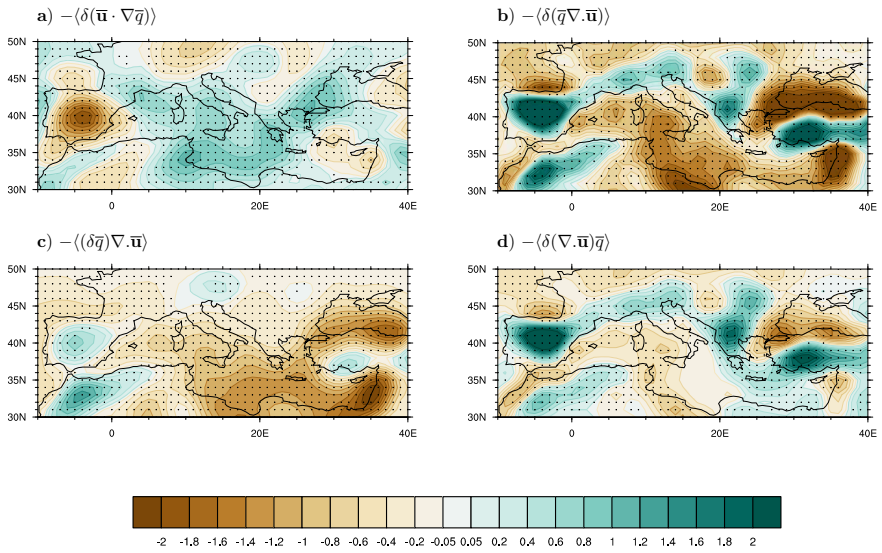


Fig. 11 Contributions from changes in (a) moisture advection, (b) wind convergence and its components due to the (c) thermodynamic and (d) dynamic responses by the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model ensemble mean for winter (JJA). Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

weak $P-E$ response. Thus, while stationary eddies contribute to changes in the time-mean moisture transport in both seasons, their relative importance and the processes associated with their response differ through the annual cycle.

5 Conclusions and discussion

In this study, we use CMIP6 projections to investigate the atmospheric processes contributing to Mediterranean ($P-E$) changes by the end of the 21st century. Consistent with previous studies, the models project widespread drying across the region, primarily associated with increased moisture divergence by the time-mean flow (Seager et al., 2014a, 2019; Tuel and Eltahir, 2020). Changes in transient eddies make a smaller contribution to the annual-mean drying and are spatially heterogeneous, locally enhancing moisture convergence over some Mediterranean land regions. Hence, although transient eddies play a central role in maintaining the climatological Mediterranean hydrological cycle (Seager et al., 2014a,b, 2019; Tootoonchi et al., 2025), changes in their moisture transport do not appear to be the primary driver of the projected regional drying.

Our results provide further insight into the mechanisms responsible for the time-mean response. Previous studies have shown how the thermodynamic response alone cannot fully account for the projected aridification in the Mediterranean region, pointing to an important role for circulation changes (Seager et al., 2014a; Byrne and

O'Gorman, 2015; Zappa et al., 2020; Tuel and Eltahir, 2020). By explicitly separating the time-mean flow into zonal-mean and stationary-eddy components, we show that much of the annual-mean response is associated with changes in stationary eddies, whereas changes in the zonal-mean circulation make a smaller contribution except at the southernmost latitudes. This provides direct moisture-budget evidence for the importance of stationary-wave changes suggested by previous work (Seager et al., 2014b; Zappa et al., 2015; Simpson et al., 2015c; Seager et al., 2019; Tuel et al., 2021) and quantifies their contribution to the projected regional drying.

The importance of stationary eddies in the time-mean response has important implications for how the dynamical response is interpreted. Projected Mediterranean drying cannot be understood solely in terms of a zonally symmetric expansion of the Hadley cell. While changes in the mean meridional circulation do contribute in some latitudinal bands and seasons, they cannot account for the magnitude and spatial structure of the time-mean moisture flux divergence response. Even when zonal variations in the meridional overturning are considered through a regional overturning-circulation framework, this circulation accounts for only part of the projected changes in descent. Instead, our results point to changes in stationary circulations as a leading component of the dynamical adjustment of Mediterranean hydroclimate.

The dominant stationary eddy drying tendency arises from changes in the zonally anomalous circulation acting on zonal mean moisture. Enhanced zonally anomalous descent and associated low-level divergence over the Mediterranean increase moisture export from the region. This tendency is partially compensated by changes in the pure stationary-eddy term, reflecting the coupling between zonally anomalous circulation and moisture. Changes in zonally anomalous moisture also influence the response through horizontal advection. These results extend our previous analyses of the climatological Mediterranean moisture budget (Tootoonchi et al., 2025), showing that the interaction between zonally asymmetric circulation and moisture is important not only for maintaining the present-day moisture budget but also for shaping its response to warming.

The relative importance of these terms varies over the seasonal cycle. In winter, circulation changes play a significant contribution to the localized drying over the central and eastern Mediterranean, where increased moisture divergence is associated with changes in the zonally asymmetric circulation. In summer, by contrast, thermodynamic changes make a larger contribution to the time-mean drying, while circulation changes are weaker and more spatially heterogeneous. Strong compensation between changes in the time-mean flow and transient eddies further limits the magnitude of the summertime $(P - E)$ response.

Taken together, our results emphasize that projected Mediterranean drying reflects both the thermodynamic amplification of the climatological moisture-divergence pattern and changes in atmospheric circulation, particularly in its zonally asymmetric components. Their relative importance varies spatially and seasonally, highlighting the need to account for both thermodynamic and dynamical processes when interpreting future Mediterranean hydroclimate change. Further investigation of the thermodynamic response itself provides a natural avenue for extending this framework. Byrne and O'Gorman (2015) proposed an extended scaling for hydroclimate change that,

beyond the increase in atmospheric moisture, accounts for changes in near-surface relative humidity and spatial gradients in surface warming. Applying such an approach to the Mediterranean could help establish how much of the regional response can be understood from an extended thermodynamic framework and, conversely, which features require changes in atmospheric circulation.

Appendix A Regional Hadley cell perspective

To assess whether the projected changes in Mediterranean descent can be interpreted in terms of a regional meridional overturning circulation, we follow the local Hadley cell framework of Zhang and Wang (2013), Galanti et al. (2022), Li et al. (2022), and Raiter et al. (2024). Unlike the conventional zonal-mean Hadley circulation, this framework allows the meridional overturning to vary with longitude.

The horizontal wind velocity ($\mathbf{u}$) is first decomposed into divergent (irrotational) and non-divergent components. Because only the divergent component is directly associated with horizontal mass convergence and divergence, and hence vertical motion, we calculate the horizontal wind divergence:

$$D = \nabla \cdot \mathbf{u} \tag{A1}$$

The velocity potential (χ) is obtained by solving $\nabla^2 \chi = D$ using spherical harmonics. The divergent wind is then computed as

$$\nabla \chi = \mathbf{u}_{div} \tag{A2}$$

where $\mathbf{u}_{div} = (u_{div}, v_{div})$. We use its meridional component v_{div} to calculate the zonally varying meridional mass streamfunction, ψ_H,

$$\psi_H = \int_0^{P_s} v_{div}(\lambda, \phi, p, t)\, \frac{dp}{g} \tag{A3}$$

where λ, ϕ, p and t denote longitude, latitude, pressure and time, respectively. The vertical pressure velocity associated with this local meridional overturning, ω_H, is obtained from the meridional gradient of the streamfunction

$$\omega_H = g \frac{\partial \psi_H}{\partial y} \tag{A4}$$

With this convention, positive (negative) values of ω_H denote ascending (descending) motion. We calculate the projected change, $\delta\omega_H$, between 2081–2100 and 1995–2014 for each CMIP6 model and then compute the multi-model mean (Fig. A1). The resulting pattern shows anomalous descent associated with the local meridional overturning over parts of the central-eastern Mediterranean. Its magnitude, however, is smaller than the total projected change in zonally anomalous vertical motion shown

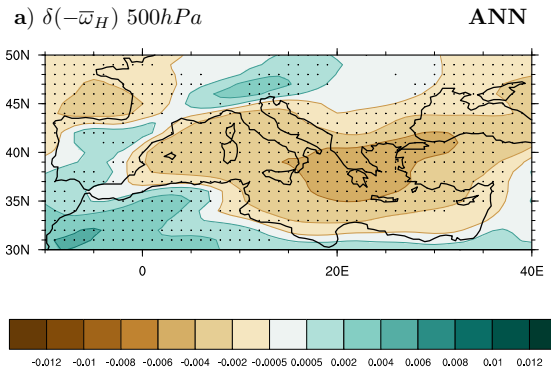


Fig. A1 Contribution from changes in the annual mean (ANN) local meridional overturning to the Mediterranean region's hydrological cycle by the $2081-2100$ period with respect to the $1995-2014$ reference period from the CMIP6 multi-model mean. Stippling indicates where more than 7 models agree on the sign of change, and the unit is Pa s^{-1}.

in Fig. 6c. Thus, the regional overturning circulation captures only part of the zonally asymmetric projected descent, supporting the interpretation that much of the response is associated with stationary circulations.

Supplementary information

This manuscript has an accompanying supplementary file.

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Declarations

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

ERA5 data are available from the Copernicus Climate Data Store (CDS) (https://doi.org/10.24381/cds.6860a573, Hersbach et al. (2023)). CMIP6 data are available from the Copernicus CDS archive (https://doi.org/10.24381/cds.c866074c).

Code availability

Codes developed for our analyses are available upon request.

Author contribution

SB conceived the study, RT performed the analyses, and RD'A provided some of the code. RT and SB wrote and edited the paper with helpful feedback from RD'A.

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