Future Mediterranean drying: The role of stationary eddies

Supplementary Information

Roshanak Tootoonchi[1,2*], Simona Bordoni[2,3*] and Roberta D'Agostino[4]

[1*]Technologies for Climate Transition Division, Euro-Mediterranean Center on Climate Change, Milan, Italy.
[2]Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy.
[3]Center Agriculture Food Environment, University of Trento, Trento, Italy.
[4]Institute of Atmospheric Sciences and Climate, National Research Council of Italy, Lecce, Italy.

*Corresponding author(s). E-mail(s): roshanak.tootoonchi@cmcc.it; simona.bordoni@unitn.it;
Contributing authors: roberta.dagostino@cnr.it;

S1 Evaluation of CMIP6 against the ERA5 Mediterranean climatological moisture budget

Here we assess how well the ensemble of ten CMIP6 models used in this study reproduce the climatological Mediterranean moisture budget by comparing the multi-model mean with ERA5 over the 1995–2014 historical period.

A comparison of the annual sector-mean moisture budget decomposition between ERA5 (Fig. S1a) and CMIP6 models (Fig. S1b) indicates that the models represent the large-scale structure and the relative importance of the different components reasonably well.

The main discrepancies are an underestimation of the transient eddy moisture flux convergence ($-\nabla \cdot \langle \overline{\mathbf{u}'q'} \rangle$, green line) at higher latitudes and an overestimation

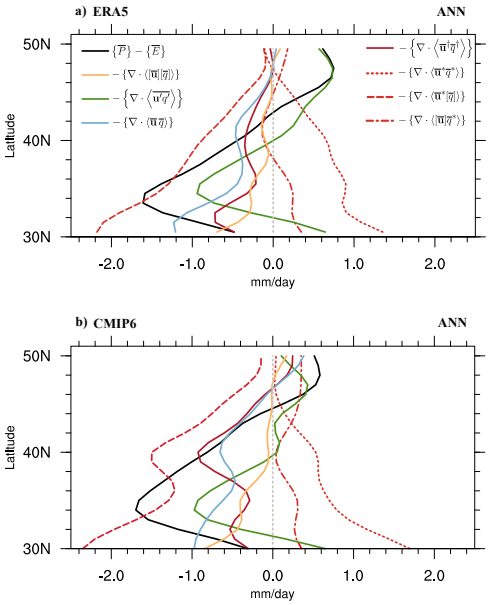


Fig. S1 Contributions from the constituent components of the atmospheric moisture budget to the annual and sector mean $P - E$ in the $1995 - 2014$ climatology across the Mediterranean sector (10°W and 40°E) for (a) ERA5 reanalysis and (b) CMIP6 multi-model mean.

of moisture divergence by the total stationary-eddy term ($-\nabla \cdot \langle \overline{\mathbf{u}}^{\dagger} \overline{q}^{\dagger} \rangle$, solid maroon line) across much of the domain. The latter primarily reflects excessive divergence of zonal-mean moisture by the zonally anomalous circulation ($-\nabla \cdot \langle \overline{\mathbf{u}}^{*} [\overline{q}] \rangle$, dashed red line).

The spatial comparison leads to a similar conclusion (Figs. S2 and S3). CMIP6 reproduces the broad spatial patterns of $P - E$ and its principal moisture-budget components, including the time-mean and stationary-eddy contributions. The largest localized discrepancies occur in $P - E$ and transient-eddy moisture transport over regions of complex topography, particularly the Alps and Balkans, where the models underestimate the strong, spatially concentrated moisture flux convergence seen in ERA5. These biases are likely related, at least in part, to the relatively coarse resolution of the GCMs and their limited representation of complex orography and Mediterranean storm systems. Similar limitations have been reported for earlier generations of climate models (Ziv et al., 2013; Seager et al., 2014). An important caveat to bear in mind is that transient eddies are calculated as a residual from monthly-mean data, which may introduce further uncertainty into this component.

Overall, despite these biases, the CMIP6 multi-model mean captures the large-scale structure and dominant components of the climatological Mediterranean moisture budget reasonably well. This provides confidence that the models represent the key processes examined here sufficiently well to investigate how they change under warming.

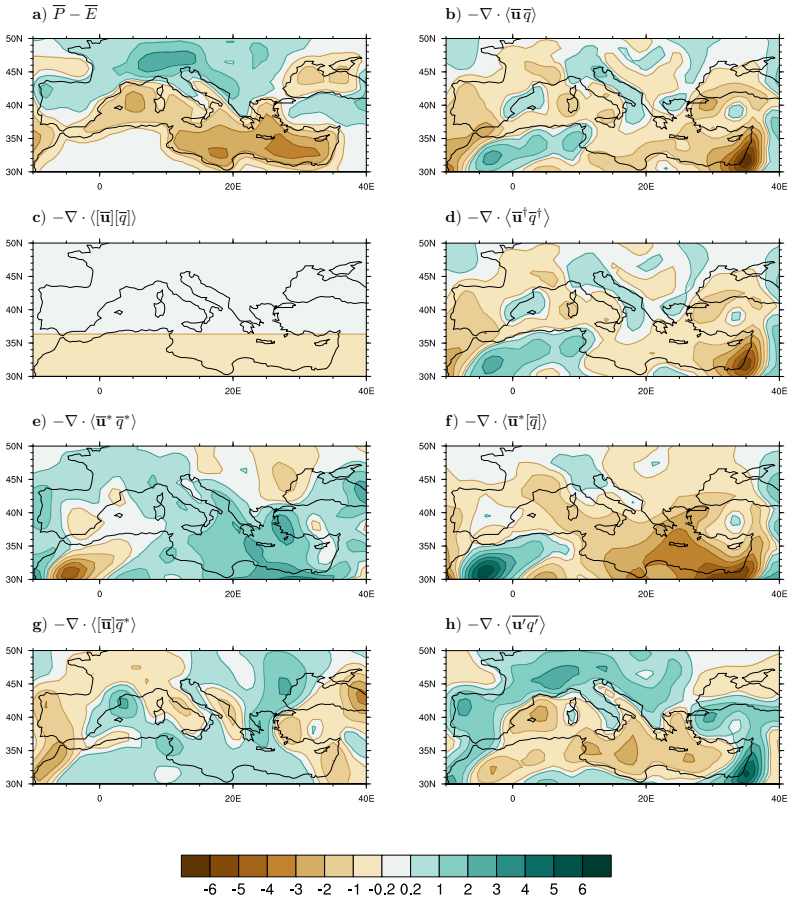


Fig. S2 The annual mean (ANN) Mediterranean moisture budget in the 1995–2014 climatology from the ERA5 reanalysis: (a) $P-E$, and moisture flux convergence by the (b) time mean flow, (c) mean meridional circulation, (d) total stationary eddies, (e) pure stationary eddies, (f) transport of zonal mean moisture by the zonally anomalous circulation, (g) transport of zonally anomalous moisture by the zonal mean circulation, and (h) transient eddies. Units are millimeters per day.

S2 Shoulder season changes

Projected changes in the Mediterranean moisture budget and its constituent components for spring (March–May, MAM) and autumn (September–November, SON) by the 2081–2100 period with respect to the 1995–2014 reference period are shown in Figs. S4–S7. Both seasons feature widespread decreases in $P-E$, broadly consistent with the annual-mean drying discussed in the main text.

In spring, the drying is primarily associated with increased moisture divergence by the time-mean flow (Fig. S4b), while transient eddies produce smaller and spatially heterogeneous tendencies (Fig. S4h). As in the annual mean, changes in the time-mean flow are dominated by stationary eddies (Fig. S4d), with only a small contribution

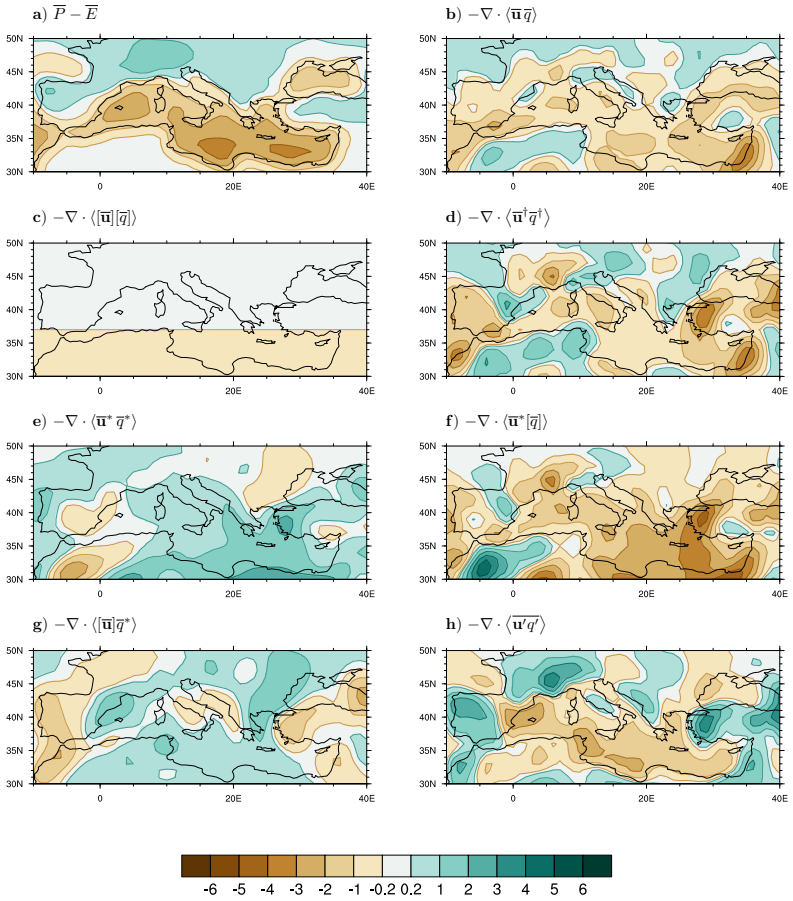


Fig. S3 The annual mean (ANN) Mediterranean moisture budget in the 1995–2014 climatology from the CMIP6 multi-model mean: (a) $P-E$, and moisture flux convergence by the (b) time mean flow, (c) mean meridional circulation, (d) total stationary eddies, (e) pure stationary eddies, (f) transport of zonal mean moisture by the zonally anomalous circulation, (g) transport of zonally anomalous moisture by the zonal mean circulation, and (h) transient eddies. Units are millimeters per day.

from the zonal-mean circulation (Fig. S4c). The stationary-eddy response reflects partial compensation between the zonally anomalous circulation acting on zonal-mean moisture (Fig. S4f) and the pure stationary-eddy term (Fig. S4e), with a smaller contribution from the transport of zonally anomalous moisture by the zonal-mean circulation (Fig. S4g).

The decomposition of the time-mean response (Fig. S5) shows that increased moisture divergence (Fig. S5b) more than offsets the generally weaker contribution from moisture advection (Fig. S5a). In MAM, this divergence response is primarily associated with circulation changes (Fig. S5d), while the thermodynamic contribution is weaker and more localized (Fig. S5c).

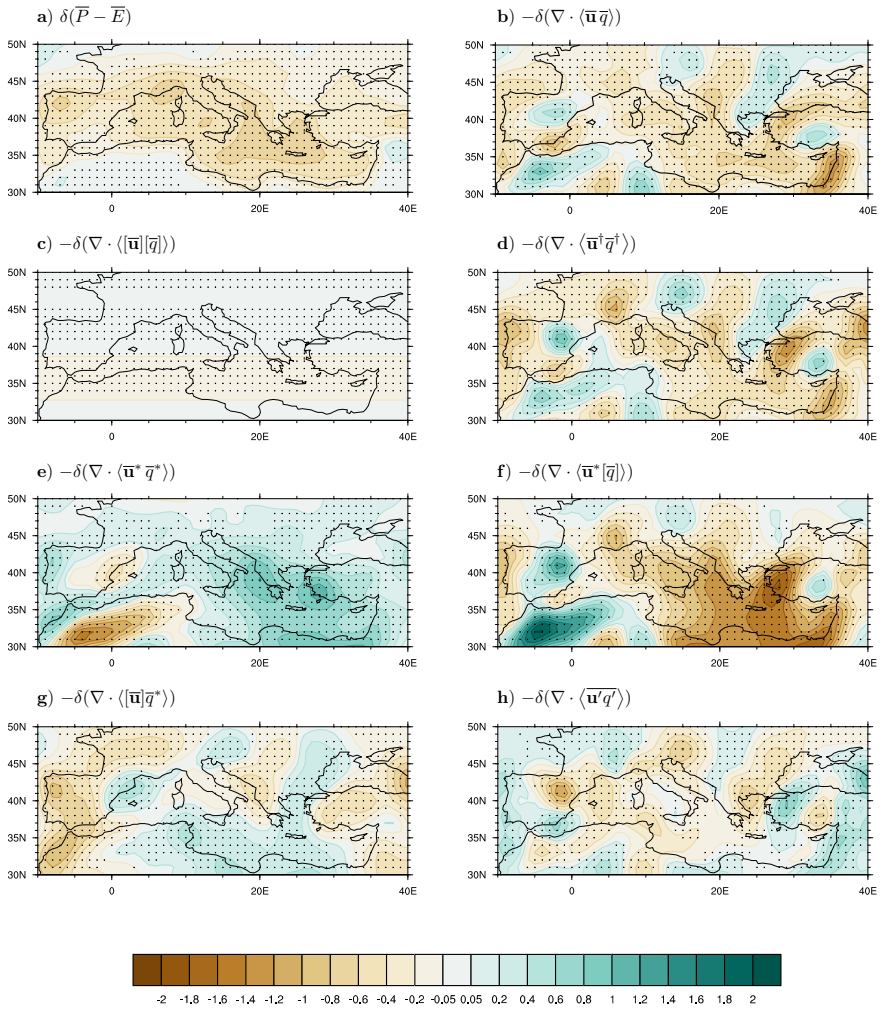


Fig. S4 Changes in the moisture budget components by the 2081–2100 period with respect to the 1995–2014 reference period for spring (MAM): Changes in (a) $P - E$, (b) time-mean flow, (c) zonal-mean flow, (d) stationary eddies, (e) pure stationary eddies, (f) zonally anomalous circulation, (g) zonally 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.

Autumn also features widespread drying associated primarily with increased moisture divergence by the time-mean flow (Fig. S6a,b). Unlike in spring, however, both stationary eddies (Fig. S6d) and the zonal-mean circulation (Fig. S6c) make appreciable contributions to the time-mean response. Stationary eddy changes again reflect compensation among their constituent terms (Fig. S6e–g), while transient eddies produce smaller, spatially varying drying and moistening tendencies (Fig. S6h).

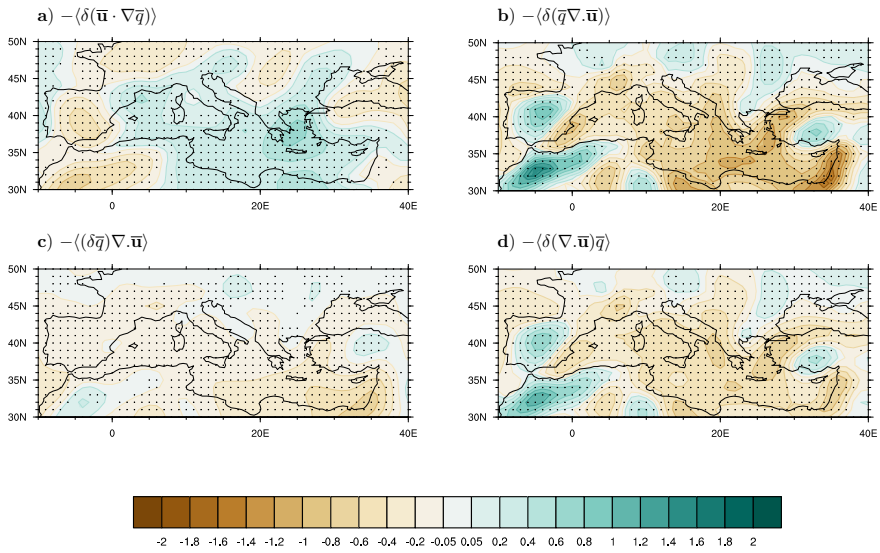


Fig. S5 Contributions from (a) moisture advection, (b) wind convergence and its components due to (c) thermodynamic changes, and (d) dynamic changes to changes in the mean flow MFC by the end of the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model mean for spring (MAM). Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.

As in spring, moisture advection (Fig. S7a) generally opposes the increased drying associated with moisture divergence (Fig. S7b). In autumn, however, both thermodynamic and dynamic changes contribute appreciably to the divergence response (Fig. S7c,d). Thus, while the shoulder seasons are broadly consistent with the importance of the time-mean flow and stationary eddies identified in the annual and solstice-season analyses, SON also shows a more substantial contribution from the zonal-mean circulation.

References

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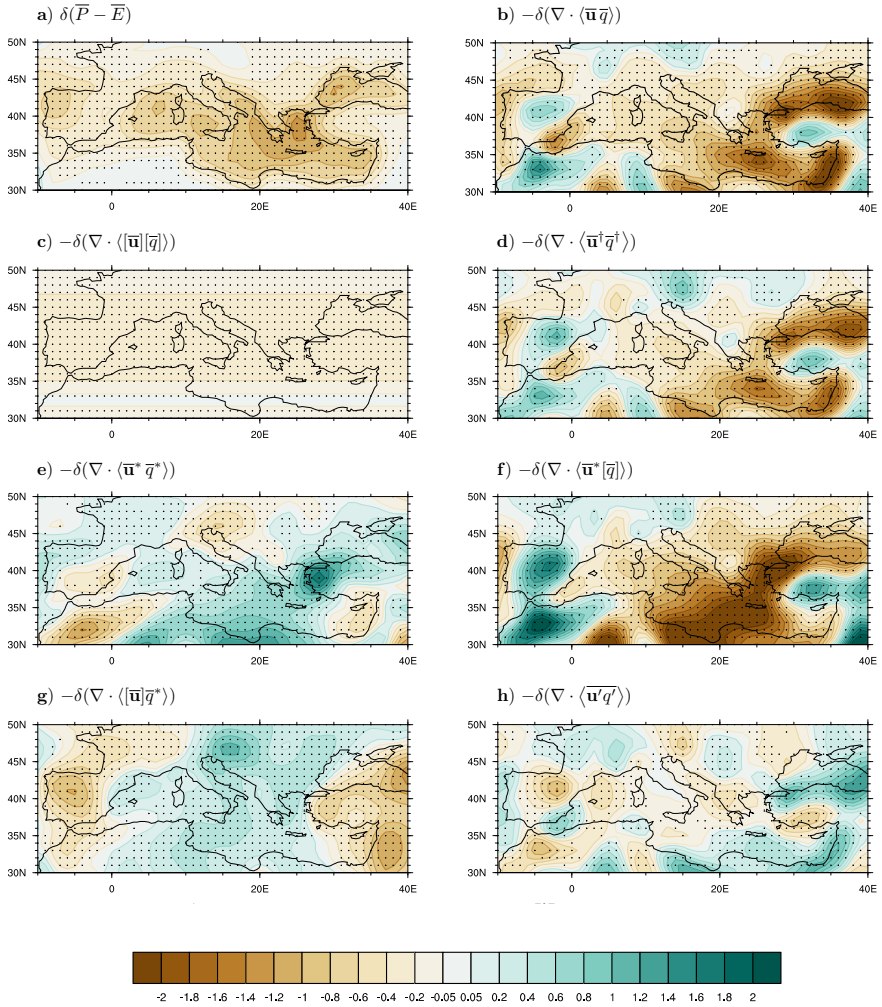


Fig. S6 Changes in the moisture budget components by the 2081–2100 period with respect to the 1995–2014 reference period for autumn (SON): Changes in (a) $P-E$, (b) time-mean flow, (c) zonal-mean flow, (d) stationary eddies, (e) pure stationary eddies, (f) zonally anomalous circulation, (g) zonally anomalous 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.

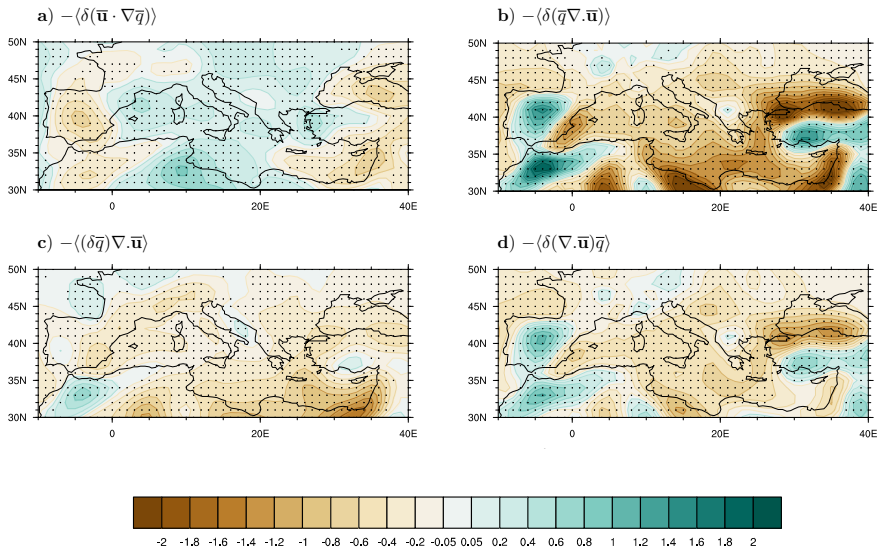


Fig. S7 Contributions from (a) moisture advection, (b) wind convergence and its components due to (c) thermodynamic changes, and (d) circulation (dynamic) changes to changes in the mean flow MFC by the end of the 2081–2100 period with respect to the 1995–2014 reference period from the CMIP6 multi-model mean for autumn (SON). Stippling indicates where more than 7 models agree on the sign of change, and units are millimeters per day.