Mediterranean Sea heat uptake variability as a precursor to winter precipitation in the Levant
Cohen et al.

Response to Reviewers

We thank the reviewers for their helpful and insightful comments, which improved the analysis and discussion in the manuscript. To address the reviewer's comments, we adapted the main text of the manuscript and added additional sections and figures to the Supplementary Materials (SM) with additional analyses. For convenience, the revised text with tracked changes is provided below.

Specifically, we added the following findings to the SM:

1. We expanded the SM section S1, elaborating on the SOM analysis and optimization, and added analyses and explanations of the method used to select the final SOM structure. Specifically, we analyzed the amount of variance explained by the different SOM structures, by an individual SOM pattern within each structure, and the Topographic errors that occur for each structure. Using these, we explain our selection of the final SOM structure, aiming to maximize the variance explained by the SOM structure and the leading pattern, and to minimize the amount of topographic errors, for the minimal amount of patterns, consistently yielding 3 very similar leading patterns in both the SOM and EOF analyses .
2. We added a section in the SM (S3) presenting the EOF analysis of ocean heat uptake and SST, and showing their correlations with Levant winter precipitation. The results are similar to those of the SOM analysis, showing that our selected patterns are not sensitive to our choice objective methodology. We decided to focus on the SOM analysis due to its slightly higher correlations (particularly with SST), as a prerequisite for defining AQA, although the EOF analysis can also be used to justify the regions chosen for the definition of AQA.
3. We added a section in the SM (S2) analyzing the relationship between Aegean Sea SST anomalies and Levant winter precipitation, showing that a similar analysis and predictive behavior can be achieved using SST, but that the results tend to be less significant. Given SST's lower predictive skill, we focused on ocean heat uptake in our analysis.
4. We added spatial maps showing the significance of the SOM patterns (added to SM section S1, Figure S4). We analyzed the statistical significance of the correlations between AQA and Levant winter precipitation (SM section S5, Figure S17).
5. To assess the robustness of the Aegean Sea's spatial definition in the calculation of AQA, we changed the area used to define the Aegean Sea by shifting it by ±0.25 degrees north and east, finding that the area defined as the Aegean Sea does not

significantly affect the correlations to Levant winter precipitation, which is the main objective of our analysis (added to SM section S5).

Additionally, following the Reviewers' comments, we tried to provide more comprehensive and clearer descriptions of our results and the analyses we performed. Specifically:

1. We elaborated on the optimization process used for the SOM analysis in the methods section, explaining the SOM method (Section 2.3), incorporating the selection method we used for the final SOM structure - minimizing the overall number of patterns, while maximizing the amount of variance explained by the SOM patterns (individually and in total) and minimizing the topographic error.
2. We added additional details on the calculation of correlations, both across SOM patterns and between SOM patterns and Levant land winter precipitation, to the captions of Figures 2 and 3, to make the analysis more straightforward.
3. We revised the manuscript to explicitly emphasize that additional analysis is needed to fully explain the physical mechanism underlying the lagged atmospheric response in the eastern Mediterranean. We addressed this question by analyzing atmospheric and surface data, but were unable to identify a relevant process at this time. We therefore hypothesize that the underlying processes driving the lag are oceanic in nature. Further analysis of the lagged response, therefore, is beyond the scope of the present analysis, and we hope to address it in future work.

Specific responses (black) to the Reviewers' comments (blue) are provided below.

Reviewer 1

The manuscript concludes that the Mediterranean heat uptake, especially in the Aegean basin, can be used as a precursor to predict winter land precipitation in the Levant (eastern Mediterranean). The topic is interesting and the manuscript has the potential to be a useful contribution. But I think a few points need to be addressed before its publication.

We thank the reviewer for the insightful comments.

Firstly, many technical details are missing, which is harmful for a good understanding of the manuscript. For example, it is really difficult to figure out what presented in Figures 2b, 2c, 3b, and 3c (tables showing correlation coefficients).

A more comprehensive description of the selection process for the SOM final structure has been added to the SM, and we also expanded our explanation about the selection process in the main text. Additionally, the captions of Figures 2 and 3 now include a more detailed description of the correlation calculations performed across and between the SOM patterns, as well as between the SOM patterns and Levant winter precipitation.

Secondly, the use of SOM is unusual and not justified in this work. Normally SOM is used with a 2-D grid of different nodes, but there are only three patterns in the manuscript.

We agree that there's some redundancy in using only three SOM patterns. This, however, is an emergent result of the selection process we used, which yielded three patterns. The selection process and rationale for using SOM patterns are now clarified in the SM and main text. Specifically, we examined both EOF and SOM patterns, aiming to maximize the variance explained by the SOM/EOF patterns with the fewest possible patterns. We found three key modes of variability in the Mediterranean, with the SOM patterns showing somewhat higher correlations with winter Levant precipitation, potentially because they are not constrained to be orthogonal to each other (as opposed to EOFs), allowing them to capture more of the variability. Since our goal was to find the modes with the highest predictive power for Levant precipitation, we base our results on the SOM patterns. However, the results are essentially not sensitive to the use of either SOM or EOF patterns.

Finally, the manuscript concludes that AQA (Aegean Sea heat uptake anomaly) is a good indicator for precipitation anomalies in the Levant. But, compared to SST which is a state variable, the heat flux is much more difficult to measure or to be deduced from observation. Its usefulness might be quite limited.

To address our unconventional decision to focus on ocean heat uptake for the definition of AQA, instead of SST (which is a state variable and much easier to measure), we added a section in the supplementary materials analyzing the correlations of monthly Aegean Sea SST anomalies, instead of ocean heat uptake, with Levant winter precipitation. The results are similar to those obtained with ocean heat uptake, but are less statistically significant. We therefore chose to focus on Aegean Sea ocean heat uptake (AQA) for the moisture balance and synoptic analysis, instead of SST. In addition, as we show in the text, ocean heat uptake is proportional to SST tendency, which explains the extended lag of about a month when considering ocean heat uptake relative to SST. This again points to ocean heat uptake as a more potent predictor. To address this point in the manuscript, we added an explanation in the results (Section 3.2) to clarify our decision to focus on ocean heat uptake rather than SST.

Furthermore, it is also a little disappointing that a clear physical mechanism is missing to link the AQA to the precipitation in the target area.

We agree that a clear mechanism accounting for the lagged response is sorely missing. We now acknowledge in the text that a complete physical mechanism is not presented, and that we still lack the explanation for the lagged response between the sea surface pattern and the synoptic conditions.
Having said that, given the seasonal timescale of the regional lagged response, we hypothesize that oceanic processes likely play a leading role, which we hope to explore further in future analysis using ocean reanalysis data and Lagrangian trajectory analysis. Initial promising

results, presented in Figure 6, show that winters following negative AQA August anomalies tend to be warm in the north-eastern Mediterranean, possibly contributing to the more unstable conditions we observe in the synoptic analysis. Nevertheless, additional analysis is needed to reach a definitive conclusion.

There are a few other points:

1. Figure 1 is used to motivate the present work exploring the role of the Mediterranean Sea in modulating precipitation in the Levant. But it is not very convincing. The signal is not remarkable in the Mediterranean, but much stronger in other basins of the global ocean.

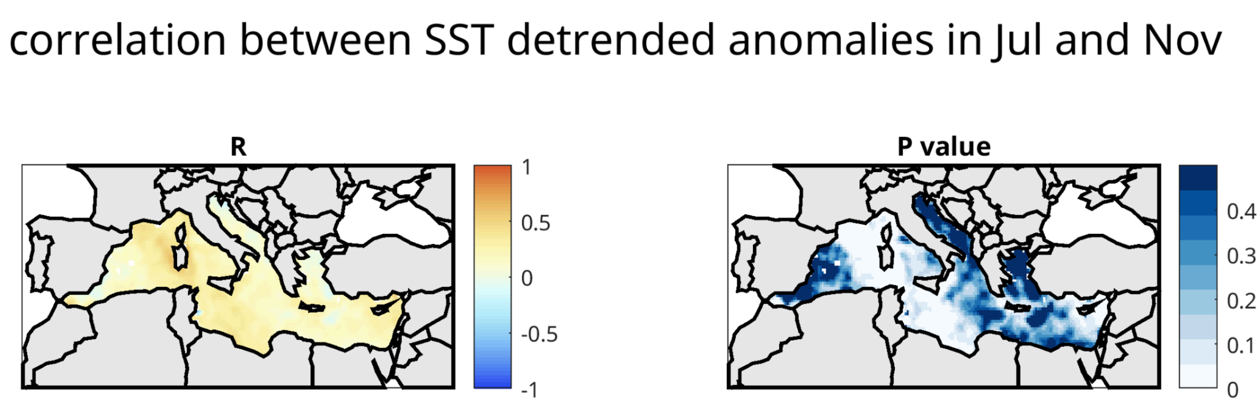
We use Figure 1 primarily to provide context for our review of existing work relating Levant precipitation to other regions (e.g., the Indian Ocean) and to show that there is considerable variation in the statistical relations observed in the leading months (Sep–Oct), suggesting nuance in the lagged relations. Indeed, somewhat surprisingly, SST correlations in the Mediterranean Sea are significant but lower than in more remote regions. But as we later show, these become significantly stronger when ocean heat uptake is considered.

2. Line 106, “The SOM algorithm is applied to detrended monthly deviations from the climatological seasonal cycle”. It is not clear how SOM is performed. Is it applied to anomalous SST, i.e., SSTa(m7:m11,y1979:y2023)?

Yes, we perform the SOM analysis on anomalies from the seasonal cycle for the entire time series, which is also detrended over the 45 years.

Is there any coherence or consistency among m7 (July) to m11 (Nov) for a same year?

To address the concern of autocorrelations in the sea surface conditions, we calculated the correlation of the detrended anomaly from the seasonal climatology of SST in July and November, and the correlations between them across the Mediterraenan:



The correlations indicate that in the Aegean Sea, where we focus our analysis, they are relatively weak (below R=0.25). Other regions in the Mediterranean exhibit stronger autocorrelation between summer and fall SST. Specifically, the western Mediterranean, and the area around Sardinia in particular, shows stronger correlations between summer and fall SST conditions.

3. Figs 2 and 3, Figure Caption, “SST monthly time series”. There is confusion for the term “time series”. More precisions are needed.

To address this, we changed the phrasing in the captions of Figures 2 and 3, so that the data we used for the SOM analysis will be more clearly stated, eliminating the phrase time-series.

4. Panels 2b, 2c, 3b, 3c. How is calculated the temporal correlation? between what and what?

We now specify in the text that the temporal correlations are performed between the time-series of the amplitude of the SOM patterns through time, and the spatial correlations are calculated across the SOM patterns themselves.

5. Line 207, “AQA is strongly correlated with Qf Pattern 2”. AQA is a time series, but the Qf SOM pattern is a geographic structure. How can they be correlated?

To address the reviewer's concern, we explicitly stated that the correlation is between AQA and the temporal amplitude of the second Qf SOM pattern.

Reviewer 2

This paper focuses on an important challenge of improving seasonal prediction of winter precipitation in the Levant region by connecting it with Mediterranean Sea heat uptake patterns. The authors use Self-Organizing Maps (SOM) to identify three main spatiotemporal patterns and develop the Aegean Qf Anomaly (AQA) index representing SOM 2, which correlates strongly with Levant winter precipitation. The research provides valuable insights for seasonal prediction. I also liked that they backed their research with physical interpretation through hydrological decomposition and synoptic analysis.

We thank the reviewer for the productive and insightful comments.

While the overall approach is solid, I have several concerns about methodological choices and explanations that need addressing. Here are my main points:

Major comments

1- SOM vs. EOF choice:

-The authors mention SOM's advantage of not requiring orthogonality, but don't fully explain why this matters for this specific analysis.

-If EOF produces similar patterns as, including at least one EOF figure in the Supplement would strengthen this justification.

To address the reviewers' comments on our decision to focus on SOM analysis rather than EOF, we added a section in the SM comparing the EOF analysis of Mediterranean SST and ocean heat uptake, which shows that the EOF-based results are very similar, albeit slightly less robust. Our conclusion that only three key modes dominate Mediterranean Sea variability, therefore, is independent of our choice between SOM and EOF analysis. We present the SOM patterns because they present somewhat higher correlations with our target region (the Levant). We hypothesize that the stronger correlations among SOM patterns are due to their not being constrained to be orthogonal (as in EOF), allowing the leading SOM patterns to capture more of the Mediterranean variability.

2- SOM parameter selection:

-The optimization approach - maximizing correlation with precipitation while minimizing pattern count - seems somewhat methodologically questionable. Why is maximizing correlation with the target variable appropriate for what should be a self organising clustering technique?

Note that the optimization was not particularly sensitive to the SOM parameters (shown in Figure S1), so that the number of patterns is essentially the key optimization parameter (as also indicated by the similar emergent patterns in the EOF analysis). In that regard, it makes sense to aim for patterns that capture Levant winter precipitation variability with the fewest degrees of freedom. We now explain this rationale in the revised text and also added more details about the SOM structure selection approach to the SM.

3- AQA index definition

-The fixed Aegean Sea box used for the AQA index appears to be visually selected based on SOM Patterns 2 and 3. While it is an effective choice, I recommend discussing the robustness of the AQA box definition.

To address the reviewer's comment, we added a note on the sensitivity of the AQA index definition in Section S5 of the SM. Specifically, we adjusted the definition of AQA by adding and subtracting 0.25 degrees north-south and east-west and calculating the correlations of the different regions with Levant winter precipitation. We find that a difference of ±0.25 degrees to the north or to the east in the definition of AQA has no significant effect on its correlations with Levant winter precipitation.

4- Correlation analysis details

-The key correlation between August AQA and winter precipitation (R = –0.60) needs more context. Please clarify exactly how Levant precipitation is calculated (sum/average over the region) and include confidence intervals for the correlations in Fig. 5b.

We added a figure to the SM showing the correlation statistics between AQA and Levant winter precipitation. It shows that the correlations in August AQA values are statistically significant at the 95% level.

The Levant land winter precipitation we analyze is calculated as the monthly weighted mean precipitation anomaly from climatology over the Levant domain identified in Figure 1. To ensure the reliability of the precipitation data, we also use in situ observations from meteorological stations around Israel. For the rain gauge data, we calculate the mean of all the stations within the domain.

5- Physical mechanisms

-While the composite analysis showing Cyprus Low persistence and subtropical jet strengthening is convincing, I would be cautious claiming independence from remote drivers (NAO, ENSO, etc.). Lack of correlation doesn't necessarily mean lack of physical connection. A mechanistic explanation would be more persuasive.

We agree with this critical point and now seek to clarify it in the Discussion. Specifically, while we show in Figure S15 that NAO and ENSO are not statistically related to AQA, we cannot exclude their potential influence in a more complex way.

Minor comments

- In abstract be specific that R = –0.60 refers to the correlation between August AQA and DJF Levant precipitation.

To address the reviewer's comment, we adapted the abstract to explicitly state that the correlation is between August AQA and DJF precipitation.

- In methods when describing heat uptake (Qf), clearly state that positive values mean the ocean gains heat and negative values mean heat transfer to the atmosphere.

We thank the reviewer for pointing out this issue. To make the manuscript clearer we explicitly stated in the text that positive heat uptake values indicate heat transfer from the atmosphere to the ocean.

- Figures 2–3: Include the cumulative variance explained by the three SOM patterns.

To address this comment, we added the variance explained by the 3 SOM patterns to the captions of Figures 2 and 3. Additionally, we added a figure in the SM (Figure S1) showing the variance explained by the different SOM structures of Qf and explaining its role in selecting the final SOM structure.

- Figure 5: Add statistical significance indicators or confidence bounds to the correlation values.

To avoid saturating the main-text Figure with detail, we added to the caption of Figure 5 a statement pointing to SM Figure S17 that shows the significance parameters (P-values and 95% upper and lower bounds) for the correlation coefficients between AQA and Levant mean anomaly land precipitation.

- Vague phrases like "optimal results" should be clarified - do you mean statistical robustness, strongest correlation, or something else?

In the revised text, we tried to avoid such vague terms. For example, we now describe the selection process for the number of SOM patterns, previously referred to as “optimization,” in more detail.

Reviewer 3

The researchers investigated the seasonal predictability of winter precipitation in the eastern Mediterranean (EM) with respect to the Mediterranean SST and heat uptake in the preceding summer/autumn. Based on both reanalysis data and observations, the authors use a SOM algorithm to classify SST and heat uptake fields into three groups. of them two show correlation to the following winter EM precipitation. Spatial patterns of lagged correlations between SST and Qf and subsequent winter precipitation in the EM are explored and compared between the two relevant groups, detecting peaks in August at the Aegean sea. The authors then define an Aegean sea anomaly index (AQA) which, when taken for August months, can act as a precursor with negative correlations to winter precipitation in the EM. Composites of positive and negative AQA-preceded winters are then further analyzed, thoroughly investigating the impact of the AQA on synoptic systems and on the decomposed hydrological balance.

The researchers conclude by proposing a cross-seasonal link between Aegean SSTs and Qf in August to winter precipitation in the EM. Through the eastward migration of the subtropical jet following negative AQA anomalies, cyclonic activity is reinforced in the EM, allowing for more persistent precipitation.

The study pursues a relevant objective in a novel approach, using reliable datasets and a range of sound methods. The manuscript is comprehensive and sound, well written and nicely structured, albeit slightly dispersed and over-informative at times.

I recommend accepting the paper after some minor concerns are answered and revisions made.

We thank the Reviewer for the useful comments and suggestions, which have been implemented in the revised text and Supplementary Materials (SM), as detailed below.

General comments:
1. There is a general feeling that the MS is constructed step by step based on its own statistical results. I recommend restructuring the MS in light of the results and the decisions taken by them, in a way that wouldn't overwhelm the reader. E.g., if the SOM shows similar results for both SST and Qf, and seeing as Qf proves to be a better predictor, why not avoid showing and discussing SST throughout? Clearly a lot of effort was put into this work, but not all must be shown to the reader.

Thanks for pointing this issue out. As mentioned by Reviewer 1, SST is a state variable that has been used in previous works and is a more intuitive choice as a potential predictor for most readers. This, in part, is the rationale for showing the relation to SST variations in Figure 1. Moreover, ocean heat uptake (Qf) and SST are related such that for a fixed mixed layer depth, the tendency of SST is proportional to Qf. The fact that the lagged correlations for Qf are lagged by an additional month compared to SST (as seen in the comparison between Figures 2 and 3) therefore shows physical consistency which bolsters our results. We estimate that providing results for both SST and Qf variations would facilitate a more intuitive interpretation of our results and make them more comparable to previous work. Thus, while we acknowledge that presenting both SST and Qf results may encumber the presentation, we tried to provide an overall balanced presentation that focuses on Qf while providing relevant context for SST where needed. In the revised text, we try to address the reviewer's concern, and provide more context for the presentation of both SST and Qf.

2. The SOM algorithm is underutilized here. The 1X3 network inherently looks for zonal variability only, leading to a rough separation that could have been easily obtained with less complex algorithms such as EOF or k-means, simplifying the interpretation of the results. Also, a significant test / standard deviations for the classified patterns is required to show regions of higher and lower confidence.

For the analysis shown in this manuscript, we used both the SOM and EOF methods, focusing on the SOM analysis for the final version and publication, because it yields higher correlations between the emergent patterns and Levant winter precipitation. To ensure the robustness of the results, we added to the EOF analysis of both SST and ocean heat uptake to the supplementary materials, showing that similar results can be achieved using EOF (incorporating more patterns and slightly weaker correlations). Additionally, to better explain the optimization method for the SOM analysis, we elaborate in the supplementary materials section on the SOM analysis and optimization, including a significance test for the SOM patterns and additional details on the optimization process. The optimization process for the final SOM structure consisted of running the SOM analysis algorithm for different SOM configurations (changing the number of columns and rows) and calculating the amount of variance explained by all the patterns, as well as the amount of variance explained by the leading SOM pattern. Additionally, we also calculated the topographical error of the SOM structure. The final optimization method used in our analysis was maximizing the amount of variance explained by the SOM structure and the leading SOM pattern, as well as minimizing topographic error and the overall number of patterns and repetitions within patterns. This optimization analysis yields the structure of 3 SOM patterns that we use in our analysis.

3. I think conciseness should be sought after in the revised MS. Some information can be removed from the figures and following discussions, increasing the focus on the main points the authors wish to convey.

This comment resonates with comment 1, and we agree with the reviewer that we should aim for a more focused and concise presentation. We tried to implement this guideline throughout the revised text.

Minor comments:
Figure 1: why is it important to show the difference between summer and winter precipitation? This panel isn't addressed in the text and the point of it is unclear.

Since Eastern Mediterranean precipitation occurs primarily in winter, winter minus summer highlights the Mediterranean regions, particularly the Levant. This is analogous to analyses of monsoonal regions, where summer minus winter precipitation is used to highlight monsoonal precipitation better. We clarify this in the revised text.

Also, the global maps are hard to see. Is it essential to have three of them? Perhaps one is enough to provide the context of remote teleconnections?

Figure 1 is used to facilitate discussion of previous similar works, examining the relationship between Levant winter precipitation and various climate indices worldwide. But the analysis of the specific influence of the Mediterranean remained lacking. We show the lagged responses to September, October, and November to demonstrate that, regardless of the specific details of the correlation for each month, the lagged relations vary significantly across months, pointing to complex dynamic influences (e.g., the tropical Atlantic and the Indian Ocean regions). In the revised text we try to better explain the motivation for Figure 1, while keeping the text as concise as possible.

L52: amplification of…

Corrected.

L179 and elsewhere: the authors refer to cluster frequency as "explained variance". I find this terminology more suitable for EOF analysis. For clarity and fluidity, consider using cluster frequency (or a similar term) throughout.

We calculated the amount of variance explained by incorporating both the pattern frequency, and the amount of variance explained by each pattern. The resulting variance explained is thus impacted by the pattern frequency, but is not identical to it. We now try to clarify this in the text and figure captions.

L184: what do you mean by “node”? please clarify

To address the comment, we removed the word “node” from the text and explained our meaning of the SOM structure and method in a more straightforward way.

Figure 2: I find the “correlation across SOM parameters” puzzling and unnecessary to propagate the reader through MS. Similarly, showing multiple months with mostly weak correlations that fluctuate from month to month does not support the robustness of the analysis. I suggest keeping the only the leading SOM input - Qf and only the most successful lead-time (August). This will make the message easier to take in.

We acknowledge that this may burden the reader and even obfuscate the results. We nevertheless elect to show the full set of results for completeness and transparency and try to do a better job of pointing the reader to the critical information.

L200: This is a methodological leap, especially since it is unclear how robust these spatial patterns are in the Aegean. More statistical testing is required to establish the Aegean Sea as an anchor for the SOM separation. E.G., did the results differ significantly when using the Ionian/Ligurian seas instead?

The Aegean Sea was selected because, consistent with the SOM patterns, it proved to be the strongest predictor of Levant winter precipitation. Thus, it was not selected based on SOM separation, but rather on its relation to Levant precipitation. We have extensively examined different regions that indicated potential predictive power (the vicinity of the Gulf of Lion in particular), but found the Aegean Sea to stand out in its statistical relation to Levant winter precipitation. We now state this in the text.

L207: anti-correlated?
To clarify that the correlation values are negative but significant, we changed the text to state that they are anti-correlated, as suggested by the comment.

Figure 4: would it be possible to denote the corresponding winter precipitation anomalies?

We have examined this. However, given that the winter precipitation anomalies consist of three-month averages and are related to AQA in a lagged manner, adding these on top of the AQAvariations is not visually particularly revealing. We therefore elect not to display these in this figure.

L275: please state that these conclusions relate to the negative AQA phase (correct?)
Yes, the conditions described are relevant for winters preceded by negative AQA values in August. We changed the text accordingly to clarify our meaning.

L280-283: this sentence is unclear. Please rephrase
To better clarify our meaning, we rephrased the sentence, expressing that the moisture balance analysis's results showing the dynamical mean component as important align with the intensified jet we observe.

L283: what do you mean by "geostrophic enhancement"?
We now explain that this refers to increasing horizontal pressure gradients with height, caused by the thermal low.

L293: I would consider rewriting this section with emphasis on the importance of this work and less speculations and general ideas that do not relate directly to this research.

We tried to make the Discussion less speculative and more focused on the results.

Mediterranean Sea heat uptake variability as a precursor to winter precipitation in the Levant

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Abstract.

The Eastern Mediterranean is experiencing severe warming and drying, associated with driven by global warming, making seasonal prediction of precipitation precipitation prediction in the region imperative. Given that the Mediterranean Sea is the primary source of regional moisture and synoptic variability, here we explore the observed relation of Mediterranean Sea variability to Levant land precipitation during winter – the dominant wet season. Using Self-Organizing Map objective analysis, we identify three dominant modes of sea surface temperature (SST) and ocean heat uptake variability in the Mediterranean Sea. Of these, two modes characterized by east-west variations are found to be statistically related to winter land precipitation in the Levant. Based on these relations, we define an Aegean Sea heat uptake anomaly index (AQA), which is strongly correlated with Levant winter precipitation. Specifically, AQA values during August are found to predict Levant land precipitation in the following winter (December–February, $R = -0.60$). Wetter winters over the Levant following negative August AQA values are associated with more persistent eastward-propagating Mediterranean storms, driven by enhanced baroclinicity and a stronger subtropical jet. The results present AQA as a useful seasonal predictor of Levant winter precipitation , and indicate that the representations of processes affecting Mediterranean cyclones, the subtropical jet, and ocean-atmosphere heat exchange , are key for are key to seasonal forecasting skill in the Levant.

1 Introduction

The Eastern Mediterranean (EM) is generally recognized as a global warming "hotspot", projected to experience significant climatic changes, including rising temperatures and intensified droughts, as well as extreme precipitation events and flooding (Giorgi, 2006; Lionello et al., 2006; Lelieveld et al., 2012; Cramer et al., 2018; Zittis et al., 2022; Hochman et al., 2022a). Seasonal prediction of precipitation (Giorgi, 2006; Lionello et al., 2006; Lelieveld et al., 2012; Cramer et al., 2018; Zittis et al., 2022; Hoc . Seasonal precipitation prediction in the Levant, a region prone to water stress, is therefore crucial for adaptation efforts. Given that the Mediterranean Sea is a critical source of moisture and a key driver of synoptic variability influencing precipitation in the Levant, we investigate the observed impact of spatiotemporal variability in the Mediterranean Sea on winter precipitation in the Levant.

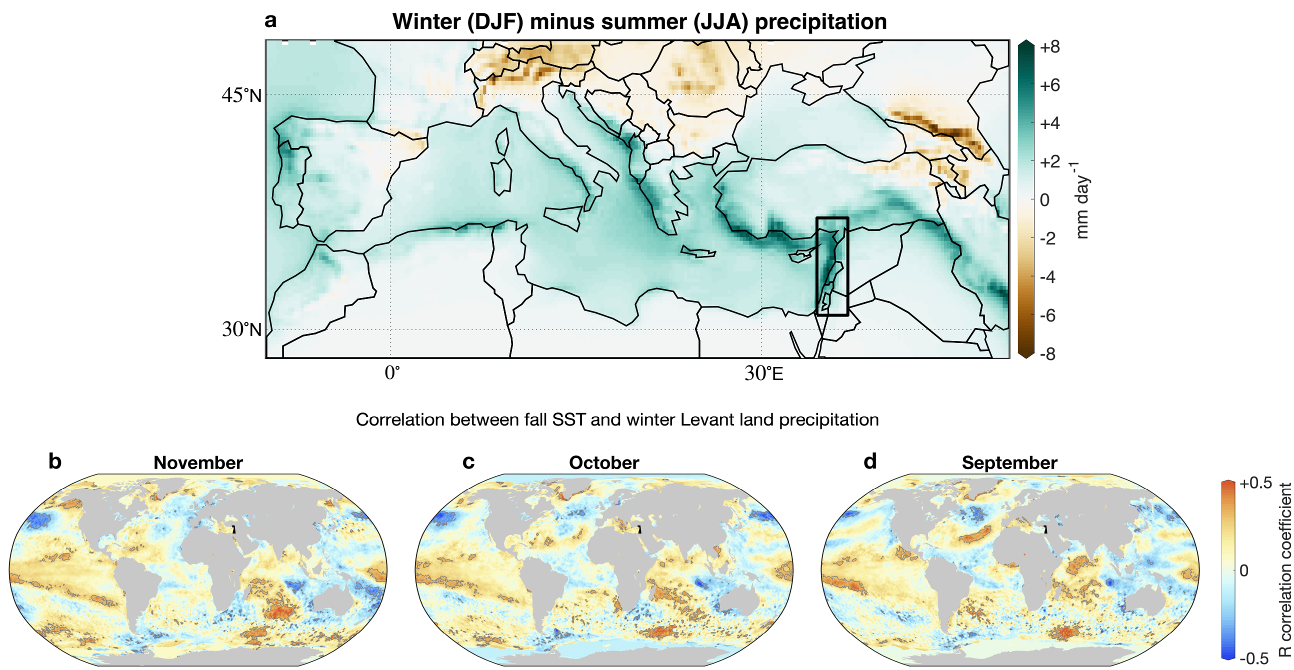

Figure 1. (**a**) Winter (December–February) minus summer (June–August) precipitation in the Mediterranean region; a black rectangle demarcates the Levant region considered in this study. (**b–d**) Pearson correlation coefficient of winter land precipitation in the Levant region and global sea surface temperature (SST) in the preceding November (**b**), October (**c**), and September (**d**) months, for the period 1979–2023. Data taken from the ERA5 reanalysis (Hersbach et al., 2020, see Section 2.1). Correlation 95% confidence bounds are shown in gray contours.

The EM lies in a transitional climate zone, subtended by temperate regions to the north and arid regions to the south (Goldreich, 2003; Ziv et al., 2006). EM climate is marked by relatively dry summers and wet winters, with the majority of precipitation occurring from December to February (Figure 1a). Seasonal synoptic patterns in the region result from the interaction of large-scale systems, such as the subtropical jet, subtropical highs, and the Asian monsoon, with smaller regional systems, and are modulated by the conditions in the Mediterranean Sea (Eshel and Farrell, 2000; Goldreich, 2003; Alpert et al., 2004b; Ziv et al., 2006; Lionello et al., 2006; Saaroni et al., 2010; Hochman et al., 2022b). The interaction of global and regional systems, therefore, critically affects precipitation predictability in the region ~~(Baruch et al., 2006)~~ (Baruch et al., 2006; Hochman et al., 2018a, 2023).

Various indices based on surface and atmospheric conditions in the Mediterranean have been used to capture precipitation and temperature variations in the Mediterranean basin (Conte et al., 1989; Palutikof, 2003; Martin-Vide and Lopez-Bustins, 2006; Criado-Aldeanueva and Soto-Navarro, 2013; Redolat et al., 2019). In particular, multiple versions of a Mediterranean

Oscillation index have been examined, motivated by the characteristic atmospheric east-west dipole in the Mediterranean basin (Conte et al., 1989). These, however, have shown limited predictive value in the EM on seasonal timescales (Redolat et al., 2019). In contrast, statistical approaches incorporating delayed interactions and ocean-atmosphere heat fluxes have shown significant potential for improving seasonal forecasting in the EM (Redolat and Monjo, 2024).

Recent work has demonstrated a delayed response of Levant precipitation to large-scale variations, which can serve as a basis for improved predictions of seasonal precipitation in the region (Amitai and Gildor, 2017; Hochman et al., 2022b, 2024). For example, statistical relations were established between Mediterranean Sea heat content in autumn and subsequent winter precipitation in several cities across Israel (Tzvetkov and Assaf, 1982; Amitai and Gildor, 2017). Synoptic weather systems in the EM were also shown to be modulated by the Mediterranean Sea, with Mediterranean SST changes affecting the development and intensity of Mediterranean cyclones, thereby delaying inland winter precipitation peaks from early to late January compared to coastal regions (Ziv et al., 2006; Flaounas et al., 2018). Such variations in sea surface conditions are expected to have both dynamic and thermodynamic impacts on EM precipitation, influencing both atmospheric flow and regional synoptic conditions, as well as the thermodynamic properties of advected air parcels (Seager et al., 2014; Elbaum et al., 2022; Tootoonchi et al., 2024; Seager et al., 2024).

~~Remote sea surface and atmospheric conditions are known to impact~~ Despite the Mediterranean's importance for Levant winter precipitation, previous work has primarily focused on remote links known to influence conditions in the EM. For example, Figure 1b-d shows global lagged correlation maps of observed SST anomalies and winter Levant land precipitation. Significant lagged correlations are seen in various regions, including the tropical Pacific, the North Atlantic, and the Indian Ocean. The positive correlation in the North Atlantic during September (Figure 1d) agrees with previous works showing links between positive phases of the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) and winter precipitation in the Levant, mediated by the effect of NAO and AO on the intensity of winter storms in the EM (Eshel and Farrell, 2000; Black, 2012; Givati and Rosenfeld, 2013; Luo et al., 2015), as well as upstream amplification of extratropical cyclones originating in the North Atlantic (Raveh-Rubin and Flaounas, 2017). The lagged correlations in the Tropical Pacific (Figure 1b-d) are consistent with previous work linking ENSO and winter precipitation in northern Israel during the second half of the 20th century (Price et al., 1998). Similarly, SST variability in the Indian and Pacific Oceans ~~has been shown to be~~ is dynamically linked to sub-seasonal precipitation variability in the Levant ~~(Hochman et al., 2024; Hochman and Gildor, 2025)~~ (Hochman et al., 2024; Hochman and Gildor, 2025; Reale et al., 2025).

Significant lagged correlations are seen in the Mediterranean Sea, which are the focus of the present analysis. In particular, the lagged spatial correlation patterns in the Mediterranean Sea vary across months, suggesting non-trivial regional links between Levant precipitation and Mediterranean Sea variability, which are explored here. Specifically, we aim to: (i) explore the observed links between objectively determined patterns of variability in the Mediterranean Sea and Levant winter precipitation; and (ii) analyze the physical processes underlying these links. Our results point to key ~~features~~ variations in the Mediterranean Sea that precede Levant winter precipitation anomalies, potentially providing a basis for improved seasonal prediction.

2 Data and methods

Our methodology is based on calculating the observed dominant spatiotemporal patterns of surface heat balance variability in the Mediterranean Sea using objective methods, and identifying which elements of these modes of variability hold predictive power for Levant precipitation. This is then followed by an analysis of the regional moisture balance (Seager et al., 2010, 2014) and synoptic conditions (Alpert et al., 2004b), providing context for the lagged response of Levant precipitation to Mediterranean Sea variability. The data, ocean mixed-layer heat balance, objective analysis methods, and analyses of moisture balance and synoptic conditions are briefly described below.

2.1 Data

For atmospheric and surface data, we use monthly and daily data from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 atmospheric reanalysis at 0.25°×0.25° grid-spacing, covering the period 1979–2023 (i.e., post-satellite era; Hersbach et al., 2020). ERA5 data has been shown in previous studies to provide reliable estimates of *in situ* observations of the hydrological cycle (Seager et al., 2024; Tootoonchi et al., 2024). ~~However, we~~ We nevertheless validate our results using *in situ* data from rain gauges distributed throughout Israel provided by the Israel Meteorological Service (IMS, *https://ims.gov.il*). In accordance with ERA5, the reference observed sea surface temperature (SST) data are taken from the HadISST2 dataset (Titchner and Rayner, 2014) up to September 2007 and from the Operational SST and Ice Analysis (OSTIA) dataset (Good, 2022) thereafter. For precipitation over land, we use ERA5-land (Muñoz-Sabater et al., 2021) at approximately 9 km resolution, which provides an improved representation of ~~land-specific~~ land processes.

2.2 Ocean mixed-layer energy balance

Upper-ocean heat content, given by the product of sea-water heat capacity c_p, ocean mixed-layer depth (h_{ml}, MLD), and SST (T), has been shown in previous work to be a contributing factor to processes affecting Levant precipitation over land, such as ocean-atmosphere heat and moisture exchange and land-ocean temperature contrasts (Amitai and Gildor, 2017; Tzvetkov and Assaf, 1982). In particular, Tzvetkov and Assaf (1982) and Amitai and Gildor (2017) demonstrated the potential of utilizing the ocean's ~~upper layer~~ upper-layer heat content during fall months to enhance predictions of winter precipitation in the Levant. Building on these results, we hypothesize that changes in Mediterranean SST and ocean heat uptake are linked to precipitation changes in the Levant. However, since estimates of MLD can vary significantly across datasets and methodologies (Kara et al., 2000; d'Ortenzio et al., 2005; Treguier et al., 2023; Keller Jr et al., 2024), we avoid using MLD as a predictor.

Specifically, the energy balance equation of the ocean mixed layer can be written as (Gill, 1982)

$$c_p h_{ml}\dot{T} + c_p\nabla\cdot(\tilde{\mathbf{u}}T) = Q_f + K_z \quad (1)$$

where $\dot{T}$ is SST tendency, $\tilde{\mathbf{u}}$ is the vertical-mean horizontal flow in the mixed layer, Q_f is the net downward heat flux at the ocean surface, and K_z is the input of heat to the mixed layer from below, associated primarily with small-scale vertical mixing. Here positive Q_f values indicate heating of the upper ocean and Negative Q_f values indicate release of heat from the ocean surface to the atmosphere. Also, for sufficiently small temporal variations of the ocean mixed layer depth, SST tendency is approximately proportional to to Q_f.

The net surface energy input into the ocean mixed layer (Q_f) consists of the net downward shortwave (SW) and longwave (LW) surface radiation, and the downward sensible (SH) and latent (LH) surface heat fluxes, minus the fraction of the shortwave radiation penetrating below the mixed layer (Q_P)

$$Q_f = SW + LW + SH + LH - Q_P \tag{2}$$

where Q_P is calculated as a 25-meter e folding decay of shortwave radiation, given by the equation $Q_P = 0.45SWe^{-\gamma h_{ml}}$, with γ being a decay rate constant equal to $0.04m^{-1}$ (Wang and McPhaden, 1999; Vallès-Casanova et al., 2025).

2.3 Self-Organizing Map (SOM) Analysis

To capture the spatial patterns of Mediterranean Sea variability, we employ the Self-Organizing Map (SOM) unsupervised neural network technique for clustering and visualizing high-dimensional data (Kohonen, 1990). For our particular analysis, SOM is advantageous over more traditional methods such as empirical orthogonal function , as well as Empirical Orthogonal Function (EOF) analysis (Hannachi et al., 2007). The two methods provide very similar results, albeit statistically stronger for the SOM analysis, potentially because it does not require the patterns extracted to be orthogonal, potentially parsing allowing its leading modes to better parse the relevant phase spacewith fewer patterns than EOF. Nevertheless, qualitatively similar results, albeit statistically weaker, were obtained by deriving the patterns of Mediterranean variability using EOF analysis. We therefore focus in the main text on the SOM patterns, but provide comparable EOF analyses in the Supplementary Materials (Section 3).

The SOM algorithm is applied to detrended monthly deviations anomalies from the climatological seasonal cycle. The SOM parameters are optimized to results are insensitive to the parameters used in the analysis such as the neighborhood function and it's radius, and the number of iterations performed in the SOM analysis. The final SOM structure is selected to maximize the correlation between the derived spatial patterns and Levant land precipitation, to maximize the amount of variance explained by the SOM structure and the leading SOM pattern, while minimizing the overall number of patterns and the topographic error of the SOM structure (see Supplementary Materials Section 1 for more details on the SOM parameters and the selection process). This yields an analysis based on three SOM patterns (with one row and three columns, see Supplementary Materials Figures S1, S2, and S3), applied to both SST and Q_f (see Supplementary Materials for more details on the SOM parameters and procedures). The usage of . The leading three EOF patterns yields similar optimal results, indicating that the emergent key patterns are not sensitive to the specific SOM algorithm parameters. Our use of monthly reanalysis data for the SOM analysis increases the sensitivity to more slowly evolving modes of variability in the Mediterranean (i.e., monthly time scales). Nevertheless, repeating our SOM analysis using 5-day ocean data yielded nearly identical spatiotemporal patterns, supporting the robustness of the derived patterns of variability.

2.4 Decomposition of precipitation variations

The steady moisture equation of the atmosphere can be written as (Seager et al., 2010)

$$\bar{P} = \bar{E} - \langle \nabla \cdot (\bar{\mathbf{u}}\bar{q}) \rangle - \langle \nabla \cdot (\overline{\mathbf{u}'q'}) \rangle - \overline{q_s \mathbf{u}_s} \cdot \nabla \bar{p}_s \tag{3}$$

where P and E represent precipitation and evaporation, respectively, $\mathbf{u}$ is the wind vector, q denotes specific humidity, p denotes pressure, and the subscript $(\,\cdot\,)_s$ denotes surface values. Angled brackets denote mass-weighted vertical integrals,

$$\langle \cdot \rangle \equiv \frac{1}{\rho_w g} \int_0^{p_s} (\cdot)\, \mathrm{d}p$$

where ρ_w is the density of water and g is Earth's gravitational acceleration; overbars and primes denote monthly temporal means and deviations thereof, respectively.

Following the methodology and terminology described in Seager et al. (2010), it follows from Eq. (3) that changes in precipitation can be decomposed into those involving changes in evaporation, the mean wind field (dynamic changes), the mean moisture field (thermodynamic changes), surface moisture transport, and transient eddies ~~(Seager et al., 2010, 2014; Kaspi and Schneider, 2013;~~ (Seager et al., 2010, 2014; Kaspi and Schneider, 2013; Wills et al., 2016; Elbaum et al., 2022; Tootoonchi et al., 2024; Bril et al., 2025) .

We define δ as the difference between two composites of monthly means,

$$\delta \equiv \overline{\overline{(\,\cdot\,)}}_2 - \overline{\overline{(\,\cdot\,)}}_1 \tag{4}$$

where a double overbar denotes a temporal average over some period. Neglecting changes associated with surface pressure, we rewrite the moisture balance equation to express the difference between two composites of winters,

$$\delta P \cong \delta E - \delta \langle \nabla \cdot (\bar{\mathbf{u}}\bar{q}) \rangle - \delta \langle \nabla \cdot (\overline{\mathbf{u}'q'}) \rangle. \tag{5}$$

In the next section, we refer to the second and third right-hand side terms as the changes in the mean and transient components of precipitation, respectively, where the mean component is further decomposed into mean thermodynamic ($-\langle \nabla \cdot (\bar{\bar{\mathbf{u}}}[\delta\bar{q}]) \rangle$) and the mean dynamic ($-\langle \nabla \cdot ([\delta\bar{\mathbf{u}}]\bar{\bar{q}}) \rangle$) components.

2.5 Semi-Objective Synoptic Classification

Due to the critical influence of synoptic-scale conditions on precipitation in the Levant (Lionello et al., 2006; Goldreich, 2003), we examine the relationship between these conditions and our calculated patterns of variability. Specifically, we classify synoptic conditions based on the semi-objective methodology proposed by Alpert et al. (2004b), which has been used in previous works to study EM seasonal synoptic variations (Alpert et al., 2004a), as well as changes under ~~global warming~~ climate change in weather patterns ~~(Hochman et al., 2018c, b, 2020) and~~ (Hochman et al., 2018c, b, 2020; Ludwig and Hochman, 2022), extreme weather events (Rostkier-Edelstein et al., 2016; Hochman et al., 2022a), and their impacts (Hochman et al., 2021a).

The classification method uses four single-level atmospheric fields: geopotential height, temperature, and the zonal and meridional components of wind; all at 1000 hPa and at a grid-spacing of 2.5°×2.5° over the EM region (defined within the coordinates 27.5°–37.5°N and 30°–40°E), sampled at 12:00 UTC each day. The synoptic classification of each day within the EM is therefore calculated using 100 data points (5×5 grid points for each of the four atmospheric fields), which are also standardized by subtracting the long-term mean and dividing by the standard deviation of the time series of each field. The classification of each day to its synoptic type is performed by comparing each of these daily datasets to 426 days that were manually classified by a team of expert meteorologists (335 days from 1985 and 91 days from the winter of 1991–1992). The synoptic type of each day is determined as that for which the Euclidean distance from each of the manually classified days is lowest. The reference 426 days are categorized into five synoptic groups (Alpert et al., 2004b), of which two are associated with winter precipitation:

~~i~~

i. **Cyprus Low (CL)**: A Mediterranean cyclone centered near Cyprus, often responsible for significant rainfall and stormy weather in the Levant region and significant impacts (Khodayar et al., 2025; Hochman et al., 2021a).

~~ii~~

ii. **Red Sea Trough (RST)**: A low-pressure trough extending from the southern Red Sea into the EM, often associated with warm, moist air advection and convective activity. It produces occasional intense precipitation during transition seasons in the southeastern Levant.

The remaining three synoptic groups are associated with warm and dry conditions:

iii. **Highs (H)**: A high-pressure system over the EM throughout the year (as an extension of the Siberian high), leading to stable, dry, and clear weather.

iv. **Persian ~~Through~~ Trough (PT)**: A thermal low originating over the Persian Gulf and extending westward, typically bringing warm and moist conditions to the EM during summer.

v. **Sharav Low (SL)**: A transient heat low forming over the western Sahara and moving eastward, bringing hot, dry, and windy conditions to the EM, typically during spring.

To better identify the driving factors impacting the synoptic change, we analyze the regional atmospheric conditions between winter composites. Accordingly, we study the changes in mean sea-level pressure conditions, the 500 hPa geopotential, and the strength and position of the subtropical jet. Additionally, to quantify the difference in the regional baroclinic conditions, we use the Eady Growth Rate, as defined in Hoskins and Valdes (1990):

$$\sigma = 0.31 f N^{-1} |\partial_z \mathbf{v}| \quad (6)$$

Where σ is the Eady Growth Rate between the 850 and 500 hPa pressure levels, f is the Coriolis parameter, N is the Brunt-Väisälä frequency, and $\partial_z \mathbf{v}$ is the vertical shear of the horizontal wind.

3 Results

We begin by calculating the spatiotemporal patterns of variability in Mediterranean SST and surface heat uptake (Q_f). Based on these patterns, we define an index that captures a strong statistical relation between summer Q_f anomalies in the Aegean Sea and winter precipitation anomalies in the Levant (December–January average over land). We then provide context for this relation using analyses of the regional hydrological cycle and synoptic conditions.

3.1 Spatiotemporal patterns of variability

We cluster the Mediterranean SST and Q_f monthly time series into three SOM patterns of variability (Figures 2a and 3a, respectively). The SOM patterns for SST and Q_f show a high degree of similarity, allowing their joint analysis. SOM pattern 1 explains 14% of SST temporal variance and 13% of Q_f temporal variance, and can be described as generally capturing a gradient between the central Mediterranean and its eastern and western parts. This pattern does not show a significant lagged correlation to Levant precipitation (Figures 2b and 3b), and is therefore not further analyzed.

The second and third SOM patterns of SST and Q_f, which account for most of the temporal variance (45% and 42% for SST and 46% and 35% for Q_f, respectively), generally capture east-west gradients across the Mediterranean basin (Figures 2a and 3a), consistent with the characteristic east-west dipole seen in atmospheric variables (Conte et al., 1989). Specifically, Pattern 2 features a ~~node~~ surface anomaly located between the Ionian and Tyrrhenian Seas (i.e., east and west of Sicily); Pattern 3 exhibits a pronounced gradient between the western Mediterranean and the Aegean Sea. For both SST and Q_f, Patterns 2 and 3 have significant lagged correlations with Levant winter precipitation (peaking during November, September, and July for SST, and during October and August for Q_f), showing potential for sub-seasonal to seasonal prediction (Figures 2b and 3b). Consistent with Eq. (1), since Q_f drives variations in SST, the peak correlation of Q_f is observed to lag that of SST by an additional month. Moreover, despite this extended lag, the highest correlation with Levant precipitation is found for Pattern 2 of Q_f in August ($R = 0.53$).

The spatial ~~and~~ correlations across the SOM patterns and the temporal correlations across the ~~SOM patterns~~ time series of the SOM patterns' amplitudes are shown in Figures 2c and 3c. For both ~~fields~~Q_f and SST, Patterns 2 and 3 are strongly spatially correlated ($|R| \geq 0.78$) but relatively weakly temporally correlated ($|R| \leq 0.36$), indicating that despite their topographical similarities, these patterns vary on different timescales.

Given that the largest correlation with Levant winter precipitation is found for the Q_f SOM patterns, and that these are statistically significant over most regions of the Mediterranean (Supplementary Materials Figure S4), we hereon focus our analysis on Q_f. During the peak correlation month of August, Q_f variations are dominated by latent heat fluxes, with minor contributions from sensible heat fluxes and negligible contributions from radiative fluxes (~~Supporting~~ Supplementary Materials Figure S1). Since latent and sensible heat fluxes are strongly dependent on near-surface winds and atmospheric conditions (such as temperature and humidity), this suggests that coupled ocean-atmosphere processes are critically linked to the lagged ~~correlation~~correlations.

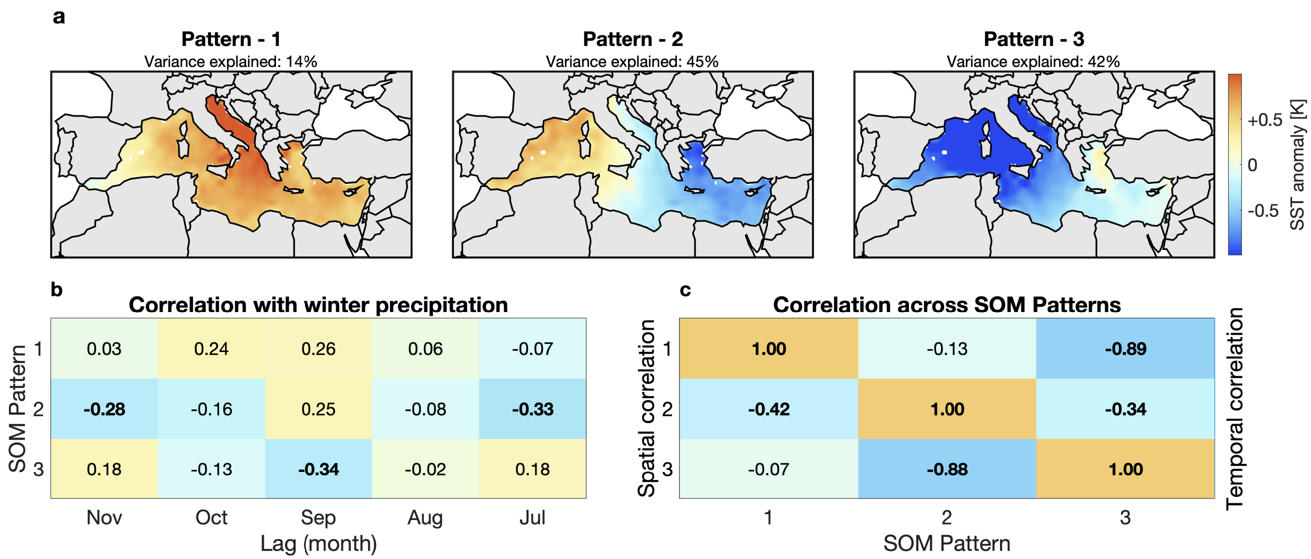

Figure 2. (a) Mediterranean ~~SST~~ monthly ~~time series~~ SST anomalies from 1979 to 2023 clustered into three SOM patterns; (b) Lagged correlation of the amplitude of each monthly SST SOM pattern during the months July–November with mean Levant winter ~~precipitation over~~ (DJF) land precipitation; (c) Spatial correlations between the SOM patterns (below diagonal) and temporal ~~(above diagonal)~~ correlations ~~across~~ between the time series of the amplitudes of the SOM patterns (above diagonal). Pearson correlation coefficients significant at the 5% level are in bold. ~~Data taken from ERA5 for the period 1979–2023.~~ The variance explained by each SOM pattern refers to the temporal variance explained by each pattern. The total variance explained by the three patterns, which takes into account the pattern frequency, is 37%. Data taken from ERA5 for 1979–2023.

3.2 Aegean Q_f Anomaly index

We find that mean Q_f values in the Aegean Sea reproduce the lagged correlations with Levant precipitation seen for SOM patterns 2 and 3. We therefore define an Aegean Sea Q_f Anomaly index (AQA) as a precursor to Levant winter land precipitation. Specifically, AQA is defined as the Q_f detrended anomaly from seasonal climatology in the north-eastern region demarcated in Figures 3a and 4(a-b) (23.5°–26.5°E, 32.5°–35°N), normalized by the standard deviation of the anomaly timeseries. Note, however, that based on SOM patterns 2 and 3, this index does not only indicate Q_f changes in the Aegean Sea, but also contrasting Q_f changes in the western Mediterranean (and similarly for SST; Figures 2 and 3). The AQA index was found to have considerably stronger predictive power compared to indices based on other regions of the Mediterranean and is not sensitive to ±0.25° variations of its boundaries. A similar AQA index based on SST yields similar but statistically weaker results (see Supplementary Materials Section 2).

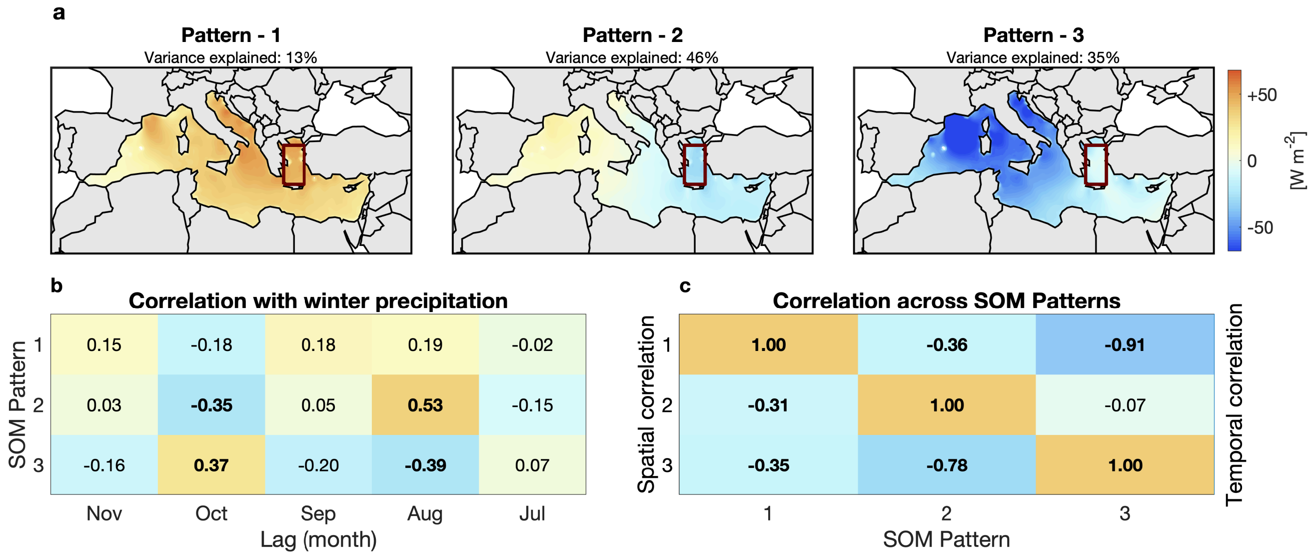

Figure 3. (a) Mediterranean ~~Q_f~~ monthly ~~time series~~ Q_f anomalies from 1979 to 2023 clustered into three SOM ~~patterns~~pattern. Red rectangle indicates region used to calculate the Aegean Q_f Anomaly index (AQA, defined in section 3.2)~~;~~. (b) Lagged correlation of the amplitude of each monthly Q_f SOM pattern ~~to~~ during the months July–November with mean Levant winter (DJF) land precipitation; (c) Spatial correlations between the SOM patterns (~~bellow~~ below diagonal) and temporal ~~(above diagonal)~~ correlations ~~across~~ between the time series of the amplitudes of the SOM patterns (above diagonal). Pearson correlation coefficients significant at the 5% level are in bold. ~~Data taken from ERA5 for the period 1979–2023.~~ The variance explained by each SOM pattern refers to the temporal variance explained by each pattern. The total variance explained by the three patterns, which takes into account the pattern frequency, is 35% (see Supplementary Materials Figure S1). Data taken from ERA5 for 1979–2023.

Monthly AQA values are shown in Figure 4c. AQA is ~~unit-less~~unitless, with positive values indicating higher ocean heat uptake in the Aegean Sea relative to climatological conditions (Figure 4a, b). AQA is strongly ~~correlated with~~ anti-correlated with the temporal amplitude of the second Q_f ~~Pattern 2~~ SOM pattern ($R = -0.85$, Figure 5a) and can therefore be interpreted as generally proportional to the amplitude of this SOM pattern.

AQA is significantly correlated with Levant winter precipitation, in both ERA5 data and *in situ* IMS rain gauges, with the strongest lagged correlation in August ($R = -0.60$), in agreement with the Q_f Patterns 2 and 3 (Figure 5a). The correlation is strongest for winter (Dec–Feb), but is significant for each of the winter months (Figure 5b). These results are not sensitive to the choice of Dec–Feb as the winter months, and remain significant for earlier, later, or longer winter months combinations (specifically, Nov–Mar, Nov–Jan, and Jan–Mar, shown in Supporting Materials Figure S2).

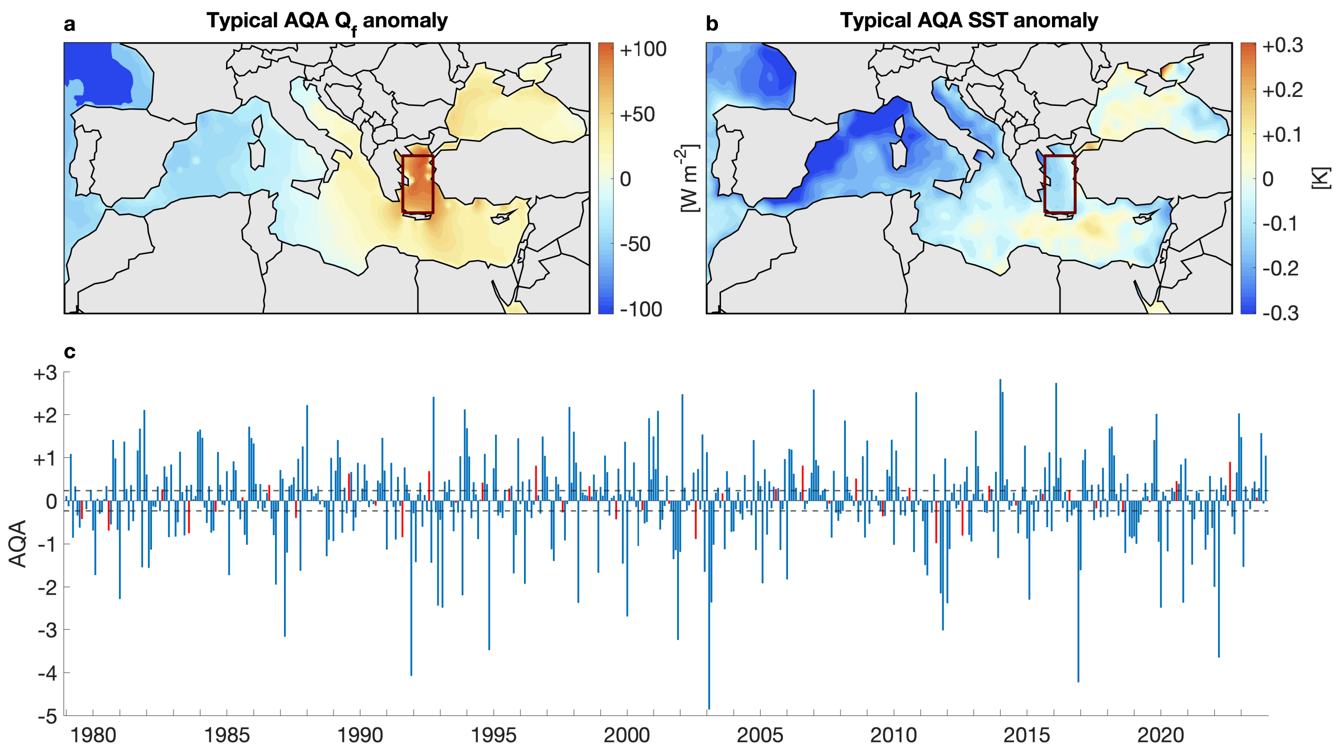

Figure 4. Aegean Q_f anomaly Index (AQA), defined as the detrended anomaly from climatology of Q_f in the Aegean Sea (23.5°–26.5 °E, 32.5°–35°N, red rectangles in panels a and b), normalized by the standard deviation of the anomaly timeseries. The typical ~~Q_f~~ difference between (a) Q_f and ~~SST~~ (b) ~~difference between~~ SST positive and negative AQA months (taken as months above or below ±0.5 the standard deviation of AQA). (c) Monthly AQA values from January 1979 to December 2023. August months, which are the most strongly correlated with winter Levant land precipitation, are shown in red. Gray dashed horizontal lines denote ±0.5 the standard deviation of August AQA values.

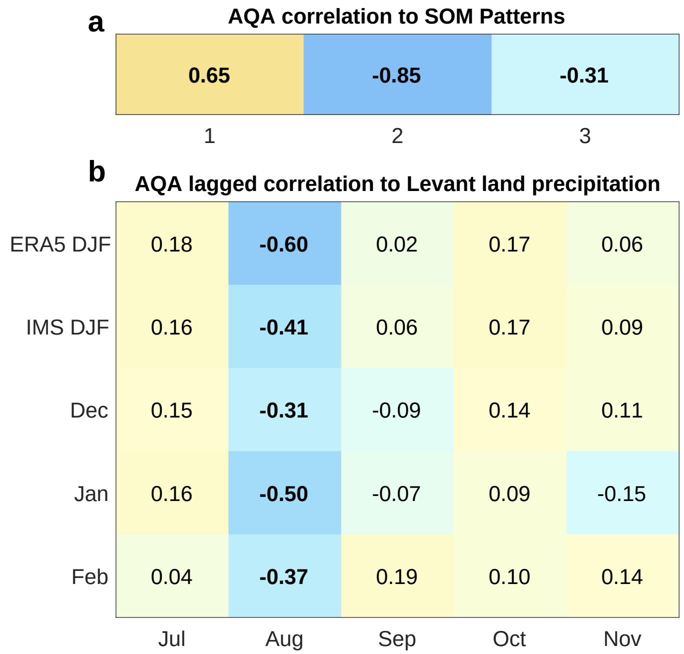

Figure 5. (a) Correlations of the Aegean Q_f anomaly index (AQA) with the Q_f SOM patterns. (b) Correlations of AQA with Levant land winter precipitation using ERA5-land data and rain gauge data from the Israel Meteorological Service (IMS, https://ims.gov.il). The p-values and 95% upper and lower bounds of the AQA correlations to Levant land precipitation anomalies are shown in Supplementary Materials Figure S17.

We now turn to analyzing the winter conditions associated with AQA variations by examining the differences between composites of winters preceded by August AQA values below and above plus and minus half of the standard deviation of August AQA values (∼13 years in each composite group; cf. Figure 4). The difference in winter SST between the two composites, shown in Figure 6a, exhibits higher SST conditions in the north-eastern Mediterranean, which persist throughout winter (not shown). The increased winter SST in the north-eastern Mediterranean is indicative of increased upward surface heat and moisture fluxes, which, in turn, imply favorable conditions for cyclogenesis and storm intensification (e.g., Flaounas et al., 2022). Accordingly, the winter Q_f difference between these winter composites (Figure 6b) shows decreased ocean heat uptake in the EM, driven primarily by increased upward latent and sensible heat fluxes during negative AQA composite winters.

The composite difference of hydrological changes is shown in Figure 7. A significant increase in precipitation is seen in the EM (Figure 7a). The majority of the precipitation increase is seen in the mean component of the moisture flux convergence (Figure 7c), with minor contribution from transient eddies in the northern Levant (Figure 7d), and negligible contribution from changes in evaporation (Figure 7b). Further decomposition of the mean component (Figure 7c) shows that the mean thermodynamic component (Figure 7e) is negligible, while the mean dynamic component dominates the precipitation response (Figure 7f).

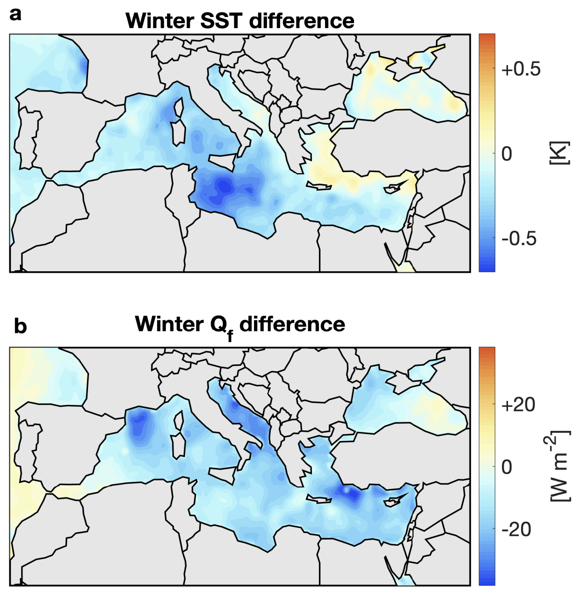

Figure 6. Mean (a) SST and (b) Q_f difference between composites of winters preceded by August AQA values below and above half the standard deviation of August AQA values, respectively.

We therefore conclude that the increased winter Levant precipitation associated with negative AQA anomalies during the preceding August is mediated by changes in regional mean flow patterns, creating more favorable conditions for precipitation by synoptic systems migrating eastward from the central Mediterranean to the Levant. Next, we turn to synoptic analysis to diagnose the meteorological conditions underlying the winter precipitation response to AQA.

3.3 Synoptic analysis

Using the semi-objective synoptic classification (Alpert et al., 2004b), we assess the difference in synoptic conditions between winters preceded by August AQA above and below half the standard deviation of August AQA values (Figure 8a). Negative August AQA values are associated with increased prevalence of Cyprus Lows (CL, 32 vs. 25 days per winter) and decreased prevalence of Red Sea Trough systems (RST, 27 vs. 35 days per winter), with negligible changes in the other synoptic groups. Given that winter precipitation in the EM is dominated by eastward propagating Mediterranean cyclones (i.e., Cyprus Lows; Saaroni et al., 2010), and that Red Sea ~~Through~~ Trough synoptic conditions rarely lead to precipitation, these results are consistent with the winter precipitation response to AQA shown in Figure 7a.

To assess whether the enhanced Cyprus Low activity results from increased number or duration of storms, we calculate the composite difference in the number of synoptic systems occurring in the region during winter (defined as the number of days minus the number of consecutive days of each synoptic type during winter; Figure 8b). The number of Cyprus Low

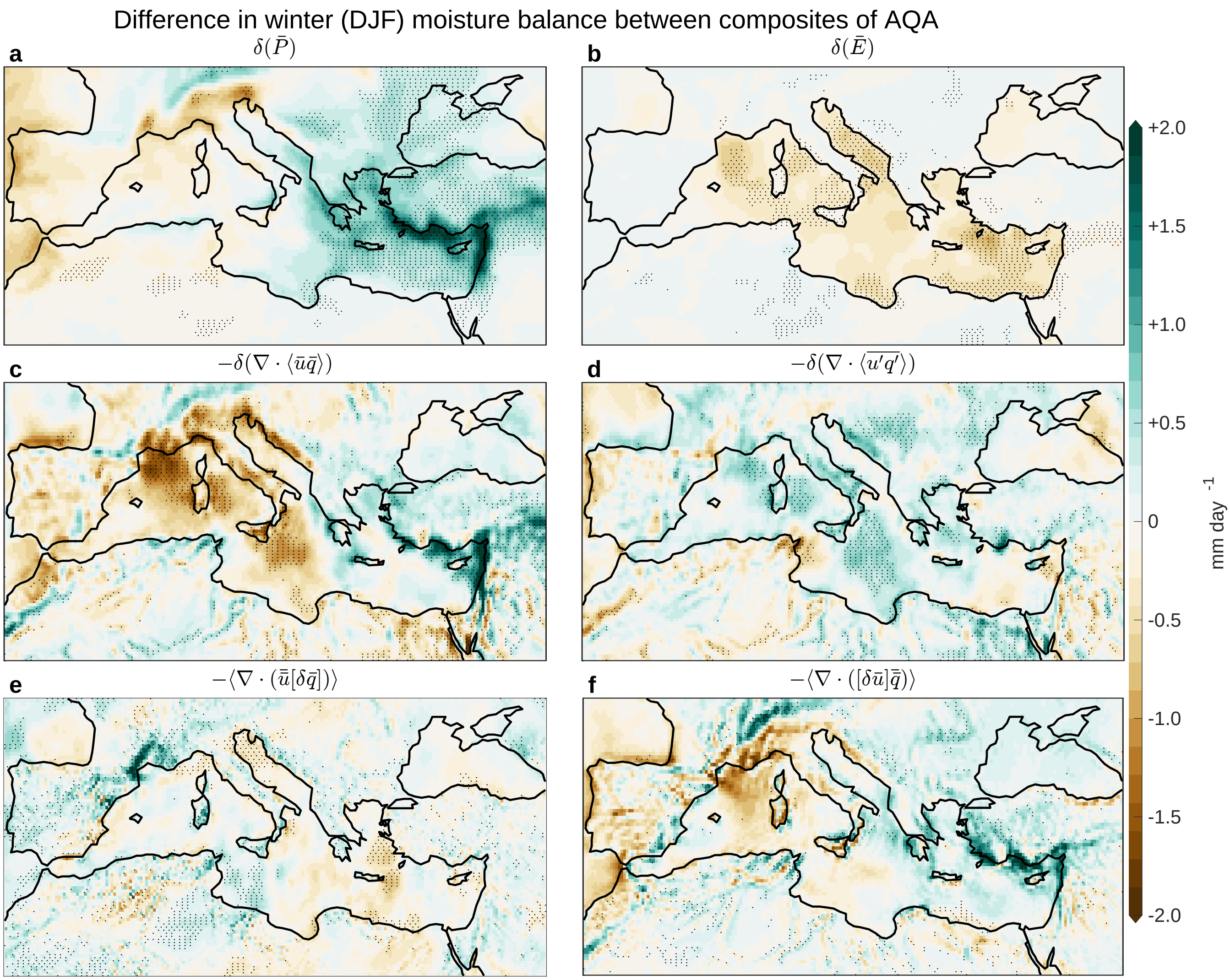

Figure 7. The decomposed hydrological balance in the Mediterranean region. Bars denote monthly means, and primes denote transient variations. Dotted regions are 95% statistically significant using a bootstrapping test. (a) Changes in precipitation between negative and positive AQA index winter composites, respectively; (b) Changes in evaporation between composites; (c) Changes in the mean vertically integrated moisture balance; (d) Changes in the transient-eddy component of the moisture flux; (e) Changes in the mean thermodynamic component; (f) Changes in the mean dynamic component.

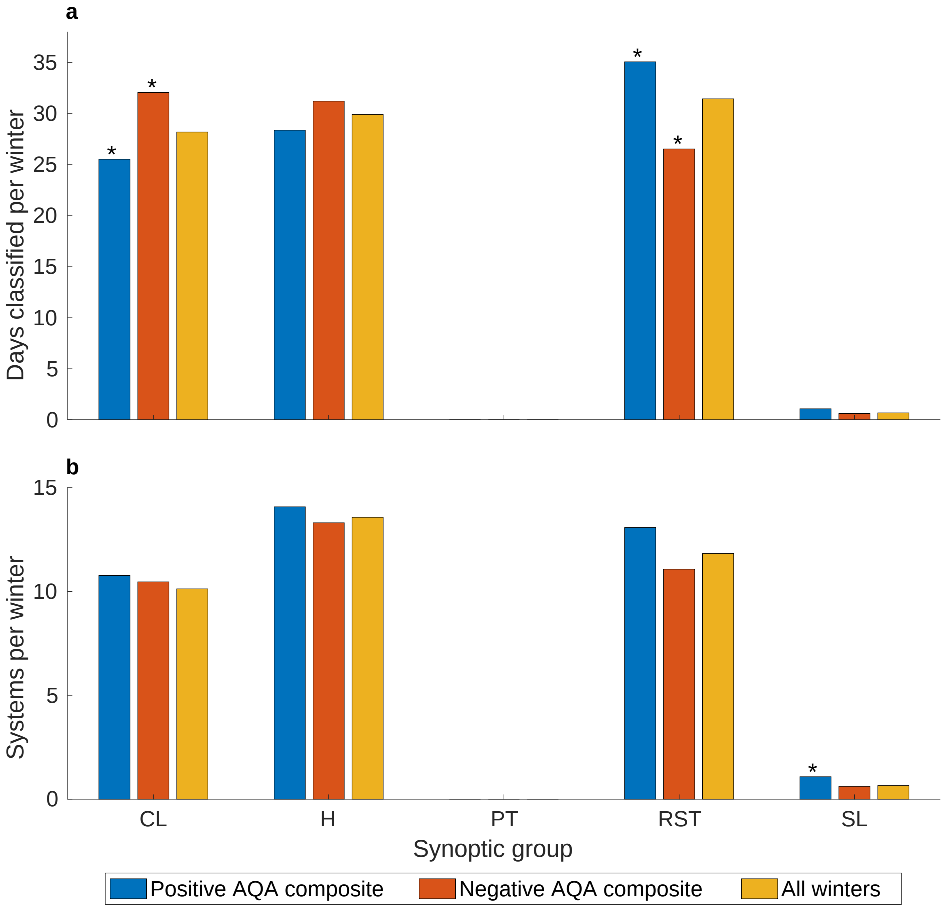

Figure 8. The difference in the number of winter days classified as each synoptic group (a), and the number of winter synoptic systems occurring (b), between composites of winters preceded by August AQA values above and below, plus and minus half of the standard deviation of August AQA values. Asterisks denote that the change is significantly different above the 90% threshold using the binomial significance test.

systems, as well as of Red Sea Trough and High systems, shows no significant sensitivity to AQA. This, in turn, indicates that the wetter Levant winters in response to negative AQA anomalies in the preceding August result from more persistent precipitating Cyprus Low systems during winter.

Since the hydrological decomposition pointed to changes in the mean flow as the primary driver of wetter Levant winters (Figure 7f), we now asses the relation of AQA to the prevailing regional westerlies. As shown in Figure 9a, negative AQA values in August are associated with a stronger subtropical jet over the EM during winter, which goes along with a low sea-level pressure anomaly over the Aegean Sea (Figure S4) and a negative 500hPa geopotential anomaly north of the Aegean Sea (Figure 9c). This large-scale jet intensification coincides with increased upper-level divergence along EM storm tracks (Supporting Material, Figure S5) and a positive anomaly in the Eady Growth Rate (Figure 9e), both indicative of more favorable conditions for baroclinic convective instability, consistent with the increased precipitation in the Levant (Figure 7a).

In summary, our findings reveal that a negative ocean heat uptake anomaly in the Aegean Sea during August is a precursor to enhanced winter precipitation in the Levant. This link is dynamically mediated by the increased persistence of precipitating Cyprus Low systems traversing the region, driven by a strengthening of the subtropical jet over the EM and a concurrent intensification of regional baroclinicity.

4 Summary and Discussion

The relation of Mediterranean Sea variability and winter precipitation in the Levant is explored. Objective analysis reveals that changes in the Mediterranean Sea heat uptake act as a precursor to inter-annual variability in Levantine winter precipitation. Based on this, we define an Aegean Sea heat uptake anomaly index (AQA), representing anomalous ocean heat uptake (Q_f) in the Aegean Sea during August. AQA shows a significant negative correlation with subsequent winter land precipitation in the Levant ($R = -0.60$). The associated increase in precipitation is driven by the more persistent eastward-migrating Mediterranean storms, which constitute the dominant source of winter rainfall in the region. This increase is linked to a strengthening of the regional subtropical jet, promoting enhanced baroclinicity and more favorable conditions for storm development and maintenance.

Specifically, using Self Organizing Map (SOM) analysis, we identify three dominant spatiotemporal patterns of variability in Mediterranean SST and Q_f (Figures 2 and 3). Of these, the patterns characterized by east-west gradients are found to predict variations in Levant winter precipitation. The statistical relations are significant for both SST and Q_f, and are qualitatively reproduced for *in situ* data in Israel. Similar patterns of variability are produced with Empirical Orthogonal Function analysis (~~not shown~~Supplementary Materials Section 3), albeit with weaker statistical relations. The Q_f anomalies, which are generally anti-correlated with SST anomalies (Figure 4), are primarily driven by changes in latent heat fluxes (Hochman et al., 2022b), highlighting the important role of ocean-atmosphere interactions in Mediterranean Sea variability, and in particular in the lagged response of Levant precipitation.

Composite analysis of winters preceded by negative ~~and positive~~ August AQA values reveals a response characterized by:

i. Enhanced precipitation in the Eastern Mediterranean (EM), particularly in the Levant and southern Turkey (Figure 7);

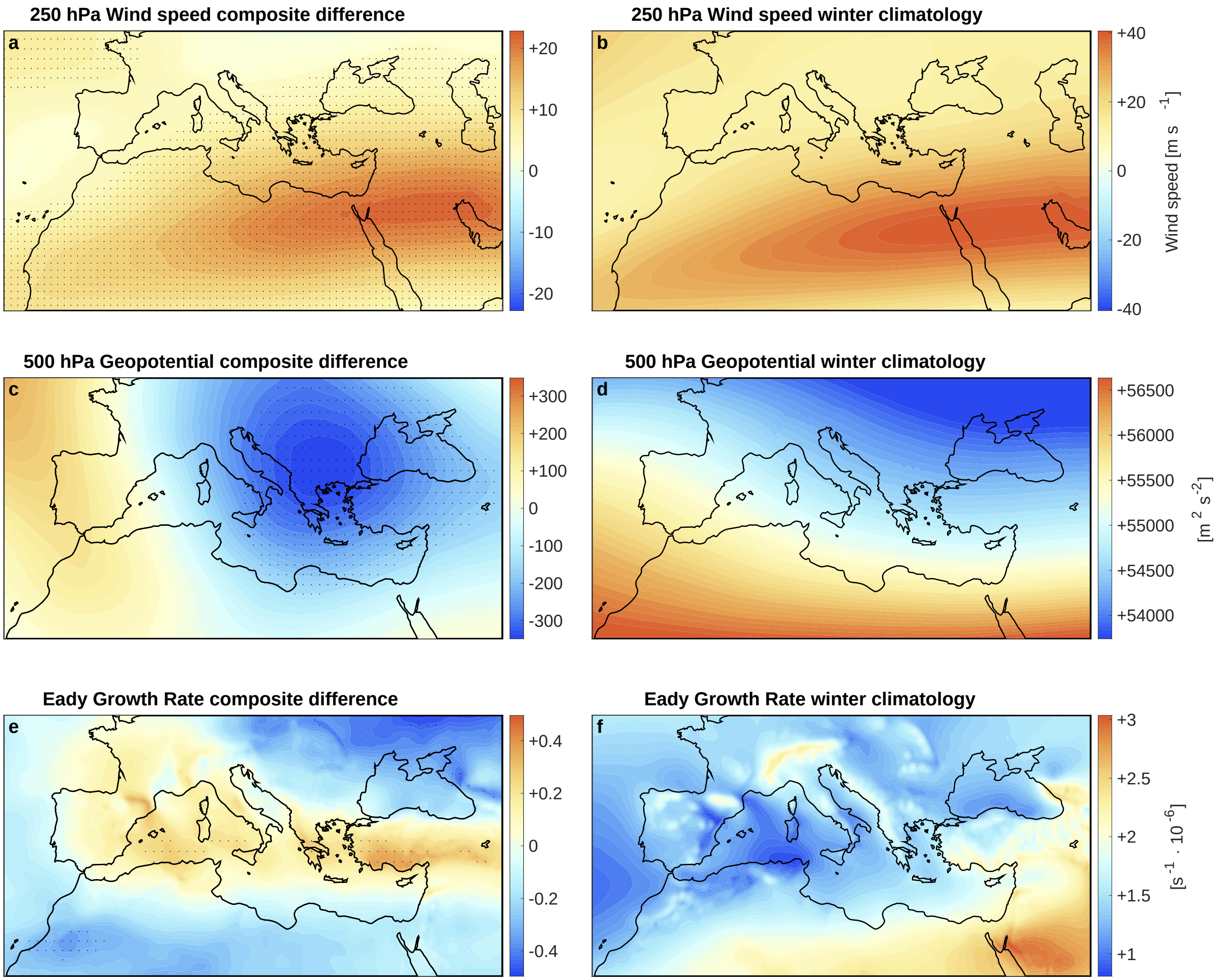

Figure 9. Composite difference between winters (Dec–Feb) preceded by negative and positive August AQA values in (a) 250 hPa wind during winter, (c) geopotential height at the 500 hPa pressure level, and (e) Eady Growth Rate. Right column panels show the respective winter climatology. Data taken from ERA5 for ~~the years~~ 1979–2023. Stippling indicates 95% confidence estimated using a bootstrap test.

ii. Elevated SST in the northern parts of the EM, a deep thermal low centered north of the Aegean Sea (Figures S4 and 9c), and reduced Q_f throughout the EM (Figure 6);

iii. More persistent eastward migrating EM Mediterranean cyclones, commonly termed Cyprus Lows (Figure 8a);

iv. Strengthened regional subtropical jet, which goes along with more baroclinic conditions in the EM, and enhanced upper-level divergence (Figures 9, and S5).

A decomposition of the winter precipitation response regional moisture balance indicates that the wetter Levant winters following negative August AQA values are associated with changes in the mean flow (Figure 7), in support the agreement with the observed strengthening of the regional jet and the associated baroclinic instability as the culprit of the inducing wetter winters. The strengthening of the subtropical jet is consistent with geostrophic enhancement (i.e., increasing horizontal pressure gradients with height) by the thermal low north of the Aegean Sea. However, additional confounding factors such as interaction with the polar jet and eddy heat and momentum fluxes may also play a role (Flaounas et al., 2022). Furthermore, the physical mechanisms underlying the lagged atmospheric response to sea surface conditions remain unclear, and may require further analysis of Mediterranean Sea dynamics, which have not been examined here. Given that remote regions are known to affect Levant precipitation (Figure 1), the relation of AQA and Levant precipitation may be mediated by contributing factors from outside the Mediterranean basin. However, we find no appreciable statistical relations between AQA and indices known to to be related to Levant precipitation, such as the North Atlantic Oscillation index (NAO), the Southern Oscillation index (SOI), and the SST anomaly in the NINO 3.4 region in the Pacific (Figure S3; Price et al., 1998; Black, 2012; Givati and Rosenfeld, 2013; Luo et al., 2015 . (Figure 1 and Supplementary Materials Figure S3; Price et al., 1998; Black, 2012; Givati and Rosenfeld, 2013; Luo et al., 2015) . Nevertheless, an indirect relation of Mediterranean Sea variability to remote regions cannot be ruled out as a contributing factor to the lagged response.

AQA, therefore, emerges as a potentially useful index for improving the skill of seasonal precipitation forecasts in the Levant, accounting for approximately one-third of inter-annual variability. In addition, the mechanisms linking AQA and Levant precipitation suggest that the representation in regional models of processes affecting Mediterranean cyclones, ocean-atmosphere heat exchange, and the subtropical jet, is key for improving seasonal forecasts (Flaounas et al., 2022; Redolat and Monjo, 2024) (Flaounas et al., 2022; Redolat and Monjo, 2024; Flaounas et al., 2025). We intend to isolate these processes the processes contributing to the lagged response and assess their influence on seasonal forecast skill in future work.

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