Response to Reviewer #1

Please note that the reviewer's comments are shown in *blue*, while our responses are shown in *red*.

RC1: 'Comment on egusphere-2025-2948', Anonymous Referee #1, 17 Jul 2025

Comments:

This study examines sea surface temperature (SST) variability in the Persian Gulf and its relationship with large-scale climate patterns (ENSO, NAO and IOD).. The authors indicated that local atmospheric anomalies significantly impact SSTs in the Gulf by modulating heat fluxes. ENSO, NAO and IOD could impact SSTs in the Gulf by modulating the local atmosphere circulation. The combined effect of ENSO and NAO on SSTs in the Gulf is also discussed. The results obtained in this study are interesting. This manuscript can be accepted after revisions.

We sincerely thank the reviewer for their positive and encouraging feedback, and for the time and effort they invested in reviewing our manuscript.

1) To confirm the results obtained from the ERA5, the authors should use other reanalysis data (e.g. MERRA2 and JRA55).

Following the reviewer's recommendation, we will present the local atmospheric conditions associated with extreme summer SSTs in the Gulf, as well as their links with large-scale climate variability modes such as ENSO and the NAO, using the two additional reanalysis datasets (MERRA-2 and JRA-55) suggested by the reviewer.

In the revised manuscript, we will show that our key results based on ERA5, namely that extreme summer Gulf SSTs are favored by lower-than-normal air pressure over the Arabian Peninsula and higher-than-normal pressure over Iran and Pakistan, leading to a weakening of the Shamal winds, are consistently reproduced in both additional reanalyses. The associated higher atmospheric moisture over the Gulf region, as well as the role of La Niña and negative NAO phases in promoting these conditions, are also captured in MERRA-2 and JRA-55. This consistency across three independent datasets strengthens confidence in the robustness of our findings with respect to the choice of reanalysis product.

Given the higher spatial resolution of ERA5 (¼°) compared to the other datasets, whose resolutions are two to five times coarser, and considering the critical role of horizontal resolution in representing regional processes over the Arabian Peninsula and the Gulf, we will keep the detailed analysis focused on ERA5 and the regional hindcast simulation. We will, however, show selected diagnostics from all three reanalysis products in the Supplementary Information to demonstrate the robustness of our main conclusions.

2) It should be noted that ENSO, IOD and NAO are not independent of each other. For instance, ENSO can affect IOD, IOD can affect ENSO, and NAO can also affect ENSO. The authors should examine the combined and relative effects of ENSO, IOD and NAO on SSTs in the Gulf using partial composite or regression analysis.

We agree with the reviewer that these climate modes are not independent but rather interact with one another. In the revised manuscript, we will add citations to some key references on the connection between these variability modes. In the correlation matrix presented in the original manuscript (Table 2, page 20), we showed that ENSO is significantly correlated with both the IOD ($r = 0.36$, $p < 0.01$) and the ISM ($r = 0.38$, $p < 0.01$), whereas its correlation with the summer NAO is not statistically significant ($r = 0.09$, $p > 0.05$).

This realization motivated our decision to perform a multiple linear regression analysis that accounts for the influence of each predictor while controlling for the others (Fig. 11 in the original manuscript). To further clarify this point and in line with the reviewer's suggestion, we will additionally conduct a partial regression analysis to show the correlation coefficients and significance levels between Gulf SST and each predictor while controlling for the remaining predictors.

Furthermore, we will apply a hierarchical partitioning approach (Mac Nally, 1996, *Australian Journal of Ecology*, 21, 224–228) to quantify the relative importance of each predictor in the multiple regression framework. This method is particularly suitable when predictors are correlated, as it is independent of the order in which variables enter the model. It decomposes the total explained variance into the unique contribution of each predictor and the variance jointly explained with other correlated predictors (shared contributions). This additional analysis reveals that, owing to its weaker correlations with the other three modes, the NAO exhibits a higher unique contribution to the explained variance compared to ENSO, which shows stronger associations with the IOD and ISM. A substantial fraction (about 20%) of the total explained variance is shared among all four modes.

3) In addition to ENSO and the NAO, I would suggest that the authors also examine the role of Arctic sea ice anomalies in shaping extreme temperatures in the Gulf. Recent studies have indicated that Arctic sea ice anomalies could have a significant impact on ENSO, NAO and IOD. I suggest add some discussions. (https://doi.org/10.1175/JCLI-D-24-0419.1.; https://doi.org/10.1038/s41612-025-00936-x.; https://doi.org/10.1175/JCLI-D-23-0733.1.).

In response to the reviewer's suggestion, we examined potential links between summer Gulf SST and both Arctic sea ice and the Arctic Oscillation (Figs. 1 and 2). We found no statistically significant correlations between Gulf SST and either variable.

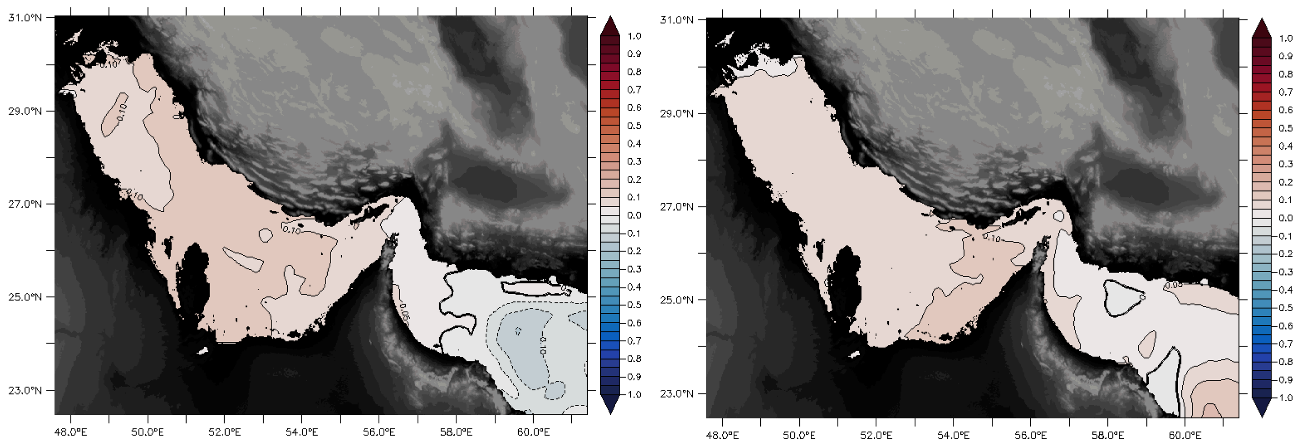

Fig 1. Zero-lag (left) and 6-month-lag (right) correlation between summer Gulf SSTs and Arctic sea ice area anomaly. Correlations are not statistically significant.

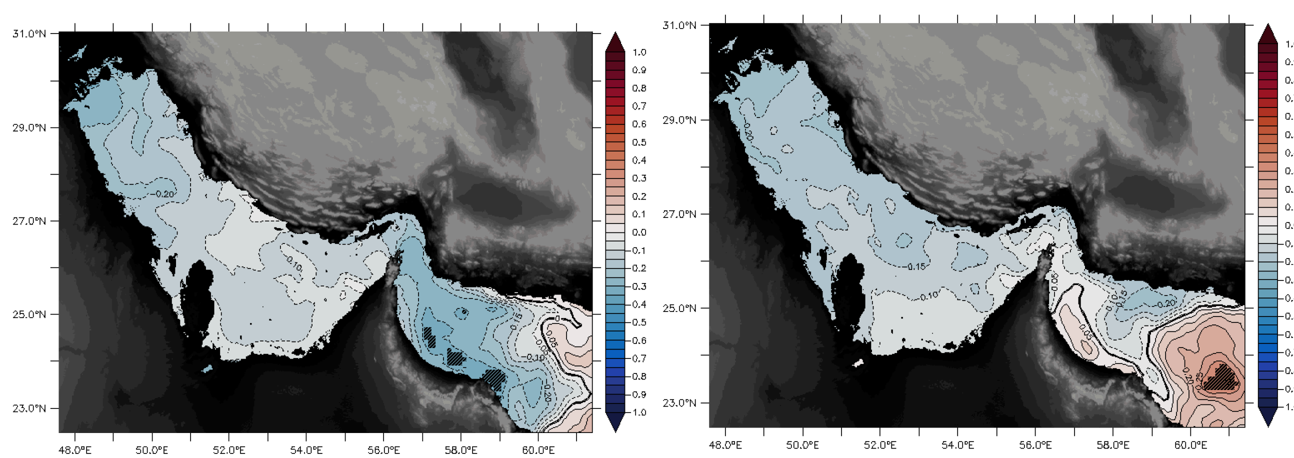

Fig 2. Zero-lag (left) and 6-month-lag (right) correlation between summer Gulf SSTs and the Arctic Oscillation index. Hatching indicates statistical significance at 95% confidence interval.

We conclude that, despite the potential connections between Arctic sea ice and the development of IOD and ENSO highlighted in the studies cited by the reviewer, these links do not appear to play a critical role in determining Gulf summer SSTs. This may be because these relationships are weaker during summer or because their influence does not substantially impact the summer atmospheric circulation over the Gulf region. Moreover, given the strong coupling between NAO and AO, we consider that any potential influence of the AO on Gulf summer SST is likely already captured by the NAO signal. These points will be briefly discussed in the revised manuscript.

4) In addition to atmospheric heat fluxes, the tendency of SST should also be significantly impacted by oceanic dynamics, such as advection and upwelling/downwelling. The authors should analyse the SST tendency equation and investigate the role of these oceanic processes.

We agree with the referee that the tendency of SST results from the balance between atmospheric heat fluxes and oceanic circulation and transport (mixing and advection). However, we argue that, due to the shallow (<30 m average) and semi-enclosed nature of the Gulf (Strait of Hormuz width: 42 km), the contribution of local oceanic circulation is strongly modulated by local atmospheric fluxes. As a result, at the scale of the Gulf, ocean dynamics do not contribute significantly to the observed SST variability independently of local atmospheric flux variability.

This is demonstrated in the analysis presented in Figure 2, which shows that up to 92% of the variance in SST can be explained by local atmospheric heat fluxes in the northern Gulf (and 83% in the southern Gulf). To further illustrate this point, the revised manuscript will include the full heat budget of the model surface layer during summer over the 39-year study period (Fig. 3). As shown in this figure, SST tendency anomalies result from the near compensation between anomalies in atmospheric heat fluxes ($r = 0.88$) and vertical transport (mixing and advection; $r = -0.87$), both of which are at least an order of magnitude larger than the tendency anomalies themselves and the anomalies in the Gulf-integrated lateral heat transport (essentially equivalent to the heat transport from the Sea of Oman).

While vertical transport is comparable in magnitude to atmospheric heat fluxes, it is almost entirely driven by atmospheric heat flux anomalies ($r = -0.99$). Therefore, at the scale of the entire Gulf, transport (both vertical and horizontal) plays a much smaller role in SST variability. At local scales, particularly near the Strait of Hormuz, the contribution of transport can be more important. However, as the focus of the current manuscript is on understanding the drivers of warm summer SSTs at the Gulf-wide scale, our emphasis remains on atmospheric heat fluxes, which explain the majority of interannual variability.

This caveat will be made clearer in the revised manuscript, and the new heat budget analysis will be included.

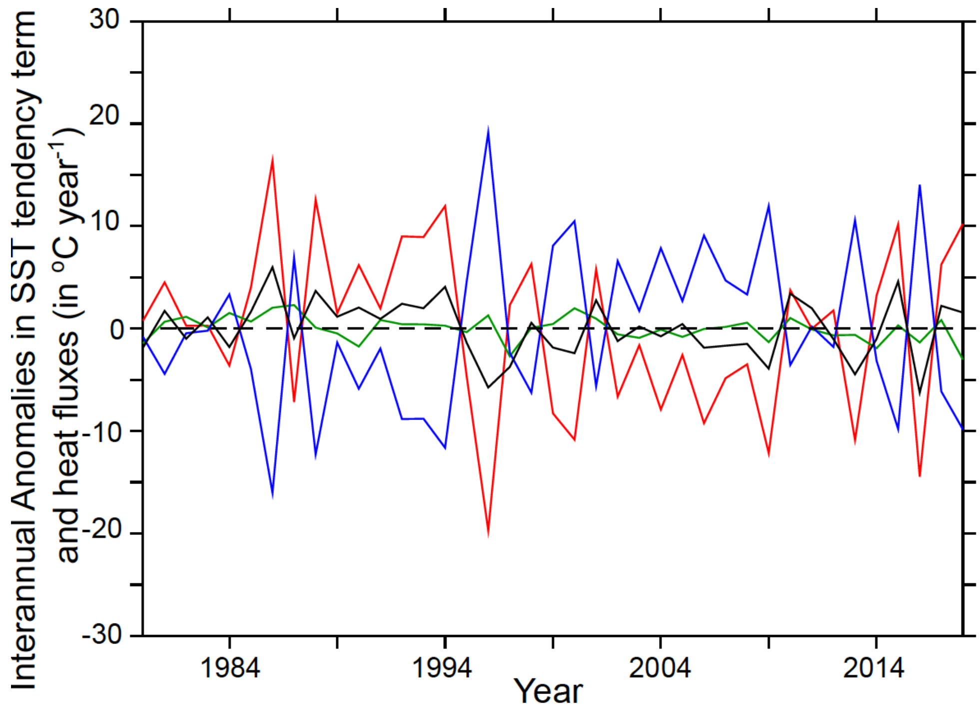

Fig 3. Interannual anomalies of the temperature tendency term (black), atmospheric heat fluxes (red), and vertical (blue) and horizontal (green) heat transport fluxes, integrated over the entire Gulf. Because the tendency term and horizontal transport fluxes are much smaller than the atmospheric heat fluxes and vertical transport fluxes, the former two are plotted in °C per year, while the latter two are shown in °C per month, allowing all four terms to be displayed on the same scale.

5) The authors discussed the possible influence of ENSO, NAO and IOD on SST anomalies in the Gulf. However, the underlying physical mechanisms have not been investigated in detail. The authors should examine the physical processes through which ENSO and NAO impact the formation of local atmospheric circulation. For example, Cheng et al. (2023; https://doi.org/10.1007/s00382-022-06616-3) indicated that AO/NAO-related atmospheric heating over the North Atlantic could trigger an atmospheric wave train from the North Atlantic to the northern Indian Ocean.

Understanding the mechanisms of global teleconnections that link large-scale climate variability modes to the modulation of regional summer atmospheric circulation over the Arabian Peninsula and Gulf region is an important open research question. However, a detailed investigation of these mechanisms is beyond the scope of the current study. This limitation will be highlighted in a new section, "Caveats and Limitations," in the revised manuscript.

Nevertheless, the revised manuscript will include a brief discussion of mechanisms proposed in studies that have explored aspects of this question. For example, Cheng et al. (2023) proposed that atmospheric heating anomalies over the North Atlantic can trigger a Rossby wave train toward the northern Indian Ocean, potentially affecting the development of the Indian Ocean Dipole (IOD) in autumn. However, as our results show that the IOD has a limited impact on Gulf summer SST, likely due to the minor influence of Indian Ocean heat advection on interannual Gulf SST variability, this mechanism may contribute only marginally to summer Gulf SST variability.

Several studies have examined the connection between ENSO and summer atmospheric circulation in the region. For instance, Yu et al. (2015) identified a statistically significant relationship between ENSO and the timing of onset and termination of summer Shamal winds, which they linked to the Iranian summer heat low. However, that study did not propose mechanisms explaining the linkage between tropical Pacific SST anomalies and the development of the Iranian heat low. Attada et al. (2019) linked a strong Indian Summer Monsoon, generally favored during La Niña conditions, to increased adiabatic warming over the region due to enhanced subsidence in the middle and upper troposphere. This is consistent with our findings, which show increased subsidence in the upper troposphere over the Arabian Peninsula.

Finally, Kuman and Ouarda (2014) investigated the link between UAE winter precipitation and ENSO. They suggested that ENSO-driven changes in regional atmospheric circulation over the Arabian Peninsula are associated with shifts in planetary Rossby waves generated in the central Pacific due to SST anomalies, which then propagate into extratropical latitudes as cyclonic and anticyclonic features in the upper troposphere near the subtropical jet stream. While that study focused on winter conditions, similar mechanisms may contribute to ENSO-related changes in regional atmospheric circulation over the Arabian Peninsula during summer.

Regarding mechanisms linking NAO to regional atmospheric circulation, fewer studies have examined this relationship, particularly in summer. Chronis et al. (2011) showed that negative summer NAO is associated with lower cloudiness and higher temperatures over the eastern Mediterranean and the Anatolian Plateau. Folland et al. (2009) demonstrated that negative summer NAO is associated with lower pressure over the northern Arabian Peninsula and Iraq. Such weakening of the high-pressure system that typically dominates the eastern Mediterranean and western Arabian Peninsula in summer can reduce the pressure gradient across the Gulf and, consequently, decrease the frequency and intensity of Shamal winds.