Large-scale drivers of compounding hot and dry events in three breadbasket regions

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Response to the Reviewer's comments

We thank the Editors and the Reviewer for their interest in our manuscript and the valuable comments they have provided which contributed to improve the robustness of the results and the overall quality of the paper.
A response to the reviewer's comments is provided below.

Reviewer 2

Minor comment: *"The author's have done a very nice job revising the manuscript.*

My only main comment still resides in the linkage between the SPI (which is a 3-month index ending the month of the identified events) and the new (and very helpful!) Hövmoller diagrams. The North American patterns appear to show a predecessor pattern (from ~135W to ~30W) that is going back at least 30 days prior to the onset of the high FA events. There appears to be a Rossby wave train starting around the start of the event (near the dateline) that plays a key role in ending the event. In the meantime, you have an uptick in SSHF. For the euro sector, the signal emerges around 25 days prior, and the Rossby wave train starting ~4-6 days prior to event onset near 90W seems to play a key role in the rapid intensification, with nothing coherent going on downstream. Here, SLHF seems to be more important than SSHF. Lastly, the AS sector has much more weak signal across the board. The take-away I'm getting at here is two-fold - I think some focus out to -60 days (even if just for the supplemental) isn't a huge lift but might be helpful for the Hövmollers (to match the time-scale of the SPI). This then leaves us with the full time period (give or take) of the SPI index to see what's leading into this cumulative 3-month sum metric. Then, I would suggest focusing not just on the signal over the region, but more focus on the upstream/downstream environment as well as any Rossby wave 'triggering' event (for example, I think the Hövmoller + hemispheric maps support the idea of Rossby wave breaking over the euro-sector given the double-jet structure and Rossby wave amplification). "

Response: We thank the reviewer for highlighting the relationship between SPI3 and the daily composites, which gave us the opportunity to deepen the exploration of the physical mechanisms underlying the installation and maintenance of the events. We have extended the daily composites to 60 days before the beginning of each selected high FA event. This covers the two calendar months preceding the SPI3 target month. The longer window provides additional antecedent context without changing the event definition of compound hot and dry events. In addition, we have enlarged the longitudinal range of the z500 Hovmöller diagrams to include the upstream and downstream environment surrounding each region. This allows to examine the anomalies within a broader circulation setting and shows whether consistent circulation anomalies are also present outside the regional boundaries.

North America: The additional month shows changing positive and negative height anomalies across the Pacific, NA and Atlantic. A positive z500 anomaly is present over western NA 60 days before the event, although their position and amplitude evolve through time. Negative anomalies interrupt this initial ridge like signal 50 days

before and afterwards, positive anomalies re-emerge around 30 days before and persist into the selected events (Fig. 6a). The u250 composite shows positive anomalies northwards and in the southern border of the region, which weaken as the later ridge develops. The z500 and u250 suggest a redistribution of upper-level flow around the ridge, compatible with a displaced jet configuration. This could steer some rain disturbances away from NA and favour reduced precipitation and persistent hot temperatures. Negative SSHF anomalies are already present 60 days before the event and persist throughout the events, indicating enhanced upward sensible transfer. The SLHF shows negative anomalies at the beginning of the analysed period, which then turn positive till the end of the event. This indicates reduced evaporative cooling which could reinforce warming while the circulation favours negative anomalies of precipitation, providing a plausible physical setting for anomalously low SPI3 along with hot temperatures in the selected events. We made the changes in the main manuscript in lines 273-299:

"We also demonstrate how the installation of the circulation featuring high FA events leads to the triggering and maintenance of the compound hot-dry events in NA. Hovmöller diagrams and line plots of daily data show the composites of anomalous z500, SSHF, SLHF and u250 (Fig. 6) for the 19 high-FA events, from 60 days before the compound hot-dry events, to 30 days after. Positive z500 anomalies over western NA are already present 60 days before the composite event (Fig. 6a). This initial ridge-like signal becomes unorganized as negative anomalies interrupt the regional pattern 50 days before the event. Positive anomalies re-emerge around 35 days before and form a persistent precursor through the final antecedent weeks and the beginning of the event. During the first part of the event, the anomaly remains within a similar longitude range while progressively changing in amplitude and spatial extent, indicating there is a persistent and slowly evolving atmospheric ridge. Towards the end of the event, the positive anomaly weakens due to a wave train that starts before the event upstream the region. The ridge structure becomes less pronounced, while the whole structure start moving to the east after the termination of the event. The u250 latitude-time composite shows the evolution of the upper-level zonal flow over the NA region (Fig. 6b). Before the event, positive u250 anomalies occur at higher midlatitudes and southwards the region, while negative anomalies are present to the north of the NA region, indicating a northward displacement of the westerly jet stream, and enhanced subtropical flow. During the event, the zonal wind anomalies become less organized, indicating a disruption of the jet stream, which together with the positive anomalies of z500 suggest a redistribution of the upper-level flow around the ridge, compatible with a displaced jet configuration.

Negative SSHF anomalies are already present before the event and persist throughout the event, indicating enhanced upward sensible heat transfer from the surface to the atmosphere (Fig. 6c). At the start of the event there is a pick which then decreases through the event. The SLHF composite shows there is a pick around 40 days before the event which then decreases due to the disorganization of the first ridge (Fig. 6d and 6a). Afterwards the surface response develops again at the start of the event and becomes more pronounced after the formation of the circulation anomaly (Fig. 6d). The positive SLHF anomalies indicate a reduction in upward latent heat flux (according to ERA5 convention positive-downward) and are associated with suppressed evaporation and reduced evaporative cooling. The time span of SLHF anomalies is consistent with the anomalously low SPI3 observed (by construction) during the event. Together, these anomalies indicate a redistribution of surface energy from latent toward sensible heating. Their timing suggest that enhanced sensible heating may contribute to the event preconditioning and maintenance, while reduced evaporative cooling reinforces the hot and dry conditions after their onset."

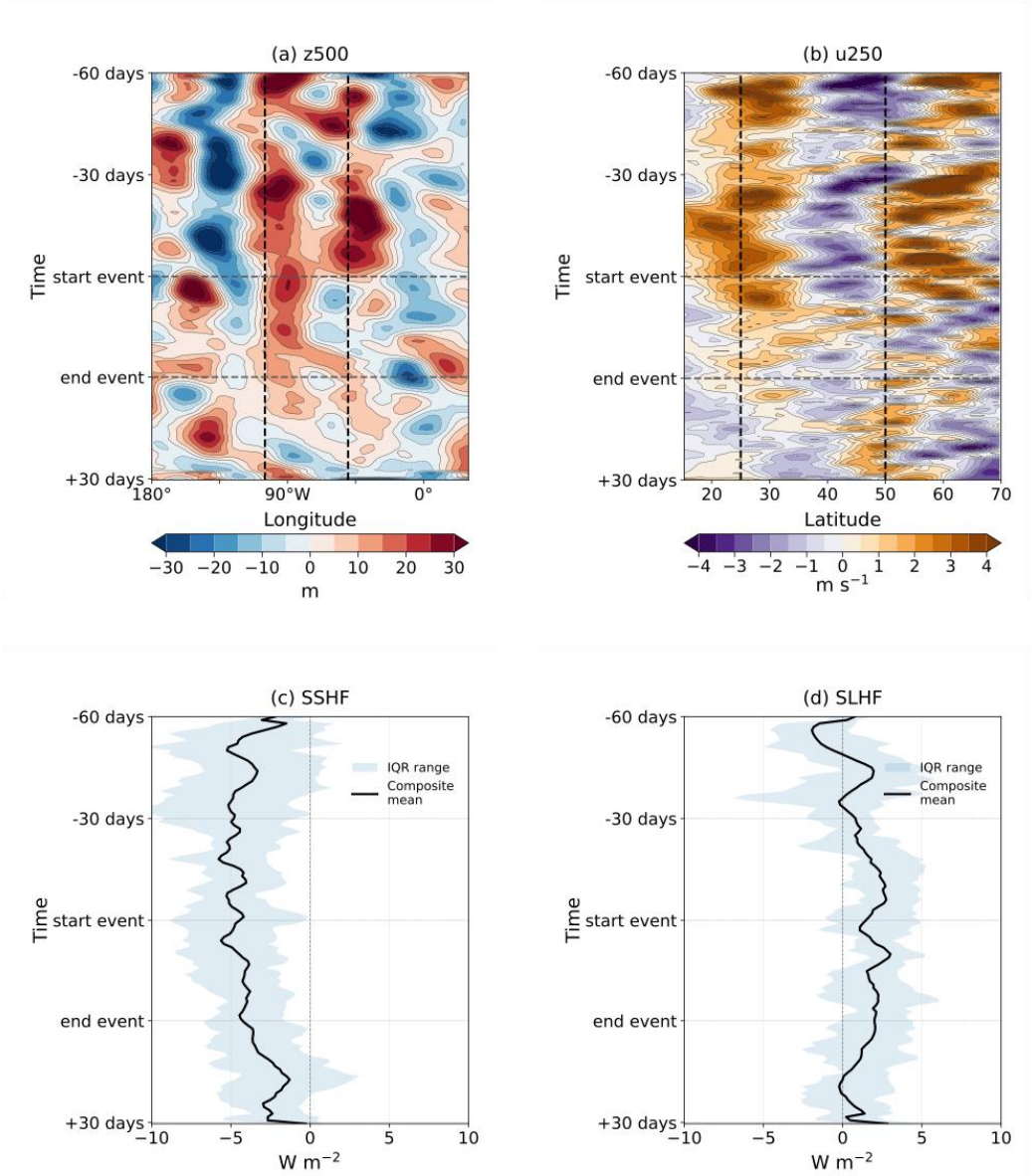

Figure 1. Composites of the daily evolution of the atmospheric circulation variables and surface heat fluxes associated with the 19 high FA events in North America. For each event and variable, daily anomalies are calculated by removing the corresponding daily climatology and filtered using a 7-day centered running mean. The event windows were aligned on a common event-centered time axis and subsequently composited across the 19 events. (a) Time-longitude Hövmoller diagram of daily 500 hPa geopotential height (z500) anomalies averaged over 37.5 - 57.5 °N. (b) Time-latitude Hövmoller diagram of daily 250 hPa zonal wind (u250) anomalies averaged over 110 – 45 ° W. (c) Surface sensible heat flux (SSHF) and in (d) surface latent heat flux (SLHF) anomalies regionally averaged over North America, with the shaded area indicating the interquartile range across the 19 events. Horizontal dashed grey lines indicate the beginning and end of the event in all panels. In panels (a) and (b), the vertical black dashed lines indicate, respectively, the longitudinal and latitudinal boundaries of the NA region.

Euro-Mediterranean: There is a transition from alternating z500 anomalies to a pronounced Atlantic through and European ridge near the selected event (Fig. 8a). Positive anomalies become more organized over the region

25 days before and become a strong ridge 5 days prior to the event due to the wave train located near 90 ºW. Farther east over Eurasia, positive anomalies are present but less organized and without a relation in the regional pattern. The ridge amplification is accompanied by weaker upper-level westerlies within central EM region, and stronger flow to its north and south flanks. This suggests flow around the ridge and a possible split jet configuration, which could deviate Atlantic disturbances away from the region and favour persistent hot temperatures and reduced precipitation. As the ridge strengthens near the start of the event, the already negative SSHF anomalies become more negative during the first part of the event, indicating enhanced sensible heating of the atmosphere (Fig. 8c). The SLHF anomalies are consistent with anomalously low SPI3 values. SLHF anomalies show positive values 35 days before the event, which then decrease 20 days before and increase again at the start and through the event, consistent with a reduction in evaporative cooling that can help maintain the hot temperatures (Fig. 8d). The sequence suggests that upstream wave development and regional ridge amplification provide dynamical setting for the intensification of hot temperatures, while the surface flux anomalies reinforce it. We modify the text at lines 349-367 and at lines 502-512 in section 4:

"The daily composites show a transition from irregular z500 anomalies to a pronounced European ridge configuration near the event onset (Fig. 8a). Positive z500 anomalies become more organized over the region around 25 days before the event, and a wave train emerging around 30 days before intensifies the amplification of a through to the west of EM that help to strength the regional ridge. This ridge eventually weakens and starts moving eastward at the termination of the event (Fig. 8a). The evolution of the z500 anomalies indicates a slowdown of a transient westerly wave-like circulation pattern, which evolve in a quasi-stationary ridge above EM during the event. The ridge amplification is accompanied by weaker upper-level westerlies within the central EM latitude band before the event onset, and stronger flow north and southwards (Fig. 8b) the region. This separation of the anomalous westerlies suggests a possible split jet configuration. The surface heat fluxes evolve consistently with the development of the hot and dry conditions. As the ridge strengthens near the events start, the already negative SSHF anomalies become more negative during the first part of the events, indicating enhanced sensible heating (Fig. 8c). In contrast, the regional SLHF composite show positive values 35 days before the event, which then decrease 20 days before and increase again at the start and through the event (Fig. 8d), consistently with anomalously low SPI3 values. This indicates a reduction in the upward latent heat flux and weaker evaporative cooling within the EM region due to the persistence of the atmospheric ridge. However, the positive SLHF anomalies associated with EM events are less robust with respect to those observed for the NA events."

"Together with the meridional wind patterns in the hemispheric composites, the thermodynamical evolution described above is consistent with upstream Rossby wave activity contributing to the establishment and reinforcement of the European ridge. The two bands of stronger westerly flow over EM are also compatible with a double jet like configuration. This circulation anomaly is consistent with the established role of blocking anticyclones and persistent double jets in shaping European summer heat extremes (Brunner et al., 2018; Rousi et al., 2022). Rossby wave breaking followed by blocking may contribute to splitting the upper-level jet, although double jets and blocking can also be interpreted as dynamically coupled components of the same circulation configuration (Rousi et al., 2022). While Rossby-wave breaking is not explicitly diagnosed in the present study, the amplified Atlantic-European through-ridge pattern and the accompanying reorganisation of the upper-level westerlies resemble circulation configurations previously associated with anticyclonic Rossby wave breaking.

Such breaking over Europe and Mediterranean has been identified in association with persistent hot spells in southwestern Europe, together with a northward–shifted jet (Pappert et al., 2024). “

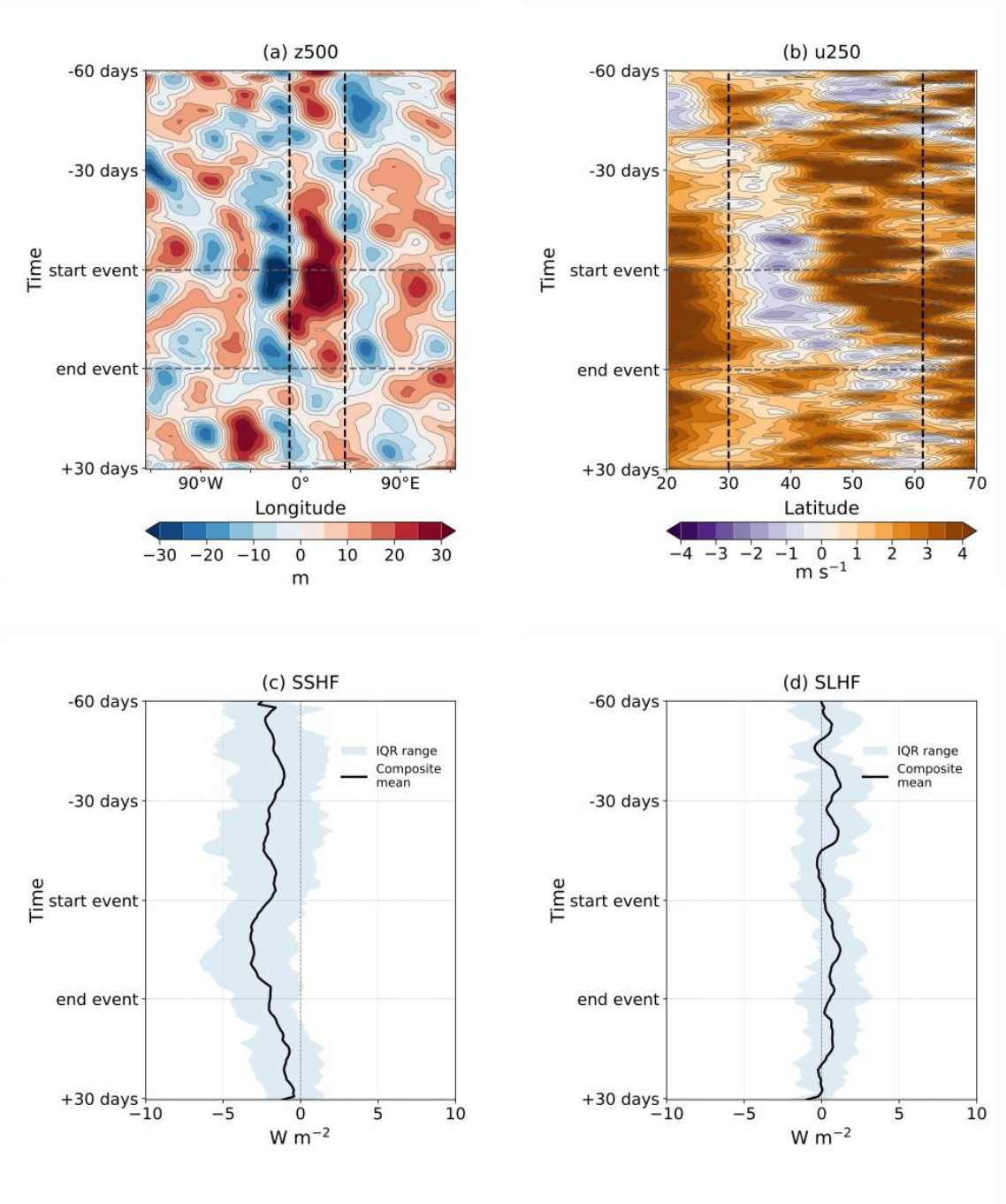

Figure 2: Same as Fig. 6 but for EM. In (b), 250 hPa zonal wind anomalies were averaged over 20ºW-45 ºE.

Eastern Asia: The AS composites show a less persistent z500 anomaly with alternating anomalies occurring upstream over Eurasia, while strong positive and negative anomalies develop downstream over the North Pacific, and across the dateline. Their timing and longitude vary, and a continuous upstream sequence leading into a persistent ridge over AS domain is less evident than for EM. The upper-level wind evolution provides a clearer

regional signal before the selected composite events. Positive anomalies are shown within the latitude band of the region 60 days before, which then change sign 30 days prior to the event and increase strength before the event onset (Fig. 10b). Upstream, positive anomalies are present before the event and dominate till the end of the composite events, which is consistent with a poleward redistribution of the westerly jet. The SSHF response mainly develops during the selected events, when values become more negative after varying near zero during the 60 days prior to the events (Fig. 10c). At the same time, discontinuous negative SLHF anomalies 60 days before and at the start of the event indicate enhanced evapotion and cooling (Fig. 10d). Enhanced upward latent heat transfer can occur during months with low SPI3 values, since SPI3 returns precipitation accumulated over three months while latent heat flux responds to conditions at the surface during the selected month. We modified the text at lines 409-435:

"The daily composites of z500 show circulation changes west and east of the region 60 days before the composite events (Fig. 10a). During this period, positive and negative z500 anomalies alternate over Eurasia, west of the AS boundary, while stronger anomalies develop downstream over the Pacific. Through the event onset, negative anomalies are shown within the AS region, while a positive anomaly forms outside the region during the last days and towards the end of the event. At the same time, the v250 daily circulation anomalies display a westerly disturbance transiting above the region (not shown) without resulting in any stationary ridging (Fig. 10a). This indicates that the mid-latitude Rossby-wave dynamics has limited effect on the occurrence of hot and dry events in AS. However, a sensitive analysis using a lower latitude band (25-45ºN, not shown) reveals positive z500 anomalies before, during and after the event within the region. This indicates that the main positive anomalies are located southwards and that the common midlatitude average captures its northern side. The anomaly evolves through time and is less continuous than the ridges identified for NA and EM, which suggests a more transient circulation configuration. The u250 composite shows weak positive anomalies within and northwards the region 60 days prior to the event (Fig. 10b). Afterwards, the positive anomalies within the region decrease and a stationary dipole is observed during the event, indicating weakened upper-level westerlies over central and southern AS and a stronger flow to the north, respectively. Those anomalies are consistent with a northward displacement of the subtropical jet stream. The displacement of the jet stream results in anticyclonic circulation over the southern part of the region leading the weak negative SSHF anomalies 60 days before, which then become more negative throughout most of the event (Fig. 10c). This indicates a slight enhancement of upward sensible heat transfer from the surface to the atmosphere. Negative SLHF anomalies occur in episodes from 60 days before and through the event (Fig. 10d), indicating enhanced upward latent heat flux and evaporative cooling which may buffer the surface warming. In this non-water-limited monsoonal region, a precipitation deficit does not necessarily imply a depletion of soil moisture, and evaporation may be maintained under high atmospheric evaporative demand while soil moisture is still available. In addition, the spatial heterogeneity of eastern Asia, and the averaging of SLHF across the full region may obscure contrasting responses between grid cells affected and unaffected by compound events. This is supported by the broad interquartile range, particularly for SLHF, indicating large variability among the individual events.

These results suggest that the high FA compound hot dry events in AS are associated with a transient, southward centred anticyclonic circulation resulting from the northward displacement of the subtropical jet stream. Due to the moisture availability in the region the evaporative cooling is more effective than in NA and the EM, leading to less frequent events associated with weaker temperature anomalies."

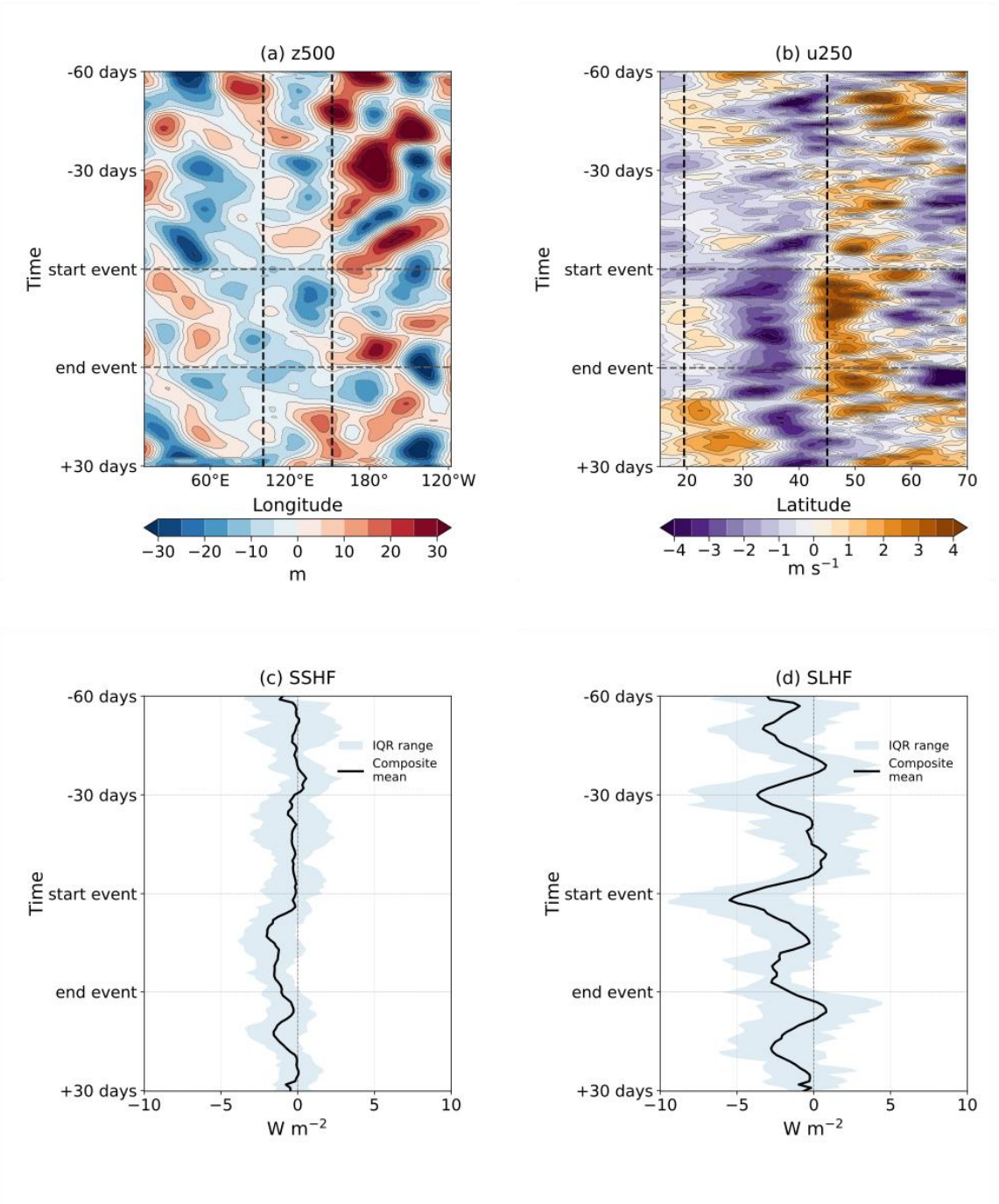

Figure 3: Same as Fig. 6 but for AS. In (b), 250 hPa zonal wind anomalies were averaged over 95-160 ºE.