

We would like to thank Referee #1 for her/his detailed comments and review of our manuscript. We believe that by addressing these comments we were able to significantly correct our analysis and thus improve the manuscript. Below we address each point raised by Referee #1 (*marked in blue, italic*) individually. Our responses to comments are shown in black. Text passages from the manuscript are included in **red** with text changes highlighted by underlining them and choosing **red, bold** font.

Best regards,
Nina Ridder, Hylke de Vries and Sybren Drijfhout

This paper presents a novel analysis of the association between atmospheric rivers (ARs) and compound events (concurrent high precipitation and high sea water level) along the Dutch coast. The study represents a step further to understand the impacts of ARs beyond the traditional focus on precipitation alone, and may help extend the consideration of ARs in situational awareness and forecast of extreme events to regions where ARs have received relatively less attention in the science and/or applications community.

The analysis procedures are sound for the most part, but needs improvement/amendment as described in my specific comments below. A major missing component is a robust accounting of the statistical significance in the differences between CEs with and without ARs, and between ARs with and without CEs. In the only case where significance test is conducted (Figure 7), the test results do not seem to make physical sense (see specific comments below), which makes me worry about whether the significance test was properly conducted.

We thank the referee for highlighting this shortcoming of the previous version of our manuscript. We revised our significance analysis used to produce Figure 7 and extended its application to the rest of the parameters as suggested by the referee. In detail, we now apply a student t-test that compares the anomalies (relative to monthly climatology) of the daily mean value of each variable during CEs (Fig. 6, 7 and 8) and ARs without CEs (Fig. 9) to the anomalies (relative to monthly climatology) of the daily mean value of each variable in the full time series. Further, we corrected the caption of Figure 7 to clarify that statistical significance is defined for areas with a p-values lower than or equal to (\leq) 0.05.

Specific comments:

Near Line 5: “accompanied by the presence of an AR”, “up to seven days before”: does this mean an event is considered AR-accompanied if an AR is

present up to seven days before the event? In any case, it would be useful to define “accompanied by an AR”.

This formulation, in the first version of the manuscript, might have been conveying a confusing message. We intended to express that we isolated the conditions before events with a lead-time of up to seven days. We rephrased the abstract as follows:

[...] we find that the majority of compound events (CEs) between 1979 -2015 has been accompanied by the presence of an AR over the Netherlands. In detail, we show that CEs have a three to four times higher chance of occurrence on days with an AR over the Netherlands compared to any random day (i.e. days without knowledge on presence of an AR). In contrast, the occurrence of a CE on a day without AR is three times less likely than on any random day. Additionally, by isolating and assessing the prevailing sea level pressure (SLP) and sea surface temperature (SST) conditions with and without AR involvement up to seven days before the events, we show [...]

Near line 10: “local ARs”: it is not totally clear what “local” means here. Some ARs travel a longer distance than other ARs, but I’m sure that’s what “local” aims to convey here.

We intended to highlight that the AR has to occur over the study area to be able to influence the conditions during a compound event. We removed the word ‘local’ to prevent confusion and reformulated the sentence slightly to:

“These conditions are clearly distinguishable from those conditions during compound events without the influence of an AR which occur under SLP conditions resembling the East Atlantic (EA) pattern [...]

Near line 5: “sever”: typo of “severe”.

Resolved.

Near line 5: “future development of future flood risk”: awkward construction.

We changed this part to **“[...] the future development of future flood risk.”**

Near line 15: “in relation with extra-tropical cyclones”: it would be more consistent with the definition in AMS Glossary of Meteorology to say “typically in relation with . . .”

Added. The sentence now reads:

“They typically develop in relation with extra-tropical cyclones [...]

Near line 15: “400 - 600 km”: add a reference for the quantitative description, or make it qualitative with something like “several hundred km”.

Done.

Near line 25: “a characteristic not previously assessed”: change to something like “, a characteristic not previously assessed for ARs affecting the Europe”, because there’s at least one study that has examined the effect of ARs on sea water level in western US; see <https://agupubs.onlinelibrary.wiley.com/doi/abstract/10.1002/2016GL070086>

We adjusted the manuscript to:

“a characteristic not previously assessed for ARs affecting Europe [...]”

Near line 30: “projected frequency enhancement and intensification of ARs”: Espinoza et al. 2018 could also be cited here to support this statement where they systematically examined and compared such changes across the globe; <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2017GL076968>

We added the mentioned reference to our citations and the relevant section in our manuscript.

Near line 5: change “on both, ” to “on both”.

Done.

Near line 10: change “both, precipitation and water level,” to “both precipitation and water level”.

Done.

Near line 10: “identify days with the presence of an AR”: for the sake of symmetry with CEs, a brief, high-level description of how AR days are identified is warranted here, i.e., based on certain quantile thresholds on intensity and geometry?

We agree with the Reviewer that this statement needs more explanation. However, to keep the Introduction concise, we chose to explain this concept in the Methods Section (Sect. 3) of the manuscript instead. We added a reference to the description to the Introduction.

The last paragraph of the Method Section now reads as follows:

“As mentioned in Section 2 the study presented in this paper isolates ARs in the database that passed over the Netherlands. For this, we isolated all days from the AR database on which an AR was detected within a box over 3.0°E-7.2°E/50.0°N-54.0°N (approximate location of the Netherlands) during at least one of the four daily time steps. This results in the equivalent treatment of days with an AR over the study area during multiple time steps and those days with an AR during only one time step. The duration of the presence of an AR over the study area is therefore neglected. This choice accounts for the frequency limitation set by the E-OBS dataset, which provides daily precipitation sums only (see Section 3.3).”

Near line 20: change “namely” to “namely,”.

Done.

Near line 15: “and provided online by Bin Guan”: consider removing as the information like this should be (and already is) in the acknowledgement section.

We removed this part of the sentence.

Near line 25: Guan et al. (2018) could also be cited here which provides more validation of the AR database based on comparing to field observations; see <https://journals.ametsoc.org/doi/abs/10.1175/JHM-D-17-0114.1>

We added this reference to the relevant citation.

Near line 15: “centred three-day precipitation”: I have difficulty understanding what “centred” conveys in this sentence. That is, the word seems unnecessary. If precipitation amounts on day 1, 2, and 3 are a, b, and c mm, respectively, the 3-day precipitation is simply a+b+c mm, i.e., there’s no “centering” needed to be done in the calculation.

We apologise for this confusion. We clarified our definition as follows:

[...] the centred three-day precipitation sum over one of the chosen regions in the study area exceeds its 95th percentile and the total water level at the associated coastal station exceeds its 95th percentile at any point during the same three-day period. The compound event is then considered to have occurred on the day in the centre of the three-day period over which the precipitation sum and the water level maximum was derived. The day before and after this are not considered compound events unless they are located in the middle of a three-day period that fulfils the above defined requirements.]

Near line 20: “number of compound events”: the numbers are not fully meaningful without first defining what an “event” is, i.e., is an event counted as a day, a 3-day period, or a continuous period ≥ 3 days?

We hope that our adjustment mentioned in our response to the Reviewer’s previous comment resolves this problem.

Near line 20: “within ± 1 days of the event”: Now I sort of understand what “centred” meant in the earlier sentence. In the example I gave above, does it mean the resulting value of a+b+c is assigned to day 2, and the 3-day period centered on day-2 is considered AR-related if an AR occurred on one or more days of day 1, 2, or 3? Please use the answer to make clarifications in the data section in terms of how a CE is defined, how an “event” is counted (e.g., if a CE lasted 6 continuous days, is it counted as one event, 2 events, or 6 events?), when a CE is considered to be AR-related or not ARrelated, what

“day of event” means, etc. Without clear and unambiguous definitions of terms, the statistics presented are hard to make sense of.

We apologise for this confusion. We clarified our definition by adding the following to the end of the section:

“[...] at any point during the same three-day period. The compound event is then considered to have occurred on the day in the centre of the three-day period over which the precipitation sum and the water level maximum was derived. The day before and after this are not considered compound events unless they are located in the middle of a three-day period that fulfils the above defined requirements.”

Near line 30: “climatological” is a typo of “climatology”, and “eseembling” a typo of “resembling”.

Corrected.

Near line 15: “probability density”: for a probability density function, if the function is integrated over all possibilities, the result should be one. But that does not appear to be the case in Figure 5. If you integrate the values over the x-y plane in Figure 5, what does the resulting number represent? That determines how the values contoured in the figure should be called.

We apologise for not providing a sufficient description of what Figure 5 is conveying. We added the following explanation to the caption of the Figure, which now is as follows:

“Joint probability distribution of three-day precipitation sums (mm) and three-day maximum total water level (m). Contours denote the area enclosing indicated percentage of data (30, 50, 70, 90, 95 and 99\% contours are shown). Dark/red contours show data for days without/with an AR over the Netherlands. Scatter plot [...] “

Near line 20: add “for” in front of “compound events without”.

Done.

Near line 10: “absolut” is a typo of “absolute”.

Corrected.

Near line 15: “persistent throughout the week before an event”: this makes me think that there are conditions during the week prior to the AR that favors the development of warm SSTs and the AR, and in that regard the ARCE (AR+CE) perhaps should be emphasized as indicative of the interplay between these conditions, instead of one causing the other.

We agree with the reviewer’s comment and highlighted this in the manuscript by adding the following sentence to the relevant passage:

“The changes in SLP conditions are also reflected in the anomalies in sea surface temperature (Fig. 7) through the connection between surface winds and ocean currents. This leads to spatial patterns that indicate the occurrence of compound events and provide a tool to predict the kind of compound event that will occur, i.e. CEs with AR association or CEs without. In case of ARs with CEs [...]”

Near line 15: “loose” is a typo of “lose”.

Corrected.

Near line 25: “Difference AR with CE and those without”: please fix the grammar.

We corrected the section title to

” **Difference between ARs with and without association to CEs**”

Near line 5: “noARCEs”: did you mean “noCEARs”? This makes think whether there’s a better way to name these events that works better for both the authors and readers, because names like noARCEs and noCEARs are just a bit too cryptic, and when used together with names like ARCEs and CEARs (which I think are identical?) they may cause unnecessary confusions to both the authors and the readers. How about something more descriptive like the following: - CEs with ARs - CEs without ARs - ARs with CEs (identical to CEs with ARs) - ARs without CEs

We agree with the Referee that the choice of abbreviation starts to be confusing in this section of the manuscript. We chose to replace the abbreviations noCEARs and CEARs with “ARs without CEs” and “ARs with CEs” respectively.

Near line 30: “early identification of compound events . . . one week in advance”: to make this statement and, more importantly, to make the main analysis of the paper more compelling, it is recommended to show that precursor conditions during the week leading to the CEs are statistically different than conditions leading to no CEs. It would be convenient to build on Figure 9 for this purpose, i.e., by expanding it to include the week before (similar to Figures 6 and 7), and adding significance test for the difference between “ARs with CEs” and “ARs without CEs”. Significance test is also suggested to be added to Figures 6 and 8 and fixed in Figure 7 for the difference between “CEs with ARs” and “CEs without ARs”. The paper heavily relies on statistical analysis (as opposed to dynamics-oriented analysis), so a robust accounting of the statistics is highly desirable.

We added an analysis of the statistical significance of the shown SLP and precipitation anomalies as requested by the Referee and adjusted the relevant figures accordingly. We think with the additional analysis we delivered results that sufficiently support this statement.

We also added a significance test the anomalies during ARs without CEs and adjusted the text accordingly. We added a final paragraph of Section 4.4 to describe this:

“[...] All features described above that characterise the mean conditions during ARs without CEs and make them different to the conditions during ARs with CEs are statistically significant (dotted areas in Fig. 6 – 9). This opens the possibility to use the here presented results in the early identification of an upcoming event.”

All adjusted Figures can be found at the end of this letter.

Near line 10: “a specific definition of ARs”: this sounds like there’re many different definitions, which I don’t think is true. My opinion is that the diversification in AR detection methods (perhaps 20 methods or more exist now) is a manifestation of the difficulty in detecting ARs, not because there’re that many different definitions.

We agree with the Referee that this formulation is misleading. We therefore changed this sentence to:

” We also note that the identification of ARs that are analysed in this study is influenced by the applied AR-detection algorithm. The particular algorithm applied here [...]

Near line 15: “their effect would be marginal”: consider removing this statement given the large variations across different AR detection methods (see <https://www.geoscimodel-dev.net/11/2455/2018/>).

Removed.

Near line 25: change “based on their poleward transport” to “based on their lacking of poleward transport”.

Done.

Table 1 and where applicable in the text: “on day of event”, “one day before or after event”: given that the precipitation is a 3-day total, and CEs are defined using a 3-day window, descriptions like these are quite ambiguous. For example, if a CE occurred during the period of January 1-3, then common sense is that “one day before event” is December 31, and “one day after event” is “January 4”. But that doesn’t seem to be what the authors intended in indicate here. Again, an unambiguous definition of terms is needed to avoid potential confusions of this kind, as also suggested earlier.

We hope that our adjustment mentioned in our response to the Reviewer’s previous comment resolves this problem.

Figure 2 caption: please define “area covered by AR”, or how it was calculated. Area would have units of m^2 , but it doesn't seem to be the case here. Did you mean AR frequency of occurrence (percent of time steps)? The latter is a more widely used and understood terminology in at least the AR community.

We adjusted this caption to convey the information more clearly. The caption now reads:

“Climatology of daily mean sea level pressure (SLP; colour shading). Contours mark regions over which ARs are located. Numbers indicate the relative amount of time that the respective area is covered by an ARs throughout the study period (1979-2015).”

Figure 3: “over NL”: what does NL refer to or is it defined somewhere? Are the numbers per single month (i.e., the climatological mean), or the total over the given month? Suppose something happens 3 times in January, and is repeated for the past 100 years, it is more sensible to say it happens 3 times per month, instead of 300 times per month, right?

We added the abbreviation “NL” to the figure caption as well as in the text within the Introduction and the Results section. Additionally we clarified that the numbers presented in the figure are monthly climatological mean values. The caption now reads:

“Monthly climatological mean number of compound events per month at the four coastal stations assessed in this study. Black columns indicate the number of all CEs (CEs with AR + CEs without AR + ARpm1dayCEs), while red bars show the number of CEs with association to an AR over the Netherlands (NL; CEs with AR).”

Figure 6: the plots and fonts are too small. Also, the caption says “The right two columns” twice, the first one of which should be “The left two columns”.

We corrected the caption and increased the font sizes in this Figure. The new figure can be found below.

Figures 6, 7, 8: “Anomalies CE with AR” etc.: please change to “Anomalies during CEs with ARs”, etc. for clarity.

Done.

Figure 7 caption: “Grey areas mark regions with a p-value below 0.05”: given that a small p-value indicates high significance, do you mean the grey areas are where the values are significant, and the color shadings are where the values are NOT significant? That makes no sense because that would mean you are highlighting the nonsignificant values, and obscuring the significant values. Also, it is against intuition that the strongest anomaly values (darkest shading in the figure) are with large p-values, i.e., non-significant.

We thank the Referee for bringing this problem to our attention. As mentioned above we have adjusted our statistical method to determine significance and corrected the Figure and caption (see end of this letter). We also changed the text passages referring to this figure.

“[...] As a result, the wind anomalies, which increase with time getting stronger closer to the event (Fig. A2), induce a **decrease in SSTs within the North Atlantic subpolar gyre that expands throughout the week before the event (Fig. 7a, c and e). On the day of the event this negative anomaly covers parts of the Labrador Sea and the subpolar North Atlantic. At the same time an** increase in SSTs develops that covers large parts of the western and central (tropical and subtropical) North Atlantic, the North Sea and parts of the Norwegian Sea on the day of the event (Fig. 7a, c and e). [...] **The negative SST anomaly pattern over the subpolar North Atlantic is most likely caused by changes in the transport of surface waters from higher latitudes to subpolar North Atlantic due to a strengthening of the north-northeasterly component of the wind field throughout the week before the event (Fig. A2).** However, [...]”

Figures

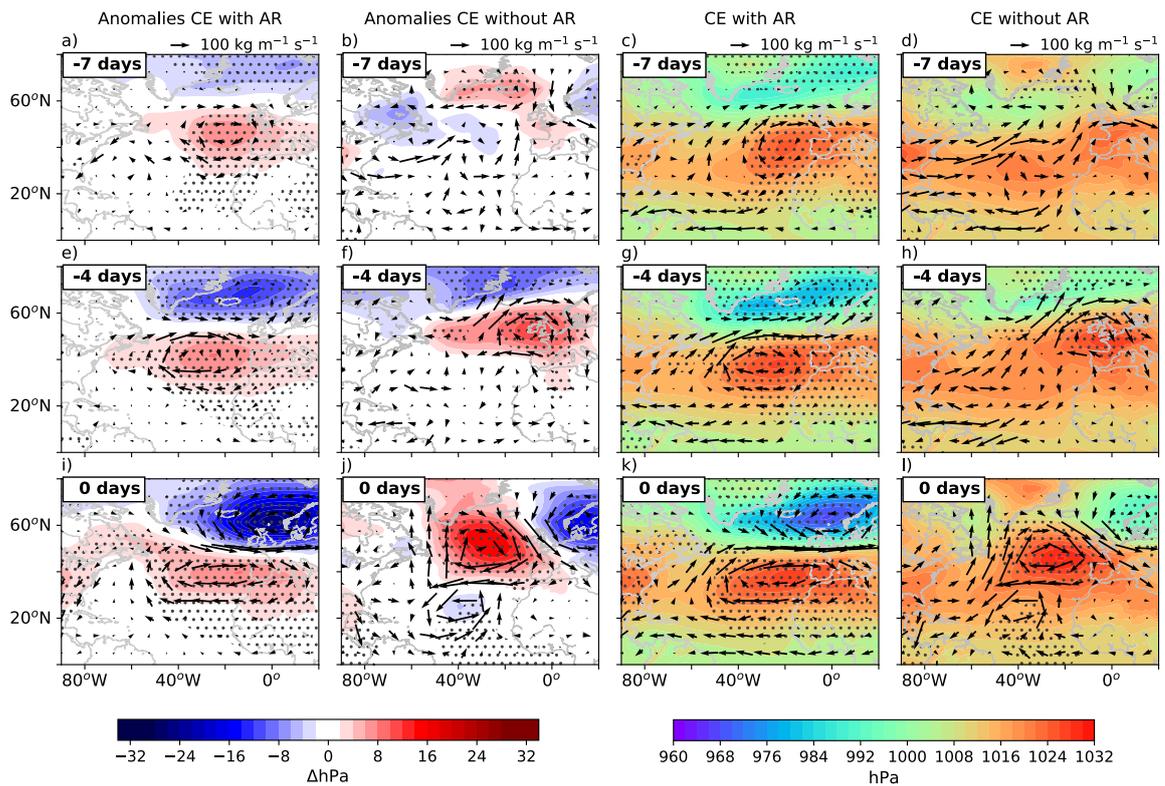


Figure 6: Temporal evolution of mean conditions seven (a-d) and four days (e-h) before a CE at Den Helder and on the day of the event itself (i-l). The left two columns, i.e. panels a, e, i and b, f, j, show the evolution of anomalies in SLP (colour shading) and IVT (vector field) during CEs with and without AR association, respectively. The right two columns, i.e. panels c, g, k and d, h, l, show the same but for absolute values of daily mean SLP and IVT. Results for the three other stations (not shown) are comparable. **Stippled areas mark regions with a p-value below 0.05 derived from student t-test of daily mean SLP values compared to the daily mean values of full time series.**

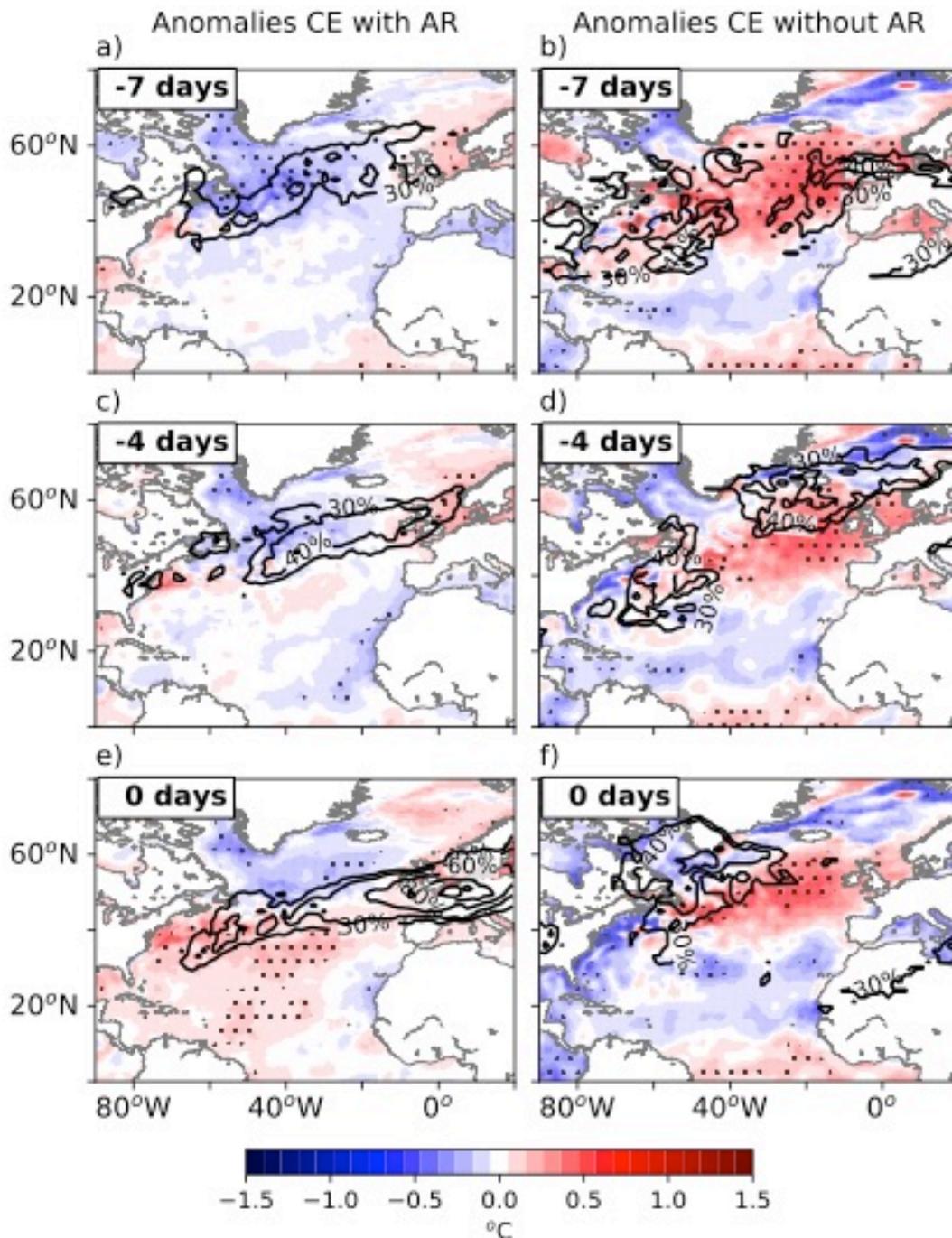


Figure 7: Anomalies in daily mean SSTs (shading) related to CEs with (left panels a, c and e) and CEs without AR association (right panels b, d and f) seven and four days before a CE (a and b; c and d, respectively) and on the day of the event (e and f). Contours mark regions that are occupied by more than 30% of all ARs in the specific category with contour intervals at 30%, 40%, 60%, 80%, 90%, 99% and 100%. **Stippled areas mark regions with a p-value below 0.05 derived from a student t-test comparing the monthly anomalies of daily mean SST values on the day of events to those throughout the full time series.**

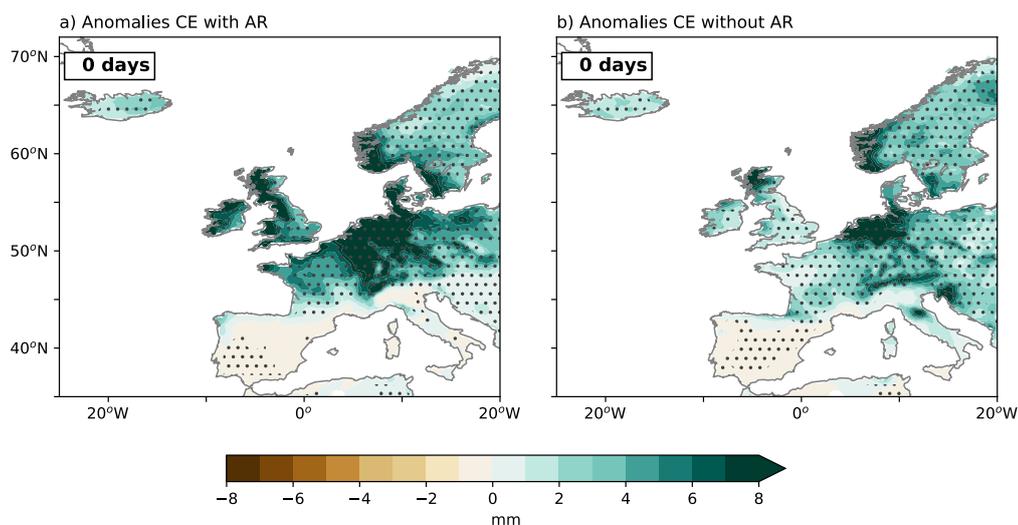


Figure 8: Anomalies of daily mean precipitation sums during CEs with (a) and without (b) AR association. **Stippled areas mark regions with a p-value below 0.05 derived from a student t-test of daily precipitation values during events and the full time series.**

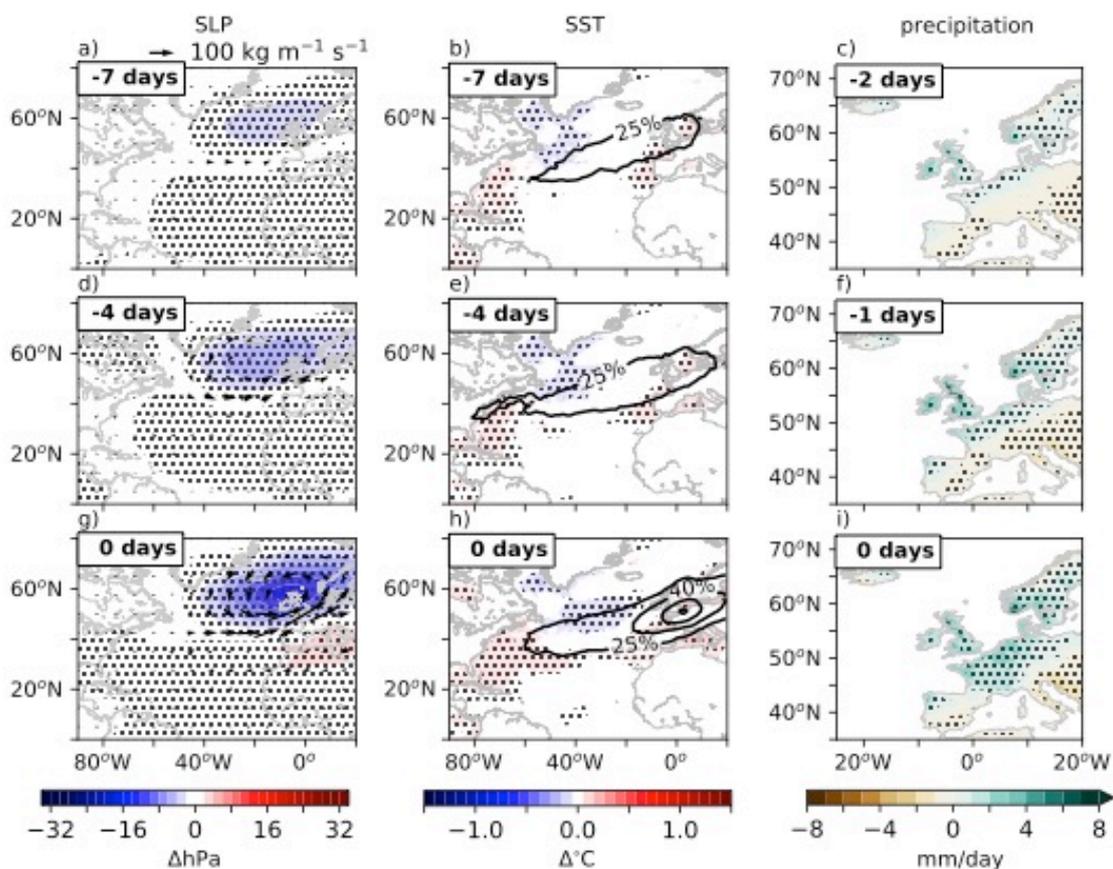


Figure 9: Anomalies of (a) SLP (colour shading) and IVT (vectors), (b) SST (colour shading) and relative number of ARs covering an area, and (c) precipitation on days with an AR over the Netherlands without the occurrence

of a CE. Stippled areas indicate regions where the difference in conditions between ARs with CEs and ARs without CEs are statistical significant with a p-value below 0.05 derived from a student t-test comparing monthly anomalies of daily mean values during events to those of the full time series.